State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2021

Jennifer L. Boldt, Elizabeth Joyce, Strahan Tucker, and Stéphane Gauthier (Editors)

Fisheries and Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, B.C. V9T 6N7

2022

Canadian Technical Report of Fisheries and Aquatic Sciences 3482

Fisheries and Oceans Canada Pêches et Océans Canada

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. II n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques.*

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développement, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report of Fisheries and Aquatic Sciences 3482

2022

STATE OF THE PHYSICAL, BIOLOGICAL AND SELECTED FISHERY RESOURCES OF PACIFIC CANADIAN MARINE ECOSYSTEMS IN 2021

Jennifer L. Boldt[1], Elizabeth Joyce[2], Strahan Tucker[1], and Stéphane Gauthier [3] (Editors)

[1]Fisheries & Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, B.C. V9T 6N7
Canada
Jennifer.Boldt@dfo-mpo.gc.ca
Strahan.Tucker@dfo-mpo.gc.ca

[2]Elizabeth Joyce Scientific Services
4412 Columbia Drive
Victoria, B.C. V8N 3J3
Canada
elizabethjoyce@shaw.ca

[3]Fisheries & Oceans Canada
Institute of Ocean Sciences
9860 West Saanich Road
Sidney, B.C. V8L 4B2
Canada
Stephane.Gauthier@dfo-mpo.gc.ca

Cat. No. Fs97-6/3482E-PDF ISBN 978-0-660-43654-8 ISSN 1488-5379

Correct citation for this publication:

Boldt, J.L., Joyce, E., Tucker, S., and Gauthier, S. (Eds.). 2022. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2021. Can. Tech. Rep. Fish. Aquat. Sci. 3482: vii + 242 p.

Table of Contents

Abstract

Boldt, J.L., Joyce, E., Tucker, S., and Gauthier, S. (Eds.). 2022. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2021. Can. Tech. Rep. Fish. Aquat. Sci. 3482: vii + 242 p.

The physical oceanography of Pacific Canadian marine ecosystems is characterized by strong seasonality in coastal upwelling and downwelling, considerable freshwater influence, and variability from coupling with events and conditions in the tropical and North Pacific Ocean. The region supports ecologically and economically important resident and migratory populations of invertebrates, groundfish, pelagic fishes, marine mammals, and seabirds. Fisheries and Oceans Canada is responsible for the management and protection of marine resources on the Pacific coast of Canada.

Since 1999 an annual State of the Pacific Ocean meeting has been held by DFO to bring together the marine science community in the Pacific Region and present the results of the most recent year's monitoring in the context of previous observations and expected future conditions. Due to the COVID-19 pandemic, the workshop to review ecosystem conditions in 2021 was convened virtually, March 8-10, 2022. This technical report includes submissions based on presentations given at the meeting and a few poster summaries.

Climate change is a dominant pressure acting on North Pacific marine ecosystems, causing, for example, increasing temperatures, deoxygenation, and acidification, and changes to circulation and vertical mixing. These pressures impact ecosystem nutrient concentrations essential to primary and secondary productivity, which then affect higher trophic levels through the food chain.

Résumé

Boldt, J.L., Joyce, E., Tucker, S., and Gauthier, S. (Eds.). 2022. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2021. Can. Tech. Rep. Fish. Aquat. Sci. 3482: vii + 242 p.

L'océanographie physique des écosystèmes marins du Canda Pacifique est caractérisée par une forte saisonnalité dans les remontées d'eaux profondes côtières et les plongées d'eaux, d'une forte influence des eaux douces, et d'une variabilité provenant des phénomènes et des conditions dans l'océan Pacifique tropical et l'océan Pacifique Nord. La région soutient des populations résidentes et migratrices écologiquement et économiquement importantes d'invertébrés, de poissons de fond et pélagiques, ainsi que de mammifères et d'oiseaux marins. Pêches et Océans Canada est chargé de la gestion et de la protection des ressources maritimes sur la côte Pacifique du Canada.

Depuis 1999, une réunion annuelle sur l'état de l'océan Pacifique est organisée par le MPO afin de réunir la communauté scientifique dans la région du Pacifique et de présenter les résultats des programmes de surveillance de la dernière année dans le contexte d'observations précédentes, ainsi que les conditions futures attendues. En raison de la pandémie de COVID-19, l'atelier pour évaluer les conditions de l'écosystème en 2021 organisé du 8 au 10 mars 2022 s'est déroulé virtuellement. Le présent rapport technique comprend des soumissions basées sur les présentations données durant l'atelier et des résumés d'affiches.

Les changements climatiques constituent une pression dominante qui agit sur les écosystèmes marins du Pacifique Nord et sont la cause, entre autres, de l'augmentation des températures, de la désoxygénation, de l'acidification et des changements dans le régime de circulation et du mélange vertical. Ces pressions ont des effets sur les concentrations d'éléments nutritifs et la productivité primaire et secondaire des écosystèmes, qui à leurs tours ont un impact sur les niveaux trophiques supérieurs par l'intermédiaire de la chaîne alimentaire.

Highlights, Introduction, and Overview

1. HIGHLIGHTS

1. Annual average sea surface temperature (SST) in the northeast Pacific was average to slightly above average. La Niña and atmospheric conditions should have led to below average SSTs; however, there were multiple marine heatwave events and a long-term trend of increasing SST in the NE Pacific.

2. During summer in southern B.C., there was an extreme atmospheric heat wave (the 'heat dome') and severe drought; whereas, in the fall, there was record precipitation with severe flooding resulting in high surface ocean sediment loads.

3. In summer, there was a rare hypoxia event on the outer southwest shelf off the west coast of Vancouver Island (WCVI); dissolved oxygen concentrations there were the lowest recorded in the last 20 years. In the Strait of Georgia (SOG), there has been a 23-year trend of decreasing oxygen at all depths.

4. Surface waters in the NE Pacific were anomalously fresh in 2021, with each of the last five years being progressively fresher. In the SOG, there has also been a trend to lower salinities in surface waters and to higher salinities at depth.

5. In the northern Salish Sea, spring pH conditions were average, but by late summer reverted to corrosive conditions. Areas closer to shore appear to be more sensitive to ocean acidification.

6. The 2021 spring transition timing of upwelling off the WCVI was early and the magnitude of summer upwelling was near the long-term average, resulting in an expectation of average to above average marine coastal productivity across trophic levels.

7. Indices of both phytoplankton and zooplankton community composition off the WCVI have generally returned to average following the 2014-16 marine heatwave. In the SOG, model results indicate 2021 was a late year for spring bloom timing, and observations indicated zooplankton biomass increased.

8. Olympia Oyster relative abundance has remained stable at most index sites between 2010 and 2021. Extreme heat events, such as the heat dome of 2021, may have a long-term effect on Olympia Oyster survival and reproduction.

9. The coastwide Pacific Herring biomass has been increasing since 2010, dominated by the SOG stock; however, in some assessed areas, such as Haida Gwaii, there have been prolonged periods of low biomass. Herring weight-at-age continued to level off or increase.

10. Fraser River Eulachon spawning biomass was at a moderately low level in 2021 (relative to 1995-2021); whereas, off the WCVI, Eulachon biomass, of mixed ages and stocks, was moderately high (2000-2022).

11. The return abundances of Sockeye Salmon indicator stocks were below the long-term average. The June heat dome generated thermal barriers in southern watersheds, migration delays, and enroute mortality. The size of returning Fraser River Sockeye and Pink Salmon has been decreasing.

12. The proportion and biomass of Pacific Hake in B.C. waters was the lowest on record; the total stock biomass off the west coast of North America was slightly above the median.

13. There was an increase in the surveyed biomass of shelf rockfish, some slope rockfish, and many flatfish species over the last 5-10 years. At the same time, Arrowtooth Flounder and Pacific Spiny Dogfish surveyed biomass declined.

14. Marine Aquatic Invasive Species are increasing in both range and abundance in B.C. For example, there has been an expansion of European Green Crab around Haida Gwaii and the Salish Sea.

15. Several populations of marine mammals have shown strong recovery trends (notably humpback whales) after commercial whaling ended in 1967.

16. Cargo vessel traffic in the SOG and Gulf Islands increased in 2021, tanker traffic in the SOG decreased, and tug and passenger vessel traffic varied.

2. INTRODUCTION

Fisheries and Oceans Canada (DFO), Pacific Region, facilitates and assembles an annual overview of the physical, chemical and biological conditions in the ocean off Canada's west coast. This compilation helps to develop a picture of how the ocean is changing and provides advance identification of important changes which may potentially impact human uses, activities, and benefits from the ocean. This is done in a two or three day meeting, usually held in February or March of the year subsequent to the year being considered. The first meeting was held in 2000 to assess conditions in 1999; reports from these reviews are available at the following link (see bottom of web page):

http://www.dfo-mpo.gc.ca/oceans/publications/index-eng.html

Reviews and reports from 2007 to 2013 were conducted under the direction of the Fisheries & Oceans Canadian Science Advice Secretariat (CSAS). In 2014, these State of the Pacific Ocean reviews were moved to a separate process and are now presented as Fisheries & Oceans Canada Technical Reports. The report from 2021 (for conditions in 2020) is available at

http://waves-vagues.dfo-mpo.gc.ca/Library/4098297x.pdf

Due to the continuing COVID-19 pandemic, the meeting on conditions observed on the west coast of Canada (Figure 2-1) in 2021 was convened virtually, March 8-10, 2022. Due to the meeting's online platform, both the 2021 and 2022 meetings reached a larger and broader audience. This year's meeting was attended by 356 researchers from the federal and B.C. governments, First Nations and Indigenous groups, academia, national and international partners, and the private sector. For example, attendees included scientists from Fisheries and Oceans Canada, Parks Canada, Environment and Climate Change Canada, 17 different First Nation and Indigenous organizations, such as Council of the Haida Nation, Cowichan Tribes First Nation, Kitselas First Nation, and Spuzzum First Nation, as well as the Province of B.C., Hakai Institute, University of British Columbia, University of Victoria, Ocean Networks Canada, North Pacific Anadromous Fish Commission, North Pacific Marine Science Organization, Grieg Seafood, and the T. Buck Suzuki Foundation, among others. These annual meetings represent a unique opportunity for scientists from different disciplines to highlight preliminary results of atmospheric, oceanographic and marine species observations in 2021 in the context of historical observations.

Figure 2-1. Map of regions described in this report.

Elder Naalthwiik from the Snuneymuxw First Nation provided a meeting welcome and closing prayer. Regional Director of Science, Andy Thomson, provided opening remarks, including comments on the challenges of ocean-monitoring that were overcome in another COVID-19 year, the importance of long-term monitoring, and the International Year of the Salmon survey that was underway during the meeting. At the meeting, 38 talks and 4 posters were presented. There was a special presentation on a Fisheries and Oceans Canada report titled *Canada's Oceans Now: Pacific Ecosystems, 2021* (EN + FR). The report is a high-level summary of status and trends in the Pacific Ocean with engaging infographics and plain language science writing; it was released during Oceans Week on June 9th (including: web page (EN+FR); infographics (EN+FR); trailer video (EN+FR)). The report was endorsed by the Intergovernmental Oceanographic Commission of UNESCO as a United Nations Decade of Ocean Science for Sustainable Development activity. This public report is based on key findings detailed in the Canadian Technical Report of Fisheries and Aquatic Sciences 3377 and 3434, State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2019 and 2020.

Elder Naalthwiik, from the Snuneymuxw FirstNation (left), provided a meeting welcome and closing prayer. Regional Director of Science, Andy Thomson (right), provided opening remarks.

The agenda for the meeting is presented in Appendix 1, Poster summaries are presented in Appendix 2, and the meeting participants are listed in Appendix 3. The meeting was co-chaired by Jennifer Boldt (Pacific Biological Station), Strahan Tucker (Pacific Biological Station), Stéphane Gauthier (Institute of Ocean Sciences), and organized by Elizabeth Joyce, and all technical aspects of the virtual meeting were run by Stephen Page (Institute of Ocean Sciences).

2022 SOPO meeting organizers, Stephen Page (top left), Strahan Tucker (top right), Jennifer Boldt (middle left), Stéphane Gauthier (middle right), and Elizabeth Joyce (bottom centre).

This technical report presents the highlights and summaries of the presentations and discussions at the workshop. These summary reports are not peer reviewed, and present the status of data, interpretation, and knowledge as of the date of this meeting. For use of, or reference to these individual presentations, please contact the individual authors.

3. OVERVIEW AND SUMMARY

Climate change continues to be a dominant pressure acting on Northeast (NE) Pacific marine ecosystems. B.C. air temperatures continued to increase (1950-2021) and set new all-time high records across southern B.C. in June 2021 (Anslow and Sobie, Section 6). This led to severe drought in southern B.C. in July-September before shifting to record wet conditions in the fall, with extreme flooding during November (Anslow and Sobie, Section 6). In 2021, river discharge in southern B.C. was greater than normal, but was close to average in northern B.C. (Anslow and Sobie, Section 6; Chandler, Section 10). In 2021, strong negative Pacific Decadal Oscillation (PDO) and La Niña conditions, that typically result in below average Sea Surface Temperatures (SSTs), were juxtaposed onto a background of long-term climate warming, resulting in near average SSTs in the NE Pacific (Ross and Robert, Section 7; Figures 3-1 and 3-2). The average annual SST, collected at shore stations along the B.C. coast, was cooler than 2020 but was still a continuation of the warm period that started in 2014 (Chandler, Section 10). Overlying multi-year oscillations in the annual SST, there is a long-term trend towards rising ocean temperatures of 0.87°C over the last 100 years (Figure 3-3; Chandler, Section 10). Surface waters in the NE Pacific were anomalously fresh in 2021; this continues a freshening trend observed for the last five years (Ross and Robert, Section 7). Increasing CO_2 in the atmosphere has increased the acidification of the ocean, which will continue to intensify with the rise of anthropogenic carbon levels in the atmosphere (Evans, Section 31). In spring 2021, marine CO_2 conditions in the northern Salish Sea improved compared to 2018-2020, but returned to more corrosive and low pH conditions for the remainder of the year (Evans, Section 31).

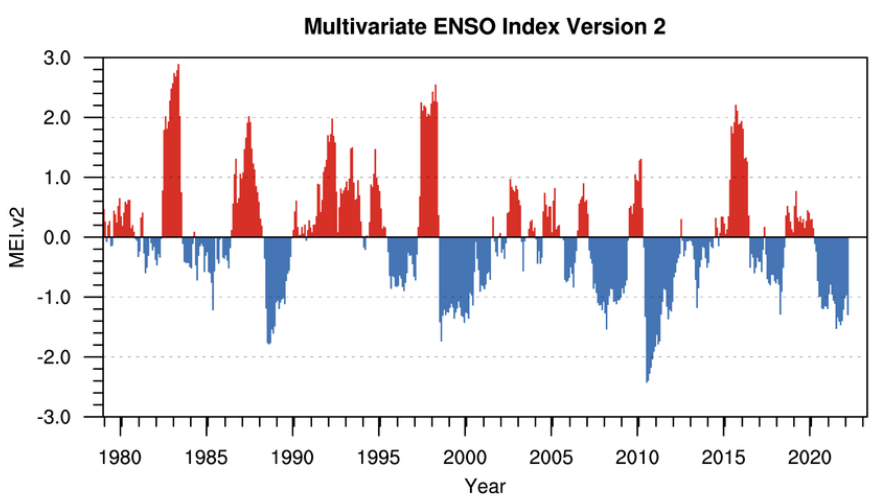


Figure 3-1. The multivariate ENSO Index. Data source: NOAA/ESRL/Physical Sciences Division – University of Colorado at Boulder/CIRES; https://psl.noaa.gov/enso/mei/

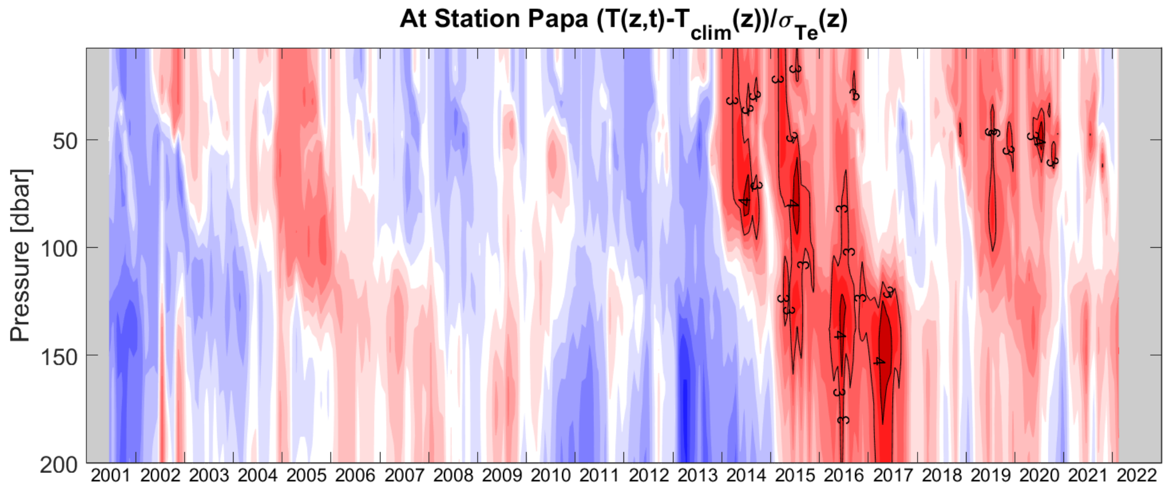


Figure 3-2. Plot of temperature anomalies relative to the 1956-2012 seasonally-corrected mean and standard deviation (from the Line P time series), as observed by Argo floats near Ocean Station Papa (P26: 5° N, 145° W). The cool colours indicate cooler than average temperatures and warm colours indicate warmer than average temperatures. Dark colours indicate anomalies that are large compared with the 1956-2012 standard deviations. The black lines highlight regions with anomalies that are 3 and 4 standard deviations above the mean. Source: Ross and Robert, Section 7.

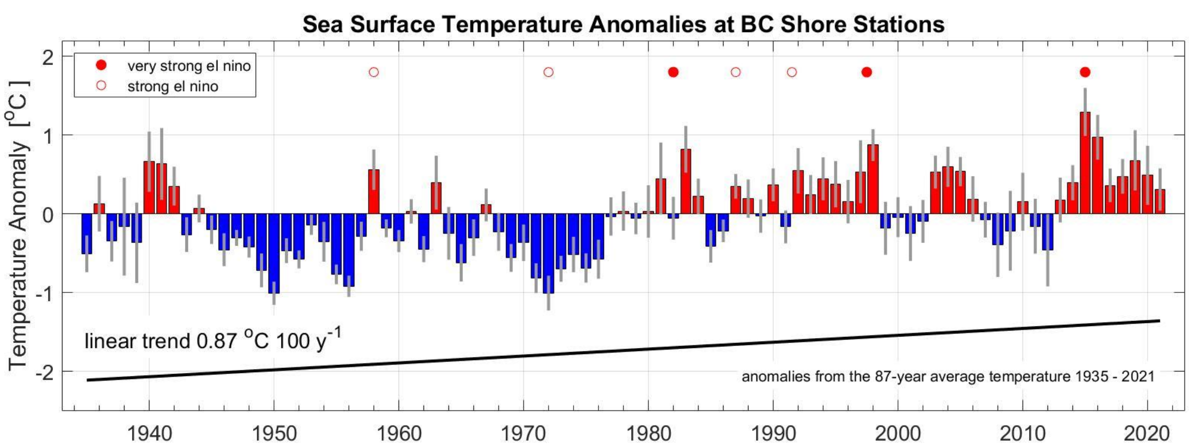


Figure 3-3. The trend in the annual temperature based on the observations of all lighthouses. Data shown are anomalies from the long-term average temperature (1935-2021). Bars represent the anomalies averaged over all stations (a coast wide indicator), (red – above average, blue – below average), vertical grey lines show the variability in the lighthouse data for each year. Source: Chandler, Section 10.

Multiple marine heatwaves (MHWs) were identified in the NE Pacific in 2021; the largest MHW areas remained offshore in the open ocean for much of the year. There was a short-lived MHW on the shelf during the atmospheric heatwave event (the “Heat Dome”, June 25 to July 1; Hilborn and Hannah, Section 11). The size, intensity, and frequency of MHWs in the NE Pacific is increasing (Hilborn and Hannah, Section 11).

Marine heatwaves are associated with reduced vertical mixing, which causes increased winter stratification. This results in decreased nutrient supply from deep to surface offshore waters. Mixing in the winter of 2020/21 was closer to normal than the previous two years, suggesting normal surface nutrient levels in the spring of 2021 (Figure 3-4; Ross and Robert, Section 7).

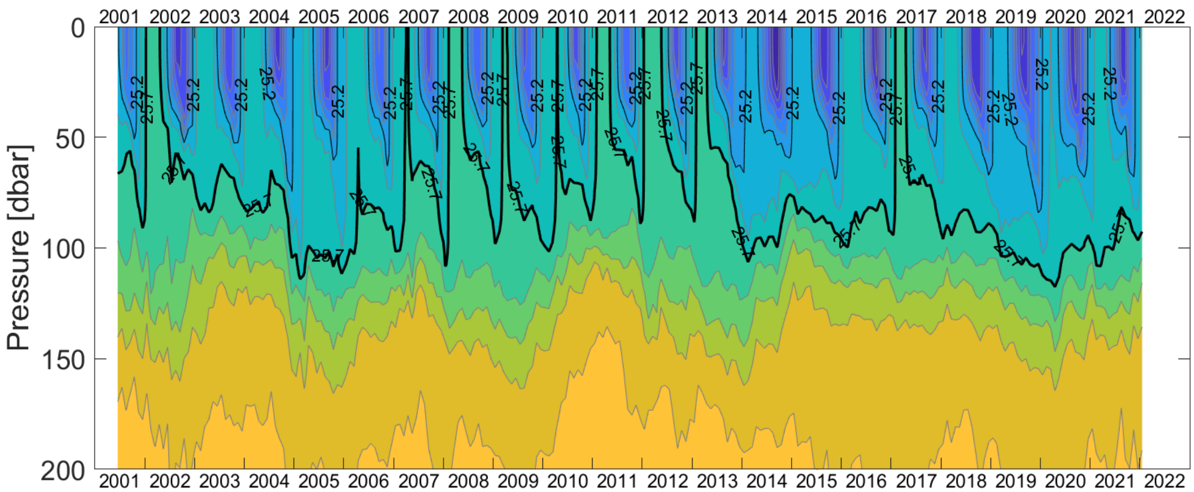


Figure 3-4. Coloured contour plot of density as observed by Argo floats near Ocean Station Papa (P26: 50º N, 145 º W). The colours indicate potential density (yellow is denser and blue lighter). Black lines highlight the σ_θ 25.2 kg/m^3 (thin) and 25.7 kg/ m^3 (thick) isopycnals. Source: Ross and Robert, Section 7.

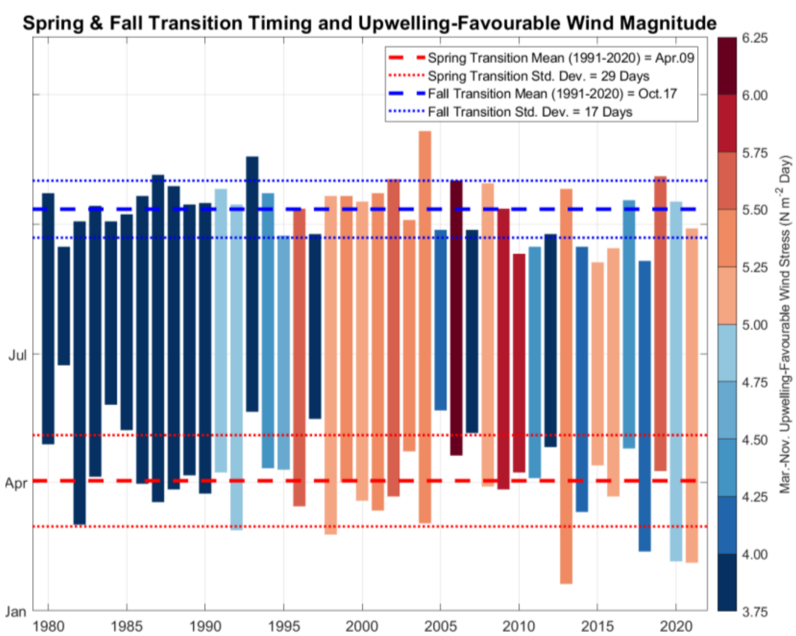


Figure 3-5. Annual spring and fall transition timing and March-November upwelling-favourable wind stress magnitude, 1980-2021. Bold dashed lines indicate the average spring (red) and fall (blue) transition dates. Light-dashed lines indicate standard deviations of the spring (red) and fall (blue) transition dates. Source: Roy Hourston, Section 8.

The timing and magnitude of upwelling of deep, nutrient-rich water off the west coast of Vancouver Island (WCVI) is an indicator of marine coastal productivity across trophic levels from plankton to fish to birds. Variability in the upwelling index corresponds with variations in the strength and/or longitudinal position of the Aleutian low-pressure system in the Gulf of Alaska. The 2021 spring transition timing of upwelling was early and the magnitude of summer upwelling was near the long-term average, resulting in an expectation of average to above average productivity

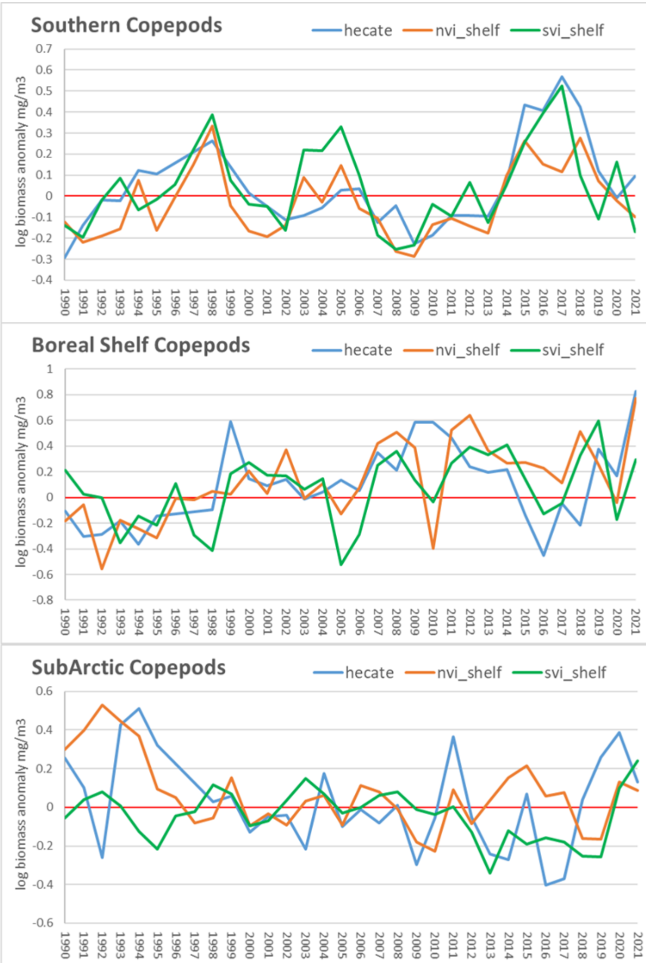


Figure 3-6. Zooplankton species-group anomaly time series. Line graphs are annual log scale anomalies. Southern Vancouver Island (SVI) green; Northern Vancouver Island (NVI) orange; Hecate Strait blue; Line P purple - for all graphs. Blank years mean no samples were collected. Source: Galbraith and Young, Section 17.

(Hourston and Thomson, Section 8; Dewey et al., Section 33; Figure 3-5).

Persistent upwelling, particularly along the southern Vancouver Island continental slope, brought California undercurrent source waters onto the shelf, supplying nutrients and saline water to surface waters and extending deep, oxygen-poor waters over the shelf eastward (Sastri et al., Section 13; Dewey et al., Section 33). In the summer, there was a rare hypoxia event on the outer southwest shelf off the west coast of Vancouver Island; dissolved oxygen concentrations were the lowest recorded in the last 20 years. Phytoplankton communities appear to be returning to average values after the MHW (2014-2016) in the shelf region (Ostle and Batten, Section 18).

The zooplankton community also returned to average values (Galbraith and Young, Section 17; Ostle and Batten, Section 18). In 2021, there were positive biomass anomalies of boreal and subarctic copepods in most areas (Galbraith and Young, Section 17; Figure 3-6). Southern copepod anomalies were negative or close to average on the shelf and in offshore areas (Figure 3-6; Galbraith and Young, Section 17; Ostle and Batten, Section 18). Large subarctic and boreal copepods are more favourable for fish growth than small, southern copepod species.

Changes to the physical environment, and phytoplankton and zooplankton communities can have impacts on higher trophic levels. Extreme heat events, such as the atmospheric heat dome of 2021, may have a long-term effect on Olympia Oyster survival and reproduction (Herder and Bureau, Section 19). The proportion and biomass of the Pacific Hake coastal migrating stock in B.C. waters was the lowest on record, despite an average year for the coast-wide total biomass (Gauthier et al., Section 25). There was an increase in the biomass of shelf rockfish, some slope rockfish, and many flatfish species in the recent 5-10 years. Arrowtooth Flounder and Pacific Spiny Dogfish biomass declined (Anderson and English, Section 24).

The growth rate of Cassin's Auklets is linked to the abundance of their primary prey, *Neocalanus cristatus* copepods, which are more abundant during relatively cold years (Hipfner et al. 2020). In 2021, the representation of *N. cristatus* in Cassin's auklet nestling diets on Triangle Island was well below what would be expected based on PDO conditions (Hipfner, Section 26). Several populations of marine mammals have shown strong recovery trends (notably humpback whales) after commercial whaling ended in 1967, and are once again important components of marine ecosystems, resulting in increased overlap with human activities and potential conflicts with fisheries (Doniol-Valcroze et al., Section 27).

In the Salish Sea, there are trends of increasing temperature and decreasing oxygen at all depths, and salinity is generally becoming fresher in surface waters and saltier at depth (Chandler, Section 32). During the spring of 2021, conditions seaward of Haro Strait were cooler, saltier, and less oxygenated than normal, while conditions in the Strait of Georgia (SOG) were near normal. In the summer, the SOG was cooler and less oxygenated than normal in the surface waters, with a warm, salty, oxygenated mid-depth layer in Juan de Fuca Strait. In the fall, there was less oxygenated water throughout the system, especially in Juan de Fuca Strait. The annual Fraser River discharge was slightly above normal in 2021, while the impact of the atmospheric river resulted in very high flows in mid-November (Figure 3-7; Chandler, Section 32) and significant freshwater discharge into the surface waters of the Salish Sea (Dewey et al., Section 33).

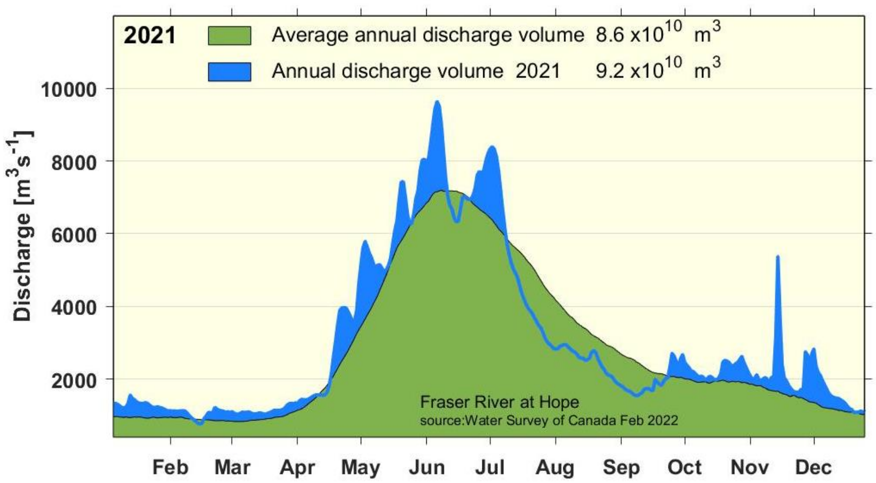


Figure 3-7. Fraser River discharge at Hope B.C.; 2021 (blue), 109-year average (green). Extracted from the Environment and Climate Change Canada Real-time Hydrometric Data web site (https://wateroffice.ec.gc.ca/mainmenu/real_time_data_index_e.html) on 10 Feb 2022. Source: Chandler, Section 32.

In the SOG in 2021, harmful algal blooms were similar to conditions in 2016 and 2017: there were no *Heterosigma akashiwo* blooms but there were blooms of silicoflagellate *Dictyocha* in some areas in July and August, and there were summer diatom blooms of *Rhizosolenia setigera* and *Pseudo-nitzschia* spp. (Esenkulova et al., Section 35). Harmful algal blooms can cause finfish and shellfish mortalities, impacts to human health, and economic losses. Marine Aquatic Invasive Species are increasing in both range and abundance in B.C. For example, there has been an expansion of European Green Crab around Haida Gwaii and the Salish Sea (Gale et al., Section 41). This high-impact invader that negatively affects eelgrass, an important fish habitat, was detected for the first time on Haida Gwaii in July 2020 (Gale et al., Section 41). Vessel traffic introduces a variety of stressors to marine ecosystems (e.g., oil, noise, shipstrikes, etc). Marine vessel traffic intensity, based on Automatic Identification System data from 2016-

2020, varied among vessel types in the Salish Sea, however cargo vessels continue to increase in the Southern Gulf Islands and SOG (O'Hara et al., Section 42). Passenger vessel traffic intensity decreased with year, but only during the summer, and likely as a result of COVID-19 associated reduced ferry service (O'Hara et al., Section 42). Commercial vessel noise is chronic in Juan de Fuca Strait and on Swiftsure Bank; whereas, in Boundary Pass and Haro Strait, it is acute with more periodic transiting of vessels (Burnham and Vagle, Section 43).

Annual variation in spring bloom timing and community composition may affect the food web, through a temporal match or mismatch between prey and their predators. In the SOG, the spring bloom timing was moderately late compared to the long-term average (Allen and Latornell, Section 34; Dewey et al., Section 33), which implies poorer feeding conditions for juvenile fish.

In 2021, however, the SOG zooplankton biomass was above the long-term average (Young et al., Section 36). The composition of the medium and large-sized copepods, important food for juvenile salmon, was similar to 2020 (Young et al., Section 36).

Coastwide Pacific Herring biomass has been increasing since 2010, dominated by the SOG stock; however, in some assessed areas, such as Haida Gwaii, there have been prolonged periods of low biomass (Cleary et al., Section 21; Figure 3-8).

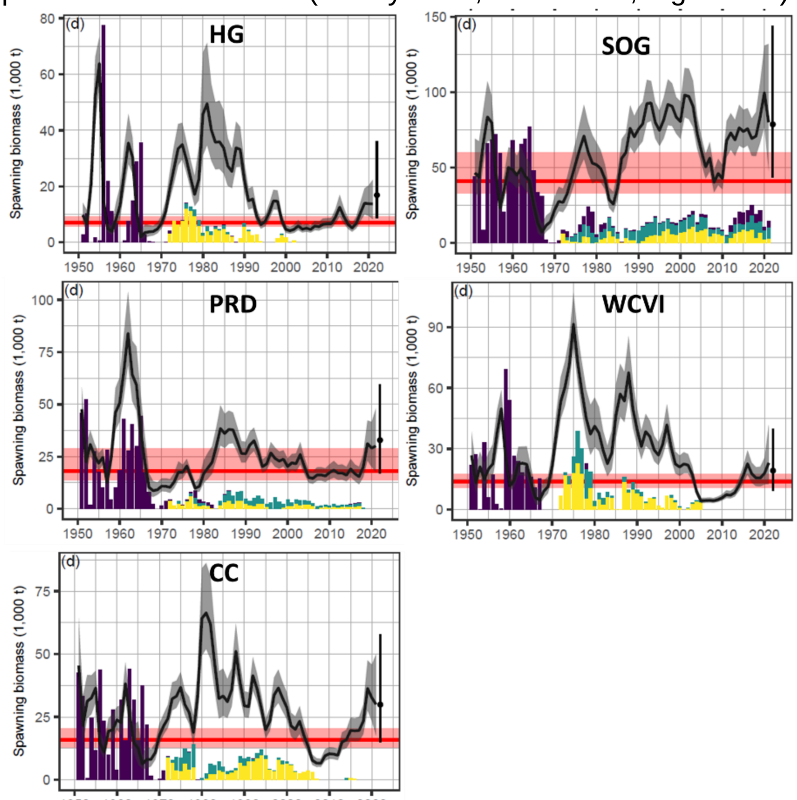


Figure 3-8. Pacific Herring spawning biomass, 1951- 2021. Black lines with surrounding grey envelopes represent medians and 5-95 % credible intervals. The projected spawning biomass given zero catch is shown at the far right (solid circle and vertical lines). Time series of thin vertical lines denote commercial catch (excluding commercial spawn-on-kelp; colours indicate different gear types; see DFO 2021). Red line = limit reference point (0.3B0). B0 = average unfished spawning biomass. Figure from DFO (2021).

In 2021, the relative biomass of age-0 Pacific Herring in the SOG was similar to that observed in 2019, but still below the time series mean and median; a very low biomass estimate of age-0 may indicate low recruitment to the adult population (Boldt et al., Section 37). In 2021, Northern Anchovy were present in 48% of the age-0 Pacific Herring survey sets; this is the second highest percentage in the time series (Boldt et al., Section 37). In 2021, the index of Fraser River Eulachon spawning stock biomass was estimated to be moderately low (~141 tonnes; Flostrand and Ens, Section 20). However, mean Eulachon catch per unit effort from a west coast of Vancouver Island multispecies bottom trawl survey was moderately high (Flostrand and Ens, Section 20). In 2021, a freshwater benthic diatom known as Didymo was confirmed to again be a major component of the material collected in the Fraser River Eulachon egg and larval survey water samples, similar to observations in 2018 and 2020 (Flostrand and Ens, Section 20). The extensive growth of Didymo in upper watersheds in B.C. and high outflow of Didymo in the lower Fraser River have unknown and possibly negative implications for upper and lower watershed habitats and ecosystem (Flostrand and Ens, Section 20).

In the summer and fall of 2021, juvenile salmon survey indices of Coho and Chum Salmon abundance (catch per unit effort) were above average (Neville, Section 38). Also, juvenile Coho Salmon were bigger than average (Neville, Section 38). The return abundances of B.C. Sockeye Salmon indicator stocks were below the long-term average, whereas Bristol Bay Sockeye Salmon, making sea entry into the Bering Sea, Alaska, achieved record returns in 2021 (68M fish: 25% above forecast; Stiff et al., Section 22). The June atmospheric heat dome generated thermal barriers to many southern salmon stocks attempting to return to natal rivers to spawn, causing migration delays and enroute mortality (Stiff et al., Section 22). There has been a decline in the size at maturation of some Pacific salmon species. Average weights of mature Fraser River Pink Salmon have declined since the 1960s and, in 2021, were the third smallest on record (Latham et al., Section 23). Sockeye Salmon sizes have declined since the 2000s and ranked as the third and fifth lowest for 3- and 2-ocean salmon, respectively (Latham et al., Section 23).

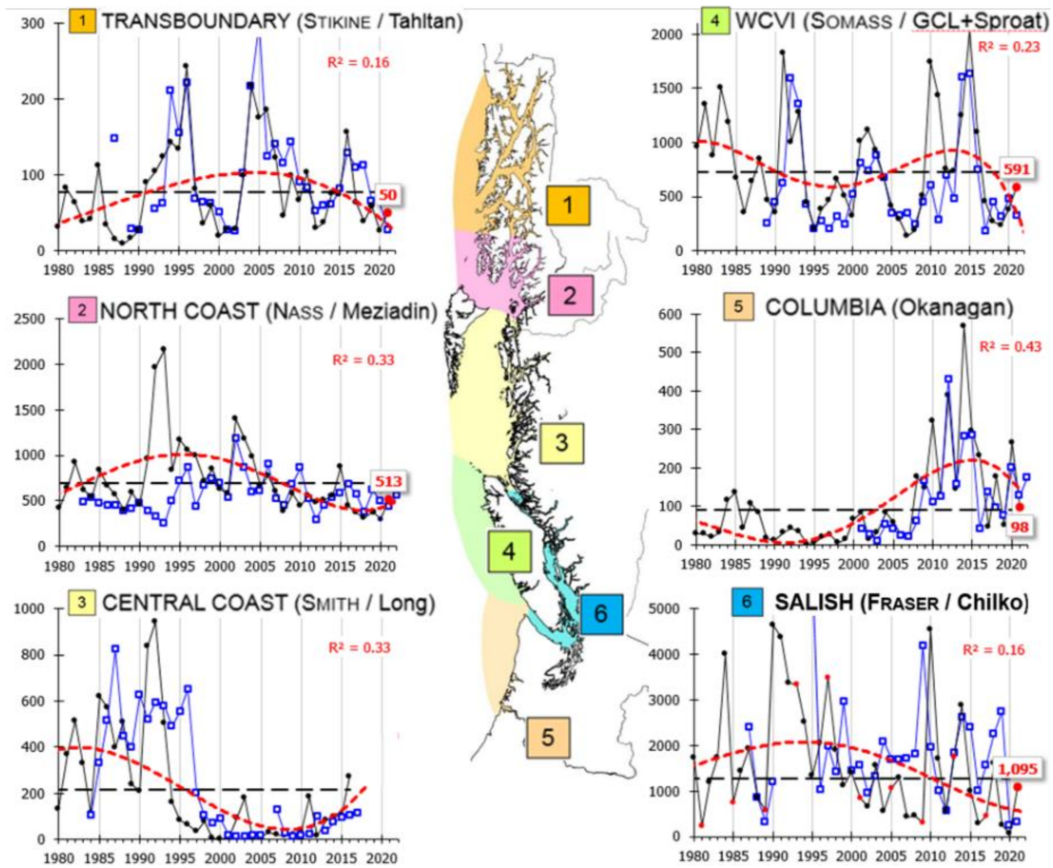


Figure 3-9. Trends in the total annual returns (black line) to 2021 (thousands of fish) and median management forecasts (blue line) to 2022 for B.C. Sockeye indicator stocks, by DOMAIN (Watershed/Management unit). Note: dashed line: 40-year average; red dashed line: quadratic fit to total returns. Source: Stiff et al., Section 22.

4. REFERENCES

DFO. 2021. Stock status update with application of management procedures for Pacific Herring (*Clupea pallasii*) in British Columbia: Status in 2021 and forecast for 2022. DFO Can. Sci. Advis. Sec. Sci. Resp. 2022/039.

Hipfner, J.M., Galbraith, M., Bertram, D.F., and Green, D.J. 2020. Basin-scale oceanographic processes, zooplankton community structure, and diet and reproduction of a sentinel North Pacific seabird over a 22-year period. Progress in Oceanography. 182: Article 102290.

5. ACKNOWLEDGMENTS

The authors and contributors to this Technical Report wish to thank all the officers and crews of the many vessels that have been involved in collecting data and maintaining monitoring stations for these studies. Without their assistance many of the reports in this document would not be possible.

Individual reports on conditions in the Northeast Pacific and British Columbia's outer coast

6. LAND TEMPERATURE AND HYDROLOGICAL CONDITIONS IN 2021

Faron Anslow, Pacific Climate Impacts Consortium, Victoria, B.C., fanslow@uvic.ca

Stephen Sobie, Pacific Climate Impacts Consortium, Victoria, B.C.

6.1. Highlights

- In 2021, B.C. experienced above normal precipitation, near normal maximum daily temperatures and above normal minimum daily temperatures.
- Normal to above normal snowpack persisted well into June before giving way to dry, low snow conditions in southern B.C.
- Record warm conditions occurred in summer, setting new all-time high temperature records in June across southern B.C. and the Pacific Northwest.
- Severe drought in southern B.C. from July through September shifted to record wet conditions in fall, with significant flooding during November.
- Trends in temperature were positive during 1950 – 2021 with daily minimum temperatures increasing faster than daily maximum temperatures. Precipitation shows no significant trend over that timescale.

6.2. Introduction

The seasonal conditions that transpire on land have impacts on nearby coastal waters through discharge, temperatures and nutrient input from rivers and streams. Wildfire events can also impact ocean waters via changes in river sediment transport. As part of a holistic approach to describing the state of the Pacific Ocean, this section will describe the evolution of seasonal weather and snowpack conditions relevant to the coastal waters of B.C. The particular records that are described are temperature and precipitation observations from the national, provincial and private weather observing networks across the province and measurements of water equivalent snow pack on a monthly basis.

6.3. Description of the time series

6.3.1. Temperature and Precipitation

Observations of temperature and precipitation made at B.C. weather stations have been compiled on an ongoing basis since 2010 under the Climate Related Monitoring Program. The dataset consists of observations from the Climate Related Monitoring Program partners: the provincially run networks, BC Hydro, the Capital Regional District, Metro Vancouver and Rio Tinto. The data set also includes data from Environment Canada's observing network and, in aggregate, span the years 1872 to present. Long-term records of daily minimum and maximum temperature and daily precipitation totals were used to calculate 30-year climate normals for each month of the year for the 1981 – 2010 averaging period. Anomalies in monthly temperature and precipitation are calculated relative to these normals and the anomaly data are then interpolated onto a 0.5º x 0.5º grid covering B.C. The time series of gridded anomalies is then spatially divided among the B.C. River Forecast Centre's Snow Index Basin regions.

Average anomalies are taken across each region for each month to form a time-series of regional anomalies that can then be used to rank individual years. The monthly data is also aggregated into seasons and annual values to assess the longer time scale fluctuations in temperature and precipitation and to rank the anomalies in time. An example of the resulting seasonal anomaly data is shown in Figure 6-1 for average daily minimum temperature (left panel) and precipitation (right panel). The temperature and precipitation anomalies are expressed as percentiles among the number of observed months/seasons in the sample. We define the first percentile and number 1 ranking as the warmest/wettest over the 122-year period of 1900-2021 and the highest percentile as the coldest/driest that corresponds to a ranking of 122 for the period. We define broad anomaly categories ranging from record cold/record dry, much below normal, below normal, near normal, above normal, much above normal, record warm/record wet. These categories are defined by the percentile bins 100th, 100th – 90th, 90th – 66th, 66th – 33rd, 33rd – 10th, 1st.

6.3.2. Snow

Measurements of the province's snowpack are made by the Ministry of Environment and Climate Change Strategy and BC Hydro on a monthly basis through manual snow surveys. Additional data are gathered from automated snow pillow stations. In addition, the Ministry of Forests Lands and Natural Resource Operations and Rural Development's River Forecast Centre compiles snowpack data from early January through June on a monthly basis. Snowpack in regions is compared with data from previous years to determine how the current year's accumulated snow amount compares with historical expectations. In terms of river flow, snowpack dictates the added potential (or lack thereof) for flooding during the spring melt season. For this section, the evolution of the mapped snowpack anomalies is described.

6.4. Status and trends

6.4.1. Temperature and Precipitation

In 2021, average annual temperatures were higher than normal across B.C. as a whole when compared with the long-term (1900 – 2021) record. Averages for daily minimum temperature were among the top 13 for northeastern B.C., the southeastern Rocky Mountains and the lower mainland, and in the top 30 everywhere else except Haida Gwaii. Averages for daily maximum temperature were closer to median values with temperatures ranking in the middle one third quantile throughout the province with the exception of cooler conditions in the Northwest and warmer maximum temperatures in the South, ranking from 27th to 41st warmest. Precipitation anomalies across the province were near normal to above normal with the highest anomalies in southern and northwestern B.C. Wetter than normal areas to the north had rankings of 30th and 37th while wetter than normal areas to the Southeast were among the 30th to 41st wettest.

On seasonal and monthly timescales, the primary anomalies lie in the conditions of summer and fall. Summer minimum temperature anomalies were the warmest on record over the entire southern half of the B.C. mainland (Figure 6-1, left), and both summer daily minimum and maximum temperatures were among the top 10 warmest for most of the province. Substantially above normal minimum temperatures in the South persisted into the fall, while daily maximum values eased to normal in most regions and below normal along the coast. Very warm summer temperatures and below normal precipitation during spring and summer resulted in severe drought conditions between July and September throughout most of southern B.C. The combination of record warm temperatures and severe drought during the summer months led to the third worst wildfire season in the province in terms of area burned.

At the start of 2021, precipitation anomalies were normal for most of B.C. Precipitation was above normal in northern B.C. during spring (4th to 5th wettest near Stewart and Smithers), while drier than normal conditions were present in the Kootenays and South Coast. Areas with lower-than-normal precipitation expanded to cover most of B.C. during the summer months. The southern two-thirds of B.C. from Stewart and Prince George southward transitioned from below normal precipitation during spring and summer to experiencing record breaking precipitation during the fall (Figure 6-1, right). Significant precipitation over multiple days during events in November led to widespread flooding across southern B.C., with several rivers experiencing record streamflow. In contrast, northern B.C. experienced normal to above normal conditions for the remainder of the year.

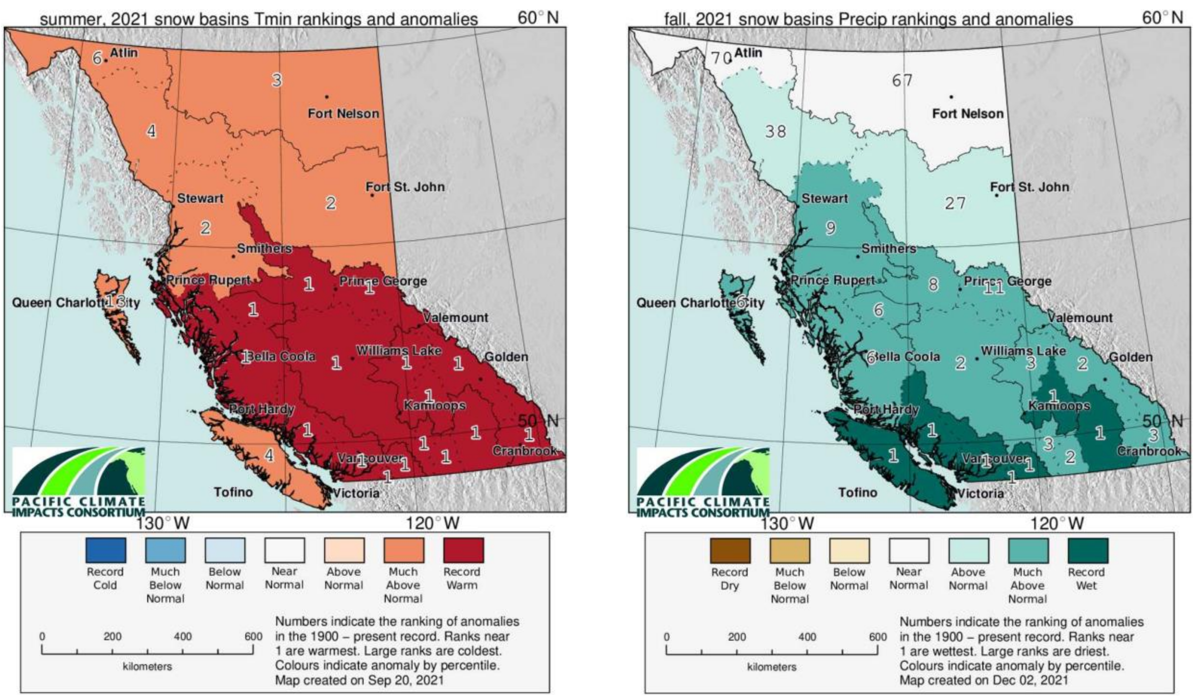


Figure 6-1. Seasonal anomalies in summer average daily minimum temperature (left panel) and fall total precipitation (right panel) for 2021 in B.C. Quantiles defining the colour scale are given in the text. Numbers on the map correspond to ranking in the 122 observation years from 1900 through 2021.

Using the province-wide seasonal and annual temperature and precipitation anomalies, trends are calculated for the full record spanning from 1900 through 2021 and for the period 1950 through 2021. Note that precipitation data early in the record are sparse and of greater uncertainty than those for temperature, thus we exclude the long-term precipitation trends. Temperature trends are more certain because of the reduced spatial and interannual variability of temperature anomalies compared to precipitation. The trend values for annual average daily minimum temperature and for annual average maximum temperature are positive and statistically significant ($p < 0.05$) for both the full and 1950 – 2021 records (Table 6-1). The trends in annual average daily minimum temperature are greater than those for daily average maximum temperature by a factor of two in the long-term record and a factor of 1.5 in the 1950 onward record. The trends in precipitation are positive but not statistically different from zero.

Table 6-1. Trends in annual average of daily minimum and daily maximum temperature and for annual total precipitation. Analysis periods are 1900 – 2021 and 1950 – 2021. The long-term trend for precipitation is not presented due to low confidence in the spatial representativeness of the precipitation network early in the century. Trends that are statistically significant trends at the 5% significance level are shown in bold font.

Trends in annual average values	*1900 – 2021*	*1950 – 2021*
Maximum Temperature (°C yr^{-1})	**0.01**	**0.02**
Minimum Temperature (°C yr^{-1})	**0.02**	**0.03**
Precipitation (% yr^{-1})		0.09

6.4.2. Snow

The evolution of B.C.'s snowpack during the winter of 2020/2021 was above normal well into spring until punctuated in western B.C. by warm, dry conditions during late spring and summer. Snow accumulation was 93% – 200% of normal at the end of March with the lowest values recorded in the East Kootenays while values in the northwest were twice that of normal (Figure 6-2, left). The warm and dry spring in southern B.C. yielded much lower snow amounts in some regions by the end of May (Figure 6-2, right). Snowpack had dropped to near or below 50% in the Bridge-Middle Fraser (47%), Boundary (48%) and Okanagan (52%) regions, while the South Thompson was at 69% of normal. To the north and west snow amounts remained well above normal, supported by above normal spring precipitation.

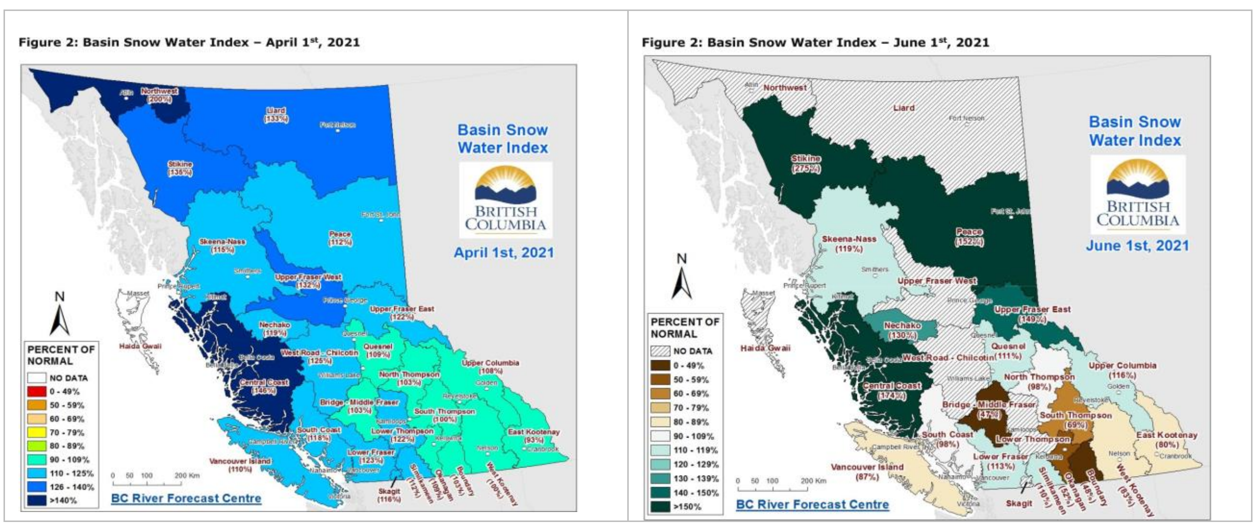


Figure 6-2. Anomalies in B.C. snowpack for April (left) and June (right), 2021. Maps are produced by the B.C. Ministry of Forests Lands and Natural Resource Operations and Rural Development's River Forecast Centre (River Forecast Centre 2021).

6.5. Factors causing trends and implications

2021 in B.C. was warmer and wetter than normal with record-breaking temperatures in summer and record-breaking precipitation in November. Daily minimum temperatures in particular were above normal in all seasons throughout B.C., and substantially so in summer and fall. Despite modestly higher-than-normal precipitation over the year, conditions in southern B.C. swung from severe drought during the summer to very wet fall months.

The observed anomalous conditions are likely due in part to ongoing warming in B.C. and preliminary analysis has attributed record-breaking temperature and precipitation events to human induced climate change (Gillet et al, in review; Philip et al., in review). Daily minimum temperatures in B.C. have risen by 0.3ºC/decade on average over the last 72 years while daily maximum temperatures have increased by 0.2ºC/decade on average. Globally, 2021 was the 6th warmest year on record.

A La Niña pattern of ocean temperatures that formed in late 2020 and persisted into mid-2021 may have contributed to the above average precipitation and accumulation of snowpack in the winter and spring. Conditions became more neutral during the late spring and summer months before a La Niña pattern reestablished in the fall and these conditions are expected to persist into the summer of 2022. Although La Niña conditions are associated with cooler than normal temperatures, the impact of El Niño Southern Oscillation on B.C. weather is typically weak during summer and leading into fall.

6.6. References

River Forecast Centre. 2021. Snow Water and Water Supply Bulletins for 2021. BC Ministry of Environment and Climate Change Strategy, Victoria, B.C., 142 p. https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/river-forecast/2020.pdf (accessed 20 February, 2022).

Gillett, N., Cannon, A., Malinina, E., Schnorbus, M., Anslow, F., Sun, Q., Kirchmeier-Young, M., Zwiers, F., Seiler, C., Zhang, X., Flato, G., Wan, H., Li, G., and Castellan, A. In review. Human Influence on the 2021 British Columbia Floods. Available at SSRN: https://ssrn.com/abstract=4025205 or http://dx.doi.org/10.2139/ssrn.4025205

Philip, S.Y., Kew, S.F., van Oldenborgh, G.J., Yang, W., Vecchi, G.A., Anslow, F.S., Li, S., Seneviratne, S.I., Luu, L.N., Arrighi, J., Singh, R., van Aalst, M., Hauser, M., Schumacher, D.L., Marghidan, C.P., Ebi, K.L., Bonnet, R., Vautard, R., Tradowsky, J., Coumou, D., Lehner, F., Wehner, M., Rodell, C., Stull, R., Howard, R., Gillet, N., and Otto, F.E.L. 2021. Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021. WWA Scientific Report.

7. NORMAL TEMPERATURES DESPITE STRONG COOL CLIMATE INDICES AND AN EMERGING FRESHENING TREND

Tetjana Ross and Marie Robert, Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Tetjana.Ross@dfo-mpo.gc.ca, Marie.Robert@dfo-mpo.gc.ca

7.1. Highlights

- Despite strong negative PDO and La Niña conditions throughout 2021 which should have led to an abnormally cool year, temperatures were near normal in the NE Pacific.
- Surface waters in the NE Pacific were anomalously fresh in 2021, each of the last five years have been progressively fresher.
- The mixing in the winter of 2020/21 was closer to normal than the previous two years, suggesting normal surface nutrient levels in the spring of 2021.

7.2. Description of the time series

Sea surface temperatures (SSTs) were collated from the NOAA Physical Science Laboratory website (NOAA Extended SST v4 http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl). Pacific climate indices examined in this report include the Oceanic Niño Index (ONI), North Pacific Index (NPI Pacific Decadal Oscillation (PDO), Southern Oscillation Index (SOI), and North Pacific Gyre Oscillation (NPGO); please see Section 7.6 for details.

Sub-surface profiles of temperature and salinity were obtained from the Line P time series. Line P is an oceanographic survey line extending from the mouth of the Juan de Fuca Strait to Station Papa at 50°N and 145°W in the middle of the Gulf of Alaska (originally the location of a Weather Ship; Freeland 2007). Routine sampling started at Station Papa in 1956, but in 1959 sampling was started along the ship's track between the coast and the weather ship location. Currently, there are typically three cruises per year, in February, June and August. Each gives specific information: the February cruise tells us the depth of the winter mixed layer (MLD) or how deep the waters are mixed with constant temperature and density, as well as how stratified the ocean is; both are key to understanding delivery of nutrients into surface waters to fuel primary productivity (the rate at which phytoplankton convert sunlight to usable energy). The June cruise allows us to see how much nutrients were consumed by phytoplankton during spring and exactly how much nutrients are still available for summer primary production, and the August cruise tells us how much of those nutrients have been used and how good the primary production was for that summer. Herein we focus on the physical data collected by the Line P program, CTD observations of Temperature, Salinity (Conductivity), and Depth (Pressure).

Argo float data are also used to create a synthetic Line P section for each calendar month. Argo floats typically profile from 2000 decibars to the surface every 10 days reporting temperature and salinity in near real-time (Wong et al. 2019). Since mid-2001, the Gulf of Alaska has supported an array of Argo floats and their observations were used to interpolate temperature and salinity profiles at each Line P station. Argo temperature and salinity data were accepted into the computation from a wide area of the Northeast Pacific, but the interpolation was carried out using a Gaussian covariance function with a 300 km e-folding scale. For each month, the mean profile is centered on the 15th and data are accepted into the interpolation with a time window of ±15 days. Since the Argo record is short, compared to the Line P time series, these Argo-based synthetic Line P data are plotted as anomalies referenced to the 1956-2012 seasonally-corrected mean temperature or salinity based on the ship data.

7.3. Status and trends

Based on NOAA land and sea surface temperature data dating back to 1880, 2021 was the sixth warmest year on record globally (NOAA State of the Climate 2021). This is consistent with the recent trend, wherein 9 of the ten warmest years are in the last decade. In ranked order, the ten warmest years are 2016, 2020, 2019, 2015, 2017, 2021, 2018, 2014, 2010, and 2013/2005. Sea surface temperatures (SSTs) in the Northeast Pacific (NE Pacific) were only slightly warm in 2021; i.e., less than 1°C above the average for the 1981-2010 base period (www.ncdc.noaa.gov/sotc/ service/global/map-blended-mntp/202101-202112.png).

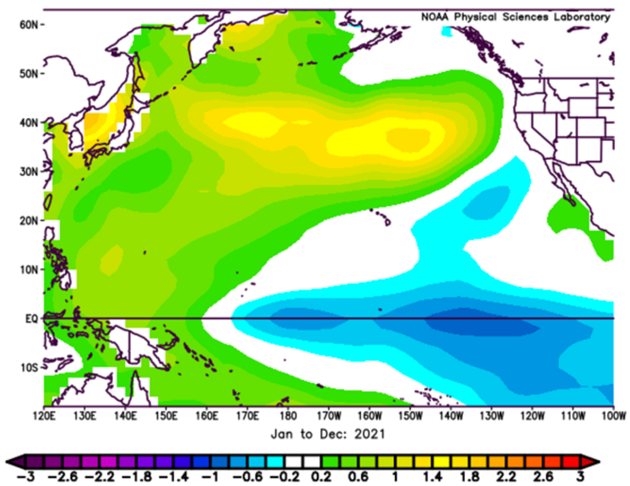
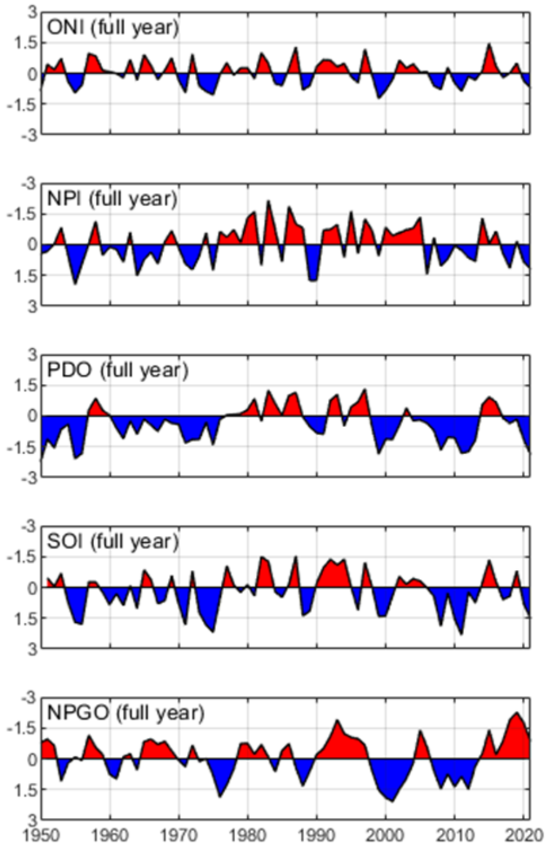


Figure 7-1. Annual average temperature anomalies in the Pacific Ocean for 2021. The colour bar shows temperature anomaly in °C relative to 1981-2010 base period. Source: NOAA Extended SST v4 http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl.

In the NE Pacific, the SSTs were close to average or slightly warm throughout 2021 (Figure 7-1). Also notable in Figure 7-1 is the below average SSTs near the equator, indicative of the strong to moderate La Niña conditions present throughout 2021 (Figure 7-2). La Niña typically decreases SST in the NE Pacific, thus it is likely the sustained La Niña conditions that ended the marine heatwave of the previous two years.

Looking at the climate indices collectively (Figure 7-2), they indicate that 2021 should have been a very cool year in the NE Pacific. While all the indices point in the same direction as in 2020, all the indices pointing to a cool period had larger amplitude than in 2020. The North Pacific Gyre Oscillation (NPGO) continued to be the lone index indicating a warmer period, but had lower amplitude than in 2020.



While temperatures were near normal in 2021 (Figure 7-3), there were significant salinity anomalies in the near-surface waters across the NE Pacific. This fresh anomaly and the emerging freshening trend in the NE Pacific was well illustrated by the Line P salinity data (Figure 7-4). Sea surface salinity maps based on Aquarius satellite data (Melnichenko et al. 2016) show that these fresh anomalies stretch across the entire NE Pacific. The salinity anomaly timeseries at Station Papa show that these recent salinity anomalies are large relative to the 1956-2012 Line P climatology with anomalies 3-4 standard deviations above the typical variability (Figure 7-5).

The winter stratification was stronger in 2020/21 than over the 2007-2013 period preceding the first big marine heatwave of the last decade (i.e., the 'Blob'), but not as strong as the previous 2 winters which showed extremely low winter mixing.

Figure 7-2. Time series of Pacific climate indices. Each of the monthly indices were averaged over the full year. Some series are inverted (negative values are above the axes) so that all series are red when B.C. temperatures are anomalously warm.

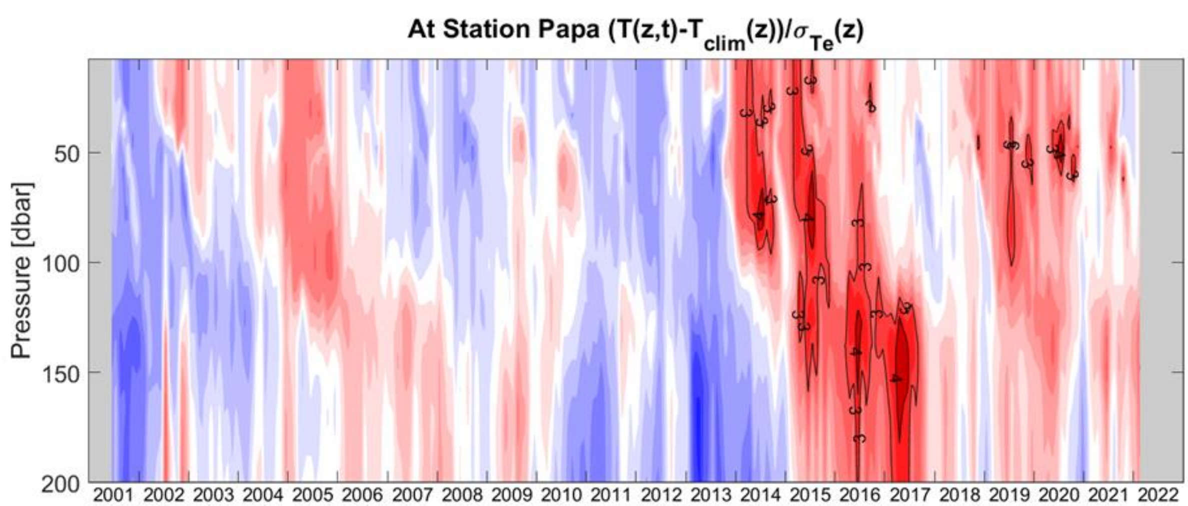


Figure 7-3. Plot of temperature anomalies relative to the 1956-2012 seasonally-corrected mean and standard deviation (from the Line P time series), as observed by Argo floats near Station Papa (P26: 50º N, 145º W). The cool colours indicate cooler than average temperatures and warm colours indicate warmer that average temperatures. Dark colours indicate anomalies that are large compared with the 1956-2012 standard deviations. The black lines highlight regions with anomalies that are 3 and 4 standard deviations above the mean.

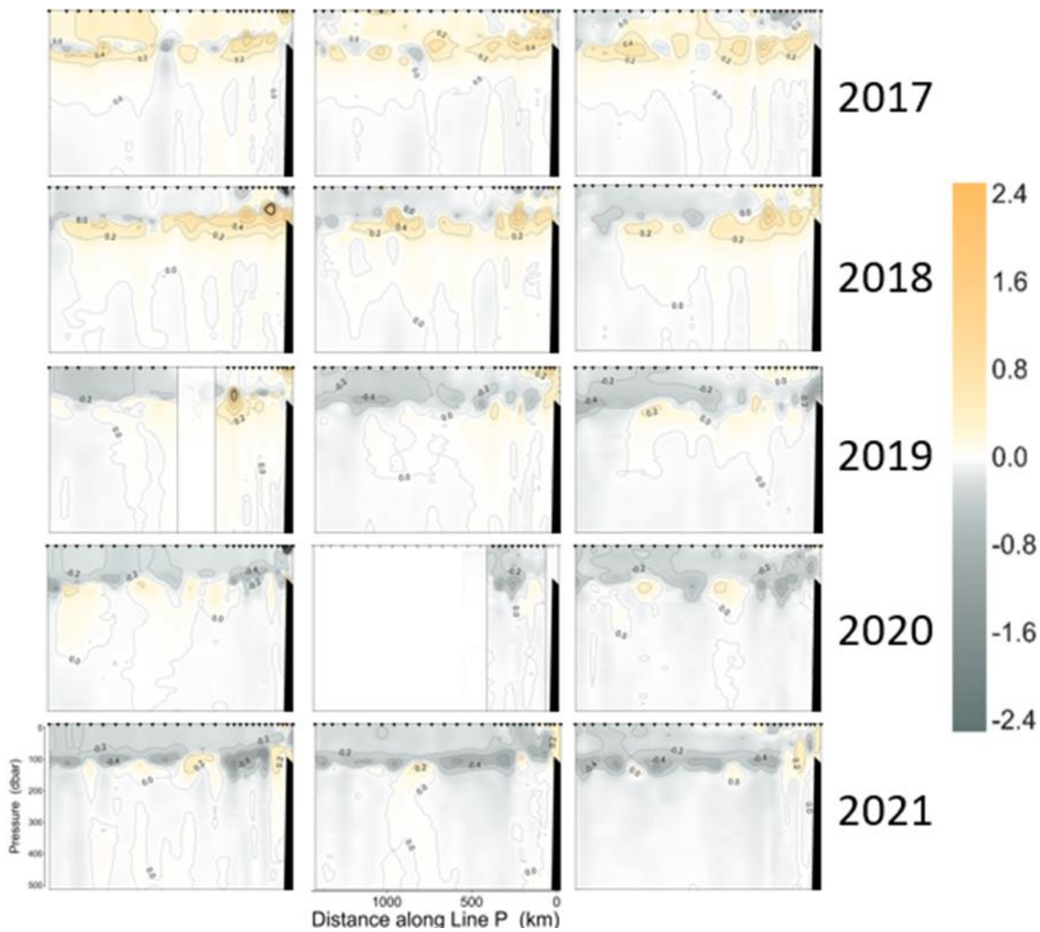


Figure 7-4. Salinity anomalies (PSU) along Line P from 2017 to 2021 with respect to the 1981-2010 mean.

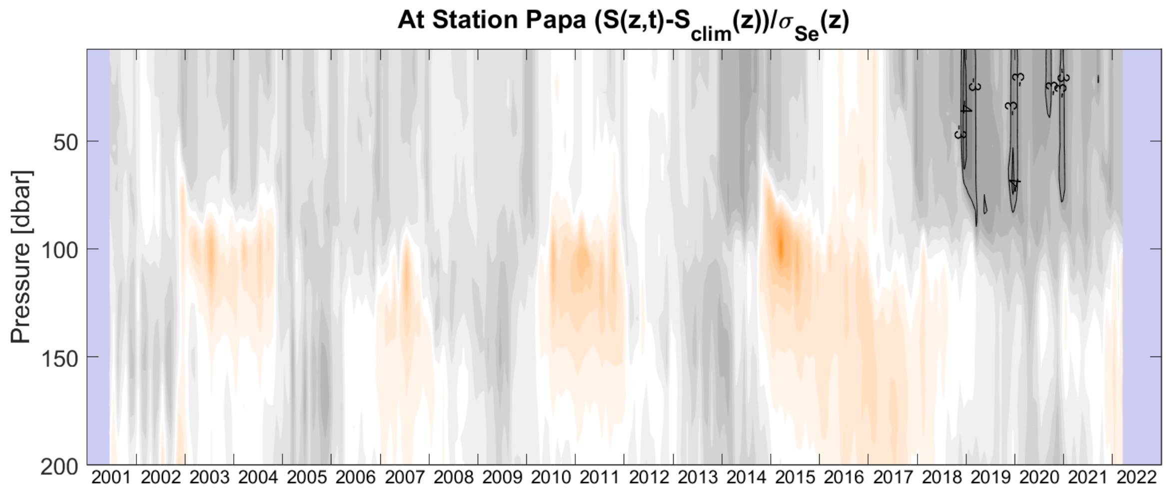


Figure 7-5. Plot of salinity anomalies relative to the Line P Climatology (1956-2012), as observed by Argo floats near Station Papa (P26: 50º N, 145º W). The grey indicates fresher than average and orange indicates saltier than average. Dark colours indicate anomalies that are large compared with the 1956-2012 standard deviations. Black lines highlight anomalies that are 3 and 4 standard deviations below the mean.

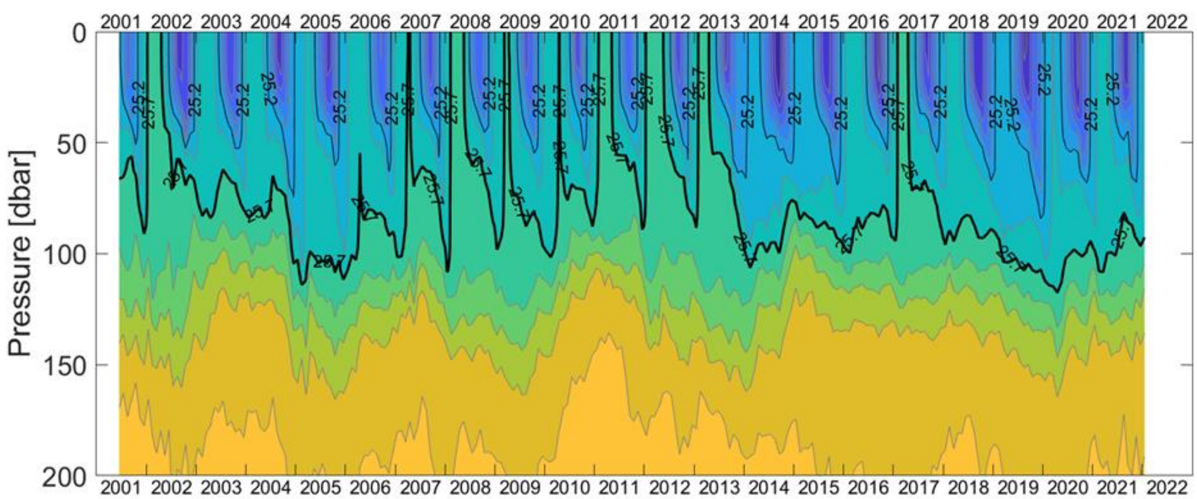


Figure 7-6. Coloured contour plot of density as observed by Argo floats near Station Papa (P26: 50º N, 145º W). The colours indicate potential density (yellow is denser and blue lighter). The black lines highlight the σ_θ=25.2 kg/m^3 (thin) and 25.7 kg/ m^3 (thick) isopycnals.

7.4. Factors influencing trends

The relatively normal temperatures observed in the NE Pacific are likely due to the juxtaposition of cool climate oscillations on a background of long-term climate warming.

7.5. Implications of those trends

With climate indices suggesting a sustained cool period, it is likely that 2021/22 will experience stronger winter mixing, though this may be tempered by the freshening trend in the surface waters.

The ‘Blob’ and the 2019-20 marine heatwave reduced winter mixing (e.g., Freeland 2015; Ross and Robert 2021), leading to surface nutrients among the lowest on record in the summer of 2019 (Peña and Nemcek 2020). The history of the σ_θ=25.7 kg/m^3 isopycnal (highlighted with a thick black line in Figure 7-6) illustrates this nicely. It remained very deep throughout the 2014-2016 marine heatwave, deeper even than much of the 2003-2005 warm period, in 2017-2018 mixing was similar to 2007-2013 and it shoaled during the winter. Mixing decreased again during 2019-20 and it has not shoaled again. This weaker mixing suggests that nutrient supply from deep waters should have been weaker and therefore early spring nutrient levels on the low side in the spring of 2021, but not quite as low as in 2019 or 2020.

7.6. Description of Climate Indices

The **Oceanic Niño Index (ONI)** is a monthly index which is a 3-month running mean of sea surface temperature (SST) anomalies in the Niño 3.4 region (5^o N-5^o S, 120^o-170^o W) plotted on the center month. The SST anomalies are calculated based on 30-year base periods that are updated every 5 years, which accounts for global warming and some of the decadal-scale SST variability (as seen in the PDO index). The ONI is provided by the NOAA’s National Weather Service National Centers for Environmental Prediction CPC and is available from: http://www.cpc.ncep.noaa.gov/products/ analysis_monitoring/ensostuff/ensoyears.shtml.

The **North Pacific Index (NPI)** is the area-weighted sea level pressure over the North Pacific Ocean from 30° N to 65° N and 160° E to 140° W. This index, like the Aleutian Low Pressure Index (ALPI; Surry and King 2015) reported last year, is a useful indicator of the intensity and a real extent of the Aleutian Low Pressure system. The NPI was generally positive (blue) from 1950 to 1976, and generally negative (red) from 1977 to 2008; a change than can be attributed to the strengthening of the Aleutian Low Pressure system after 1977. From 2008 to present, the NPI was mostly positive, due to weaker Aleutian Lows. The NPI anomaly, plotted in Figure 7-2, was calculated from the NPI by removing the 1950-2018 mean. Monthly time series of the NPI are provided by the Climate Analysis Section, NCAR at Boulder, Colorado and based on Trenberth and Hurrell (1994): https://climatedataguide.ucar.edu/sites/default/ files/cas_data_files/asphilli/npindex_monthly.txt.

The **Pacific Decadal Oscillation (PDO) Index** is defined as the leading mode of monthly sea surface temperature variability (1st principal component [PC] of SST) in the North Pacific (Mantua et al. 1997). It represents a long-lived El Niño-like pattern of Pacific climate variability, generally indicating warm/cool patterns that persist for a decade or more. The PDO is provided by the Joint Institute for Studies of Atmosphere and Ocean of NOAA and is available from: http://research.jisao.washington.edu/pdo/.

The **Southern Oscillation Index (SOI)** is the anomaly in the sea level pressure difference between Tahiti (17°40′ S 149°25′ W) and Darwin, Australia (12°27′0″ S 130°50′0″ E). It is a measure of the large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific (i.e., the state of the Southern Oscillation) and, as it represents the changes in winds that set up El Niño/La Niña events, the ONI follows it quite closely. SOI is provided by the NOAA’s National Weather Service National Centers for Environmental Prediction CPC and is available from: www.cpc.ncep.noaa.gov/data/indices/soi.

The **North Pacific Gyre Oscillation (NPGO)** is a climate pattern that emerges as the second dominant mode of sea surface height (SSH) variability (2nd PC of SSH) in the Northeast Pacific. The NPGO has been shown to be significantly correlated with fluctuations of salinity, nutrients and chlorophyll-a from long-term observations in the California Current (CalCOFI) and Gulf of Alaska (Line P) (Di Lorenzo et al. 2008). Monthly values of NPGO are available from: http://www.o3d.org/npgo/.

7.7. References

Di Lorenzo, E., Schneider, N., Cobb, K.M., Chhak, K., Franks, P.J.S., Miller, A.J., McWilliams, J.C., Bograd, S.J., Arango, H., Curchister, E., Powell, T.M., and Rivere, P. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. Geophys. Res. Lett. 35: L08607. doi:10.1029/2007GL032838.

Freeland, H. 2015. The “Blob” or Argo and other views of a large anomaly in the Gulf of Alaska in 2014/15. In: Chandler, P.C., King, S.A., and Perry, R.I. (Eds.). 2015. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2014. Can. Tech. Rep. Fish. Aquat. Sci. 3131: vi + 211 p. Available online: http://www.dfo-mpo.gc.ca/Library/358018.pdf

Freeland, H. 2007. A short history of Ocean Station Papa and Line P. Progress in Oceanography. 75(2): 120-125.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on production. Bulletin of the American Meteorological Society. 78: 1069-1079.

Melnichenko, O., Hacker, P., Maximenko, N., Lagerloef, G., and Potemra, J. 2016. Optimum interpolation analysis of Aquarius sea surface salinity, J. Geophys. Res. Oceans. 121, 602-616, doi:10.1002/2015JC011343. Data available from: http://iprc.soest.hawaii.edu/users/oleg/oisss/GLB/Aquarius_SMAP_OISSS_monthly/

NOAA State of the Climate 2021: NOAA National Centers for Environmental Information, State of the Climate: Global Climate Report for Annual 2021, published online January 2022, retrieved on February 27, 2022 from https://www.ncdc.noaa.gov/sotc/global/202113.

Peña, A., and Nemcek, N. 2020. Nutrients and Phytoplankton Along Line P and West Coast of Vancouver Island. In: Boldt, J.L., Javorski, A., and Chandler, P.C. (Eds.). 2020. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377: x + 288 p. Available online: https://waves-vagues.dfo-mpo.gc.ca/Library/40884569.pdf

Ross, T., and Robert, M. 2021. Marine Heatwave Persists Despite Growing La Niña. In: Boldt, J.L., Javorski, A., and Chandler, P.C. (Eds.). 2021. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2020. Can. Tech. Rep. Fish. Aquat. Sci. 3434: vii + 231 p. Available online: https://waves-vagues.dfo-mpo.gc.ca/Library/4098297x.pdf

Surry, A.M., and King, J.R. 2015. A New Method for Calculating ALPI: the Aleutian Low Pressure Index. Can. Tech. Rep. Fish. Aquat. Sci. 3135: 31 + v p.

Trenberth, K.E., and Hurrell, J.W. 1994. Decadal atmosphere-ocean variations in the Pacific. Climate Dynamics. 9: 303-319.

Wong, A.P., Wijffels, S.E., Riser, S.C., Pouliquen, S., Hosoda, S., Roemmich, D., Gilson, J., Johnson, G.C., Martini, K., Murphy, D.J. and Scanderbeg, M. 2020. Argo data 1999–2019: two million temperature-salinity profiles and subsurface velocity observations from a global array of profiling floats. Frontiers in Marine Science 7 (700). https://doi.org/10.3389/fmars.2020.00700

8. WIND-DRIVEN UPWELLING/DOWNWELLING ALONG THE NORTHWEST COAST OF NORTH AMERICA: TIMING AND MAGNITUDE

Roy A.S. Hourston, and Richard E. Thomson, Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Roy.Hourston@dfo-mpo.gc.ca, Richard.Thomson@dfo-mpo.gc.ca

8.1. Highlights

- Based on the timing of alongshore currents, the 2021 Spring Transition timing was very early relative to the 1991-2020 mean. Early timing is associated with average to above-average upwelling-based coastal productivity.
- Stronger-than-average upwelling-favourable winds are generally associated with increased coastal productivity. Between 45°-60° N, the magnitude of upwelling-favourable winds in 2021 was near the 1991-2020 average during the warm season. This favoured average upwelling-based coastal productivity.
- The winter of 2020-2021 was characterized by near-average downwelling-favourable winds, indicating winter storm activity was near-normal over the winter overall. The winter of 2021-22 also appears to be near average as of January 2022.

8.2. Description of time series

Spring and fall transition timing: The shift in spring from predominantly downwelling-favourable poleward winds in winter to predominantly upwelling-favourable equatorward winds in summer is referred to as the Spring Transition. The reverse process in fall is called the Fall Transition. The alongshore winds drive a seasonal cycle in the alongshore surface currents over the continental slope, from poleward in winter to equatorward in summer. The Spring and Fall Transitions for the Pacific coast are derived using along-shore wind stress time series from NCEP/NCAR Reanalysis-1 (Kistler et al. 2001), along-shore wind velocity from the Environment and Climate Change Canada meteorological buoy 46206, and the along-shore current velocity at 35 and 100 m depth at mooring A1 (Figures 8-1 and 8-2; Folkes et al. 2017; Thomson et al. 2013).

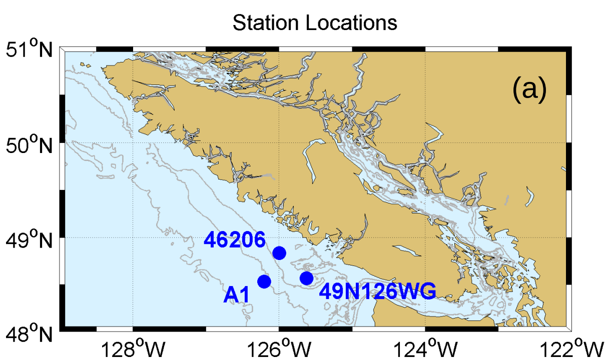


Figure 8-1. Locations of observations delineating historical Spring and Fall Transitions.

Upwelling Index: Because they drive offshore surface Ekman transport and compensating onshore transport at depth, the strength (duration and intensity) of upwelling-favourable (northwesterly) winds are considered indicators of coastal productivity, e.g., Xu et al. (2019). To gauge low-frequency variability in coastal productivity, we have summed upwelling-favourable-only wind stresses by month along the West Coast of North America from 45°-60° N latitude (Figure 8-3) using the NCEP/NCAR Reanalysis-1 analyses (Kistler et al. 2001) and subtracted the 1991-2020 mean to derive the Upwelling Index.

Downwelling Index: Analogous to the Upwelling Index, the Downwelling Index is derived in the same way but by only considering poleward (downwelling-favourable) wind stress (Figure 8-4). Since this is typically stronger in winter as a result of storms tracking eastward across the North Pacific, this index can reflect the strength of storms hitting the B.C. coast, a shift of storm tracks closer or further away from the coast, a longer or shorter storm season, or some combination of all three. The index also reflects the strength/weakness of wintertime vertical mixing of the surface water column near the coast.

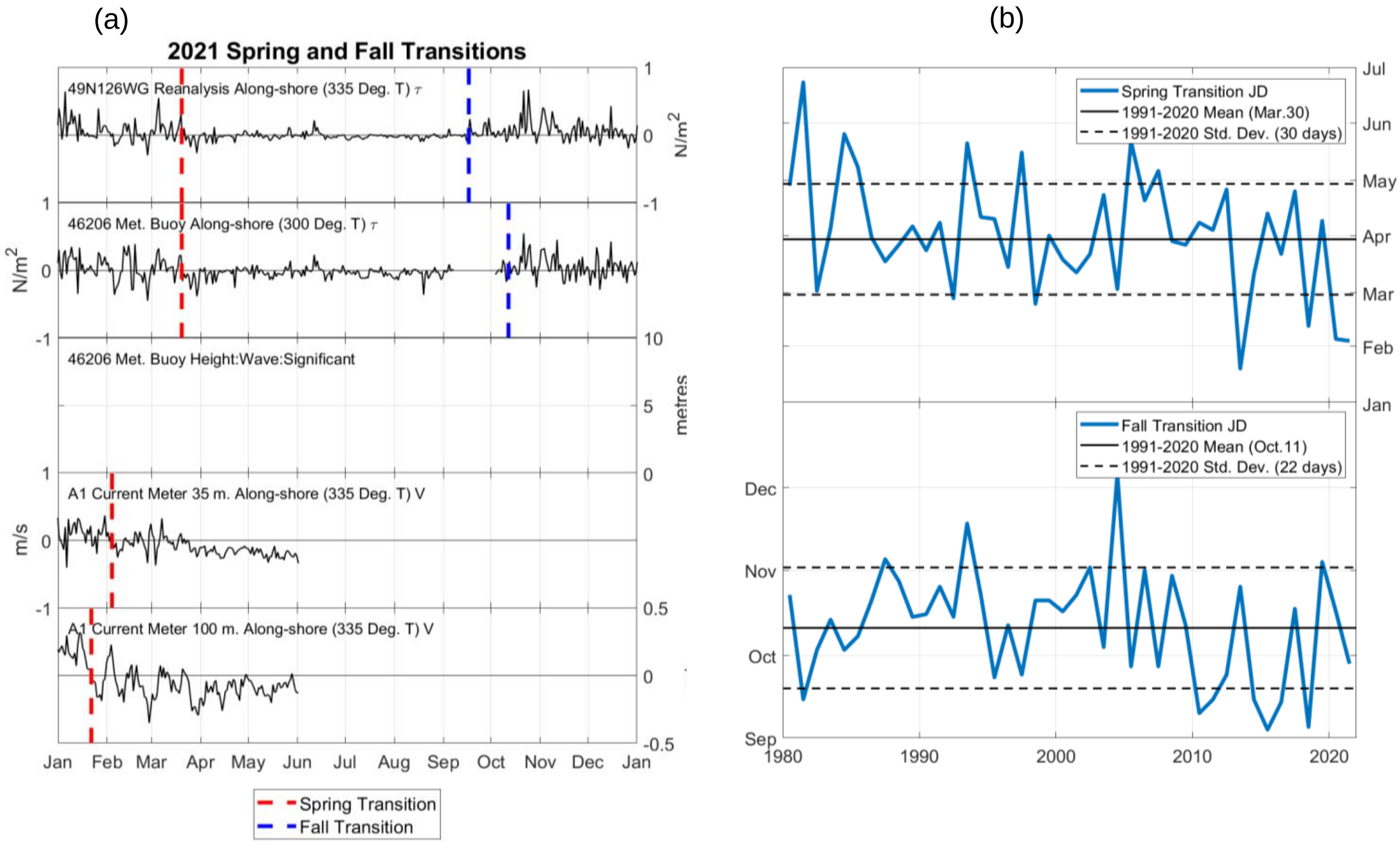


Figure 8-2. (a) Time series depicting the Spring and Fall Transitions off the West coast of Vancouver Island in 2021. Wind stress at Reanalysis-1 grid point 49°N 126°W and meteorological buoy 46206; significant wave height at 46206; along-shore current velocity at 35 and 100 m depth at mooring A1 (Folkes et al. 2017; Thomson et al. 2013). Positive flow is poleward (downwelling-favourable) and negative flow is equatorward (upwelling-favourable). Vertical dashed lines show derived transition times using a cumulative sum approach (e.g., Foreman et al. 2011). (b) The annual Spring and Fall Transitions derived from time series in panel (a).

8.3. Status and trends

8.3.1. Spring and Fall Transition timing

In 2021, the Spring Transition timing was very early compared to the 1991-2020 mean (Figures 8-1 and 8-5), and the second earliest since 2013. The 2021 Fall Transition appears average to early, although the lack of subsurface current data gives this assessment less confidence. Since 2005, there appears to be a slight trend to an earlier spring transition. The same appears to be the case for the Fall Transition timing (from upwelling to downwelling conditions, also shown in Figures 8-1, 8-2, and 8-5). These trends mean that the upwelling season may be trending earlier, but not longer. Over a more recent period, since 2015, the Fall Transition is trending later, such that the upwelling season has been getting longer – and the downwelling (storm) season has been getting shorter. This may have implications related to the amount of winter ocean surface mixing.

8.3.2. Upwelling Magnitude: The Upwelling Index

The Upwelling Index time series (Figure 8-2) indicates that upwelling-favourable wind stress was near average over the 45°-60° N latitude range over the 2021 warm season. In contrast, February and March upwelling-favourable winds were much higher than average. No recent trends in upwelling-favourable winds are evident in Figure 8-3.

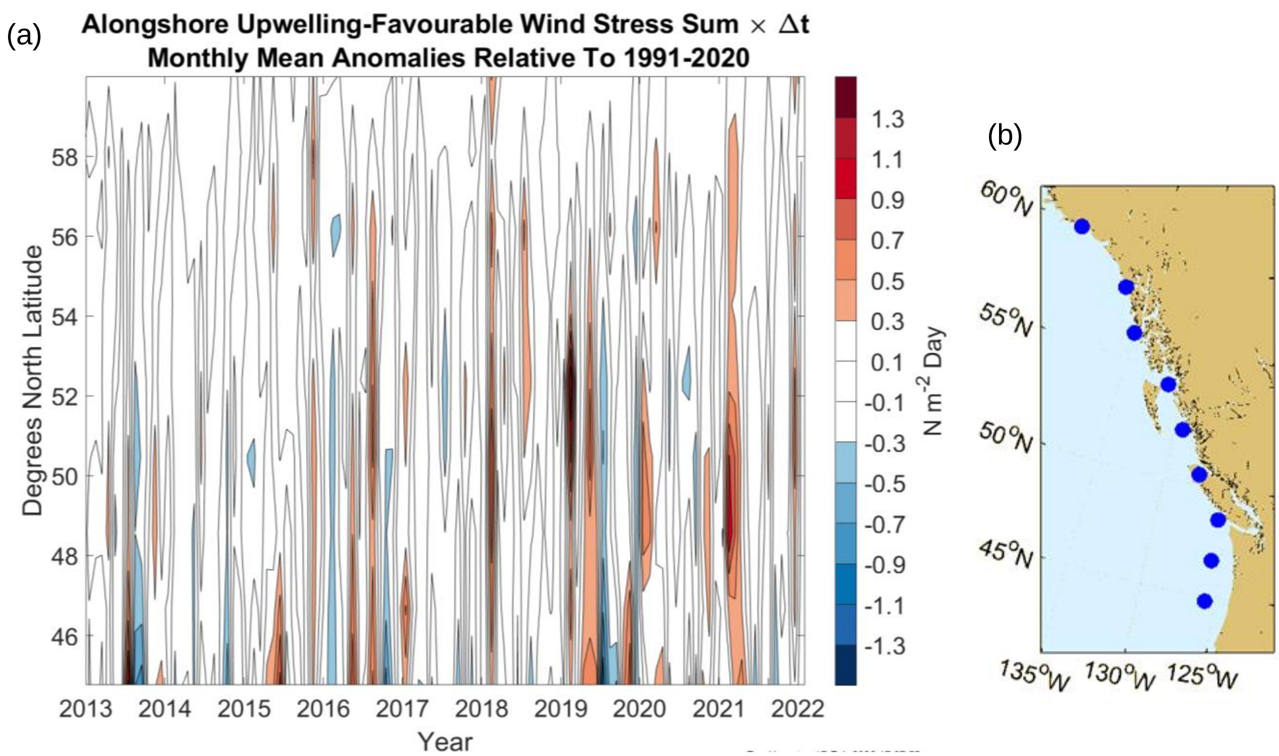


Figure 8-3. Recent (2013 to 2021) monthly mean anomalies (relative to 1991-2020) of monthly sums of alongshore upwelling-favourable (equatorward) wind stress (a) from the NCEP/NCAR Reanalysis-1 coastal surface wind stress grid locations, 45-60° N (b).

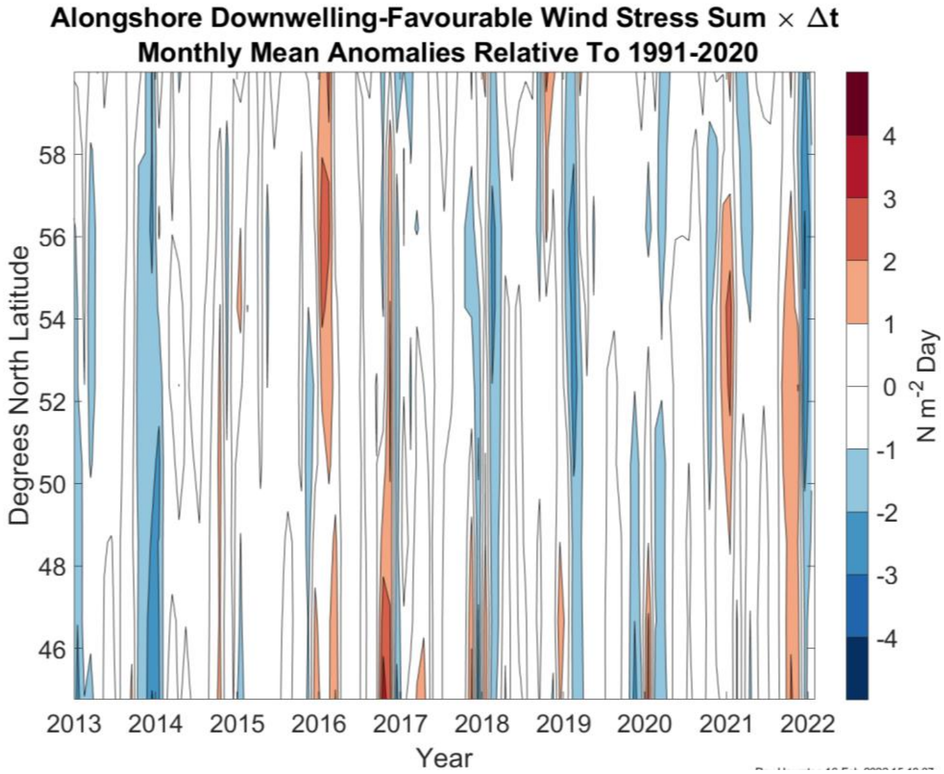


Figure 8-4. Recent (2013 to 2021) monthly mean anomalies (relative to 1991-2020) of monthly sums of alongshore downwelling-favourable (poleward) wind stress from the NCEP/NCAR Reanalysis-1 coastal surface wind stress grid locations, 45-60° N in Figure 8-3(a).

8.3.3. Downwelling Magnitude: The Downwelling Index

Over the previous winters of 2017-2018, 2018-2019, and 2019-2020, the Downwelling Index was lower than average, like the winter of 2013-2014, but not quite as low (Figure 8-4). This indicates reduced wintertime surface mixing near the coast and is usually associated with higher surface temperatures the following summer, such as the marine heatwave conditions observed in 2014 and 2019. Over winter 2020-2021, it was about average overall, but very strongly positive in December, 2020. So far over the winter of 2021-2022, it was positive during September-November and then strongly negative in December.

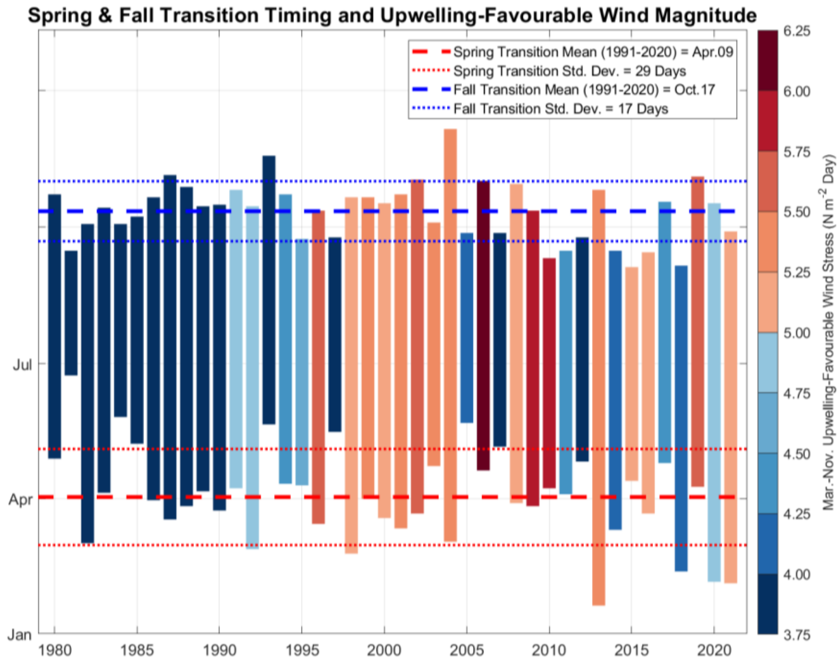


Figure 8-5. Annual Spring and Fall Transition Timing and March-November upwelling-favourable wind stress magnitude, 1980-2021.

8.4. Factors influencing trends

Why the Spring Transition may possibly be occurring earlier over the last 15 years is unknown. While the Upwelling and Downwelling indices were higher than average for ten years over the 2000-2010 period (indicating a period of consistently both stronger summertime and wintertime winds), the Downwelling Index had been lower than average 2012-2020 north of 50° N, excluding 2015-2016. This indicates weaker winter storms, or a shorter winter storm season, or winter storms that are tracking further northwest away from the coast, or some combination of the three factors. The significantly weaker-than-average Downwelling Index in the winter of 2013-2014 was an accurate indicator of the weaker than average wintertime winds associated with the marine heatwave that year (Bond et al. 2015), and is likely also the case for 2019, 2020, and possibly 2021.

8.5. Implications of those trends

The onset of seasonal upwelling that accompanies the Spring Transition varies from year to year (Thomson et al. 2014). In years such as 2005 and 2010, when the Spring Transition was relatively late, marine coastal productivity across trophic levels, ranging from plankton to fish to birds, was generally average to below-average, and was particularly poor in 2005 (DFO 2006). In years when the spring transition timing was average to early, such as 1999 and 2014, productivity was generally average to above-average (cf. Chandler et al. (2015) reports on outer B.C.). The 2021 Spring Transition timing was very early, favouring above-average upwelling-based coastal productivity. Between 45°-60° N, the magnitude of upwelling-favourable winds in 2021 were near average, favouring average upwelling-based coastal productivity. Recent years of a weaker-than-average Downwelling Index are associated with, and may be precursors to, marine heatwave events.

8.6. Acknowledgements

NCEP/NCAR Reanalysis-1 wind stress provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at http://www.esrl.noaa.gov/psd/.

8.7. References

Bond, N.A., Cronin, M.F., Freeland, H., and Mantua, N. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophys. Res. Lett. 42: 3414– 3420. doi: 10.1002/2015GL063306.

Chandler, P.C., King, S.A., and Perry, R.I. (Eds.). 2015. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2014. Can. Tech. Rep. Fish. Aquat. Sci. 3131: vi + 211 p.

DFO. 2006. State of the Pacific Ocean 2005. DFO Sci. Ocean Status Report. 2006/001.

Folkes, M., Thomson, R., and Hourston, R. 2017. Evaluating Models to Forecast Return Timing and Diversion Rate of Fraser Sockeye Salmon. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/nnn. vi + 220 p.

Foreman, M.G.G., Pal, B., and Merryfield, W.J. 2011. Trends in upwelling and downwelling winds along the British Columbia shelf. Journal of Geophysical Research: Oceans 116 (C10).

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woolen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van del Dool, H., Jenne, R., and Fiorino, M. 2001. The NCEP–NCAR 50-year reanalysis: monthly means CD-ROM and documentation. Bulletin of the American Meteorological Society 82: 247–267.

Thomson, R.E., Hessemann, M., Davis, E.E., and Hourston, R.A.S. 2014. Continental microseismic intensity delineates oceanic upwelling timing along the west coast of North America, Geophys. Res. Lett. 10.1002/2014GL061241.

Thomson, R., Hourston, R., and Tinis, S. 2013. OSCURS for the 21st Century: Northeast Pacific Salmon Tracking and Research (NEPSTAR) Project, Year 3 Interim Report. Annual report submitted to the Pacific Salmon Commission. 37p.

Xu, Y., Fu, C., Peña, A., Hourston, R., Thomson, R., Robinson, C., Cleary, J., Daniel, K., and Thompson, M. 2019. Variability of Pacific herring (*Clupea pallasii*) spawn abundance under climate change off the West Coast of Canada over the past six decades. Journal of Marine Systems 200: 103229. https://doi.org/10.1016/j.jmarsys.2019.103229.

9. VANCOUVER ISLAND WEST COAST SHELF BREAK CURRENTS, TEMPERATURES, AND WIND STRESS

Roy A.S. Hourston, and Richard E. Thomson, Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Roy.Hourston@dfo-mpo.gc.ca, Richard.Thomson@dfo-mpo.gc.ca

9.1. Highlights

- Sea surface temperatures were near average throughout most of 2021 at weather buoy 46206 on the west coast of Vancouver Island, but were significantly above average from late June to early July during the atmospheric heat dome event.
- Alongshore flow at mooring A1 in 2021 was anomalously and strongly equatorward (upwelling-favourable) in February and March for the fourth year in a row.
- In 2021, west coast shelf-break wind stress and surface and subsurface currents continued to be below-average in magnitude (stronger equatorward and/or weaker poleward).
- Temperatures, that were higher than average throughout the water column over 2014-2016, returned to near-average near the surface over the past few years.

9.2. Description of the time series

Subsurface temperature and current velocities at the shelf break have been observed at mooring A1, water depth ~500 m (Figure 9-1) since 1985. Nearby meteorological buoy 46206 has provided sea surface temperature at 80 cm depth and wind velocity time series at 5 m elevation since 1988. We have combined these series to obtain the vertical structure of temperature and flow through the water column.

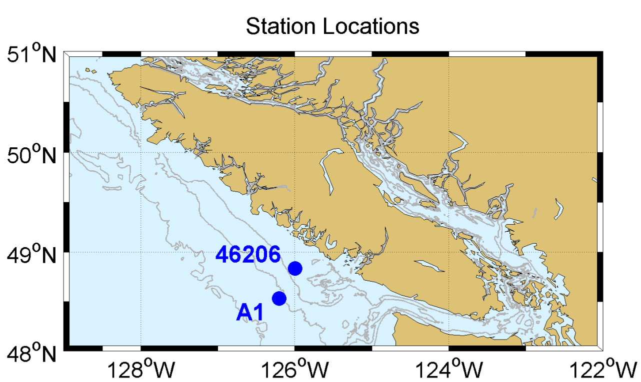


Figure 9-1. Locations of mooring A1 and meteorological buoy 46206.

9.3. Status and trends

Water temperatures at the surface were near average throughout most of 2021 except in late June/early July when they were significantly above average during the summer atmospheric heat dome event (Figure 9-2, left). There were no temperature data at subsurface depths because no instruments were deployed.

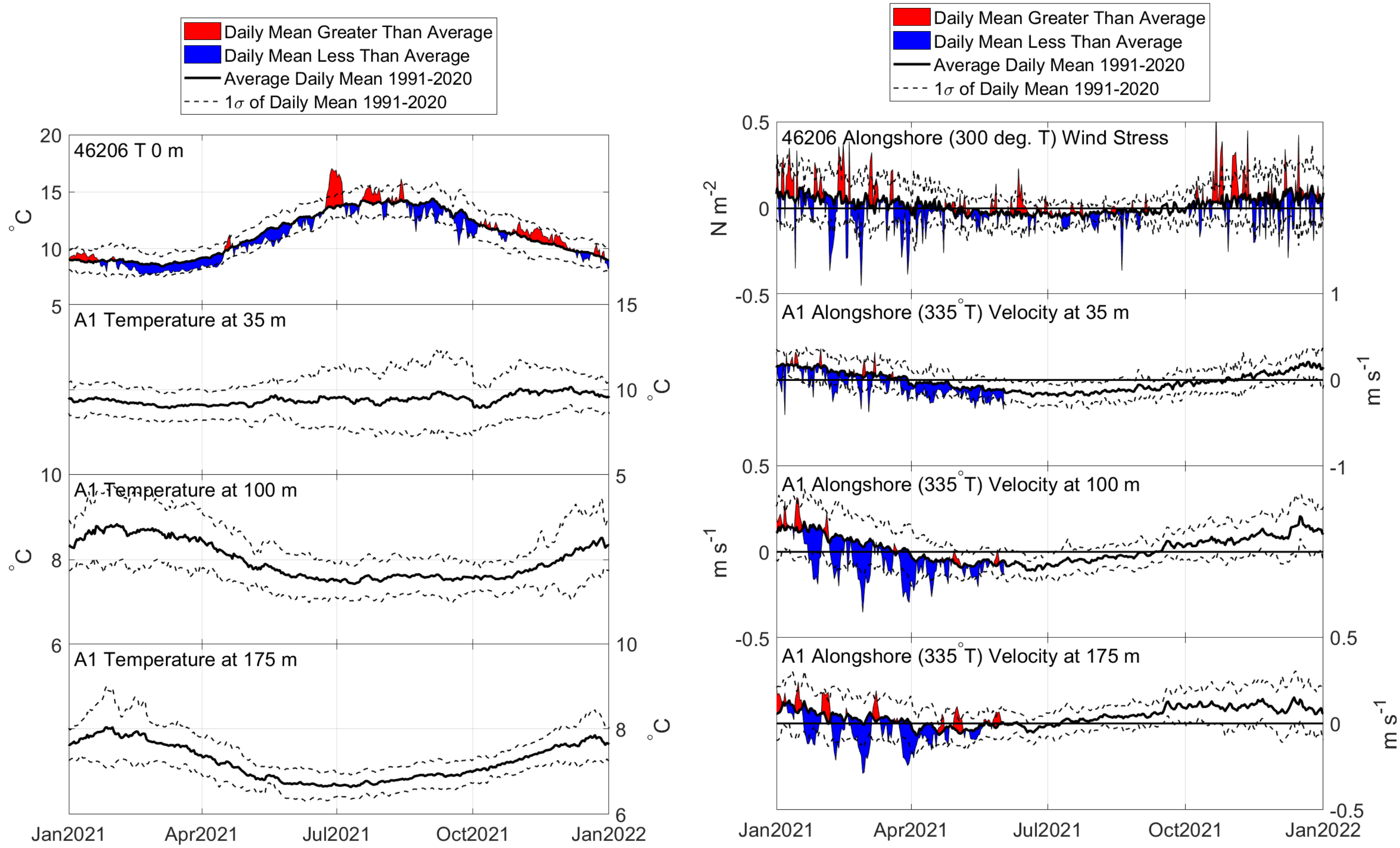


Figure 9-2. Daily mean values of temperature (left panels) and alongshore wind stress/ocean current (right panels) at the surface, 35 m, 100 m, and 175 m depth from meteorological buoy 46206 and mooring A1. Angle in brackets (ºT) is the principal direction of the wind or current vector in degrees true compass bearing.

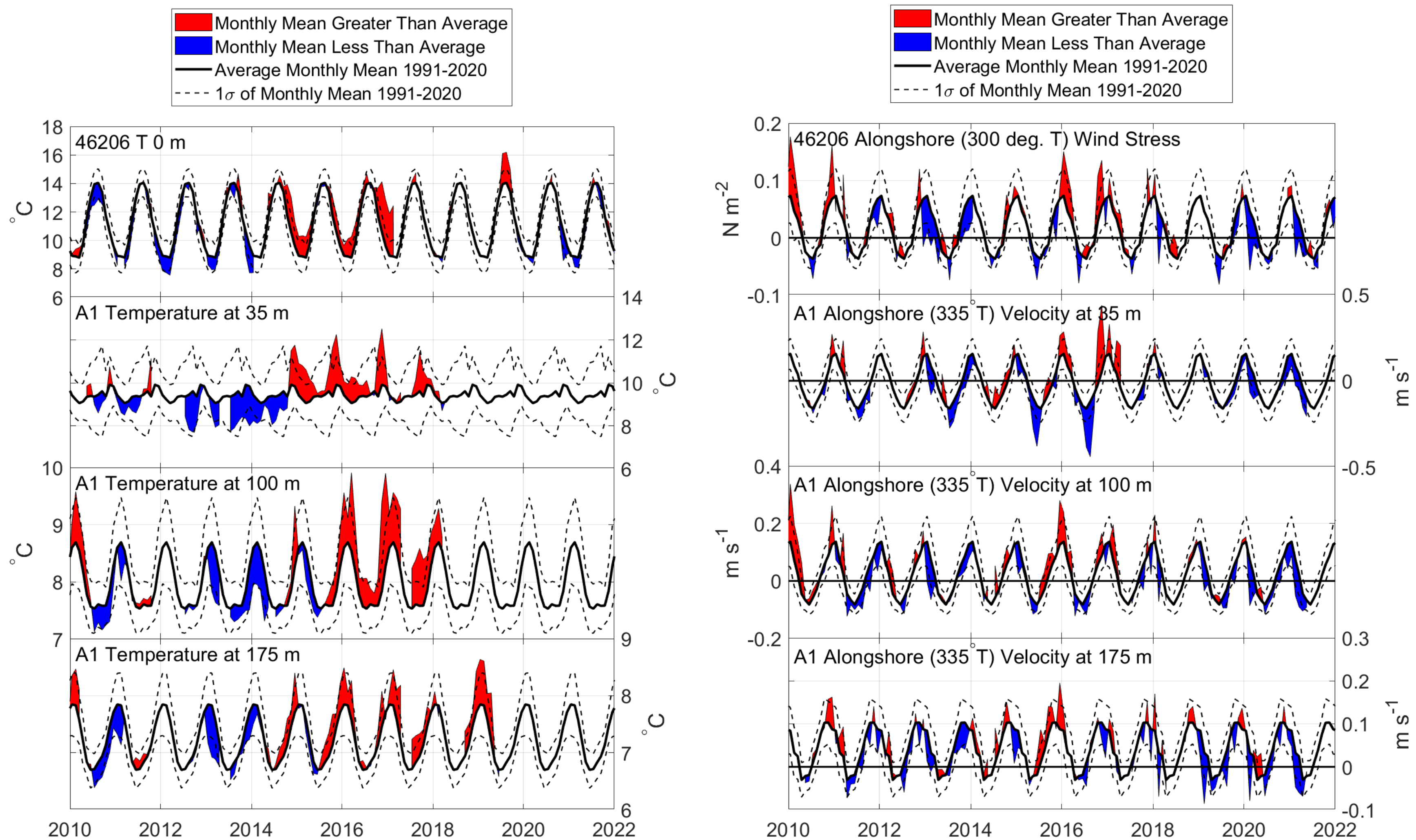


Figure 9-3. Monthly mean values of temperature (left panels) and alongshore wind stress/ocean current (right panels) at the surface, 35 m, 100 m, and 175 m depth from meteorological buoy 46206 and mooring A1. Angle in brackets (°T) is the principal direction of the wind or current vector in degrees true compass bearing.

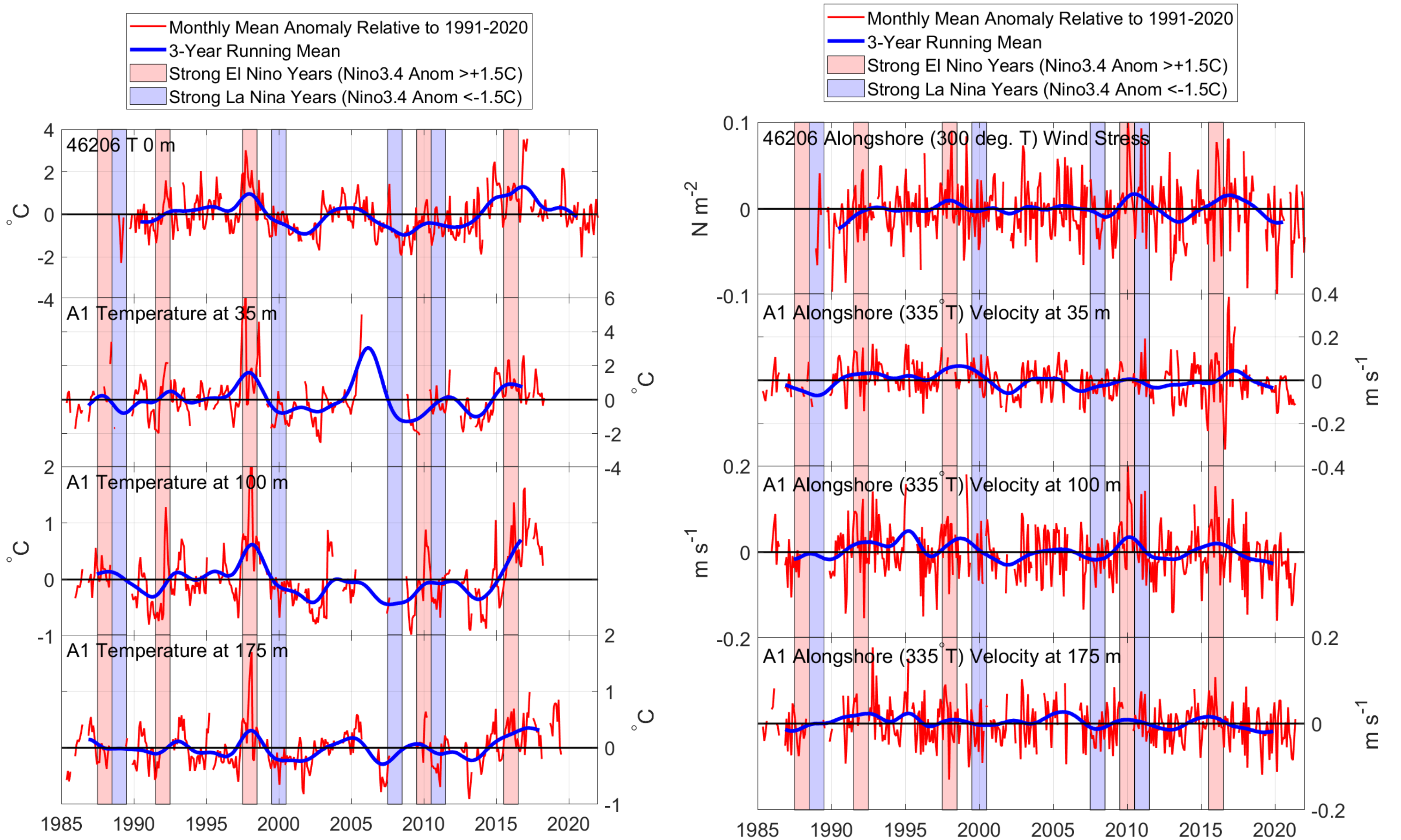


Figure 9-4. Monthly anomalies of temperature (left panels) and alongshore wind stress/ocean current (right panels) at the surface, 35 m, 100 m, and 175 m depth from meteorological buoy 46206 and mooring A1. Angle in brackets (°T) is the principal direction of the wind or current vector in degrees true compass bearing.

Alongshore surface winds and currents were generally near 1991-2020 average conditions (Figure 9-2, right). However, flow was consistently and anomalously strongly equatorward (upwelling-favourable) in February-March, for the fourth straight year. There are no subsurface data after July as that mooring deployment will be recovered in summer, 2022.

Temperature anomalies were positive during the marine heatwave and El Niño over 2014-2016 (Figures 9-3 and 9-4). Positive temperature anomalies reappeared in 2019 at the surface and continued at 175 m depth but there were no data at other depths. For alongshore flow, strong anomalies occurred in 2013 (weak poleward flow in winter preceding the 2014 marine heatwave). There was enhanced equatorward flow in the summers of 2015 and 2016, and enhanced poleward flow over the winters of 2015-2016 and 2016-2017. These features are likely due to stronger large-scale surface atmospheric circulation features (Aleutian Low and North Pacific High) associated with El Niño. The stronger poleward flow may also have been due to an eastward shift of winter storm tracks toward the coast. For the fourth year in a row, in 2021 there was anomalous strong equatorward (upwelling-favourable) flow in February/March. This reflected a recurring stronger and more northward-shifted North Pacific High atmospheric circulation system early in these years.

Higher temperatures and enhanced poleward flow were also observed during the strong 1997-1998 El Niño (Figure 9-4). While flow now appears to be more equatorward (or weaker poleward) than average, temperature anomalies are near average at the surface compared to recent years. A lack of recent observed subsurface temperature anomalies prevents their assessment.

There do not appear to be trends in surface and subsurface temperatures and currents on the shelf/shelf break on the west coast of Vancouver Island over 1985-2021.

9.4. Factors influencing trends

Although long-term trends do not appear evident, the strong El Niño of 2015-16 and recent years of increased occurrences of marine heatwaves are reflected in higher-than-average ocean temperatures at the surface and at depth. Weaker than average poleward flow in winter is also associated with marine heatwaves. This in turn reflects weaker storm activity and/or storm activity shifted westward and/or a stronger winter North Pacific High. Strong El Niños like that of 2015-2016 are associated with enhanced poleward flow in winter which was evident over the 2015-2016 winter.

9.5. Implications of those trends

Recent El Niño and marine heatwave events were associated with significant departures from average ocean surface and subsurface temperatures and currents. However, conditions returned to average a year or two after these events. The most recent observations indicate conditions are below average, but no long-term trend is apparent. If these sorts of events increase in frequency in the future, they could influence long-term trends.

10. SEA SURFACE TEMPERATURE AND SALINITY OBSERVED AT SHORE STATIONS AND WEATHER BUOYS ALONG THE B.C. COAST IN 2021

Peter Chandler, Fisheries & Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Peter.Chandler@dfo-mpo.gc.ca

10.1. Highlights

- The average annual sea surface temperature (SST) from the 12 contributing shore stations in 2021 (10.42°C) was generally cooler than in 2020 with a coast-wide average annual decrease in SST of 0.19°C.
- 2021 was a continuation of a warm period that started in 2014. This nine-year span of above normal annual SST is the longest warm period on record (1935-2021).
- The average annual SST from coastal wave buoys in 2021 (10.44°C) was cooler than in 2020 with a coast-wide average annual decrease in SST of 0.32°C.
- The long-term data (1935-2020) from the shore stations show a linear trend to warmer coastal SSTs at a rate of 0.87°C per 100 years.
- Annual salinity observations showed a decrease from 2020 to 2021 with an average coast wide decrease of 0.67 (standard deviation of 0.40).
- Fewer marine heatwaves were observed at the coastal wave buoy locations in 2021 than in 2020; the most prominent heatwave was observed at Halibut Bank ODAS buoy (Central Strait of Georgia) from mid-June to early August (44 days as a category one marine heatwave and 7 days as a category 2 marine heatwave).

10.2. Description of the time series

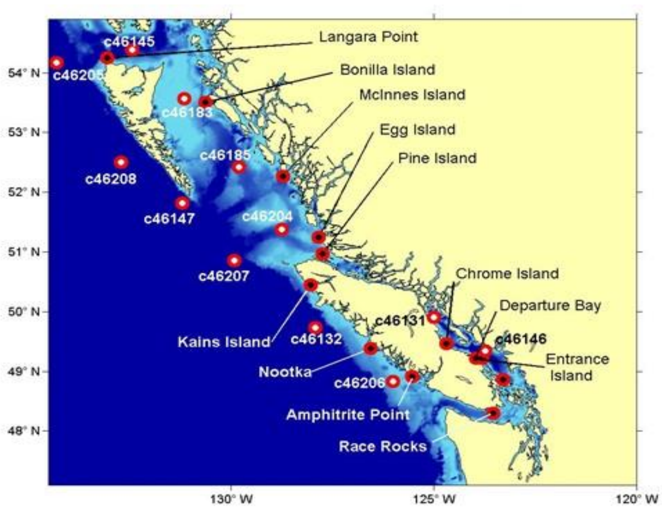


Figure 10-1. Red dots with black centers show the locations of 12 shore stations. Red dots with white centers show the locations of 12 weather buoys in the Canadian weather buoy network. See table below for details.

Station	Years of data	Buoy ID	Buoy Location	Years of data
Departure Bay	107	c46146	Halibut Bank	29
Race Rocks	99	c46131	Sentry Shoal	29
Nootka	54	c46206	La Perouse	33
Amphitrite	87	c46132	South Brooks	27
Kains	86	c46207	East Dellwood	32
Langara	85	c46147	South Moresby	28
Entrance	85	c46208	West Moresby	31
Pine Island	84	c46205	West Dixon	33
McInnes	67	c46145	Central Dixon	30
Bonilla	61	c46204	West Sea Otter	32
Chrome	60	c46185	South Hecate	30
Egg Island	51	c46183	North Hecate	30

Two sources of data were used to describe changes in sea surface conditions in the coastal waters of B.C. in 2021. As part of the British Columbia Shore Station Oceanographic Program, SST and salinity are measured daily at 12 shore stations, at the first daylight high tide. Most stations are at lighthouses (Figure 10-1), with observations taken by lighthouse keepers using a handheld electronic instrument (YSI Pro 30). The buoy data are provided by Environment and Climate Change Canada from a network of Offshore Data Acquisition System (ODAS) buoys that collect data hourly.

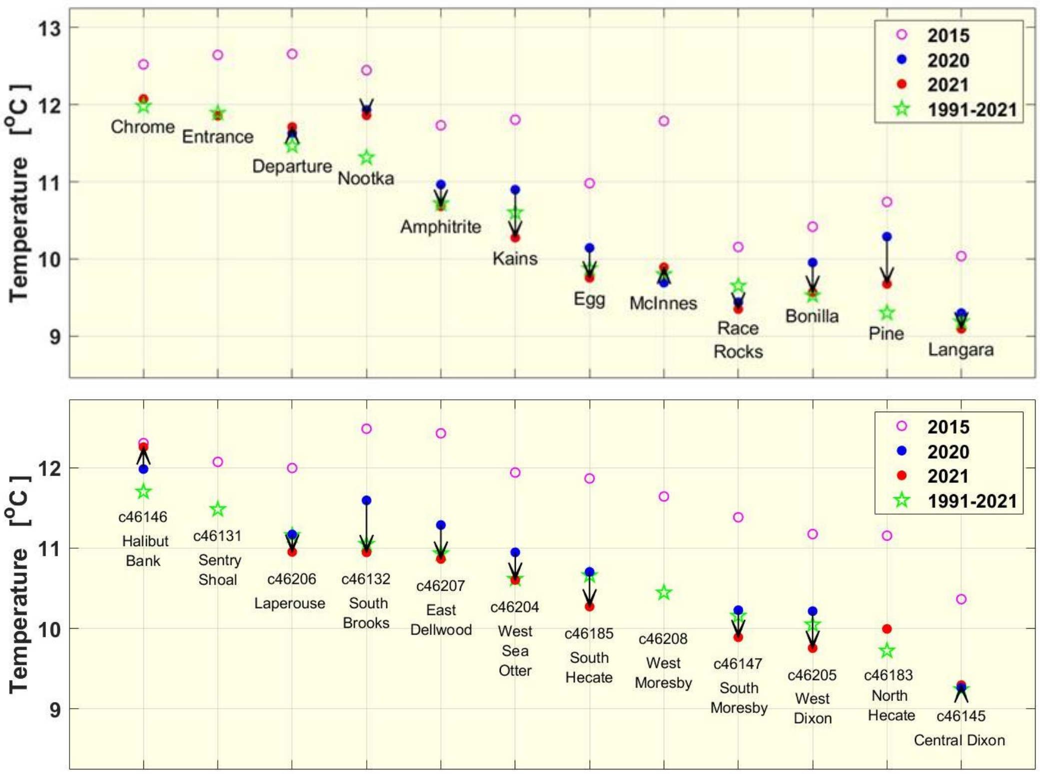


Figure 10-2. Upper panel. The average SST in 2020 (dark blue dots), and 2021 (red dots) from daily observations at shore stations along the west coast of Canada. The stars represent the new climatological mean annual temperature. Lower panel. The average SST from hourly observations at weather buoys along the west coast of Canada. The open circles show conditions in 2015 when SST was significantly higher than normal.

10.3. Status and trends

The observations from the 12 shore stations show that the annual average daily SST (Figure 10-2, upper panel) at all stations was generally cooler in 2021 than in 2020, with a coast-wide mean decrease of 0.19°C. The ODAS buoys data show an annual average decrease in daily SST from 2020 to 2021 of 0.32°C. The coast-wide SST in 2021 remains consistently lower than conditions in 2015 during the marine heatwave known as “the Blob”. The climatological SST is calculated as the mean temperature using the values between 1991 and 2021.

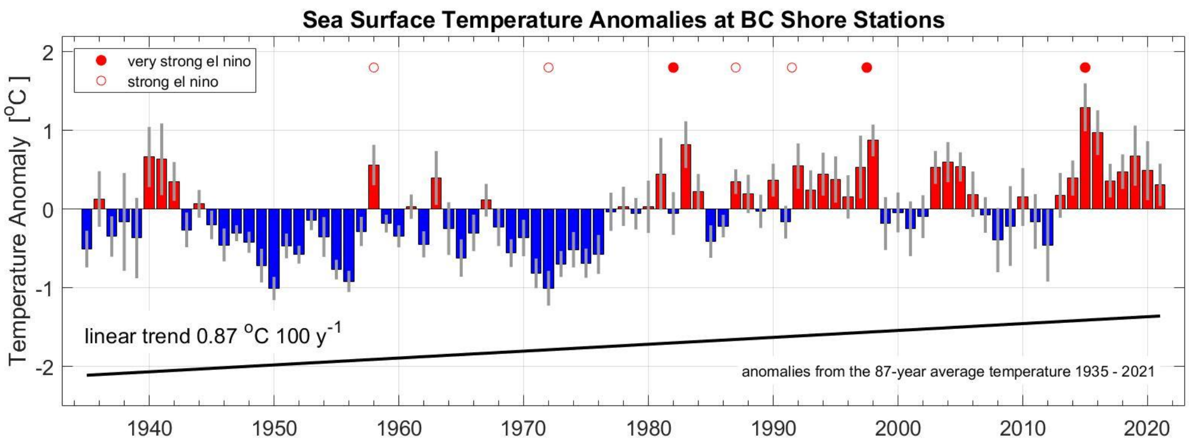


Figure 10-3. The trend in the annual temperature based on the observations of all lighthouses (black line). The bars represent the anomalies averaged over all stations (a coast wide indicator), (red – above average, blue – below average), the vertical grey lines show the variability in the lighthouse data for each year (1935-2021).

Assuming a linear change over the entire data record, the time series of temperature at all of the shore stations show a warming trend at a 95% confidence level. Figure 10-3 shows a coast wide warming trend (using data from all shore stations) as 0.87˚C over 100 years.

Figure 10-4 shows sea surface freshening at representative stations for each of three regions (North Coast, west coast Vancouver Island, and the Strait of Georgia). A linear trend analysis applied to the salinity shows a continuing long-term trend toward less saline conditions.

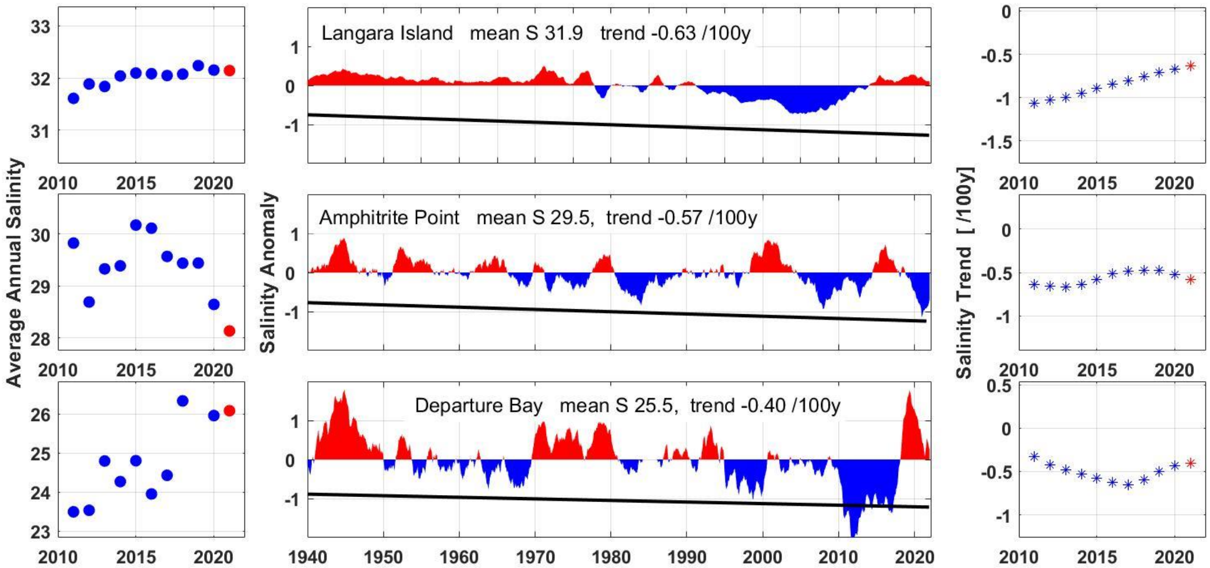


Figure 10-4. Time series of daily salinity observations, averaged over 12 months, at stations representing the North Coast (top row), west coast of Vancouver Island (middle row) and Strait of Georgia (bottom row). Positive anomalies from the average salinity of the entire record are shown in red, negative in blue. The left panel shows the annual mean salinity for the year shown on the x-axis. The right panel shows the slope of the trend lines calculated using only data up to the year shown on the x-axis.

10.4. Factors influencing trends

Ocean temperature is an important environmental indicator because it influences physical processes such as circulation and mixing, chemical process such as deoxygenation, and the condition and behaviour of species that live in the ocean. SST is an effective indicator of long-term change because direct observations have been made for many decades and can also be measured with satellite sensors, autonomous monitoring platforms and other technical advances. The amount of data included in SST analyses continues to expand.

Although SSTs were warmer during the marine heatwave of 2014-16, the conditions in 2021 continue the period of warmer than normal water (where normal is defined as the average on the long-term SST record starting in 1935). This warm water period has lasted for nine years, the longest span of above normal temperature in the time series. While the record shows multi-year oscillations in the annual SST there remains a long-term trend towards rising ocean temperatures.

The long-term salinity observations show a trend to less saline conditions at most stations along the B.C. Coast. Variability in the salinity signal along the Pacific coast is governed by a combination of the integrated effects of atmospheric forcing and coastal precipitation; the Strait of Georgia is strongly influenced by the discharge from the Fraser River (Cummins and Masson 2014). The influence of the 2021 atmospheric rivers that occurred in southwestern B.C. in November of 2021 can be seen in the salnity records of shore stations along the west coast of Vancouver Island (Figure 10-4).

10.5. Implications of those trends

There is growing interest in determining the predictability of the physical processes of the North Pacific Ocean, including associated biological responses, on time scales of months to years. The models that are being used for this are similar to those used for climate change studies. The process of developing, evaluating, and improving forecast systems can provide important insights into the key processes controlling physical, chemical, and biological ocean properties. It remains an open question the extent to which the ecosystem responses to slow warming will resemble those that were associated with the recent marine heatwaves. The impacts of these changes will depend on the time and space scales relevant to organisms of interest and are described for various trophic levels in B.C. waters in Galbraith (Section 17), and Neville (Section 38).

10.6. References

Cummins, P.F., and Masson, D. 2014. Climatic variability and trends in the surface waters of coastal British Columbia. Progress in Oceanography. 120: 279–290.

11. SEA SURFACE TEMPERATURE DURING 2021: HEAT WAVES AND HEAT DOMES

Andrea Hilborn[1] and Charles Hannah[2]

[1]Fisheries and Oceans Canada, Dartmouth, N.S., Andrea.Hilborn@dfo-mpo.gc.ca

[2]Fisheries and Oceans Canada, Sidney, B.C., Charles.Hannah@dfo-mpo.gc.ca

11.1. Highlights

- Multiple marine heatwave events were identified in the Northeast Pacific in 2021, with the largest contiguous Marine Heat Wave area spanning over 3 million km^2 during May.
- A large atmospheric heatwave event (the “Heat Dome”, June 25 to July 1) with record-breaking high air temperatures corresponded to anomalously high marine buoy and satellite measurements of sea surface temperature. The waters surrounding Vancouver Island were elevated to Marine Heat Wave status during this period.
- The Marine Heat Wave on the shelf during the Heat Dome was short lived, however the Strait of Georgia remained anomalously warm for approximately six weeks after the Heat Dome ended.

11.2. Description of the time series

The NOAA Optimal Interpolation (OI) spatially continuous sea surface temperature (SST) product (0.25 degree spatial resolution) was used to produce weekly averaged anomaly maps spanning 1981 to the end of 2021, from which the area falling under marine heatwave (MHW) status was extracted. The study area was limited to the region 30 to 61.5 degrees North and 120 to 160 degrees West (corresponding to integratedecosystemassessment.noaa.gov/regions/california-current/cc-projects-blobtracker).

MHWs were defined as any pixel from the current weekly mean SST exceeding 1.29 times its climatological standard deviation (~90th percentile in a normal distribution, Hobday et al. 2016). For each week over 1982 to 2021 the largest contiguous area falling into MHW status was retained, and its total area was calculated by summing the pixel surface area corrected for the curvature of the earth’s surface. The MHW areas were also separately calculated for the Canadian Pacific EEZ. The 30-year period 1991-2020 was used to calculate climatological fields.

Data were also retrieved for Environment and Climate Change Canada’s Halibut Bank (C46146) and La Perouse Bank (C46206) buoys. Buoy data and status flags were accessed from the CIOOS ERDDAP server (data.cioospacific.ca/erddap/info/DFO_MEDS_BUOYS/index.html, dataset ID “DFO_MEDS_BUOYS”; Kellogg et al. 2021).

All analyses and maps were produced using R. Satellite data was accessed from the CoastWatch ERDDAP server (coastwatch.pfeg.noaa.gov/erddap/index.html), and maps and processed data set up to automatically update on Github (github.com/BIO-RSG/Pacific_SST_NRT_Monitoring).

11.3. Status and trends

The weekly time series of MHW-classified area over the period 1982 – 2021 (Figure 11-3a) showed intermittent MHW events in the Northeast Pacific (NEP) greater than 1 million km^2, with events rarely exceeding 2 million km^2 prior to 2013. In late 2013, there was a dramatic increase in size of MHW-classified area; contiguous areas greater than 500,000 km^2 in the NEP sustained MHW status for nearly 52 consecutive weeks, corresponding to the dramatic MHW event referred to as the “Blob” (Bond et al. 2015).

The beginning of 2021 was characterized by a large area of the NEP under MHW status (Figure 11-3b), which declined until April. Large contiguous MHW areas formed from late April to early June, which dispersed somewhat, then grew again until October.

The 2021 MHW areas remained offshore in the open ocean for much of the year. Two events where a large area of the Exclusive Economic Zone (EEZ) was in MHW status (Figure 11-3d) occurred during the week of June 25th to July 1st (98,600 km^2, or 21.7% of the EEZ; Figure 11-1) and July 30th to August 5th (96,600 km^2, or 21.3% of the EEZ; Figure 11-2). However, this is much smaller compared to the area of the EEZ that was in sustained MHW status during the Blob in 2014 (see Figure 11-3c).

The week of June 25th (Figure 11-1) corresponded to the “Heat Dome” weather event, with waters surrounding Vancouver Island reaching MHW status at the time of the heatwave. A large MHW area was also present far offshore. Following the Heat Dome heatwave, the Strait of Georgia remained in MHW status for approximately six weeks. This corresponded to elevated daily mean temperatures at the Halibut Bank buoy, which exceeded the upper 90th percentile of its climatology until late August (Figure 11-4a). La Perouse, on the other hand (Figure 11-4b), was slightly cooler than usual prior to the Heat Dome heatwave; during the Heat Dome the daily mean temperature was elevated to greater than its upper 90th percentile for a week, after which it returned to more typical daily temperatures according to its climatology.

The MHW area during the week of July 30th corresponded to a more wide-spread MHW, with anomalously warm pixels extending southwest of Vancouver Island, northward along the shelf waters of B.C. and Alaska, and in the Gulf of Alaska. As mentioned, the temperature recorded at Halibut Bank remained anomalously warm during this period.

11.4. Factors influencing trends

Warming temperatures of the surface ocean have been observed throughout the Northeast Pacific and Canadian Pacific EEZ. For example, B.C. shore station measurements taken over the course of a century have shown an increase of 0.88 ^{o}C per century (Chandler 2021). At the larger scale, Laufkötter et al. (2020) and Hobday et al. (2018) showed increasing duration, intensity, and frequency of MHWs globally in the last decade and Tanaka and Houtan (2022) showed that at least 50% of the North Pacific has been in a MHW state since 2014.

The temperatures reached during the Heat Dome event of June-July 2021 were anomalous even when considering the impacts of climate change. A rapid analysis placed its probability as approximately 1 in 1000 years likelihood (Philip et al. 2021), but 150 times more likely compared to pre-industrial climate, and “virtually impossible” without the warming that has occurred to date. Warming during the Heat Dome was sustained via a combination of a polar vortex instability, blocking ridge in the troposphere, and subsidence / solar heating, and had similarities to the Siberian heatwave in June 2020 (Overland 2021). There is not yet consensus on whether the blocking events like what was observed are increasing in frequency or severity. It appears that it was a very low probability event in any case (Philip et al. 2021).

11.5. Implications of those trends

We can expect that MHWs will continue to increase in size, intensity, and frequency (Laufkötter et al. 2020; Hobday et al. 2018) and indeed the NEP appears to have reached its “Point of No Return”, where the temperature of more than 50% of the surface area exceeds the climatological values of the previous century (Tanaka and Houtan 2022).

Marine heatwaves (MHWs) can have large-scale negative effects on the marine environment. The marine heatwave of 2014-2016 (the “Blob”) included mass mortality events, lowered primary production, and contributed to harmful algae blooms in the Northeast Pacific (Crozier 2015). A relationship has also been found between the number of days with SST >= 11 C and kelp forest loss (Starko et al. 2019). Hardy et al. (2021) showed that the number of days exceeding the 11°C threshold has increased in Gwaii Haanas over the period 1982-2019 by 6.6 days per decade.

Given that the resilience of some species and ecosystems are reduced as the ocean warms and MHW frequencies are expected to increase, the changes occurring may have irreversible consequences. For example, observations in the Gulf of Alaska show that the trophic level changes caused by the Blob MHW do not appear to be appreciably returning to pre-Blob conditions (Suryan et al. 2021).

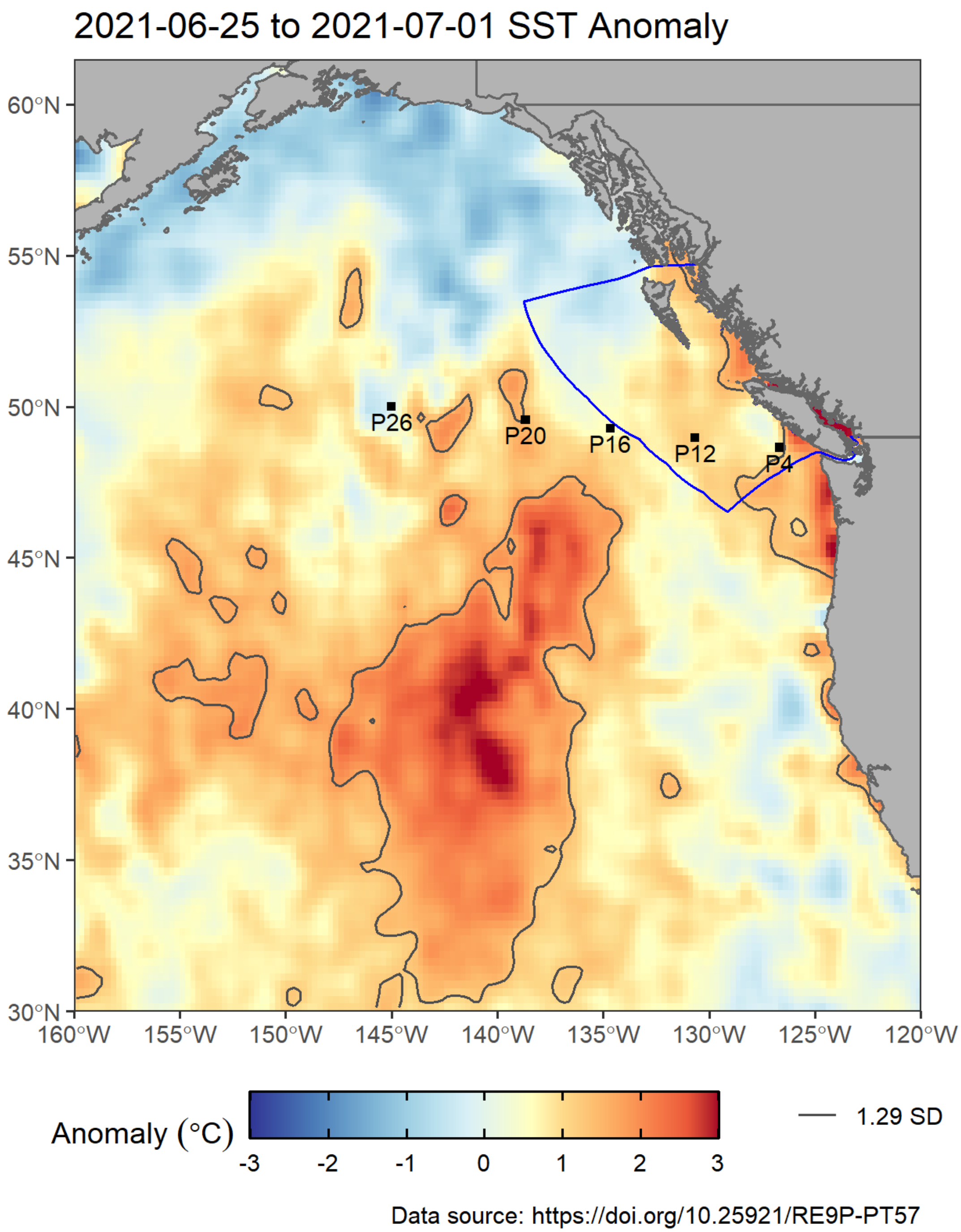


Figure 11-1. Map of week June 25 to July 7, 2021 of the study region, corresponding to the Heat Dome, with EEZ delineated in blue, and selected Line P stations indicated.

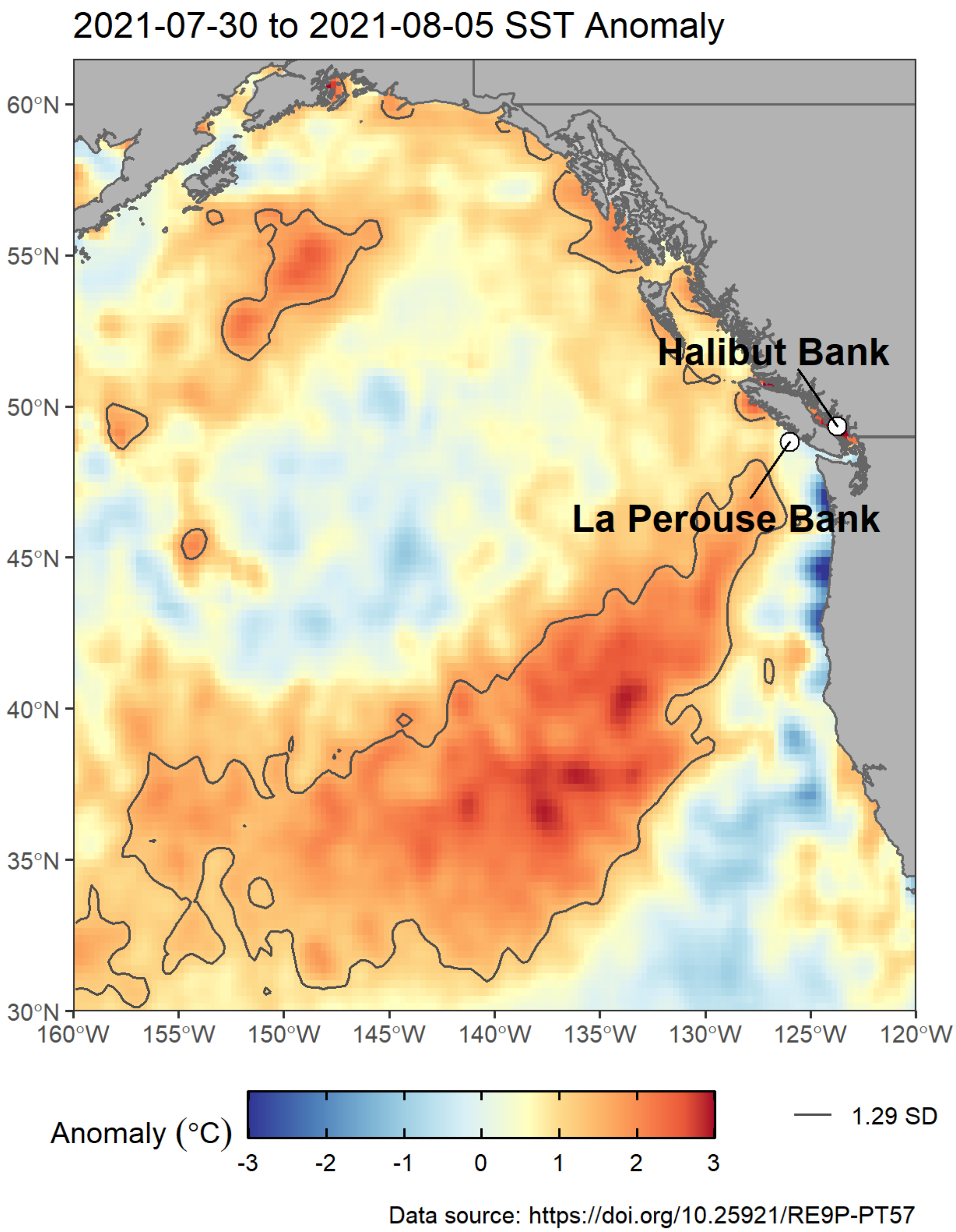


Figure 11-2. Map of week of July 30 to August 5, 2021, showing Halibut Bank and La Perouse Bank buoy locations.

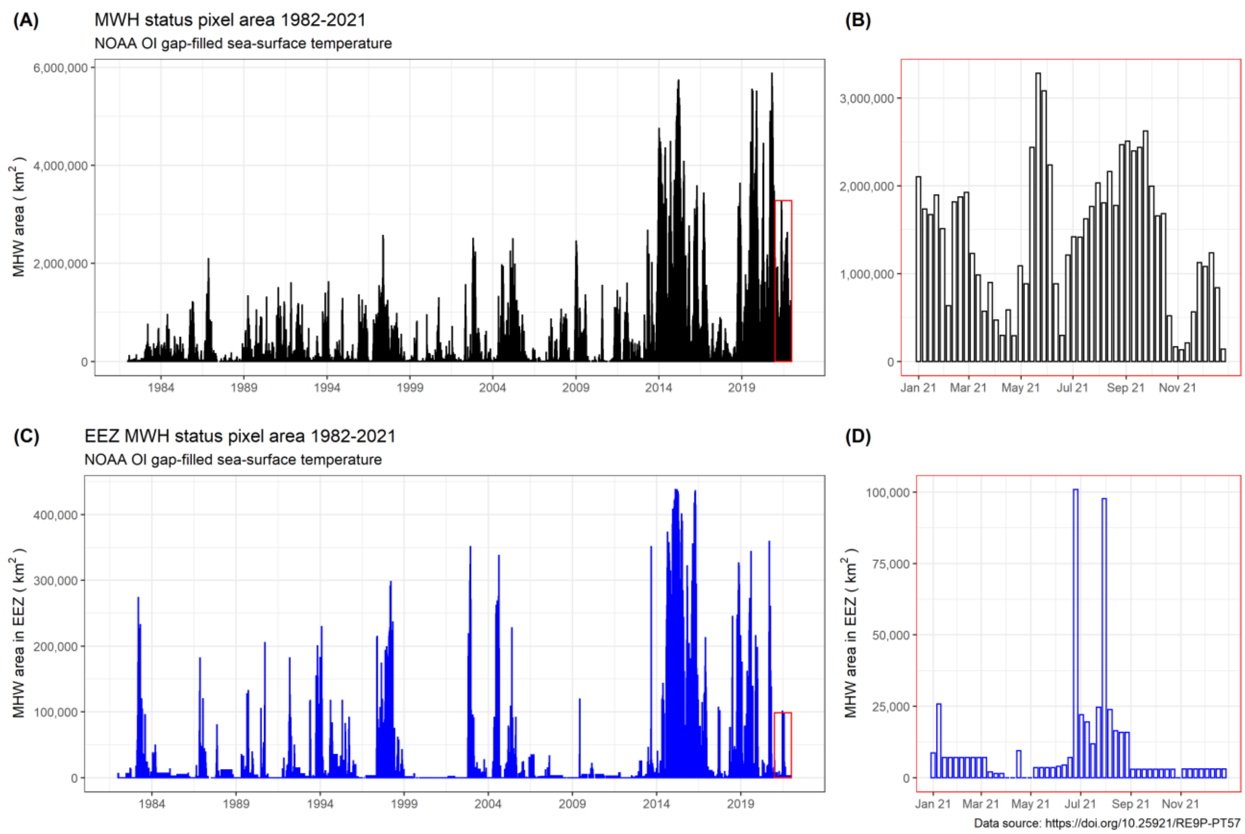


Figure 11-3. Area of the study region classified with MHW status over the full years 1982 to 2021 (A), with zoom on 2021 shown (B, red box), and then for the EEZ alone (C) with 2021 shown separately (D). The total area of the B.C. Pacific EEZ is approximately 454,180 km^2.

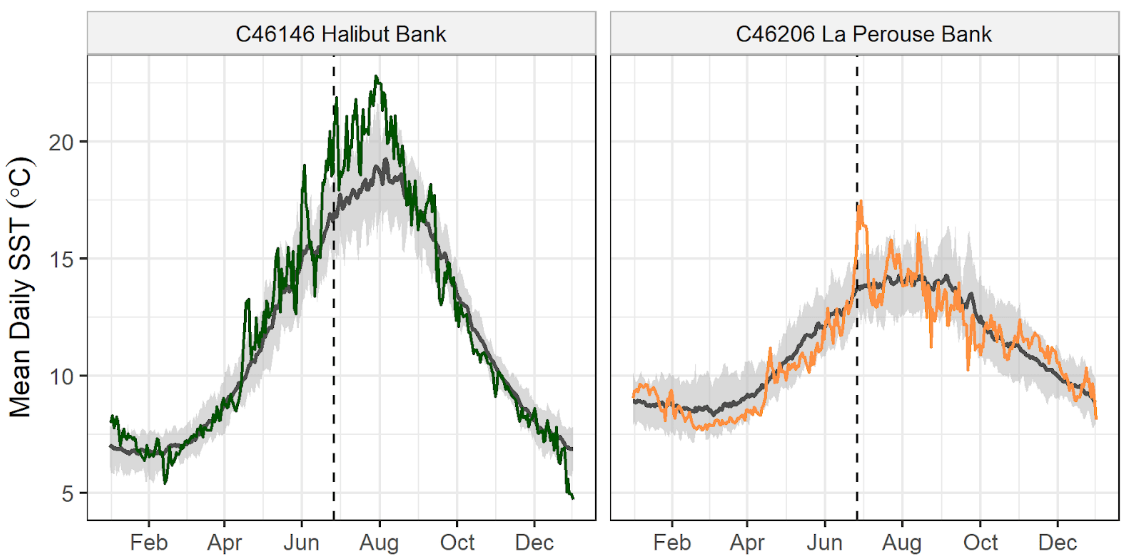


Figure 11-4. Halibut Bank (left) and La Perouse Bank (right) buoy climatology and 2021 daily mean temperature. The dashed vertical line indicates June 26th, 2021.

11.6. References

Bond, N.A., Cronin, M.F., Freeland, H., and Mantua, N. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophysical Research Letters. 42: 3414-3420. https://doi.org/10.1002/2015GL063306

Chandler, P.C. 2021. Sea surface temperature and salinity observed at shore stations and weather buoys along the B.C. coast in 2020. In: Boldt, J.L., Javorski, A., and Chandler, P.C. (Eds.). State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2020. Can. Tech. Rep. Fish. Aquat. Sci. 3434: vii + 231 p.

Crozier, L. 2015. Impacts of climate change on salmon of the Pacific Northwest. Technical Review, National Marine Fisheries Service, National Oceanic and Atmospheric Administration. 46 p.

Hardy, M., Devred, E., and Hannah, C. 2021. Satellite observations of the Northeast Pacific Ocean. Can. Tech. Rep. Hydrogr. Ocean Sci. 335: vii + 46 p. http://waves-vagues.dfo-mpo.gc.ca/Library/4092855x.pdf

Hobday, A., Alexander, L., Perkins, S., Smale, D., Straub, S., Oliver, E., Benthuysen, J., Burrows, M., Donat, M., Feng, M., Holbrook, N., Moore, P., Scannell, H., Sen Gupta, A. and Wernberg, T. 2016. A hierarchical approach to defining marine heatwaves. Progress in Oceanography. 141, 227-238, https://doi.org/10.1016/j.pocean.2015.12.014

Hobday, A.J., E.C.J. Oliver, A. Sen Gupta, J.A. Benthuysen, M.T. Burrows, M.G. Donat, N.J. Holbrook, P.J. Moore, M.S. Thomsen, T. Wernberg, and D.A. Smale. 2018. Categorizing and naming marine heatwaves. Oceanography 31(2):162–173, https://doi.org/10.5670/oceanog.2018.205.

Kellogg, J., Rosenstock, N., Page, S., Hourston, R., Devred, E. and Hannah, C. 2021. Quality Control of Weather/Wave Buoy Temperature Data Provided by Environment and Climate Change Canada. https://catalogue.cioospacific.ca/dataset/ca-cioos_b9c71eb2-b750-43d5-a50a-aee173916736 (accessed 28 February, 2022).

Laufkötter, C., Zscheischler, J. and Frölicher, T.L. 2020. High-impact marine heatwaves attributable to human-induced global warming. Science. 369(6511): 1621-1625. https://doi.org/10.1126/science.aba0690

Overland, J.E. 2021. Causes of the Record-Breaking Pacific Northwest Heatwave, Late June 2021. Atmosphere. 12 (11): 1434. https://doi.org/10.3390/atmos12111434

Philip, S.Y., Kew, S.F., van Oldenborg, G.J. et al. Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021. World Weather Attribution. https://www.worldweatherattribution.org/wp-content/uploads/NW-US-extreme-heat-2021-scientific-report-WWA.pdf (accessed 26 February, 2022).

Starko, S., Bailey, L.A., Creviston, E., James, K.A., Warren, A., Brophy, M.K., Danasel, A., Fass, M.P., Townsend, J.A., and Neufeld, C.J. 2019. Environmental heterogeneity mediates scale-dependent declines in kelp diversity on intertidal rocky shores. PLOS ONE. 14(3). https://doi.org/10.1371/journal.pone.0213191

Suryan, R.M., Arimitsu, M.L., Coletti, H.A. et al. 2021. Ecosystem response persists after a prolonged marine heatwave. Sci. Rep. 11, 6235. https://doi.org/10.1038/s41598-021-83818-5

Tanaka, K. and Houtan, K. 2022. The recent normalization of historical marine heat extremes. PLOS CLIM. 1(2): e0000007. https://doi.org/10.1371/journal.pclm.0000007

12. WATER CURRENTS AND TRANSPORT OFF THE BRITISH COLUMBIA COAST

Guoqi Han[1]

[1]Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Guoqi.Han@dfo-mpo.gc.ca

12.1. Highlights

- In 2021, satellite altimetry indicated that the equatorward shelf-edge surface current at a West Vancouver Island transect was stronger than normal in summer and the year-round poleward surface current at a Queen Charlotte Sound transect was stronger than normal.
- Model hindcasts showed that in 2021 the water transport associated with the Vancouver Island Coastal Current was weaker than normal and the water transport associated with the California Undercurrent was close to normal.

12.2. Description of the time series

Geostrophic surface currents were calculated at two transects (Figure 12-1) by using 10-day interval along-track satellite altimetry sea surface height data from October 1992 to December 2021 and following the method outlined in Han et al. (2014) and Han and Chen (2022). One transect was located off the west coast of Vancouver Island (WCVI) and the other was located at the mouth of Queen Charlotte Sound (QCS). The geostrophic surface currents are in the direction normal to the transect (positive poleward) and approximately represent the longshore flow. The calculated geostrophic surface currents are further averaged both seasonally and over-transect. At the WCVI transect (Figure 12-2, upper panel) the winter surface current is poleward and the summer surface current is equatorward, with the long-term mean surface current close to zero. At the Queen Charlotte Sound transect (Figure 12-2, lower panel), the surface current is poleward year-round; stronger in winter and weaker in summer.

Water transport at transects off Vancouver Island (Figure 12-1) was calculated for the inshore current (to represent the Vancouver Island Coastal Current), the upper-layer shelf-edge current, and the sub-surface shelf-edge current (to represent the California Undercurrent), based on the model output from a newly developed 1/36˚ Northeast Pacific Ocean Model (NEPOM). The model was evaluated against current meter data at a long-term monitoring site from January 1993 to May 2021, showing that the model currents are reasonably good at representing monthly longshore currents over the shelf edge (Figure 12-3). The annual-mean water transport of the model Vancouver Island Coastal Current is poleward (Figure 12-4). The annual-mean water transport is poleward for the model California Undercurrent and fluctuates between equatorward and poleward for the upper-layer shelf-edge current (Figure 12-4).

12.3. Status and trends

There is no apparent long-term trend in the altimetric surface current over 1992-2021. Interannual variations are evident. In summer 2021, the altimetric equatorward surface current at the WCVI transect was much stronger than normal. The altimetric poleward surface current at the QCS transect was stronger than normal in 2021, except in winter.

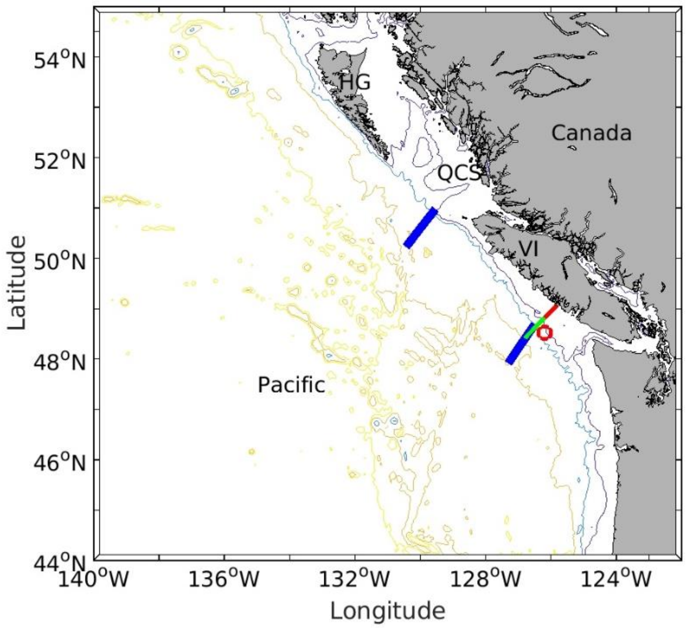


Figure 12-1. The study area showing the location of two altimetry transects (blue), bathymetry (200-, 1000-, 2000- and 3000-m isobaths), transects for calculating the water transport associated with the inshore current (red) and the shelf-edge currents (green), as well as a long-term monitoring site (red open circle). HG: Haida Gwaii. QCS: Queen Charlotte Sound. VI: Vancouver Island.

There are substantial interannual variations in the modelled water transport. The annual-mean water transport of the modelled Vancouver Island Coastal Current was weaker than normal in 2021. The annual-mean water transport of the modelled California Undercurrent was close to normal in 2021; so was the annual-mean water transport of the modeled upper-layer shelf-edge current.

12.4. Factors influencing trends

Stronger surface currents at the WCVI transect have occurred in El Niño and La Niña years, consistent with Hourston and Thompson's (2020) results from *in situ* measurements. The surface currents could also be influenced by the Pacific Decadal Oscillation, possibly via its impacts on regional wind patterns.

The Vancouver Island Coastal Current may be linked to buoyancy forcing associated with the fresher outflow from the Juan de Fuca Strait and longshore surface winds (Masson and Cummins 1998). The California Undercurrent may be linked to longshore winds off the Oregon-California coast, longshore baroclinic pressure gradients, and processes in the equatorial Pacific (Thomson and Krassovski 2015). Therefore, these two currents may be linked to large-scale climate processes such as El Niño, La Niña, and the Pacific Decadal Oscillation.

In 2021 there was a moderate La Niña and an intensified cool phase of the Pacific Decadal Oscillation (see Ross and Robert, Section 7).

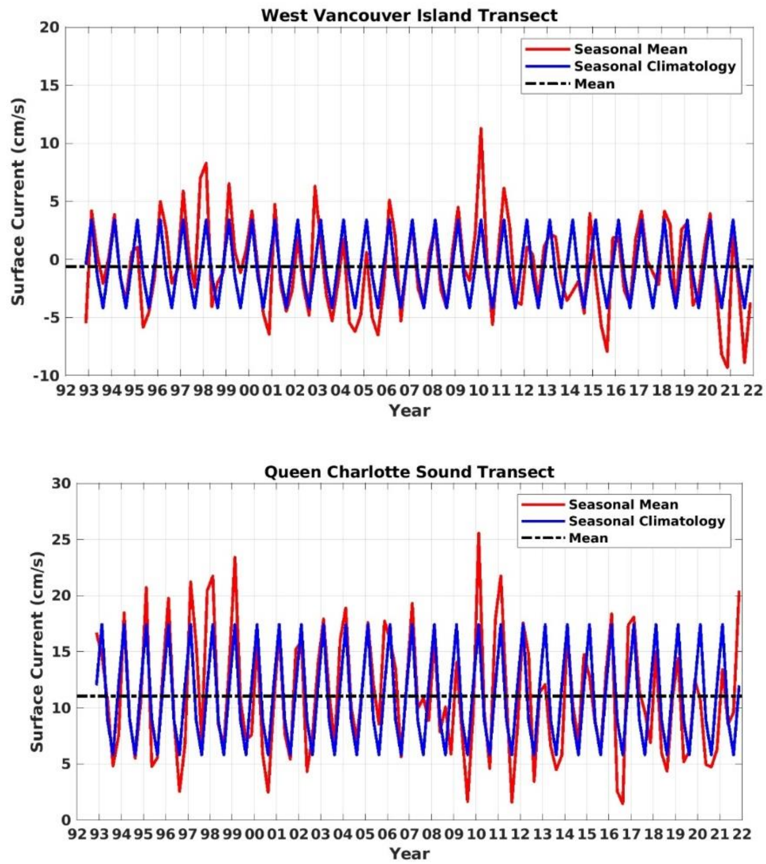


Figure 12-2. Seasonal-mean geostrophic surface currents (positive poleward) at the two transects located off the west coast of Vancouver Island (WCVI) (upper panel) and at the mouth of Queen Charlotte Sound (QCS) (lower panel).

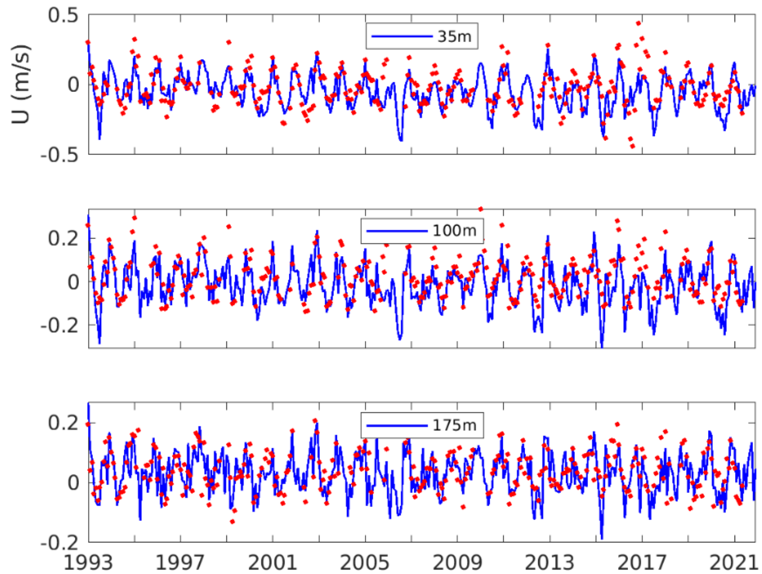


Figure 12-3. Modelled (blue line) and observed (red dot) monthly-mean longshore currents at depths of 35 m, 100 m and 175 m at a long-term monitoring site off Vancouver Island (See Figure12-1 for location).

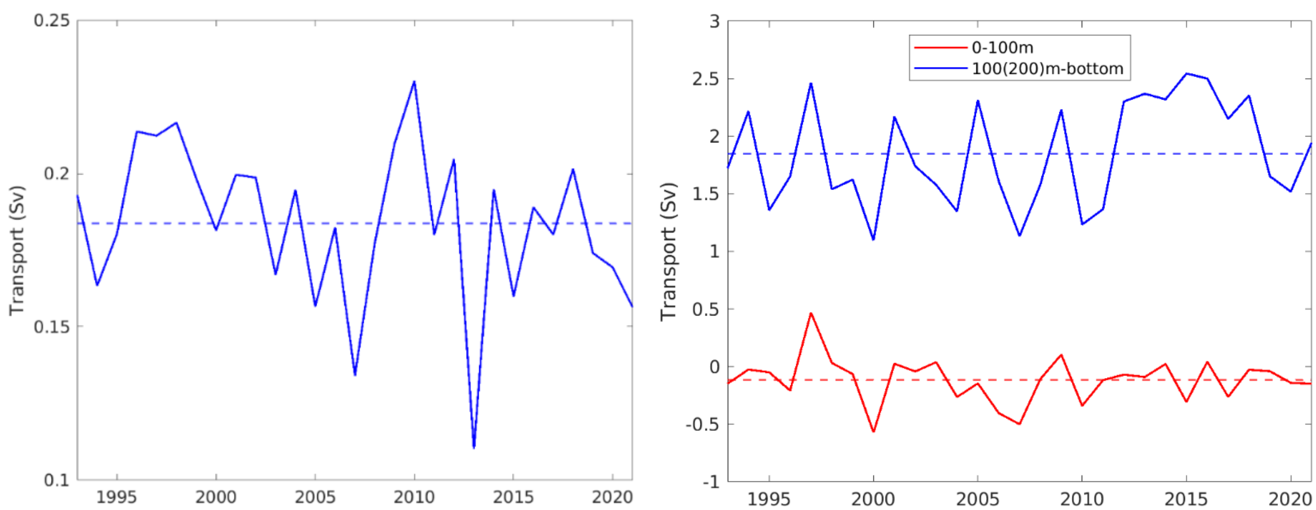


Figure 12-4. Annual-mean water transport (positive poleward) associated with the Vancouver Island Coastal Current (left panel) and the shelf-edge currents off the west coast of Vancouver Island (right panel). In the right panel, the upper-layer shelf-edge current transport (red curve) is calculated from the sea surface to 100-m depth; the lower-layer shelf-edge current transport (blue curve) is calculated by considering poleward transport from 100-m to the bottom in fall and winter and from 200-m to the bottom in spring and summer to represent the California Undercurrent. The dashed lines are the mean transport averaged over 1993-2020. 1 $S_v = 10^6\ m^3/s$.

12.5. Implications of those trends

These currents can affect water properties such as temperature, salinity, nutrients, dissolved oxygen off the B.C. coast (Thomson and Krassovski 2010 and 2015). They can also impact transport and distribution of fish eggs and larvae. Folkes et al. (2018) showed that surface currents can be a useful predictor for the return timing and northern diversion rate of Fraser sockeye salmon.

12.6. References

Masson, D., and Cummins, P.F. 1998. Numerical Simulations of a Buoyancy-Driven Coastal Countercurrent off Vancouver Island. Journal of Physical Oceanography. 29: 428-435.

Folkes, M.J.P, Thomson, R.E. and Hourston, R.A.S. 2018. Evaluating models to forecast return timing and diversion rate of Fraser sockeye salmon. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/021. vi + 220 p.

Han, G., and Chen, N. 2022. Variability of Longshore Surface Current on the Shelf Edge and Continental Slope off the West Coast of Canada. Remote Sensing. 14: 1407. https://doi.org/10.3390/rs1406140.

Han, G., Chen, N., and Ma, Z. 2014. Is there a north-south phase shift in the surface Labrador Current transport on the interannual-to-decadal scale? Journal of Geophysical Research – Oceans. 119: 276-287, DOI:10.1002/2013JC009102.

Hourston, R., and Thomson, R. 2020. Vancouver Island West Coast shelf break currents, temperatures and wind stress. In: Boldt, J.L., Javoski, A., and Chandler, P. (Eds.) 2020. State of physical, biological and selected fisheries resources of Pacific Marine ecosystem in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377: x +288 p.

Thomson, R. E., and Krassovski, M. 2010. Poleward reach of the California Undercurrent extension, J. Geophys. Res. 115 C09027. doi:10.1029/2010JC006280.

Thomson, R.E., and Krassovski, M. 2015. Remote alongshore winds drive variability of the California Undercurrent off the British Columbia-Washington coast. Journal of Geophysical Research - Oceans. 120: 8151-8176, doi:10.1002/2015JC011306.

13. OCEANOGRAPHIC CONDITIONS OFF THE WEST COAST OF VANCOUVER ISLAND: 2021

Akash Sastri, Bill Crawford, Angelica Peña, and John Nelson, Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Akash.Sastri@dfo-mpo.gc.ca, Bill.Crawford@dfo-mpo.gc.ca, Angelica.Pena@dfo-mpo.gc.ca, John.Nelson@dfo-mpo.gc.ca

13.1. Highlights

- In May, the upper water column (< 50 m) along the west coast of Vancouver Island (WCVI) was cooler and saltier than average over the shelf and cooler and fresher over the continental slope and offshore.
- Upper water column conditions in late-summer 2021 shifted to warmer and fresher than average, but not to the same extent as seen in the 2019 marine heatwave.
- Dissolved oxygen concentrations at 125 m on the outer southern shelf were < 1.4 ml/l and the lowest early and late summer values recorded since 1979.

13.2. Description of the time series

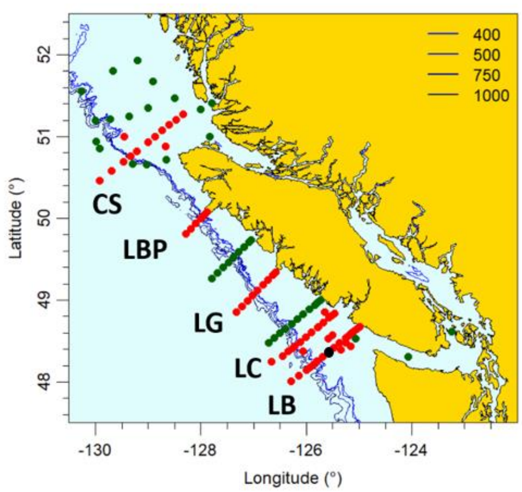


Figure 13-1. Map of the La Perouse-west coast of Vancouver standard survey stations. Stations for each of the survey lines (labelled) discussed in this report are identified with red symbols. Black symbol on LB line represents station LB08. Bathymetric contours indicate the shelf break and contour-specific depths (m) and are identified in the legend.

The zooplankton survey of the WCVI continental margin was conducted from 1979 to present for southern WCVI, and from 1990 to present for northern WCVI. The La Perouse/WCVI survey generally takes place in May and September each year and provides synoptic snapshots of physical, chemical, and biological patterns at shelf, slope, and offshore stations. Each of the biannual surveys is 11-13 days in duration and generally falls within the annual upwelling period. The May survey typically occurs within 30 days of the onset of upwelling positive winds (Hourston and Thomson Section 8; Dewey et al. Section 33). Transition timing from upwelling to downwelling varies with latitude; however, the September survey generally precedes this transition along southern WCVI. This report focuses on the most regularly sampled lines (red symbols in Figure 13-1): 1) LB, LC, and LG lines for southern WCVI; and 2) LBP and CS lines for northern WCVI. The time series average for all lines was estimated as the average temperature or salinity for each station-specific pressure-bin for the annual cycle (days of the year 100-300) for the 1991-2020 period. Anomalies were then calculated as the difference in temperature and salinity for each 2021 survey station-specific pressure bin and its corresponding time-series average interpolated to day of the year. Here we continue some of the long-term (1979-present) subsurface dissolved oxygen (ml/l) observations previously reported by Crawford and Peña (2013) and Crawford and Peña (2021). Section plots of oxygen for the LB line rely on sensor-based (SBE 43) measurements and the 125 m time-series observations for station LB08 rely on oxygen titrations of discrete seawater samples.

13.3. Status and trends

Upper ocean salinity and temperature in the survey area vary with latitude, season, and bottom depth. Here, 'mixed layer' refers to the surface mixed layer (surface to the depth of maximum squared buoyancy frequency, N^2). The mixed layer depth over the broad northern shelf (as represented by CS line stations) was deeper and more variable (19-95 m) than the mixed layer depth (~10 m) over the narrow shelf (LBP line) during the May 2021 survey (Figure 13-2). Mean mixed layer salinities for CS and LBP shelf stations were slightly fresher and much saltier (0.7 psu) than each time series average for this time year. The surface mixed layer for CS slope and offshore stations was slightly saltier than average and fresher than average for LBP line. The cross-shelf pattern of salinity anomaly for LBP line was similar for the three southern lines, LG, LC, and LB lines. Salinity anomalies over the southern shelf were all positive and line-specific averages were 0.37, 0.58, and 0.43 psu for LG, LC, and LB lines, respectively. Surface mixed layer salinity for southern slope and offshore stations were all slightly negative relative to time series averages.

Surface mixed layer temperatures were cooler than the long-term, late-May average for most of the shelf and slope/offshore stations surveyed in the northern and southern WCVI regions (Figure 13-3). Mean temperature along the broad northern shelf in May 2022 was ~9 °C, which was 0.6 °C cooler than average. Mean surface mixed layer temperatures for the narrow shelf stations (LBP line) were also cooler (0.76 °C) than average. Slope and offshore stations for both CS and LBP lines were 0.33 and 0.44 °C cooler than each time series average. Surface mixed layer temperatures along the southern lines were ~0.36 °C cooler than average with progressively larger anomalies from north (LG line) to south (LB line).

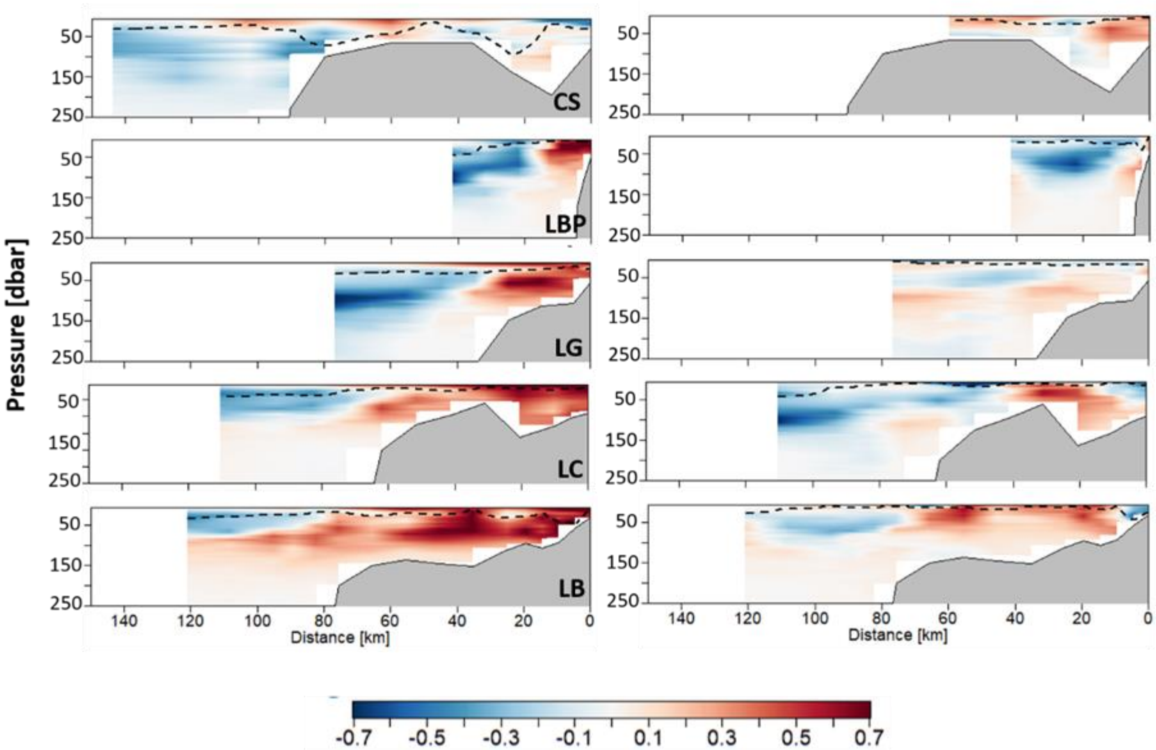


Figure 13-2. Salinity anomaly (psu) section plots across each sampling line. Maximum depth set at 250 dbar. Top to bottom represents northern to southern lines (see Figure 13-1). Left and right represent May and September surveys, respectively. The time series average for all lines was estimated as the average salinity for each station-specific pressure-bin for 1990-2020 and the annual period corresponding to each survey. Anomalies were calculated as the difference in salinity for each 2021 survey station-specific pressure bin and its corresponding time-series average. Salinity values greater and less than the time series averages are represented by 'warm' and 'cool' colours, respectively. Dashed lines represent depth of the maximum buoyancy frequency squared (N^2) used here as a proxy for the base of the surface mixed layer.

The second annual survey took place September 7-21, 2021. The average surface mixed layer depths for CS line (broad northern shelf) and LBP line (narrow northern shelf) stations were 19 m and 23 m, respectively. Average salinity over the shelf for CS and LBP lines was near the seasonal long-term average and 0.2 psu fresher than average for LBP slope/offshore stations. Note, CS line slope/offshore stations were not sampled due to rough conditions. Surface mixed layer depths for the southern WCVI were generally shallower relative to the northern WCVI. LG line (Figure 13-1) salinity was similar to and slightly fresher than the time series seasonal average over the shelf and slope/offshore stations, respectively. Further south, LC and LB line shelf stations were 0.3 psu and 0.38 psu fresher than average and near normal for slope/offshore stations.

The start of the September survey corresponded to the greatest areal extent of the 2022 NEP Marine Heatwave (Hilborn and Hannah, Section 11). With the exception of LC line shelf stations (-0.16 °C cooler than average); the surface mixed layer for all shelf and slope/offshore stations along the WCVI were warmer than the seasonal average. There were no obvious north-trends, but > 1 °C anomalies were estimated over the shelf LBP line in the north and for slope/offshore LC line stations in the south. All other positive temperature anomalies were < 0.5 °C warmer than the seasonal average. WCVI surface mixed layer temperature anomalies in September stand in contrast to temperature anomalies in May; however, they were not as extreme as measured in 2015 or 2019.

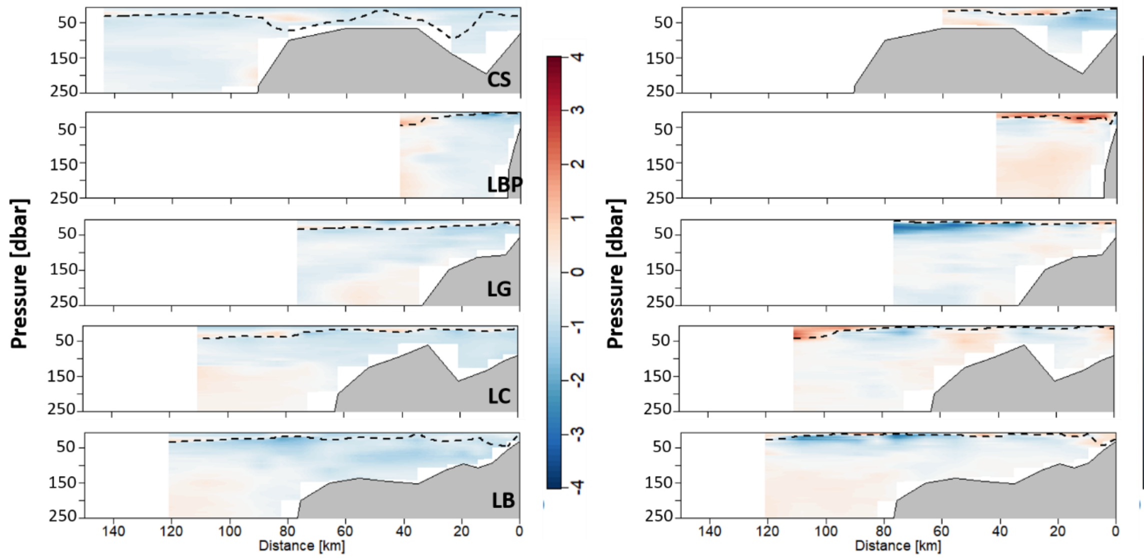


Figure 13-3. Temperature anomaly (°C) section plots across each sampling line. Maximum depth set at 250 dbar. Top to bottom represents northern to southern lines (Figure 13-1). Left to right represent May and September survey sections, respectively. The time series average for all lines was estimated as the average temperature for each station-specific pressure-bin for 1990-2014 and the annual period corresponding to each survey. Anomalies were calculated as the difference in temperature for each 2021 survey station-specific pressure bin and its corresponding time-series average. Temperature values greater and less than the time series averages are represented by 'warm' and 'cool' colours, respectively. Dashed lines represent depth of the greatest buoyancy frequency squared (N^2) used here as a proxy for the base of the surface mixed layer.

The California undercurrent flows poleward along the WCVI slope and its core (200-300 m depth) is characterized by low oxygen associated with the 1.4 and 2.1 ml/l oxygen contours in both May and September (Figure 13-4). Seasonal upwelling, particularly along the southern shelf, extends these contours over the shelf. The lowest dissolved oxygen concentration on the shelf in May, 2021, was centered at station LB08 (red symbol in Figure 13-4). This was also the case in September, however, the depth of the 1.4 ml/l oxygen contour had shoaled to ~60 m below the surface. Discrete bottle-based measurements of dissolved oxygen were 1.32 and 0.57 ml/l for May and September, respectively (Figure 13-5). These 125 m measurements represent the minimum seasonal extremes for the entire time series from 1979 to 2021. The oxygen-nitrate ratio decreased during the summer and the 2021 estimates (at 125 m for LB08) represent the extreme low for oxygen for both May and September, suggesting that respiration of organic material at depth was high, contributing to the observed extremes.

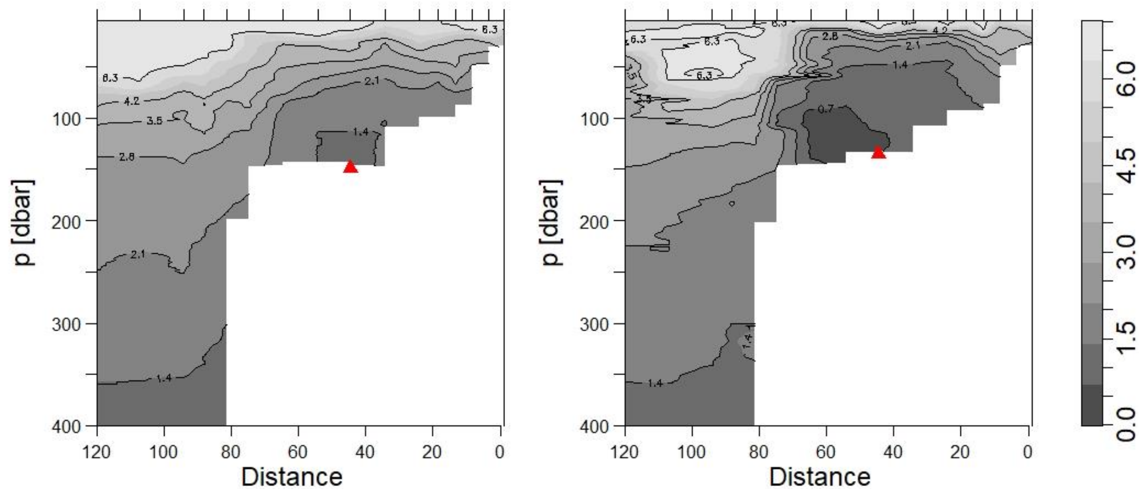


Figure 13-4. Section plots of dissolved oxygen (ml /l) along LB line (Figure 13-1) in mid-May 2021 (left panel) and early September 2021 (right panel). The red triangle shows the location of the station LB08.

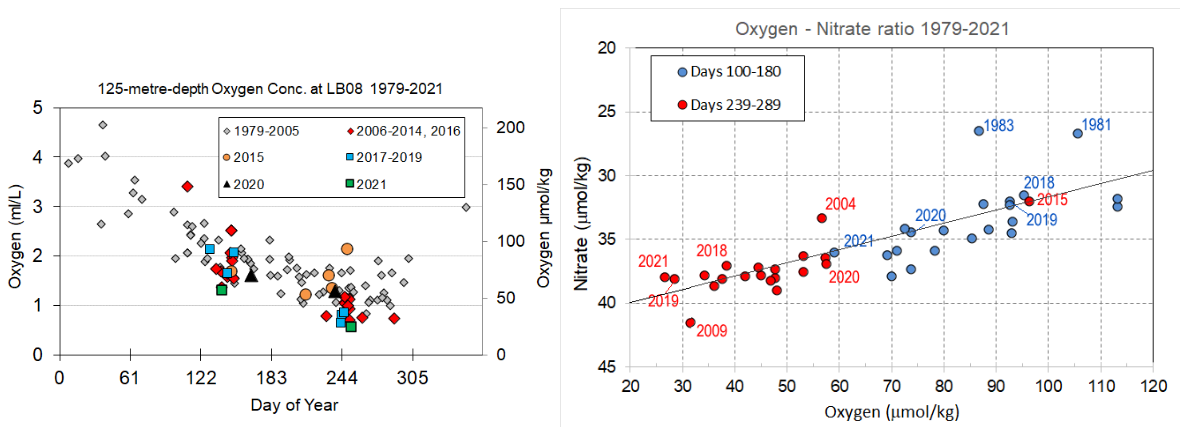


Figure 13-5. Annual cycle of 125 m dissolved oxygen concentration (ml/l and µmol/kg) at station LB08 highlighting time series extremes (left panel). Green symbols identify the 2021 low oxygen extremes for this time series (1979-2021). Interannual and seasonal variation of 125 m oxygen-to-nitrate ratios at station LB08 (1979-2021; right panel). Low oxygen to nitrate indicates greater oxidation of organic material with 2021 early and late summer ratios representing extreme lows for the time series.

13.4. Factors influencing trends

La Niña conditions, beginning in late 2020 and persisting through to the May 2021 survey, were accompanied by cooler than average water column temperatures along the outer B.C. coast (Chandler, Section 32). Upwelling started earlier than average and was near constant throughout the summer and leading up to September 2021 survey (Hourston and Thomson, Section 8; Dewey et al, Section 33). Persistent upwelling, particularly along the southern WCVI continental slope, brought California undercurrent source waters onto the shelf supplying nutrient and salt-rich water to the surface and extending deep oxygen-poor waters over the shelf eastward. The extremely low seasonal oxygen to nitrate ratios at LB08 suggest high respiration of organic material perhaps enhanced by high seasonal production of phytoplankton in the surface. A pronounced atmospheric heating event (‘heat dome’) in June as well as a marine heatwave developing offshore of Vancouver Island throughout the summer (Ross and Robert, Section 7; Hilborn and Hannah, Section 11) may have contributed to the warmer than average surface mixed layer observed along most of the WCVI in late summer.

13.5. Implications of those trends

Warmer than average mixed layer temperatures along the WCVI are often associated with a greater abundance and biomass of smaller, less lipid-rich zooplankton relative to the larger, lipid-rich, boreal and subarctic groups which tend to dominate under cooler conditions (Galbraith, Section 17). Spring and early 2021 were characterized by cooler than average conditions which have been linked to seasonally average timing and normal to high biomass for larger subarctic zooplankton assumed to support productivity of pelagic fish and seabirds (Mackas et al. 2007; Hipfner et al. 2020); whereas the late summer was characterized by warmer than average temperatures more amenable to small lipid-poor zooplankton. Lower than average, and extremely low, hypoxic subsurface oxygen concentrations pose particular risks to sessile benthic organisms and may limit the distribution of fish (e.g. Pacific Hake) which normally migrate through and feed in WCVI shelf waters.

13.6. References

Crawford, W.R., and Peña, M.A. 2013. Declining oxygen on the British Columbia continental shelf. Atmosphere Ocean. 51(1): 88–103.

Crawford, W.R., and Peña, M.A. 2021. Oxygen concentration in subsurface waters. In: Boldt, J.L. Javorski, A., and Chandler, P.C. (Eds.). 2021. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2020. Can. Tech. Rep. Fish. Aquat. Sci. 3434: vii + 231 p.

Hipfner, M.J., Galbraith, M., Bertram, D.F., and Green, D.J. 2020. Basin-scale oceanographic processes, zooplankton community structure, and diet and reproduction of a sentinel North Pacific seabird over a 22-year period. Prog. Oceanogr. 182: 102290. doi.org/10.1016/j.pocean.2020.102290.

Mackas, D.L., Batten, S., and Trudel, M. 2007. Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific. Prog. Oceanogr. 75: 223-252.

14. C-PROOF 2021 OCEAN GLIDER DATA FROM LINE P AND QUEEN CHARLOTTE SOUND WITH A FOCUS ON OXYGEN

Hayley Dosser[1,2], Khushboo Jhugroo[2] and Tetjana Ross[1]

[1]Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Hayley.Dosser@dfo-mpo.gc.ca, Tetjana.Ross@dfo-mpo.gc.ca

[2]University of British Columbia, Department of Earth, Ocean and Atmospheric Sciences, Vancouver, B.C., khush.jhugroo@hakai.org

14.1. Highlights

- Ocean glider data captured seasonal differences in dissolved oxygen concentration in Queen Charlotte Sound, as well as spatial variations including a subsurface minimum on the shelf and a subsurface maximum beyond the shelf break, both present in summer.
- An anomalously high oxygen concentration was observed in the oxygen minimum zone along Line P during September and October, with otherwise fairly normal conditions.
- Hypoxic conditions were present unusually far north on the shelf near Tofino during September, during the low oxygen event that occurred in summer 2021 off the west coast of Vancouver Island. However, hypoxic conditions had ended by the time the ocean glider crossed the shelf on the LC Line in mid-October.

14.2. Description of the time series

C-PROOF, the Canadian-Pacific Robotic Ocean Observing Facility, operates a fleet of autonomous ocean gliders equipped with sensors for high-resolution measurements of temperature, salinity, dissolved oxygen concentration, chlorophyll, CDOM, and backscatter, collected between the surface and 1,000 m depth. C-PROOF maintained two sustained glider monitoring lines in 2021: the Calvert Line, which crosses Queen Charlotte Sound from Calvert Island to beyond the shelf break following Goose Trough, and Line P, with the glider crossing the shelf from near Tofino to station P4, then following Line P out to Ocean Station Papa.

These glider monitoring lines provide the ability to resolve the small scales important to upper ocean physical and biological processes, and an ongoing record that allows for comparisons with both existing historical datasets and previous years of glider data. On the Calvert Line (Figure 14-1), ten glider surveys between July 2020 and August 2021 provided a full annual cycle with 8,050 profiles. On Line P, two glider surveys from January to May 2021 and from September to December 2021 provided 4,818 profiles. The latter half of the second Line P survey was atypical, with the glider sampling the LC Line and then heading offshore to Cobb Seamount (Figure 14-3), in order to sample the shelf area where the low oxygen event occurred in summer 2021.

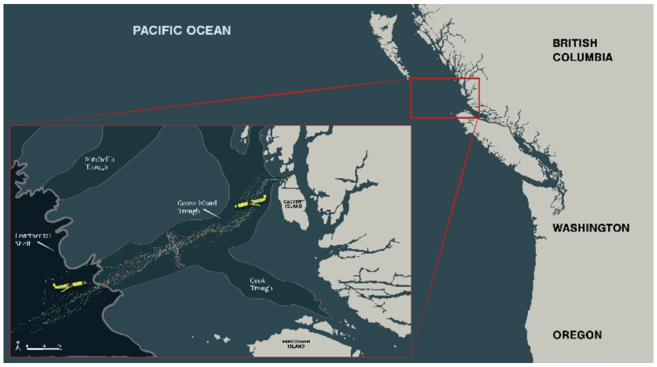


Figure 14-1. Ocean glider tracks for the ten glider surveys conducted in Queen Charlotte Sound in 2020-2021 (coloured dotted lines). Credit: Josh Silberg and Will McInnes, Hakai Institute.

14.3. Status and trends

The ocean glider time series captured high seasonal variability in dissolved oxygen concentration across Queen Charlotte Sound, with higher values shelf-wide in winter and lower, more variable values in summer (Figure 14-2). Small-scale features of note were observed from August through October and include a subsurface oxygen minimum centered at roughly 100 m on the continental shelf and a subsurface oxygen maximum centered at roughly 50 m in the open ocean at a distance of less than 100 km beyond the shelf break.

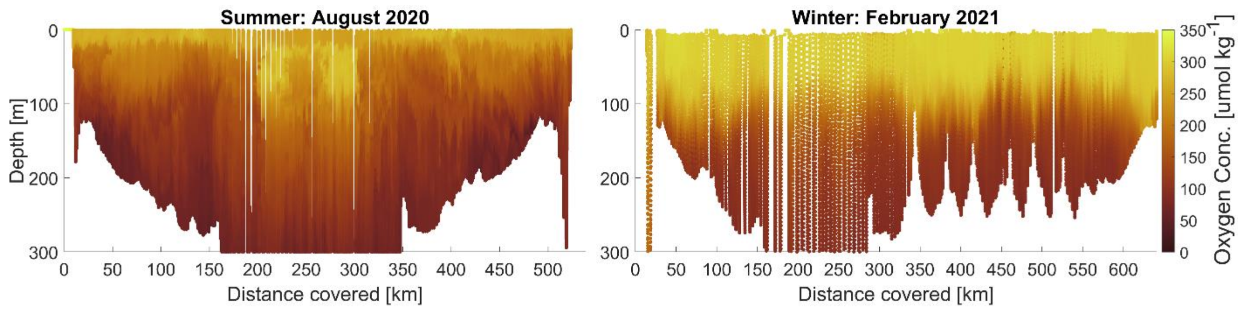


Figure 14-2. Dissolved oxygen concentration along the Calvert Line in Queen Charlotte Sound for August 2020 (left) and February 2021 (right), plotted vs. depth and vs. distance covered by the glider after deployment near the coast. The glider dives down to 1,000 m, only the upper 300 m is shown here. Note that the shelf break is located approximately 150 km from the coast.

Along Line P, oxygen concentration was evaluated relative to a climatology created using Line P hydrographic station data by Dr. Tetjana Ross, with a climatological average from 1991 to 2020.

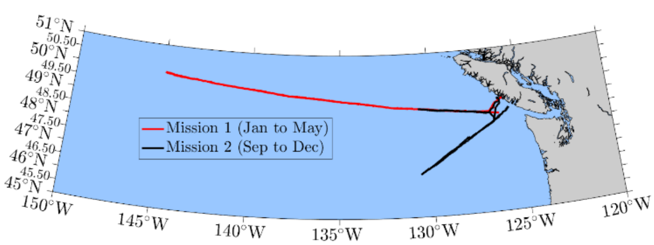


Figure 14-3. Map showing the two 'Line P' glider missions in 2021. Mission 1 (red) followed Line P while Mission 2 (black) was atypical and included sampling along the LC Line with an offshore extension to Cobb Seamount.

Dissolved oxygen values along Line P (Figure 14-4) were fairly typical during Mission 1 (Jan 21 to May 18). During Mission 2 (Sep 2 to Dec 4), oxygen was notably higher than average within the oxygen minimum zone. This deep positive anomaly had a mean magnitude of 5 μmol/kg between 700 m and 1,000 m depth, and was also present in the Line P hydrographic station bottle data collected between Aug 25 and Sep 2 (not shown), with a magnitude of 3 μmol/kg between 700 m and 1,000 m depth. A deep isopycnal located within the oxygen minimum zone, σ = 30 (representing a potential density of 1,030 kg/m^3) also had a positive anomaly of magnitude 5 μmol/kg, confirming that this anomaly was not caused by isopycnal displacement within the water column.

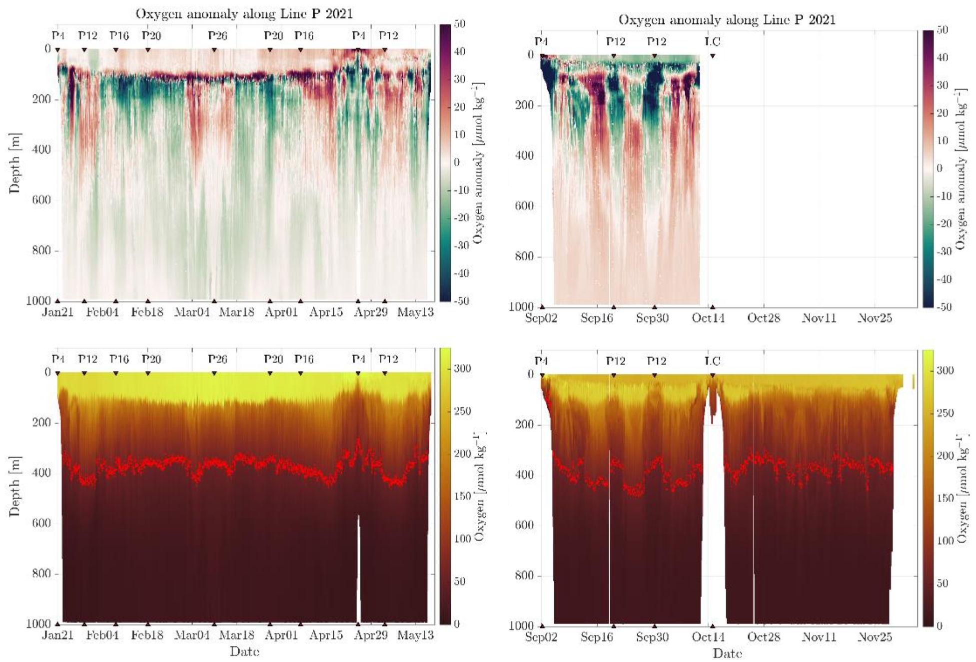


Figure 14-4. Oxygen anomaly along Line P (top) relative to a 1991-2020 climatology and dissolved oxygen concentration (bottom) with the 60 µmol/kg contour in red. Note no anomaly is calculated from mid-October onwards as the glider departed Line P.

Finally, hypoxia was observed unusually far north on the continental shelf near Tofino at the beginning of September (Figure 14-5), during a low oxygen event that occurred in summer 2021 off the west coast of Vancouver Island. By mid-October when the glider crossed the shelf on the LC Line, no hypoxic conditions were observed, indicating the low oxygen event had ended.

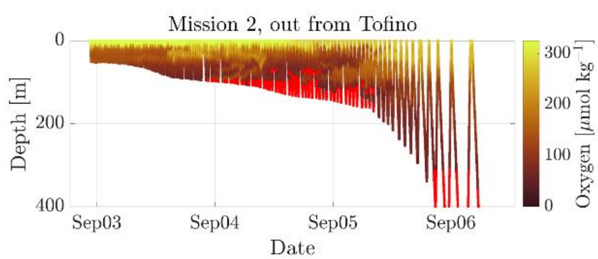


Figure 14-5. Oxygen concentration during early September as the glider crossed the continental shelf from the deployment location near Tofino heading towards hydrographic station P4. The red colour indicates hypoxic values <60 µmol/kg.

14.4. Factors influencing trends

Lower oxygen levels are typically found deeper in the water column on the continental shelf, with the lowest values observed on the shelf in the summer off southwest Vancouver Island due to a combination of increased upwelling and biological respiration (Crawford and Peña 2013). Low and even hypoxic oxygen values are also common on the broad continental shelf in Queen Charlotte Sound, despite weaker upwelling favorable winds at that location. However, the hypoxic waters observed on the shelf near Tofino were anomalous for September.

Along Line P, oxygen values are known to have large decadal variability, with an overall decline at Ocean Station Papa since 1956 and no trend at P4 (Crawford and Peña 2016). Dissolved oxygen is less soluble at higher temperatures, however changes in solubility explain only a small part of the observed decline (Cummins and Ross 2020). Temperatures below the permanent pycnocline along Line P were fairly typical during 2021 (not shown), with slightly warmer than average values between February and April, and slightly cooler than average values in May, September, and early October. These cooler than average temperatures may partially explain the positive oxygen anomaly observed in the oxygen minimum zone in September, with changes in water mass age, ventilation, or biological processes being other potential contributing factors.

14.5. Implications of those trends

In Queen Charlotte Sound, the ocean glider data from 2020 and 2021 provided a high-resolution full-depth observational record that can be used for comparison with oxygen in future years, which is projected to decline due to shoaling of the oxygen minimum zone and changes in upwelling, with more frequent extreme states of hypoxia (Holdsworth et al. 2021).

The causes of the anomalously high oxygen in the oxygen minimum zone along Line P are unclear, however it is in contrast to ongoing oxygen declines in the upper 3,000 m of the Northeast Pacific over the last 60 years (Ross et al. 2020). Ongoing glider monitoring along Line P will assist in assessing future changes, in combination with DFO hydrographic cruises.

Decreases in dissolved oxygen and anomalous hypoxic conditions in continental shelf waters such as those observed near Tofino in September are detrimental to ecosystems and marine life, and the associated low oxygen event is described in detail by Franco et al. (Section 15).

14.6. References

Crawford, W.R., and Peña, M.A. 2013. Declining oxygen on the British Columbia continental shelf. Atmosphere-Ocean 51(1): 88-103.

Crawford, W.R., and Peña, M.A. 2016. Decadal trends in oxygen concentration in subsurface waters of the Northeast Pacific Ocean. Atmosphere-Ocean 54(1): 171-192.

Cummins, P.F., and Ross, T. 2020. Secular trends in water properties at Station P in the Northeast Pacific: an updated analysis. Prog. in Oceanogr. 186, 102329.

Holdsworth, A.M., Zhai, L., Lu, Y., and Christian, J.R. 2021. Future changes in oceanography and biogeochemistry along the Canadian Pacific continental margin. Front. Mar. Sci. 8, 602991.

Ross, T., Du Preez, C., and Ianson, D. 2020. Rapid deep ocean deoxygenation and acidification threaten life on Northeast Pacific Ocean seamounts. Glob. Change Biol. 26, 6424.

15. EXTREMELY UNUSUAL HYPOXIA IN THE SHELF OF BRITISH COLUMBIA IN LATE SUMMER 2021

Ana C. Franco[1], Akash Sastri[2], Charles Hannah[2], Debby Ianson[2], Marie Robert[2], Germaine Gatien[2]

[1]Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, B.C., Canada, [2]Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, B.C., Canada, afranco@eoas.ubc.ca

15.1. Highlights

- The lowest dissolved oxygen concentration in the last 20 years was recorded on the mid-shelf off the west coast of Vancouver Island (WCVI) in late August, 2021.
- Oxygen reached hypoxic concentrations (i.e., less than 60 µmol kg^{-1}) at depths as shallow as 40 m and through the water column, potentially impacting pelagic and benthic aerobic organisms.
- Extreme low oxygen and multiple stressor events are projected to become more frequent as climate change progresses.

15.2. Description of the time series

We used historical dissolved oxygen (O_2) and hydrographic data from the Line P program and the La Perouse program for the months of August and September. We focused on a station located at 48.57°N, 125.5°W. This location has been consistently sampled by the Line P program (Station P01) in mid- to late-August and, approximately 2 weeks later (typically late August to early September), by the La Perouse program (Station B8). All the data are publicly available on the Water Properties website (https://waterproperties.ca/).

15.3. Status and trends

In late August 2021, hypoxic conditions (< 60 µmol kg^{-1}) were recorded in the mid-shelf off the WCVI (station P01) at approximately 40 m (Figure 15-1). These are the lowest O_2 values recorded at such a shallow depth in the last 20 years. For most of the profile below 25 m, O_2 was 50 to 60 µmol kg^{-1} lower than the climatological profile for August (solid black line in Figure 15-1). This is an extreme low oxygen event where deviations from the climatology were more than two standard deviations larger than the climatological variability (calculated for the period from 2003-2020). The physical environment was also anomalous, with water between 0.3 to 0.6 kg m^{-3} denser than the climatological value and outside the range of natural variability over the last 20 years (not shown).

Spatially, low O_2 concentrations (< 2 standard deviations of the climatological value for a given depth) were widespread over most of the continental shelf, including the shelf off Washington. Strong negative oxygen anomalies were also widespread among the southern stations of the La Perouse cruise in early September 2021. Hypoxic water was also observed at Ocean Network Canada's Folger Deep node in the mouth of Barkley Sound (Dewey et al., Section 33). The temporal evolution of this low oxygen event is described in Ross et al. (2022).

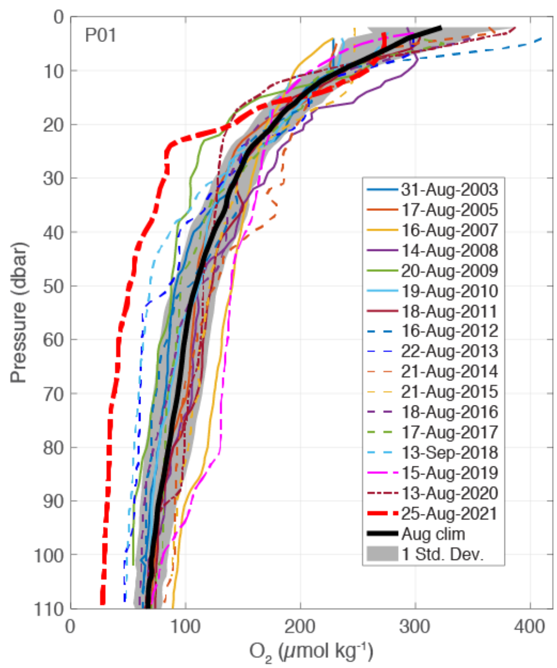


Figure 15-1. Summer dissolved oxygen concentration at station P01 from the Line P cruise (48.57°N, 125.5°W). August climatology (black line) and the standard deviation (grey shaded area) over the period 2003-2020 is indicated.

15.4. Factors influencing trends

Two potentially related drivers might have contributed to the stronger than usual hypoxia observed on the WCVI shelf in August 2021. More in-depth analysis of the mechanisms is currently being developed. Here we present only a brief summary:

1) Higher than usual (>1 standard deviation) satellite chlorophyll was detected in the month of May in the region of interest (not shown). A larger than usual increase in organic matter production and subsequent local aerobic respiration is a potential cause for a reduction in oxygen concentrations.
2) Stronger than usual upwelling in May, July and August 2021 was recorded at a location south of station P01 at 42°N (the border of Oregon and California). It has been suggested that such remote upwelling might trigger coastally trapped waves (CTW) with the potential to modify the pycnocline and water properties off the west coast of Canada (Engida et al. 2016). Such CTW-related shifts in pycnocline depth might in turn stimulate primary productivity by injecting more nutrients into the euphotic zone (Hickey and Banas 2008).

15.5. Implications of those trends

Hypoxic conditions encompassed the whole water column and near ocean floor in summer 2021 off Vancouver Island. Such low oxygen conditions have the potential to cause large negative impacts to pelagic and benthic organisms, such as die offs previously seen in the past (Chan et al. 2008). Extreme low oxygen and compound events (i.e., those events involving more than one stressor, such as low pH or high temperatures) are projected to become more frequent as climate change keeps progressing (Gruber et al. 2021).

15.6. References

Chan, F., Barth, J.A., Lubchenco, J., Kirincich, A., Weeks, H., Peterson, W.T., and Menge, B.A. 2008. Emergence of anoxia in the California current large marine ecosystem. Science. 319: 920.

Engida, Z., Monahan, A., Ianson, D., and Thomson, R.E. 2016. Remote forcing of subsurface currents and temperatrues near the northern limit of the California Current System. J. Geophys. Res. Oceans. 121: 7244-7262.

Gruber, N., Boyd, P.W., Frölicher, T.L., and Vogt, M. 2021. Biogeochemical extremes and compound events in the ocean. Nature. 600: 395-407.

Hickey, B., and Banas, N. 2006. Why is the northern California Current System so productive? Oceanography. 21(4): 90-107.

Ross, T., Franco, A.C., Barth, J.A., Sastri, A., Robert, M., Ianson, D., Hannah, C., Chan, F., Feely, R.A., Dewey, R., and Peña, A. 2022. Northeast Pacific Update: Summer 2021 low oxygen event on the west coast of North America. PICES Press. 20(1).

16. MARINE BIOREGIONS OF BRITISH COLUMBIA USING SENTINEL-3 CHLOROPHYLL-A DATA: SPATIAL-TEMPORAL DYNAMICS 2016-2020

Christian Marchese[1,3], Brian Hunt[1], Fernanda Giannini[2], Matthew Ehrler[3], and Maycira Costa[3]

[1]University of British Columbia, Vancouver, B.C., c.marchese@oceans.ubc.ca, b.hunt@oceans.ubc.ca
[2]Universidade Federal do Rio Grande, R.S. (Brazil), fe.giannini@usp.br
[3]University of Victoria, Victoria, B.C., mehrler@uvic.ca, maycira@uvic.ca

16.1. Highlights

- The use of the high spatial resolution of the OLCI (Ocean and Land Colour Instrument) sensor allowed the delineation of bioregion boundaries with high precision. The classification procedure recognized separation between offshore regions and those in shelf and coastal waters.
- In offshore bioregions, autumn peaks in chlorophyll-a are, on average, more prominent than spring peaks.
- Shelf bioregions are overall more productive and characterized by different phytoplankton dynamics.
- The spring bloom timing varies spatially with earlier blooms observed, on average, south of ~51°N of latitude.
- The spring bloom timing also differs inter-annually and markedly among bioregions.

16.2. Introduction

Satellite oceanographic datasets are vital for the long-term, large-scale monitoring of oceanographic conditions as they provide access to synoptic information about the ocean, both spatially and temporally. Here, we delineate the coastal oceans of B.C. and Southeast Alaska using remotely sensed data, aiming to better understand the spatial and temporal heterogeneity of this complex oceanic region. A two-step classification procedure, using a Self-Organizing Maps (SOM; Kohonen 1982) analysis followed by the affinity propagation clustering method (Frey and Duke 2007), was developed to define marine bioregions based on the seasonal climatology of high-spatial-resolution Sentinel-3 surface Chlorophyll-a data (a proxy for phytoplankton biomass), for the period 2016-2020. The procedure leads to separate clusters according to the seasonal cycle of surface chlorophyll-a concentration. A workflow using the Microsoft Azure platform and Docker containers was also developed to optimize the data processing and create an automated tool to facilitate future analyses and monitoring programs.

16.3. Satellite time series

Satellite-derived chlorophyll-a Level-1 images from OLCI Sentinel-3A (ESA – European Space Agency) from April 2016 to December 2020 were obtained from the EUMETSAT distribution through CODA (Copernicus Online Data Access). A total of ~8000 Level-1 daily scenes comprising the study area were downloaded. The Level-1 dataset was submitted to the atmospheric correction (AC) using POLYMER processor (v 4.10), generating the Level-2 dataset. The POLYMER quality flags were used, as recommended, to remove insufficient quality data (Steinmetz et al. 2011). The POLYMER "*Case-2*" flag was also used to remove pixels where the chlorophyll-a estimates are highly overestimated (Giannini et al. 2021). Finally, the POLYMER Level-2 data were binned into 8-day composites, generating the Level-3 dataset with 300 m spatial resolution for the coastal oceans of B.C. and Southeast Alaska. Excluding 2019, all other years (i.e., 2016, 2017, 2020) of the Level-3 chlorophyll-a time series were characterized by excellent spatiotemporal coverage (Figure 16-1). Notably, most images presented more than 50% (red dashed line in Figure 16-1) of data coverage between February and November. Finally, it is noticeable that satellite images with the most missing data often occur during the spring-summer period. The Level-3 weekly (8-day) time series was used as input for the two-step classification procedure.

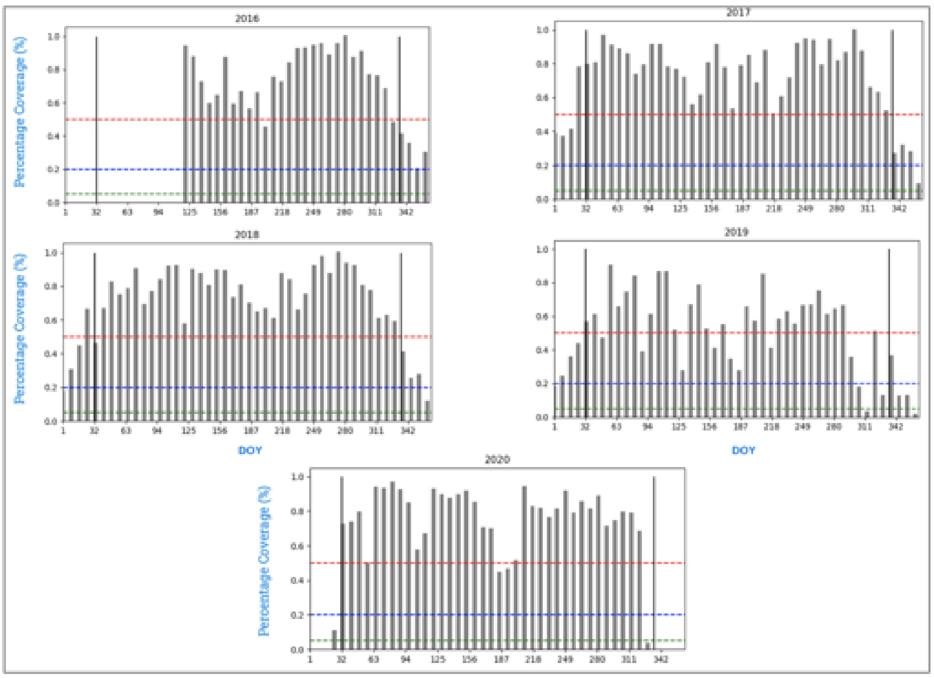


Figure 16-1. Spatiotemporal coverage (%) of the chlorophyll-a data from 2016 to 2019. Each vertical gray bar represents a weekly (8-day) composite image. Note that the y-axis scale goes from 0 (0%) to 1 (100 %). The red dashed line denotes 50%, the blue dashed line marks 20% of coverage, while the green dashed line only 5%. The two vertical black lines indicate the period (i.e., mid-February to mid-November) considered for the biogeographic analysis.

16.4. Summary on bioregions

The identification of bioregions across the coastal oceans of B.C. and Southeast Alaska was based on a two-step classification procedure. First, a SOM approach was used to explore the spatiotemporal patterns of the input data (i.e., chlorophyll-a) and synthesize the most relevant features in a two-dimensional map. Subsequently, a clustering algorithm was applied to reduce the number of classes from the initial SOM partition into an objective number of clusters (i.e., bioregions). Finally, the cumulative sum (CUSUM) technique was applied to detect the timing of the spring bloom (i.e., the first increase in biomass after winter). Specifically, the time at which the cumulative biomass curve reaches 15% of the total biomass was identified as the bloom initiation (Chiba et al. 2012). The choice of the 15% threshold was based on tests done using other threshold percentages (i.e., 5%, 10%, and 20%) and comparing the results. The 15% threshold yielded estimates closer to those obtained in previous studies.

The proposed classification identified ten bioregions. Specifically, the two-step classification recognized the separation between bioregions beyond the continental shelf-break (i.e., #2, 4, 5, and 7) from those in shelf and coastal waters (i.e., #1, 3, 6, 8, 9, and 10). Each bioregion was characterized by a distinctive seasonal cycle. Offshore bioregions were characterized by autumn peaks that, on average, were more prominent than spring peaks. Shelf bioregions were overall more productive and characterized by different phytoplankton dynamics. Results also show that the spring bloom timing varies spatially with earlier blooms observed, on average, south of ~51°N of latitude. However, localized zones characterized by earlier (later) phytoplankton blooms are also noticeable throughout the whole study area. The spring bloom timing differed between bioregions and inter-annually (Figure 16-2). For instance, the spring bloom started earlier in bioregions #1 and #2 and much later in #8. Among the studied years, in 2019, the entire region displayed early seasonal increases in chlorophyll-a, with an earlier spring bloom in seven of the ten bioregions. In contrast, the year 2020 was marked by later blooms, with an apparent time lag in the onset of spring bloom for some bioregions (e.g., #5, #6, #7).

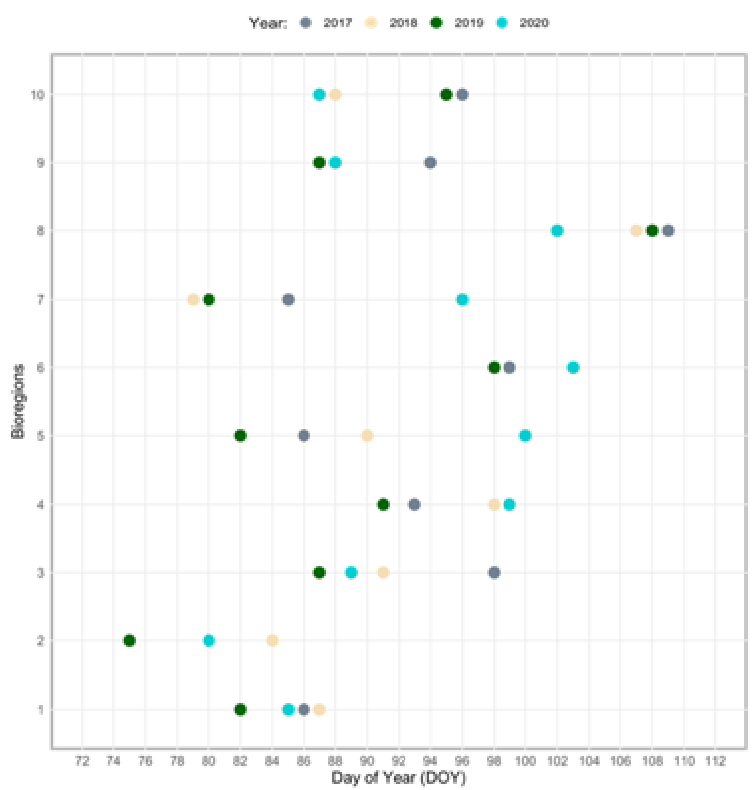


Figure 16-2. Interannual variability (2017-2020) of the bloom initiation by bioregion. The cumulative sum (CUSUM) technique was applied to detect the timing of the bloom. The time at which the cumulative biomass curve reaches 15% of the total biomass is identified as the bloom initiation. Years are denoted by different colors, while bioregions are on the y-axis. The days of the year (DOY) are shown on the x-axis.

16.5 Conclusions and Outlook

The main findings of this work strengthen the understanding that the coastal oceans of B.C. and Southeast Alaska cannot be considered homogeneous entities. The 300 m spatial resolution imagery of the Sentinel-3 OLCI sensor and the proposed methodology allowed delineation of bioregion boundaries with high precision, allowing for the definition of distinctive phytoplankton bloom dynamics, including spring bloom timing for each bioregion. This bioregionalization based on phenological patterns analysis provides a framework to enhance our understanding of the relationships between ocean dynamics, environmental drivers, and fish stocks. For instance, bioregionalization may help disentangle and elucidate the match-mismatch dynamics between zooplankton and phytoplankton (Suchy et al. 2022), and thus the potential impacts on higher trophic levels. Finally, as more Sentinel-3 data becomes available, the application of the method should account for the variability (stability) in the spatial distribution of the bioregions. The Sentinel-3 (2016 - ongoing) mission will ensure continuity and consistency of observations, supporting operational applications (e.g., sampling strategy and deployment of observation systems), and monitoring purposes across the target area. Therefore, the proposed regionalization may have a practical and extensive implementation in the future.

16.6 References

Chiba, S., Batten, S., Sasaoka, K., Sasai, Y., and Sugisaki, H. 2012. Influence of the Pacific Decadal Oscillation on phytoplankton phenology and community structure in the western North Pacific: PDO and Phytoplankton Ecology. Geophysical Research Letters. 39. doi: 10.1029/2012GL052912.

Frey, B.J., and Dueck, D. 2007. Clustering by Passing Messages Between Data Points. Science 315: 972-976.

Giannini, F., Hunt, B.P.V., Jacoby, D., and Costa, M. 2021. Performance of OLCI Sentinel-3A satellite in the Northeast Pacific coastal waters. Remote Sensing of Environment 256: 112317.

Kohonen, T. 1982. Self-organized formation of topologically correct feature maps. Biol. Cybern. 43: 59-69.

Steinmetz, F., Deschamps, P.-Y., Ramon, D. 2011. Atmospheric correction in the presence of sun glint: application to MERIS. Opt. Express 19: 9783.

Suchy, K.D., Young, K., Galbraith, M., Perry, R.I., and Costa, M. 2022. Match/Mismatch Between Phytoplankton and Crustacean Zooplankton Phenology in the Strait of Georgia, Canada. Front. Mar. *Sci.* 9, 832684. doi: 10.3389/fmars.2022.

17. WEST COAST BRITISH COLUMBIA ZOOPLANKTON BIOMASS ANOMALIES 2021

Moira Galbraith, and Kelly Young, Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Moira.Galbraith@dfo-mpo.gc.ca, Kelly.Young@dfo-mpo.gc.ca

17.1. Highlights

- Sub-arctic and boreal copepods dominated in the late spring into early summer, and were replaced by southern copepods in the fall.
- Gelatinous zooplankton decreased in biomass throughout all regions returning to the long term mean in comparison to positive anomalies of 2014-2019.
- During the early summer months, salps were found in large numbers along the shelf break and offshore areas.

17.2. Description of the time series

Zooplankton time-series are available for Southern Vancouver Island (SVI; 1979-present), Northern Vancouver Island (NVI; 1990-present), Line P (1980-present), and Hecate Strait (1990-present), although with lower density and/or taxonomic resolution for NVI and Hecate Strait earlier in the time series. For this report, we present data from 1990 onwards except for Line P which is 1996 to present. The 'standard' sampling locations are averaged within the SVI, NVI, Line P and Hecate regions (Figure 17-1). Additional locations are included in averages when they are available. See Mackas et al. 2001 for methodology of zooplankton surveys along the west coast.

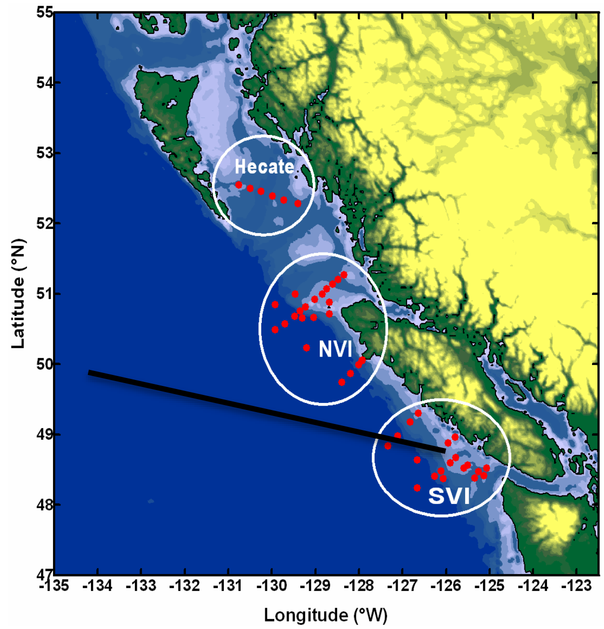


Figure 17-1. Zooplankton time series sampling locations (red dots; Line P – black line) in B.C. marine waters. Data are averaged for samples within each area. There are more samples included in the analysis than shown in figure.

A zooplankton climatology was estimated for each region, using the data from the start of each time series through to 2008 as a baseline, and compared to monthly conditions during any single year to produce a biomass anomaly time series. For a more detailed description see Mackas 1992, Mackas et al. 2001 and Mackas et al. 2013b.

Zooplankton species from the west coast of B.C. with similar zoogeographic ranges and ecological niches usually have a very similar anomaly time series (Mackas et al. 2006); therefore, multiple species were averaged within species groups (and size classes within major taxa) to show interannual variability (Galbraith and Young 2017; Mackas et al. 2013a; Irvine and Crawford 2013). All data presented here are very preliminary as sample identification and enumeration continues; numbers will change as analysis is completed but directions of trends *usually* do not change.

17.3. Status and trends

The biomass anomaly time series for copepod species groups ‘southern’, ‘subarctic’ and ‘boreal shelf’ focus on SVI and NVI shelf/offshore, P4-P12 and Hecate Strait regions (Figures 17-2, 17-3, and 17-4). Cool years tend to favour endemic ‘northern’ taxa; whereas warm years favour colonization by ‘southern’ taxa. See Mackas et al. 2013b for pre-1995 anomalies, and descriptions on how to interpret the anomaly patterns.

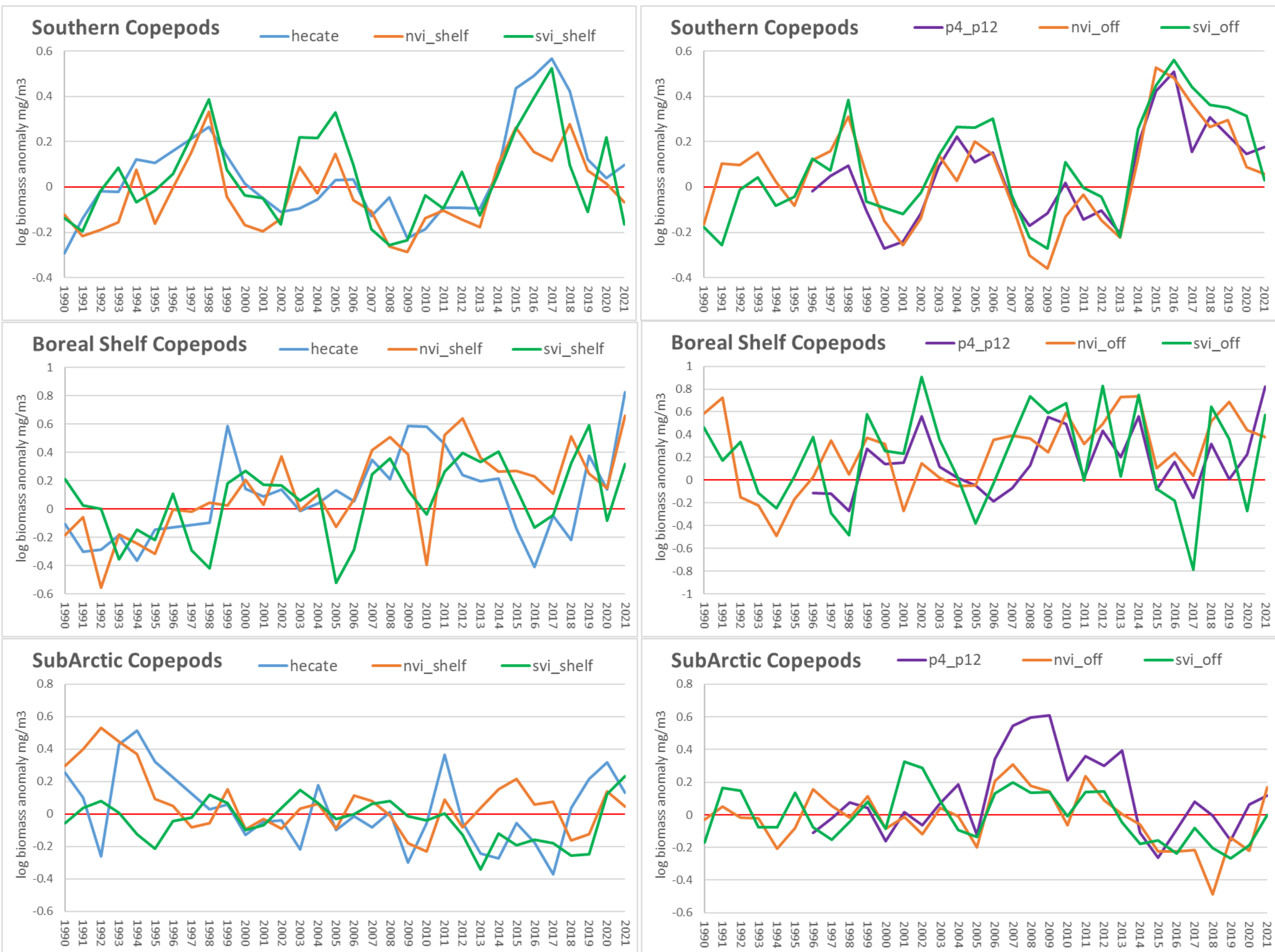


Figure 17-2. Zooplankton species-group anomaly time series for the regions shown in Figure 17-1. Southern Vancouver Island (SVI) green; Northern Vancouver Island (NVI) orange; Hecate Strait blue; Line P purple - shelf areas on left and offshore areas on right panels. Blank years mean no samples were collected.

In 2021, southern copepod species were more prevalent in the offshore region than on the shelf but continuing to decline in abundance in all areas by comparison to previous years (Figure 17-2). Boreal shelf and subarctic copepods increased in biomass across all areas, with the exception of subarctic copepods on the NVI shelf and Hecate, although they were still above the long-term mean. The slight dip in the subarctic copepods in 2021 on the shelf may be a result of high numbers in the early summer (cooler waters) to the almost complete absence in the late summer/early fall warming.

When shown as monthly averages for spring versus fall (not all months were sampled), northern and boreal shelf copepod peak biomass occurs in the spring whereas southern copepod biomass peaks in late summer/fall (Fig 17-3). The northern (subarctic) and boreal shelf copepods increase in biomass through the spring and into the summer, entering diapause (subarctic) or overwintering (boreal) populations by fall and early winter. Southern copepods move into areas outside of their typical ranges with heat waves, El Niños or the fall northern flow of the California Current.

Euphausiid biomass peaks are also species-specific (Fig 17-3). The majority of the changes in biomass for the euphausiids are a result of growth; early in the year most are larval and as the year progresses they grow to juvenile or adult stages. Euphausiid biomass on the shelf was about the same as 2020 but slightly higher in the offshore area for all species.

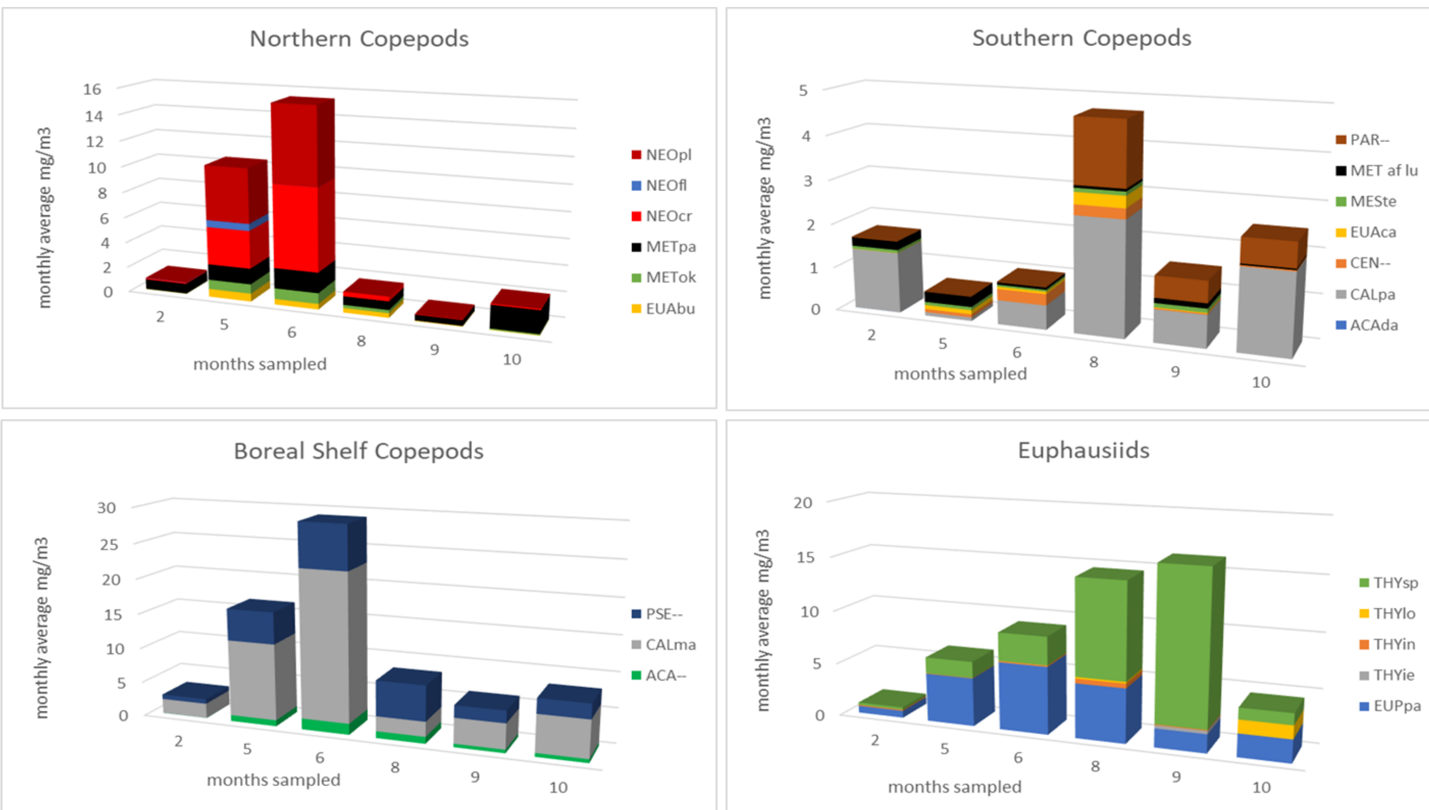


Figure 17-3. West coast Vancouver Island and Hecate Strait shelf areas showing monthly average biomass per species where months are in numerical order . Missing months mean no samples were collected. Abbreviations: Northern: NEOpl Neocalanus plumchrus NEOfl Neocalanus flemingeri, NEOcr Neocalanus cristatus, METpa Metridia pacifica, METok Metridia okhotensis, EUAbu Eucalanus bungii; Southern: PAR—Paracalanus species, MET af lu Metridia aff. lucens, MESte Mesocalanus tenuicornis, EUAca Eucalanus californicus, CEN—Centropages species, CALpa Calanus pacificus, ACAda Acartia danae; Boreal: PSE—Pseudocalanus species, CALma Calanus marshallae, ACA—Acartia species; Euphausiids: THYsp Thysanoessa spinifera, THYlo Thysanoessa longipes, THYin Thysanoessa inspinata, THYie Thysanoessa inermis, EUPpa Euphausia pacifica.

Larvaceans, siphonophores and hydromedusae biomass anomalies continued to be positive for 2021 in all regions. There was a sharp decrease in doliolid biomass across all regions, beginning in 2020 and continuing into 2021. This had a moderating effect on the CSIndex or "Crunchies (crustacean): Squishies (gelatinous)" Index (see Galbraith and Young 2019 for detailed explanation) through the averaging of regional data. For Line P, the cnidarian community did not show much change. Large numbers of salps were sampled in the offshore stations and along Vancouver Island and Hecate shelf break in the summer months but not the fall.

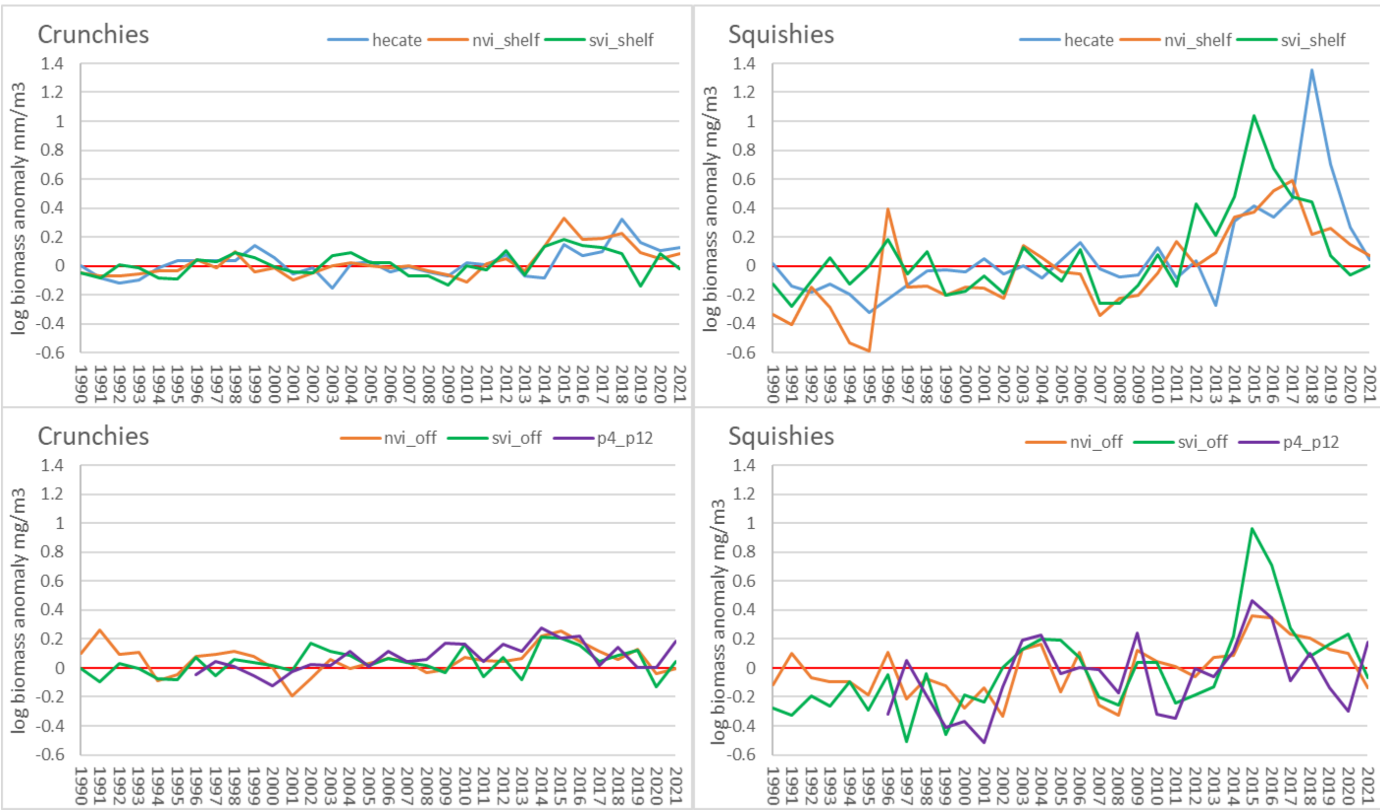


Figure 17-4. Biomass anomalies for selected crustaceans (left side: Crunchies) and gelatinous (right side: Squishies).

All areas showed positive gelatinous and crustacean biomass anomalies but reduced overall except for Vancouver Island offshore areas where it was negative for both (Figure 17-4). The index reflects a return to average biomass which would imply lower biomass overall for 2021 in comparison to previous years (which were all above-average).

Pteropods were removed from squishies category as they appear to be reacting to different physical parameter(s) whereas the CSIndex tracks changes in community structure due to oceanic sea surface temperatures and salinities. Long term trends of *L. helicina* are declining over all areas, except Hecate (Figure 17-5).

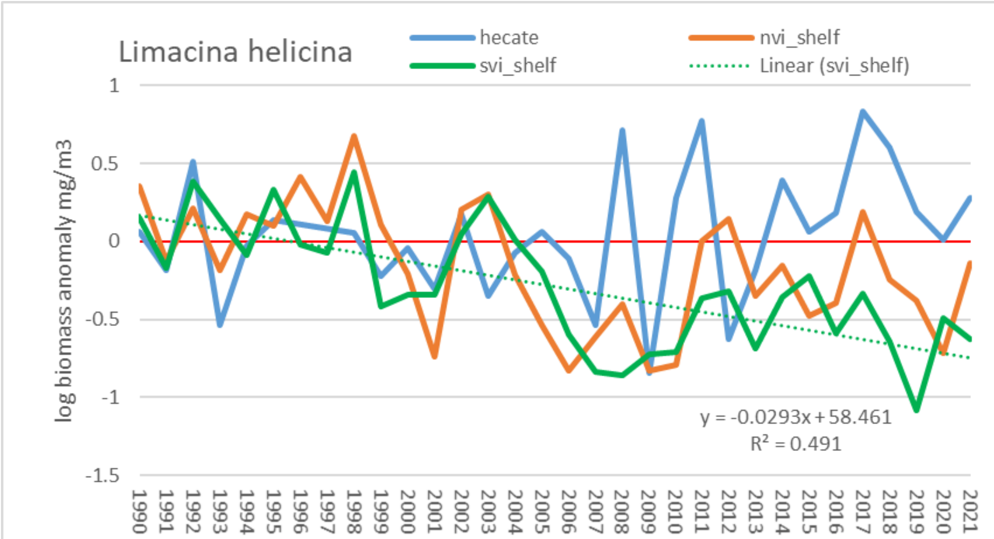


Figure 17-5. Limacina helicina, biomass anomalies across the Vancouver Island shelf area. Linear trend is shown for Southern Vancouver Island Shelf.

17.4. Implications of those trends

Overall, 2021 saw a return to near-average biomass for crustaceans and gelatinous animals of the boreal/subarctic community in most regions. The near-average euphausiid biomass anomalies, coupled with the spring/early summer increase of subarctic and boreal copepods (high lipid) may be a good match for larval fish, juvenile fish (especially out-migrating salmon smolts), and planktivorous sea birds feeding in the spring. However, average to negative biomass for crustaceans along Vancouver Island shelf in fall and early winter may lead to poorer survival of juvenile fish and fledgling seabirds foraging for zooplankton in the nearshore areas.

17.5. References

Galbraith, M., and Young, K. 2017. Zooplankton along the B.C. continental margin 2016. In: Chandler, P.C., King, S.A., and Boldt, J. (Eds.). State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2016. Can. Tech. Rep. Fish. Aquat. Sci. 3225: 243 + vi p.

Galbraith, M., and Young, K. 2019. West coast British Columbia zooplankton biomass anomalies 2018. In: Boldt, J.L., Leonard, J., and 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.

Irvine, J.R., and Crawford, W.R. 2013. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/032. viii + 140 p.

Mackas, D.L. 1992. The seasonal cycle of zooplankton off southwestern British Columbia: 1979-89. Can. J. Fish. Aquat. Sci. 49: 903-921.

Mackas, D.L., Thomson, R.E., and Galbraith, M. 2001. Changes in the zooplankton community of the British Columbia continental margin, and covariation with oceanographic conditions, 1985-1998. Can. J. Fish. Aquat. Sci. 58: 685-702.

Mackas, D.L., Peterson, W.T., Ohman, M.D., and Lavaniegos, B.E. 2006. Zooplankton anomalies in the California Current system before and during the warm ocean conditions of 2005. Geophys. Res. Lett. 33: L22S07, doi: 10.1029/2006GL027930.

Mackas, D.L, Galbraith, M., Faust, D., Masson, D., Young, K., Shaw, W., Romaine, S., Trudel, M., Dower, J., Campbell, R., Sastri, A., Bornhold Pechter, E.A., Pakhomov, E., and El-Sabaawi, R. 2013a. Zooplankton time series from the Strait of Georgia: Results from year-round sampling at deep water locations, 1990–2010. Progr. Oceanogr. 115: 129-159.

Mackas, D.L, Galbraith, M., Yelland, D., and Young, K. 2013b. Zooplankton along the Vancouver Island continental margin: an above-average year for “cool-ocean” zooplankton. In Irvine, J.R., and Crawford, W.R. 2013. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/032. viii + 140 p.

18. LOWER TROPHIC LEVELS IN THE NORTHEAST PACIFIC

Clare Ostle[1] and Sonia Batten[2]

[1]Marine Biological Association, The Laboratory, Plymouth, UK, claost@mba.ac.uk

[2]North Pacific Marine Science Organization (PICES), Sidney, B.C., Canada, sonia.batten@pices.int

18.1. Highlights

- In 2021, the mean copepod size (an index of community composition) appears to be returning to average following the marine heatwaves that started in 2014, and copepods typically associated with warmer waters have declined in abundance, in both the offshore and shelf regions around B.C.
- Phytoplankton community indicators appear to be returning to values of pre-heatwave (2014-2016) conditions in the offshore region.
- Sampling using the Continuous Plankton Recorder (CPR) has been able to continue during the COVID-19 pandemic due to its semi-autonomous methodology.

18.2. Sampling

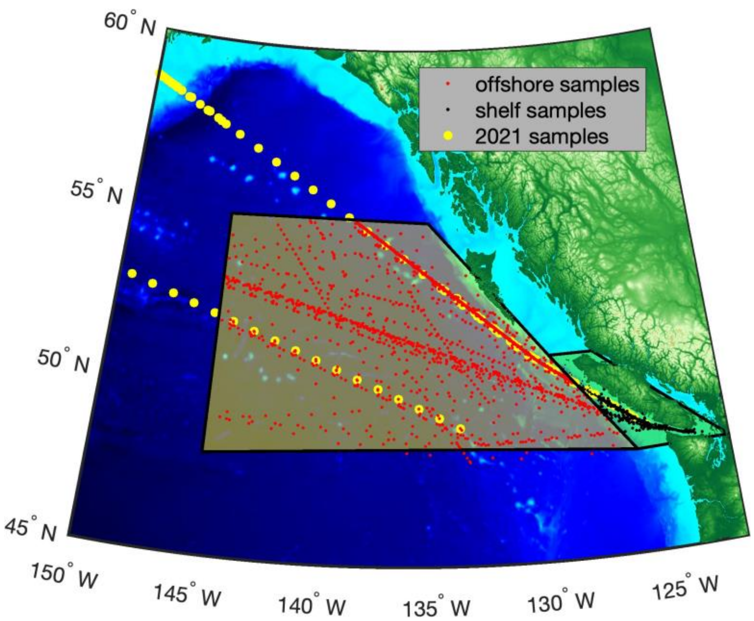


Figure 18-1. Map showing the location of historic CPR samples (2002-2020) red = offshore, black = shelf. Yellow circles are the location of the 2021 samples, note some 2021 samples are not yet analysed so are not shown.

Sampling from commercial ships, towing a CPR, occurred approximately monthly, 6-9 times per year, between March and October in the NE Pacific, continuing a time series that began in 2000 (Figure 18-1). Each CPR sample contained the near-surface (about 7 m depth) plankton from an 18.5 km length of transect, filtered using 270 µm mesh, and afterwards analyzed microscopically to give taxonomically resolved abundance data. 2021 CPR data presented within this report are provisional and only include months May, June, July, as the rest of the samples are still being analysed.

Fortunately, the 2021 CPR sampling was not impacted by the COVID-19 pandemic; since CPR sampling is semi-autonomous, the ships were comfortable in taking the equipment on board and deploying it. All 2021 tows were completed as scheduled (Figure 18-1, see yellow circles). 2021 data have not yet been finalized (where shown) and are therefore provisional and likely to change.

Sea Surface Temperature (SST) data from 2000 to 2021 were obtained from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS, 1° enhanced data, www.esrl.noaa.gov/psd/data/gridded/data.coads.1deg.html) for each region to characterize the physical environment.

18.3. Description of the Plankton Time Series

18.3.1. Phytoplankton

The CPR effectively retains larger phytoplankton cells, especially chain forming diatoms and hard-shelled dinoflagellates, and several time series are generated which reflect abundance and community composition changes in the offshore and shelf regions: i) mean monthly diatom abundances, ii) broad community composition, and iii) mean annual Community Temperature Index (CTI) using each taxon's mean abundance and Species Temperature Index (STI; mean temperature in which the taxon was found in CPR samples with in situ temperature recorded; taxa found in warmer waters have a higher STI than taxa found in colder waters).

18.3.2. Zooplankton

Mesozooplankton, especially crustacea, are well sampled by the CPR and several zooplankton time series are generated: i) total zooplankton abundance, ii) taxon specific lengths and abundances are used to calculate the mean copepod length each month, and iii) annual mean zooplankton abundance for zooplankton groups of interest, such as warm water species.

18.4. Status and Trends

18.4.1. Phytoplankton

The SST recorded in both regions in 2021 was lower than it has been in recent years. The 2021 phytoplankton community composition had relatively low numbers of rodlike diatoms and dinoflagellates, and high numbers of round diatoms in the offshore region (Figure 18-2).

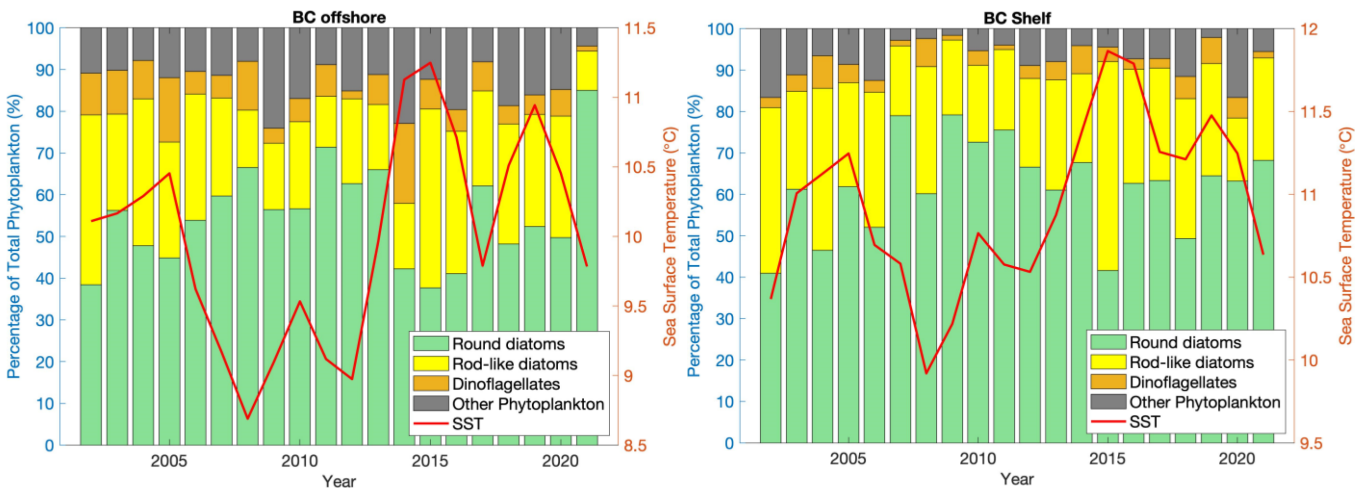


Figure 18-2. Contribution of each group to the mean annual phytoplankton community offshore (left) and on the shelf (right). SST is shown in red (right-hand axis, °C). Note: 2021 CPR data are provisional.

Both offshore and shelf regions show similar trends in phytoplankton CTI which correlate with observed SST; warmer communities in the mid-2000s, cooler communities in the 2006 to 2013 period before reaching a maximum in 2015 (Figure 18-3) and a warm period following. The phytoplankton CTI values for the offshore region in 2021 are lower than they have been since 2012, whereas the shelf region have a phytoplankton CTI that is still elevated and similar to recent warm years.

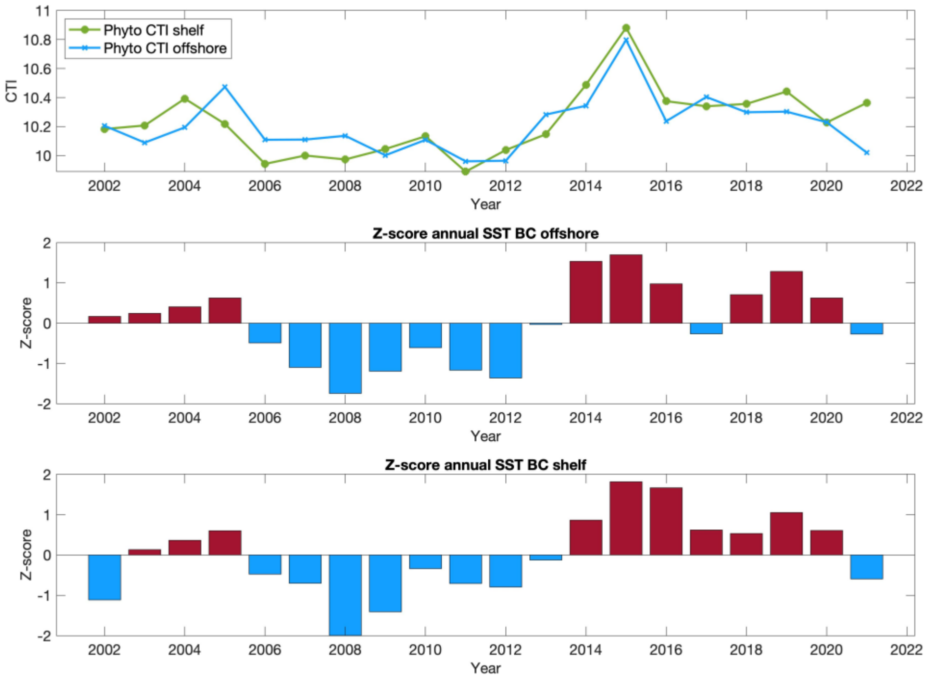
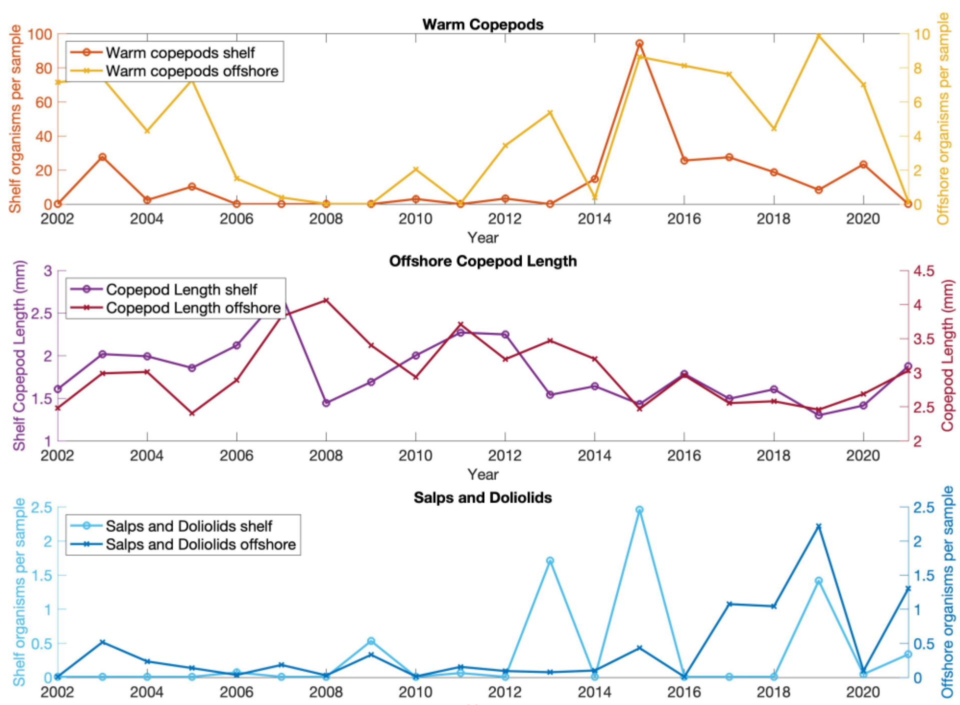


Figure 18-3. The mean annual phytoplankton Community Temperature Index for each region (top subplot) and the annual standardized z-score for Sea Surface Temperature in the offshore (middle subplot) and shelf (bottom subplot) region. Note: 2021 CPR data are provisional.

18.4.2. Zooplankton



The numbers of copepods typically associated with warm waters were low and the mean size of copepods increased in both regions in 2021 (Figure 18-4). Numbers of salps and doliolids (gelatinous plankton) also increased in 2021 in both regions.

Figure 18-4. The mean annual abundance of warm water copepods (top), copepod length (middle), and salp and doliolid abundance (bottom) for both the shelf (left axis) and offshore (right axis) regions of BC. Note: The CPR only captures small or fragments of salps and doliolids. Note: in March 2019 high numbers of thecosomes (a small pteropod) on the shelf were reported though not plotted here. Note: 2021 data are provisional.

18.5. Factors Influencing the trends

In 2021, ocean temperatures in both the shelf and offshore regions around B.C. were lower than the mean, 2002-2021 (Figure 18-3), with the plankton communities appearing to be returning to average values following the marine heatwaves of 2014-2016 (DiLorenzo and Mantua 2016) and 2019 (Amaya et al. 2020). The phytoplankton associated with warmer waters were lower in abundance in the offshore region, reducing the community temperature index there relative to the shelf region (Figure 18-3), and the copepods associated with warmer waters were lower in numbers in both regions in 2021 (Figure 18-4). Anomalously warm surface waters can increase stratification thereby reducing nutrient availability. Lower nutrients can affect the phytoplankton composition by promoting growth of smaller and narrower cells because of a relatively larger surface area over which to absorb nutrients. In turn, the size and composition of the phytoplankton will impact the zooplankton that are able to feed on them, and so the effects pass up the food chain.

18.6. Implication of these trends

Warmer waters favour certain (often smaller) taxa over others, as seen by the fact that warmer water taxa are more prevalent and there are higher CTI values during warm years. Such communities may apparently persist for several years after a heatwave event, especially if waters remain warm, however it appears that after 7 years of warmer than average conditions, the plankton recorded in 2021 are returning to more typical sub-arctic/temperate communities. The return of average values of large copepod abundance on the shelf and offshore regions could influence the food web functioning, since these copepods store more lipids to overwinter. While we cannot be certain how changing taxonomic composition of the prey affects predators via nutritional contributions to their diet, there could be some benefits of plankton communities returning to average.

18.7. References

Amaya, D.J., Miller, A.J., Xie, S.P. and Kosaka, Y. 2020. Physical drivers of the summer 2019 North Pacific marine heatwave. Nature Communications. 11(1): 1-9, doi:10.1038/s41467-020-15820/

DiLorenzo, E., and Mantua, N. 2016. Multi-year persistence of the 2014/15 North Pacific marine heatwave. Nature Climate Change. 6: 1042-1047, DOI:10.1038/nclimate3082.

19. SURVEYS FOR OLYMPIA OYSTERS (*OSTREA LURIDA* CARPENTER, 1864) AT SIX INDEX SITES IN BRITISH COLUMBIA, 2010-2021

Erin Herder, Dominique Bureau, Marine Invertebrates Section (MIS), Stock Assessment and Research Division (StAR), Fisheries and Oceans Canada, Nanaimo, B.C., Erin.Herder@dfo-mpo.gc.ca, Dominique.Bureau@dfo-mpo.gc.ca

19.1. Highlights

- Relative abundance of Olympia Oysters has remained stable at most index sites between 2010 and 2021. Mean density was highest in the time series in 2021 for four of six index sites.
- Density trends varied across sites with one site showing a decline in density, two sites showing an increase in density, and three sites remaining relatively stable over time.
- Extreme heat events, such as the heat dome of 2021, may have long-term effects on Olympia Oyster survival and reproduction.

19.2. Description of the time series

Thirteen locations around Vancouver Island were chosen as Olympia Oyster index sites in 2009 (DFO 2009). Between 2009 and 2017, each index site was surveyed two to four times (Norgard et al. 2018). The number of index sites was reduced to six in 2018 so that each site could be sampled annually (there are a limited number of very low tides (< 0.2 m) when surveys can occur each year). Annual surveys would more rapidly identify abundance trends and provide a better understanding of population dynamics. These six sites are: 1) Swy-a-lana Lagoon, Nanaimo, 2) Transfer Beach, Ladysmith, 3) Joes Bay, Barkley Sound, 4) Hillier Island, Barkley Sound, 5) Harris Point, Barkley Sound, and 6) Port Eliza, Nootka Sound. Each of these sites has been surveyed annually since 2018, except in 2020 when the COVID-19 pandemic halted survey activities. Surveys were conducted during the lowest tides of the month (typically < 0.1 m tides) and took 1-3 days to complete. Olympia Oyster index site surveys followed a stratified two-stage survey design (Gillespie and Kronlund 1999; Norgard et al. 2010) which ensured that sampling was distributed over the entire survey area. Counts of Olympia Oysters were split into two size categories: >15 mm (large) and ≤15 mm (small) since it is difficult to distinguish between Olympia Oysters and Pacific Oysters when they are <15 mm shell length.

19.3. Status and trends

Olympia Oyster was designated as a species of Special Concern in 2003 under the Species at Risk Act (SARA). A management plan was developed for Olympia Oyster in 2009. One of the objectives of the management plan is to ensure the maintenance of the relative abundance of Olympia Oysters at index sites. Since the start of the time series in 2010, the large size class (> 15 mm) of Olympia Oysters at index sites have shown varying long-term trends (Figure 19-1).

Port Eliza, Nootka Sound: Despite high densities overall, the density of Olympia Oysters in the large size class have declined since the start of the time series; from 278.9 ± 73.5 oysters m^{-2} in 2010 to 84.3 ± 29.5 oysters m^{-2} in 2021.

Harris Point, Barkley Sound: Density of Olympia Oysters (large size class) increased steadily from 52.7 ± 18.4 oysters m^{-2} in 2012 to 176.6 ± 28.9 oysters m^{-2} in 2021 (highest value of the time series). In 2010 small and large Olympia Oysters were not distinguished from each other, however, density of both size classes was 47.0 ± 10.9 oysters m^{-2}.

Hillier Island, Barkley Sound: Density of Olympia Oysters generally increased over the time series. In 2010, density of large Olympia Oysters was 27.5 ± 9.7 oysters m^{-2}. Density increased to 43.7 ± 20.5 oysters m^{-2} in 2012 and decreased to 16.9 ± 3.9 oysters m^{-2} in 2018 and increased again to 93.0 ± 17.6 oysters m^{-2} in 2021, the highest in the time series.

Joes Bay, Barkley Sound: Only results from Stratum 2 are discussed (Stratum 1 is very small and was only surveyed in 2014 and 2015). Density of large Olympia Oysters in Stratum 2 increased from 1.9 ± 1.2 Olympia Oysters m^{-2} in 2014 to 30.3 ± 11.3 Olympia Oysters m^{-2} in 2017. Density has remained relatively stable since 2017. Density was the highest in the time series in 2021 (31.8 ± 9.0 oysters m^{-2}).

Swy-a-lana Lagoon, Nanaimo: Small and large Olympia Oysters were not distinguished in 2010. Between 2013 and 2021 density of large Olympia Oysters fluctuated. In 2013, density was 35.3 ± 8.4 oysters m^{-2}. Density increased, decreased and increased again to 82.0 ± 23.0 oysters m^{-2} in 2021, the highest value in the time series.

Transfer Beach, Ladysmith: Density of large Olympia Oysters remained fairly constant at this site over the time series with density ranging between a low of 19.8 ± 4.7 oysters m^{-2} in 2021 and a high of 28.4 ± 6.9 oysters m^{-2} in 2019 (in 2011 and 2016 only one stratum was surveyed so these data were not include in the density range reported here).

19.4. Factors influencing trends

Location and size of survey strata at some sites were inconsistent in the early years (e.g. Port Eliza, Joes Bay, Transfer Beach), the number of strata surveyed at some sites varied from year to year with some strata being dropped from the sampling plans, and gaps of several years between surveys at some sites makes interpretation of trends difficult. The data from 2018 onward followed a consistent sampling design and should allow us to determine trends of abundance over time more reliably. Found in the low intertidal zone, Olympia Oyster survival and reproduction is affected by extreme fluctuations in temperature (DFO 2009). The heat dome of June 2021 may have affected Olympia Oyster survival, especially in the Strait of Georgia where some of the lowest tides of the year occurred in the afternoon. This led to long exposures of oysters out of the water at the time of day when the heat was most intense. Surveys in 2022 may provide more insight into how the heat dome affected the Olympia Oyster population.

19.5. Implications of those trends

Olympia Oyster density varied across Vancouver Island as did density trends, suggesting that different factors may influence populations dynamics at each index site. In 2010, Port Eliza had the highest density of all sites in the time series (278.9 ± 73.5 oysters m^{-2}). Despite a large decrease in density since 2010, Port Eliza remains a relatively high-density site. The three sites located in Barkley Sound each showed their highest respective densities in 2021. Density at the two sites in the Strait of Georgia was relatively stable over the time series. These results suggest that the management objective of maintaining density at the index sites is being achieved.

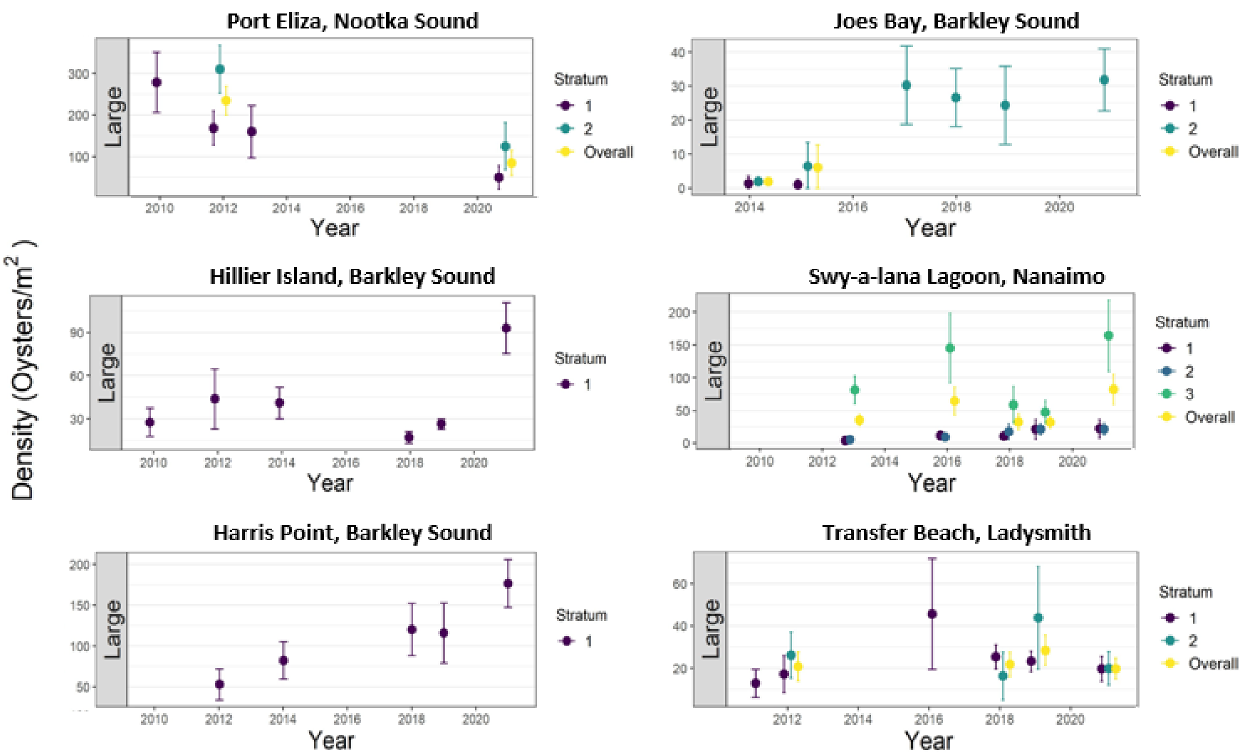


Figure 19-1. Density of large (>15mm shell length) Olympia oyster, between 2010 and 2021, at index sites located around Vancouver Island.

19.6. References

DFO. 2009. Management plan for the Olympia oyster (*Ostrea conchaphila*) in Canada. Species at Risk Act Management Plan Series. Fisheries and Oceans Canada, Ottawa. v + 31 p. Available online: https://www.registrelep-sararegistry.gc.ca/virtual_sara/files/plans/mp_olympia_oyster_0509_e.pdf.

Gillespie, G.E. and A.R. Kronlund. 1999. A manual for intertidal clam surveys. Can. Tech. Rep. Fish. Aquat. Sci. 2270. x + 144 p. Available online: http://waves-vagues.dfo-mpo.gc.ca/Library/234406.pdf.

Norgard, T., Davies, S., Stanton, L., and Gillespie, G.E. 2010. Evaluation of survey methodologies for monitoring Olympia Oyster (*Ostrea lurida* Carpenter, 1864) populations in British Columbia. Can. Sci. Advis. Sec. Res. Doc. 2010/006. iv +56 p. Available online: http://waves-vagues.dfo-mpo.gc.ca/Library/340695.pdf.

Norgard, T.C., Bigg, M.I., MacConnachie, S.E.M., Finney, J.L., and Gillespie, G.E. 2018. Index site surveys for Olympia oysters (*Ostrea lurida* Carpenter, 1864) in British Columbia – 2009 to 2017. Can. Tech. Rep. Fish. Aquat. Sci. 3153: viii + 88 p.

20. EULACHON STATUS AND TRENDS IN SOUTHERN B.C.

Linnea Flostrand and Nicholas Ens, Fisheries, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, B.C., Linnea.Flostrand@dfo-mpo.gc.ca, Nicholas.Ens@dfo-mpo.gc.ca

20.1. Highlights

- In 2021, the Fraser River Eulachon egg and larval survey index of Eulachon spawning stock biomass was moderately low (~141 tonnes), comparable to estimates for 1998, 2000, 2012, 2013 and 2019.
- In 2021, similar to 2018 to 2020 observations, fragments of the freshwater benthic diatom known as Didymo were a major component of the material collected in the Fraser River Eulachon egg and larval survey water samples. Analysis of 2021 water samples to estimate Didymo density and outflow has not been done but is being planned.
- Mean Eulachon catch per unit effort estimates from an annual spring west coast of Vancouver Island multispecies bottom trawl survey in 2021 were moderately high, suggesting an increasing trend since 2018 for relatively small and large sized fish despite not having 2020 survey observations.

20.2. Description of indices

Indices of Eulachon (*Thaleichthys pacificus)* used to monitor population dynamics over time are based on:

1) An annual springtime Fraser River Eulachon egg and larval survey (1995 to 2021) used to characterize spawner abundance (Hay et al. 2002; McCarter and Hay 2003),
2) Eulachon catches and catch samples from spring small-mesh multispecies bottom trawl surveys off the west coast of Vancouver Island (WCVI, 1973-2019, 2021) and in the Queen Charlotte Sound (QCS, 1998-2012, 2016),
3) In river catches of spawning Eulachon from past commercial fishing in the Fraser River (1900-2004), in the Columbia River (1888-2010 and 2014-2015), and from standardized gillnet surveys in the Fraser River (1995-2004 and; 2017-2021; not reported here).

Didymo *(Didymosphenia geminata)* was detected in notable amounts in Lower Fraser River Eulachon egg and larval survey water samples from 2018 to 2021. As reported in Boldt et al (2021), a subset of 2020 water samples were analysed to characterize trends in Lower Fraser River Didymo density and outflow over the survey season. Additional Didymo water sample analysis is being planned for 2021 (and 2022) water sample collections.

20.3. Status and trends

Long-term declines of spawning Eulachon have been observed in many rivers throughout their distribution from California to Alaska in the past 2-4 decades. The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed Eulachon in B.C. as three designatable unit (DUs) populations in 2011. The Fraser River and Central Pacific Coast DUs were assessed as endangered, and the Nass/Skeena DU was assessed as a species of special concern (COSEWIC 2011, 2013).

Eulachon is an important First Nations fishery resource and in-river Eulachon Food, Social and Ceremonial fisheries have occurred in years up until and including 2021 (DFO 2021). Commercial fishing for Eulachon has been closed since 2004 but there was an active commercial fishery for Eulachon in the Fraser River for over 90 years until a closure in 1997, followed by temporary openings in 2002 and 2004 (DFO 2021).

In 2021, the index of Eulachon spawning stock biomass in the Fraser River was estimated to be moderately low (~141 tonnes), comparable to estimates for 1998, 2000, 2012, 2013 and 2019, which is considerably lower than estimates for 1995, 1996, 2015, 2018 and 2020, but higher than estimates for all other years from 1997 to 2017 (Figure 20-1).

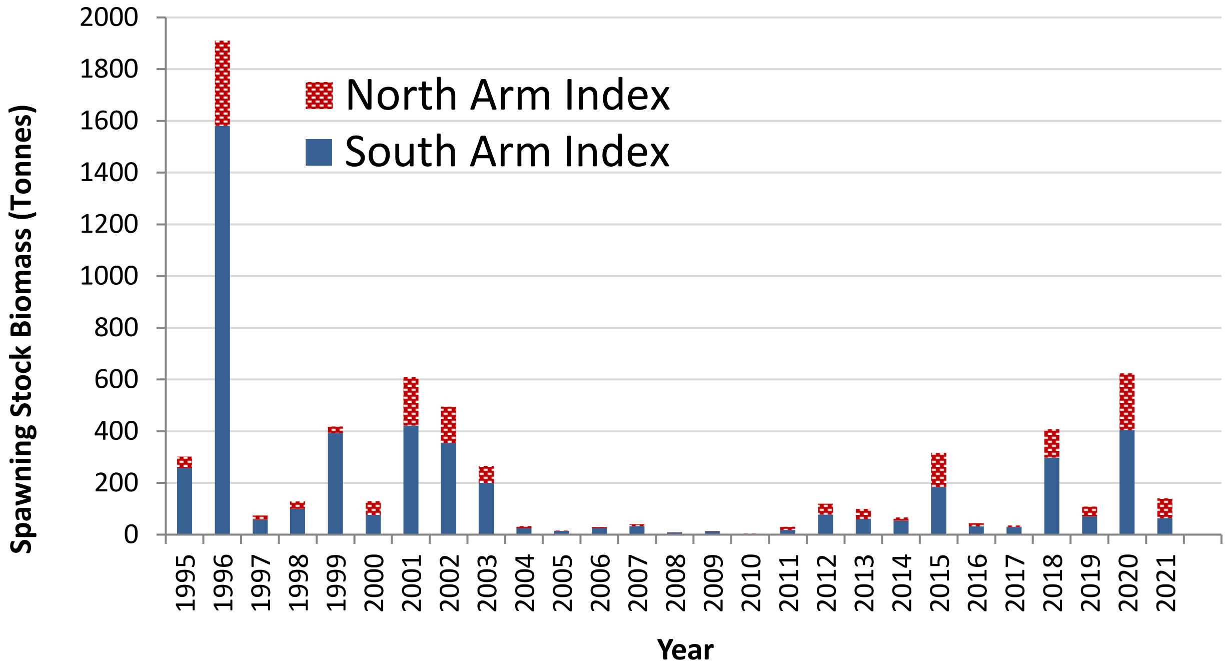


Figure 20-4. Estimated spawning stock biomass indices (SSB in tonnes) of Eulachon from the South and North Arms of the Fraser River, 1995-2021.

In 2021, mean Eulachon catch per unit effort (CPUE) observations from the spring WCVI multispecies trawl survey showed increases from 2019 for size groups less than or equal to 12.5 cm and greater than 12.5 cm (Figure 20-2). There are no 2020 observations because the 2020 survey was cancelled due to COVID-19 operating restrictions.

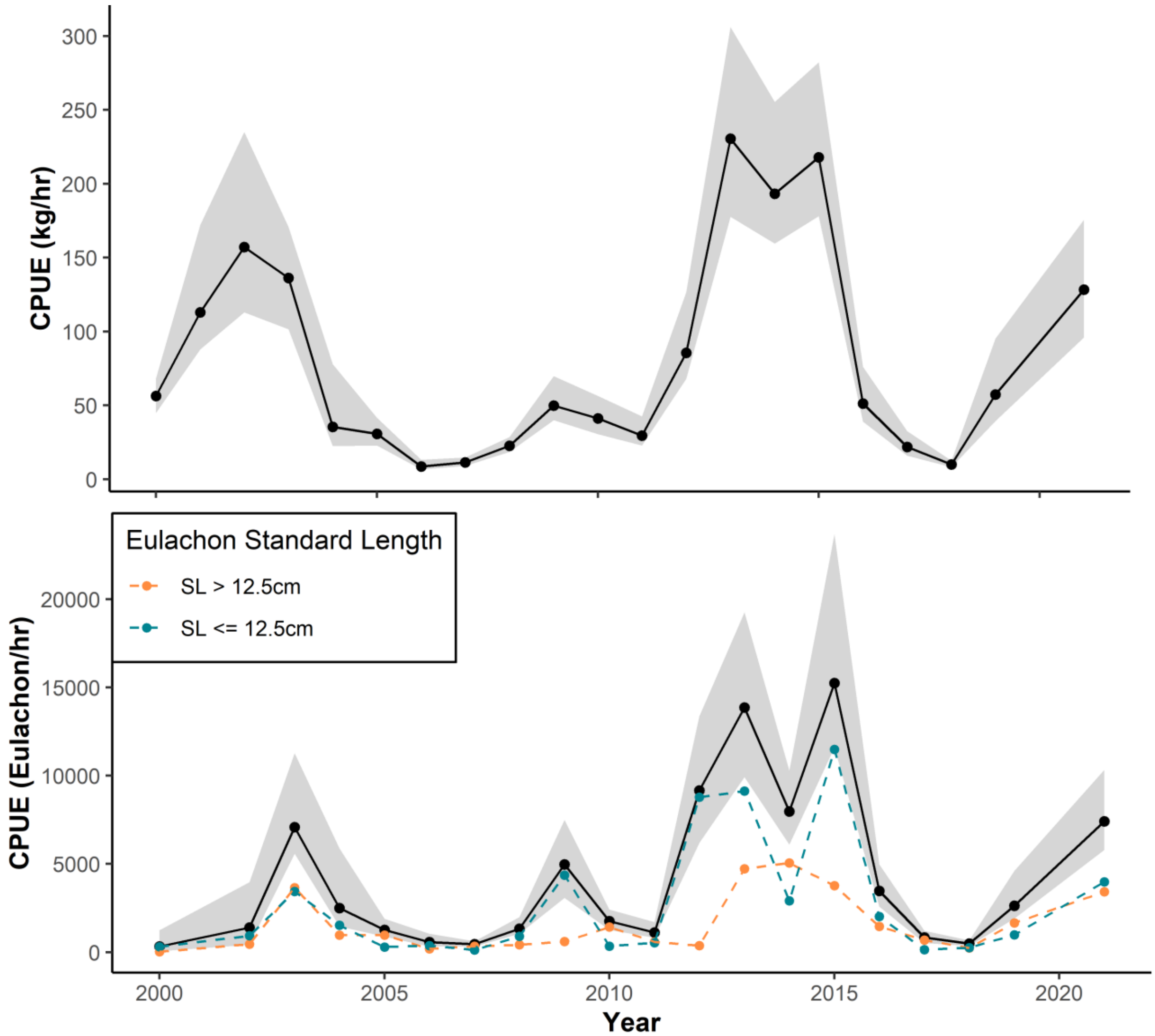


Figure 20-5. Eulachon mean CPUE from spring WCVI multispecies trawl surveys (2000- 2021, no survey in 2020) and 95% studentized bootstrap confidence intervals (gray envelopes), as catch weight per trawl tow duration (kg/hour, top panel) and number of fish per tow duration (bottom panel). Dashed lines represent mean catch number per unit effort of Eulachon greater than 12.5 cm standard length (orange) or less than or equal to 12.5 cm standard length (blue).

In 2021, Eulachon standard length observations from the spring WCVI multispecies trawl survey appeared to have a bi-modal distribution with peaks within the ranges of 7-10 cm and 13-17 cm (Figure 20-3). Annual Eulachon standard length frequency distributions are represented in two ways. One way shows statistically unweighted standard length frequency histograms (Figure 20-3, right panel) where fish length observations were pooled across all fishing events (therefore each fish specimen observation has equal statistical weight). The other way shows standard length frequency histograms where samples of fish length observations were statistically weighted by the estimated total number of Eulachon caught in each fishing event and standardized by the fishing duration (in hours) of each fishing event (Figure 20-3, left panel). This weighting method resulted in a shift to more small-sized Eulachon for several surveys years (i.e., 2011, 2012, 2013 and 2021).

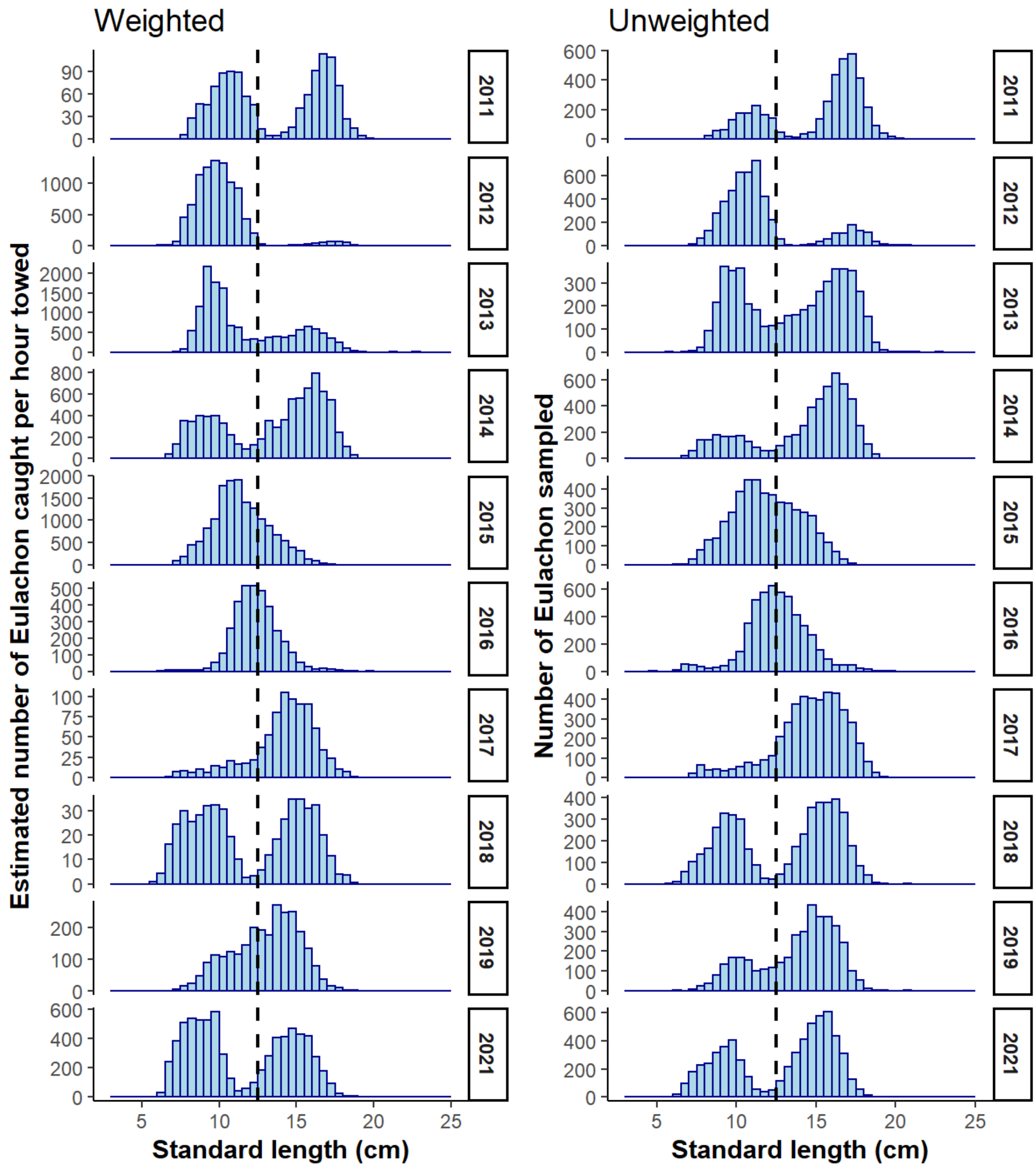


Figure 20-3. Eulachon standard length frequency histograms (in cm) from 2010-2019 WCVI survey samples, from statistically weighting by the estimated total number of Eulachon caught in each fishing event and standardizing by the fishing duration (left panel) and from pooling sample data by year (right panel). Dashed vertical lines are visual markers at 12.5 cm to assist comparisons between positions and shapes of length distributions.

20.4. Factors causing those trends

There is considerable uncertainty associated with the ecology and stock dynamics of Eulachon. The reasons for the large interannual variation in Fraser Eulachon spawner index estimates in recent years is not well understood. The moderately low 2021 index after a relatively high 2020 index was not anticipated. It is uncertain what age range and composition comprise the spawning stock each year and to what degree spawning stocks and cohorts may mix and be under metapopulation influences. It is generally believed that most Eulachon die after spawning but there is some evidence to suggest that some individuals (especially females) may repeat spawn (Dealy and Hodes 2019).

For years when low Eulachon spawner levels are evident, it is stated in Schweigert et al. (2012) that "no single threat could be identified as most probable for the observed decline in abundances among DUs [designatable units] or in limiting recovery. However, mortality associated with coastwide changes in climate, fishing (direct and bycatch) and marine predation were considered to be greater threats at the DU level, than changes in habitat or predation within spawning rivers."

20.5. Implications of those trends

Reduced biomass of Eulachon has negative implications for First Nations, commercial and recreational fishers. Eulachon are socially and culturally significant to many First Nations who have been harvesting Eulachon at low levels. Commercial and recreational fisheries targeting Eulachon have been closed for over a decade (DFO 2021). Incidental capture of Eulachon in the marine environment has negative implications on trawl fisheries targeting other species, as trawl fisheries may be subject to area closures or reduced fishing effort to reduce Eulachon mortality.

Reduced Eulachon abundance also likely has negative impacts on their predators. Important predators of Eulachon include: marine mammals (particularly seals and sea lions at or near estuaries), White Sturgeon, Spiny Dogfish, Chinook and Coho Salmon, Pacific Hake, Pacific Halibut, Walleye Pollock, Sablefish, rockfish, Arrowtooth Flounder, and others (Levesque and Therriault 2011). Diet data time series of Eulachon and their predators would improve our ability to examine temporal trends in predator-prey interactions and the implications of those trends.

20.6. References

Boldt, J.L. Javorski, A and Chandler, P.C. (Eds). 2021. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2020. Can. Tech. Rep.Fish. Aquat. Sci. 3434: vii + 231p.

COSEWIC. 2011. Committee on the Status of Endangered Wildlife in Canada assessment and status report on the Eulachon, Nass/Skeena Rivers population, Central Pacific Coast population and the Fraser River population *Thaleichthys pacificus* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xv + 88pp.

COSEWIC. 2013. Committee on the Status of Endangered Wildlife in Canada assessment and status report on the Eulachon, Nass/Skeena population, *Thaleichthys pacificus* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xi + 18 pp.

Dealy, L.V., and Hodes, V.R. 2019. Monthly distribution and catch trends of Eulachon (*Thaleichthys pacificus*) from Juan de Fuca Strait to the Fraser River, British Columbia, October 2017 to June 2018. Can. Manuscr. Rep. Fish. Aquat. Sci. 3179: viii + 39 p.

DFO 2021. Pacific Region Integrated Fisheries Management Plan January 1-December 31, 2021, Eulachon Fraser River. https://waves-vagues.dfo-mpo.gc.ca/Library/40930506.pdf

Hay, D.E., McCarter, P.B., Joy, R., Thompson, M., and West, K. 2002. Fraser River Eulachon Biomass Assessments and Spawning Distribution: 1995-2002. Canadian Stock Assessment Secretariat Research Document. 2002/117.

Levesque, C., and Therriault, T. 2011. Information in support of a recovery potential assessment of (*Thaleichthys pacificus*) in Canada. Canadian Stock Assessment Secretariat Research Document. 2011/101.

McCarter, P.B., and Hay, D.E. 2003. Eulachon embryonic egg and larval outdrift sampling manual for ocean and river surveys. Can. Tech Rep. Fish. Aquat. Sci. 2451: 33p.

Schweigert, J., Wood, C., Hay, D., McAllister, M., Boldt, J. McCarter, B., Therriault, T.W., and Brekke, H. 2012. Recovery potential assessment of eulachon (*Thaleichthys pacificus*) in Canada. Canadian Stock Assessment Secretariat Research Document. 2012/098.

21. PACIFIC HERRING IN BRITISH COLUMBIA, 2021

Jaclyn Cleary, Sarah Hawkshaw, Matt Grinnell, Sarah Power, Ashley Burton, Matt Thompson, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, B.C., Jaclyn.Cleary@dfo-mpo.gc.ca

21.1. Highlights

- In recent years, following a declining trend from approximately 1980 to 2010, weight-at-age for all B.C. stocks of Pacific herring have either remained unchanged or have increased.
- Total B.C. coastwide spawning biomass summed across the 5 major stocks has been increasing since 2010. The estimated herring spawning biomass varied among the assessed stocks with more than 50% of the B.C. stock biomass occurring in the Strait of Georgia (SOG).

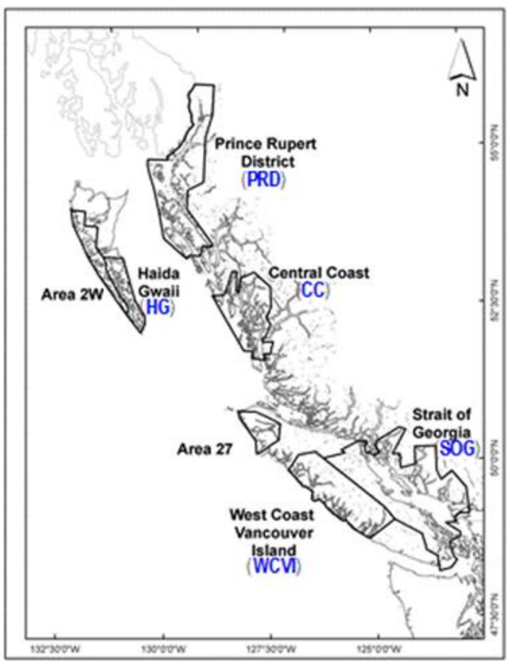


Figure 21-1. Location of the five major (Strait of Georgia, West Coast of Vancouver Island, Prince Rupert District, Haida Gwaii, and Central Coast) as well as two minor (Area 2W, and Area 27) Pacific Herring stocks in B.C.

21.2. Summary

In B.C., Pacific Herring are managed as five major stocks (SOG; West Coast of Vancouver Island, WCVI; Prince Rupert District, PRD; Haida Gwaii, HG; and Central Coast, CC), and two minor stocks (Area 2W and Area 27) (DFO 2021; Figure 21-1). For each stock, herring population trends are based on stock-specific model estimates of biomass. Statistical catch-at-age models are fit to time series data: commercial and test fishery biological samples (age, length, weight, sex, etc.), herring spawn survey data (spawn index), and commercial harvest data (DFO 2021).

21.3. Status and trends

In all five major herring stocks there was a declining trend in weight-at-age from the 1980s through to 2010, with a leveling off or increase in recent years (Figure 21-2). Since 2000, the HG stock has been in a low biomass state and below the limit reference point (LRP) for most years between 2000-2017 (DFO 2021). The estimated stock biomass for PRD is above the LRP and increased in 2019-2021. The CC survey biomass is above the LRP and shows an increasing trend, though it declined from 2020 to 2021. The SOG spawning biomass decreased in 2021 but remains above the LRP and is still relatively high compared to historic estimates (Figure 21-3). WCVI stock biomass has slowly increased since 2012 and is currently above the LRP (DFO 2021; Figure 21-3).

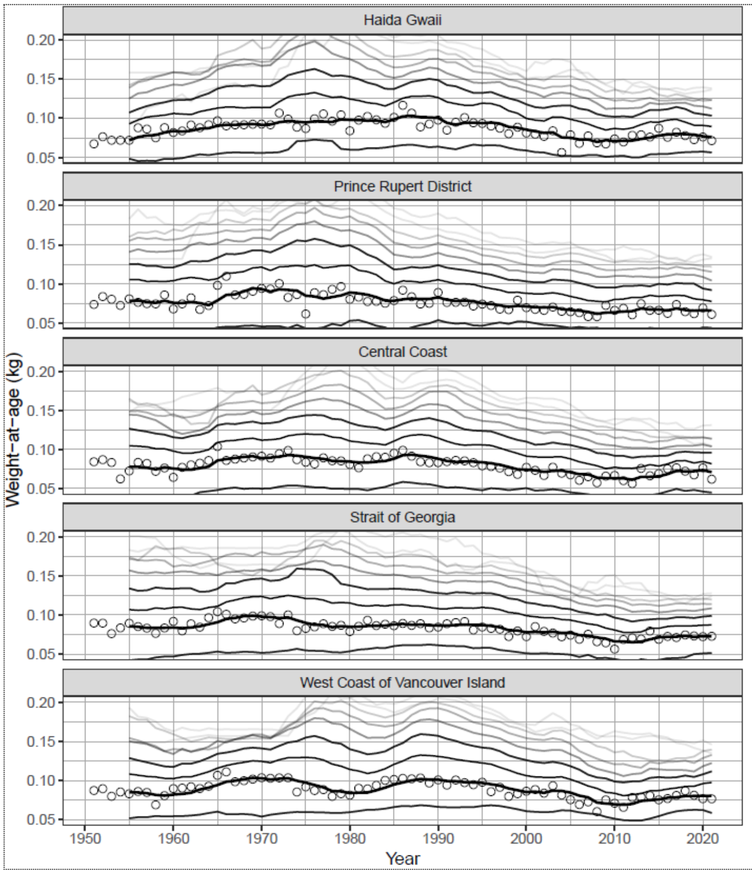


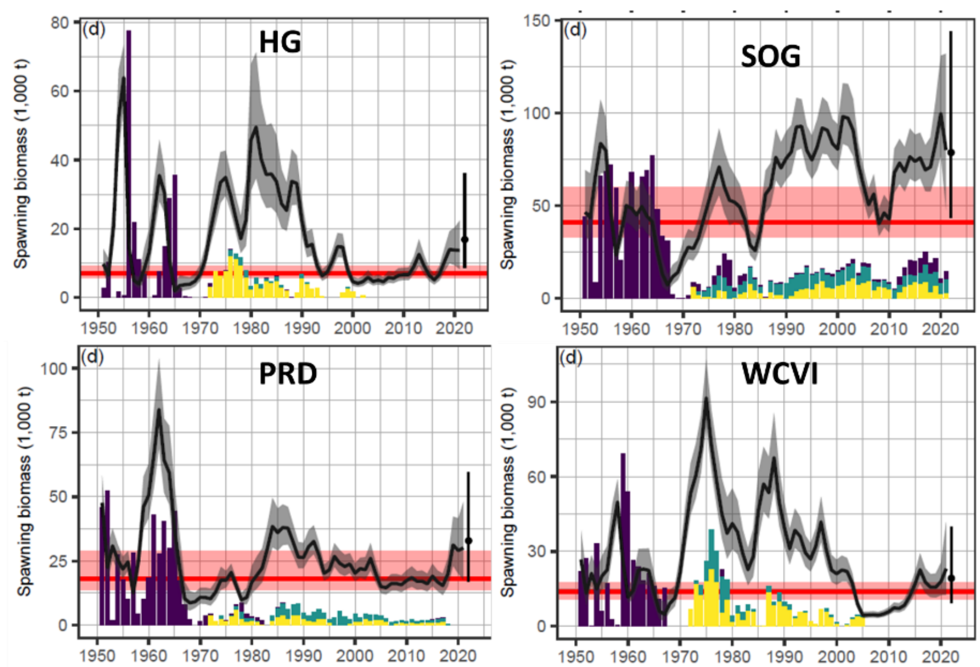
Figure 21-2. Observed weight-at-age 3 (circles) and five-year running mean weight-at-age 3 (dark line) for major Pacific Herring stocks, 1951 to 2021. Thinner black lines represent five-year running mean weight-at-age 2 (lowest) and ages 4-10+ (incrementing higher from age 3). Figure from DFO (2021).

21.4. Factors influencing trends in herring biomass

Common trends in herring weight-at-age observed for all B.C. stocks suggests that large-scale factors may be influencing herring growth. Changes in environment, food supply and quality, predator abundance, and competition are factors that could affect trends in herring biomass and weight-at-age (Schweigert et al. 2010; Hay et al. 2012).

Pacific Herring are zooplanktivorous, consuming primarily euphausiids (krill) and some copepods (Wailes 1936). Changes in ocean conditions, such as temperature or currents, could affect the amount and types of prey available. For example, a northerly current direction results in the presence of California current waters off the WCVI and may bring southern zooplankton species that have a lower energetic value, creating poorer feeding conditions for herring (Schweigert et al. 2010; Mackas et al. 2004).

There are a wide variety of herring predators, including Pacific Hake, Lingcod, Spiny Dogfish, Pacific Cod, Sablefish, Arrowtooth Flounder, Pacific Halibut, Steller Sea Lions, Northern Fur Seals, Harbour Seals, California Sea Lions, and Humpback Whales (Schweigert et al. 2010). Herring – predator interactions have been studied off of the WCVI, where the abundance of most marine mammal predators has increased (Olesiuk 2010; DFO 2021; Wright et al. 2021). Spatio-temporal model results suggest that the strongest drivers of summer distribution and biomass of Pacific Herring off the WCVI include: 1) zooplankton prey availability, 2) predator avoidance, particularly Pacific Hake, and 3) competition with sardines (Godefroid et al. 2019).



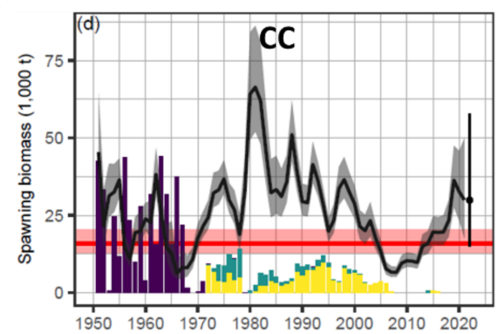


Figure 21-3. Pacific Herring spawning biomass, 1951- 2021. Black lines with surrounding grey envelopes represent medians and 5-95 % credible intervals. The projected spawning biomass given zero catch is shown at the far right (solid circle and vertical lines). Time series of thin vertical lines denote commercial catch (excluding commercial spawn-on-kelp; colours indicate different gear types; see DFO 2021). Red line= limit reference point (0.3B_0). B_0 = average unfished spawning biomass. Figure from DFO (2021).

21.5. Implications of trends

Trends in herring biomass have implications for both fisheries and predators. Pacific Herring are an important component of commercial fisheries in British Columbia. Harvest options (total allowable catch, TAC) considered by Fisheries Management reflect application of simulation tested management procedures (MP) to one-year forecasts of herring biomass. All TAC options reflect MPs that meet the conservation objective of avoiding the LRP with a minimum 75% probability.

Trends in herring biomass have implications for herring predators, such as fish, marine mammals and seabirds. The relative importance of herring in each predator's diet varies; however, herring may represent up to 88% of Lingcod diet (Pearsall and Fargo 2007), 40% of Pacific Cod and Pacific Halibut diets (Ware and McFarlane 1986), and 35% to 45% of pinniped diets (Olesiuk et al. 1990; Womble and Sigler 2006; Trites et al. 2007; Olesiuk 2008). Depending on the level of diet specialization and ability to switch to alternate prey, herring abundance and condition may affect predators' growth and abundance. Time series of diets of animals in this ecosystem would improve our ability to examine temporal trends in predator-prey interactions and implications of those trends.

21.6. References

DFO. 2021. Stock status update with application of management procedures for Pacifc Herring (*Clupea pallasii*) in British Columbia: Status in 2021 and forecast for 2022. DFO Can. Sci. Advis. Sec. Sci. Resp. 2022/039.

DFO. 2021. Trends in Abundance and Distribution of Steller Sea Lions (Eumetopias Jubatus) in Canada. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2021/035.

Godefroid, M., Boldt, J.L., Thorson, J., Forrest, R., Gauthier, S. Flostrand, L., Perry, R.I., Ross, A.R.S., and Galbraith, M. 2019. Spatio-temporal models provide new insights on the biotic and abiotic drivers shaping Pacific Herring (*Clupea pallasi*) distribution. Progress in Oceanography. 178, 102198.

Hay, D., Schweigert, J., Boldt, J.L., Cleary, J., Greiner, T.A., and Hebert, K. 2012. Decrease in herring size-at-age: a climate change connection? In Irvine, J.R., and Crawford, W.R. 2012. State of the physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2011. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/072. xi +142 p.

Mackas, D.L., Peterson, W.T., and Zamon, J.E. 2004. Comparisons of interannual biomass anomalies of zooplankton communities along the continental margins of British Columbia and Oregon. Deep-Sea Research. II 51: 875-896.

Olesiuk, P.F. 2010. An assessment of population trends and abundance of harbour seals (Phoca vitulina) in British Columbia. DFO Can. Sci. Advis. Sec.r Res. Doc. 2009/105. vi + 157 p.

Olesiuk, P.F. 2008. Abundance of Steller sea lions (*Eumatopias jubatas*) in British Columbia. DFO Can. Sci. Advis. Sec.Res. Doc. 2008/063. iv + 29 p.

Olesiuk, P.F., Bigg, M.A., Ellis, G.M., Crockford, S.J., and Wigen, R.J. 1990. An assessment of the feeding habits of harbour seals (*Phoca vitulina*) in the Strait of Georgia, British Columbia, based on scat analysis. Canadian Technical Report of Fisheries and Aquatic Sciences. 1730. 135 p.

Pearsall, I.A., and Fargo, J.J. 2007. Diet composition and habitat fidelity for groundfish assemblages in Hecate Strait, British Columbia. Canadian Technical Report of Fisheries and Aquatic Sciences. 2692. 149 p.

Schweigert, J.F., Boldt, J.L., Flostrand, L., and Cleary, J.S. 2010. A review of factors limiting recovery of Pacific herring stocks in Canada. ICES J. Mar. Sci. 67: 1903-1913.

Trites, A.W., Calkins, D.G., and Winship, A.J. 2007. Diets of Steller sea lions (*Eumatopias jubatus*) in southeast Alaska, 1993-1999*.* Fishery Bulletin. 105: 234-248.

Wailes, G.H. 1936. Food of *Clupea pallasi* in southern British Columbia waters. Journal Biological Board of Canada. 1: 477-486.

Ware, D.M., and McFarlane, G.A. 1986. Relative impact of Pacific hake, sablefish and Pacific cod on west coast of Vancouver Island herring stocks. International North Pacific Fisheries Commission Bulletin. 47: 67-78.

Womble, J.N., and Sigler, M.F. 2006. Seasonal availability of abundant, energy-rich prey influences the abundance and diet of a marine predator, the Steller sea lion *Eumatopias jubatus*. Marine Ecology Progress Series. 325: 281-293.

Wright, B.M., Nichol, L.M., Doniol-Valcroze, T. 2021. Spatial density models of cetaceans in the Canadian Pacific estimated from 2018 ship-based surveys. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/049. iii + 46 p.

22. COAST-WIDE SOCKEYE SALMON INDICATOR STOCKS: REGIONAL TRENDS, 2021 RETURNS, AND 2022 OUTLOOK

Howard Stiff, Cameron Freshwater, Athena Ogden, and Kim Hyatt, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, B.C., Howard.Stiff@dfo-mpo.gc.ca

22.1. Highlights

- Returns of B.C.'s north coast, transboundary, west coast Vancouver Island, and Fraser Sockeye Salmon 'Indicator Stocks' were above median management forecasts in 2021 except for the most southerly management unit, Okanagan Sockeye. However, all abundance estimates fell below long-term averages.
- Sockeye indicator stocks from south of the Aleutian Islands Peninsula, with migration to sea in 2018-**2019**[1] and maturation in the Gulf of Alaska (GOA) in 2019 and **2020**, displayed sub-average returns in **2021,** in contrast to exceptional returns for Bristol Bay Sockeye, with sea-entry and maturation in the Bering Sea (north of the Aleutian Islands).

22.2. Description of the time series – Annual Returns of Coast-wide "Sockeye Indicator Stocks"

Hyatt et al. (2020a) describe a *de facto* international network of Sockeye Indicator Stocks (SIS), spanning 2,400 km of the west coast from Alaska to the Oregon border (Figure 22-1) going back to 1980, from which inferences about spatial and temporal trends in patterns of abundance and biological traits may be made.[2] Production trends of these "data-rich" Sockeye stock aggregates are assumed to be representative of populations that share similar marine domains immediately after ocean entry.

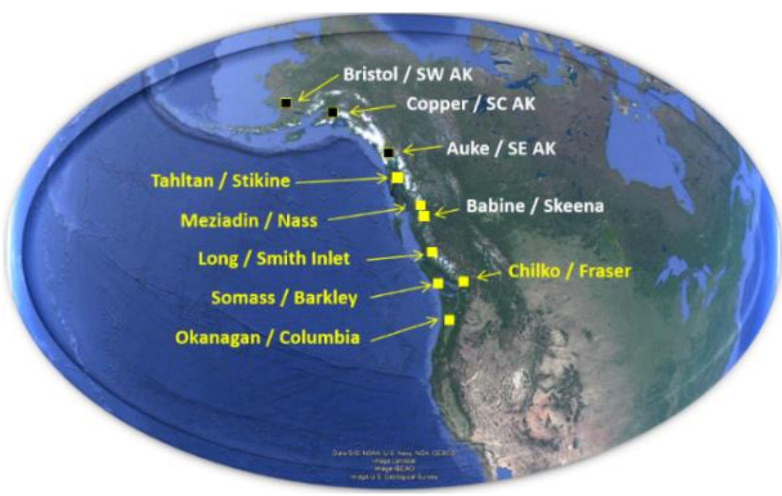


Figure 22-1. Coast-wide Sockeye Performance Indicator Stocks. Approximate points of sea entry for a network of relatively data-rich Sockeye stocks monitored by DFO (yellow) and ADFG (black) on an annual basis for biological traits (age-at-return, size-at-return, return timing etc.) and total returns (catch plus escapement) relative to predicted returns.

[1] Year in bold represents year of dominant age class returning in 2021.

[2] Historical returns and pre-season forecasts are generally available as published or unpublished observations from biologists and resource managers at Fisheries & Oceans Canada (DFO), Pacific Salmon Commission (PSC), and Alaska Department of Fish and Game (ADFG).

22.3. Status and Trends Exhibited by Coast-wide Sockeye Indicator Stocks

Status: Total adult returns exceeded forecasts for four of the five B.C. SIS reporting in 2021, reflecting unexpected improvements in survival for Tahltan, Meziadin, Somass, and Chilko Sockeye relative to previous years or cycle line abundances (Figure 22-2). For all B.C. SIS, 2021 returns were < 40-year average, with only limited harvests permissible. SIS returns ranged from 50,000 Tahltan (+44% of forecast), 513,000 Meziadin (+15%), 591,000 Somass (+45%) and 1,095,000 Chilko Sockeye (+72%; comprising 43% of Fraser Sockeye returns). Okanagan returns of 105,000 were 20% below forecast.

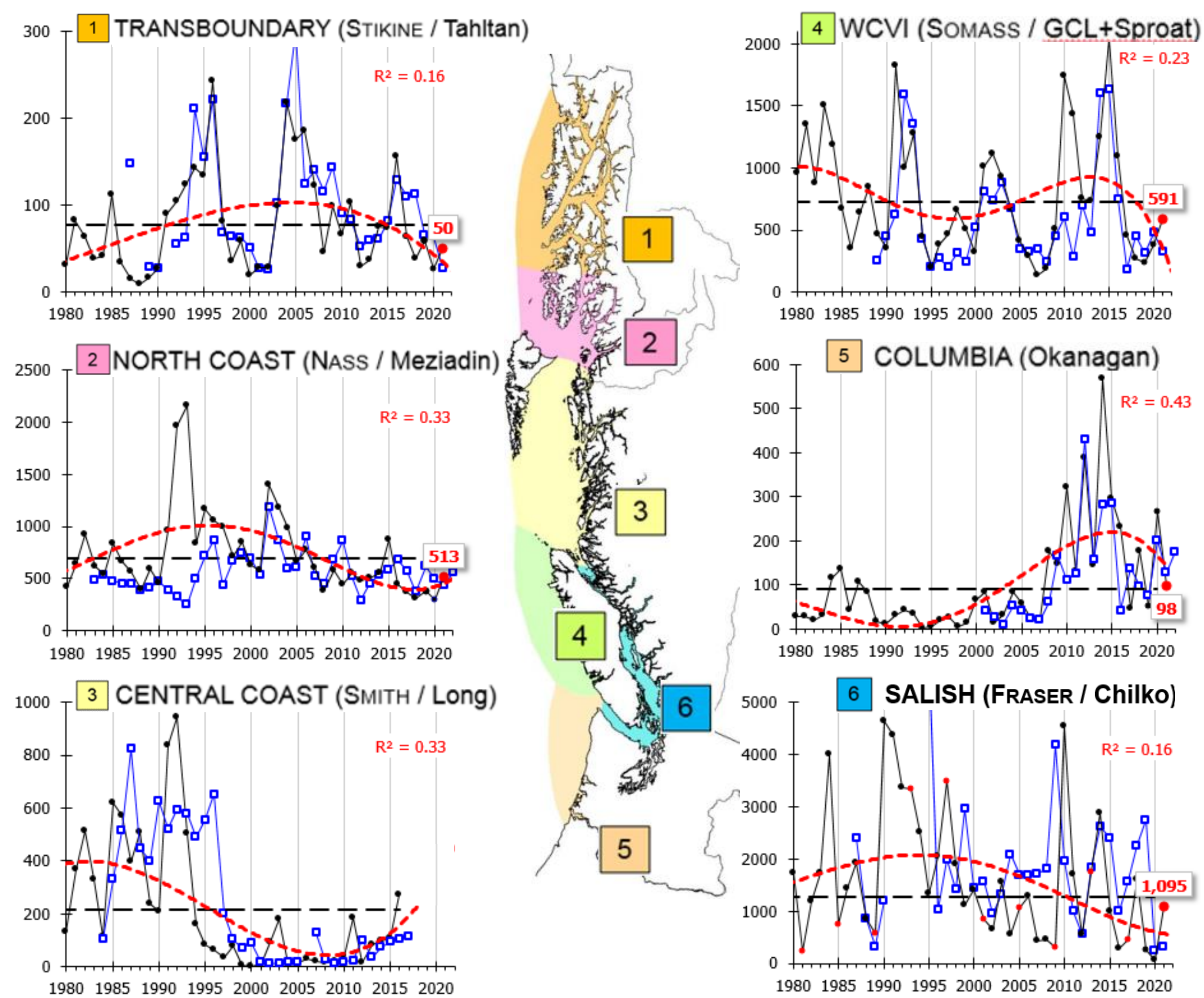


*Figure 22-2. Trends in the **total annual returns** (black line) to **2021** (thousands of fish) and median management forecasts (blue line) to **2022** for B.C. Sockeye indicator stocks, by DOMAIN (WATERSHED/MU). Note: dashed line: 40-year average; red dashed line: quadratic fit to total returns.*

Trends: Environmental conditions in the NE Pacific region over the past seven years, including the combined impacts of a string of marine heat waves (2014-2016, 2019, 2020) and multiple El Niños (2016, 2019) (Ross and Robert 2021), have imposed serial controls on salmonid survival over cumulative freshwater and marine life stages (Hyatt et al. 2020b; Grant et al. 2019). This has led to overall declines in Sockeye abundance, smaller body sizes, reduced fecundity, and generally greater variability in total production since the 1990s (DFO 2020).

By contrast, Bristol Bay Sockeye, making sea entry into the Bering Sea, achieved record returns in 2021 (68M fish: 25% over forecast)[3]. High returns to Bristol Bay, average or sub-average returns to south-central and southeast[4] Alaska (ADFG 2021a; 2021b; 2021c), and weak returns to B.C. over the past decade comprise a persistent south-to-north inverse production gradient for Sockeye salmon stocks in the eastern Pacific (Peterman et al. 1998; Pyper et al. 2005).

22.4. Factors Influencing Trends in Abundance and Biological Traits of Sockeye

Freshwater conditions in B.C. that can negatively affect early salmonid life-stages varied from 2016-2019[5], but generally included higher river and lake temperatures, earlier snowmelt in snow-dominated freshwater habitats, high-flow scour and flood effects and summer drought (Anslow 2020 and 2021; DFO 2020).

Marine biological conditions encountered by Sockeye smolts entering the sea in 2018-2019 "continued to reflect a warmer ocean" (DFO 2020, p. 54), characterized by less nutritious zooplankton prey, predators 'foreign' to juvenile salmon, and competitive invertebrate populations (Galbraith and Young 2020). Combined with additional MHWs in the NE Pacific in 2019 and 2020 (Amaya et al. 2020)[6], ocean conditions were potentially limiting to growth and survival of Sockeye returning in 2021.

In the GOA in 2021, water temperatures were near the long-term average, but the biological community is still in transition from the MHWs as evidenced by mixed trends in the prey base.[7,8] North of the Aleutian Islands, the eastern Bering Sea has seen a persistent warm phase since 2014, with SSTs higher than the 1985-2014 average; however, these conditions appear to be beneficial to Bristol Bay Sockeye marine survival (Siddon 2021).

The ENSO index[9], which identifies multi-year alternations in "warm" vs "cold" sea surface temperatures (SST), has been a reasonable predictor of marine survival of Sockeye stocks that directly enter the northern California Current System (CCS)[10] and possibly the Salish Sea (Hyatt et al. 2020a; MacDonald et al. 2018). Prevalence of neutral-to-cool ENSO and cool PDO

---

[3] However, average weight for Sockeye salmon was 1 lb < than the 20-year average of 5.7 pounds (ADFG 2021a).
[4] Pers. comm. S. Vulstek, Auke Bay Research Station (NOAA), Juneau [25-Feb-2021].
[5] Warmer than average air temperatures characterized 2017-2021 (PCIC Seasonal Anomaly Maps, | Feb 2022)
[6] String of Marine Heatwaves Continues to Dominate Northeast Pacific | NOAA Fisheries | Dec 2020
[7] NOAA: Central Gulf of Alaska Marine Heatwave Watch
[8] There is evidence of the large population of Pink salmon impacting the food web in the western GOA (i.e., reduced abundance of large copepods (Pink salmon prey) and reduced reproductive success of black-legged kittiwakes (competitors of Pink salmon for large copepods)) (NOAA: GOA-Ecosystem Status Report Brief 2021_Final 13Dec21)
[9] ENSO: El Niño Southern Oscillation – or Oceanic Niño Index (ONI 3.4) (Barnston and Tippett 2013).
[10] However, see Hyatt et al. (2020b) for contrasting results for Somass Sockeye (Barkley Sound, WCVI).

conditions in 2017-2018 likely reduced the impacts of the 2019-2020 MHW (Ross & Robert 2021) on ocean survival, enabling a slight uptick in adult returns in 2021.

Adult upstream migration was, however, impeded by high freshwater temperatures in 2021, at least for southern stocks, by the climate-driven "heat dome" that settled over SW B.C. and the U.S. Pacific NW in late June 2021 (Philip et al. 2021). Mainstem rivers (Fraser, Somass, Columbia, and Okanogan) warmed early in the season, challenging fisheries management efforts to ensure sufficient adults reached the spawning grounds.[11,12]

22.5. Implications and Outlook for Returns in 2022

Implications: Sockeye salmon have complex life histories with multiple sensitive life stages in diverse aquatic environments affecting growth, survival, and reproductive success. The cumulative impacts of sequential climate-related stresses (e.g., MHWs), driving habitat and food web alterations in freshwater, estuarine and marine environments, appear to be limiting Sockeye productivity coast-wide in B.C. Protecting population diversity will be key to sustaining population adaptability through uncertain climate futures (DFO 2005).

Outlook: The onset of a weak La Niña in late 2019 and a stronger one in 2020-22, associated with a return of B.C. outer coast temperatures closer to the climatological mean, signal some potential for improvement in survival for juvenile Sockeye going to sea in 2020 and 2021 to return in 2022 after one or two ocean years (e.g., 3_2 jacks or 4_2 or 5_3 adults). Persistence of the current La Niña through spring 2022[13] should favour improved survival for returns in 2023-2024. The evident improvement in local physical and biological indicators for salmonids entering the northern CCS[14] in 2021 may reflect in higher Somass and Okanagan Age 3 returns in 2022, and their older siblings in 2023 and 2024.

Preliminary forecasts[15] based on DFO area manager expertise indicate average or sub-average returns in 2022 for most southern and central coast Sockeye stocks, and average or above average for some northern B.C. stocks (e.g., Skeena, Nass, Tahltan). Above average returns are anticipated for Chilko Sockeye.

22.6. References

ADFG. 2021a. 2021 Bristol Bay Salmon Season Summary. September 29. 2021.

ADFG. 2021b. 2021 Cook Inlet Salmon Season Summary. November 15. 2021.

ADFG. 2021c. 2021 Prince William Sound Salmon Season Summary. November 5. 2021.

Amaya, D.J., Miller, A.J., Xie, SP. 2020. Physical drivers of the summer 2019 North Pacific marine heatwave. Nature Communications. 11: 1903.

[11] On the positive side, adult migrants to Chilko River and other upper Fraser watersheds were reported to be freely ascending the recently-completed "nature-like" fish ladder at Big Bar.

[12] Survival of Okanagan-bound Sockeye between the Columbia River and the spawning grounds was estimated at ~15% (vs 2010-2020 average ~35%). Spawner condition and fecundity were poor (H. Alex, Penticton Hatchery).

[13] ENSO: Recent Evolution, Current Status and Predictions (NOAA Feb 2022)

[14] Oceanic, atmospheric, and local physical / biological indicators characterizing ocean conditions in the CCS (NOAA Ocean Condition Indicators) are all 'neutral' or 'good' for early marine survival of salmon for the first time since 2008.

[15] Pacific Salmon Outlook 2022 (Preliminary) - Pers. comm. D. Lewis – Pac. Sci. Salmon Assessment - 15-Dec-2021

Anslow, F. 2020. Land temperature and hydrological conditions in 2019. In: Boldt, J.L., Javorski, A., and Chandler, P.C. (Eds.). 2020. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377: x+288p.

Anslow, F. 2021. Land temperature and hydrological conditions in 2020. In: Boldt, J.L., Javorski, A., and Chandler, P.C. (Eds.). 2021. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2020. Can. Tech. Rep. Fish. Aquat. Sci. 3434: vii+231p.

Barnston, A.G., and Tippett, M.K. 2013. Predictions of Nino3.4 SST in CFSv1 and CFSv2: a diagnostic comparison. Climate Dynamics. 41: 1615-1633. DOI: 10.1007/s00382-013-1845-2.

DFO. 2005. Wild Salmon Policy: Canada's Policy for Conservation of Wild Pacific Salmon.

DFO. 2020. Fisheries and Oceans Canada (Pacific). Integrated Fisheries Management Plan – June 2019 - May 2020. Southern BC Salmon. Pacific Region Final. 561 pp.

Galbraith, M., and Young, K. 2020. West Coast BC zooplankton biomass anomalies 2019. In Boldt, J.L., Javorski, A., Chandler, P.C. (Eds.). 2020. State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2019. CTRFAS. 3377. x + 288 p.

Grant, S.C.H., MacDonald, B.L., and Winston, M.L. 2019. State of Canadian Pacific Salmon: Responses to Changing Climate and Habitats. Can. Tech. Rep. Fish. Aquat. Sci. 3332. ix + 50 p.

Hyatt, K.D., Stiff, H.W., and Stockwell, M.M. 2020a. Sockeye Salmon indicator stocks – Regional overview of trends, 2019 returns, and 2020 outlook. In: Boldt, J.L., and Chandler, P.C. (Eds.). 2020. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377: 288 p.

Hyatt, K.D., Stiff, H.W., and Stockwell, M.M. 2020b. Impacts of the 2013-2016 marine heatwave on Barkley Sound Sockeye Salmon. In: Boldt, J.L., and Chandler, P.C. (Eds.). 2020. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377: x + 288 p.

MacDonald, B.L., Grant, S.C.H., Patterson, D.A., Robinson, K.A., Boldt, J.L., Benner, K., Neville, C.M., Pon, L., Tadey, J.A., Selbie, D.T., and Winston, M.L. 2018. State of the Salmon: Informing the survival of Fraser Sockeye returning in 2018 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3271: 52 p + Appendix.

Peterman, R.M., Pyper, B.J., Lapointe, M.F., Adkison, M.D., and Walters, C.J. 1998. Patterns of covariation in survival rates of BC and Alaskan sockeye salmon stocks. CJFAS*. 55:* 2503-2517.

Pyper, B.J., Mueter, F.J., and Peterman, R.M. 2005. Across-Species Comparisons of Spatial Scales of Environmental Effects on Survival Rates of Northeast Pacific Salmon. Trans. Am. Fish. Soc*. 134:* 86-104.

Philip, S.Y., Kew, S.F., van Oldenborgh, G.J., Yang, W., Vecchi, G.A., Anslow, F.S., Li, S., Seneviratne, S.I., Luu, L.N., Arrighi, J., Singh, R., van Aalst, M., Hauser, M., Schumacher, D.L., Marghidan, C.P., Ebi, K.L., Bonnet, R., Vautard, R., Tradowsky, J., Coumou, D., Lehner, F., Wehner, M., Rodell, C., Stull, R., Howard, R., Gillet, N., and Otto, F.E.L. 2021. Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021. WWA Scientific Report.

Ross, T. and Robert, M. 2021. Marine heatwave persists despite growing La Nina. In: Boldt, J.L., Javorski, A., and Chandler, P.C. (Eds.). 2021. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2020. CTRFAS. 3434: vii + 231 p.

Siddon, E. 2021. Ecosystem Status Report 2021: Eastern Bering Sea, Stock Assessment and Fishery Evaluation Report, N. Pac. Fish. Mgmt Council, 400-1007 West Third, Anchorage AK 99501.

23. SIZE OF MATURE FRASER SOCKEYE AND PINK SALMON

Steve Latham, Angela Phung, Dejan Brkic, Julie Sellars, Catherine Ball, Eric Taylor, Chris Dailey, Serena Wong, and Merran Hague, Benia Nowak, Pacific Salmon Commission, Vancouver, B.C., Latham@psc.org, Phung@psc.org, Brkic@psc.org, Sellars@psc.org, Ball@psc.org, Taylor@psc.org, Dailey@psc.org, Wong@psc.org, Hague@psc.org, Nowak@psc.org

23.1. Highlights

- Mature Fraser River Pink Salmon have been consistently small for more than half of the ~60 year time series and were third smallest on record in 2021.
- The decline in size observed since the 2000s estimated for 3-ocean Sockeye Salmon exceeded the decline for 2-ocean Sockeye, and sizes in 2021 ranked third and fifth lowest for 3- and 2-ocean Fraser Sockeye, respectively.

23.2. Description of the time series

Body size measurements of maturing Sockeye and Pink salmon likely integrate both bottom-up and top-down effects. Two time series are examined to evaluate size-at-age of mature Fraser River Sockeye Salmon.

The first Sockeye Salmon timeseries is average length (mm) of carcasses on spawning grounds from 1956-2021. Using ages derived from otoliths and applying a minimum sample size threshold for each sex of each stock (n = 20 and n = 10 per year for 2-ocean and 3-ocean Sockeye, respectively), age and sex-specific annual standard-length anomalies are calculated as the difference between year-specific average lengths and the all-years average length. These anomalies are averaged between the sexes. Some estimates from the earliest years were considered unreliable and excluded. Of 26 possible stocks, 13 and 4 stocks were analyzed for 2-ocean and 3-ocean ages, respectively.

The second Sockeye Salmon timeseries is condition factor for returning spawners in the lower Fraser River 2003-2021. Samples are obtained from fisheries (gear types: variable mesh gillnet, purse seine, and reef net) in the lower Fraser River and marine approach areas. Post-orbital fork length (POF), and weight data are used to calculate condition factor on a stock-, age- and sex-specific basis for these fish during their return to the Fraser River. Fish were included if the posterior probability of their DNA-based stock identity was greater than 50%, and stock-year combinations were only included for stocks exceeding n = 10 matching weight and length measurements for each sex. Anomalies were averaged for the sexes. Condition factor, K, was calculated using the POF in mm, weight in grams, and a stock- and sex-specific exponent of the arithmetic form of the length-weight relationship (β) as $K = (\text{fish mass} \cdot 10^5)/POF^{\beta}$.

A third time series, average weight of Fraser River Pink Salmon (which return to the Fraser River only on odd-numbered years), was obtained and is based on purse seine catches in Juan de Fuca Strait in 1959-2021. In 2015-2019, data from catches of reef net gear also had to be included due to poor availability of samples.

23.3. Status and trends

23.3.1. Spawning ground lengths of Fraser River Sockeye Salmon

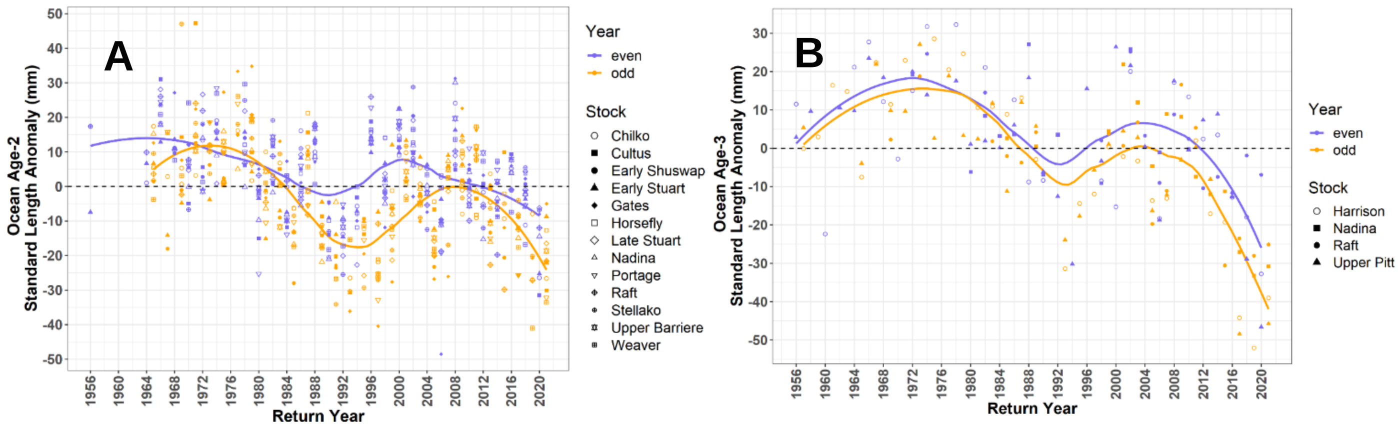


Figure 23-1. Average standard lengths of Fraser Sockeye Salmon on their spawning grounds. Annual anomalies were calculated relative to long term averages for 2-ocean (panel A) and 3-ocean fish (panel B), respectively. LOESS curves were fit to aggregate anomalies among stocks, summarizing even- and odd-numbered years separately.

Mature 2-ocean Sockeye tend to be smaller in odd-numbered years than in even-numbered years (Figure 23-1A), and this was also observed in 3-ocean fish, although this biennial cycle was less pronounced for the older Sockeye (Figure 23-1B). A sharp decline in size occurred, across stocks and ages, from the 1970s to the 1990s. Recent declines in average size (since the 2000s) seem more severe for 3-ocean Sockeye than for 2-ocean Sockeye. Spawning ground lengths were among the smallest on record in 2021 (the average anomaly across stocks ranked 3rd lowest for 3-ocean and 5th lowest for 2-ocean Sockeye) but were larger than in 2019.

23.3.2. Weight and condition factor of returning Fraser Sockeye

Weights and condition factors of Sockeye as they approach the Fraser River may be more informative regarding the marine conditions encountered than the lengths of fish that eventually reach the spawning grounds. Weights appeared to decrease over the time series, in agreement with spawning ground lengths in recent years, and although low in 2021, weights were higher than the very low weights observed in 2019 (not shown). Body condition strongly exemplified a biennial pattern (Figure 23-2). Sockeye caught during even-numbered years weighed more (β = 188 g, $p < 0.001$) and had a higher condition factor anomaly (β = +5 %, $p < 0.001$) on average than those caught in odd-numbered years.

23.3.3. Fraser Pink Salmon size-at-maturity

Average weights of Fraser River Pink Salmon declined from approximately 2.5 kg in the 1960s to generally less than 2.0 kg from 2001-2021, with the largest decline occurring during the 1980s (Figure 23-3). Record low average weights were observed in 2015 (<1.5 kg), whereas in 2017 weights were higher (2.1 kg) than observed in any other year since 1985. In 2021, Fraser River Pink Salmon were the 3rd smallest on record (1.7 kg).

Figure 23- 2. Average condition factor anomalies (%) of Fraser Sockeye in fisheries. Simple linear regressions were fit separately for odd- and even-numbered return years.

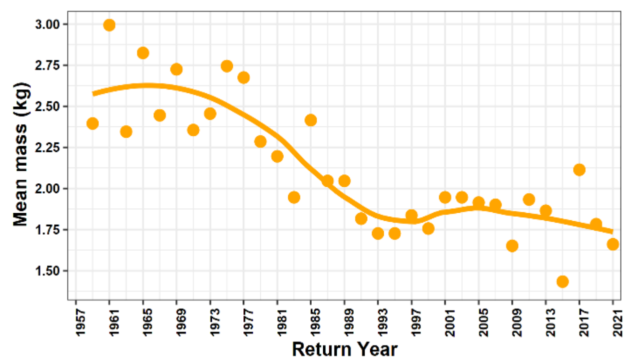


Figure 23-3. Average fishery weights (kg) of Fraser Pink Salmon. A LOESS curve with a span of 0.5 was fit as in Figure 23-1.

23.4. Factors influencing trends

These time series demonstrate historical and recent declines in length-at-age of Fraser Sockeye and a biennial fluctuation in which Sockeye tend to be shorter, lighter, and skinnier when returning in odd-numbered years. There was an historical reduction in average weight of Fraser Pink Salmon that centered on the 1980s, contemporaneous with the first major decline in Fraser Sockeye lengths. One hypothesis for these trends involves a mixture of direct and indirect effects of sea surface temperatures. Increased marine temperatures result in increased metabolic demands of Sockeye (Cox and Hinch 1997) and also result in reduced abundance and/or quality of food resources (DFO 2020). These may negatively affect Fraser Sockeye even in the absence of competition with Pink Salmon, but increased temperatures may also result in exacerbated impacts from Pink Salmon, whose overall abundance throughout the North Pacific Ocean has benefitted from warming temperatures (Connors et al. 2020).

Weight anomalies of Fraser River Pink Salmon in the last two decades are not correlated with length anomalies of Fraser Sockeye: $r = 0.14$, $p > 0.5$, for 2001-2021 (in contrast to the strong correlation between 2 and 3-ocean Fraser Sockeye in the same years: $r = 0.9$, $p < 0.001$). This argues against direct competition between Fraser Sockeye and Fraser Pink Salmon. Similarly, direct competition among Fraser Sockeye stocks, or between Fraser and other Sockeye stocks, is unlikely to explain size variation in Fraser Sockeye in recent years. The recent steep decline in Fraser Sockeye sizes has coincided with record low Fraser Sockeye run sizes. Direct competition with Alaskan Sockeye may be proposed as an explanation, owing to very large returns that have occurred there in recent years, but decreases in size-at-age of Alaskan Sockeye have been minor (Oke et al. 2020). Climatological conditions and other populations of North Pacific Pink Salmon may interact to affect the sizes of both Fraser Sockeye and Fraser Pink Salmon.

23.5. Implications of those trends

Size of salmon is of great importance to their value, both in fisheries and on the spawning grounds (where egg size and fecundity are strongly related to body size, and nutrient transport to natal locations from the ocean relies directly on body size; Oke et al. 2020). Size may also directly influence marine survival, success of upriver migration, and successful egg deposition. In Prince William Sound, competition with hatchery Pink Salmon was estimated to reduce the productivity of wild Pink Salmon populations by approximately 15% through resulting reductions in body size (Wertheimer et al. 2004). Fraser Sockeye and Pink Salmon (and other stocks rearing in the Gulf of Alaska) may also be less productive through this mechanism. Spawning escapement targets and other fisheries management considerations for these fish do not currently consider trends in body size (e.g., DFO 2020).

23.6. References

Connors, B., Malick, M.J., Ruggerone, G.T., Rand, P., Adkison, M., Irvine, J.R., Campbell, R., and Gorman, K. 2020. Climate and competition influence Sockeye Salmon population dynamics across the Northeast Pacific Ocean. Can. J. Fish. Aquat. Sci. 77: 943-949.

Cox, S.P., and Hinch, S.G. 1997. Changes in size at maturity of Fraser River Sockeye Salmon (*Oncorhynchus nerka*) (1952-1993) and associations with temperature. Can. J. Fish. Aquat. Sci. 54: 1159-1165.

DFO. 2020. Integrated Fisheries Management Plan – June 2019 - May 2020. Southern B.C. Salmon. Pacific Region Final. 561 p. https://waves-vagues.dfo-mpo.gc.ca/Library/40799104.pdf

Oke, K.B., Cunningham C.J., Westley, P.A.H., Baskett, M.L., Carlson, S.M., Clark, J., Hendry, A.P., Karatayev, V.A., Kendall, N.W., Kibele, J., Kindsvater, H.K., Kobayashi, K.M., Lewis, B., Munch, S., Reynolds, J.D., Vick, G.K., and Palkovacs, E.P. 2020. Recent declines in salmon body size impact ecosystems and fisheries. Nat. Commun., 11: 4155. https://doi.org/10.1038/s41467-020-17726-z

Wertheimer, A.C., Heard, W.R., Maselko, J.M., and Smoker, W.M. 2004. Relationship of size at return with environmental variation, hatchery production, and productivity of wild Pink Salmon in Prince William Sound, Alaska: does size matter? Rev. Fish. Biol. Fisher. 14: 321-334.

24. TRENDS IN PACIFIC CANADIAN GROUNDFISH STOCK STATUS AND SURVEYS

Sean C. Anderson, Philina A. English

Pacific Biological Station, Fisheries and Oceans Canada, Nanaimo, B.C., Sean.Anderson@dfo-mpo.gc.ca, Philina.English@dfo-mpo.gc.ca

24.1. Highlights

- Average groundfish stock status declined from 1950 to around 2000, and following management changes, has remained relatively stable since then.
- Three stocks (Strait of Georgia Lingcod [Area 4B] and inside and outside Quillback Rockfish) had a $>$ 5% probability of being below their Limit Reference Point. Conversely, two-thirds of assessed stocks had a high (>75%) probability of being in the "healthy zone".
- All assessed shelf rockfish (Bocaccio, Canary, Redstripe, Silvergray, Widow, Yellowtail) and several slope rockfish increased in surveyed biomass over the last ~5 years.
- Surveyed biomass for several flatfish (Petrale, English, Rex, and Dover Sole) increased over the last 5–10 years but declined for Arrowtooth Flounder.
- Survey indices for North Pacific Spiny Dogfish stocks had the steepest declines across all stocks—particularly for inside Vancouver Island waters in 2021.

24.2. Introduction

DFO conducts a suite of randomized surveys using bottom trawl, longline hook, and longline trap gear that, in aggregate, cover Canada's Pacific Coast (Anderson et al. 2019). Synoptic trawl surveys in Queen Charlotte Sound (Areas 5A and 5B) and Hecate Strait (Areas 5C and 5D) are conducted in odd numbered years, while the West Coast of Vancouver Island (WCVI; Areas 3C and 3D) and the west coast of Haida Gwaii (WCHG; Area 5E) surveys are conducted in even numbered years. In addition, four biennial Hard Bottom Longline (HBLL) surveys are conducted, two in "inside" waters (east of Vancouver Island; Area 4B) and two in "outside" waters (everywhere else). Lastly, a coast-wide longline trap survey targeting sablefish is conducted every year and DFO collects biological information from the International Pacific Halibut Commission (IPHC) Setline Survey. In 2021, in addition to the usual odd numbered year surveys, the synoptic WCVI trawl survey and inside HBLL south surveys were conducted to make up for missing them in 2020 due to COVID-19. At the time of writing, the outside HBLL data are not yet available in DFO's survey databases.

Assessment scientists conduct regular stock assessments for major fish stocks in B.C. These assessments combine fishery-dependent data (such as commercial catches) with fishery-independent data (data from scientific surveys) to estimate quantities such as spawning stock biomass, growth and maturity, and to derive measures of fishing intensity and stock status. Stock status is typically assessed with respect to two reference points: (1) the Limit Reference Point (LRP), a "status below which serious harm is occurring to the stock"; and (2) the Upper Stock Reference Point (USR), which represents the "threshold below which removals must be progressively reduced in order to avoid reaching the LRP". While stock assessments represent the gold-standard of estimated trends in population status, assessments are time and labour intensive and therefore frequently lag behind high quality datasets such as indices of abundance from scientific surveys, which often closely reflect population trends from assessments. Geostatistical spatiotemporal models allow spatially adjacent areas surveyed in various years to be combined into single annual indices that can help track changes in surveyed abundance between assessments.

This year, we explored population trends for groundfish stocks using two methods: (1) we updated a hierarchical Bayesian state-space time-series model from last year (Anderson et al. 2021) to explore trends until the year 2021, and (2) we developed model-based indices from relevant surveys for all assessed stocks, as well as stocks with outstanding requests for Science Advice.

24.3. Methods

We gathered Bayesian posterior distributions of estimated biomass from assessments for 26 stocks, including five updated assessments (Yellowmouth Rockfish coastwide stock, Rougheye/Blackspotted Rockfish south and north stocks, Pacific Cod 5ABCD and 3CD stocks). We did not have access to the updated Bocaccio assessment data (DFO 2022a) at the time of writing and so included the projection from (DFO 2022a). From these distributions, we modelled overall (i.e., all stocks combined) mean log stock status as a latent random walk with individual stocks assumed to have an auto-regressive observation model with their 'true' status drawn from their stock-assessed posterior distribution. The approach is an extension of a model in Hilborn et al. 2020, to include uncertainty on stock status and implement the model in Stan (Carpenter et al. 2017); details are available in Anderson et al. 2021.

For these 26 stocks, as well as stocks with outstanding requests for Science Advice, and stocks with assessments that lacked the necessary posterior distributions for inclusion in the above model, we selected the relevant surveys (40 total stocks). We combined regional surveys that used the same gear and protocols (e.g., north and south outside HBLL surveys, or various synoptic trawl surveys). We then fit geostatistical models of biomass density with TMB (Kristensen et al. 2016) via the R package sdmTMB (Anderson et al. 2022). These models accounted for latent spatial factors with a constant spatial Gaussian random field and allowed spatiotemporal deviations to evolve as a Guassian random field random walk. For each stock–survey type combination, we fit both Tweedie and delta-gamma (binomial and gamma) observation error models and reported the model that produced the most precise index estimates on average; for most stocks (~80%), this was the delta-gamma model. We then predicted and summed biomass or abundance density across the appropriate 2 x 2 km survey grid(s) (e.g., Anderson et al. 2019) and scaled the survey index to the existing stock assessment biomass trend based on the geometric mean in overlapping years. Data and code to reproduce our analysis are available at https://github.com/pbs-assess/gftrends.

24.4. Status and trends

Across all stocks, there was a decline in average stock status until approximately 2000 (Figure 24-1). The late 1990s and early 2000s marked the beginning of a relatively stable average status. We estimated the overall mean B/LRP (biomass divided by the LRP) in 2021 to be 3.4 (95% CI: 2.8–4.1). The overall mean B/USR and B/B_{MSY} (biomass divided by biomass at maximum sustainable yield) in 2021 was 1.6 (95% CI: 1.3–2.0) and 1.4 (95% CI: 1.2–1.8), respectively (Figures 24-1 and 24-2). Despite the overall pattern in the average biological status, there was considerable variation within and across individual stocks, especially when recent survey trends are also considered (Figure 24-3).

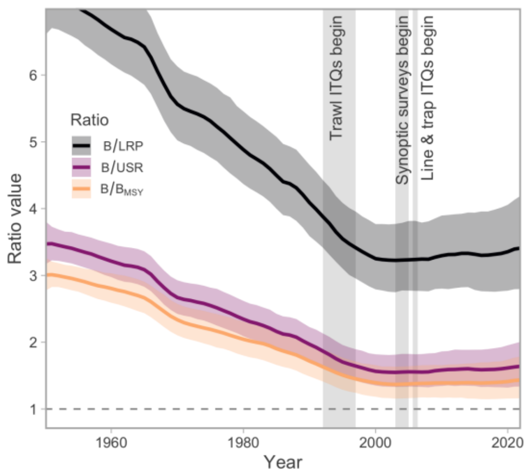


Figure 24-1. Overall mean biomass status across all stocks for B/LRP, B/USR, and B/B_{MSY} (see text for definitions) from the hierarchical time-series model. Dark lines represent the posterior median and shaded ribbons represent 95% quantile credible intervals. ITQ= individual transferable quota.

Estimated biomass was above the LRP and USR for most stocks as of the most recent assessment (Figure 24-2). Of the stocks with full posterior distributions available, 4B Lingcod was the only stock with $>$ 5% posterior density below its LRP as of its most recent assessment (Figure 24-2). Coastwide Bocaccio had $>$ 5% posterior density below the LRP in 2020 (DFO 2020a) but effectively 0% by 2021 after a large recruitment cohort in 2016 (DFO 2022a). Quillback Rockfish in both outside and inside waters had $>$ 5% posterior density below their LRPs as of the 2011 assessment, but the full posterior distribution was not available (quantiles shown in Figure 24-3). Pacific Cod in 3CD had a 0.02 probability B $<$ LRP in 2020. Considering the USR instead of the LRP, 8/23 of the stocks in Figure 24-2 had > 25% probability of being below their USR as of their most recent assessment.

When we used survey indices to explore more recent changes across species, additional patterns emerged. Survey indices for all assessed shelf rockfish (Bocaccio, Canary, Redstripe, Silvergray, Widow, Yellowtail), and some slope rockfish (e.g., Yellowmouth) increased in the past ~5 years (Figure 24-3). The survey indices also allowed us to explore surveyed population trends of species that have not yet received full assessments, such as many flatfish and Chondrichthyans. Most of the included flatfish (soles: Petrale, English, Rex, Dover Sole) appeared to increase in survey biomass over the last 5–10 years. However, the trawl survey index suggested that Arrowtooth Flounder have declined since the last assessment (Figure 24-3). Trends among the skates generally appeared stable or positive. North Pacific Spiny Dogfish (herein 'dogfish') stocks, however, experienced the steepest declines of all stocks (Figure 24-3), with a particularly steep decline in inside Vancouver Island waters in 2021.

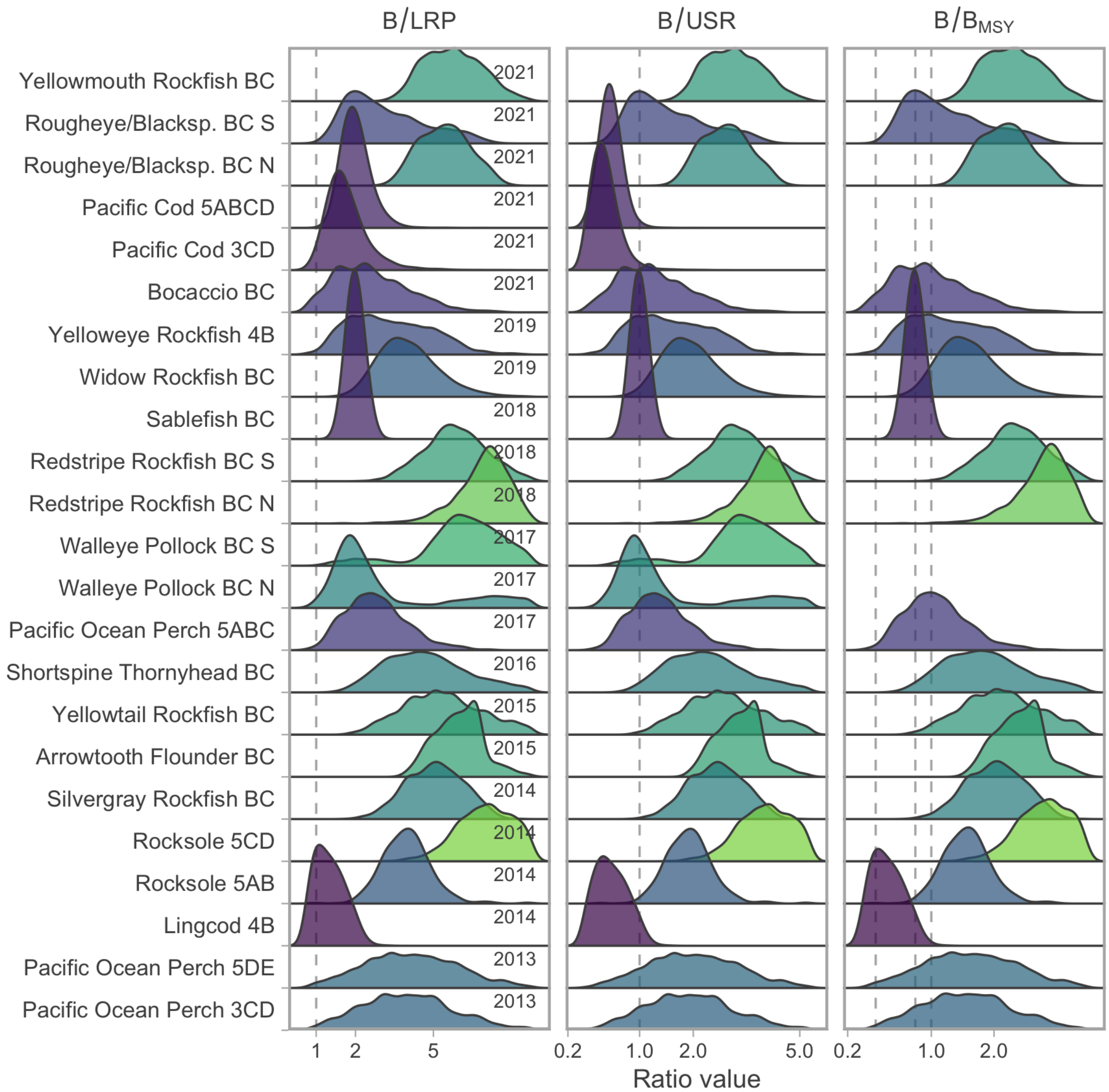


Figure 24-2. Posterior distribution of the three measures of stock status for 23 of the 26 stocks (Edwards et al. 2011, 2013; Edwards et al. 2014; DFO 2015, 2019, 2020a, 2020b, 2020c, 2020d, 2022b; Holt et al. 2016a, 2016b; Starr et al. 2016; Grandin and Forrest 2017; Starr and Haigh 2017, 2021a; DFO 2021; Starr and Haigh 2021b). Stocks are arranged in order of assessment with the most recent assessments at the top; years in the first column indicate the year the status represents. Colours represent the mean B/LRP value such that green is highest and purple is lowest. Stocks with missing data in the B/B_{MSY} column are assessments where historical reference points were used instead of MSY-based reference points. Vertical dashed lines are at values of 1.0 in all columns and also at values of 0.4 and 0.8 in the B/B_{MSY} column (0.4 and 0.8 B_{MSY} are provisional LRP and USR values). The x-axis has been square-root transformed to slightly compress high ratio values for visualization. In a few cases (e.g., Bocaccio) the status represents a one- or two-year projection from the last year of available data (DFO 2020a). The full posteriors were not available for Quillback or Canary Rockfish stocks, which are shown in Figure 24-3 (Stanley et al. 2009; Yamanaka et al. 2011).

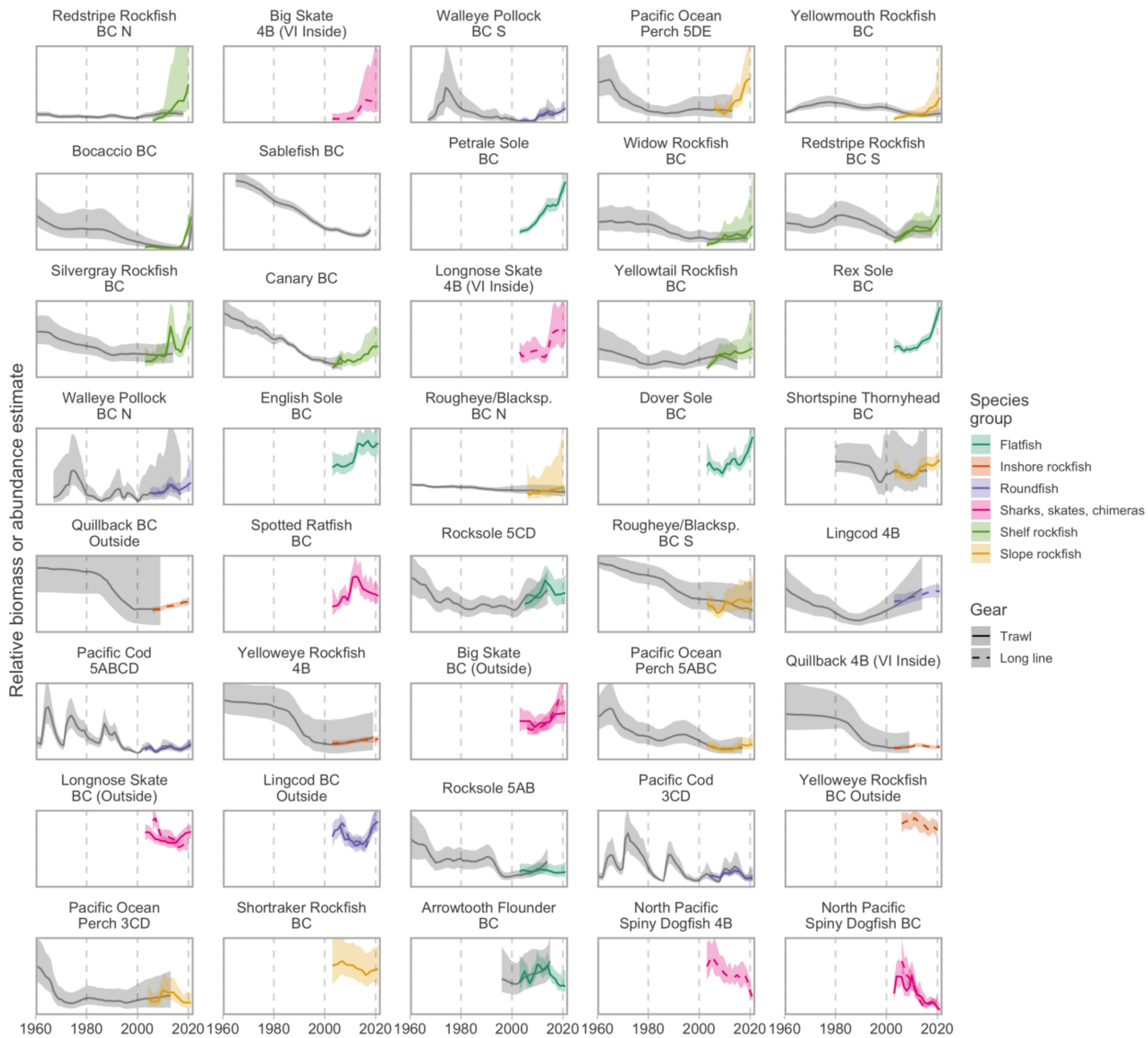


Figure 24-3. Trends in B.C. groundfish stocks with assessments in the last ~15 years or outstanding requests for Science Advice. Dark grey lines and ribbons represent output from stock assessments: trajectories of median B/LRP 95% quantile credible intervals (see citations in Figure 24-2 caption). Coloured lines and ribbons represent model-based indices for the most relevant survey(s) for each stock. Survey trends are scaled to existing assessments based on the geometric mean in overlapping years.

24.5. Factors influencing trends

The long term overall groundfish trend is likely to have been primarily influenced by fishery removals and management interventions. The transition from declining average B/LRP and B/USR to a relatively stable trajectory coincided with the implementation of individual transferable quotas (ITQs) for the trawl fleet, the introduction of 100% at-sea observer coverage over the period 1992–1997 (Turris 2000), and the initiation of the current synoptic trawl surveys in 2003. Furthermore, ITQs and electronic at-sea monitoring were introduced into the longline and trap fisheries in 2006 (Stanley et al. 2015).

Other patterns may be driven by species interactions and climatic effects. For example, dogfish are not currently heavily affected by any fishery, so the cause of their survey declines is unknown. One possibility is that climate change is driving a northward range shift or that seasonal distribution patterns have changed as seen in the northwest Pacific Ocean (Kanamori et al. 2022). For several species, there is evidence that temperature velocity—the pace a fish would have to move to maintain consistent temperature—may be related to a fine-scale redistribution of population density in Canadian Pacific waters (English et al. 2022). Effects of recent oceanographic conditions on spawning habitat are hypothesized to have led to years of low recruitment in some groundfish (e.g., Pacific Cod in nearby Alaskan waters, Laurel and Rogers 2020). On the other hand, after decades of consistently low recruitment, recent increases in several shelf rockfishes species—most notably Bocaccio—may in part by driven by transient availability of oxygen-rich water at depth during gestation (Schroeder et al. 2019; DFO 2022a).

24.6. Implications of those trends

The Sustainable Fisheries Framework and the Fish Stocks provisions of the *Fisheries Act* require that major fish stocks be maintained above their LRP with high probability. Three stocks had $>$ 5% probability of being below their LRP as of their last assessment. Roughly one-third of assessed stocks had $>$ 25% probability of being in the cautious zone where removals should be progressively reduced to avoid reaching the LRP. Rebuilding and precautionary management of stocks in the critical and cautious zones, respectively, should help ensure stock status improves over time in response to reduced fishing pressure and favourable environmental conditions if and when they occur.

24.7. Acknowledgements

We thank Rowan Haigh, Brendan Connors, Robyn Forrest, Chris Grandin, Dana Haggarty, and Kendra Holt for providing stock assessment output data and contributing to the initial version of the time series model (Anderson et al. 2021). We thank all those involved in coordinating and conducting the synoptic and longline surveys (especially Malcolm Wyeth, Norm Olsen, Maria Cornthwaite, and Dana Haggarty) as well as many others who have contributed to the collection of survey data that make analyses such as these possible.

24.8. References

Anderson, S.C., Connors, B.M., English, P.A., Forrest, R.E., Haigh, R., and Holt, K.R. 2021. Trends in Pacific Canadian groundfish stock status. bioRxiv. 2021.12.13.472502. doi: https://doi.org/10.1101/2021.12.13.472502.

Anderson, S.C., Keppel, E.A., and Edwards, A.M. 2019. A reproducible data synopsis for over 100 species of British Columbia groundfish. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/041: vii + 321 p.

Anderson, S.C., Ward, E.J., English, P.A., Barnett, L.A.K. 2022. sdmTMB: an R package for fast, flexible, and user-friendly generalized linear mixed effects models with spatial and spatiotemporal random fields. bioRxiv. 2022.03.24.485545. doi: https://doi.org/10.1101/2022.03.24.485545.

Carpenter, B., Gelman, A., Hoffman, M.D., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M., Guo, J., Li, P., and Riddell, A. 2017. Stan: A Probabilistic Programming Language. Journal of Statistical Software. 76(1): 1-32. https://doi.org/10.18637/jss.v076.i01.

DFO. 2015. Yellowtail Rockfish (*Sebastes Flavidus*) stock assessment for the coast of British Columbia, Canada. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/010.

DFO. 2019. Widow Rockfish (*Sebastes entomelas*) stock assessment for British Columbia in 2019. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/044.

DFO. 2020a. Bocaccio (*Sebastes paucispinis*) stock assessment for British Columbia in 2019, including guidance for rebuilding plans. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/025.

DFO. 2020b. Rougheye/Blackspotted Rockfish (*Sebastes aleutianus/melanostictus*) stock assessment for British Columbia in 2020. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/047.

DFO. 2020c. Evaluating the robustness of candidate management procedures in the BC Sablefsh (*Anoplopoma fimbria*) fishery for 2019–2020. DFO Can. Sci. Advis. Sec. Sci. Resp. 2020/025.

DFO. 2020d. Evaluation of management procedures for the inside population of Yelloweye Rockfish rebuilding plan in British Columbia. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/056.

DFO. 2021. Status update of Pacific Cod (*Gadus macrocephalus*) for West Coast Vancouver Island (area 3CD), and Hecate strait and Queen Charlotte sound (area 5ABCD) in 2020. DFO Can. Sci. Advis. Sec. Sci. Resp. 2021/002.

DFO. 2022a. Update of the 2019 Bocaccio (*Sebastes paucispinis*) stock assessment for British Columbia in 2021. DFO Can. Sci. Advis. Sec. Sci. Resp. 2022/001.

DFO. 2022b. Yellowmouth Rockfish (*Sebastes reedi*) Stock Assessment for British Columbia in 2021. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2022/001.

Edwards, A.M., Starr, P.J., and Haigh, R. 2011. Stock assessment for Pacific Ocean Perch (*Sebastes alutus*) in Queen Charlotte Sound, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/111: vi + 172 p.

Edwards, A.M., Haigh, R., and Starr, P.J. 2013. Pacific Ocean Perch (*Sebastes alutus*) stock assessment for the north and west coasts of Haida Gwaii, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/092: vi + 126 p.

Edwards, A.M., Haigh, R., and Starr, P.J. 2014. Pacific Ocean Perch (*Sebastes alutus*) stock assessment for the west coast of Vancouver Island, British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/093: vi + 135 p.

English, P.A., Ward, E.J., Rooper, C.N., Forrest, R.E., Rogers, L.A., Hunter, K.L., Edwards, A.M., Connors, B.M., and Anderson, S.C. 2022. Contrasting climate velocity impacts in warm and cool locations show that effects of marine warming are worse in already warmer temperate waters. Fish and Fisheries. 23(1): 239-255.

Grandin, C.J., and Forrest, R.E. 2017. Arrowtooth Flounder (*Atheresthes stomias*) stock assessment for the west coast of British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/25: v + 87 p.

Hilborn, R., Amoroso, R.O., Anderson, C.M., Baum, J.K., Branch, T.A., Costello, C., de Moor, C.L., Faraj, A., Hively, D., Jensen, O.P., Kurota, H., Little, L.R., Mace, P., McClanahan, T., Melnychuk, M.C., Minto, C., Osio, G.C., Parma, A.M., Pons, M., Segurado, S., Szuwalski, C.S., Wilson, J.R., and Ye, Y. 2020. Effective fisheries management instrumental in improving fish stock status. Proceedings of the National Academy of Sciences. 117(4): 2218–2224.

Holt, K.R., King, J.R., and Krishka, B.A. 2016a. Stock assessment for Lingcod (*Ophiodon elongatus*) in the Strait of Georgia, British Columbia in 2014. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/013: xi + 186 p.

Holt, K.R., Starr, P.J., Haigh, R., and Krishka, B. 2016b. Stock assessment and harvest advice for rock sole (*Lepidopsetta* spp.) In British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/009: ix + 256 p.

Kanamori, Y., Yano, T., Okamura, H., and Yagi, Y. 2022. Spatio-temporal model and machine learning method reveal process of phenological shift under climate change of North Pacific spiny dogfish. bioRxiv. 2022.03.01.482455. doi: https://doi.org/10.1101/2022.03.01.482455.

Kristensen, K., Nielsen, A., Berg, C.W., Skaug, H., and Bell, B.M. 2016. TMB: Automatic differentiation and Laplace approximation. Journal of Statistical Software. 70(5): 1–21.

Laurel, B.J., and Rogers, L.A. 2020. Loss of spawning habitat and prerecruits of Pacific cod during a Gulf of Alaska heatwave. Canadian Journal of Fisheries and Aquatic Sciences. 77(4): 644-650. NRC Research Press.

Schroeder, I.D., Santora, J.A., Bograd, S.J., Hazen, E.L., Sakuma, K.M., Moore, A.M., Edwards, C.A., Wells, B.K., and Field, J.C. 2019. Source water variability as a driver of rockfish recruitment in the California Current Ecosystem: Implications for climate change and fisheries management. Canadian Journal of Fisheries and Aquatic Sciences. 76: 950-960.

Stanley, R.D., Starr, P.J., and Olsen, N. 2009. Stock assessment for Canary rockfish (*Sebastes pinniger*) in British Columbia waters. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/013: xxii + 198 p.

Stanley, R.D., Karim, T., Koolman, J., and McElderry, H. 2015. Design and implementation of electronic monitoring in the British Columbia groundfish hook and line fishery: A retrospective view of the ingredients of success. ICES Journal of Marine Science. 72(4): 1230-1236.

Starr, P.J., and Haigh, R. 2017. Stock assessment of the coastwide population of Shortspine Thornyhead (*Sebastolobus alascanus)* in 2015 off the British Columbia coast. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/015: ix + 174 p.

Starr, P.J., and Haigh, R. 2021a. Redstripe Rockfish (*Sebastes proriger*) stock assessment for British Columbia in 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/014: vi + 340 p.

Starr, P.J., and Haigh, R. 2021b. Walleye Pollock (*Theragra chalcogramma*) stock assessment for British Columbia in 2017. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/004: vii + 265 p.

Starr, P.J., Haigh, R., and Grandin, C. 2016. Stock assessment for Silvergray Rockfish (*Sebastes brevispinis*) along the Pacific coast of Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/042: vi + 170 p.

Turris, B.R. 2000. A comparison of British Columbia's ITQ fisheries for groundfish trawl and sablefish: Similar results from programmes with differing objectives, designs and processes. Food and Agriculture Organization FAO Fisheries Technical Paper. (No. 404/1): 254–261.

Yamanaka, K.L., McAllister, M.K., Etienne, M.-P., and Flemming, R. 2011. Stock assessment and recovery potential assessment for Quillback Rockfish (*Sebastes maliger*) on the Pacific coast of Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/135: vii + 151 p.

25. DISTRIBUTION AND ABUNDANCE OF PACIFIC HAKE (*MERLUCCIUS PRODUCTUS*) FROM THE U.S.A.-CANADA JOINT ACOUSTIC-TRAWL SURVEY

Stéphane Gauthier[1], Chelsea Stanley[1], Andrew M. Edwards[2], and Chris J. Grandin[2]

[1] Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Stephane.Gauthier@dfo-mpo.gc.ca; Chelsea.Stanley@dfo-mpo.gc.ca
[2] Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, B.C., Andrew.Edwards@dfo-mpo.gc.ca; Chris.Grandin@dfo-mpo.gc.ca

25.1. Highlights

- The 2021 total survey estimate of Pacific Hake of 1.524 million t was slightly above the median of the time series, but lower than the previous survey estimate of 2019.
- Under 5% of the total estimated survey biomass was encountered in Canadian waters (the lowest of the survey time series), and the distribution of hake was limited and mostly confined to the southern end of west coast Vancouver Island.

25.2. Description of the time series

Pacific Hake ranges from southern California to northern B.C. (25-55° N). It is a migratory species that is thought to spawn mainly off of the southern to central California coast during January to March (Saunders and McFarlane 1997). Adult Pacific Hake then migrate north in the spring and, by the summer, can be detected in large aggregations from northern California to the northern end of British Columbia, with distributions sometimes exceeding these boundaries. Size and age generally increase with increasing latitude during the migratory season. The populations of Pacific Hake found in the Strait of Georgia and Puget Sound are genetically distinct and not included in this survey (Iwamoto et al. 2004; King et al. 2012).

The Pacific Hake fishery is one of the largest fisheries on the west coast of the U.S. and Canada, and is Canada's largest commercial wild fishery (by volume). The joint U.S. and Canadian integrated acoustic-trawl survey is the primary fishery-independent source of data used to assess the distribution, abundance and biology of the Pacific Hake population (see Edwards et al. 2022). The survey was completed on a triennial basis during 1995-2003, when the decision to switch to a biennial basis was made; there was an additional survey in 2012.

The acoustic survey typically starts in southern California in mid-June and progresses northward in a continuous and uninterrupted sequence, ending in northern Canada in early September. The survey design consist of E-W transects from the 50 m to the 1500 m isobaths, or beyond if signals extend beyond this limit. The transects are 10-20 nmi apart. Acoustic marks are targeted with a midwater trawl to assess species composition and collect biological samples. Backscatter values assigned to Pacific Hake are interpolated between transects using kriging to obtain an overall estimate of abundance for the entire coast. Using the biological information gained from the midwater trawls, the backscatter is scaled to biomass using the fish length to target strength relationship (Traynor 1996).

25.3. Status and trends

The 2021 survey encountered several issues related to vessel problems and COVID-19 restrictions and protocols, which prevented survey continuity from South to North. There were gaps in timing (of more than 7 days) between some adjacent transects (off Newport OR and Barkley Sound, Vancouver Island), and some areas were surveyed simultaneously (Washington coast and northern Canada). These issues may have introduced bias (double counting of aggregations, or missed aggregations), and added uncertainty to the survey results. Distribution of Pacific Hake has been variable over the history of the survey, with the widest distribution seen in 1998. In 2021, the distribution in Canadian waters was mostly confined off the southern end of west coast Vancouver Island, with a few aggregations observed off western Hecate Strait, which may have been a local stock from Milbanke Sound, but this will need confirmation from genetic sample analyses (Figure 25-1). The 2021 estimated total biomass of 1.524 million tons was higher than the median of the time series but lower than the previous survey of 2019 (Figure 25-2). Catch data from the survey indicated a dominance of the 2017, 2016, 2014 and 2010 year classes. No age-1 (nor age-0) Pacific Hake were observed in Canadian waters. Less than 5% of the estimated biomass of adult Pacific Hake (age-2+) from the survey was observed in Canadian waters, the lowest proportion (and lowest biomass) of the time series (Figure 25-2).

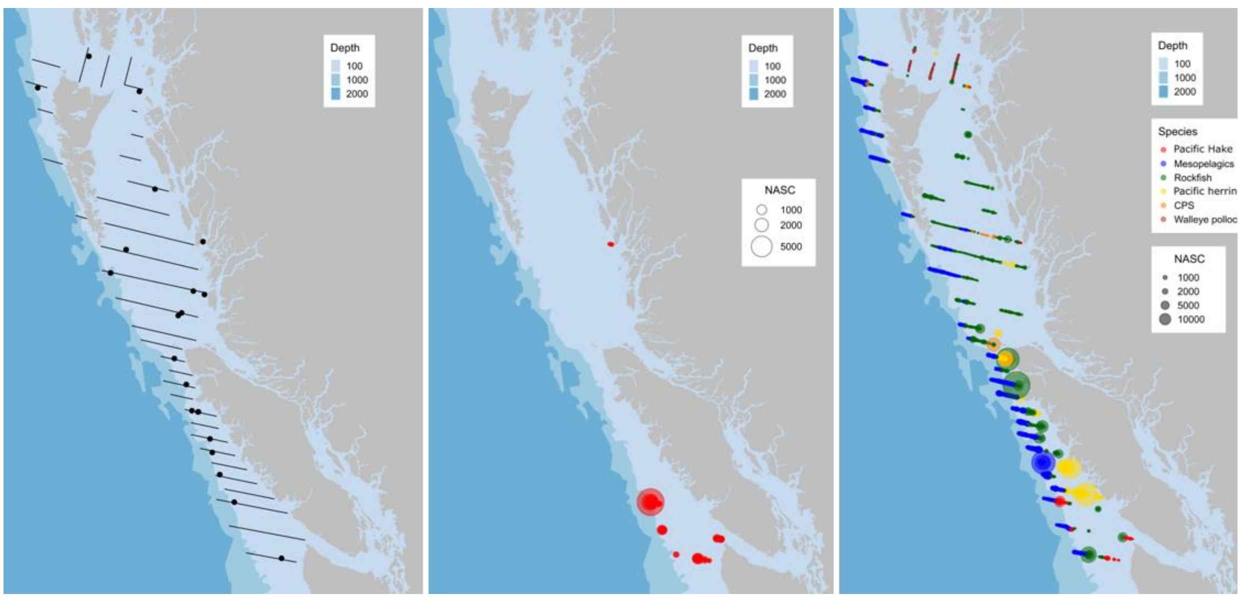


Figure 25-1. Map of acoustic transects and midwater trawl locations (black circles) for the Canadian portion of the survey (left panel), Nautical Area Scattering Coefficients (NASC, m^2nmi^{-2}) of detected Pacific Hake aggregations (central panel), and NASC of other pelagic species observed (right panel).

Assessment results show how the Pacific Hake population is characterized by occasional large recruitment events with many years of very low recruitment (Figure 25-3). The inclusion of the age-1 index from the 2021 survey allowed the assessment model to estimate that the 2020 recruitment was likely above average, and potentially very large (Figure 25-3).

Figure 25-2. Survey estimated biomass of adult (age 2+) Pacific Hake (Merluccius productus) in Canadian and U.S.A. waters from 1995 to 2021.

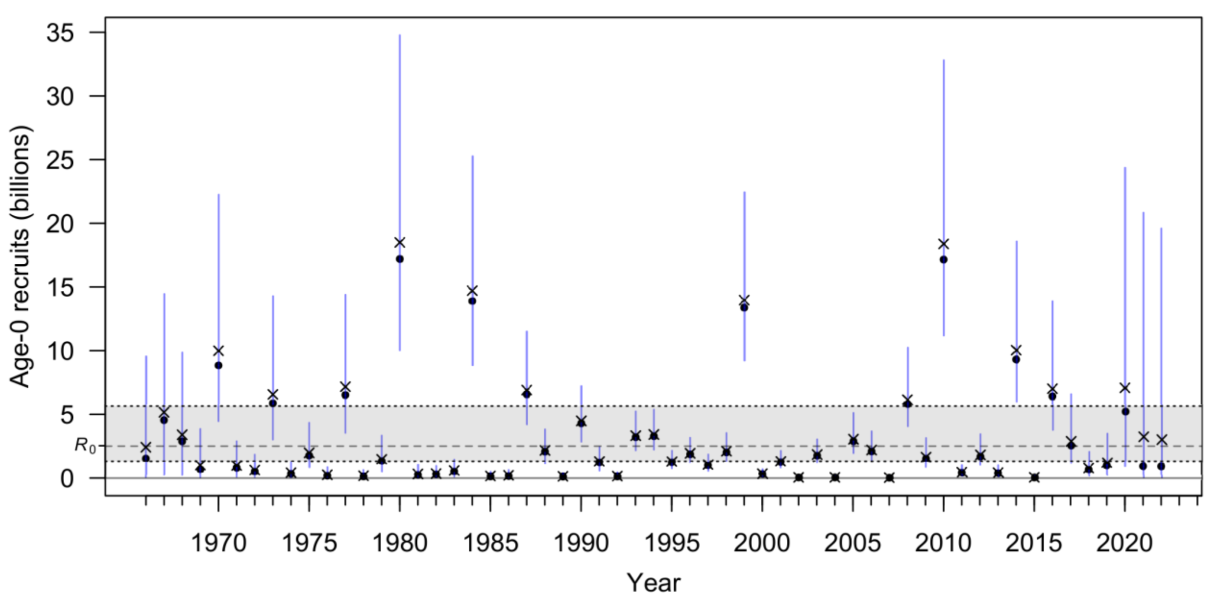


Figure 25-3. Recruitment of Pacific Hake (billions of age-0 fish) as estimated from the stock assessment model (Figure f of Edwards et al. 2022), shown as medians (solid circles), means (×) and 95% credible intervals (blue lines). The median of the posterior distribution of the mean unfished equilibrium recruitment (R_0) is shown as the horizontal dashed line with the 95% posterior interval shaded between the dotted lines.

25.4. Factors influencing trends

It has been observed that during warm ocean conditions (such as the 1998 El Niño event) a larger proportion of the stock migrates into Canadian waters, apparently due to intensified northward transport (Agostini et al. 2006). This was also observed in 2015 (with the so-called warm ”Blob”), although the distribution did not extend much beyond the northern tip of Vancouver Island. The proportion of Pacific Hake that migrated into Canadian waters in 2017 was over 27% and the largest observed since 2005, while in 2019 the proportion in Canadian waters was only of 11%. In 2021 this proportion was less than 5% and the lowest of the time series. There were also no aggregations recorded off the north end of west coast Vancouver Island, and very little (if any) recorded further north. These observations are in line with the prevailing La Niña conditions for 2021 and the somewhat return to cooler (or pre-Blob) conditions. For other pelagic species, high acoustic backscatter for Pacific Herring (*Clupea pallassi*) were recorded off southern/central west coast Vancouver Island, while pelagic rockfish species (*Sebastes* spp.) were recorded in high numbers off the northern end of west coast Vancouver Island and throughout Hecate Strait and the west coast Haida Gwaii. A sizeable population of Walleye Pollock (*Theragra chalcogramma*) was recorded in Dixon Entrance (Figure 25-1). New time series of abundance and distribution for these species are being developed from the Pacific Hake historical surveys. These trends and observations emphasize the need for more research into the links between environmental variables and the distribution and migration of Pacific Hake and associated fauna.

25.5. Implications of those trends

During the strong El Niño of 1998, Pacific Hake extended well into Alaska, but during recent warming events the distribution was retracted and confined mostly to the west coast of Vancouver Island. These trends suggest that temperature alone may not be a good predictor of Pacific Hake northward migration extent, but that other mechanisms (such as the source and onset of the warming conditions) have differential effects on poleward currents, distribution and availability of prey, or other factors influencing the distribution of these fish. This points to the need for more research on Pacific Hake movements. Efforts focusing on these topics are currently underway.

25.6. References

Agostini, V.N., Francis, R.C., Hollowed, A., Pierce, S.D., Wilson, C.D., and Hendrix, A.N. 2006. The relationship between Pacific hake (*Merluccius productus*) distribution and poleward subsurface flow in the California Current system. Canadian Journal of Fisheries and Aquatic Sciences. 63: 2648-2659.

Edwards, A.M., Berger, A.M., Grandin, C.J. and Johnson, K.F. 2022. Status of the Pacific Hake (whiting) stock in U.S. and Canadian waters in 2022. Prepared by the Joint Technical Committee of the U.S. and Canada Pacifc Hake/Whiting Agreement, National Marine Fisheries Service and Fisheries and Oceans Canada. 238 p. https://media.fisheries.noaa.gov/2022-02/2022-hake-assessment-post-srg.pdf

Iwamoto, E., Ford, M.J., and Gustafson, R.G. 2004. Genetic population structure of Pacific hake, *Merluccius productus*, in the Pacific Northwest. Environmental Biology of Fishes. 69: 187-199.

King, J.R., McFarlane, G.A., Jones, S.R.M., Gilmore, S.R., and Abbott, C.L. 2012. Stock delineation of migratory and resident Pacific hake in Canadian waters. Fisheries Research. 114: 19-30.

Saunders, M.W., and McFarlane, G.A. 1997. Observation on the spawning distribution and biology of offshore Pacific hake. Calif. Coop. Oceanic Fish. Invest. Rep. 38: 147-160.

Traynor, J.J. 1996. Target-strength measurements of walleye pollock (*Theragra chalcogrammma*) and Pacific whiting (*Merluccius productus*). ICES Journal of Marine Science. 53: 253-258.

26. SEABIRD OBSERVATIONS ON THE OUTER B.C. COAST IN 2021

Mark Hipfner

Environment and Climate Change Canada, Wildlife Research Division, Pacific Wildlife Research Centre, Delta, B.C., Mark.Hipfner@canada.ca

26.1. Highlights

- Diets fed to nestling Cassin's Auklets on Triangle Island included substantially less of the subarctic copepod *Neocalanus cristatus*, their most important prey, than expected from the negative PDO in the 6 months preceding the breeding season.
- Diets fed to nestling Rhinoceros Auklets on Pine island and Lucy Island were dominated by Pacific Sand lance and Pacific Herring, perhaps indicative of a return to more favourable conditions that existed prior to the Blob.

26.2. Description of the time series

Annually since 1996, Environment Canada and Fisheries and Oceans Canada has monitored the diets of Cassin's Auklet (*Ptychoramphus aleuticus*) nestlings on Triangle Island as indicator of survival as well as zooplankton prey availability (Hipfner et al. 2020). Note that due to COVID, sampling was limited to late June in 2021; therefore, analyses include only data collected in late June in all years.

In addition, scientists have been annually quantifying predation by Rhinoceros Auklets (*Ptychoramphus aleuticus*) on fish, including salmon smolts, since 2006 as an indicator of seabird feeding success and salmon mortality (Tucker et al. 2016). Nestling diets in 2021 were quantified at Pine, Lucy, Triangle, Cleland islands, and at S'Gang Gwaay, and in the U.S., collaborators quantified diets on Protection Island.

26.3. Status and Trends

<u>Diets fed to Cassin's Auklet nestlings</u>

In 2021, the representation of *N. cristatus* in Cassin's Auklet nestling diets was well below what would be expected from PDO based on the existing relationship for 1996-2019 (Figure 26-1).

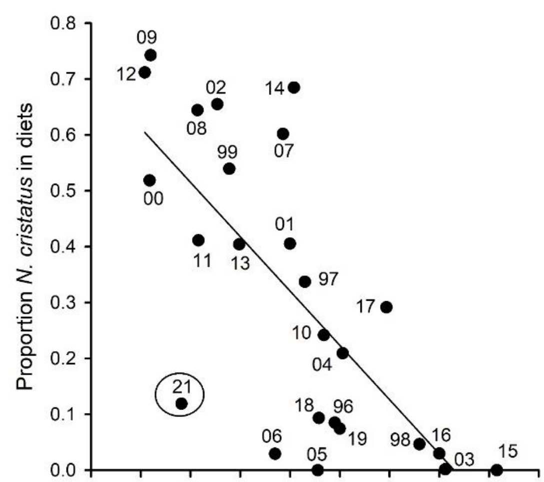


Figure 26-1. Proportion of Neocalanus cristatus in diets fed to nestling Cassin's Auklets in late June as a function of the PDO,1996 to 2019.

Diets fed to Rhinoceros Auklet nestlings

In 2021, diets fed to nestling auklets on two colonies in B.C., Pine Island (in southern Queen Charlotte Sound) and Lucy Island (in Chatham Sound), were dominated by Pacific Sand Lance (*Ammodytes personatus)* and Pacific Herring (*Clupea pallasii*) (Figure 26-2). Comparison with an existing time series (2006-2019) indicates that this might indicate a return to more favourable conditions such as existed over the several years prior to the arrival of the Blob.

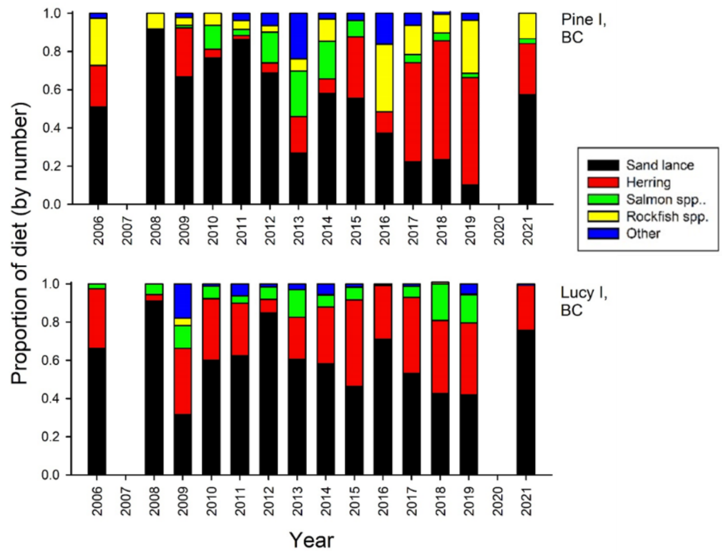


Figure 26-2. Species composition (by number) of the diets delivered to nestling Rhinoceros Auklets on 2 colonies in B.C. in 2006-2021.

26.4. Factors influencing trends

The zooplankton-based diets fed to nestling Cassin's Auklets on Triangle Island, the world's largest breeding colony, are affected very strongly by oceanographic conditions, which have a profound influence on seasonal patterns of prey availability. In general, nestling auklets grow more quickly on Triangle Island in cold-water, PDO-negative years when the subarctic copepod *N. cristatus* is abundant in offshore waters and persists in their diets through the bulk of the provisioning period from mid-May to late June (Hipfner et al. 2020).

The fish-based diets fed to nestling Rhinoceros Auklets on colonies in B.C. are also affected by oceanographic conditions (Thayer et al. 2008). In general, nestling auklets grow more quickly in years in which their diets include more Pacific Sand Lance, a small forage fish (Borstad et al. 2011).

26.5. Implications of those trends

Lower proportions of the subarctic copepod *N. cristatus* in diets of Cassin's Auklet nestlings may result in lower growth rates. Low growth rates of nestlings will translate to low survival and lower population growth.

On their northerly seaward migration, the vast majority of Pink Salmon (*O. gorbuscha*), Chum Salmon (*O. keta*) and Sockeye Salmon (*O. nerka*) smolts from stocks in southern and central B.C. funnel past aggregations of hundreds of thousands of Rhinoceros Auklets breeding on colonies scattered along the province's Central and North coasts. The auklets are wing-propelled, pursuit-diving seabirds that forage mainly in the top 5-10 m of the water column and within ~90 km of their breeding colonies. The smolts' migration occurs in June and July, coinciding with the period when the auklets are delivering whole and intact fish, including salmon smolts, to their nestlings. These predators could potentially have an impact on salmon survival.

26.6. References

Borstad, G., Crawford, W., Hipfner, J.M., Thompson, R. & Hyatt, K. 2011. Environmental control of the breeding success of rhinoceros auklets at Triangle Island, British Columbia. Mar. Ecol. Progr. Ser. 424: 285-302.

Hipfner, J.M., Galbraith, M., Bertram, D.F. & Green, D.J. 2020. Basin-scale oceanographic processes, zooplankton community structure, and diet and reproduction of a sentinel North Pacific seabird over a 22-year period. Prog. Oceanogr. 182: 102290.

Thayer, J.A., Bertram, D.F., Hatch, S.A., Hipfner, J.M., Slater, L, Sydeman, W.J., and Watanuki, Y. 2008. Forage fish of the Pacific Rim as revealed by diet of a piscivorous seabird: synchrony and relationships with sea surface temperature. Can. J. Fish. Aquat. Sci. 65: 1610–1622.

Tucker, S., Hipfner, J.M., and Trudel, M. 2016. Size- and condition- dependent predation: a seabird disproportionately targets substandard individual juvenile salmon. Ecology. 97(2): 461-471.

27. ABUNDANCE, DISTRIBUTION AND DENSITY OF CETACEANS FROM SHIP-BASED SURVEYS IN PACIFIC CANADIAN WATERS

Thomas Doniol-Valcroze, Linda Nichol, Brianna Wright, Eva Stredulinsky, Lisa Spaven and Robin Abernethy, Cetacean Research Program, Pacific Biological Station, Fisheries and Oceans Canada, Nanaimo, B.C., Thomas.Doniol-Valcroze@dfo-mpo.gc.ca.

27.1. Highlights

- Many cetacean species were depleted in Canadian Pacific waters by commercial whaling, which ended in 1967. Although some populations have since shown evidence of recovery, there is limited information about the current abundance and geographic distribution of many species, particularly in difficult-to-survey offshore regions.
- The Pacific Region International Survey of Marine Megafauna (PRISMM) was conducted between July 4 – September 5, 2018, using two Canadian Coast-Guard vessels, and resulted in 2,800 sightings of 20 marine mammal species.
- Resulting abundance and density estimates, compared to past studies and historical whaling data, show the extent of recovery of previously harvested populations. The return of these predators to habitats from which they were previously extirpated will likely have important ecosystem-level implications.

27.2. Description of the time series

Systematic surveys were conducted by non-government researchers in B.C.'s coastal waters during 2004 – 2008, to estimate abundance of ten marine mammal species (Best et al. 2015). For most cetaceans, however, abundance estimates are not current (>10 yr old) or are lacking altogether, especially in offshore areas. Therefore, there was no information available to estimate trends over time. To fill that gap, the Pacific Region International Survey of Marine Megafauna (PRISMM), a multi-species, ship-based, systematic line transect survey, was conducted between July 4 and September 5, 2018 to estimate current abundance and distribution of cetacean species in Canadian Pacific waters.

27.3. Status and trends

Density and abundance were estimated for nine cetacean species using either standard line transect analyses or density surface modelling, and were corrected for availability of animals at the surface taking into account each species' diving behaviour. Maps of modelled distribution were produced for the four most commonly-encountered species (Humpback Whales, Fin Whales, Dall's and Harbour Porpoises).

Trends were examined for species with enough information. The total abundance estimate for Humpback Whales in 2018 in Pacific Canadian waters was 12,116 (95% CI 8,070 – 18,189). This includes the offshore area (~8,500 whales) for which no previous abundance estimate was available, and where the vast majority of sightings were made on the continental shelf off the west coast of Vancouver Island (Figure 27-1). The abundance for the Central Coast was ~3,300, which can be compared to the earlier estimate of 1,540 in the same strata based on survey data collected between 2004-2008 (Best et al. 2015), which shows that Humpback

Whales have continued to reoccupy and expand their range within B.C. waters. Moreover, earlier systematic surveys did not detect any Humpback Whales in the Salish Sea whereas 2018 abundance was estimated at ~360 in that region, indicating that Humpback Whales have expanded into an area from which they were still largely absent in the early 2000's.

Previous surveys (2004-2008) had estimated a total of 329 (95% CI= 274-395) Fin Whales for the North Coast stratum (Best et al. 2015), whereas the PRISMM sightings produced a lower abundance estimate of 161 Fin Whales (Figure 27-2; although with a wide 95% CI of 64-407), suggesting a possible decline in recent years. Prior to PRISMM, there were no available estimates of abundance for Fin Whales in the offshore areas of Pacific Canadian waters. Aerial surveys conducted in 2012-2015, however, found that Fin Whales off of the west coast of Vancouver Island were more likely to be encountered in deeper water to the west of the continental shelf break. Fin Whale distribution predicted by spatial models of PRISMM data indicates a similar pattern (Figure 27-2), with more individuals located immediately west of the shelf break, for an estimated abundance of 2,732 (95% CI 2,044 – 3,651).

Dall's Porpoise abundance in the North Coast stratum was estimated at 5,303 (95% CI = 4,638-6,064), which is very similar to the estimates from previous surveys, suggesting limited population growth or immigration from other areas during the previous 10 years. Similarly, the estimated abundance of 6,147 Harbour Porpoises in the coastal strata (with an additional 1,015 in the offshore area) is similar to the 6,631 porpoises estimated in previous studies for the 2004-2008 period, and the different surveys have mostly identified the same high-density areas.

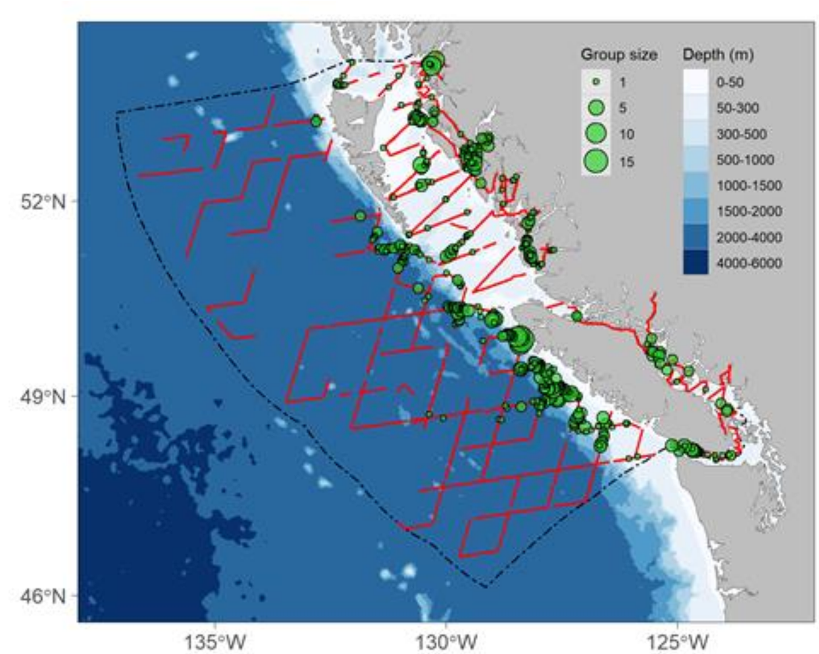


Figure 27-1. Sightings of Humpback Whales (green circles) made in 2018 during PRISMM. Red lines indicate realized survey lines and black dashed lines show the extent of the survey area.

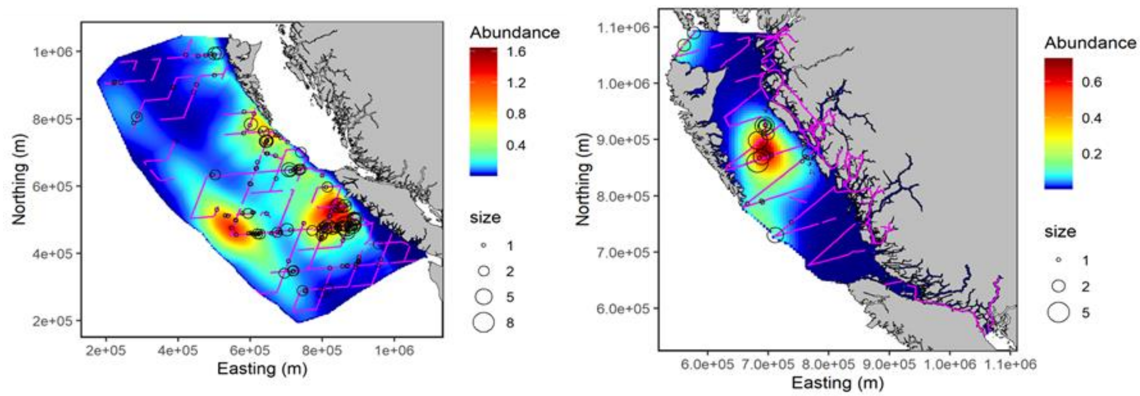


Figure 27-2. Estimated densities (fill colour indicates the number of individuals per 25 km² grid cell) of Fin Whales in the offshore (left) and north coast (right) strata, based on model predictions. Sighting locations for Fin Whales used in the model are indicated by the open circles (group size is denoted by relative circle size). Visual effort track lines are indicated by the magenta lines.

27.4. Factors influencing trends

Humpback and Fin whales were depleted by commercial whaling in the North Pacific over the period 1870 – 1967. Following their protection from exploitation, the Humpback Whale population at the ocean basin scale has increased at rates of 8% per year. This increase in overall numbers and the reoccupation of historical habitat along B.C. shores are the factors underlying the dramatic increase of Humpback Whale sightings in Pacific Canadian waters over the last twenty years. The factors influencing the trends of other species, such as Fin Whales and porpoises, are not known but are likely linked to prey abundance and availability, as well as sources of anthropogenic mortality (ship strikes and entanglement in fishing gear).

27.5. Implications of those trends

Several populations of marine mammal in Pacific Canadian waters have shown strong recovery trends and are once again important components of marine ecosystems (Calambokidis and Barlow 2020; Shields et al. 2018) resulting in increased overlap with human activities and potential conflicts with fisheries. The return of these predators to habitats from which they were previously extirpated (or at low numbers) may have important ecosystem-level implications. For instance, Humpback Whales consume large amounts of biomass (zooplankton and forage fish) and may have impacts on fish populations. Their increased presence and abundance in coastal waters also increases the risk of ship strikes and entanglement.

27.6. References

Best, B.D., Fox, C.H., Williams, R.W., Halpin, P.N., and Paquet, P.C. 2015. Updated marine mammal distribution and abundance estimates in British Columbia. Journal of Cetacean Research and Management. 15: 9-26.

Calambokidis, J. and Barlow, J. 2020. Updated abundance estimates for blue and humpback whales along the U.S. West Coast using data through 2018, U.S. Department of Commerce, NOAA Technical Memorandum. NMFS-SWFSC-634.

Shields, M.W., Hysong-Shimazu, S., Shields, J.C. and Woodruff, J., 2018. Increased presence of mammal-eating killer whales in the Salish Sea with implications for predator-prey dynamics. PeerJ. 6, p.e6062.

Wright, B.M., Nichol, L.M., Doniol-Valcroze, T. 2021. Spatial density models of cetaceans in the Canadian Pacific estimated from 2018 ship-based surveys. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/049. iii + 46 p.

28. A PROPOSED MONITORING FRAMEWORK FOR THE SGAAN KINGHLAS-BOWIE SEAMOUNT MARINE PROTECTED AREA: RESEARCH DOCUMENT

Cherisse Du Preez[1], Skil Jáada (Vanessa Zahner)[2], Laís Chaves[2], and Heidi Gartner[1]

[1]Fisheries and Oceans Canada (DFO), Pacific Region, B.C., Cherisse.Dupreez@dfo-mpo.gc.ca Heidi.Gartner@dfo-mpo.gc.ca
[2]Council of the Haida Nation (CHN), Haida Gwaii, B.C., mpp.marine.bio@haidanation.com lais.chaves@haidanation.com

28.1. Highlights

- Our DFO and CHN science team completed the SGaan Kinghlas-Bowie Marine Protected Area (SK-B MPA) Monitoring Framework Research Document and the Canadian Scientific Advisory Secretariat (CSAS) meeting in May 2022.
- During the 2018 North Pacific Seamount expedition, we established dozens of potential monitoring sites with markers and surveyed them using high-resolution photography and a CTD. During the 2021 expedition, we completed our first repeat surveys (5 sites on Dellwood Seamount). During the upcoming 2022 expedition, we are prioritizing repeat surveys of the 17 sites established on the SK-B MPA seamounts.

28.2. Description of time series

In recognition of their ecological and cultural significance, SK-B and its two sister seamounts were designated by the Haida Nation as a **Xaads siigee tl'a damaan tl'a king giigangs** *Haida MPA* in 1997 and by the Canadian Government as an *Oceans Act MPA* in 2008. The SK-B MPA Management Plan was completed in July 2019 by the Management Board (CHN and DFO 2019). On behalf of the Management Board, DFO Oceans requested that DFO Science provide science advice related to indicators, protocols, and strategies to support the development of the Monitoring Plan. The Monitoring Framework was reviewed at the CSAS meeting, May 3rd to 5th, 2022 (Du Preez et al. in progress).

The CSAS Research Document builds on the six ecological Operational Objectives of the Management Plan, the Ecological Risk Assessment Framework (DFO 2015), identified representative seamount areas (DFO 2021a), and existing DFO Monitoring Frameworks (e.g., DFO 2021b). For the purpose of the CSAS, we assigned each of the identified Significant Ecosystem Component (SEC) species and habitats groups to four higher-level groupings (cold-water coral and sponges, invertebrates, fishes, and sensitive benthic habitats) and 17 lower-level biological indicator groupings based on phylogeny, morphology, life-history traits, and habitat preference (e.g., gorgonian coral, glass sponges, mobile invertebrates, shallow benthic fish, macroalgae). In addition to the biological indicators, we proposed 16 biological, chemical, and physical oceanographic indicators. Based on the 33 indicator groupings, we then discussed appropriate metrics, protocols, and strategies.

In the absence of a dedicated long-term monitoring plan or strategy, existing data from SK-B MPA are from individual surveys supporting a diverse range of science and management objectives. We anticipate some of these data will be incorporated into time series for baseline and monitoring management effectiveness. However, analyses are ongoing or still in the planning phase. For example, in 2018, DFO and CHN led an expedition to SK-B MPA. They initiated pilot studies for monitoring indicators and protocols (e.g., established 17 long-term monitoring sites on the seafloor) (Gartner et al. 2022). The team is planning a return expedition in June 2022 to conduct repeat surveys. In summer 2021, the same team successfully completed their first repeat surveys of monitoring sites on Dellwood Seamount (established as part of the same pilot study; within the Area of Interest for a second seamount-focused MPA in the Offshore Pacific Bioregion) (Figure 28-1).

28.3. Status and trends

The focus of the 2022 CSAS was ecological performance monitoring of the SK-B MPA, including the proposed indices, protocols, and strategies for baseline and time series data.

Ecological analyses of the 2018 and 2021 Dellwood high-resolution photo-mosaics are in progress. Preliminary investigations indicate no notable differences between years in biological metrics such as community composition, abundance, distribution, the ratio of living and dead—with individual organisms unchanged in size, shape, and condition (Figure 28-1). A notable characteristic of the sites is their high proportion of dead sponges.

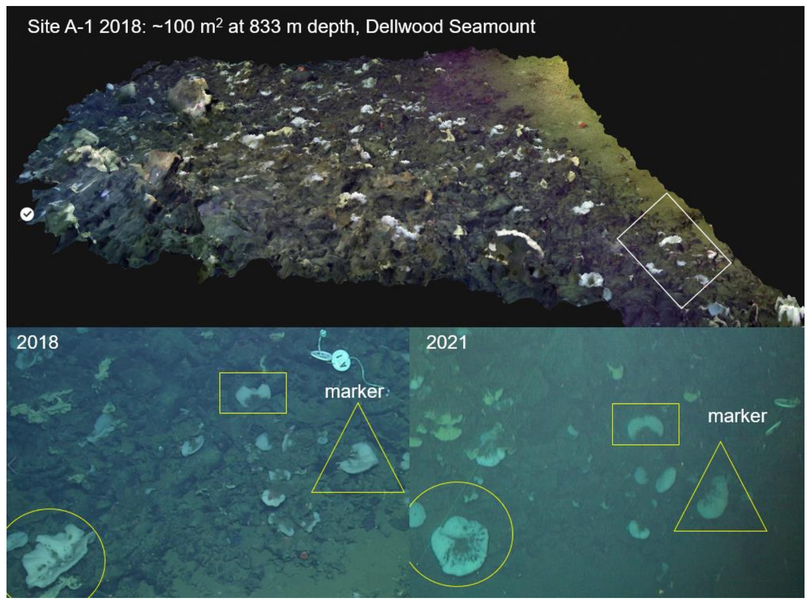


Figure 28-1. A high-resolution 3D photo-mosaic of the 10 m by 10 m monitoring site A1 at 833 m on Dellwood Seamount (within the severely hypoxic zone, <0.5 ml/l O_2). The area is largely rock covered in dead sponges (dark brow) and patches of living glass sponges (white). Individual organisms can be tracked for changes over time. Mosaics were processed and provided by Georgia Clyde (DFO Pacific Region, MSEA).

28.4. Factors influencing trends

SK-B MPA seamounts were heavily fished with destructive bottom-contact gear for decades before the 2018 fisheries closure. Therefore, adversely impacted SECs are either in a post-disturbance “lag” or “recovery” phase. While there is the potential for recovery, ongoing and future human pressures may still cause degradation (e.g., climate change).

Many of the 2018 seamount monitoring sites were strategically established at transitional zones associated with the region’s Oxygen Minimum Zone, between 480 and 1,700 m depth. While glass sponges are known to tolerate low oxygen, the oxygen concentrations may be approaching fatal levels due to climate change (with a 15% decrease in oxygen in the past 60 years; Ross et al. 2020). Sponges and other deep-sea animals tend to be long-lived and slow-growing. As a result, the lag phase between a disturbance (e.g., fatal oxygen levels) and a detectable response (e.g., change in condition or abundance) may be years to centuries and require multiple generations to play out in their entirety.

28.5. Implications of those trends

The majority of the proposed biological indicators in the Research Document have long generation times (e.g., sponges can live decades and corals can live centuries). If changes beyond the range of the natural state are occurring (e.g., recovery from fisheries or degradation from climate change), the timelines required to detect significant changes will likely be in the order of decades to centuries. In comparison, some of the proposed oceanographic indicators change relatively quickly and, therefore, may be helpful in predicting future biological responses.

There will be a need for variable frequencies of long-term monitoring strategies for different indicators—all of which will require baseline data to resolve. The Monitoring Plan should consider valuable existing long-term time series (e.g., Line P), schedule regular benthic visual surveys (e.g., North Pacific seamount surveys), add new sites to existing programs (e.g., new biological oceanography sites), and prioritize the use of non-destructive tools and feasible strategies (e.g., visual surveys, water sampling, satellite data).

The SK-B MPA Management Plan appropriately focuses on the removal or reduction of human activities that do not align with the protection and conservation objectives. Unfortunately, stressors outside the control of regional spatial management will likely result in the continued degradation of seamount ecosystem health and function.

28.6. References

CHN and DFO. 2019. SGaan Kinghlas–Bowie Seamount Gin siigee tl’a damaan kinggangs gin k’aalaagangs Marine Protected Area Management Plan. 2019. 45 p.

DFO. 2015. Application of an ecological risk assessment framework to inform ecosystem-based management for SGaan Kinghlas-Bowie Seamount and Endeavour Hydrothermal Vents Marine Protected Areas. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/037.

DFO. 2021a. Identification of Representative Seamount Areas in the Offshore Pacific Bioregion, Canada. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2021/041.

DFO. 2021b. A National Monitoring Framework for Coral and Sponge Areas Identified as Other Effective Area-Based Conservation Measures. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2021/048.

Du Preez, C. Skil Jáada (Zahner, V.), Gartner, H., Chaves, Laís; Hannah, C., Swan, K., and Norgard, T. (in progress). Proposed Monitoring Framework For SGaan Kinghlas-Bowie Seamount Marine Protected Area, British Columbia, Canada. *CSAP Working Paper* 2016OCN03.

Gartner, H., Norgard, T., Yakgujanaas, J., Rangeley, R., Leith, M., MacIntosh, H., Du Preez, C. 2022. Pacific Seamounts 2018 Expedition Report (Pac2018-103 & NA097). Can. Tech. Rep. Fish. Aquat. Sci. 3460: ix + 147 p.

Ross, T., Du Preez, C. and Ianson, D., 2020. Rapid deep ocean deoxygenation and acidification threaten life on Northeast Pacific seamounts. Global change biology. 26(11): 6424-6444.

29. UNUSUAL EVENTS IN CANADA'S PACIFIC MARINE WATERS IN 2021

Jennifer L. Boldt[1], R. Ian Perry[1], Peter C. Chandler[2]

[1]Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, B.C., Jennifer.Boldt@dfo-mpo.gc.ca
[2]Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C.

29.1. Highlights

- Unusual events occur in Canada's Pacific marine waters every year but are often not reported or related to the broader environmental context.
- Some unusual events in 2021 that were reported include: 105 containers fell overboard and are still missing from the container ship MV Zim Kingston; a heatwave in June killed millions of intertidal animals; there were more observations of emaciated, dead grey whales. In 2021 and early 2022, there were rare sightings of marine mammals in B.C. waters, such as a North Pacific Right Whale, and in the Salish Sea, Risso's Dolphins and a Fin Whale. A record number Humpback Whales were observed in the Salish Sea.

29.2. Description of the time series

Every year, unusual marine events occur in the Northeast Pacific: some are reported to DFO, many are not. These are often seen as "one-off" events, which are isolated from other events, in time, space, and by different observers. It is therefore difficult to make a complete story or a synthesis of such observations. However, if enough of these events are observed and reported, it may be possible to identify broader patterns and processes that collectively tell us how our marine ecosystems are changing and responding to diverse pressures. For example, the REDMAP (Range Extension Database and Mapping Project; http://www.redmap.org.au) program in Australia engages citizen scientists and the interested public to report their observations of unusual organisms and events to a structured network, which can subsequently be used in scientific (and other) publications (e.g., Pecl et al. 2014; Lenanton et al. 2017). This report presents a selection of unusual events in Canada's Pacific waters in 2021 that have been reported to or noted by DFO Science staff. Some of these events may be included in other reports in this document, whereas other observations may not be presented in detail or at all. In addition, participants were invited to provide their own observations of weird and wonderful unusual events during the State of the Pacific Ocean meeting, which are included in this report.

29.3. Status and trends

Observations in 2021 that were reported to DFO by participants at the 2022 State of the Pacific Ocean workshop are presented in Table 29-1. For example, on Oct. 22, 2021, the MV Zim Kingston cargo ship caught fire, the fire spread to containers (some of which carried potassium amylxanthate, a hazardous substance), and containers were lost overboard (4 washed up on the north coast of Vancouver Island and 109 are still missing). In June, 2021, B.C. and the Pacific northwest US experienced a heatwave with temperatures never previously observed; this was attributed to human-caused climate change and caused hundreds of human deaths, poor air quality, and killed seashore animals. There were some unusual sightings of fish (e.g., a

Pacific Electric Ray, Lancetfish, King-of-the-Salmon) and several rare sightings of marine mammals (e.g., Risso's Dolphins, Sei Whales, North Pacific Right Whale). Other unusual occurrences are listed in Table 29-1.

Table 29-1. Observations of weird, wonderful and/or unusual marine events reported during 2021 or reported at the 2022 State of the Pacific Ocean meeting.

Event	Where	When	Reported by	(Brief) Details
Emaciated, dead Grey Whale	Northern Vancouver Island	May 5, 2021	Angela Menzies, DFO, Chek news	Third year in a row of spotting dead, emaciated whales; 2019-2021 is recognized as an 'Unusual Mortality Event'
Skinny, Grey Whale present in winter	Haro Strait	Jan.-Mar. 2022	https://wildwhales.org/2022/01/27/greywhale_victoria/, Ocean Wise's WhaleReport app, and DFO	A skinny, Grey Whale (CRC 2440) was spotted intermittently; rare for this time of year.
King of the Salmon	a. Witty's Lagoon; b. Sooke	a. May 12; b. June 2021	a. JMT Photos; b. Don MacDonald	a. Washed ashore dead in Victoria; b. observed live nearshore off Sooke
Heatwave	Pacific coast B.C. and US	June, 2021	Philip et al. in review; Chris Harley (UBC)	Temperatures never previously observed, attributed to human-caused climate change; hundreds of human deaths; poor air quality; killed seashore animals
>300 dead fish	Sidney's Reay Creek	June 4, 2021	5-year old boy and Peninsula Streams Society, Chek news	318 cutthroat trout, three coho, 13 sculpins and 11 sticklebacks dead in the creek
North Pacific Right Whale	Off coast of Haida Gwaii	June 15, 2021	Jared Towers, James Pilkington	Only the 4th one of its kind confirmed in Canada in the last 70 years.
Lancetfish washed ashore	Esquimalt Lagoon	June 30, 2021	Thomas Lotz	Washed ashore alive, released in deeper water
Warm Fraser R. temperatures	Fraser River	July, 2021	Dave Patterson (DFO)	>19 °C in-river temperatures
Sei Whales (25-30) in B.C. waters	~300 km offshore of central Vancouver Island	July, 2021	Thomas Doniol-Valcroze, John Ford (DFO)	25 to 30 sei whales, a species rarely found in coastal B.C. waters.

Southern Resident Killer Whales absent	Salish Sea	July, 2021	Orca Behaviour Institute, Chek news	J- and K-pods absent from the Salish Sea for much of the summer 2021
Dead sea cucumbers	Dolphin Beach, Tyee Cove and Wall Beach, near Parksville; Comox; Sechelt	Aug. 29, 2021	Kathleen Reed, Pacific Sea Cucumber Harvesters Association, CBC news	Hundreds of dead cucumbers on the sea floor observed during dive at in 10-25 m depth.
Sunflower Sea Star wasting disease is ongoing	B.C.	2021	https://www.nature.org/en-us/newsroom/california-sea-star-endangered/	Sea star wasting disease; International Union for Conservation of Nature to list the sunflower sea star (*Pycnopodia helianthoides*) as Critically Endangered today
MV Zim Kingston fire, loss of containers, and hazardous substance	41 nautical miles west off entrance to Juan de Fuca	Oct. 22, 2021	Global news	Fire spread to containers; some containers carried potassium amylxanthate; ~109 missing containers; 4 containers washed up on north coast Vancouver Island.
Weather "bomb"	Vancouver Island and B.C.'s south coast	Oct. 25, 2021	CBC news	Lowest central pressure system ever recorded in the Pacific Northwest.
Beluga whale	West coast Vancouver Island	Oct., 2021	NOAA	Swam from the Beaufort Sea and the high Arctic to Puget Sound.
Record number humpback whales	Salish Sea	Oct. 22, 2021	Pacific Whale Watch Association, Global News	Twenty-one new calves photographed in the waters off British Columbia and Washington State.
Fin whale sighted	North Seattle, Puget Sound	Jan. 9-16, 2022	Seattle news and whale watching associations, CTV news	Offshore species; only the third time the species has been seen in Puget Sound since 1930.
Pacific Electric Ray (*Tetronarce californica*)	north of Balance Rock, Skidegate, Haida Gwaii, B.C.	Jan. 17, 2022	Found by Guujaaw; reported by Lynn Lee, Gwaii Haanas Parks Canada	Found on beach at high tide line in the morning, looking freshly deceased. Known distribution is Baja California to B.C.

Risso's dolphins sighted	Campbell River, Nanoose, Strait of Georgia	Jan. 21, 2022	John Ford (DFO emeritus), and CTV news	Mainly in warmer waters – e.g., off California. Can be seen off the west coast of Vancouver Island and near Haida Gwaii; rarely found in inshore waters of Vancouver Island, especially in the Strait of Georgia. Last sighting Aug/Sep 1978.

29.4. Factors influencing trends

Potential factors influencing these events include a changing climate, natural population changes, and anthropogenic pressures. Disease is a potential factor causing mortality, but is difficult to assess. As the climate changes, extreme weather will continue to be a factor affecting marine biology and long-term temperature increases will continue. Increased temperatures will bring species from warmer waters into B.C.'s marine ecosystems.

29.5. References

Lenanton, R., Dowling, C., Smith, K., Fairclough, D., and Jackson, G. 2017. Potential influence of a marine heatwave on range extensions of tropical fishes in the eastern Indian Ocean —Invaluable contributions from amateur observers. Regional Studies in Marine Science. 13: 19–31.

Pecl, G., Barry, Y., Brown, R., Frusher, S., Gärtner, E., Pender, A., Robinson, L., Walsh, P., and Stuart-Smith, J. 2014. REDMAP: ecological monitoring and community engagement through citizen science. The Tasmanian Naturalist. 136: 158-164.

Philip, S. Y., Kew, S. F., van Oldenborgh, G. J., Anslow, F. S., Seneviratne, S. I., Vautard, R., Coumou, D., Ebi, K. L., Arrighi, J., Singh, R., van Aalst, M., Pereira Marghidan, C., Wehner, M., Yang, W., Li, S., Schumacher, D. L., Hauser, M., Bonnet, R., Luu, L. N., Lehner, F., Gillett, N., Tradowsky, J., Vecchi, G. A., Rodell, C., Stull, R. B., Howard, R., and Otto, F. E. L. In review. Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021, Earth Syst. Dynam. Discuss. [preprint], https://doi.org/10.5194/esd-2021-90.

Individual reports on inside waters (including the Strait of Georgia)

30. RIVERS INLET, BURKE CHANNEL, AND BUTE INLET WATER PROPERTIES IN 2021 COMPARED TO A HISTORICAL TIME SERIES

Jennifer Jackson, Hakai Institute, Victoria, B.C., jennifer.jackson@hakai.org

30.1. Highlights

- In Rivers Inlet, waters throughout the water column cooled, showing that the impacts of the 2014 to 2016 marine heatwave are over.
- In deep water, oxygen concentrations in Rivers Inlet were higher than previous years and near the 1951 to 1990 climatology.
- Intermediate and deep waters in Bute Inlet also cooled but oxygen concentrations remained low.

30.2. Description of the time series

Temperature, salinity, and oxygen data have been collected in Rivers Inlet, Burke Channel, and Bute Inlet since 1951. From 1951 to 1993, temperature was measured with a reversing thermometer, and salinity and oxygen were measured from water collected by a Niskin or Nansen bottle. Since 1998, temperature and salinity have been measured using a Seabird or RBR CTD sensor and oxygen has been measured with a Seabird or Rinko oxygen sensor.

From 1951 to 1987, the University of British Columbia collected data. From 1990 to 2018 in Rivers Inlet, 1978 to 2011 in Burke Channel, and 1989 to 2014 in Bute Inlet, Fisheries and Oceans Canada collected data. From 2008 to present in Rivers Inlet, 2021 to present in Burke Channel, and 2017 to present in Bute Inlet, the Hakai Institute collected data. The focus of this report is station DFO2 (maximum depth 334 m) in Rivers Inlet, station BUR5 (maximum depth 600 m) in Burke Channel, and station BU4 (maximum depth 626 m) in Bute Inlet (Figure 30-1). As of January 2022, 178 temperature and salinity profiles and 154 oxygen profiles have been collected at DFO2, with more than 96% of the data collected since 2000; 24 temperature and salinity profiles and 19 oxygen profiles have been collected at BUR5, with 50% of the data collected since 2000. At station BU4,140 temperature and salinity profiles and 115 oxygen profiles have been collected, with 36% of the data collected since 2000.

Following water type definitions in fjords (Farmer and Freeland 1983; Jackson et al. 2021), three water types were defined. These water types were surface (potential density relative to surface pressure of less than 1022.5 kgm^{-3}), intermediate (from the base of surface layer to sill depth) and deep (below sill depth). Based on sill depths in Pickard (1961), the base of the intermediate water was 140 m at DFO2, 44 m at BUR5, and 355 m at BU4. The deep water was then defined as 141 to 334 m at DFO2, 45 to 600 m at BUR5, and 356 to 626 m at BU4. To compare the monthly 2021 data to the long-term time series, a monthly climatology of temperature, salinity and oxygen was calculated from two time periods: 1951 to 2010 and 1991 to 2020. Monthly averages were only calculated when data had been collected in a given month for at least 3 separate years. Data were limited at BUR5 and since it is near DFO2, the 2021 properties were compared to the DFO2 climatology.

30.3. Status and Trends

Figure 30-1. Rivers Inlet is a fjord about 46 km long and 3 km wide located on British Columbia's central coast, with a sill that is approximately 140 m deep (Pickard 1961), and a maximum basin depth of 340 m. Burke Channel is a fjord about 104 km long and 2.5 km wide with a sill that is approximately 44 m deep (Pickard 1961) and a maximum basin depth of 600 m. Bute Inlet is a fjord about 76 km long and 4 km wide, with a sill that is about 355 m (Pickard 1961), and a maximum depth of 660 m. For this study, results are from station DFO2 in Rivers Inlet, station BUR5 in Burke Channel, and station BU4 in Bute Inlet.

30.3.1. Rivers Inlet

In 2021, Rivers Inlet surface water (Figure 30-2) was fresher and had less oxygen than either the 1951 to 2010 or 1991 to 2020 average. The coldest surface temperature (6.7 °C) was observed in February and the warmest surface water (12.3 °C) was observed in September. The freshest surface water (14.8) was observed in June, which is similar to the typical June freshet (Wolfe et al. 2015) and the June salinity minimum (Tommasi et al. 2013) observed from 2006 to 2010. With the exception of September, the surface waters were cooler than the 1991 to 2020 climatology.

In 2021, intermediate (Figure 30-3) water was in general cooler than the 1991 to 2020 climatology. The warmest water (9.6 °C) was observed in November and the coldest water (7.6 °C) was observed in May. In general, intermediate water was saltier and had less oxygen than the 1951 to 2010 and 1991 to 2020 climatologies. Recent research has identified a subsurface oxygen minimum in intermediate water that typically forms from May to September (Jackson et al. 2021a). In 2021, this feature was present at DFO2 from at least April 12 to September 2 and the lowest oxygen concentration (2.49 mL/L) was observed at 112 m on May 9 (not shown).

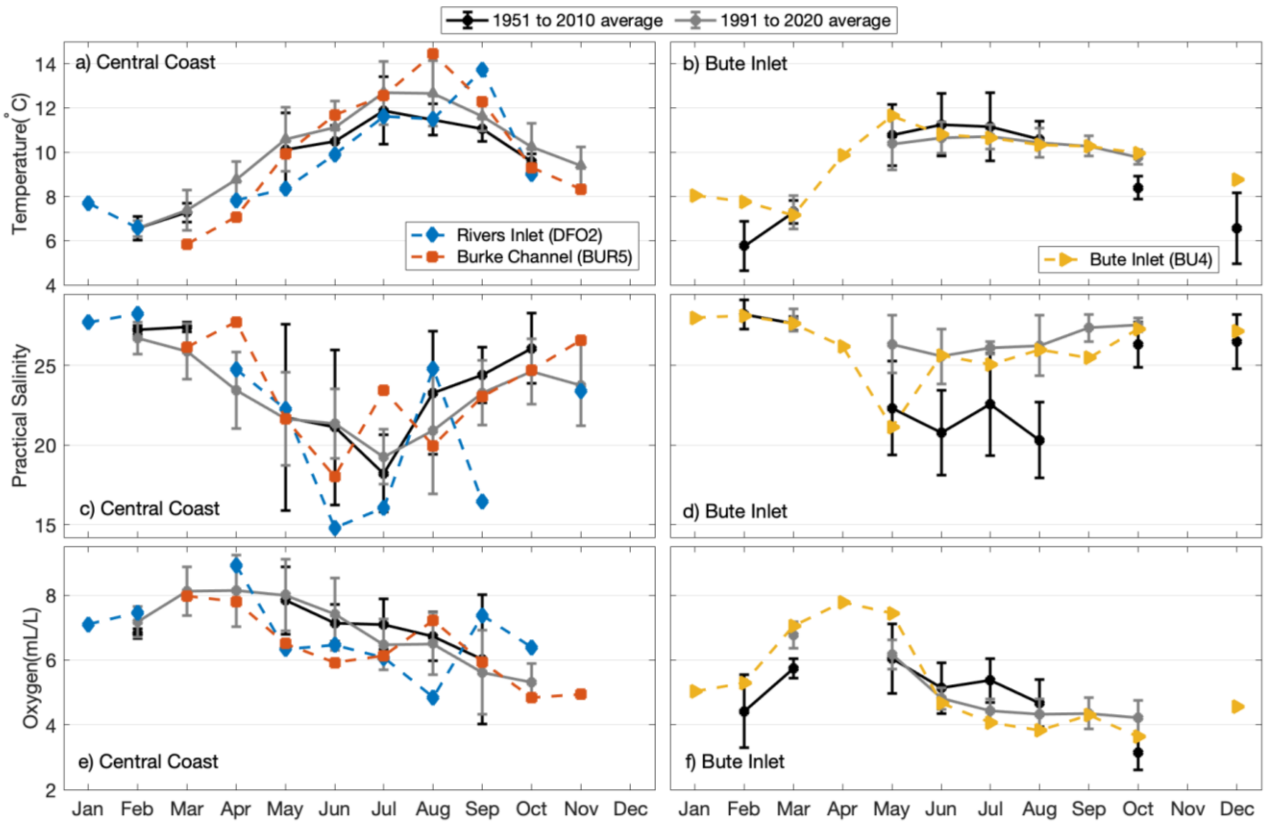


Figure 30-2. The monthly average surface (defined as water fresher than 1022.5 kgm^{-3}) conditions for (top) temperature, (middle) practical salinity, and bottom (oxygen) at stations DFO2 in Rivers Inlet and BUR5 in Burke Channel (panels a), c) and e)) and BU4 in Bute Inlet (panels b), d), and f)). The solid black line denotes the monthly average from 1951 to 2010, the solid grey line represents the monthly average from 1991 to 2020, and the dashed lines shows the 2021 monthly average at each station. Error bars represent the standard deviation of the 1951 to 2010 and 1991 to 2020 time series and only months that were sampled on at least 3 different years were shown.

In 2021, the deep (Figure 30-4) water in January through May was similar to the 1991 to 2020 climatology but then cooled in June so that it was similar to the 1951 to 2010 climatology for the remainder of the year, with the coldest temperature (6.8 °C) in September. These results suggest that deep water has returned to conditions observed before the 2014 to 2016 marine heatwave (Jackson et al. 2018). Salinity in 2021 was similar while oxygen concentrations were higher to the 1991 to 2020 climatology.

30.3.2. Burke Channel

This is the first year that Burke Channel has been included in this report. Historical data in Burke Channel are limited so conditions were compared to Rivers Inlet since both fjords are in a similar region. In general, all water types follow a similar seasonal pattern to Rivers Inlet. The main difference between the inlets is that both intermediate and deep water are fresher and warmer in Burke Channel than Rivers Inlet.

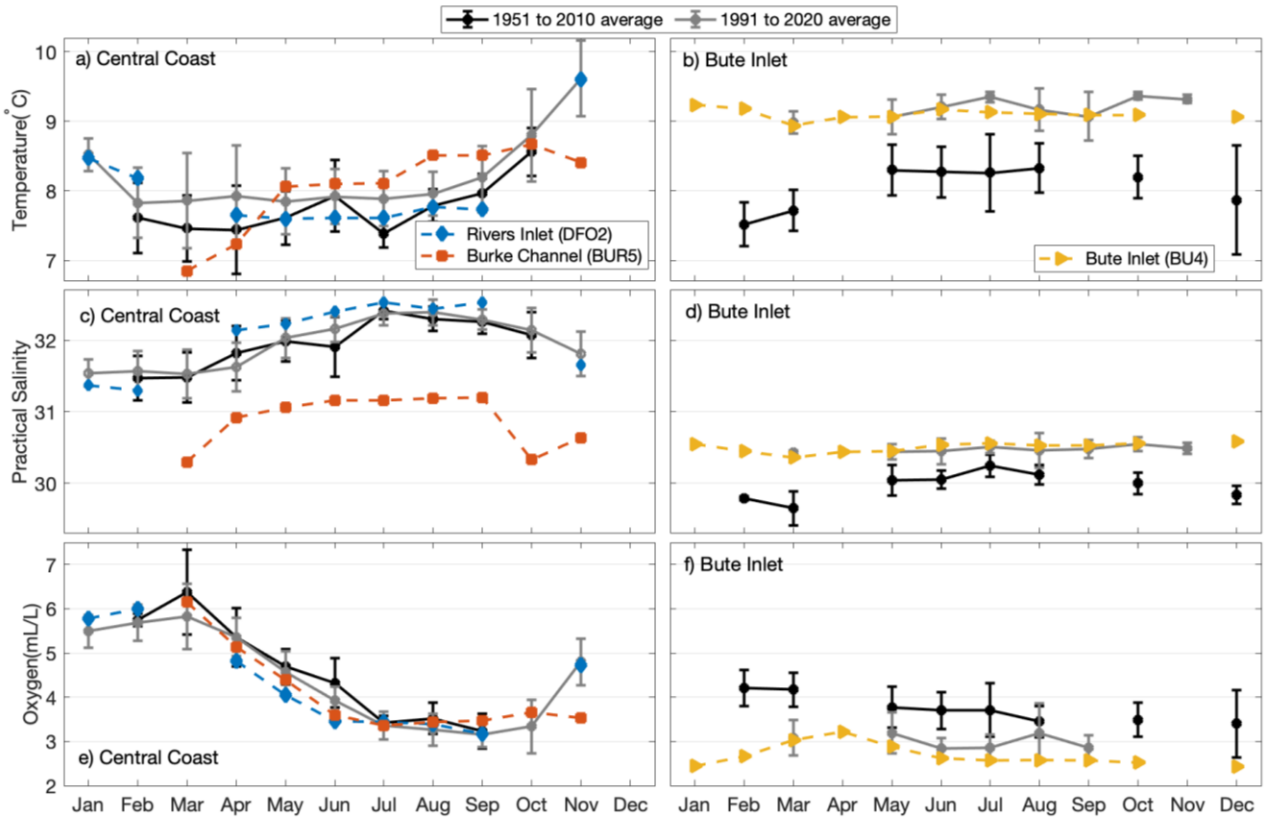


Figure 30-3. As in Figure 30-2, but for intermediate water, which was defined as water between the base of the surface layer and the 140 m sill depth for DFO2 (Rivers Inlet), to the 44 m sill depth at BUR5 (Burke Channel), and to the 355 m sill depth for BU4 (Bute Inlet).

30.3.3. Bute Inlet

In 2021, the surface temperature and salinity in Bute Inlet were similar to the 1991 to 2020 climatology, but oxygen was considerably higher than both climatologies from January through May (Figure 30-2). At the surface, the coldest water (7.2 °C) was observed in March and the warmest water (11.6 °C) was observed in May. The freshest water (21.1) was observed in May and the highest oxygen concentration (7.8 mL/L) was observed in April.

In 2021, both intermediate (Figure 30-3) and deep (Figure 30-4) water were warmer, saltier, and less oxygenated than the 1951 to 2010 climatology. Similar to Rivers Inlet, deep water was about 0.5 °C cooler than observed in 2020 but oxygen concentrations were close to those observed in 2020.

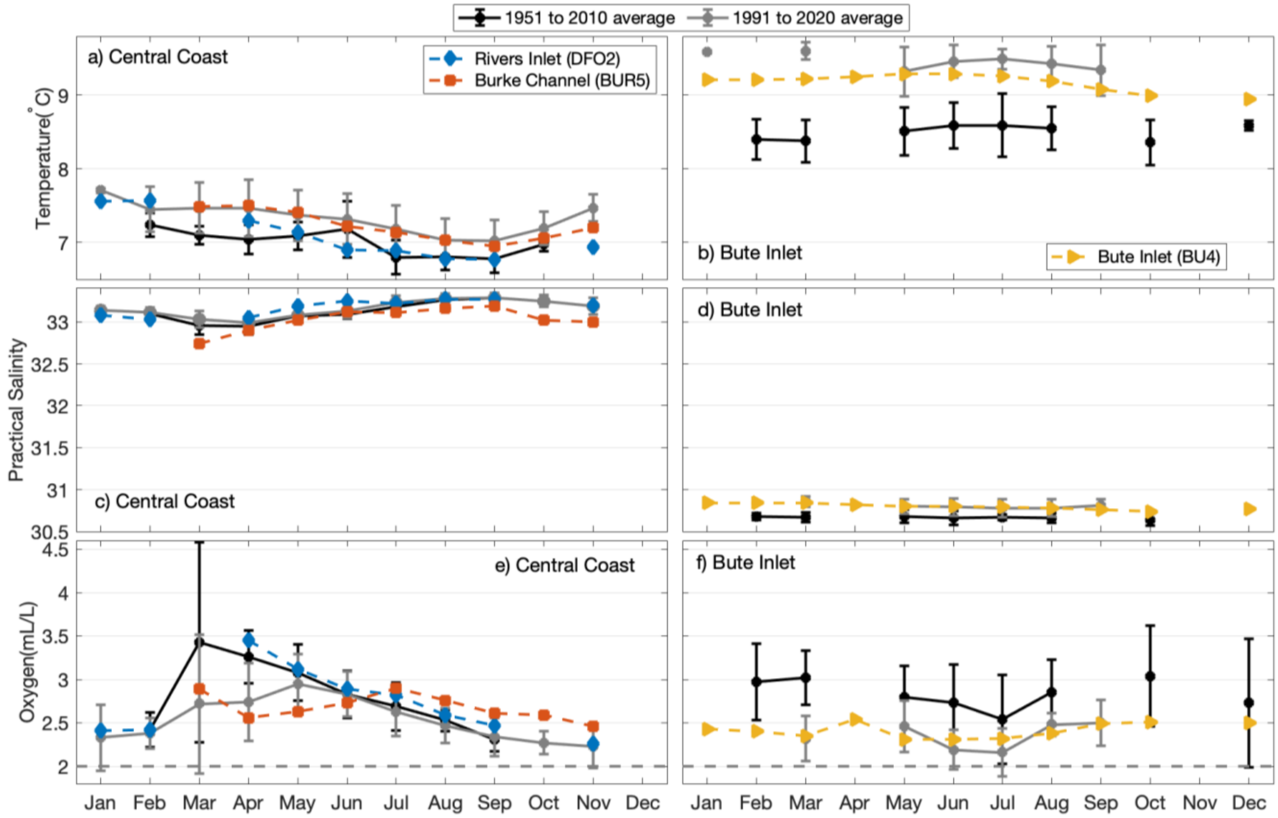


Figure 30-4. As in Figure 30-2, but for deep water, defined as water between the sill depth of 140 m and the bottom (334 m) in Rivers Inlet, between the sill depth of 45 m and the bottom (600 m) in Burke Channel, and between the sill depth of 355 m and the bottom (632 m) in Bute Inlet. The horizontal grey dashed line in the bottom panel indicates 2 mL/L of oxygen, or hypoxic water.

30.4. Factors influencing trends

In 2021, deep water in Rivers Inlet was the coldest it has been since 2009 (not shown). Deep water is renewed annually in spring through summer, and the source of this deep water is offshore (Jackson et al. 2018). Anomalously warm water from the 2014-2016 marine heatwave persisted in Rivers Inlet until the spring of 2021 because offshore waters below the surface mixed layer remained warm until 2020 (Ross and Robert, Section 7). Once the offshore source waters cooled in 2021, deep water in Rivers Inlet was replaced by colder waters. Deep waters in Bute Inlet also cooled, though the data gap from 2002 to 2017 prevents comparison to conditions before and during the 2014-2016 marine heatwave. Colder deep waters were coupled with higher oxygen concentrations in Rivers Inlet, but not in Bute Inlet.

30.5. Implications of those trends

Colder and more oxygenated deep waters should be beneficial to the marine ecosystem, which was severely impacted by the marine heatwave (Hipfner et al. 2020). It is possible that the return to colder waters will result in a higher abundance of subarctic zooplankton species, which are more nutritious for many species including juvenile salmon, some marine seabirds, and forage fish.

30.6. References

Farmer, D.M., and Freeland, H.J. 1983. The physical oceanography of fjords. Progress in Oceanography 12: 147-220.

Hipfner, J.M., Galbraith, M., Bertram, D.F., and Green, D.J. 2020. Basin-scale oceanographic processes, zooplankton community structure, and diet and reproduction of a sentinel North Pacific seabird over a 22 year period. Progress in Oceanography. 182: 102290. https://doi.org/10.1016/j.pocean.2020.102290

Jackson, J.M., Johnson, G.C., Dosser, H.V., and Ross, T. 2018. Warming from recent marine heatwave lingers in deep British Columbia fjord. Geophysical Research Letters. 45(18): 9757-9764. https://doi.org/10.1029/2018GL078971.

Jackson, J.M., Johannessen, S., Del Bel Belluz, J., Hunt, B.P.V., and Hannah, C.G., 2021a. Identification of a seasonal subsurface oxygen minimum in Rivers Inlet, British Columbia. Estuaries and Coasts. https://doi.org/10.1007/s12237-021-00999-y.

Jackson, J.M., Bianucci, L., Hannah, C.G., Carmack, E.C., and Barrette, J. 2021. Deep waters in British Columbia mainland fjords show rapid warming and deoxygenation from 1951 to 2020. Geophysical Research Letters. 48, e2020GL091094, https://doi.org/10.1029/2020GL091094.

Pickard, G.L. 1961. Oceanographic features of inlets in the British Columbia mainland coast. J. Fish. Res. Bd. Canada 18(6): 907-999.

Tommasi, D., Hunt, B.P.V., Pakhomov, E.A, and Mackas, D.L. 2013. Mesozooplankton community seasonal succession and its drivers: Insights from a British Columbia, Canada fjord. Journal of Marine Systems. 115-116: 10-32.

Wolfe, A.M., Allen, S.E., Hodal, M., Pawlowicz, R., Hunt, B.P.V., and Tommasi, D. 2015. Impact of advection loss due to wind and estuarine circulation on the timing of the spring phytoplankton bloom in a fjord. ICES Journal of Marine Science. 73(6): 1589-1609. doi:10.1093/icesjms/fsv151.

31. CO_2 OBSERVATIONS IN COASTAL WATERS OF BRITISH COLUMBIA DURING 2021

Wiley Evans, Katie Pocock, Carrie Weekes, Zoe Sandwith, and Jennifer Jackson, Hakai Institute, Campbell River, B.C., wiley.evans@hakai.org

31.1. Highlights

- Observations from multiple research cruises on the central B.C. coast during 2021 highlight shallower aragonite saturation horizons with increased sensitivity to ocean acidification at the KC10 time series site and other near shore locations.
- A brief period of reprieve from low pH and corrosive conditions for calcite was seen during spring in the northern Salish Sea, however, low pH and corrosive conditions returned during late summer.

31.2. Description of the time series

Marine CO_2 system time series are presented from two regions: the central B.C. coast in the area of Fitz Hugh Sound, and the northern Salish Sea. Observations from Fitz Hugh Sound were collected from a hydrographic station (KC10; 51.650396°N, 127.9508157°W) at a near monthly frequency with samples collected at 12 depths through the water column to a maximum depth of 300 m. Additional profiles are shown from stations around Calvert Island as well as from stations in Rivers Inlet and Burke Channel. Time series observations from the northern Salish Sea were made at a hydrographic station (QU39; 50.03044358°N, 125.1052797°W) where discrete samples were collected every 2 weeks from 12 depths through the water column to a maximum depth of 260 m. Along with the marine CO_2 system data, observations of oxygen and density from conductivity-temperature-depth (CTD) profilers are included for oceanographic context.

31.3. Patterns in marine CO_2

31.3.1. Fitz Hugh Sound / Kwakshua Channel

Marine CO_2 conditions within Fitz Hugh Sound through the water column were not largely different in 2021 compared to 2020. Apparent oxygen utilization (*i.e.*, the difference in oxygen content from saturated values) and aragonite saturation horizon (*i.e.,* the depth in the water column where the saturation state for aragonite is equal to 1) were comparable between years except for a brief period of increased oxygen content in the spring that had no discernable impact on the depth of the saturation horizon (Figure 31-1). Oxygenation of the upper water column and depth of the aragonite saturation horizon follow a seasonal pattern set by wintertime downwelling conditions. Storms and downwelling conditions in winter oxygenate the upper water column and deepen the aragonite saturation horizon. Over the 2020 and 2021 winters, aragonite saturation horizon reached ~150 m depth. During spring when downwelling conditions relax, denser seawater appears at shallower depths, aragonite saturation horizon shoals to near 50 m, and oxygen utilization increases below 50 m. These patterns reverse in the autumn when downwelling conditions intensify. Unlike in the previous few years, calcite undersaturation was not observed during the summer in Fitz Hugh Sound.

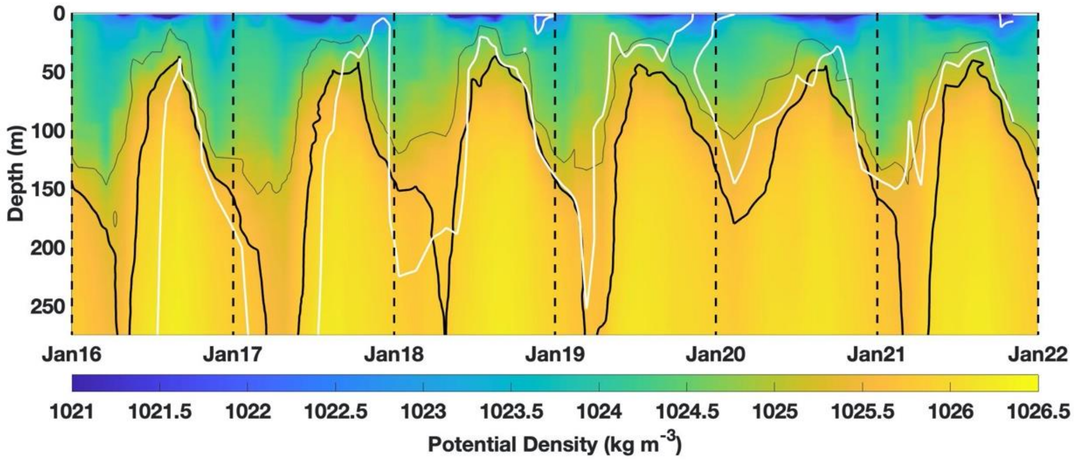


Figure 31-1. Time series of potential density (kg m^{-3}) at hydrographic station KC10. Also shown are isopleths of apparent oxygen utilization values of 100 and 150 µmol kg^{-1} in black, and the saturation horizon for aragonite (depth where aragonite saturation state = 1) in white.

Marine CO_2 observations were collected during four surveys over May and June in 2021, and helped to determine if the patterns seen at KC10 (Figure 31-1) are representative of the broader open continental shelf. These surveys included the U.S. National Oceanic and Atmospheric Administration (NOAA) West Coast Ocean Acidification cruise, two Fisheries and Oceans Canada (DFO) surveys, and a Hakai Institute survey around Calvert Island and into Rivers Inlet and Burke Channel. Observations from the large-scale NOAA and DFO cruises showed consistently deeper aragonite saturation horizons over the continental shelf, ranging from 80 to 100 m, compared to the observations in Fitz Hugh Sound. Observations from the Hakai Institute survey around Calvert Island showed elevated apparent oxygen utilization in the upper 100 m in Fitz Hugh Sound, Rivers Inlet, and Burke Channel compared to the stations exposed to the open continental shelf (Figure 31-2). This zone of higher apparent oxygen utilization was accompanied with higher dissolved inorganic carbon relative to alkalinity leading to weakly-buffered seawater (*i.e.,* high Revelle factor) and corrosive conditions for aragonite over more of the water column than seen at offshore stations.

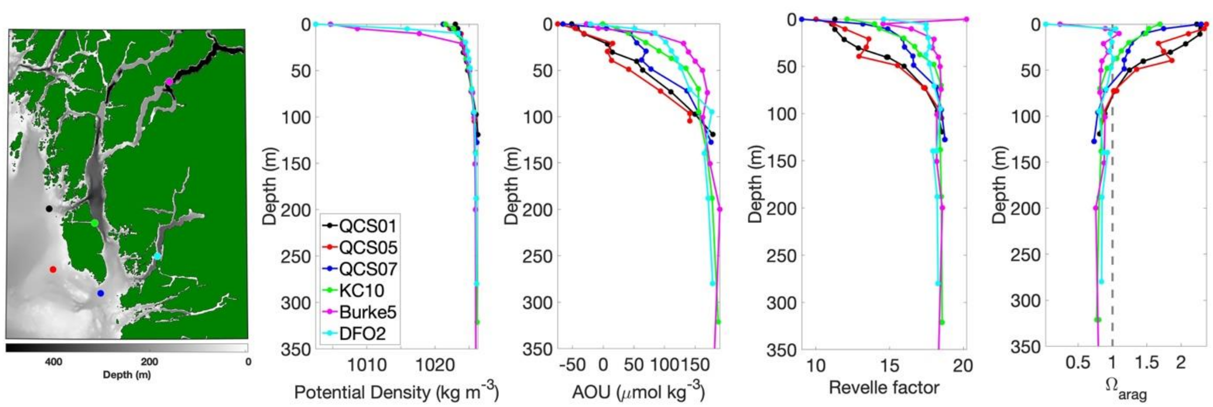


Figure 31-2. Station locations (left map) and depth profiles of potential density (kg m^{-3}), apparent oxygen utilization (AOU; µmol kg^{-1}), Revelle factor, and aragonite saturation state (Ω_{arag}).

31.3.2. Northern Salish Sea

Marine CO_2 conditions in the northern Salish Sea during 2021 improved during spring compared to the previous few years. Undersaturation with respect to calcite was less evident and pH values were higher relative to spring conditions in 2018, 2019, and 2020. These marine CO_2 system changes occurred in conjunction with a decrease in apparent oxygen utilization (*i.e.,* increase in oxygen concentration). The early 2021 reprieve from the more corrosive and low pH conditions seen over previous years did not last through 2021, however, as apparent oxygen utilization increased beginning in late summer along with a shoaling of the calcite saturation horizon to a depth near 50 m, which indicated that ~80% of the water column was corrosive to calcite (Figure 31-3). pH values also decreased in the latter half of the year and with lowest values most evident in the mid-water column.

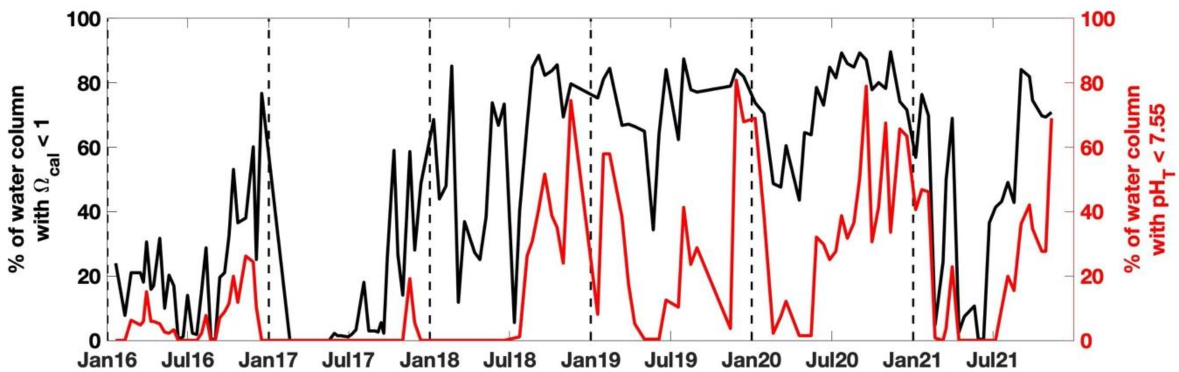


Figure 31-3. Percent of the water column with Ω_{cal} values < 1 (black) and pH_T values < 7.55 (red) in the northern Salish Sea.

31.4. Factors influencing trends

The pattern of corrosive conditions occurring over a greater portion of the water column near shore on the central coast of B.C. is likely supported by high organic matter input leading to greater apparent oxygen utilization relative to the open continental shelf (Jackson et al. 2021). The remineralization of organic matter not only consumes oxygen, but also produces dissolved inorganic carbon that enhances corrosive conditions and increases vulnerability to ocean acidification in this nearshore region. The northern Salish Sea is a semi-enclosed sea known to be vulnerable to ocean acidification due to enriched dissolved inorganic carbon and low alkalinity (Cai et al. 2021; Evans et al. 2019; Ianson et al. 2016). Inter-annual variability in springtime deep-water renewal events may at present provide a period of reprieve from corrosive and low pH conditions.

31.5. Implications of those trends

The implications of a shallower saturation horizon within a deep water column near shore are that species residing over more of the water column become subjected to adverse conditions potentially leading to stress or impairment of biological processes across multiple species groups (Haigh et al. 2015). The prevalence of more weakly-buffered seawater throughout the water column also means that continued input of anthropogenic CO_2 will further amplify these adverse conditions. The brief period of reprieve observed in the northern Salish Sea was short-lived in 2021, and illustrates how the water column can transition from near 0 to 80% corrosive for calcite over a year. However, this variability in calcite saturation is expected to decrease as anthropogenic CO_2 in the ocean continues to increase, eventually leading to the conditions we observe for aragonite saturation with only the surface layer over-saturated during the spring and summer months due to CO_2 drawdown via primary productivity.

31.6. References

Cai, W.J., Feely, R.A., Testa, J.M., Li, M., Evans, W., Alin, S.R., Xu, Y.-Y., Pelletier, G., Ahmed, A., Greeley, D.J., Newton, J.A., and Bednarsek, N. 2021. Natural and Anthropogenic Drivers of Acidification in Large Estuaries. Annual Review of Marine Science. 13: 23-55.

Evans, W., Pocock, K., Hare, A., Weekes, C., Hales, B., Jackson, J., Gurney-Smith, H., Mathis, J.T., Alin, S.R., and Feely, R.A. 2019. Marine CO2 Patterns in the Northern Salish Sea. Frontiers in Marine Science. 5(536): doi: 10.3389/fmars.2018.00536.

Haigh, R., Ianson, D., Holt, C.A., Neate, H.E., and Edwards, A.M. 2015. Effects of Ocean Acidification on Temperature Coastal Marine Ecosystems and Fisheries in the Northeast Pacific. PLoS ONE. 10(2): doi: 10.1371/journal.pone.0117533.

Ianson, D., Allen, S.E., Moore-Maley, B.L., Johannessen, S.C., and Macdonald, R.W. 2016. Vulnerability of a semienclosed estuarine sea to ocean acidification in contrast with hypoxia. Geophysical Research Letters. 43: 5793-5801. doi:10.1002/2016GL068996.

Jackson, J., Johannessen, S., Del Bel Belluz, J., Hunt, B.P.V., and Hannah, C.G. 2021. Identification of a Seasonal Subsurface Oxygen Minimum in Rivers Inlet, British Columbia. Estuaries and Coasts. doi.og/10.1007/s12237-12021-00999-y.

32. SALISH SEA TEMPERATURE, SALINITY AND OXYGEN OBSERVATIONS IN 2021

Peter Chandler, Fisheries & Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Peter.Chandler@dfo-mpo.gc.ca

32.1. Highlights

- Three seasonal water properties surveys were carried out in 2021:
  - During the spring survey of 2021 conditions seaward of Haro Strait were cooler, saltier, and less oxygenated than normal, while conditions in the Strait of Georgia were near normal.
  - Conditions in the summer of 2021 were cooler and less oxygenated than normal in the surface waters of the Strait of Georgia, with a warm, salty, oxygenated mid-depth layer in Juan de Fuca Strait.
  - The fall survey revealed less oxygenated water throughout the system, especially in Juan de Fuca Strait.
- The 23-year time series show trends of increasing temperature and decreasing oxygen throughout the system at all depths. Salinity is generally trending towards fresher conditions at the surface and saltier conditions at depth.
- The annual Fraser River discharge was slightly above normal in 2021, while the impact of an atmospheric river resulted in very high flows in mid-November.

32.2. Description of the time series

Two sources of data are used to describe changes in the water properties of the Strait of Georgia and Juan de Fuca Strait. The first is profile data collected with a SeaBird 911 CTD during the Salish Sea water properties surveys (Figure 32-1). In 2021, surveys were carried out April 4-15, June 16-21, and October 5-10. The second dataset is provided by the Department of National Defence from temperature and salinity profiles collected in 2020 with a SeaBird 19 CTD at its Maritime Experimental and Test Range (CFMETR) near Nanoose. Data from both sources collected since 1999 are used to calculate long-term averages and identify the 2021 anomalies from these average conditions.

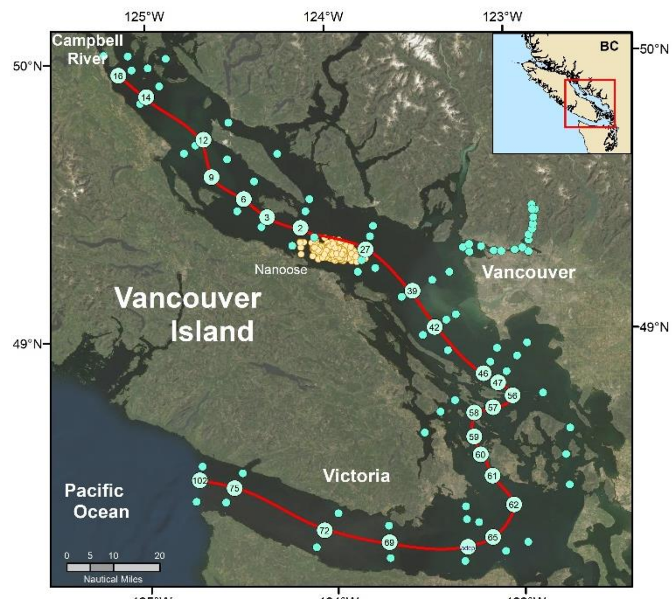


Figure 32-1. Blue dots show the locations of stations sampled during the water properties surveys. The thalweg is shown as the red line joining the deepest stations along the centerline of the Straits. The yellow dots mark the CFMETR data positions.

32.3. Status and trends

Observations of temperature, salinity and oxygen made in 2021 are compared to the 1999-2021 averages and shown as anomalies in Figures 32-2 – 32-4. During the April survey, near-surface oxygen concentrations in the Strait of Georgia were generally higher than normal likely due to sampling during the Spring Bloom. Conditions in April also revealed near-normal temperature and salinity in the Strait of Georgia and cooler, saltier conditions seaward of Haro Strait.

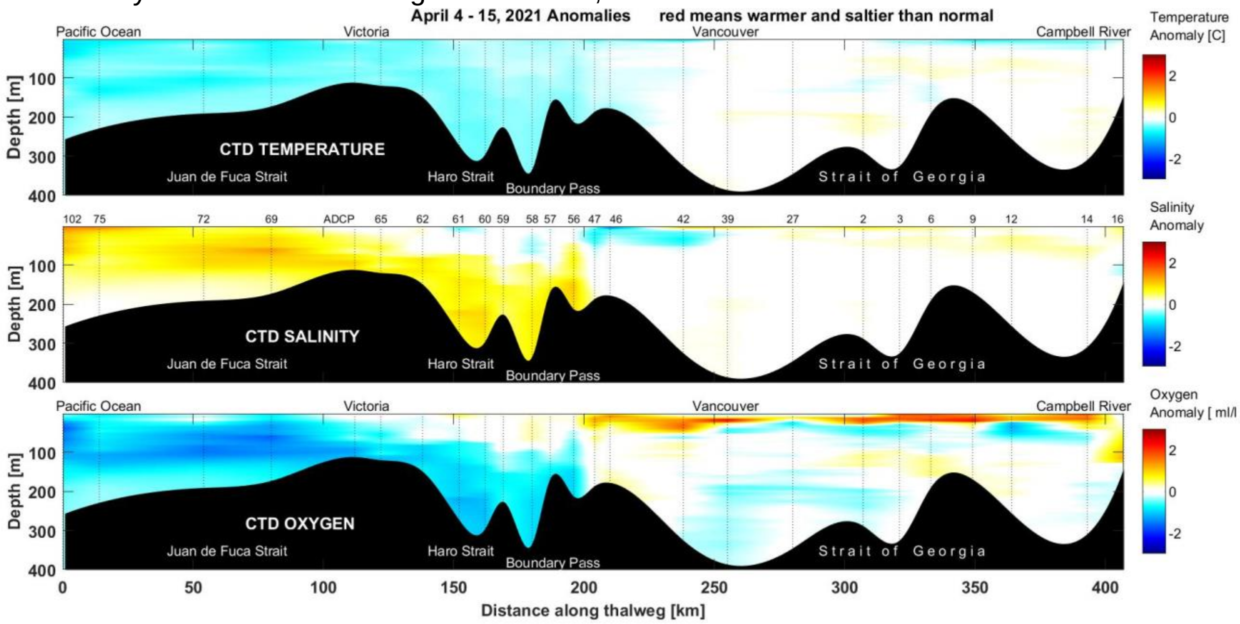


Figure 32-2. Temperature, salinity and oxygen anomalies along the thalweg observed in the spring of 2021.

Evident in the June survey, a mid-depth layer of warm, salty, oxygenated water intruded from the Pacific up Juan de Fuca Strait as far as Victoria.

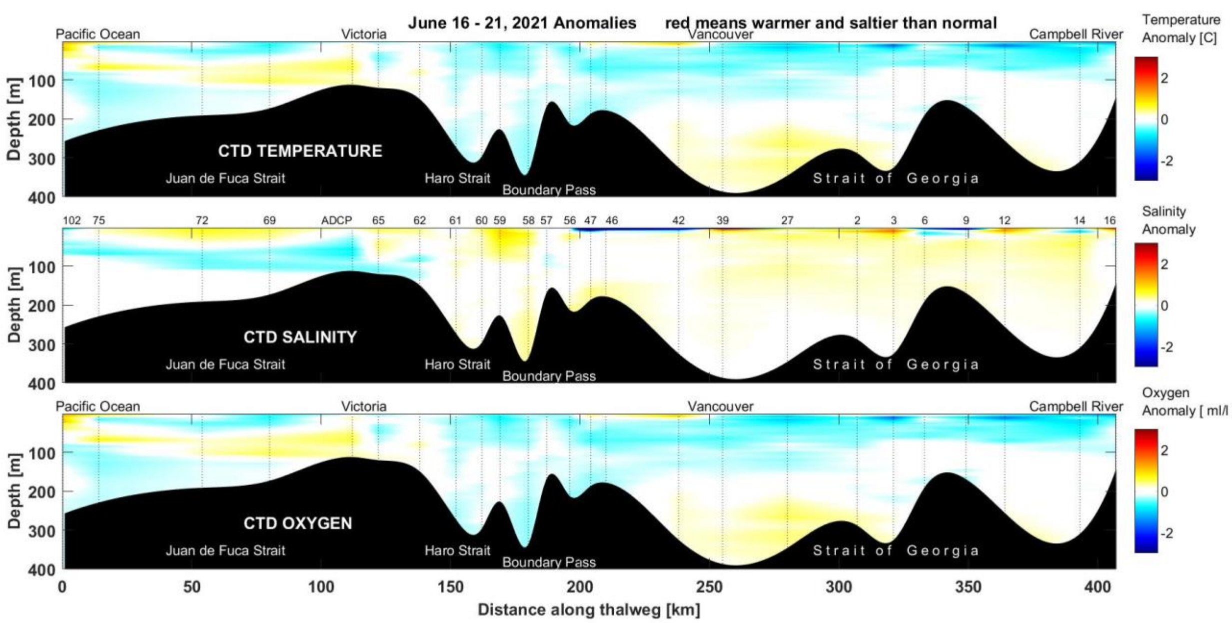


Figure 32-3. Temperature, salinity and oxygen anomalies along the thalweg observed in the summer of 2021.

In the October data and as in previous years, low oxygen water from the Pacific is evident in the Salish Sea.

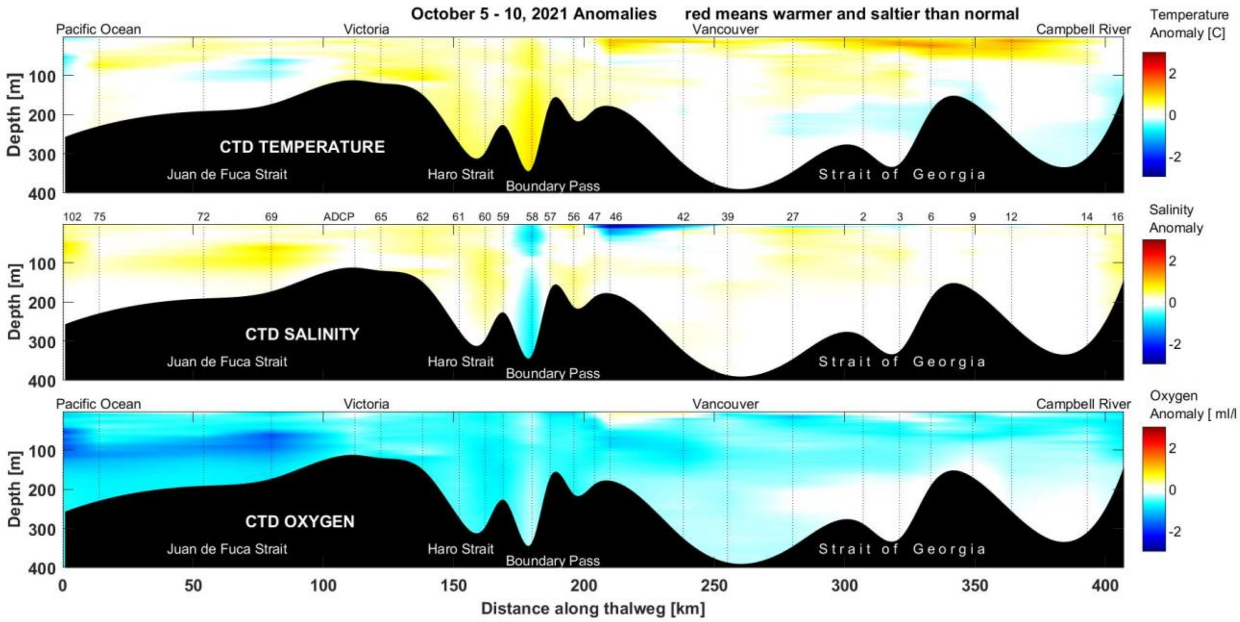


Figure 32-4. Temperature, salinity and oxygen anomalies along the thalweg observed in the fall of 2021.

The interannual variations in the depth averaged water temperature collected near Nanoose (Figure 32-5, upper panel) show depth averaged temperatures in 2021 at levels consistent with the past few years, although the lack of 2021 data make it difficult to resolve any detail in the annual cycle. The long-term temperature time series shows a warming trend at a linear rate of 1.08 ºC per 100 years.

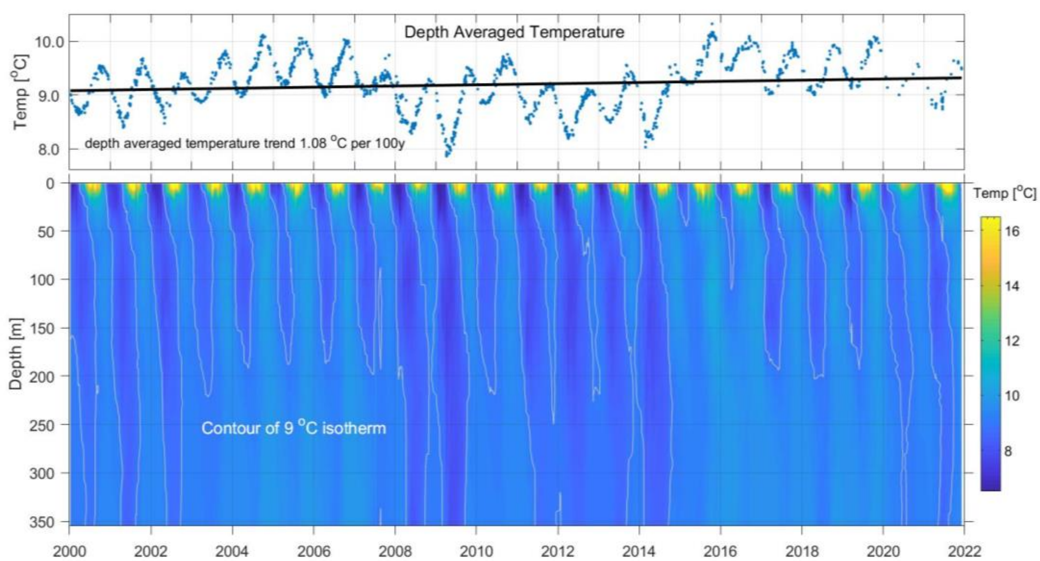


Figure 32-5. The time series of depth averaged temperature collected near Nanoose in the central Strait of Georgia (upper); the vertical distribution of these data (lower). Source: The Canadian Forces Maritime Experimental and Test Range (CFMETR).

The Fraser River discharge influences the salinity of the surface waters of the central and southern Strait of Georgia, and is a driving force for the Vancouver Island buoyancy current that flows northwards along the west coast of Vancouver Island. The 2021 annual discharge of the Fraser River measured at Hope, B.C. (Figure 32-6) was above average, and the annual discharge of the Fraser River is increasing at a rate of 4.27 x10^9 m^3 per 100 years.

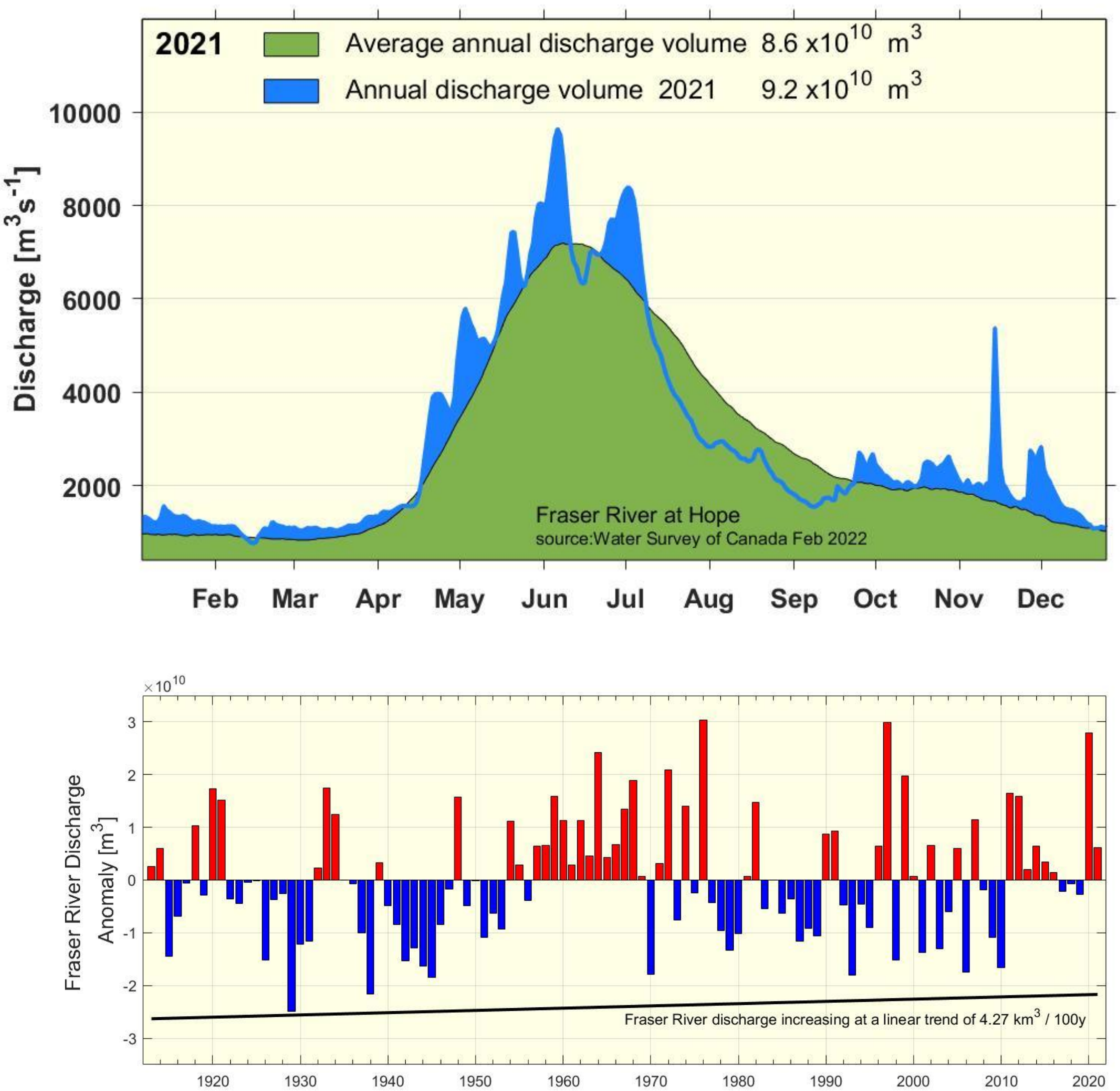


Figure 32-6. (Upper panel) Fraser River discharge at Hope B.C.; 2021 (blue), 109 year average (green). (Lower panel) The time series of the annual Fraser River discharge anomaly. Extracted from the Environment and Climate Change Canada Real-time Hydrometric Data web site (https://wateroffice.ec.gc.ca/mainmenu/real_time_data_index_e.html) on 10 Feb 2022.

32.4. Factors influencing trends

Water properties in the Salish Sea are considerably influenced by ocean conditions at the western entrance of the Strait of Juan de Fuca, and the freshwater discharge of rivers, primarily the Fraser River. In addition to summer warming and winter cooling, seasonal changes occur as salty, oxygen-poor ocean water is upwelled during the summer months, and Fraser River runoff peaks during the early summer. The global trends of ocean warming are reflected directly in the Salish Sea water temperature, and the trend of increased discharge of the Fraser River as glacier melt increases. The intense tidal mixing that occurs in Haro Strait effectively controls the exchange of water masses between Juan de Fuca Strait and the Strait of Georgia (Masson 2002; Pawlowicz et al. 2007).

32.5. References

Environment and Climate Change Canada. Real-time Hydrometric Data web site (https://wateroffice.ec.gc.ca/mainmenu/real_time_data_index_e.html), extracted on 23 Feb 2021.

Masson, D. 2002. Deep Water Renewal in the Strait of Georgia. Estuarine, Coastal and Shelf Science. 54: 115-126.

Pawlowicz, R., Riche, O., and Halverson, M. 2007. The circulation and residence time of the Strait of Georgia using a simple mixing-box approach. Atmosphere-Ocean. 45(2): 173-193.

33. OCEAN OBSERVATORY CONTRIBUTIONS TO ASSESSING 2021 SOUTHERN B.C. COASTAL CONDITIONS

Richard Dewey, Steve Mihaly, Megan Kot, Manman Wang
Ocean Networks Canada, University of Victoria, Victoria, B.C., rdewey@uvic.ca

33.1. Highlights

- Off of southern Vancouver Island, strong downwelling in early 2021 was followed by a few upwelling events in early and late February 2021. The summer upwelling season started early (March 21) through to Sept 15, nearly six months in duration. Strong downwelling periods in the fall (Oct and Nov) correspond to intense atmospheric river events.
- A southern province “heat dome” in late June caused a short burst of downwelling-favourable winds in June. Marine heat did not seem to penetrate below 20m.
- The early and sustained upwelling season may have contributed to low oxygen waters across much of the Washington shelf in July, extending to the Vancouver Island shelf in August. A CTD survey on August 18 revealed extensive regions with hypoxic bottom waters.
- Low oxygen waters on the shelf west of Vancouver Island did not influence bottom waters in the Salish Sea, while the early upwelling and warm spring conditions resulted in a long deep renewal water season.

33.2. Description of the Time Series

Here we report on several time series recorded from a number of permanent installations and a ship-based survey, including upwelling winds west of Cape Flattery, cabled platforms at Folger Passage (Barkley Sound) and Saanich Inlet, ship-based CTDO2 profile data, and Strait of Georgia CODAR (Figure 33-1).

1. NOAA Reanalysis Upwelling Index (48°N 125°W), the Bakun Upwelling index, is available from the NOAA Pacific Fisheries Environmental Laboratory website: https://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html The Bakun Index takes the daily average scaled (by f) along-shore wind stress component derived from reanalysis (re-constructed surface pressure fields) resulting in a volume estimate of the amount of ocean transported off (positive - upwelling) or on-shore (negative - downwelling) per 100m of coastline. The upwelling indices are summed cumulatively for each year, revealing the winter/fall downwelling and summer upwelling strength and seasons.
2. ONC’s Folger Passage [Deep (100m) and Pinnacle (25m)] site is a fixed-point cabled installation at 48° 48’ N and 125° 17’ W (Ocean Networks Canada Oceans 3.0 Data Portal: https://data.oceannetworks.ca/home). The instrument platforms are located on the west coast of Vancouver Island inner shelf at the mouth of Barkley Sound, and the time series discussed here started Sept. 2009. This time series provides an indicator of the near shore, mid-depth and near-surface water properties (T, S, O_2) that are strongly influenced by local upwelling and downwelling conditions.

3. During our August 2021 observatory maintenance expedition, we conducted a CTD & O_2 profile survey on August 18 at 9 standard DFO stations on the southern Vancouver Island shelf. These stations include: LB03, LB04, LB06 LB08, P01, LC02, LC04, LC06, and LC08.
4. Ocean Network Canada's (ONC's) Saanich Inlet cabled observatory platform (96 m) at the mouth of Patricia Bay (48° 39'N 123° 29.2'W), with a CTD & O2 record extending back to February 2006. Data are used to detect deep water renewal events, which are linked to weak mixing periods associated with neap tides (Soetaert et al., 2022)
5. CODAR (HF Radar) data from the southern Strait of Georgia provided wide regional coverage of ocean surface currents throughout 2021 from four shore-based antennae at: Pt Atkinson, Iona, West Port, and Georgia Pt.

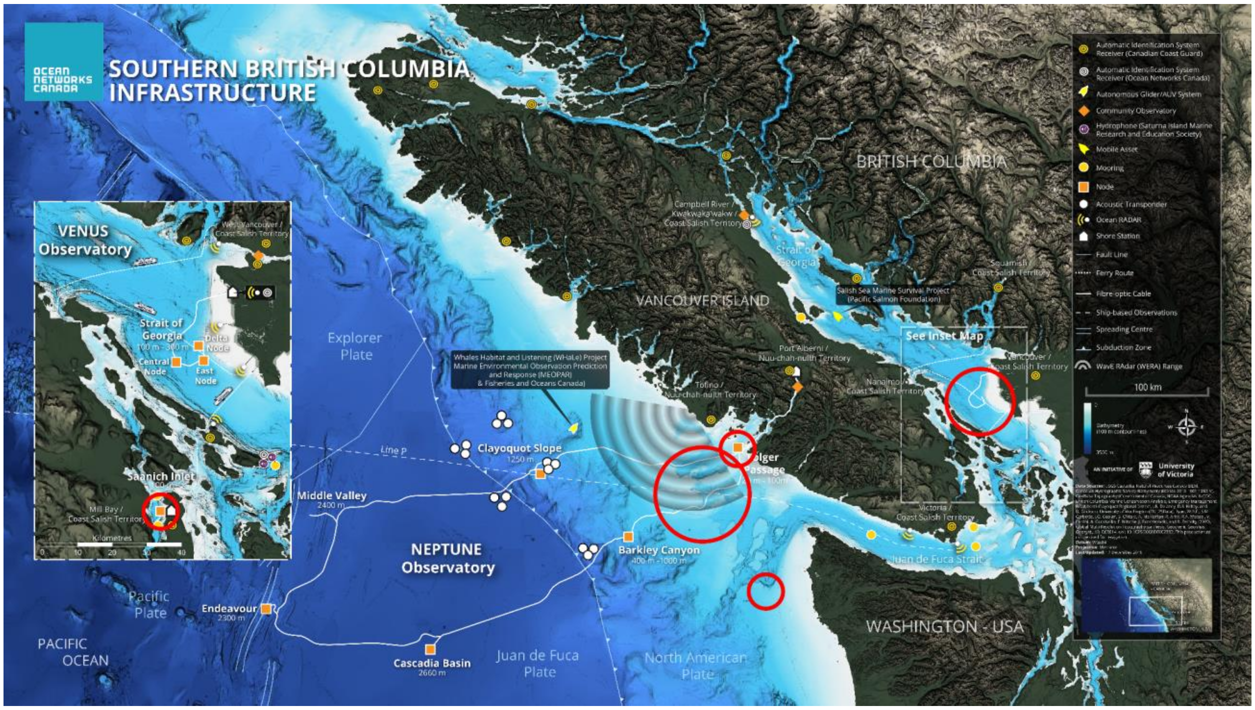


Figure 33-1. Southern coast of B.C., showing ONC's installed and instrumented assets. Sites where data will be shown have been highlighted with red circles (NOAA Upwelling [48°N 125ºW], CTDs west of Vancouver Island, cabled platforms from Folger Passage and Saanich Inlet (inset), and southern Strait of Georgia (CODAR)).

33.3. Status and Trends - 2021

33.3.1. Upwelling

The coastal waters of B.C. and the Salish Sea are strongly influenced by upwelling conditions along the West Coast. For the Salish Sea, this includes the region near the southern continental shelf and entrance to Juan de Fuca Strait. Prevailing summer winds blow towards the south, are associated with the development of the North Pacific High-pressure zone off the west coast of North America, and are upwelling-favourable. North bound winds, are generally associated with winter and storm conditions, the establishment of the Aleutian Low in the Gulf of Alaska, and are downwelling-favourable. Upwelling winds push surface waters off-shore, bringing deeper off-shore (salty nutrient rich) waters closer to shore, and into the Juan de Fuca Canyon and Strait. During downwelling conditions, surface waters (typically warmer and fresher) are pushed towards the coast, pushing down the deeper salty, nutrient rich waters. For the cumulative plot

(Figure 33-1), downward trending segments indicate downwelling (negative index) conditions and upward trending segments indicate upwelling (positive index) conditions.

A strong storm system in early January was followed by a series of weak downwelling and upwelling reversals, with a few upwelling pulses in early and late February 2021 (Figure 33-2). The persistent “summer” upwelling season started on March 21, 2021, over a full month ahead of the climatological (55 year) mean of April 26. Upwelling strength was average, but the net upwelling season was six months, rather than the average 5 months. It was briefly interrupted by a downwelling period in June associated with the “heat dome” that developed over southern B.C. Fall downwelling started on September 15, coinciding with climatology, and was punctuated by several strong storm events in October and November associated with atmospheric rivers.

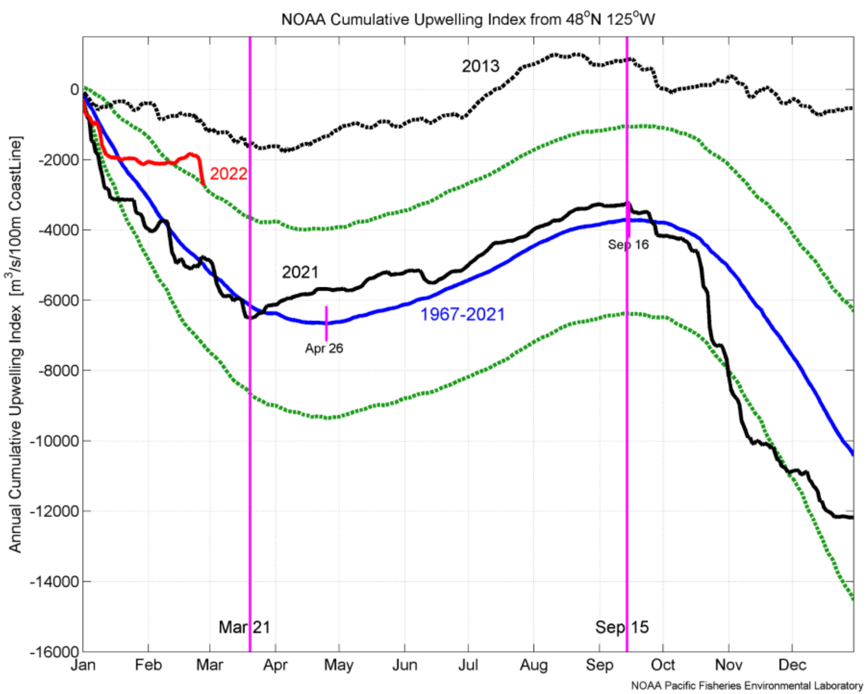


Figure 33-2. The cumulative daily upwelling index from reanalysis wind stress at 48°N 125°W, west of Washington State (Figure 33-1). Downward (downwelling, negative indices) trends occur during northward winds (winds from the south) and upward (upwelling, positive indices) trends occur during southward winds (winds from the north). 2021 is shown in a solid black line. The blue curve is the long-term (55 year) average, with plus and minus one standard deviations (green dashed curves). 2013 is shown as the weakest downwelling year on record, contributing to the development of the warm blob in the Northeast Pacific. The vertical lines indicate the beginning (March 21) and end (Sept 15) of the 2021 upwelling season.

33.3.2. Folger Passage

Variations in CTD and oxygen records for Folger Passage (100m) have strong linkages with the regional upwelling and downwelling signals. The cold, salty upwelling season in 2021 started early (late March) and was sustained for over 6 months (late September; Figure 33-3). The heat dome of June is not apparent at 100m, nor by the CTD at Folger Passage Pinnacle at 25m depth (not shown).

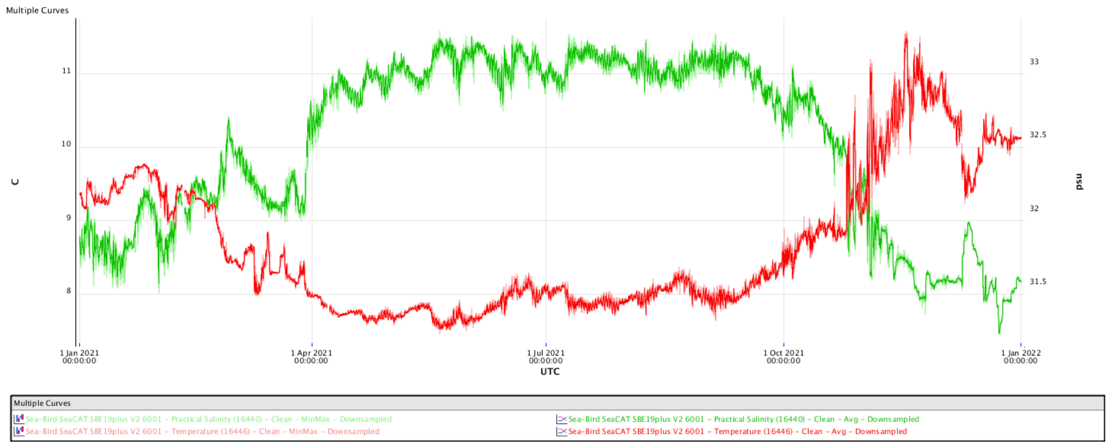


Figure 33-3. Time series of water properties from the cabled station at Folger Passage Deep (100m) located near the entrance to Barkley Sound along the west coast of Vancouver Island (Figure 33-1). Shown are (top to bottom): Oxygen, Density (σ_t), Salinity (green), and Temperature (red). Instrument failures in early 2018 and late 2019 have introduced data gaps, and a plugged Oxygen sensor in late 2021 impacted data quality.

33.3.3. Vancouver Island Shelf Bottom Water Hypoxia

Surveys by NOAA off the coast of Washington State in July 2021 suggested that the early upwelling had pushed very low oxygen waters up onto the continental shelf earlier than seen in other years (https://research.noaa.gov/article/ArtMID/587/ArticleID/2779/Low-oxygen-waters-off-Washington-Oregon-coasts-risk-becoming-large-%E2%80%9Cdead-zones%E2%80%9D). Hints of low oxygen values at Folger Passage stimulated ONC to make extra hydrographic CTD & O_2 profile measurements at 9 DFO stations (Figure 33-4) during our August expedition. Plotting the oxygen as sections revealed hypoxic conditions (O_2 < 1.4 ml/l) over a large area of the southern shelf (Figure 33-4).

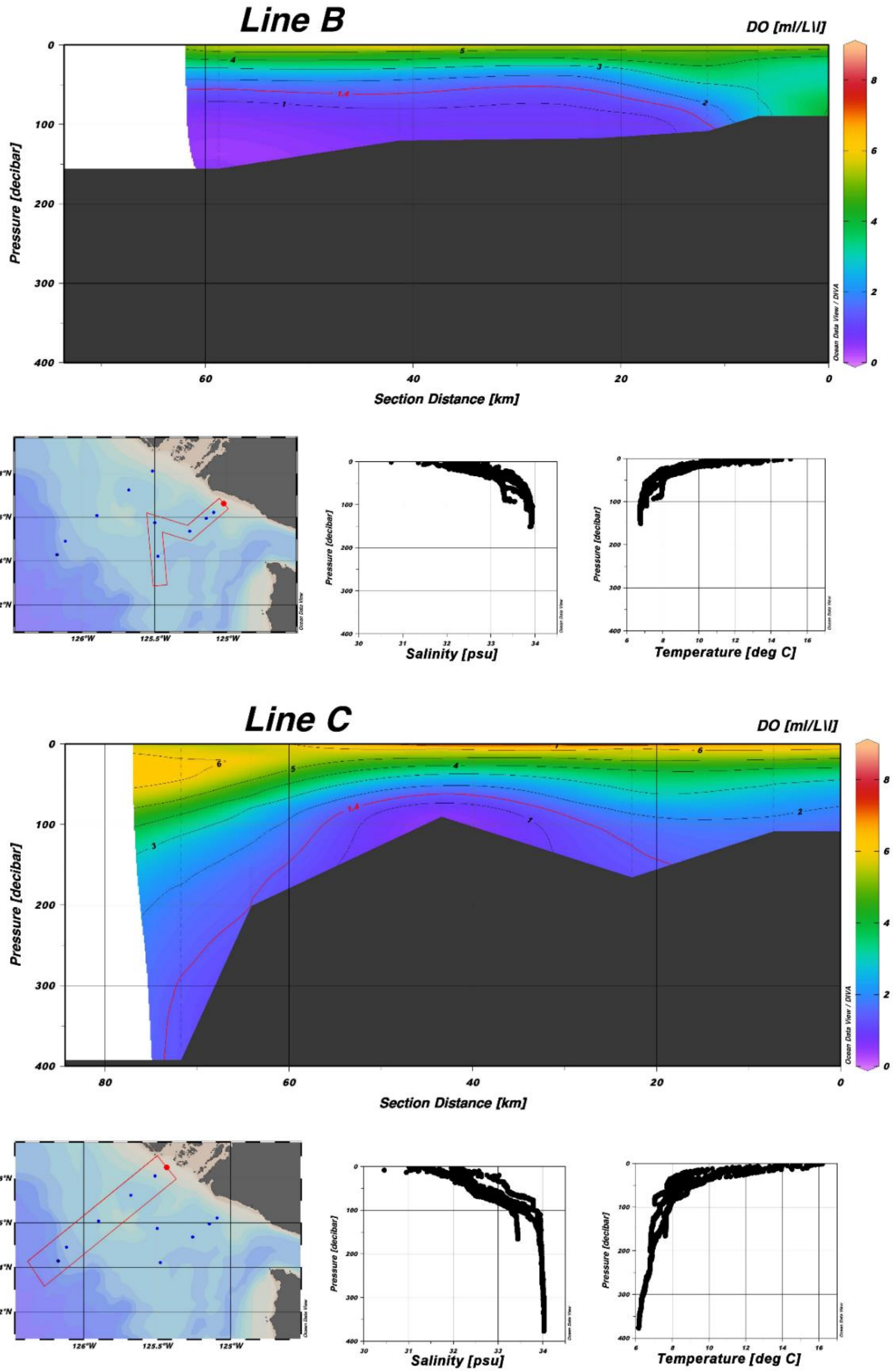


Figure 33-4. Dissolved Oxygen concentration sections from CTD & O2 profiles collected at stations labeled LB and LC on August 18, 2021.

33.3.4. Deep Water Renewal Events in the Salish Sea

Of interest is whether the low oxygen waters over the continental shelf in the summer of 2021 made their way into the Salish Sea. Estuarine circulation driven by the Fraser River causes a general summer exchange of surface waters out of the Salish Sea, replaced by deep waters along the bottom. Deep (~250m) waters typically enter into Juan de Fuca Strait via the Juan de Fuca Canyon (e.g., Figure 33-4). Inspection of the conditions in bottom waters throughout the Salish Sea indicates that the low oxygen waters on the shelf west of Vancouver Island did not influence bottom waters in the Salish Sea, while the early upwelling and warm spring conditions resulted in a long deep renewal water season (Masson 2002; Figure 33-5). The combined effects of a warm, early and sustained upwelling season resulted in an 8-month renewal season, the second longest on our 16-year record (only surpassed by 2009; Figure 33-5).

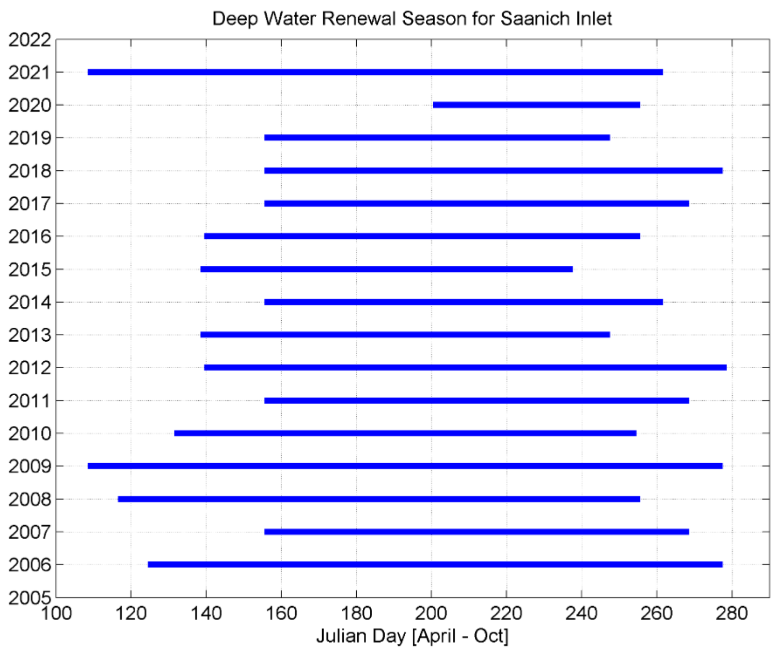


Figure 33- 5. The deep water renewal season as revealed by the ONC Saanich Inlet CTD & O2 time series. Deep water renewals can occur during the weakest neap tides of each month from early summer to early fall. 2021 was one of the earliest and longest renewal seasons since 2009.

33.3.5. CODAR Surface Currents

While nothing extraordinary was recorded by ONC's Strait of Georgia bottom sensors, the surface currents as measured by the ONC High Frequency Radar (CODAR) network reveals the strong influence of the Fraser River discharge on surface salinities. HF Radar couples with the conducting ocean surface to carry the signal over the horizon. When surface salinity drops (roughly <14 ppt), HF Radar signals de-couple and the performance of surface current systems such as CODAR drops. Shown in Figure 33-6 is a map showing the percent data coverage for each CODAR cell for 2021, and in Figure 33-7 the significant drop in coverage resulting from the spring freshet and the intense rains of November 2021.

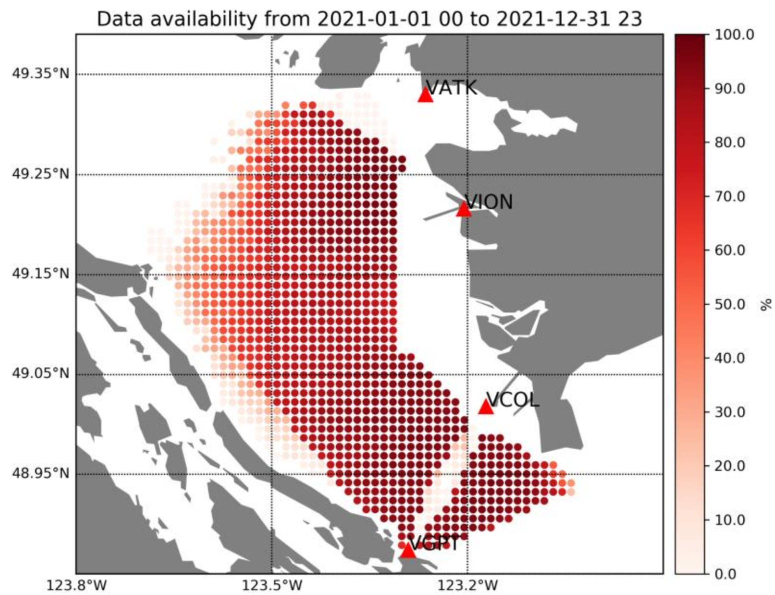


Figure 33-6. A map showing the percent good data for the CODAR surface current grid for 2021. There are roughly 1100 1x1 km grid cells.

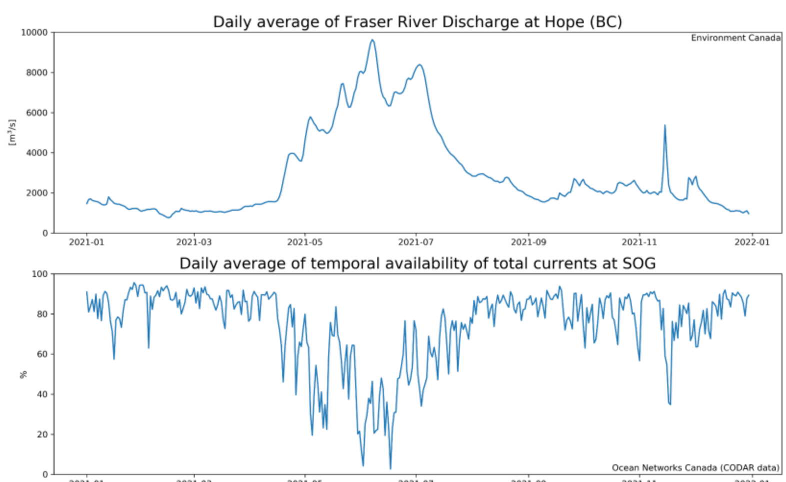


Figure 33-7. The Fraser River discharge at Hope (top) and the percent good CODAR data for the Strait of Georgia.

33.4. Summary

In 2021, the major characteristics recorded by ONC for the southwest coast of Vancouver Island included an early (start March 21) and sustained upwelling season and a large region of low oxygen bottom waters over much of the southern shelf in August 2021. In the Salish Sea, there was a long, 8-month deep water renewal season and significant freshwater discharge into surface waters in both May-June and Oct-Nov, 2021.

33.5. References

Masson, D. 2002. Deep Water Renewal in the Strait of Georgia. Estuarine, Coastal and Shelf Science. 54: 115-126.

NOAA Pacific Fisheries Environmental Laboratories Upwelling Indices: https://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html

Ocean Networks Canada Oceans 3.0 Data Portal:https://data.oceannetworks.ca/home

Soetaert, G., Hamme, R.C., and Raftery, C.E. *In press*. Renewal of seasonally anoxic Saanich Inlet is temporally and spatially dynamic. Frontiers.

34. SPRING PHYTOPLANKTON BLOOM TIMING IN THE STRAIT OF GEORGIA

Susan Allen and Doug Latornell, Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, B.C., sallen@eoas.ubc.ca, dlatornell@eoas.ubc.ca

34.1. Highlights

- The timing of the spring bloom in 2021 was moderately late. The spring bloom timing changed significantly compared to 2020.
- The timing of the 2022 spring bloom is predicted to be average.

34.2. Description of the time series

Here we use a numerical model to show interannual variations in the phytoplankton in the Strait of Georgia (SoG). As described in previous reports, SOG is a vertical one-dimensional physical model coupled to a Nitrate-Diatom biological model (Collins et al. 2009). All lateral oceanographic processes not resolved by the model are parameterized. The model location, STRATOGEM station S3, is on the Tsawwassen to Duke Point ferry route in central SoG (Perry et al. 2021). The model is forced by winds measured at Sand Heads, clouds and temperature measured at YVR (Vancouver) airport and river flow measurements at Hope and the Englishman River or Nanaimo River when the Englishman is not available (e.g., 2021, 2022). The flow at Hope represents the snow melt dominated part of the Fraser River while the Englishman River or Nanaimo River represents all other rivers and the rainfall dominated part of the Fraser River. We have produced a time series of spring bloom time back to 1967 (Allen and Wolfe 2013).

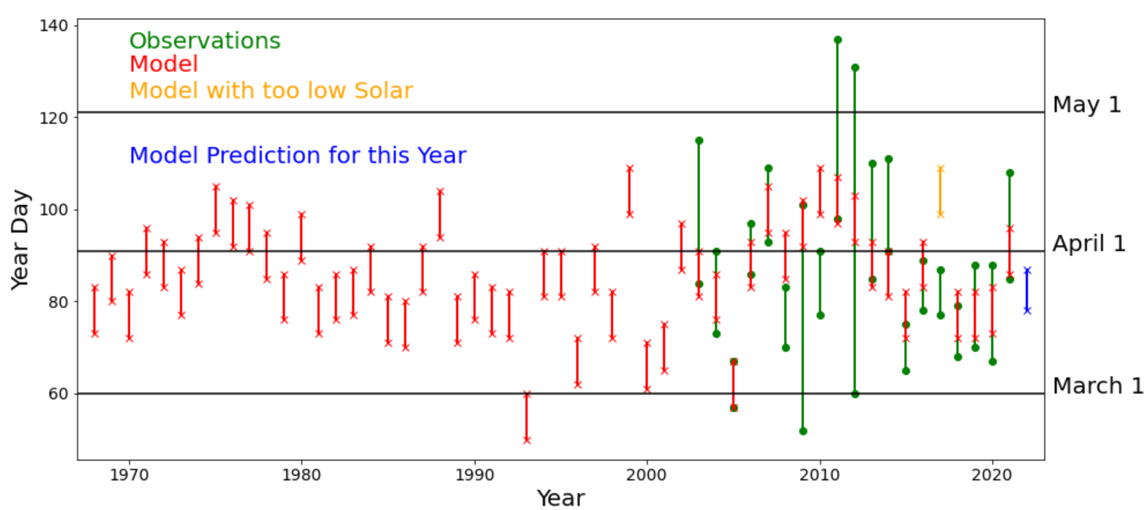


Figure 34-1. Time series of the timing of the peak of the spring phytoplankton bloom. Green- observations from observation systems, see Esenkulova et al., Section 35. Red – SOG model. Orange – SOG model with too little solar radiation (see Allen et al. 2018). Blue –SOG prediction for 2022 as of Mar 19, 2022.

34.3. Status and trends

The 2021 spring bloom happened between March 27 – April 6, 2021 according the SOG model (Figure 34-1). The Pacific Salmon Foundation's Citizen Science program observations showed the spring bloom occurring between March 26 – April 18, 2021 (Figure 34-1; see Esenkulova et al., Section 35). As of March 19, 2022, the 2022 spring bloom is predicted to peak between March 20 – April 1, 2022.

The 2021 spring bloom was moderately late, sitting at the third quartile of dates. The mean/median of the SOG timeseries is March 26/27 with the first quartile on March 18 and the third quartile on April 1. As noted last year, from 2011 – 2020, the spring bloom timing did not vary strongly between years. However, 2020 marks a significant shift to a later spring bloom. This nearly two-week shift is the largest shift since 2006.

34.4. Factors influencing trends

According to the SOG model, the 2021 spring bloom commenced in mid-March as winds decreased after the storms of March 2 – 7, 2021 (Figure 34-2). The bloom was interrupted by a large storm in mid-March and smaller storms into late March suppressed growth. The bloom finally peaked on April 1.

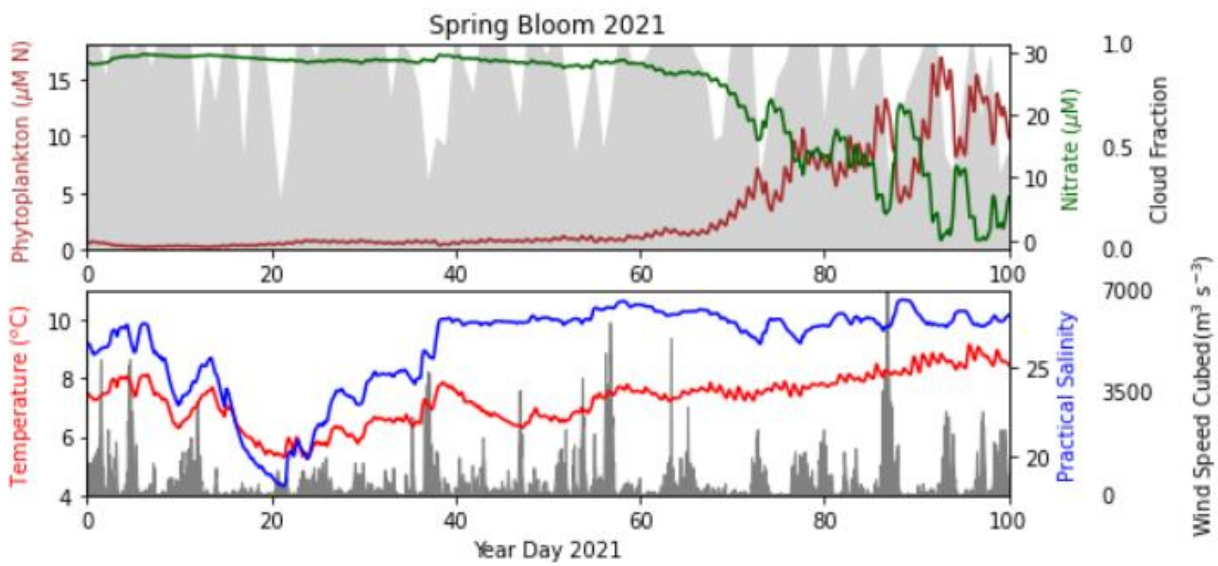


Figure 34-2. Hindcast of the 2021 spring bloom and related conditions in the Strait of Georgia. The lower panel shows temperature (in red) and salinity (in blue) averaged over the upper 3 m of the water column; in grey is the wind-speed cubed which is directly related to the strength of the mixing. The top panel shows phytoplankton biomass (in dark red) and nitrate (in green); in grey is the cloud fraction averaged over the day. The 2021 spring bloom was April 1 plus or minus 5 days. Plots span the period January 1, 2021 to April 10, 2021.

34.5. Implications of those trends

The timing of the spring phytoplankton bloom can impact age-0 herring abundance, with abundance being larger for blooms with typical timing (Boldt et al. 2018). Extreme shifts of timing have led to poor zooplankton growth (e.g., Sastri and Dower 2009) and late spring blooms are also associated with fewer large and medium copepods (Perry et al. 2021). With the 2021 spring bloom on the third quartile and a nearly two-week shift in timing, one might expect a decrease in zooplankton, particularly copepods and age-0 herring abundance. However, these results were not seen in 2021 (Young et al., Section 36; Boldt et al., Section 37). Thus third quartile is perhaps not a late enough spring bloom, and a two-week shift is not large enough, to dominate the response of zooplankton and larval herring.

34.6. References

Allen, S.E., Olson, E., Latornell, D.J., Pawlowicz, R., Do, V., Stankov, K., and Esenkulova, S. 2018. Spring phytoplankton bloom timing, interannual summer productivity. In: Chandler, P.C., King, S.A., and Boldt, J. (Eds.). State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2017. Can. Tech. Rep. Fish. Aquat. Sci. 3266: viii + 245 p.

Allen, S.E., and Wolfe, M.A. 2013. Hindcast of the timing of the spring phytoplankton bloom in the Strait of Georgia, 1968-2010. Prog. Oceanogr. 115: 6-13.

Boldt J., Thompson, M., Rooper, C., Hay, D., Schweigert, J., Quinn, T.J. II, Cleary, J., and Neville, C. 2018. Bottom-up and top-down control of small pelagic forage fish: factors affecting age-0 herring in the Strait of Georgia, British Columbia. Mar. Ecol. Prog. Ser. 617: 53-66.

Collins, A.K., Allen, S.E., and Pawlowicz, R. 2009. The role of wind in determining the timing of the spring bloom in the Strait of Georgia. Can. J. Fish. Aquat. Sci. 66: 1597-1616.

Perry, R.I., Young, K., Galbraith, M., Chandler, P., Velez-Espino, A., and Baillie, S. 2021. Zooplankton variability in the Strait of Georgia, Canada, and relationships with the marine survivals of Chinook and Coho salmon. Plos one. 16(1): e0245941.

Sastri, A.R., and Dower, J.F., 2009. Interannual variability in chitobiase-based production rates of the crustacean zooplankton community in the Strait of Georgia, British Columbia, Canada. Mar. Ecol. Prog. Ser. 288: 147-157.

35. SPRING-SUMMER OCEANOGRAPHIC CONDITIONS AND HARMFUL ALGAL BLOOMS IN THE STRAIT OF GEORGIA 2021

Svetlana Esenkulova[1], Rich Pawlowicz[2], Nicole Frederickson[1], Andrew Ross[3], and Isobel Pearsall[1]

[1] Pacific Salmon Foundation (PSF), Vancouver, B.C., svesen@uvic.ca, nicolehfrederickson@gmail.com, pearsalli@psf.ca
[2] University of British Columbia (UBC), Vancouver, B.C., rich@eos.ubc.ca
[3] Department of Fisheries and Oceans Canada (DFO), Victoria, B.C., Andrew.Ross@dfo-mpo.gc.ca

35.1. Highlights

- Surface waters were slightly warmer/fresher in 2021.
- The spring bloom occurred between 26 March and 18 April 2021, about one week later than averages over the last 20 years.
- There were thick blooms of *Noctiluca scintillans* in April; dinoflagellates *Alexandrium* spp. and *Dinophysis* spp. that can cause paralytic shellfish poisoning and diarrhetic shellfish poisoning, respectively, were very abundant in the March-September period.
- There were no *Heterosigma akashiwo* blooms. There were local summer *Dictyocha* spp. blooms and diatom blooms (*Rhizosolenia setigera*, *Pseudo-nitzschia* spp.), *Ditylum brightwellii* was unusually abundant in June and July.

35.2. Citizen Science Program

A Citizen Science (CitSc) oceanography program has been operated by the Pacific Salmon Foundation (PSF) since 2015. This program includes several dozen trained citizens from different communities throughout the Strait of Georgia. Members are organized into crews working on 7-10 vessels. Technical support is provided by PSF, as well as its partners at Ocean Networks Canada (ONC), Fisheries and Oceans Canada (DFO), and the Universities of Victoria and British Columbia (UBC). Surveys are undertaken across the Strait of Georgia (SoG) on a regular schedule (about 20 times a year). More details about the CitSci program, associated datasets and figures showing oceanographic conditions are provided in Pawlowicz et al. (2020) and the digital "Atlas of oceanographic conditions in the Strait of Georgia" (sogdatacentre.ca/atlas), which is updated annually.

35.3. Description of the time series

In 2021, CitSci sampling occurred at approximately ~55 sites (Figure 35-1) 2 to 3 times a month between February and October with some additional "winter" sampling (19 surveys). Conductivity, temperature, depth, dissolved oxygen, chlorophyl fluorescence (CTD/O_2/Fl) profiles down to 150 m were collected at all stations for a total of 873 profiles. AML© CTD probes were used and raw data were archived by ONC, who also processed these data into 1 m binned profiles. Nutrient samples were collected at two depths (0 and 20 m) at ~30 stations (~1600 nutrient samples in total), phytoplankton samples at the surface at all stations and additional 5, 10, and 20 m at ~30 stations (~1400 phytoplankton samples in total). Surface seawater and filter samples were also collected at 3 stations for biotoxin analysis.

Sample/measurement processing and analysis was done at the PSF, UBC, ONC, and DFO. Phytoplankton samples were analyzed on a Sedgewick-Rafter slide; the identification of specimens was done to the lowest taxonomic level possible and the enumeration (as cells mL^{-1}) was performed for the species or group that was dominant in the sample and species that were known or suspected to have a negative effect on aquaculture in B.C. (Haigh et al. 2004). A complete dataset with additional quality control is available at the Strait of Georgia Data Centre (sogdatacentre.ca).

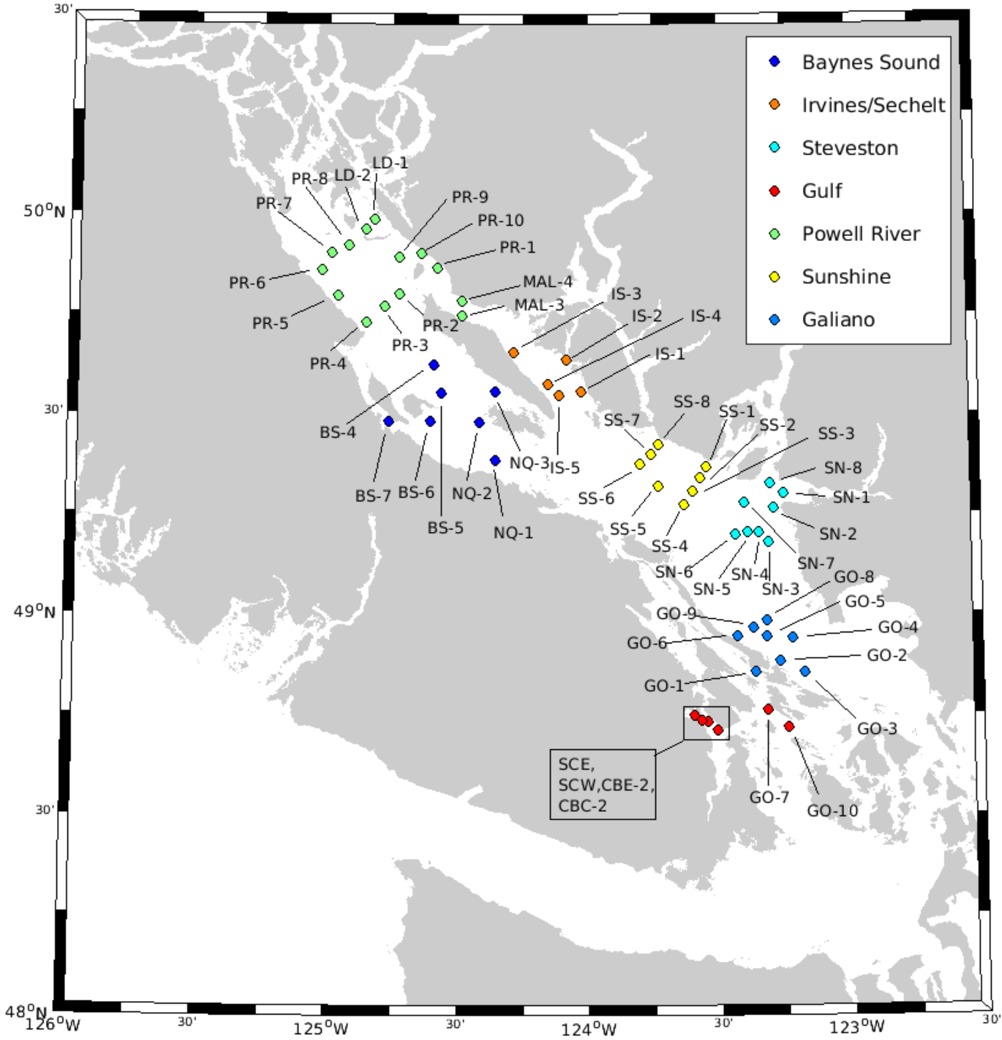


Figure 35-1. Map of the Strait of Georgia with CitSci program sampling locations in 2021. Different colours represent different patrols.

35.4. Status and trends

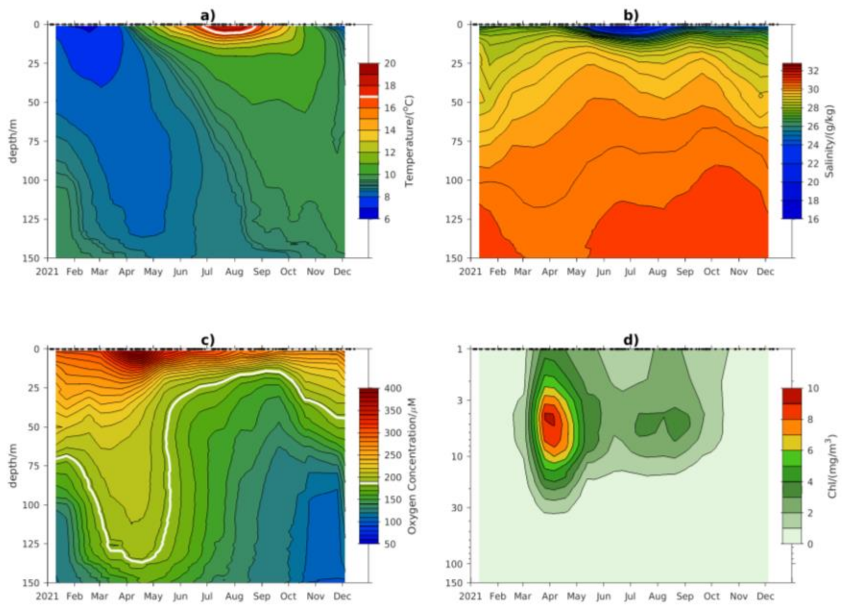


Figure 35-2: Annual cycle for water properties in the Strait of Georgia in 2021. a) Temperature. b) Salinity. c) Dissolved Oxygen. d) Chlorophyll. White lines mark conservative physiological boundaries for salmonids, with a warmest temperature of 17°C in a) and a lowest O_2 of 6ppm or 187 uM in c).

Averaging over the whole Strait, dissolved oxygen levels were less than 6ppm or 187 uM in waters deeper than 15 m depth in late summer (Figure 35-2c). For salmonids in particular, studies found avoidance behaviors at concentrations of 4.5 to 6 ppm (BCMECCS 1997b). B.C. Water Quality Guidelines suggest an acceptable instantaneous oxygen threshold of 5 ppm to prevent harm to all stages of aquatic life (BCMECCS 1997a). Based on expert recommendations, we highlight a slightly more conservative upper limit of 6 ppm (or 187 μM) in our figures. Similarly, temperatures greater than about 17 °C are thought to cause physiological stress in salmonids (US EPA 2003) and the upper 6 m of the water column exceeded this in July and August (Figure 35-2a).

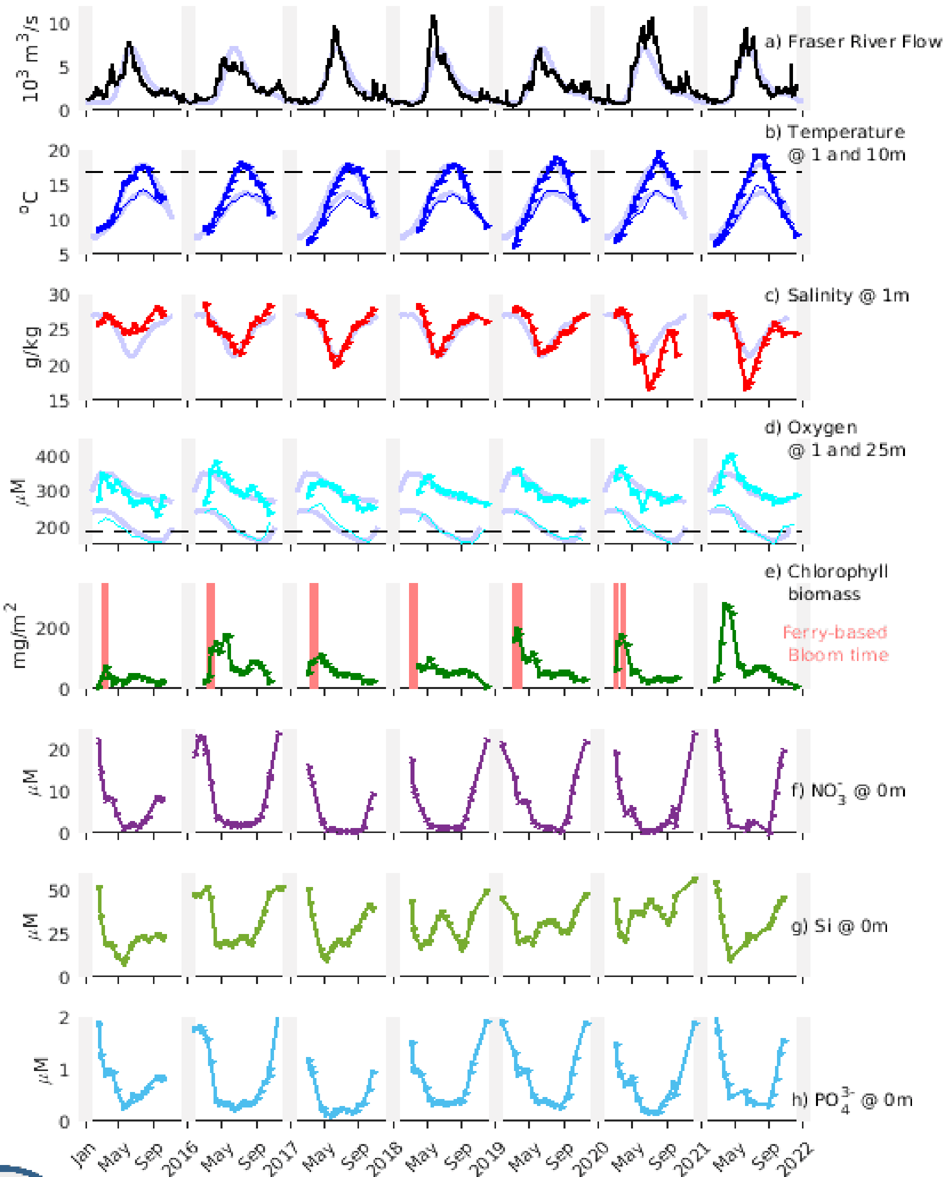


Figure 35-3. Strait-wide trends in surface properties 2015-2021. a) Fraser Riverflow. b) Temperature. c) Salinity. d) Dissolved Oxygen. e) Chlorophyll biomass. f) Nitrate. g) Silicic acid. h) Phosphate.

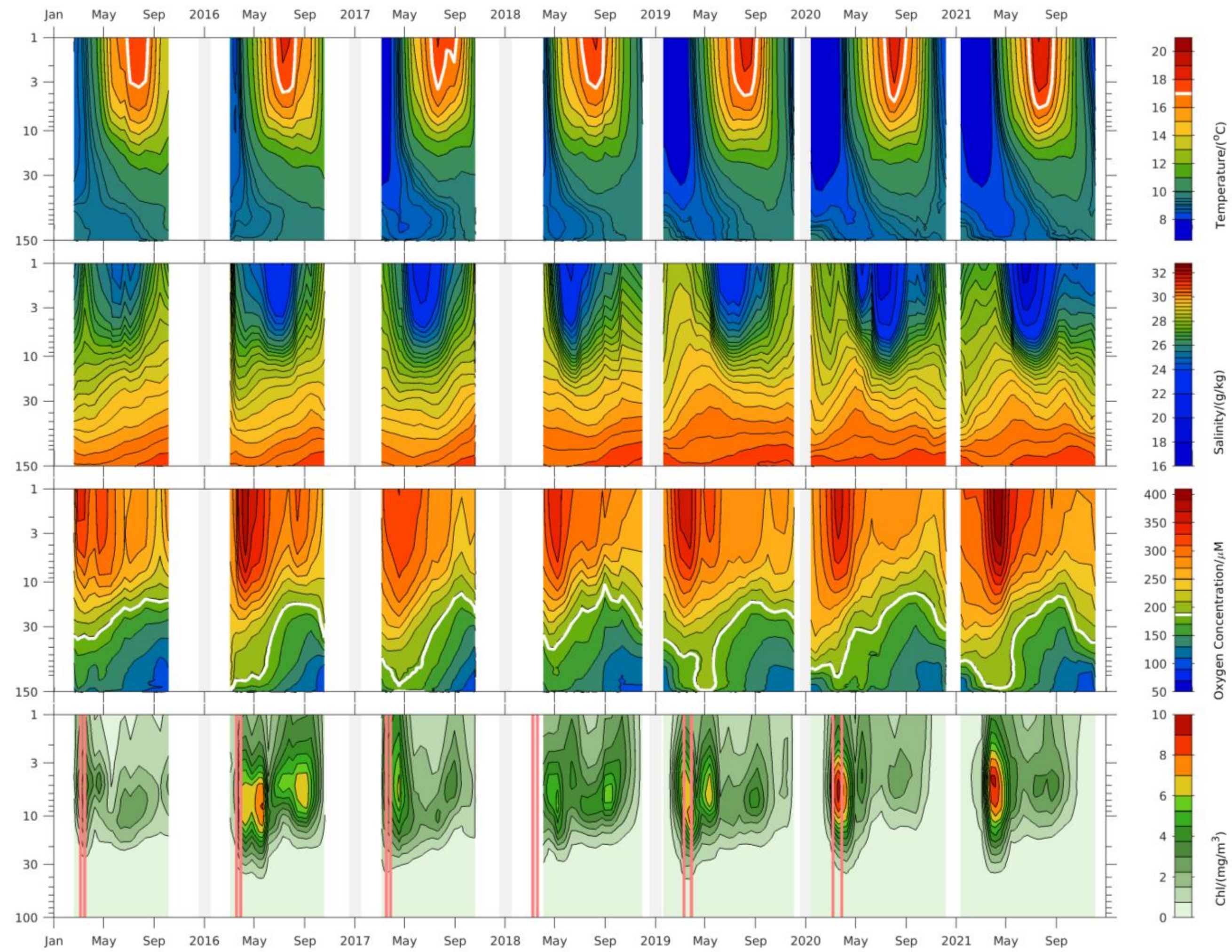


Figure 35-4. Strait-wide trends in water column properties from 2015-2020. From top to bottom: Temperature, Salinity, Dissolved Oxygen and Chlorophyll biomass. Note y-axis scale for depths is logarithmic.

Comparing 2021 to previous years (Figure 35-3), near surface water temperatures in summer were slightly warmer than all years, dissolved oxygen (DO) levels were slightly higher than in 2020, especially in the early summer, and surface salinities were lower, although this may be because the station plan includes more southern Strait stations this year. There is a link between salinities and larger Fraser River flows, especially in mid-summer. Integrating our chlorophyll fluorescence profiles (after calibrating to water samples), we found a large spring bloom between 26 March and 18 April, about a week later than a 20-year average time. Comparison with bloom timing observations from a B.C. monitoring program in the southern Strait operated by Ocean Networks Canada suggests that the CitSci program may not have captured the bloom in some earlier years. Although no ferry observations were available in 2021, the magnitude of the peaks suggests the bloom was captured in 2021. After the bloom, summer phytoplankton biomass was higher in 2021 than in 2020, but not as high as in earlier years. The depth of the mean 17 °C contour (~6 m) was similar to that seen in 2020, but the water reached this level earlier so that the period of warm water was longer than in 2020 (Figure 35-4). However, depths of the 6 ppm DO limit are the same as in previous years. Oxygen levels near the surface were high in all summers, and were particularly high during the spring bloom period, related to the high levels of primary productivity at this time (Wang et al. 2019).

The annual spring bloom was comprised of several diatom species, similar to 2016-2020 (but different from the nearly monospecific spring bloom of 2015). Subsequently multiple algal blooms were noted. Similar to 2018, there were thick, vivid orange blooms of *Noctiluca scintillans* (up to 3200 cells per mL) seen in late April at several coastal areas from Texada Island to Victoria (Figures 35-6 and 35-7). These blooms were seen from space (Figure 35-7). At the same time, *Noctiluca* blooms were also observed in several coastal areas on the other side of the Pacific Ocean (Dr. Tatiana Orlova, personal communication). During the summer

Figure 35-5. Gabriola Island, April 18 2021. photo by D. Backe

Figure 35-7. Gabriola Island, April 18 2021: Image B. Timmer/M. Costa, Spectra Lab.

Figure 38-6. Gabriola Island April 20, 2021. Photo P. Iverson

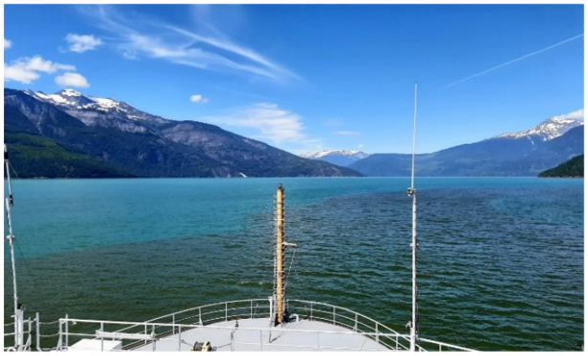


Figure 35-8. Bute Inlet from CCGS Sir John Franklin, June 23, 2021.

DFO juvenile salmon survey a *Heterocapsa triquetra* bloom (up to 9000 cells per mL) was encountered in Bute Inlet (Figures 35-8 and 35-9).

There were no blooms of ichthyotoxic raphidophyte - *Heterosigma akashiwo*. However, there were blooms (up to 150 cells per mL) of silicoflagellate *Dictyocha* in some areas of the Strait in July and August. This situation (*Dictyocha* blooms, no *Heterosigma* blooms) was similar to 2016 and 2017. Also similar to most of the previous years in our time series, there were summer diatom blooms - *Rhizosolenia setigera* (up to 500 cells per mL) and *Pseudo-nitzschia* spp. (up to 1800 cells per mL). Dinoflagellate taxa producing PSP and DSP toxins (*Alexandrium* and *Dinophysis*) were relatively abundant throughout the Strait, however both DSP producing taxa and measured DSP toxins at IS-2 station were generally less abundant in August-October of 2021 than in 2020 (Figure 35-10). Overall, *Dinophysis* abundance in 2021 was the highest in our 7-year time series and similar to 2018 year (second highest). Remarkably, both these years were the ones with *Noctiluca* blooms. A potential link between spring *Noctiluca* blooms and high *Dinophysis* summer abundance in the Strait was noted in 2018 (Esenkulova et al. 2021) and requires further investigation.

For the first time in our seven years of monitoring, *Ditylum brightwellii* was very abundant in June and July as opposed to end of summer and fall. Another unusual SoG algae related event was a first confirmed (by BC Centre for Disease Control) infection in a human caused by *Shewanella* algae which is presumably typical for tropical waters (Nanaimo News).

35.5. Factors influencing trends

Phytoplankton dynamics are directly governed by primary environmental factors. Harmful algae concentrations in SoG are linked to environmental parameters (Esenkulova et al. 2021).

35.6. Implications of those trends

Salmonids are vulnerable to warm waters and hypoxia. The SoG was warm and approached the DO limits for salmonids in several areas at the end of summer 2021. Thick blooms reduce water clarity and led to low dissolved oxygen. Blooms of *Heterosigma* in SoG have been linked to poor salmon returns (Rensel et al. 2010). High abundance of *Alexandrium* and *Dinophysis*

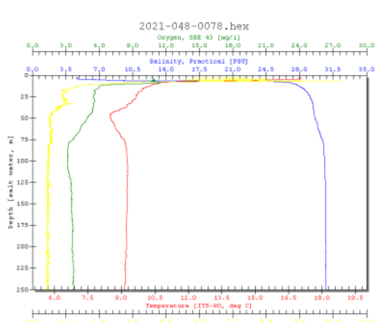


Figure 35-9. CTD cast inside of the bloom, Bute Inlet, June 23 2021. CTD plot by J. Yeongha.

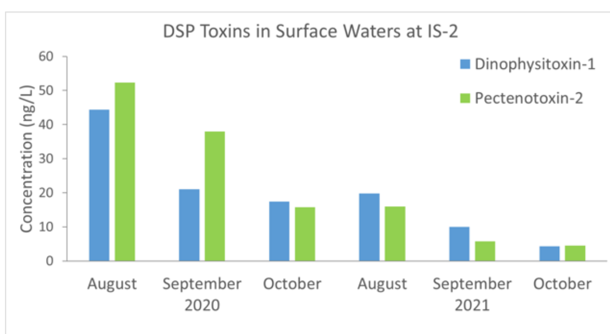


Figure 35-10. Measured DSP toxins at station IS-2 in 2020 and 2021.

can lead to high PSP and DSP toxin concentrations in shellfish. High abundance of *D. brightwellii* was shown to have a negative effect on copepod (*Calanus pacificus*) recruitment patterns in lab conditions (Ban et al. 1997).

35.7. References

BCMECCS. 1997a. British Columbia Ambient Water Criteria for Dissolved Oxygen. Overview Report. BC Ministry of Environment and Climate Change Strategy, Available from https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/ water-quality/water-quality-guidelines, 7 p.

BCMECCS. 1997b. British Columbia Ambient Water Guidelines for Dissolved Oxygen. Technical Report. BC Ministry of Environment and Climate Change Strategy, Available from https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/ water-quality/water-quality-guidelines, 84 p.

US EPA. 2003. EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards. EPA 910-B-03-002. U.S. Environmental Protection Agency, Region 10 Office of Water, Seattle, WA, Available from www.epa.gov/r10earth/temperature.htm, 57 p.

Wang, C., Pawlowicz, R., and Sastri, A. 2019. Diurnal and seasonal variability of near-surface oxygen in the Strait of Georgia. J. Geophys. Res. 124: 2418-2439, DOI: 10.1029/2018JC014766.

Ban, S., Burns, C., Castel, J., Chaudron, Y., Christou, E., Escribano, R., and Wang, Y. 1997. The paradox of diatom-copepod interactions. *Marine Ecology Progress Series*. 157: 287-293.

Esenkulova, S., Suchy, K.D., Pawlowicz, R., Costa, M., and Pearsall, I.A. 2021. Harmful Algae and Oceanographic Conditions in the Strait of Georgia, Canada Based on Citizen Science Monitoring. *Frontiers in Marine Science*. 1193.

Haigh, N., Whyte, J.N.C., and Sherry, K.L. 2004. Biological and oceanographic data from the harmful algae monitoring program associated with salmon farm sites on the west coast of Canada in 2003. Can. Data Rep. Fish. Aquat. Sci. 1158: v + 157p.

Nanaimo News. *https://www.nanaimobulletin.com/news/denman-island-mans-infection-from-rare-bacteria-raising-questions/* Retrieved August 9, 2021.

Pawlowicz, R., Suzuki, T., Chappel, R., and Esenkulova, S. 2020. Atlas of Oceanographic Conditions in the Strait of Georgia (2015–2019) based on the Pacific Salmon Foundation's Citizen Science Dataset. Can. Tec. Rep. Hydrogr. Ocean Sci. 3374: vii + 116 p.

Rensel, J.J., Haigh, N. and Tynan, T.J., 2010. Fraser river sockeye salmon marine survival decline and harmful blooms of Heterosigma akashiwo. *Harmful Algae*. *10*(1): 98-115.

36. ZOOPLANKTON STATUS AND TRENDS IN THE CENTRAL AND NORTHERN STRAIT OF GEORGIA, 2021

Kelly Young[1], Moira Galbraith[1], Akash Sastri[1], and R. Ian Perry[2]

[1]Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Kelly.Young@dfo-mpo.gc.ca, Moira.Galbraith@dfo-mpo.gc.ca, Akash.Sastri@dfo-mpo.gc.ca
[2]Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C. and Pacific Biological Station, Nanaimo, B.C., Ian.Perry@dfo-mpo.gc.ca

36.1. Highlights

- 2021 zooplankton biomass was highest in May as there was lower than average biomass in July.
- Small copepods dominated by numbers (abundance), but 'fish food' plankton (medium-large calanoids, euphausiids and amphipods) had a higher contribution by biomass.
- Overall zooplankton biomass has been increasing, with 2021 having higher than average biomass (preliminary).

36.2. Description of the time series

Zooplankton samples have been collected at approximately 20 standardized stations monthly from February to October since 2015, with historic (but sporadic sampling effort) data going back to 1995.

For this report, we described current trends of abundance (m^{-3}) and biomass (mg m^{-3}) as monthly averages of all samples processed in 2021 in the deep (bottom depths greater than 50 m, and vertical net haul samples which covered over 70% of the water column) central and northern Strait of Georgia (averaged together, Figure 36-1). Data were restricted to the central and northern regions as they have the most complete time series available at this time. Sample processing is ongoing to fill in the other regions, and the results are preliminary.

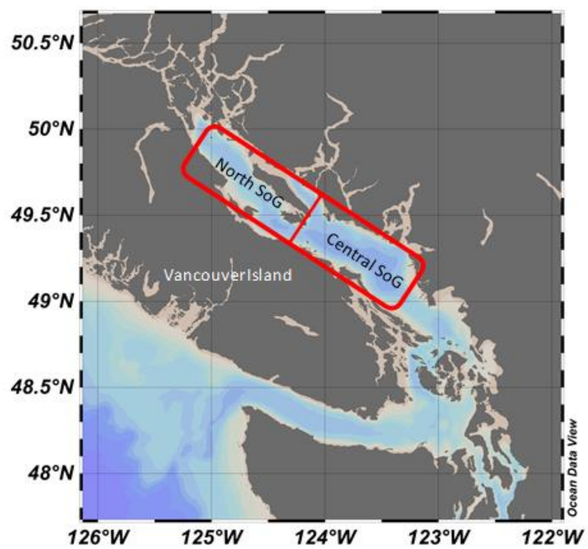


Figure 36-1. The central and northern Strait of Georgia (SoG) shown by the red boxes.

For historical comparison, the seasonal variability in the zooplankton data was removed by calculating a regional, log-scale biomass anomaly for selected species for a given year. A multi-year (1996-2021; previous reports used 1996-2010) average seasonal cycle ("climatology") was calculated as a baseline to compare monthly conditions during any single year. Seasonal anomalies were then averaged within each year to give an annual anomaly (Mackas et al. 2013; Perry et al. 2021).

36.3. Status and trends

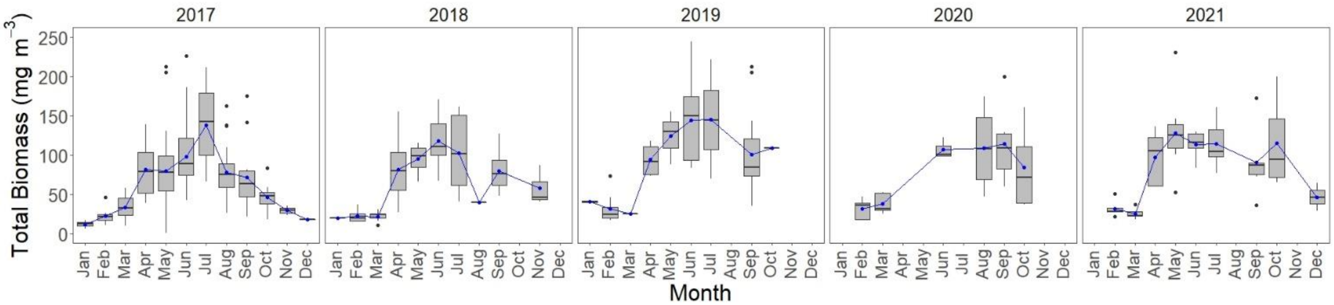


Figure 36-2. Average total biomass (mg m^{-3}) of zooplankton by month in the north and central (averaged together) Strait of Georgia for 2017-2021. Boxplots show median and spread of data, blue dot and line follows the mean biomass.

The total zooplankton biomass in 2021 ranged from 18.1- 230.7 mg m^{-3}, with the lowest biomass occurring in the winter and peaking in the late spring (May; Figure 36-2). The May 2021 peak was similar to 2019 and higher than 2017-2018 and 2020 May values. The summer 2021 biomass was lower; however, no samples were collected in July 2020 or Aug 2021 (Figure 36-2).

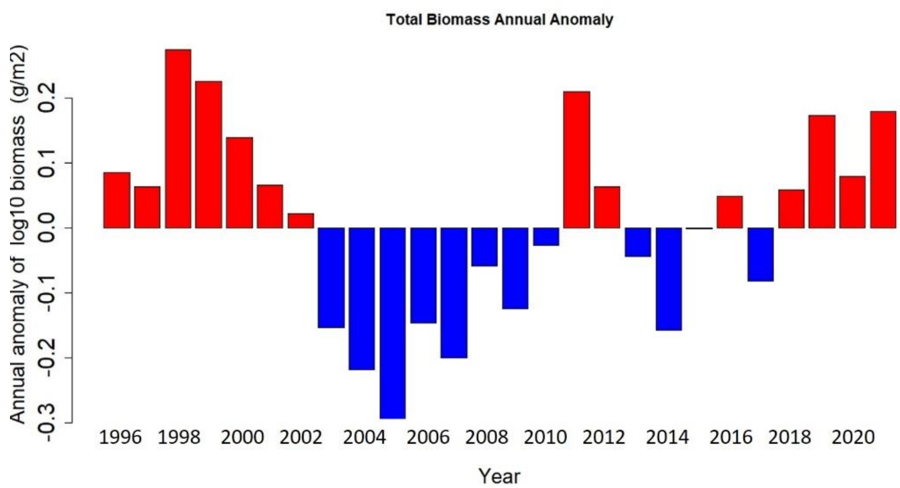


Figure 36-3. Annual biomass anomalies of total zooplankton biomass in the deep waters of the central and northern Strait of Georgia, 1996-2021.

Overall, total biomass was above average in 2021 (Figure 36-3).

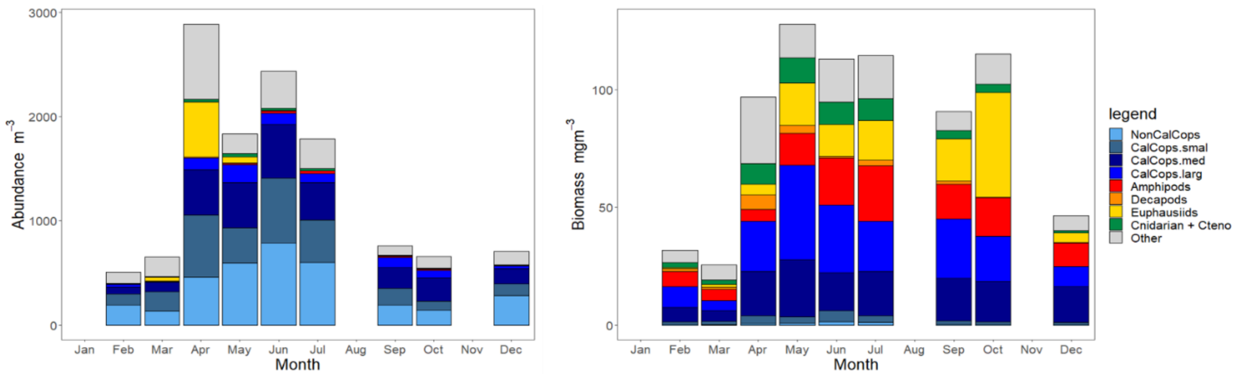


Figure 36-4. Taxonomic composition of zooplankton from northern and central Strait of Georgia in 2021, averaged by month. Left: abundance (m^{-3}); Right: biomass (mg m^{-3}). Legend: CalCops.larg – calanoid copepods, prosome length (PL)>3mm; CalCops.med – calanoid copepods PL 1-3mm; CalCops.smal – calanoid copepods PL <1mm; NonCalCops – all other copepods; Amphipods – all amphipods (hyperiid and gammarid); Decapod – all decapods (shrimp, crab larvae); Euphausiid – all euphausiids (eggs, larvae and adults); Cnidarian + Cteno – all Cnidarian (medusa and siphonophores) and Ctenophores; Other – everything else: Molluscs, Polychaetes, Chaetognaths, Ichthyoplankton, Larvaceans, etc.

The peak timing of the abundance and biomass of the zooplankton in the SoG varied by species (Figure 36-4), and followed similar trends as previous years (e.g. Young et al. 2020). Copepods, particularly calanoid copepods, dominated the zooplankton by abundance (Figure 36-4, left). Medium- and large-body calanoid copepods and the larger crustaceans (euphausiids and amphipods) dominated the biomass (Figure 36-4, right). The composition of the medium and large-sized copepods was similar to 2020 (Young et al. 2020), with *Eucalanus bungii* making up the majority of the copepod biomass. Euphausiid biomass in 2021 was lower than average in summer, and higher than average in October (Figure 36-5).

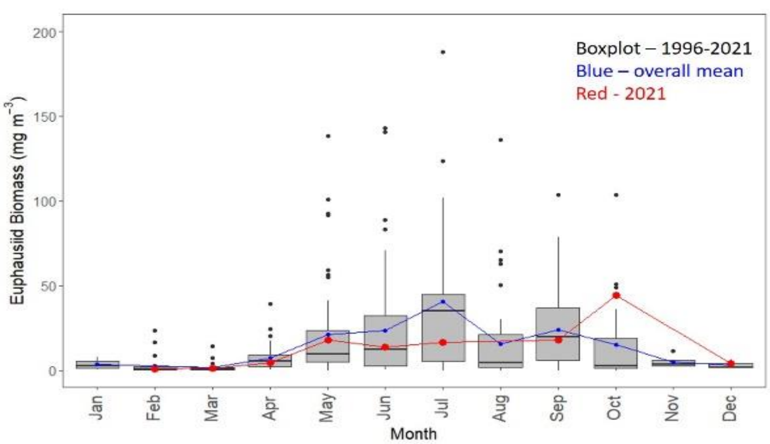


Figure 36-5. Average biomass (mg m^{-3}) of euphausiids (all stages) for 1996-2021. Boxplots show median and spread of data, blue dot and line follows the mean biomass. Red dot and line represent 2021 data.

36.4. Factors influencing trends

Trends in zooplankton composition and biomass have been linked to large scale climate indices (Li et al. 2013; Mackas et al. 2013; Perry et al. 2021), as well as local factors such as timing of the Fraser River freshet (Mackas et al. 2013), sea surface salinity and timing of the peak date of the spring phytoplankton bloom (Perry et al. 2021).

36.5. Implications of those trends

Medium and large sized crustaceans (calanoid copepods, euphausiids and amphipods) dominated the total biomass of zooplankton in the Strait, and variations in these groups over time have been shown to be important variables in the modeled marine survival of some Chinook and Coho Salmon populations that enter the Strait as juveniles (Figure 36-6; Perry et al. 2021). A consistent zooplankton monitoring program in the Salish Sea can assist with projections of future abundances of juvenile salmon.

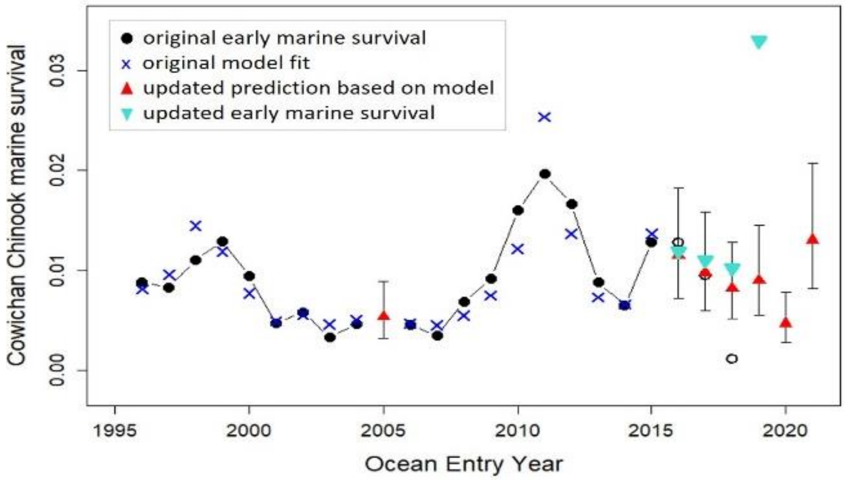


Figure 36-6. Modelled early marine survival of Cowichan River Chinook, updated from Perry et al., 2021 (their Fig. 9). Updated preliminary Chinook early marine survival for 2016-2019 are from TCCHINOOK 2021-05.

36.6. References

Li, L., Mackas, D. Hunt, B, Schweigert, J., Pakhomov, E., Perry, R.I., Galbraith, M., and Pitcher, T.J. 2013. Large changes in zooplankton communities in the Strait of Georgia, British Columbia, covary with environmental variability. Progr. Oceanogr. 115: 90-102.

Mackas, D.L, Galbraith, M., Faust, D., Masson, D., Young, K., Shaw, W., Romaine, S., Trudel, M., Dower, J., Campbell, R., Sastri, A., Bornhold Pechter, E.A., Pakhomov, E., and El-Sabaawi, R. 2013. Zooplankton time series from the Strait of Georgia: Results from year-round sampling at deep water locations, 1990–2010. Progr. Oceanogr. 115: 129-159.

Perry, R.I., Young, K., Galbraith, M., Chandler, P., Velez-Espino, A., Baillie, S. 2021. Zooplankton variability in the Strait of Georgia, Canada, and relationships with the marine survivals of Chinook and Coho salmon. PLoS ONE 16(1): e0245941. https://doi.org/10.1371/journal.pone.0245941

TCCHINOOK. 2020 Exploitation Rate Analysis. Pacific Salmon Commission, Joint Chinook. Technical Committee Report. Report TCCHINOOK (2021)-05. 2021. Available at www.psc.org/publications/technical-reports/technical-committee-reports/chinook/

Young, K., Galbraith, M., and Perry, I. 2020. Zooplankton status and trends in the central and northern Strait of Georgia, 2019. In: Boldt, J.L., Javorski, A., and Chandler, P.C. (Eds.). 2020. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3377: x + 288 p

37. STRAIT OF GEORGIA JUVENILE HERRING SURVEY

Jennifer L. Boldt[1*], Matt Thompson[1], Hilari Dennis-Bohm[1], Matthew H. Grinnell[1], Jaclyn Cleary[1], Chris Rooper[1], Jake Schweigert[2], Doug Hay[2]

[1]Fisheries and Oceans Canada, Pacific Biological Station, B.C., [*]Jennifer.Boldt@dfo-mpo.gc.ca
[2]Emeritus, Fisheries and Oceans Canada, Pacific Biological Station, B.C.

37.1. Highlights

- The index of the relative biomass of age-0 herring in 2021 was similar to that observed in 2019, but still below the time series mean and median.
- Age-0 herring were smaller than average, but their condition was above average.
- Northern Anchovy were present in 48% of the fishing sets in 2021; this is the second highest percentage in the time series.

37.2. Description of indices

The Strait of Georgia (SoG) juvenile (age-0) Pacific Herring survey is a monitoring program that samples the nearshore pelagic fish community, the zooplankton community, and physical water column properties. A goal of the survey is to estimate an index of the relative biomass (abundance) of age-0 herring as a potential predictor of the abundance of age-3 herring recruits estimated in the annual stock assessment model. This index may also represent trends in potential prey availability to Coho and Chinook Salmon and other predators.

Ten core transects, each with three to five core stations (total 48 core stations), distributed around the perimeter of the SoG, have been sampled consistently during September-October since 1992 (except 1995 and 2020; Thompson et al. 2013; Thompson et al. 2003; Boldt et al. 2015; Figure 37-1). In 2021, two transects were added. Sampling was conducted after dusk when herring were near the surface with purse seine sets at predetermined stations. Species' catch weights were estimated and, in the laboratory, fish were sorted to species, weighed, and measured (nearest mm). The age-0 herring index of catch weight per-unit-effort (CPUE and associated variance) was calculated using Thompson's (1992) two-stage (transect, station) method and variance estimator (see Boldt et al. 2015). In addition, herring condition was calculated as residuals from a double-log-transformed length-weight regression (Boldt et al. 2019). In 2021 scientific echosounder data were collected at core transects to supplement the survey. These data along with acoustic moorings and stereo-optic camera collections will be presented in future contributions.

37.3. Status and trends

In 2021, 40 of the 48 core stations plus 5 stations on one new transect were sampled. Weather prevented sampling of some stations. Age-0 herring were caught in 26 of the 45 stations sampled (Figure 37-1). Estimates of age-0 catch weight CPUE varied annually, with no overall linear trend during 1992-2021 (Figure 37-1). The age-0 herring index tended to peak every two or three years, with the peaks occurring in even years during 2004-2012. During 2013-2021, the index was intermediate-low compared to the peaks in the time series. In 2021, the index (excluding the new transect) was similar to that observed in 2019, but still below the time series mean and median. High estimates of variability are associated with peak estimates; the survey coefficient of variation (CV) was 0.48.

Age-0 herring length-weight residuals increased during 1997-2012, and were positive in 2005 and 2007-2021 (Figure 37-1). However, the average length and weight of age-0 herring was low compared to all previous years (Figure 37-1). In 2021, Northern Anchovy were present in many sets; they were caught at 24 of 45 stations sampled, which was the second highest proportion of sampled stations observed in the time series, following 2017 (Figure 37-2).

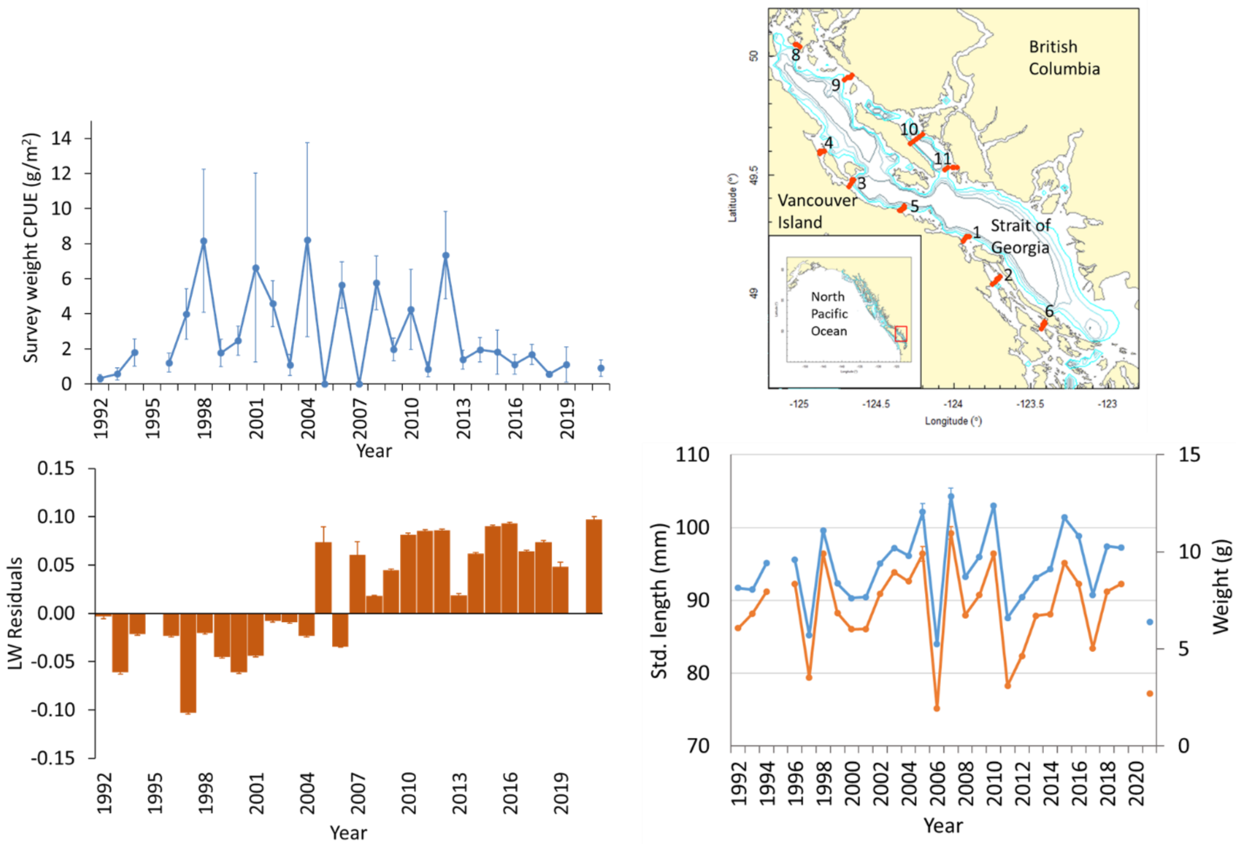


Figure 37-1. Mean catch weight per-unit-effort (CPUE; top left panel), mean condition (residuals from a double log-transformed length-weight regression; bottom left panel), and standard lengths (orange line) and weights (blue line; bottom right panel) of age-0 Pacific Herring in the Strait of Georgia at core transects and stations (top right panel) during 1992-2021 (no survey in 1995 or 2020; Boldt et al. 2015). Standard error bars are shown.

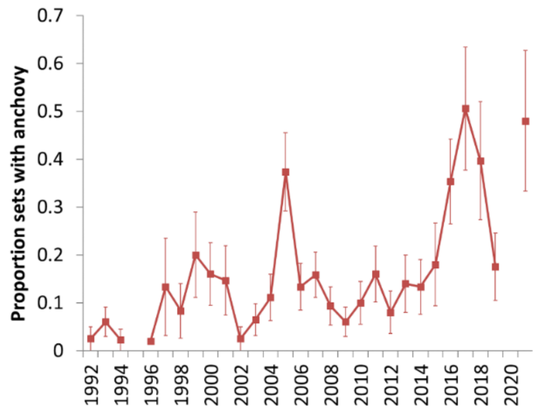


Figure 37-2. Proportion of purse seine sets that contained Northern Anchovy, 1992-2021 (no survey in 1995 and 2020). Time series updated from Duguid, et al. 2019. Standard error bars are shown.

37.4. Factors causing trends

Bottom-up processes (prey-driven) are the main factors affecting the interannual variability in age-0 herring abundance and condition (Boldt et al. 2018). Bottom-up factors include zooplankton prey availability, herring spawn biomass, temperature, and the date when most herring spawn relative to the spring bloom date. The timing or match-mismatch between spawning herring and subsequent availability of prey to juveniles appears to be important in determining abundance of age-0 herring in the fall (Schweigert et al. 2013; Boldt et al. 2018). In a previous study, no negative effects of the juvenile salmon competitors or predators were detected on age-0 herring abundance (Boldt et al. 2018), implying that when conditions are good for age-0 herring, they are also good for juvenile salmon species. Herring recruitment and survival has also been linked to water temperatures (Tester 1948; Ware 1991) and bottom-up control of production (Ware and Thompson 2005; Perry and Schweigert 2008; Schweigert et al. 2013).

37.5. Implications of trends

Age-0 herring survey indices may provide a leading indicator of low recruitment years. In 2005 and 2007, there were low age-0 and subsequent low age-3 recruit abundances. Juvenile and adult Pacific Herring are prey for piscivorous fish, marine mammals, and seabirds and are important commercial species in B.C.'s coastal waters. Changes in herring abundance may affect availability to commercial fisheries as well as the survival of predators, such as Coho and Chinook Salmon. Age-0 herring in better condition may be more energy dense (Paul et al. 1998; Boldt and Rooper 2009). Fish that have a higher energy density have an improved chance at surviving reduced feeding opportunities during winter (Paul et al. 1998; Foy and Paul 1999) and they present a more energy-rich prey for predators. Understanding trends in the populations of small pelagic fish species and factors that affect their abundance and condition requires long-term monitoring of the nearshore pelagic ecosystem.

37.6. Acknowledgments

In memory of and with thanks to Doug Henderson for many years of hard work and good cheer as skipper and to Dr. Terrance J. Quinn II for his support with initial analyses. The 2019 Strait of Georgia juvenile herring survey was funded by the Department of Fisheries and Oceans; some previous surveys were partially funded by the Herring Conservation and Research Society and the Pacific Salmon Foundation. Thank-you to skipper Phil Dupuis for helping with the survey in 2019 and 2021.

37.7. References

Boldt, J.L., and Rooper, C.N. 2009. Abundance, condition, and diet of juvenile Pacific ocean perch (*Sebastes alutus*) in the Aleutian Islands. Fish. Bull. 107(3): 278-285.

Boldt, J.L., Thompson, M., Fort, C., Rooper, C.N., Schweigert, J., Quinn II, T.J., Hay, D., and Therriault, T.W. 2015. An index of relative biomass, abundance, and condition of juvenile Pacific Herring (*Clupea pallasi*) in the Strait of Georgia, British Columbia. Can. Manuscr. Rep. Fish. Aquat. Sci. 3081: x + 80 p.

Boldt, J.L, Thompson, M., Rooper, C.N., Hay, D.E., Schweigert, J.F., Quinn, T.J. II, Cleary, J.S., Neville, C.M. 2018. Bottom-up and top-down control of small pelagic forage fish: factors affecting age--0 herring in the Strait of Georgia, British Columbia. Mar. Ecol. Prog. Ser. https://doi.org/10.3354/meps12485.

Boldt, J.L., Thompson, M., Grinnell, M.H., Cleary, J., Dennis-Bohm, H., Rooper, C., Schweigert, J., Quinn II, T.J., Doug, D. 2019. Strait of Georgia juvenile herring survey. p. 151-155 In. Boldt, J.L., Leonard, J., Chandler, P.C. (Eds.). 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.

Duguid, W.D.P., Boldt, J.L., Chalifour, L., Greene, C.M., Galbraith, M., Hay, D., Lowry, D., McKinnell, S., Qualley, J., Neville, C., Sandell, T., Thompson, M., Trudel, M., Young, K., and Juanes, F. 2019. Historical fluctuations and recent observations of Northern Anchovy *Engraulis mordax* in the Salish Sea. Deep Sea Research II: Topical Studies in Oceanography. 159: 22-41. 10.1016/j.dsr2.2018.05.018.

Foy, R.J., and Paul, A.J. 1999. Winter feeding and changes in somatic energy content of age-0 Pacific Herring in Prince William Sound, Alaska. Trans. Am. Fish. Soc. 28: 1193-1200.

Paul, A.J., Paul, J.M., and Brown, E.D. 1998. Fall and spring somatic energy content for Alaskan Pacific herring (*Clupea pallasi* Valenciennes 1847) relative to age, size and sex. J. Exper. Mar. Biol. and Ecol. 223: 133-142.

Perry, R. I., and Schweigert, J.F. 2008. Primary productivity and the carrying capacity of herring in NE Pacific marine ecosystems. Progress in Oceanography. 77: 241–251.

Schweigert, J.F., Thompson, M., Fort, C., Hay, D.E., Therriault, T.W., and Brown, L.N. 2013. Factors linking Pacific herring (*Clupea pallasi*) productivity and the spring plankton bloom in the Strait of Georgia, British Columbia, Canada. Progress in Oceanography. 115: 103-110.

Tester, A.L. 1948. The efficacy of catch limitation in regulating the British Columbia herring fishery. Transactions of the Royal Society of Canada, Vol. XLII: Series III: 135-163.

Thompson, S.K. 1992. Sampling. John Wiley and Sons, Inc. New York. 343 p.

Thompson, M., Hrabok, C. Hay, D.E., Schweigert, J. Haegele, C., and Armstrong, B. 2003. Juvenile herring surveys: methods and data base. Can. Manuscr. Rep. Fish. Aquat. Sci. 2651: 31 p.

Thompson, M., Fort, C., and Schweigert, J. 2013. Strait of Georgia juvenile herring survey, September 2011 and 2012. Can. Manuscr. Rep. Fish. Aquat. Sci. 3016: vi + 63 p.

Ware, D.M., 1991. Climate, predator and prey: behavior of a linked oscillating system, pp. 279–291. In: Kawasaki, T. (Ed.), Long-term Variability of Pelagic Fish Populations and their Environment. Pergamon Press, Tokyo.

Ware, D., and Thomson, R. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the northeast Pacific. Science. 308: 1280-1284.

38. JUVENILE SALMON IN THE STRAIT OF GEORGIA 2021

Chrys Neville, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, B.C., Chrys.Neville@dfo-mpo.gc.ca

38.1. Highlights

- In the summer of 2021, the CPUE of Coho Salmon was one of the highest observed in the time series. Fall CPUE of Coho Salmon was similar to high values consistently reported since 2010.
- Chum CPUE was above average in the summer survey and one of the three largest observed in the fall survey.
- Catch of Northern Anchovy and Spiny Dogfish was lower than recent years.

38.2. Description of the time series

Most juvenile salmon enter the SoG from April to June. The juvenile trawl surveys conducted by the Salmon Marine Interactions Program are designed to sample juvenile salmon throughout the Strait of Georgia (SoG) in the early summer, shortly after they enter the ocean and in the fall, after their first marine summer. As many juvenile salmon remain and rear in the SoG until the fall, the two surveys provide the ability to examine changes in the condition of the fish over this important early marine period. In 2021, both the summer and fall surveys were completed but had reduced science staff due to Covid protocols. The Canadian Coast Guard Ship (CCGS),Sir John Franklin, completed the summer survey and the charter vessel Nordic Pearl conducted the September survey. Both vessels fished with the same gear following following survey protocols. The LFS 7742 net was used for the second time in the 23-year survey. This net has a similar mouth opening size and codend mesh size as the Cantrawl 350 which was fished until 2019. A comparison of the gear was completed in 2018 and suggested similar catchability (Anderson et al. 2019). However, as this is only the second year using this gear, the 2021 results should be interpreted with caution when comparing to historic data fished with the Cantrawl 350 net.

In 2021, the standard track line was fished using the protocols in Beamish et al. (2010) and Sweeting et al. (2003). Catch-per-unit-effort (CPUE) was calculated using trawl sets conducted on this standard track line covering the main basin of the SoG (Canadian waters) and integrated across known species-specific habitat depths (Chinook Salmon 0-60 m, Coho Salmon 0-45 m, Pink, Chum and Sockeye Salmon 0-30 m) (Beamish et al. 2000; Sweeting et al. 2003). For the given sets, the total catch and area surveyed was used to calculate average catch per hour. In addition to CPUE, change in the average length of juvenile salmon in both the summer and fall surveys over the 23-year time series is examined.

38.3. Status and Trends

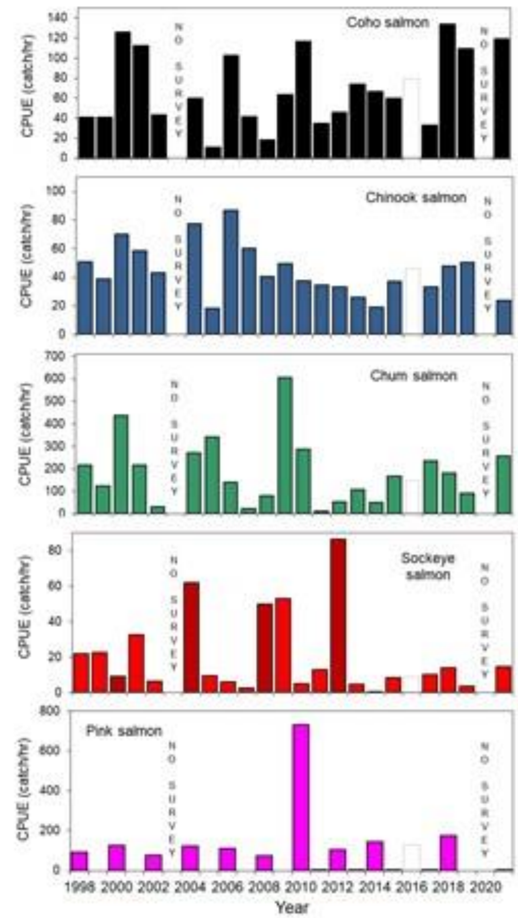


Figure 38-1. CPUE of ocean age 0 salmon in June-July 1998-2021. The survey in 2016 was late and is not considered in time series. Note y axis differ between species.

In the summer of 2021, the CPUE of Coho Salmon was one of the three highest observed in the time series since 1998 (Figure 38-1). In the fall, the trend of high CPUE that started in 2010 (Beamish and Neville 2021) continued (Figure 38-2). Additionally, the size of the Coho Salmon was above average and followed the trend that has occurred since 2010. In the summer the Chinook Salmon CPUE was below average for the time series but average for the past decade. The fall CPUE was less than 50% of the observed value in 2020 but remained above average for the time series. It is important to note that summer and fall catches have different stock compositions with late ocean entry South Thompson stocks dominating in the fall. Therefore, changes in CPUEs of Chinook Salmon cannot be directly compared between seasons. However, in 2021 the South Thompson stocks declined from an average of 70% of the catch to less than 50% of the juveniles sampled. Additional analysis is required to determine if this shift is due to a decline in the abundance of South Thompson Chinook Salmon or an improved summer survival of other stocks. The CPUE of Chum Salmon in the summer has been variable over the past decade. This continued in 2021 and although average for the time series, it was the highest since 2010. In September the CPUE was the third largest observed since 1998 and, with the exception of 2019, was about four to five times larger than that of the past decade.
Sockeye Salmon typically return as four year old fish and have four cycle lines with varying levels of production. We therefore compare the 2021 juveniles to juveniles that entered the ocean in 2017, 2013, 2009 etc. In 2001, the CPUE of Sockeye Salmon in June was improved over recent years (2013, 2017) but remained lower than earlier years (2009 and 2001). In September, Sockeye Salmon in the SoG are dominated by the ocean type Harrison stock representing on average 70% of the catch. These ocean type fish enter the ocean in the year they emerge and have a different ocean entry and ocean migration pattern that differs from most other Fraser River Sockeye salmon. In 2021, the catch of these fish within the SoG remained low, but was the highest since 2014. Pink Salmon was not a dominant run year for the Fraser River stocks entering the SoG and were therefore not expected in large numbers in 2021.

In addition to salmon, other species are captured in the survey. In 2021 there were some notable changes. Northern Anchovy, that had been abundant for several years up to 2019, were only caught in small numbers (< 100) within the standard track line. Larger abundances were observed in Desolation Sound in the fall. Additionally, the catch of Spiny Dogfish continued to be low in both surveys.

The size and condition of juvenile salmon, especially Coho Salmon, suggested good early marine growth for this species within the SoG. Although there was a decline of Chinook Salmon from a very high observation in 2020, the CPUE remained above average for the survey years Only a proportion of Chum Salmon remain in the SoG in the fall, however they continue to be the most abundant salmon species by number in this inland sea. With no information on stock structure of this species in our surveys, it is unknown if the increase observed was a trend from all stocks or was influenced by a few stocks.

38.4. Factors influencing trends

Changes and fluctuations in the 23-year time series demonstrates that there were both interannual changes and longer-term trends in the abundance, distribution, and condition of juvenile salmon rearing in the SoG. Changes and trends observed in the catch rates and distribution and size of juvenile salmon in the SoG over time indicate that factors regulating these are not random. Several hypotheses suggest that growth and energy storage during the first marine summer are directly related to the ability of fish to survive their first marine winter and affect their total marine survival. The shift in trend of both Coho Salmon abundance and size in 2010 (Beamish and Neville 2021) and shift in plankton production within the SoG around a similar time period (Perry et al. 2021) suggests distinct production periods occur within the Strait of Georgia. Identifying the shifts or changes between the production periods are important in understanding changes in salmon and other small pelagic productivity.

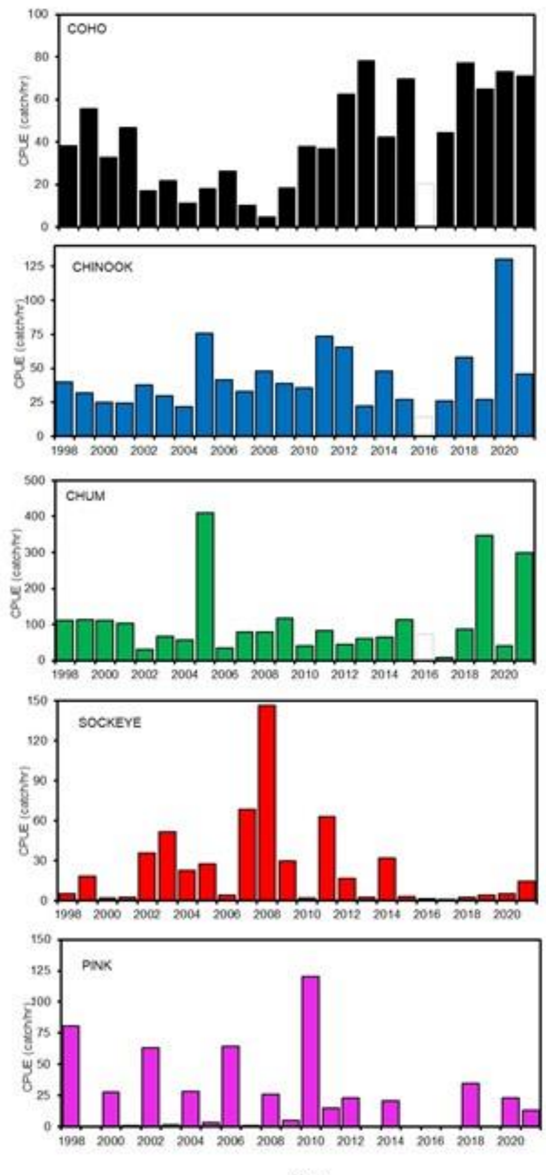


Figure 38-2. The CPUE of ocean age-0 salmon in the September survey 1998-2021.

38.5. Implications of those trends

A productivity shift in the SoG for Coho Salmon around 2010 resulted in increased CPUE and size of the juveniles by September (Beamish and Neville 2021). There was increased variability between the abundance of these juveniles in the fall and subsequent returns, suggesting that conditions after the first marine winter may have also increased variability. Declines in the catch of juvenile Chinook Salmon and increases in Chum

Salmon require further research but the ability to understand the drivers of these changes and the implications to total marine survival may provide new tools to facilitate early forecasts of the marine residence of these species.

38.6. References

Anderson, E.D., Zubkowski, T.B. and King, J.R. 2019. Comparison of Juvenile Salmon Catch in Cantrawl 250 and LFS 7742 Mid-Water Trawl Nets. Can. Tech. Rep. Fish. Aquat. Sci. 3306: v + 87 op.

Beamish, R.J., and Neville, C.M. 2021. The natural regulation and relevance of wild and hatchery Coho Salmon production in the Strait of Georgia. Fisheries 46(11): 539-551. DOI: 10.1002/fsh.10651

Beamish, R.J., McCaughran, D., King, J.R., Sweeting, R.M., and McFarlane, G.A. 2000. Estimating the abundance of juvenile coho salmon in the Strait of Georgia by means of surface trawls. North American Journal of Fisheries Management 20: 369-375.

Beamish, R.J., Sweeting, R.M., Lange, K.L., Noakes, D.J., Preikshot, D., and Neville, C.M. 2010. Early marine survival of coho salmon in the Strait of Georgia declines to very low levels. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 2: 424-439.

Perry, R.I., Young, K., Galbraith, M., Chandler, P., Velez-Espino, A., Baillie, S. 2021. Zooplankton variability in the Strait of Georgia, Canada, and relationships with the marine survivals of Chinook and Coho salmon. PLoS ONE 16(1): e0245941. https://doi.org/10.1371/journal.pone.0245941

Sweeting, R.M., Beamish, R.J., Noakes, D.J., and Neville, C.M. 2003. Replacement of wild coho CSalmon by hatchery-reared coho CSalmon in the Strait of Georgia over the past three decades. North American Journal of Fisheries Management 23: 492-502.

39. BRITISH COLUMBIA COASTAL ECOSYSTEM STRUCTURE THROUGH THE LENS OF ADULT CHINOOK SALMON DIETS

Will Duguid[1], Bridget Maher, Wesley Greentree, Jessica Qualley, Micah Quindazzi, Katie Innes and Francis Juanes[2], University of Victoria, Victoria, B.C., [1]willduguid@hotmail.com, [2]juanes@uvic.ca

39.1. Highlights

- Pacific Herring remained the most important prey for Chinook Salmon in all regions in both summer and winter in 2021.
- Stomach fullness was highest in the Strait of Georgia and lowest in the Strait of Juan de Fuca.
- Winter stomach fullness in the Haro Strait and Southern Gulf Islands region was higher in 2021 than in other years, with diets dominated by small age-0 Pacific Herring.
- As in previous years, Howe Sound was the only region where Northern Anchovy were important in diets in 2021. The importance was reduced relative to 2017/18.

39.2. Description of the time series

The Adult Salmon Diet Program (ASDP) is a citizen science initiative of the Juanes Lab at the University of Victoria (Quindazzi et al. 2020) and was supported by Pacific Salmon Foundation, Project Watershed and Fisheries and Oceans Canada in 2021. The ASDP employs analysis of salmon stomach contents to better understand forage fish communities in coastal B.C. Diet sampling can provide insights into fine scale distribution and relative abundance of different age/size classes of forage fish that may not be available through other research methods (Thayer et al. 2008) and can be a valuable complement to traditional fishery-independent surveys. In the short term, the ASDP seeks to characterize spatial and seasonal variation in adult salmon diets and provide insight into the ecology of forage species. Over the long term, the program will provide a novel perspective on variability and trends in forage fish populations and their implications for salmon trophic ecology. This is the 5th year of data in the timeseries.

Digestive tracts of Chinook and Coho Salmon captured in the public fishery were submitted by individual fishers or collected at fish cleaning stations or derbies. Samples were frozen with a catch card indicating species, capture location, capture date, adipose fin status (clipped or unclipped) and length and/or weight along with additional capture observations. In the lab, stomach items were allocated to a prey category and weights were recorded. Presence and absence of diagnostic hard parts of a subset of prey categories in the intestines were also recorded, although results are not presented here.

To investigate temporal changes in diet composition and feeding intensity on different forage species, mean “partial fullness scores” (Magnussen 2011) for prey categories were compared among regions, seasons, and years. These scores were calculated as 1000 * prey category weight (g) divided by the cube of salmon length (cm). A length-based index of fullness was utilized as lengths of Chinook Salmon were more frequently available than weights. Seasons were defined as winter (October to March) and summer (April to September). To prevent splitting the winter between calendar years, the months of October to December were assigned

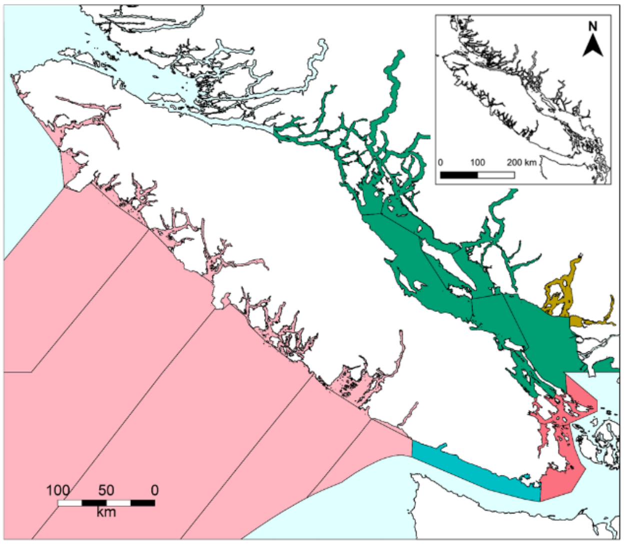


Figure 39-1. PFMA groupings for Chinook Salmon diet data reported in this document. Regions are referred to as Strait of Georgia (green), Howe Sound (orange), Haro Strait and Southern Gulf Islands (red), Strait of Juan de Fuca (teal) and West Coast Vancouver Island (pink).

to the following calendar year. The periods from April 1 to July 15 (Strait of Georgia) or April 1 to July 31 (Haro Strait/Gulf Islands, Howe Sound and Strait of Juan de Fuca) were excluded from analysis as retention of Chinook Salmon was partially or completely closed during these periods beginning in 2019. We undertook cluster analysis of a Bray-Curtis dissimilarity matrix of mean percent weight of prey categories pooled into Pacific Fishery Management Areas (PFMAs) within the Salish Sea from April to September (Greentree 2021). This resulted in identification of four distinct regions with varying diets (Figure 39-1). Fullness scores were also aggregated for West Coast Vancouver Island although data for this region were not included in the cluster analysis which was focused only on the Salish Sea. Of the 2872 Chinook Salmon diet samples processed to date by the ASDP, 1969 were used for the time series presented here.

39.3. Status and trends

Pacific Herring dominated Salish Sea Chinook Salmon diets across years and were the most important prey in all regions and seasons in 2021 (Figure 39-2). As in past years, the highest overall stomach fullness was observed in the Strait of Georgia in both summer and winter, with the lowest fullness in summer observed in the Strait of Juan de Fuca (no winter samples were available from this region in 2021). Preliminary length reconstructions for Pacific Herring in diets, based on otolith width to standard length regression (Greentree, unpublished), suggest that Strait of Georgia summer diets are dominated by age-2+ Pacific Herring (mean contribution to diets = 48%). While age-0 and age-1 Pacific Herring were important to summer diets in other regions, age-2+ fish were much less important (mean contribution to diets: Southern Gulf Islands = 8%; Strait of Juan de Fuca: = 6%).

Stomach fullness in the Haro Strait and Southern Gulf Islands region was higher in winter 2021 than in other years. This fullness was apparently driven by elevated occurrence of age-0 Pacific Herring that would have hatched in spring 2020. Preliminary length reconstruction further suggested that these juveniles were smaller than in previous years.

Northern Anchovy remained important in winter diets in Howe Sound but not in other regions, with a mean partial fullness score similar to 2019 and 2020 but approximately half of that measured in 2017 and 2018 (only a small sample of 14 stomachs were obtained for this region in winter 2021). As in previous years, summer diets on the West Coast of Vancouver Island in 2021 contained more invertebrates (primarily squid) than in other regions. It should be noted that in the initial years of the ASDP (2017-2018) Pacific Sand Lance were primarily encountered between April and July in the Haro Strait and Gulf Island Region. The time series presented here, therefore, do not accurately represent the importance of Pacific Sand Lance in diets.

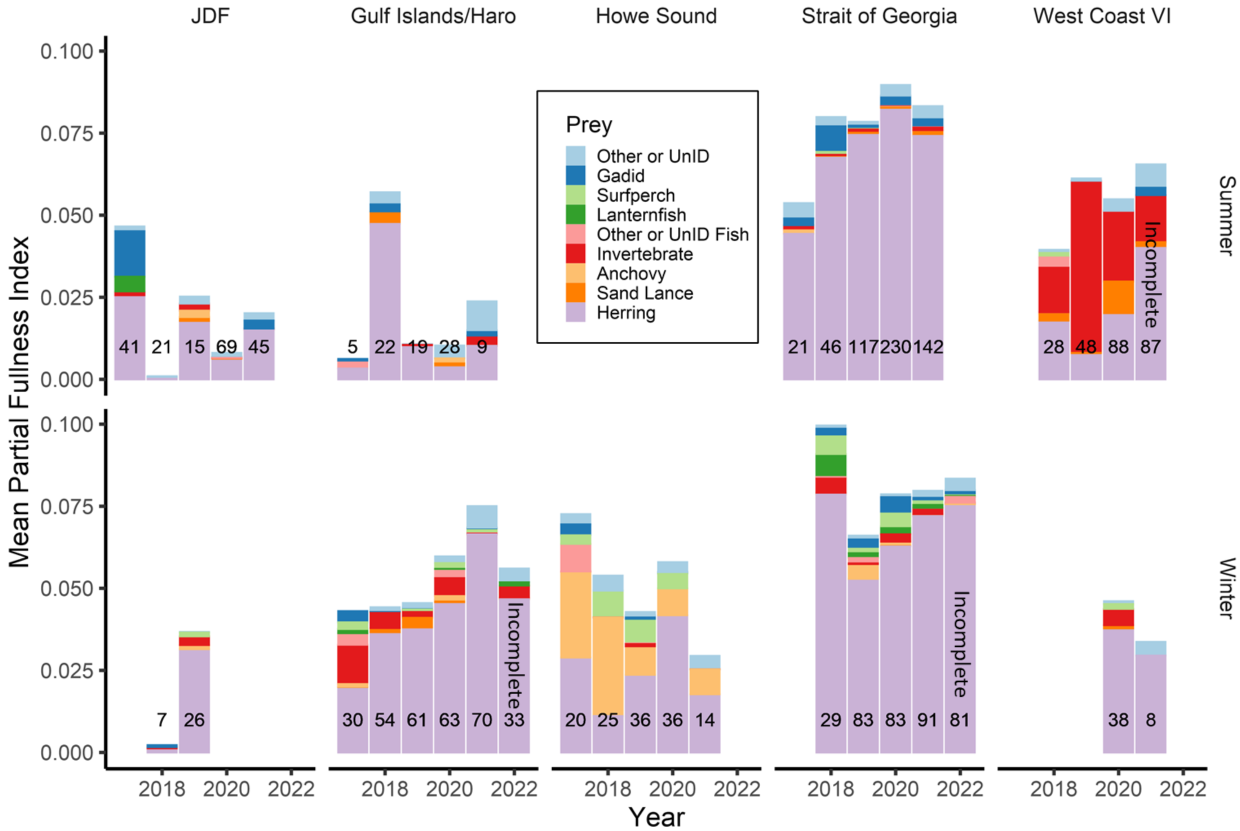


Figure 39-2. Mean prey group-specific partial fullness indices for Chinook Salmon stomachs in summer (April to September) and winter (October to March) for five regions (Figure 39-1) of Coastal B.C. from 2017 to early 2022. Note that the October-December have been moved to the following calendar year to prevent splitting a season. Total sample size is overlayed. JDF= Juan de Fuca; VI= Vancouver Island.

39.4. Factors influencing trends

As the ASDP is relatively new, trends in the data should be interpreted cautiously. The consistently high stomach fullness and large contribution of age 2+ Pacific Herring to Chinook Salmon diets in the Strait of Georgia is interesting given that the main assessed Strait of Georgia Pacific Herring stock is considered to be primarily migratory. The Strait of Georgia Pacific Herring spawning stock biomass has been high throughout the duration of the ASDP (Cleary et al. 2022, Section 21). We lack an understanding of the factors which might control whether Pacific Herring remain within the Strait of Georgia in summer and, in turn, regulate their availability to salmon and other predators. This is an important subject for future research.

Northern Anchovy abundance in the Salish Sea was anomalously high during warm conditions in 2015 and 2016 (Duguid et al. 2019). Declining importance of Northern Anchovy in adult Chinook Salmon diets after 2018 mirrored reduced frequency of occurrence of Northern Anchovy in the age-0 Pacific Herring survey in fall 2019 (Boldt et al., Section 37). While the fall 2021 age-0 Pacific Herring survey detected increased occurrence of juvenile Northern Anchovy (no survey occurred in fall 2020), the availability of these fish will primarily be reflected in 2022 adult salmon diets.

39.5. Implications of those trends

Changes in the partial fullness scores for different prey groups may reflect both changes in the abundance of those prey groups and in the abundance of alternative prey. An example of this is provided by winter diets in the Haro Strait and Southern Gulf Islands region where the frequency of occurrence of both empty stomachs and invertebrate prey has decreased with increasing frequency of occurrence of Pacific Herring and with overall stomach fullness. Going forward, prey-specific and aggregate partial fullness scores will reveal whether Chinook Salmon are able to obtain adequate alternative prey in regions and periods where herring are less abundant. Summer Chinook Salmon diet samples from the Strait of Georgia also provide an index of the abundance of non-migratory Pacific Herring, a potentially critical ecosystem component for which we otherwise lack indicators. Changes in abundance of these fish could result from changes in either migratory patterns or abundance of the aggregate spawning stock. The Chinook Salmon diet-based index will facilitate interpretation of the possible causes and ecological consequences of future changes in non-migratory Pacific Herring abundance. The ASDP is also well placed to detect the geographic extent and importance to Chinook Salmon of climate change-driven changes in range or abundance of species such as Northern Anchovy.

39.6. References

Duguid, W.D.P., Boldt, J.L., Chalifour, L., Greene, C.M., Galbraith, M., Hay, D., Lowry, D., McKinnell, S., Qualley, J., Neville, C., Sandell, T., Thompson, M., Trudel, M., Young, K., and Juanes, F. 2019. Historical fluctuations and recent observations of Northern Anchovy *Engraulis mordax* in the Salish Sea. Deep Sea Research II: Topical Studies in Oceanography. 159: 22-41.

Greentree, W. 2021. Using adult Chinook salmon diets to understand the spatial structure of forage assemblages in the Salish Sea. University of Victoria. BSc (Honours) thesis.

Magnussen, E. 2011. Food and feeding habits of cod (*Gadus morhua*) on the Faroe Bank. ICES J Mar. Sci. 68: 1909-1917.

Quindazzi, M.J., Duguid, W.D.P., Innes, K.G., Qualley, J., and Juanes, F. 2020. Engaging recreational salmon anglers in fisheries ecology. Fisheries. 45(9): 492-494.

Thayer, J.A., Bertram, D.F., Hatch, S.A., Hepfner, M.J., Slater, L., Sydeman, W.J. and Watanuki, Y. 2008. Forage fish of the Pacific Rim as revealed by diet of a piscivorous seabird: synchrony and relationships with sea surface temperature. Can. J. Fish. Aquat. Sci. 65: 1610-1622.

40. THE SAANICH INLET ROV TRANSECT 2021: UPDATE TO A COLD-WATER CORAL COMMUNITY IMPACTED BY A MARINE HEATWAVE

Jackson W.F. Chu

Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Jackson.Chu@dfo-mpo.gc.ca

40.1. Highlights

- The density of the key hypoxia indicator taxa, Slender Sole, Squat Lobster, and Spot Prawn, remain at levels comparable to the benchmark period and have recovered since a notable marine heatwave (MHV) that occurred from 2015 to 2017.
- The Sea Whip population remains at <5% of their peak abundance numbers and has not recovered.
- A stable population of a sea whip predator, the striped nudibranch, remains in this system after being introduced during the severe hypoxia event in 2016.

40.2. Description of the time series

This annual visual benthic survey is the longest-running time series in Canada that was designed to monitor seafloor biodiversity using standardized remotely-operated vehicle (ROV) methods (Chu et al. 2020). Since 2006, ROVs with onboard CTD and dissolved oxygen (DO) sensors and high-definition cameras have repeated the same benthic transect (n=18) in Patricia Bay, Saanich Inlet, B.C. (Chu and Tunnicliffe 2015; Gasbarro et al. 2019). The transect begins in the deep basin and transitions through zones of low-to-high oxygen over a gradual soft-bottom slope from 180 to 40 m bottom depths. This survey has documented 55 species at this site and has generated non-destructive abundance data (individuals m^{-2}) with concomitant CTD+DO measurements made within 1 m above the seabed.

The benthic habitat conditions at 96 m depth have also been continuously monitored with CTD+DO instrumentation (with one-minute or finer intervals) by the VENUS cabled observatory off Ocean Network Canada (ONC), since 2006. The stationary VENUS instrument platform (VIP) sits at approximately the mid-way point along the transect. Annual hypoxia was calculated as the cumulative days in each year that the ONC-VENUS VIP measured below two thresholds (0.88 ml L^{-1} is an average hypoxia threshold among species from the Northeast Pacific while the severe hypoxia threshold of 0.5 ml L^{-1} is associated with fish kills (Chu and Gale 2017).

Trends in the distribution and abundance of six indicator taxa are presented to reflect the diversity of biological traits and responses to hypoxia in this system. Among mobile species, Slender Sole (*Lyopsetta exilis*) and Squat Lobster (*Munida quadrispina*) are indicators of the hypoxia-tolerant community, and Spot Prawn (*Pandalus platyceros*) are indicators of the hypoxia-sensitive community. Sea Whip (*Balticinia willemoesi*) is a sessile cold-water coral, an indicator of vulnerable marine ecosystems, and has since been shown to be the most impacted by sustained exposure to severe hypoxia (Gasbarro et al. 2019). The abundance of Striped Nudibranch *Armina californica* and the White Sea Cucumber *Pentamera* cf. *pseudocalcigera* have also been monitored after they established populations during the MHW.

40.3. Status and trends

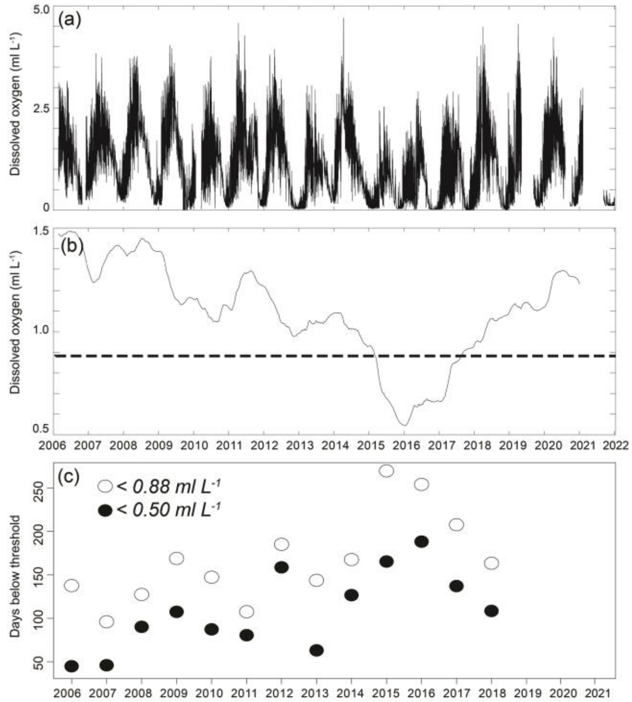


Figure 40-1. The 16-year continuous ONC-VENUS dissolved oxygen record at 96 m in Patricia Bay, Saanich Inlet. (a) The per-minute records illustrate the seasonal hypoxia cycle. (b) A one-year running mean illustrates the sustained hypoxia event that lasted from 2015 to 2017. The dashed line at 0.88 ml L^{-1} is the average hypoxia threshold among species from the East Pacific. (c) Hypoxia exposure in the cumulative annual days below the Northeast Pacific and severe hypoxia (0.5 ml L^{-1}) thresholds. Data gaps in the ONC-VENUS record have prevented calculation of exposure duration for 2019, 2020, and 2021.

The continuous ONC-VENUS DO record resolves the seasonal hypoxia cycle in Saanich Inlet (Figure 40-1a). Previously, the rate of oxygen decline, as measured by the entire ONC-VENUS DO record, was reported to be between -0.03 and -0.05 ml L^{-1} $year^{-1}$ (Chu et al. 2020). However, annual data gaps lasting several months have occurred since 2019 and prevent a meaningful update from being calculated. During 2015 to 2017, the system was below 0.88 ml L^{-1} for more than half the calendar year (Figure 40-1c). While hypoxia exposure could not be calculated for 2021, species population trends resolved by the ROV time series suggest the system has remained above critical hypoxia exposure thresholds since 2018.

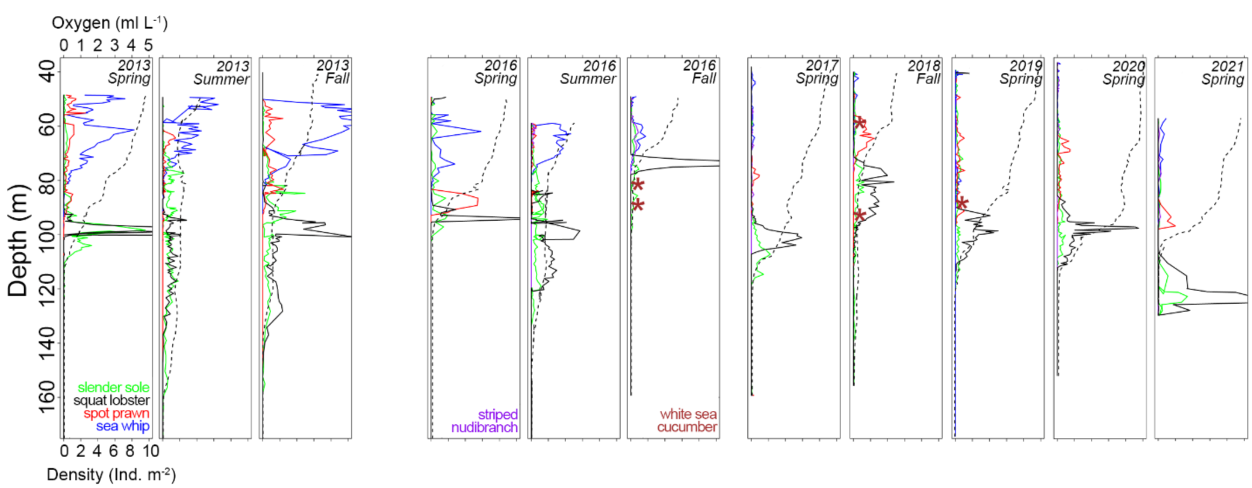


Figure 40-2. Depth distribution and density of indicator species relative to the hypoxia gradient (dashed line). No surveys were conducted in 2014-2015. Earlier surveys (2006-2012) are not presented but are published in Chu and Tunnicliffe (2015).

During a sustained period of severe hypoxia from 2015 to 2017 (Figure 40-1b,c), community disassembly started in the Fall of 2016 (Gasbarro 2017; Chu et al. 2018; Gasbarro et al. 2019). Loss of community structure was characterized by the absence of Spot Prawn and other commercial shrimp species (*P. jordani* and *P. hypsinotus*), generally low populations of other epifauna, functional extinction of the Sea Whip population, and the introduction of two species (Striped Nudibranch, White Sea Cucumber) which had not been observed in this system prior to 2016 (Gasbarro et al. 2019).

In 2021, Slender Sole, Squat Lobster, and Spot Prawn had distributions, abundance, and densities that were typical of patterns observed prior to the hypoxia-induced community disassembly in 2016 (Figures 40-2 and 40-3). The White Sea Cucumber was absent for the second year in a row. The Striped Nudibranch population persists in this system and is now observed to be a predator on the reduced Sea Whip population. Only 80 Sea Whip were observed in 2021, which remains relatively unchanged from the 75 individuals observed in 2020. No juvenile recruitment was observed in 2021. Sea Whip remain at <5% of the pre-MHW population when 3,876 individuals were observed in the Fall of 2013.

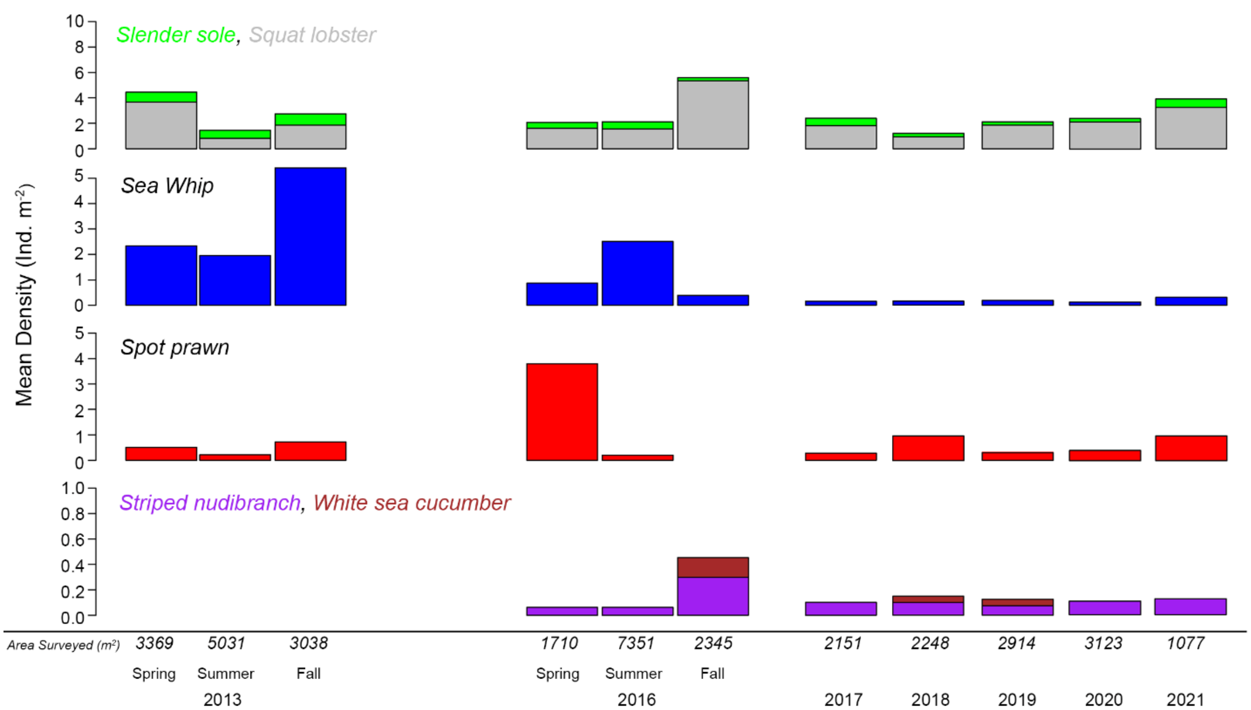


Figure 40-3. Average densities of key species per survey. Total area surveyed (m²) each year is indicated on the x-axis. Differences in area surveyed among years is attributable to truncation of the start and end areas of the transect and varying field performance among different ROV platforms. No surveys were performed in 2014-2015. Average densities were calculated from abundances occurring in 20 m² sections along the transect. Earlier surveys (2006-2012) are presented in Chu and Tunnicliffe (2015).

40.4. Factors causing trends

While multiple co-occurring climate stressors can drive change in marine biodiversity, sustained exposure to severe hypoxia was the primary driver of concomitant shifts in community structure and function in the Saanich system (Gasbarro et al. 2019).

40.5. Implications of these trends

Among mobile species (Slender sole, Squat Lobster, Spot Prawn), MHW-induced decline and subsequent population recovery was relatively quick, based on the distribution, abundance, and density. There was an approximately five-year period between the initial signs of community decline (severe habitat compression of Spot Prawn, Gasbarro et al. 2019) and the relatively stabilized stage of recovery for the mobile species assemblage at present. In comparison, the time period required for the recovery of certain slow-growing sessile taxa like Sea Whip is much longer. Full functional recovery of the Sea Whip population will require several decades based on published growth rates of Sea Whip (Wilson et al. 2002). The lack of population recovery of Sea Whip coupled with a persistent population of Striped Nudibranch suggests the post-MHV community may have stabilized into an alternative state relative to the beginning of this time series.

A community-level assessment is needed to best capture the biological variability that characterizes how a system responds to a MHW. Given the slow recovery rates of sessile species, non-destructive methods that do not remove individuals would be needed to disentangle the impacts of climate-related events, such as MHWs, from other drivers of population dynamics. In Canada, this time-series remains as the only benthic, ROV-based monitoring program that has directly linked an extreme climate event with biological responses.

40.6. Acknowledgements

We thank ONC for donating ship time and taking the initiative to continue this time series with the use of the ROV *Oceanic Explorer* in March 2021. We are additionally grateful to the captain and crew of the CCGS JP Tully, the ROV team, and staff at ONC for logistics support. All contribute towards making the continuation of this novel time-series possible.

40.7. References

Chu, J.W.F., Curkan, C., and Tunnicliffe, V. 2018. Drivers of temporal beta diversity of a benthic community in a seasonally hypoxic fjord. R. Soc. Open Sci. 5: 172284.

Chu, J.W.F., and Gale, K.S.P. 2017. Ecophysiological limits to aerobic metabolism in hypoxia determine epibenthic distributions and energy sequestration in the northeast Pacific Ocean. Limnol. Oceanogr. 62: 59-74.

Chu, J.W.F., Grupe, B.M., Gasbarro, R., and Curtis, J.V. 2020. The Saanich Inlet Transect 2019: Slow recovery of a cold-water coral population indicates vulnerability to a major climate stressor. In: Boldt, J.L., Javorski, A., and Chander, P.C. (Eds.). State of the physical, biological, and selected fishery resources of Pacific Canadian Ecosystems in 2019. Can. Tech. Rep. Fish. Aquat. Sci. 3378: vii + 248 p.

Chu, J.W.F., and Tunnicliffe, V. 2015. Oxygen limitations on marine animal distributions and the collapse of epibenthic community structure during shoaling hypoxia. Glob. Chang. Biol. 21: 2989-3004.

Gasbarro, R. 2017. Benthic ecology in two British Columbia fjords: compositional and functional patterns. MSc Thesis. University of Victoria.

Gasbarro, R., Chu, J.W.F., and Tunnicliffe, V. 2019. Disassembly of an epibenthic assemblage in a sustained severely hypoxic event in a northeast Pacific basin. J. Mar. Syst. 198: 103184.

Wilson, M.T., Andrews, A.H., Brown, A.L., and Cordes, E.E. 2002. Axial rod growth and age estimation of the sea pen, Halipteris willemoesi Kölliker. Hydrobiologia. 471: 133-142.

41. UPDATE ON THE DISTRIBUTION OF AQUATIC INVASIVE SPECIES AND MONITORING ACTIVITIES IN THE PACIFIC REGION

Katie S.P. Gale, Brett. R. Howard, Thomas W. Therriault, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, B.C., Katie.Gale@dfo-mpo.gc.ca, Brett.Howard@dfo-mpo.gc.ca, Thomas.Therriault@dfo-mpo.gc.ca

41.1. Highlights

- Marine Aquatic Invasive Species (AIS) continue to spread in B.C.
- The range of European Green Crab (*Carcinus maenas*) is expanding throughout Haida Gwaii, following its discovery there in 2020.
- Early detection of AIS can inform management and policy.
- Preventing the spread of AIS requires management and monitoring of anthropogenic pathways and vectors.

41.2. Description of indices – Monitoring Aquatic Invasive Species in Pacific Region

Marine Aquatic Invasive Species (AIS) are increasingly common throughout B.C. Two long-term monitoring programs are reported on here: the Settlement Plate Program, which monitors fouling AIS province-wide, and the European Green Crab Trapping Program, which targets the invasive European Green Crab (*Carcinus maenas*) (Figure 41-1). These monitoring programs have improved our understanding of the role of anthropogenic pathways, aided early detection and rapid response efforts, and resulted in productive partnerships with First Nations and stakeholders.

41.2.1. Settlement Plate Program

Since 2014, the standardized method for monitoring fouling AIS in B.C. has been weighted PVC plates (14 cm^2) deployed from floating docks. Plates are analyzed for both the presence/absence and abundance of AIS. Because this method detects fouling species most likely to establish in the upper water column and on anthropogenic structures, it is an effective method for understanding the risk of spread of fouling AIS by small vessels (Clarke Murray et al. 2011) and static structures like floating fishing lodges and docks (Iacarella et al. 2019).

41.2.2. European Green Crab Trapping Program

European Green Crabs have been monitored in B.C. since 2006, eight years after their introduction from the United States via natural larval dispersal (Gillespie et al. 2007). Because Green Crabs are an intertidal species, they are trapped at or above chart datum using baited Fukui fish traps. Although trapping surveys have historically been conducted between May and October, Green Crabs are increasingly being targeted year-round. The dataset generated by the trapping program is useful for understanding the ongoing spread of European Green Crabs throughout coastal B.C., and has been the basis for species distribution modelling and genetic studies. Moreover, the program has led to the early detection and targeted eradication of

European Green Crabs in new areas, including the Salish Sea and Haida Gwaii. The data presented here represent the work of DFO AIS Science, DFO AIS Core Program (Fish and Fish Habitat Protection Program; FFHPP), Council of the Haida Nation and Parks Canada, and other partners.

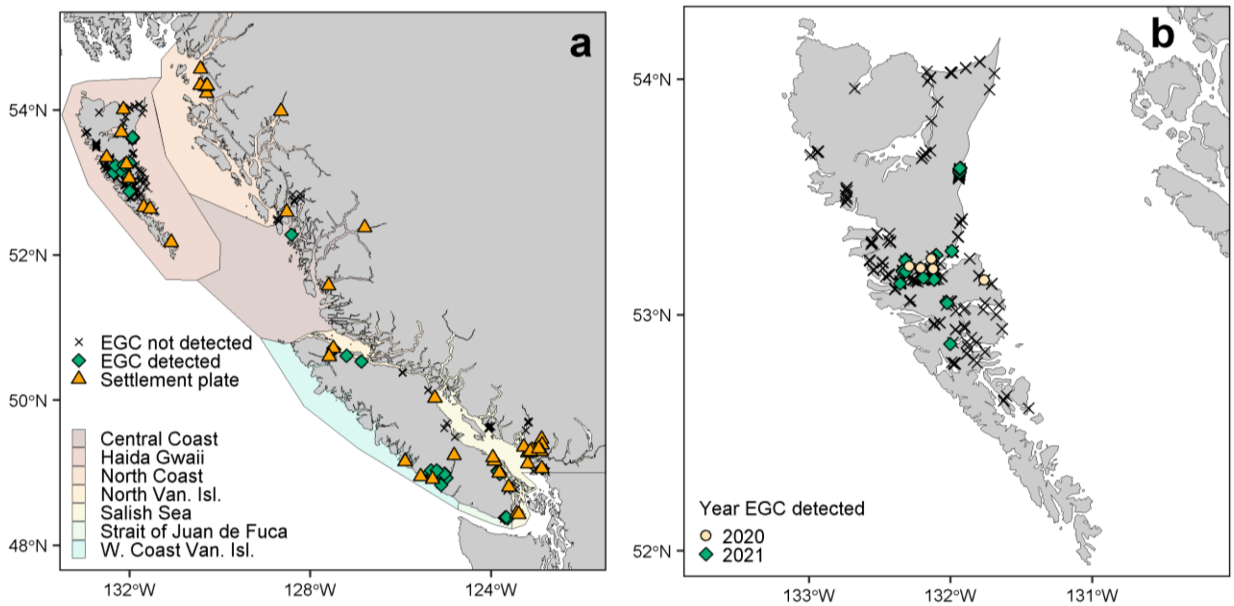


Figure 41-1. a) Locations of European Green Crab (EGC) trapping and settlement plate deployment in 2021; b) Spread of EGC on Haida Gwaii from 2020-2021.

41.3. Status and Trends

41.3.1. Settlement Plate Program

No new species of biofouling AIS were detected in B.C. in 2021, although several range expansions of known AIS were observed (Figure 41-2). The barnacle *Amphibalanus improvisus* was detected for the first time on the west coast of Vancouver Island (Port Alberni), having previously been observed in the Salish Sea (Esquimalt) and throughout Metro Vancouver. In the Salish Sea, the solitary ascidian *Molgula manhattensis* was observed for the first time at Fisherman's Wharf in Victoria, near the southernmost observation of this species in our dataset (Victoria Inner Harbour, ~1 km away). Since 2007, *M. manhattensis* has been detected at eight other sites in Metro Vancouver and the Salish Sea, but has not been observed in Victoria since 2016. In Metro Vancouver, *A. improvisus* and the widespread bryozoans *Schizoporella japonica* and *Cryptosula pallasiana* were detected in several new sampling locations. In the Prince Rupert area, the compound ascidian *Diplosoma listerianum* was observed for the first time since 2015, approximately 2 km from the single previous observation at Rushbrook Marina.

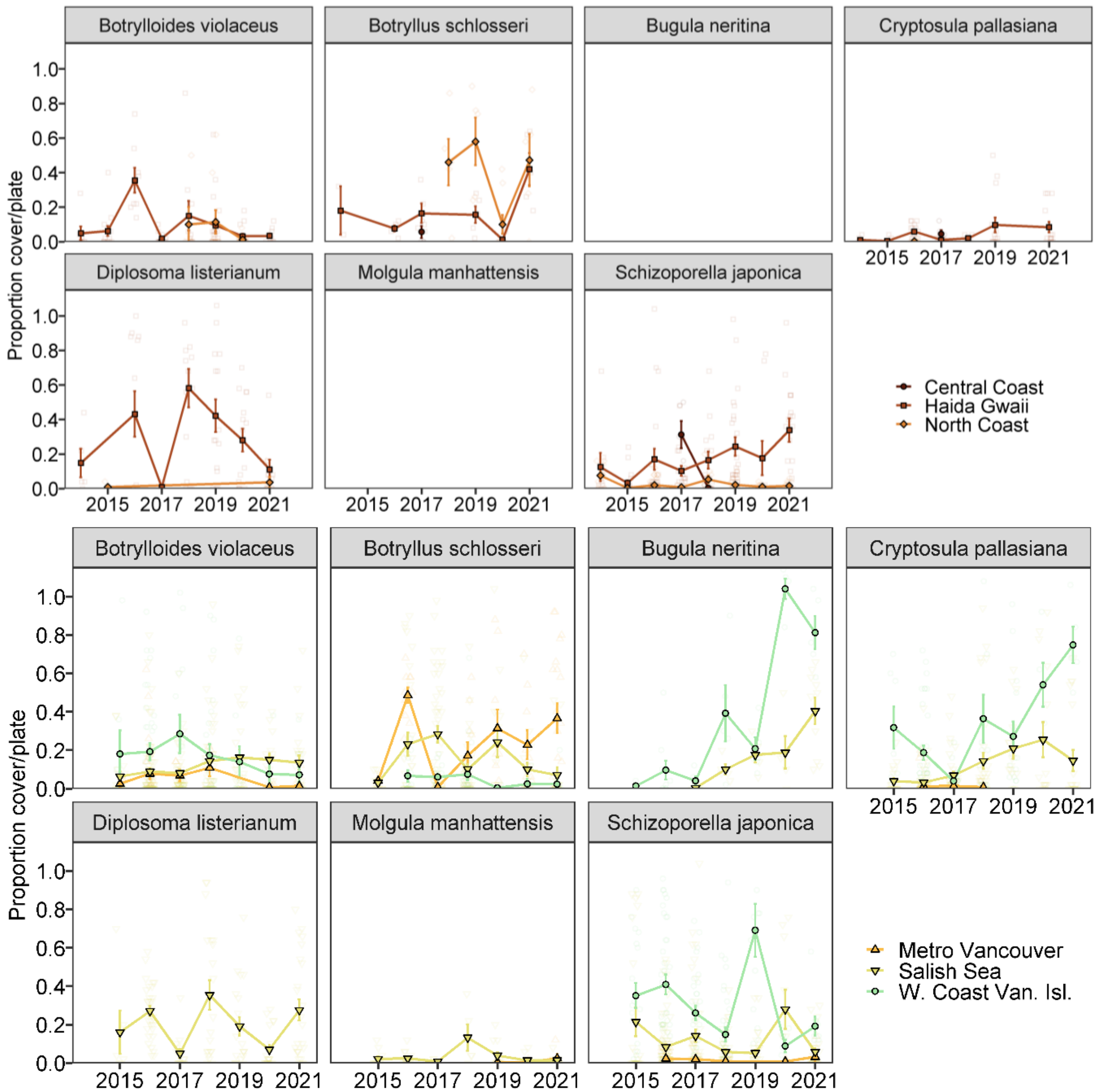


Figure 41-2. Change in abundance of some AIS found on settlement plates in three areas in northern B.C. (top) and southern B.C. (bottom), presented as the mean proportion of the plates covered (± standard error), by each species, per area. Grey points are proportion AIS cover for individual plates (raw data). Proportions can be greater than 1.0 due to species growing in layers (i.e., more than one occurrence of AIS may be recorded per point).

41.3.2. European Green Crab Trapping Program

Following the first detection in the summer of 2020, the spread of European Green Crabs through Haida Gwaii is being monitored by the Council of the Haida Nation and Parks Canada (Gwaii Haanas National Park, National Marine Conservation Area, and Haida Heritage Site) with support from DFO. Widespread trapping effort across Haida Gwaii indicates European Green Crabs are spreading from Skidegate Inlet in Central Haida Gwaii, where they were found in 2020, north to Tlell and south to Sewall Inlet near Louise Island (Figure 41-1b). Catch per unit effort (CPUE) was relatively low in both 2021 and 2022 (Figure 41-3b). Monitoring for and removing these small populations is critical to prevent the species from becoming established on Haida Gwaii.

In Barkley Sound on the west coast of Vancouver Island, catches were the lowest in the time-series since 2012, including in areas known to be European Green Crab “hotspots” (e.g., Pipestem Inlet). As we were unable to return to Barkley Sound to explore these patterns further, we currently have no explanation for these record low catches. However, it is unlikely to represent a real decrease in the abundance of Green Crabs, as the Coastal Restoration Society, with which DFO is collaborating, caught over 100,000 crabs in Clayoquot Sound during their 2021 elimination trapping program. These data were not available for analysis at the time of publishing.

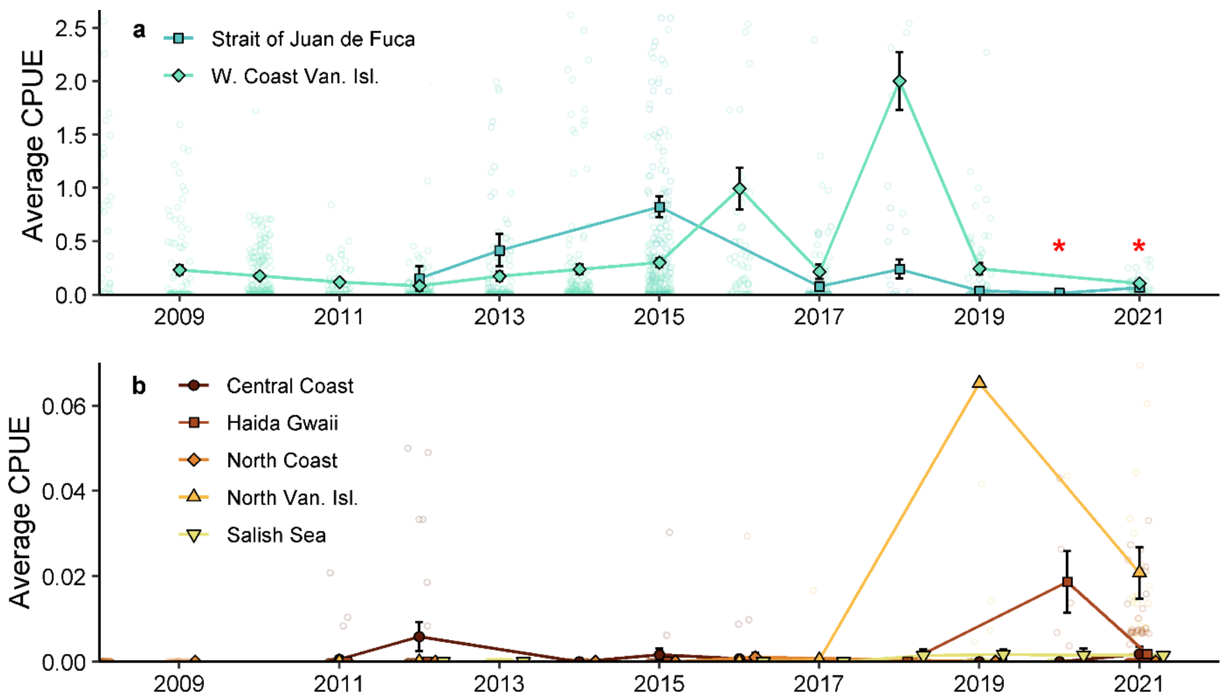


Figure 41-3. Annual average CPUE for European Green Crabs (± SE) for all traps set on a) the West Coast of Vancouver Island (WCVI) and the Strait of Juan de Fuca (JDF), and b) elsewhere in B.C. (note scale differences). Empty points indicate individual trapping events within each area. All raw data are plotted, but most CPUEs are too small for points to be visible. Note the following differences from last year’s report (Howard and Therriault 2021): the JDF region has been separated from the Salish Sea; the North Vancouver Island region has been separated from the Central Coast; and additional trapping events have been added for previous years (i.e., surveys conducted outside the regular summer trapping program). Red stars indicate caution when interpreting WCVI and JDF data as the trapping program was interrupted in 2020 due to Covid-19, and the 2021 data includes two spring surveys (February-March) and one summer survey Barkley Sound (WCVI), in which catches were anomalously low (see text).

41.4. Factors influencing spread and abundance of AIS

In B.C., climate change is likely to permit the survival of AIS currently restricted to more southern locations, and periods of significant warming will facilitate population spikes and natural long-range larval dispersal events for AIS (Gillespie et al. 2007; Brasseale et al. 2019). The potential for additional anthropogenic spread of AIS via infested vessels, structures, and equipment will continue to be a primary vector for both existing (known) and novel AIS in B.C.

41.5. Implications of AIS range expansions in the Pacific Region

The potential for localized, anthropogenic spread of AIS combined with their increasing abundance means AIS will continue to have greater impacts on native species, ecosystems, and industry. Expanded AIS Regulations in the Fisheries Act and new management plans for high-risk AIS are being developed.

The Settlement Plate Program has been a useful proxy for tracking dispersal of fouling AIS and has led to increased public awareness of these species. By engaging with the public and focusing management on key vectors, there is a better chance of reducing spread of both established AIS and newly introduced or undetected ones whose impacts are not yet known.

European Green Crabs are known to have significant negative impacts on bivalve populations, especially clams, and on eelgrass habitats (Howard et al. 2019). The continued spread of this species has resulted in the Salish Sea Transboundary Action Plan for Invasive European Green Crab (Drinkwin et al. 2019), a joint management plan between DFO and Washington State partners, and a dedicated early detection and eradication program managed by FFHPP. However, the arrival of Green Crab on Haida Gwaii has highlighted the need for similar multiagency management plans for other parts of B.C., including transboundary areas like Alaska, in order to limit the ecosystem impacts of this invader.

41.6. References

Brasseale, E., Grason, E.W., McDonald, P.S., Adams, J., and MacCready, P. 2019. Larval transport modeling support for identifying population sources of European green crab in the Salish Sea. Estuaries Coasts 42: 1586-1599.

Clarke Murray, C., Pakhomov, E.A., and Therriault, T.W. 2011. Recreational boating: A large unregulated vector transporting marine invasive species. Divers. Distrib. 17: 1161-1172.

Drinkwin, J., Pleus, A., Therriault, T.W., Talbot, R., Grason, E.W., McDonald, P.S., Adams, J., Hass, T., and Litle, K. 2019. Salish Sea Transboundary Action Plan for Invasive European Green Crab. Puget Sound Partnership.

Gillespie, G.E., Phillips, A.C., Paltzat, D.L., and Therriault, T.W. 2007. Status of the European green crab, *Carcinus maenas*, in British Columbia - 2006. Can. Tech. Rep. Fish. Aquat. Sci. 2700: vii-39.

Howard, B.R., Francis, F.T., Côté, I.M., and Therriault, T.W. 2019. Habitat alteration by invasive European green crab (*Carcinus maenas*) causes eelgrass loss in British Columbia, Canada. Biol. Invasions 21: 3607-3618.

Howard, B.R., and Therriault, T.W. 2021. Ongoing range expansions of invasive marine invertebrates in the Pacific Region. *In* Boldt, J.L., Javorski, A., Chandler, P.C. (eds). State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2020. Can. Tech. Rep. Fish. Aquat. Sci. 3434: vii + 231 p.

Iacarella, J.C., Davidson, I.C., and Dunham, A. 2019. Biotic exchange from movement of ‘static’ maritime structures. Biol. Invasions 21: 1131-1141.

42. RECENT TRENDS IN MARINE TRAFFIC AND ASSOCIATED THREATS IN THE SALISH SEA BASED ON AUTOMATIC IDENTIFICATION SYSTEM FOR SHIPS (AIS)

Patrick D. O'Hara[1], Leh Smallshaw[2], and Gregory O'Hagan[2]

[1]Canadian Wildlife Service, Environment and Climate Change Canada, Institute of Ocean Sciences, Sidney, B.C., Patrick.OHara@canada.ca
[2]CORAL, Department of Geography, University of Victoria, Victoria, B.C., LehSmallshaw@gmail.com, GregoryOHagan@gmail.com

42.1. Highlights

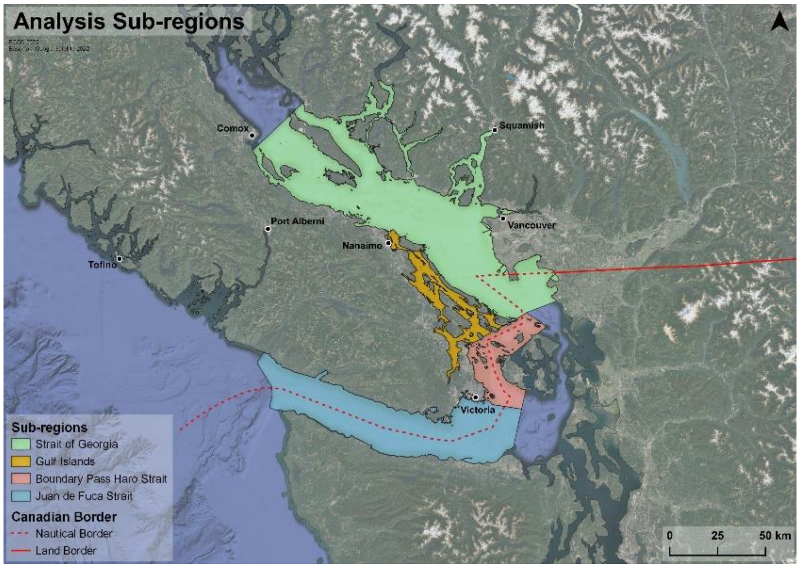
- Marine vessel traffic intensity based on AIS data from 2016-2020 varied inconsistently among vessel categories in the Salish Sea, however Cargo vessels continue to increase in the Southern Gulf Islands and the Georgia Strait.
- Passenger vessel traffic intensity decreased with year, but only during the summer, and likely as a result of COVID associated reduced ferry service.
- Trends and associated stressors estimated based on AIS data and interpretations of these estimates should take into account the under-representation for some types of vessels in AIS data.

42.2. Introduction

Documenting and understanding spatial and temporal variability in marine vessel traffic patterns is fundamental for the conservation of marine species and important habitats upon which they depend. There are a number of threats or stressors associated with marine vessel movements including oily discharges (Fox et al. 2016), noise pollution (Williams et al. 2015), disturbance (Bejder et al. 2006), interactions with fisheries (Fox et al. 2021), introduced species (Herborg et al. 2009), and ship-strikes (Williams and O'Hara 2010; Nichol et al. 2017). Increasingly, research and conservation efforts depend on Automatic Identification System (AIS) for ships to monitor vessel movements and collect data for assessing threats associated with marine vessels. Although we identified challenges at the last State of the Pacific Ocean (2021) when using AIS as a proxy for some of these stressors, we also confirmed that some vessel categories were well represented by AIS data such as Cargo, Tanker and Passenger vessels. AIS representation is nearly 100% in these categories of vessels (O'Hara et al. unpublished data).

Here we report on trends in marine vessel traffic in the Salish Sea based on data collected using Canadian Coast Guard AIS receivers from 2016 to 2020 (full calendar years) and provided to us in a useable data format by Ocean Networks Canada. We break down our analyses into seasons (summer = Apr – Sept, winter = Oct – Mar), and by subregion (see Figure 42-1). We also look at the onset of COVID restrictions and how marine vessel trends were affected.

42.3. Marine Vessel Annual and Seasonal Trends in Salish Sea Subregions



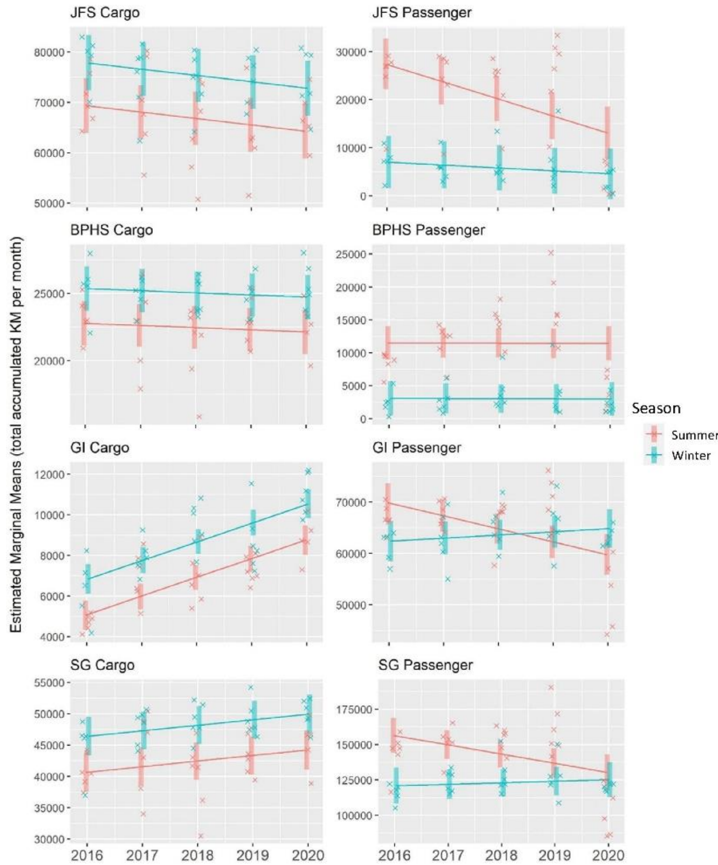


Figure 42-1. Salish Sea subregions (above) and annual trends in marine traffic intensity (right) for Cargo and Passenger vessels in each subregion (refer to table 42-1 for significance of trends) in summer and winter based on estimated marginal means. Errors = 95% confidence intervals. The winter intercepts were significantly larger in winter for Cargo vessels in all subregions with p-values less than or equal to 0.01. Subregions: 'JFS' = Juan de Fuca Strait; 'BPHS' = Boundary Pass/Haro Strait; 'GI' = Southern Gulf Islands; and 'SG' = Strait of Georgia.

We fit a linear mixed model to monthly total kilometers (KMs) traveled for all vessels transiting a subregion within each vessel category with season and year as fixed variables, and month as a random variable. In general, traffic intensity varied differently among the subregions, seasons, and vessel classes over the years. Cargo vessels increased consistently during the summer and winter months in the Gulf Islands and Strait of Georgia, but decreased in the Juan de Fuca (Figures 42-1 and Table 42-1). Other categories of vessels, such as Tankers and Fishers, showed either no change or slight decreases since 2016 consistently between seasons. Passenger and Tug vessels had significant seasonal-annual interactions. Passenger vessels showed strong declines in summer months over the years in three of the four subregions, and no change during the winter months (Figure 42-1 and Table 42-1), while Tugs only declined during the winter in the Strait of Georgia.

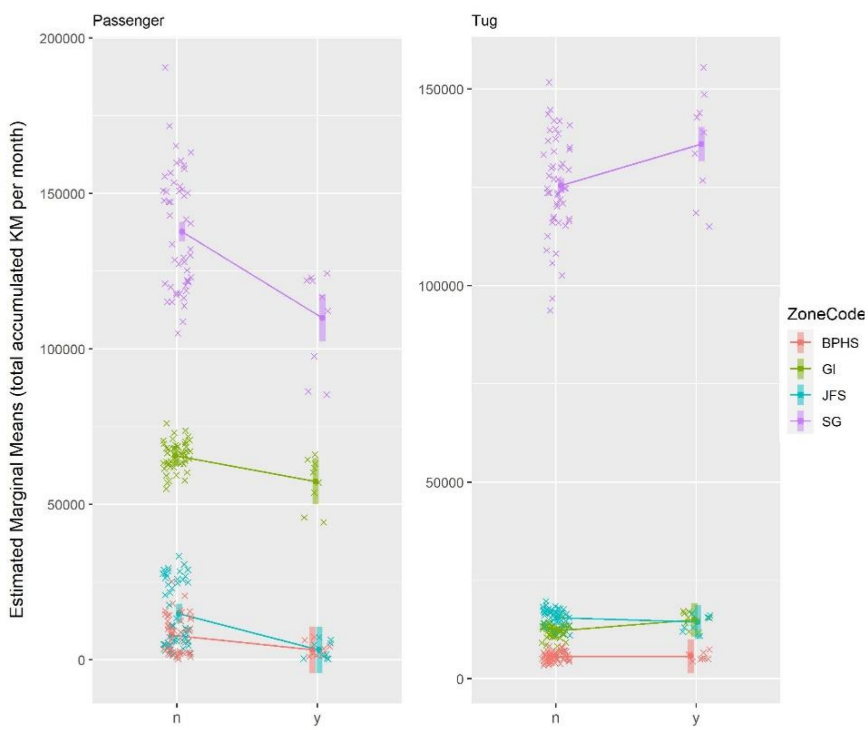
*Table 42-1. Annual trends in total vessel tracks per month from 2016-2020 per vessel category and subregion. NS= "non-significant" and p-values are indicated as * < 0.05; ** < 0.01; and ***<0.001 (***). Red indicates negative and green positive annual trends. Cells with / indicate a significant interaction between season and years (summer/winter).*

	Vessel Category					
Subregion	Cargo	Tanker	Fisher	Tug	Passenger	Recreational
Juan de Fuca	**	NS	NS	NS/NS	***/NS	***/NS
Boundary Pass/Haro Strait	NS	NS	NS	**	NS	NS
Gulf Islands	***	NS	**	*	***/NS	NS
Strait of Georgia	***	**	NS	NS/**	***/NS	NS

42.4. COVID associated changes to trends

We tested the hypothesis that the onset of COVID restrictions in March 2020 may have resulted in reduced traffic intensity seen in many vessel categories among the different regions. In particular, strong declines in intensity was seen during the summer months for Passenger vessels (including ferry traffic). We assigned months and years as pre- or post-covid and ran a linear mixed model based again on total cumulative KMs for all vessels within each category with subregion and pre/post covid as fixed variables and month nested with year as random. Tug and Passenger were the only two vessel categories showing intensity changes associated with COVID onset, and these changes were inconsistent among subregions (Tugs: Chi-square = 17.6, df =3, p < 0.001; Passenger vessels: Chi-square = 40.7, df = 3, p < 0.001).

Figure 42-2. COVID associated vessel intensity trends (x-axis: 'n' = pre-onset of COVID restrictions March 2020; 'y' = post onset) for Tug and Passenger in each subregion (refer to text above for significance) based on estimated marginal means. Errors = 95% confidence intervals. Subregions indicated as ZoneCode: 'JFS' = Juan de Fuca Strait; 'BPHS' = Boundary Pass/Haro Strait; 'GI' =



Passenger vessels showed a decrease in traffic intensity with COVID onset, in all subregions except for Boundary Pass/Haro Strait (estimated means contrasts p-values < 0.05), while Tugs showed an increase in the Strait of Georgia only (p-value < 0.001; Figure 42-2). The large decrease for Passenger vessels is likely a result of reduced BC Ferry service in the Gulf Islands and Strait of Georgia and the Coho Ferry transiting Juan de Fuca Strait.

42.5. Implications of those trends

At the last State of the Pacific Ocean meeting (2021), we reported on increasing trends in marine traffic for Passenger and Cargo vessels in parts of the Salish Sea, in particular Boundary and Active Passes (McWhinnie et al. 2021). Here we expand the analyses to include more subregions and years for estimating traffic intensity trends more broadly. Our results are somewhat consistent with earlier detected trends, with continued increases in Cargo vessel traffic in the Gulf Islands and Strait of Georgia, but inconsistent in the Boundary Pass/Haro Strait and Juan de Fuca Strait where no trends were detected. As well, onset of COVID does not help explain the negative trend in Juan de Fuca Strait. Passenger vessel intensity decreased during the summer in three regions, Georgia Strait, Gulf Islands and Juan de Fuca; subregions where we also detected COVID onset associated declines in Passenger vessel activity. Tug traffic intensified after the onset of COVID in the Strait of Georgia, which was contrary to the declining trend detected over the years during the winter, and warrants further investigation.

It is important to monitor larger vessel movement patterns such as Cargo, Tanker, Ferries, Passenger (including both Cruise and B.C. Ferry vessels), which are well represented by AIS data. These movement patterns can have important implications with associated threats and stressors particularly for Southern Resident Killer Whales (SRKW) and larger whale species such as the Humpback Whale, whose numbers have been increasing in this region. Increased intensity of these vessels likely results in increased exposure to noise pollution, oily discharges, disturbance, and ship-strike. Ship-strike is one the biggest threats challenging conservation of large whale species (see Williams and O'Hara 2010; Nichol et al. 2017) and a recent study has shown that it is also a threat for Southern Resident Killer Whales as well (Raverty et al. 2020).

Smaller vessels such as Fishers, Tugs and Recreational vessels are poorly captured by AIS, and for this reason we cannot at this stage rely on trends documented here. Although we used AIS data as an index of trends in these categories, we cannot be certain proportion of vessels tracked using AIS is consistent among vessel categories, or subregions or across time (see Serra Soga et al. 2021). Without complementary measures such as vessel data from optical imagery-based monitoring systems (i.e., see Serra Sogas et al. 2021; O'Hara et al. unpublished data) for example, AIS should not be used as proxies for these vessel categories, as well as for the stressors that have been associated with these components of marine traffic such as fishery interaction (Fox et al. 2021), oil pollution (NRC 2003; Bertazzon et al. 2014; Fox et al. 2016), and noise (Hermanssen et al. 2019).

42.6. Acknowledgements

We would like to thank Norma Serra-Sogas, Lauren McWhinnie, and Nicole LeBaron, for early discussions and brainstorming that resulted in ongoing studies such as this. We thank Dr Rosaline Canessa, the Coastal and Ocean Resource Analysis Lab (CORAL) of the University of Victoria, Institute of Ocean Sciences, and the Canadian Wildlife Service for in-kind support.

42.7. References

Bejder, L., Samuels, A., Whitehead, H., and Gales, N. 2006. Interpreting short-term behavioural responses to disturbance within a longitudinal perspective. Animal behaviour. 72(5): 1149-1158.

Bertazzon, S., O'Hara, P.D., Barrett, O., and Serra-Sogas, N. 2014. Geospatial analysis of oil discharges observed by the National Aerial Surveillance Program in the Canadian Pacific Ocean. Applied Geography. 52: 78-89.

Fox, C.H., O'Hara, P.D., Bertazzon, S., Morgan, K., Underwood, F.E., and Paquet, P.C. 2016. A preliminary spatial assessment of risk: Marine birds and chronic oil pollution on Canada's Pacific coast. Science of the Total Environment. 573: 799-809.

Fox, C.H., Robertson, C., O’Hara, P.D., Tadey, R., and Morgan, K.H. 2021. Spatial assessment of albatrosses, commercial fisheries, and bycatch incidents on Canada’s Pacific coast. Marine Ecology Progress Series. 672: 205-222.

Herborg, L.M., O’Hara, P., and Therriault, T.W., 2009. Forecasting the potential distribution of the invasive tunicate *Didemnum vexillum*. Journal of Applied Ecology. 46(1): 64-72.

Hermannsen, L., Mikkelsen, L., Tougaard, J., Beedholm, K., Johnson, M., and Madsen, P.T. 2019. Recreational vessels without Automatic Identification System (AIS) dominate anthropogenic noise contributions to a shallow water soundscape. Scientific reports. 9(1): 1-10.

McWhinnie, L.H., O'Hara, P.D., Hilliard, C., Le Baron, N., Smallshaw, L., Pelot, R., and Canessa, R., 2021. Assessing vessel traffic in the Salish Sea using satellite AIS: A killer whale critical habitat. Ocean & Coastal Management. 200: 105479.

NRC (US National Research Council). 2003. Oil in the sea. III. Inputs, fates, and effects. National Research Council of the National Academies (Ocean Studies Board, Marine Board, Divisions of Earth and Life Studies, and Transportation Research Board). National Academy of the Sciences. Washington, DC: National Academies Press.

Nichol, L.M., Wright, B.M., O’Hara, P., and Ford, J.K. 2017. Risk of lethal vessel strikes to humpback and fin whales off the west coast of Vancouver Island, Canada. Endangered Species Research. 32: 373-390.

Raverty, S., St. Leger, J., Noren, D.P., Burek Huntington, K., Rotstein, D.S., Gulland, F.M., Ford, J.K., Hanson, M.B., Lambourn, D.M., Huggins, J., and Delaney, M.A. 2020. Pathology findings and correlation with body condition index in stranded killer whales (*Orcinus orca*) in the northeastern Pacific and Hawaii from 2004 to 2013. PloS one. 15(12): e0242505.

Serra-Sogas, N., O’Hara, P.D., Pearce, K., Smallshaw, L. and Canessa, R., 2021. Using aerial surveys to fill gaps in AIS vessel traffic data to inform threat assessments, vessel management and planning. Marine Policy. 133: 104765.

Williams, R., and O’Hara, P. 2010. Modelling ship strike risk to fin, humpback and killer whales in British Columbia, Canada. Journal of Cetacean Research and Management. 11(1): 1-8.

Williams, R., Wright, A.J., Ashe, E., Blight, L.K., Bruintjes, R., Canessa, R., Clark, C.W., Cullis-Suzuki, S., Dakin, D.T., Erbe, C., Hammond, P.S., Merchant, N.D., O'Hara, P.D., Purser, J., Radford, A.N., Simpson, S.D., Thomas, L. and Wale, M.A. 2015. Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management. Ocean & Coastal Management. 115:17-24. doi: 10.1016/j.ocecoaman.2015.05.021

43. WHAT WE HAVE LEARNT ABOUT THE SOUNDSCAPE IN THE SALISH SEA SINCE 2018

Rianna Burnham and Svein Vagle, Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., rianna.burnham@dfo-mpo.gc.ca, svein.vagle@dfo-mpo.gc.ca

43.1. Highlights

- Spatiotemporal patterns of noise additions from wind and vessels to ambient sound levels in the Salish Sea were considered.
- Wind noise was typically elevated in the winter especially in regions exposed to offshore winds. Noise from smaller, recreational vessels increased during summer.
- Commercial vessel noise is chronic in Juan de Fuca Strait and on Swiftsure Bank whereas in Boundary Pass and Haro Strait it is more acute with noise from transiting vessels punctuating otherwise relatively quiet ambient noise levels.

43.2. Passive Acoustic Data Collection and Analysis

Passive acoustic moorings have been deployed throughout the Salish Sea since February 2018 at locations with different sound field conditions, water properties and proximity to shipping lanes (Figure 43-1). The recordings are continuous with an acoustic bandwidth between 10 Hz and 100 kHz.

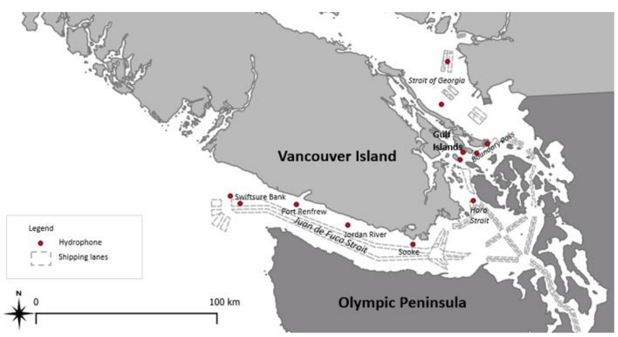


Figure 43-1. Map of soundscape monitoring locations.

Sound spectral levels for every minute of data were averaged to hourly and daily levels. Wind noise was estimated from wind speed data from the SalishSeaCast model (Soontiens et al. 2017) and converted to equivalent noise levels using available empirical relationships (Vagle et al. 1990). Vessel presence was characterised from Automatic Identification Systems (AIS) data differentiating Class A Tugs, and Deep-sea, Fishing, Passenger, and Class B vessels, where Class B vessels are smaller commercial or recreational vessels that voluntarily carry AIS-systems. Vessel noise was characterised in the 100–1000 Hz decadal band, and 63-Hz and 125-Hz centered 1/3 octave bands. Also, a higher-frequency range, centered around 50 kHz, was used to represent the presence of smaller vessels. A vessel noise model (Aulanier et al.

2017) at 125 Hz was used to interpolate between mooring locations and consider depth-dependence in the sound field. Recordings from transects of a known vessel noise source were used to characterise the variability in the transmission of anthropogenic noise sources. Recordings from each of the moorings were contrasted to define spatial patterns in soundscapes. These were also contrasted over various scales (season, month, week, day, diurnal) to define temporal patterns in the recordings.

43.3. Spatiotemporal trends in the soundscape

Each mooring showed distinct sound fields; however, similarities were seen between two adjacent pairs of moorings; Port Renfrew and Jordan River, and Haro Strait and Boundary Pass. There was a spatial distinction between the more exposed moorings in the west and those in more protected waters in the east from the influence of wind noise. Temporally, the soundscape showed strong seasonal patterns. Wind noise was greater in the winter, except at Sooke where localised increases in the summer months were seen (Figure 43-2).

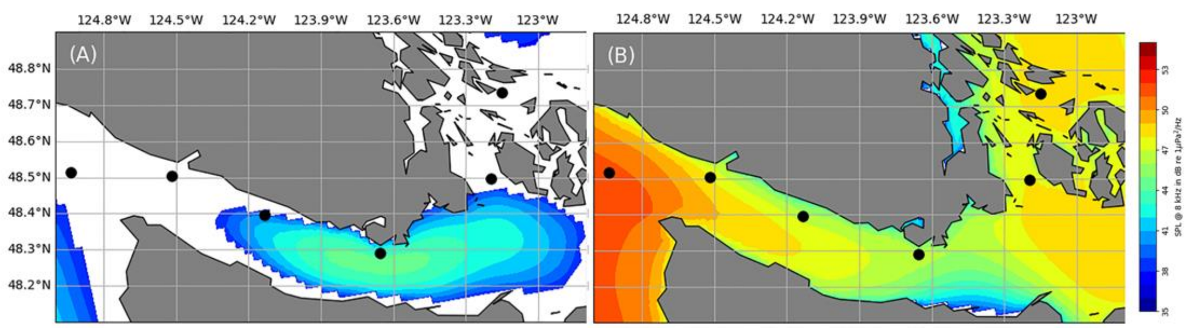


Figure 43-2. Summer (A) and winter (B) wind noise additions in the Salish Sea.

Swiftsure Bank showed the greatest vessel passage rate, with low-frequency vessel noise a constant in the soundscape. Again, similarities in the recordings of Port Renfrew and Jordan River and Haro Strait and Boundary Pass were seen when considering anthropogenic inputs. Whereas recordings from west Juan de Fuca Strait showed consistent vessel noise predominantly from vessels in the shipping lanes, Haro Strait and Boundary Pass, showed more acute additions, resulting from direct passages of vessels. For the moorings in Juan de Fuca Strait and Swiftsure Bank, the acoustic metrics suggested an increase in fishing and recreational vessels during the summer. Sound levels in the 50 kHz frequency were elevated at weekends compared to weekdays, and during the day compared to night (Burnham et al. 2021a). The patterns seen in the acoustic record are consistent with increased pleasure craft activity and recreational fishing, which typically increase from April to October. Experimental measures and the vessel noise model showed that sound speeds increase with depth and were increased in the upper water column in the summer. Tide, bathymetry, and seasonal stratification in water properties were also influential (Figure 43-3; Vagle et al. 2021).

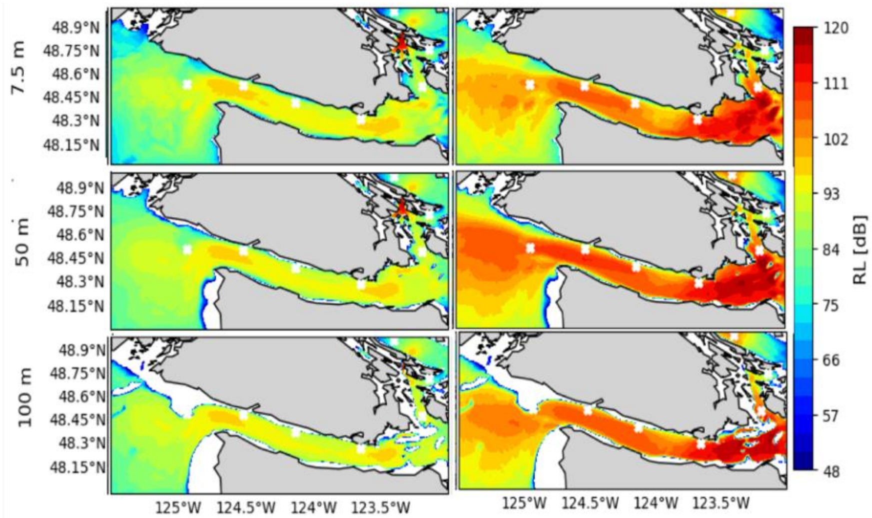


Figure 43-3. Received noise levels (RL) from commercial vessels at 7.5, 50 and 100 m water depth in summer (left) and winter (right).

43.4. Applications

These findings form a reference point that is being used to evaluate management measures (e.g., Vagle and Neves 2019; Vagle 2020; Burnham et al. 2021b) and to make predictions for impacts on the soundscape using possible scenarios of altered vessel presence, speed, and/or routing. Vessel numbers are expected to increase so this work will act as a baseline to compare future changes.

43.5. References

Aulanier, F., Simard, Y., Roy, N., Garvaise, C., and Bander, M. 2017. Effects of shipping on marine acoustic habitats in Canadian Arctic estimated via probabilistic modeling and mapping. Mar. Poll. Bull. 125: 115-131.

Burnham, R.E., Vagle, S., O'Neill, C. 2021a. Spatiotemporal patterns in the natural and anthropogenic additions to the soundscape in parts of the Salish Sea, British Columbia, 2018-2020. Mar. Poll. Bull. 170:112647.

Burnham, R.E., Vagle, S., O'Neill, C., and Trounce, K. 2021b. The efficacy of management measures to reduce vessel noise in critical habitat of southern resident killer whales in the Salish Sea. Front. Mar. Sci. 8: 664691.

Soontiens, N. and Allen, S.E. 2017. Modelling sensitivities to mixing and advection in a sill-basin estuarine system. Ocean Model. 112:17-32.

Vagle, S. 2020. Evaluation of the efficacy of the Juan de Fuca lateral displacement trial and Swiftsure Bank plus Swanson Channel interim sanctuary zones, 2019. Can. Tech. Report Hyd. Ocean Sci. 332: vi + 60 p.

Vagle, S., and Neves, M. 2019. Evaluation of the effects on underwater noise levels from shifting vessel traffic away from Southern Resident Killer Whale foraging areas in the Strait of Juan de Fuca in 2018. Can. Tech. Report Hydro. Ocean Sci. 329 : vi + 64 p.

Vagle, S., Large, W.G., and Farmer, D.M. 1990. An Evaluation of the WOTAN Technique of Inferring Oceanic Winds from Underwater Ambient Sound. J. Atmosph. Ocean. Tech. 7:576-595.

Vagle, S., Burnham, R.E., O'Neill, C., and Yurk, H. 2021. Variability in anthropogenic underwater noise due to bathymetry and sound speed characteristics. J. Mar. Sci. Eng. 9: 1047.

Appendix 1 - Poster Abstracts

44. ASSESSING OCEAN HABITAT FOR SEABIRDS – SCOTT ISLANDS MARINE NATIONAL WILDLIFE AREA

Greg Jones, Charles Hannah, Andrea Hilborn, Stephen Page, and Roy Hourston
Department of Fisheries and Oceans, Sidney, B.C., reshook@shaw.ca, Charles.Hannah@dfo-mpo.gc.ca, Andrea.Hilborn@dfo-mpo.gc.ca, Stephen.Page@dfo-mpo.gc.ca, Roy.Hourston@dfo-mpo.gc.ca

44.1. Highlights

- During the heat dome of summer 2021, satellite sea-surface-temperature data (SST) showed that temperatures in the National Wildlife Area (NWA) were elevated by a mean of 1.8°C meeting the standard for a marine heat wave.
- Sub-surface mooring data in the NWA showed that winter temperatures at 100m depth declined 2016 – 2021, likely due to recovery from the elevated temperatures from the major marine heat wave of 2014 to 2016 (the Blob). Each year, wind-driven mixing in the fall and winter results in similar temperatures from the surface to at least 100m depth.
- GPS surface drifters provide information to assess the risk of transport of anthropogenic substances into the NWA from various areas, and the risk of items leaving the NWA. Results from drifters support development of spill response, and search and rescue plans.

44.2. Description of the time series

The Scott Islands NWA was established by the Government of Canada in 2018. The NWA provides for conservation and research on migratory seabirds, and the ocean foraging habitats essential to support their breeding and productivity. About 40% of seabirds breeding in Canada's Pacific Ocean breed on the Scott Islands, including about ½ of the worlds Cassin's Auklet (*Ptychoramphus aleuticus*), and about 7% of the worlds Rhinoceros Auklet (*Cerorhinca monocerata*). Seabirds are true marine wildlife as all their food comes from the ocean. Marine conditions influence seabird breeding and populations through effects on forage species.

In 2015, the Canadian Wildlife Service of Environment and Climate Change Canada, and Ocean Sciences Division of Fisheries and Oceans Canada developed a Collaborative Agreement, recently renewed to 2025-2026. The Scott Islands project is part of the long-term ocean monitoring to understand causes and effects of changes in the ocean environment on the marine ecosystem and resources. Results will assist in the management of the NWA and other marine protected areas.

GPS drifters reveal potential for anthropogenic items, and natural living or inorganic substances, on the surface to be transported to an area. These results assist management agencies to develop plans to respond to incidents, including search and rescue as well as handling substance releases. Drifters used for research in this report are designed to travel with the surface layer of water, affected by winds, currents and waves. These drifters have a mean life span of about 9 days. There is wide variation in life span, one released in the NWA transmitted successfully for 28 days while drifting. Drifters that beach may last longer as they stop broadcasting when not moving. Locations are transmitted to satellite usually at either 5 or 10-

minute intervals, may be viewed in near real time, and are stored for subsequent analysis (Hourston et al. 2021).

44.3. Status and Factors influencing trends

Drifters released east of the NWA or near the entrance to Queen Charlotte Strait in all seasons demonstrated high potential for substances to enter the NWA and the adjacent southern reef of the Sponge Reefs MPA (Figure 44-1.). In the spring and summer, there is moderate potential for substances to be carried southward from Hecate Strait into the NWA. Substances released near the northern, southern and eastern boundary have high potential to enter in spring and summer. There is also high potential to enter the NWA from the south along the shelf in fall and winter. Northward travel along the shelf in fall through winter is expected due to normal northward currents in these seasons. There is low potential to enter from the south in spring and summer when currents along the shelf tend southward (Freeland et al. 1984).

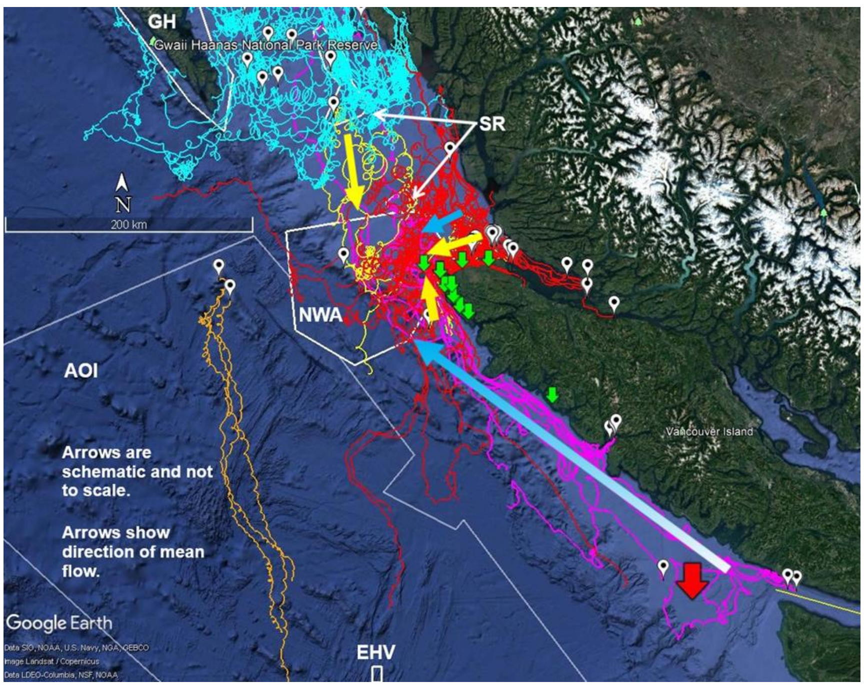


Figure 44-1. Potential for anthropogenic releases to enter the NWA from outside, all seasons 2014-2021. Figure shows drifters released outside the NWA. Yellow arrows: Enter NWA in spring and summer. Blue arrows: Enter NWA in fall and winter. Yellow: Released in NWA, exited then turned around and entered. Red: Released east of NWA. Magenta: Released south of NWA. Orange: Released west of NWA. Blue: Released north of NWA. White balloons: Start of drifters. Red arrow: Multiple ship containers entered water October 2021. Green arrows: Ship debris landed October 2021. Solid lines - Existing MPA's: NWA - Scott Islands Marine National Wildlife Area; GH - Gwaii Haanas National Park Reserve; EHV – Endeavour Hydrothermal Vents; SR: Hecate Strait/Queen Charlotte Sound Glass Sponge Reefs MPA, Central and Southern Reefs. Faded lines – AOI - Offshore Pacific Area of Interest.

Results of three drifters released west of the NWA in June suggested low potential to enter the NWA from the west. Drifters released inside the NWA in spring and summer demonstrated high potential to drift southward, northward and eastward. No drifters released in the NWA went westward past the western boundary into deep water (Figure 44-2).

Satellite observations showed that sea-surface-temperatures in the NWA were elevated during the heat dome of summer 2021 by 1.3°C to 2.3°C with a mean of 1.8°C, and within the definition of a marine heat wave as 1.29 standard deviations above the 30-year climate mean (Figure 44-3). The 1.29 SD standard is consistent with the NOAA heatwave tracker (Hilborn and Hannah

Section 11): https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-projects-blobtracker).

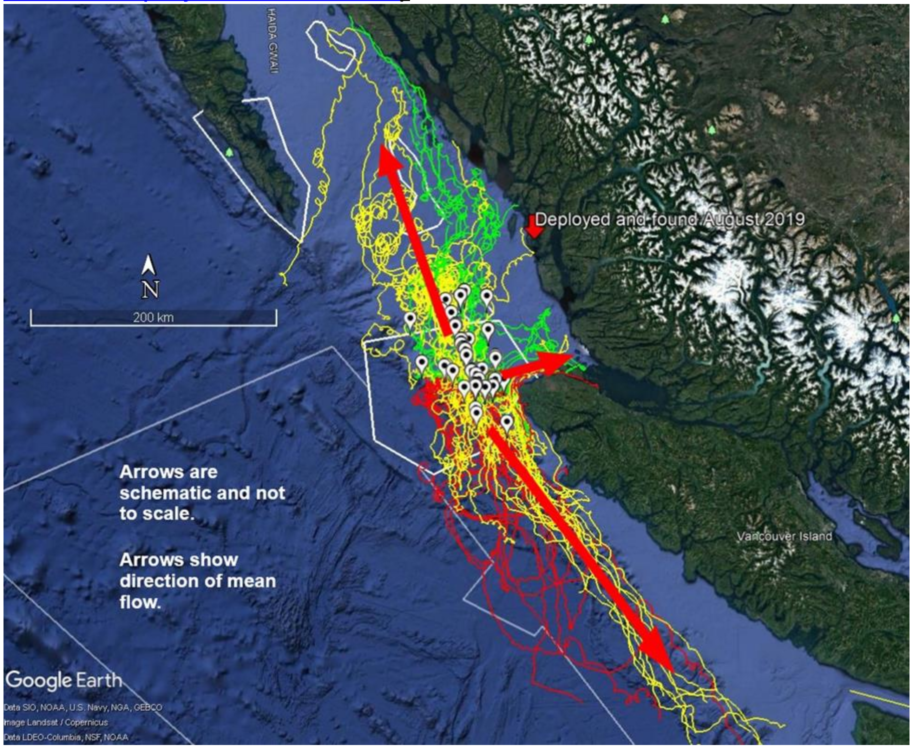


Figure 44-2. Potential for anthropogenic releases within the NWA to drift to other areas: May through September 2016 – 2021. Figure shows drifters released in or near the NWA. Red arrows: Exit NWA spring, summer, early fall. Yellow: May, June and July. Red: August. Green: September. No drifters were released in the NWA in late fall or winter. The other symbols and lines are as defined for Figure 44-1.

Analysis of trends in SST showed increases in winter, summer and fall in the Scott Islands NWA, and winter in all regions of the Northeast Pacific (Devred et al. 2021). Detailed information on SST and Chlorophyll-a levels in all MPA's, and existing defined areas under study as well as the wider marine ecosystem are found in this link:
SST and Chl-a Regional Summaries (bio-rsg.github.io)

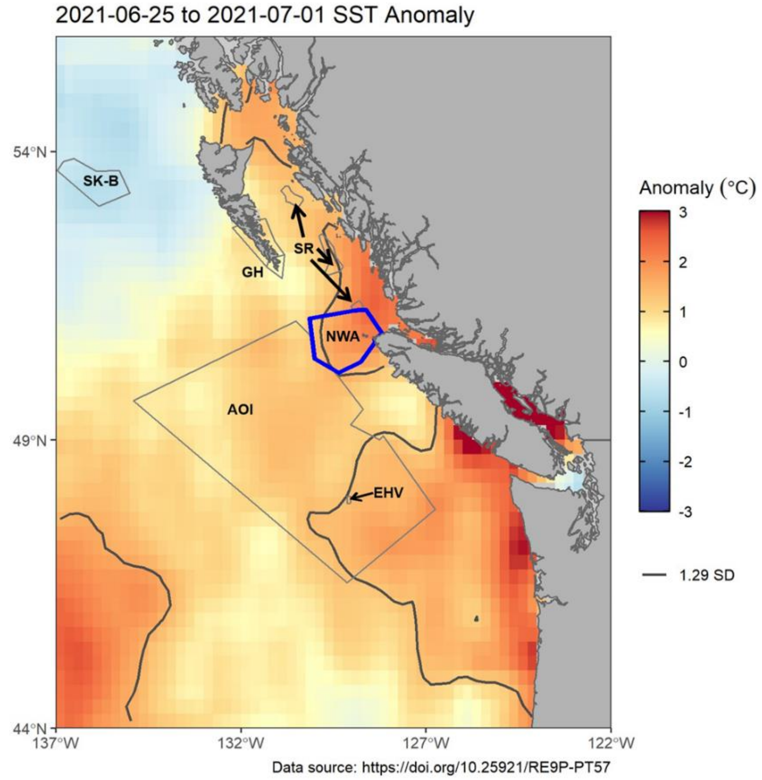


Figure 44-3. Sea Surface Temperature anomalies June 25 to July 1, 2021. Existing MPA's: NWA - Scott Islands Marine National Wildlife Area; GH - Gwaii Haanas National Park Reserve; SR: Hecate Strait/Queen Charlotte Sound Glass Sponge Reefs MPA, North, Central and Southern reefs. SK-B: SGaan Kinghlas-Bowie Seamount Marine Protected Area. EHV: Endeavour Hydrothermal Vents Marine Protected Area. Study area: AOI - Offshore Pacific Area of Interest.

Data recorded by a sub-surface mooring in the NWA shows seasonal variations in water temperatures at specified depths from mid 2016 to June 2021. Winter temperatures at 100m depth declined over this period, likely due to recovery from elevated ocean temperatures experienced 2014 to 2016 (Figure 44-4). Temperatures from sea surface to 100m below are similar from late fall into winter, due to wind-driven mixing of the water levels (Figure 44-4; SST provided by NOAA https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C01606/html).

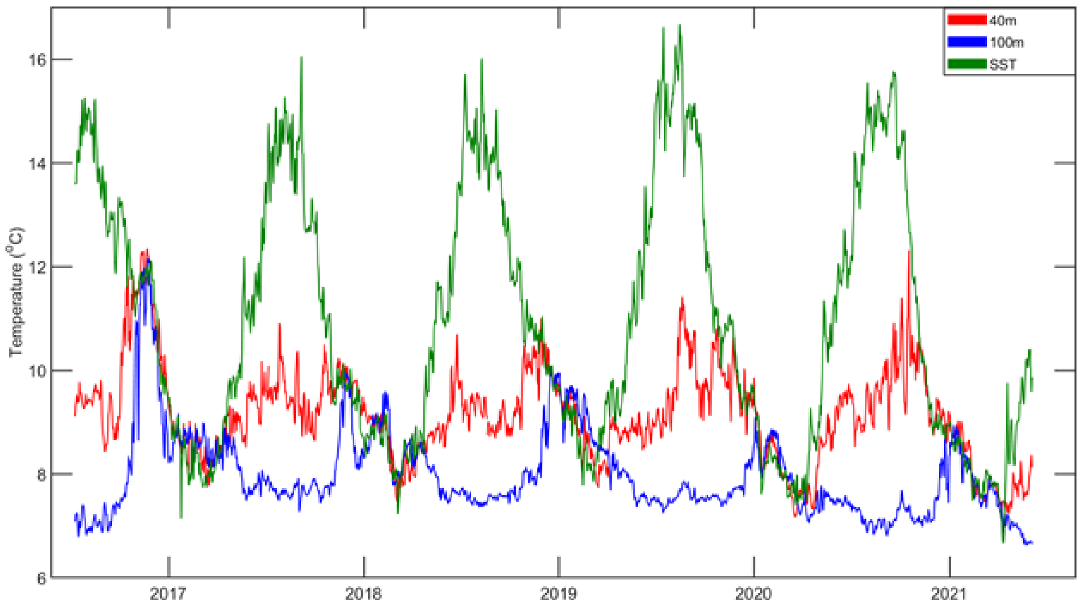


Figure 44-4. Water temperatures at 40m, 100m measured by sub-surface mooring Scott2 in the Scott Islands NWA from summer 2016 to June 2021. Satellite SST is also shown. Satellite SST data provided by NOAA: https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C01606/html

44.4. Implications of those trends

Marine heat waves which elevate ocean temperatures may result in significant mortality of the planktivorous Cassin's Auklet, due to reduced availability of nutritious plankton species (Jones et al. 2018). Similarly, growth of Cassin's Auklet chicks is reduced on Triangle Island, one of the Scott Islands, when SST is elevated in a strongly positive state of the Pacific Decadal Oscillation, resulting in lower availability of quality forage (Hipfner et al. 2020). In October 2021 substantial numbers of shipping containers were lost from the Zim Kingston on the La Perouse Bank (Unpublished data). One was carried northward towards, then eastward through the NWA along the Vancouver Island shore and was beached near the eastern boundary of the NWA. Other debris from this incident landed within or near the NWA. This incident shows that items entering the NWA from the south can drift eastwards into the NWA, as well as northward or westward (Figure 44-1; Department of Fisheries and Oceans, 2021).

44.5. References

Devred, E., Hardy, M., and Hannah, C. 2021. Satellite observations of the Northeast Pacific Ocean. Can. Tech. Rep. Hydrogr. Ocean Sci. 335: vii+46 p.

Freeland, H.J., Crawford W.R., and Thomson, R.E. 1984. Currents along the pacific coast of Canada. Atmosphere-Ocean. 22(2): 151-172. DOI:10.1080/07055900.1984.9649191

Hipfner, J.M., Galbraith, M., Bertram, D.F., and Green, D.J. 2020. Basin-scale Oceanographic processes, zooplankton community structure, and diet and reproduction of a sentinel North Pacific seabird over a 22-year period. Progress in Oceanography. 182: 102290, ISSN 0079-6611, https://doi.org/10.1016/j.pocean.2020.102290

Hourston, R.A.S., Martens, P.S., Juhász, T., Page, S.J. and Blanken, H. 2021. Surface ocean circulation tracking drifter data from the Northeastern Pacific and Western Arctic Oceans, 2014-2020. Can. Data Rep. Hydrogr. Ocean Sci. 215: vi + 36 p.

Jones, T., Parrish, J.K., Peterson, W.T., Bjorkstedt, E.P., Bond, N.A., Balance, L. T., Bowes, V., Hipfner, J.M., Burgess, H.K., Dolliver, J.E., Lindquist, K., Lindsey, J., Nevins, H.M., Robertson, R.R., Roletto, J., Wilson, L., Joyce, T., and Harvey, J. 2018. Massive mortality of a planktivorous seabird in response to a marine heatwave. Geophysical Research Letters. 45: 3193–3202. https://doi.org/10.1002/2017GL076164

45. SEA LEVEL IN BRITISH COLUMBIA, 1910 TO 2021

Dave Riedel and Anne Ballantyne, Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Dave.Riedel@dfo-mpo.gc.ca, Anne.Ballantyne@dfo-mpo.gc.ca

45.1. Highlights

- The annual mean water levels at Victoria, Tofino and Prince Rupert for 2021 were above the long-term trend line, though not significantly.
- Removing the vertical tectonic uplift changes the long-term trend at the three locations, particularly in Tofino, where it is reversed.
- The post-1993 rate of sea level rise in B.C. is, at present, substantially less than that seen in the global mean sea level data.

45.2. Summary

The Canadian Hydrographic Service performs long-term monitoring of sea levels along the B.C. coast. Particularly long time-series have been collected at Tofino and Victoria (1910-present) and at Prince Rupert (1912-present). The annual deviations from the long-term average (1981-2010) are shown for these stations in Figure 45-1.

A linear trend line was fitted to the entire data-set for each location. In 2021, the average sea level for all three stations was above the trend line (not significant); a reversal of the situation from 2020. There is considerable variability in the record.

The linear sea level rise trend at each location (in cm/century) is +7.3 cm for Victoria, +10.7 cm for Prince Rupert, and -12.1 cm for Tofino. The latter value is of interest in that the local sea level (measured relative to the land) is decreasing at an average of 12cm/per 100 years. This is the result of a tectonic

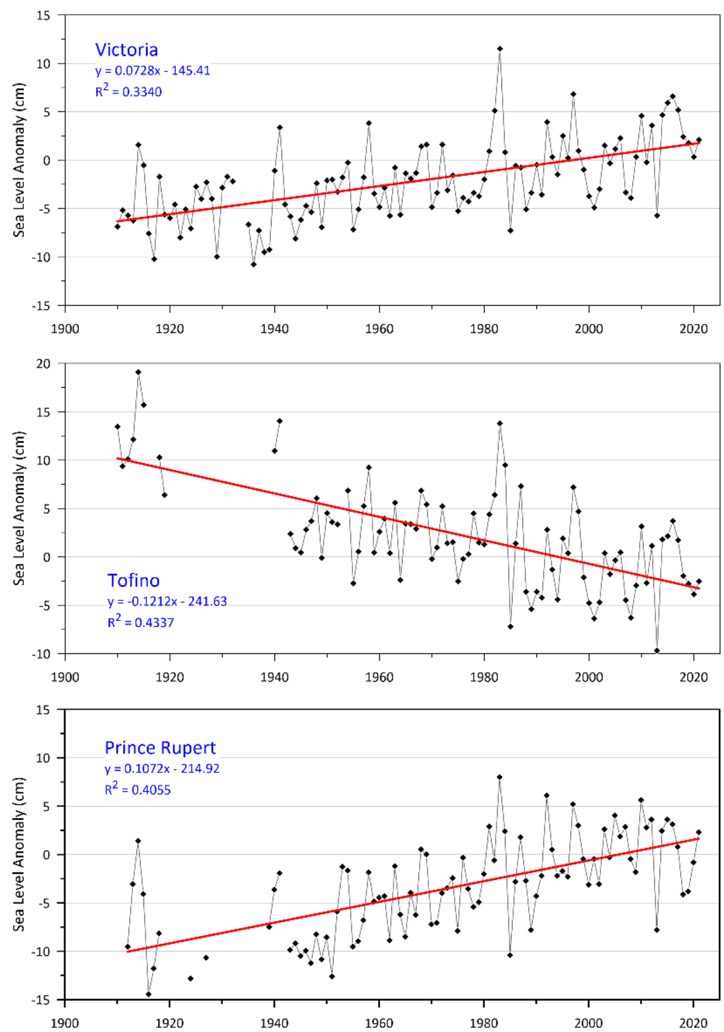


Figure 45-1. Annual-average sea level anomalies at three B.C. ports. Reference years for anomaly calculation are 1981 to 2010. Linear trends shown in red.

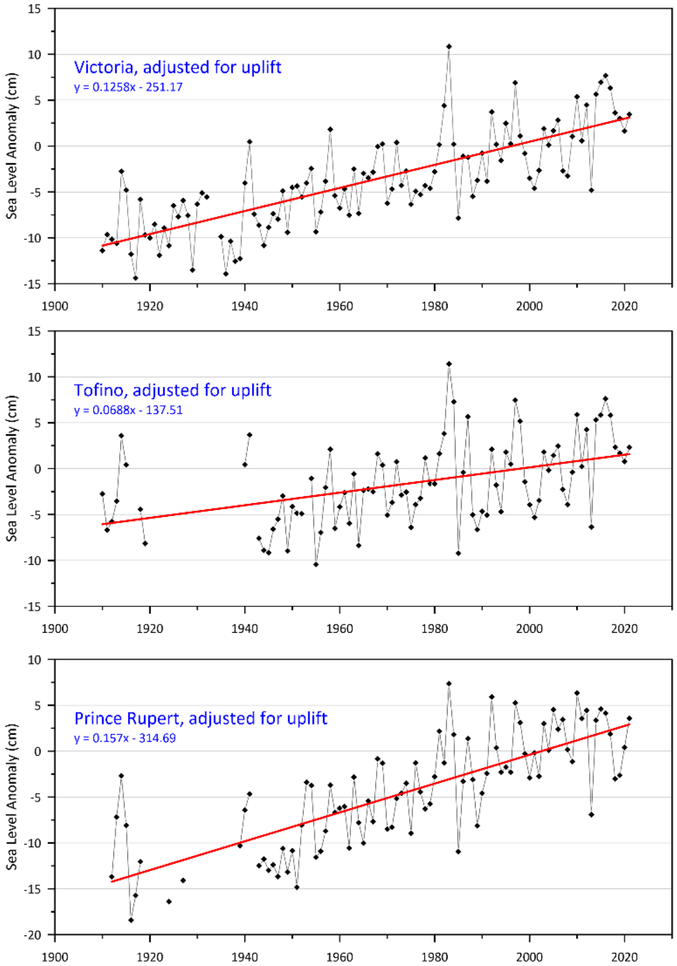


Figure 45-2. Annual-average sea level anomalies (relative to the average from 1981 to 2010) at three B.C. ports with vertical land movement removed.

process. As the Juan de Fuca tectonic plate moves beneath the North American plate, coastal B.C. and in particular western Vancouver Island experiences uplift at a rate of a few millimetres annually. The amount decreases as you move eastward nearing zero as you reach Vancouver (Thomson, et. al., 2008). As a result of this uplift, the land at Tofino is rising faster than the sea level. Removing the tectonic motion of 1.9 mm annual uplift, derived as the average from 1994 to 2017 (Thomas James, Geological Survey of Canada, pers. comm. 2018), from the sea level values at Tofino from 1910 to 2021 results in a linear trend of +6.9 cm per century.

More modest uplift is present at Victoria (+0.53 mm/year) and Prince Rupert (+0.5 mm/year). When this movement is removed from the Victoria data, the linear trend becomes +12.6 cm per century and at Prince Rupert the linear trend becomes +15.7 cm per century. The three uplift-adjusted time-series are shown in (Figure 45-2).

The linear sea level rise trend at each port corrected for vertical land movement (in cm/century) is +12.6 cm at Victoria, +15.7 cm at Prince Rupert and +6.8 cm at Tofino.

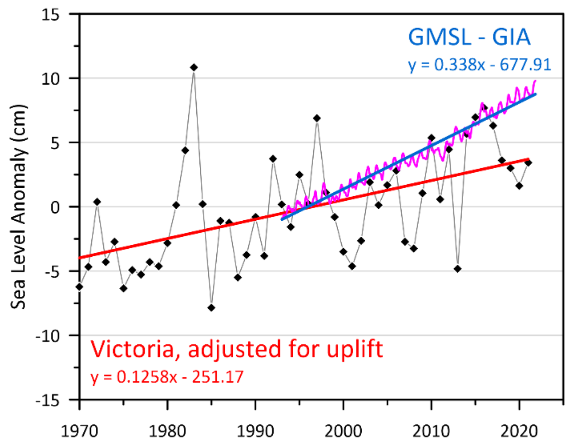


Figure 45-3. Annual-average sea level anomaly at Victoria (vertical land movement removed) in contrast to global mean sea level (GMSL) with global isostatic adjustment (GIA). Red and blues lines are linear fits to the Victoria and GMSL data respectively.

Global sea levels rose by 17± 5 cm in the 20th century (Church and White 2011). The Intergovernmental Panel on Climate Change (IPCC 2014) predicts sea level to rise from 26 to 55 cm to 45 to 82 cm toward the end of the 21st century, but recent observations of ice melt in Greenland and Antarctica suggest these projections might be too low. Therefore, we can expect to observe greater rates of sea level rise in B.C. in the future than we saw in the 20th century.

However, we have not observed significant acceleration thus far. Global mean sea level data have been collected via by NASA's Goddard Space Flight Center since 1993. These data (corrected for global isostatic adjustment, GIA) with respect to 20-year TOPEX/Jason collinear mean reference show rates of sea level rise of +3.4 mm/year, or +34 cm/century (Figure 45-3). This is substantially higher than the observed rates of sea level rise in B.C. presented here.

45.3. References

Church, J.A, and White, N.J. 2011. Sea-level rise from the late 19th to the early 21st Century. Surveys in Geophysics. 32: 585-602.

GSFC, 2021. Global Mean Sea Level Trend from Integrated Multi-Mission Ocean Altimeters TOPEX/Poseidon, Jason-1, OSTM/Jason-2, and Jason-3 Version 5.1. Ver. 5.1 PO.DAAC, CA, USA. Dataset accessed [2022-02-28] at https://doi.org/10.5067/GMSLM-TJ151.

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 p.

Thomson, R.E., Bornhold, B.D., and Mazzotti, S. 2008. An Examination of the Factors Affecting Relative and Absolute Sea Level in Coastal British Columbia. Can.Tech. Rep. Hydrogr. Ocean Sci. 260. 49 p.

46. EFFECTS OF THE HUNGA TONGA – HUNGA HA'APAI VOLCANIC TSUNAMI OF JANUARY 15, 2022 ON THE BRITISH COLUMBIA COAST

J. Patrick McNeill[1], Caden Martin[1], Denny Sinnott[1], and Alexander Rabinovich[1,2]

[1]Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C.,
Patrick.McNeill@dfo-mpo.gc.ca, Caden.Martin@dfo-mpo.gc.ca, Denny.Sinnott@dfo-mpo.gc.ca
[2]Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia,
a.b.rabinovich@gmail.com

46.1. Highlights

- Tsunami waves were observed at 26 active water level gauges on the B.C. coast with wave heights generally ranging from 10 to 50 cm.
- This event was the first tsunami with a volcanic origin observed by water level instrumentation within Canadian waters.
- Atmospheric pressure disturbances associated with the eruption's shockwave were observed and induced small meteotsunamis at some gauges prior to the arrival of the primary waves.
- The volcanic source, rather than a seismic event with a defined magnitude, resulted in the National Warning Centres having difficulty predicting the tsunami heights and arrival times at coastal locations.

46.2. Extended abstract

At approximately 04:00 UTC on January 15, 2022 a significant volcanic eruption occurred at the shallow submarine volcano, Hunga Tonga – Hunga Ha'apai, in the southwest Pacific nation of Tonga (Global Volcanism Program 2022). A tsunami advisory was issued for the B.C. coast with the initial waves anticipated to arrive between 08:30-08:50 PST (16:30-16:50 UTC). The volcanic eruption created a significant tsunami in Tonga with minor tsunamis being reported throughout the entire Pacific basin. While the tsunami signal was weak in Canadian waters it was observed at 26 stations maintained by the Canadian Hydrographic Service (CHS) (Figure 46-1). The waves began arriving on the B.C. Coast around 04:30 PST (12:30 UTC) with heights generally ranging from 10-50 cm.

The data analysis was performed using established methods by Rabinovich et al. (2006 and 2013). This involved first processing the raw water level observations to remove errors, gaps, and spikes. Using a least squares analysis the tides were computed and subtracted from the observations to normalize the records. Furthermore, to supress low-frequency sea-level fluctuations, largely atmospheric driven, the tide corrected time-series were filtered using a 4-hour Kaiser-Bessel (KB) window. These filtered time-series were then plotted to analyze the tsunami waves and their properties.

This event was the first known tsunami to be observed within Canadian waters with a volcanic origin. Being an abnormal event there were some unique effects that were observed and difficulties encountered with predicting the heights and arrival times of the tsunami at coastal

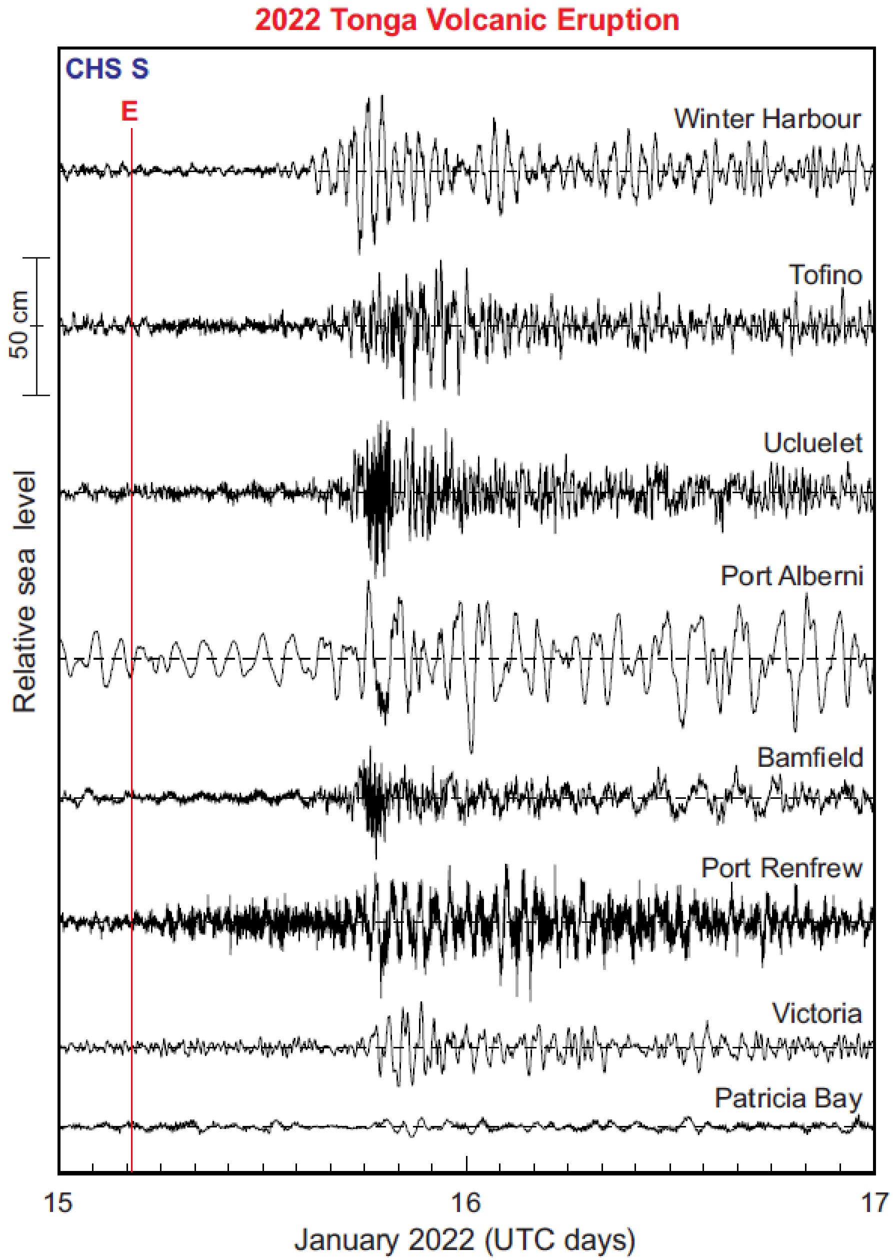


Figure 46-1. Tide corrected and filtered tsunami observations for eight stations on Vancouver Island. The red line marked E corresponds to the time of the eruption.

locations. There are no existing National Tsunami Warning Centre forecasting tools designed for events with a non-seismic source. Furthermore, the eruption generated an air pressure (shock) wave which induced water level oscillations prior to the arrival of the primary tsunami waves, resulting in incorrect estimates of arrival times (NOAA Centre for Tsunami Research 2022). These pressure spikes were detected by barometers located at four of the CHS' tidal stations with early air pressure driven meteotsunamis being observed (Figure 46-2). The magnitude of the event was generally well forecasted with the observed tsunami waves being within advisory levels for all locations in B.C.

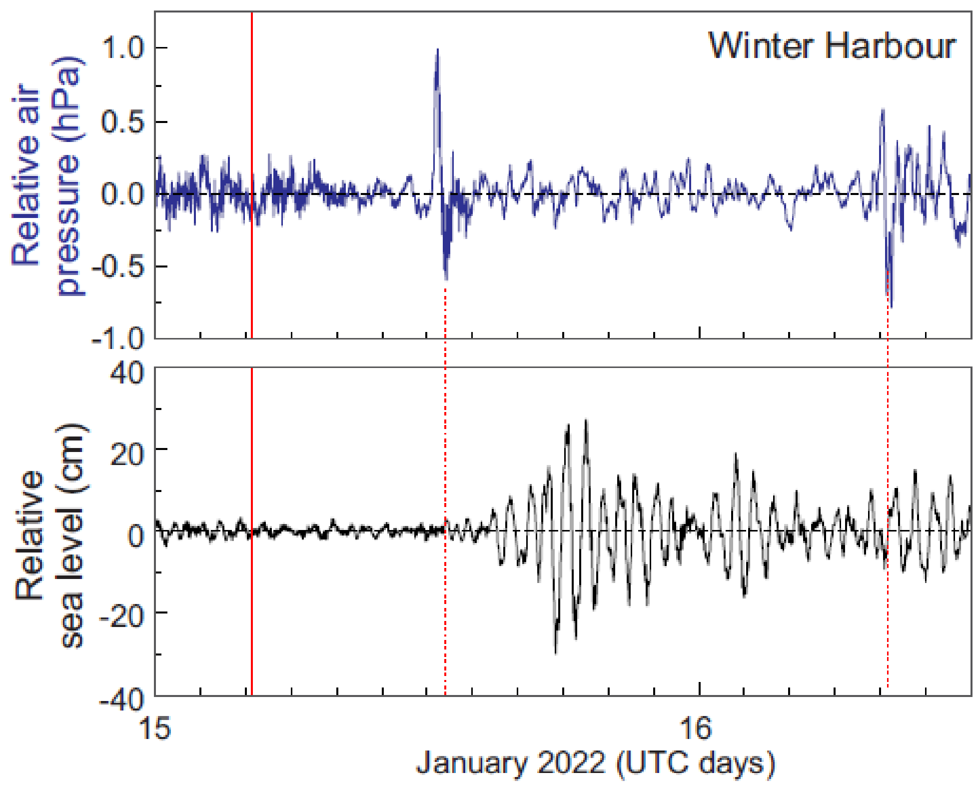


Figure 46-2. Relative air pressure and sea level at Winter Harbour showing the impact of the air pressure (shock) wave on water levels. The solid red line corresponds to the time of the eruption and the dashed red lines correspond to the times of the observed air pressure waves.

46.3. References

Global Volcanism Program. 2022. Report on Hunga Tonga-Hunga Ha'apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 12 January-18 January 2022. Smithsonian Institution and US Geological Survey. https://volcano.si.edu/showreport.cfm?doi=GVP.WVAR20220112-243040 (accessed 21 February, 2022).

NOAA Centre for Tsunami Research. 2022. Hunga Tonga-Hunga Ha'apa Volcano-generated Tsunami, January 15, 2022. Pacific Marine Environmental Laboratory and the National Oceanic and Atmospheric Administration. https://nctr.pmel.noaa.gov/tonga20220115/ (accessed 24 February, 2022).

Rabinovich, A.B., Thomson, R.E., and Stephenson, F.E. 2006. The Sumatra Tsunami of 26 December 2004 as observed in the North Pacific and North Atlantic Oceans. Surveys in Geophysics. 27: 647-677.

Rabinovich, A.B., Thomson, R.E., and Fine, I.V. 2013. The 2010 Chilean tsunami off the west coast of Canada and the northwest coast of the United States. Pure and Applied Geophysics. 170 (9-10): 15291565; doi: 10.1007/s00024-012-0541-1.

47. OCEAN MONITORING OF GWAII HAANAS NATIONAL PARK RESERVE, NATIONAL MARINE CONSERVATION AREA RESERVE, AND HAIDA HERITAGE SITE

Stephen Page[1], Charles Hannah[1], Lynn Lee[2], David Spear[1], Cindy Wright[1]

[1]Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, B.C., Stephen.Page@dfo-mpo.gc.ca
[2]Gwaii Haanas Park Reserve, National Marine Conservation Area Reserve, and Haida Heritage Site, Parks Canada Agency, Queen Charlotte, B.C.

47.1. Highlights

- 2021 January to March upper ocean temperatures were comparable to previous years, however, spring bottom ocean temperatures were colder than previous years.
- Moored instrumentation in Gwaii Haanas shows a strong seasonal cycle and little inter-annual variability over past five years.

47.2. Description of the time series

Gwaii Haanas management partners - Fisheries and Oceans Canada, Parks Canada Agency and Council of the Haida Nation - have been collaboratively conducting oceanographic monitoring in Gwaii Haanas since 2016. An oceanographic instrumented subsurface mooring was first installed in Juan Perez Sound in 2017 and has been recovered and re-deployed every summer since. This subsurface mooring is outfitted to measure temperature, salinity, dissolved oxygen, pH and water currents. The mooring provided insights into the oceanographic conditions in Juan Perez Sound over time. Ship-based oceanographic operations occurred in Juan Perez Sound in 2021, which provided a cross-section of oceanographic conditions spatially in the study area over a short time frame.

47.3. Status and trends

Juan Perez Sound is well stratified for temperature and salinity in the summer, and well mixed during the winter for temperature and oxygen, but only briefly for salinity. Because the mooring is a subsurface mooring, instrument data is only downloaded when the mooring is recovered, a year after deployment. Seasonal trends follow very closely to what is seen at the south end of Hecate Strait (Figures 47-1 and 47-2).

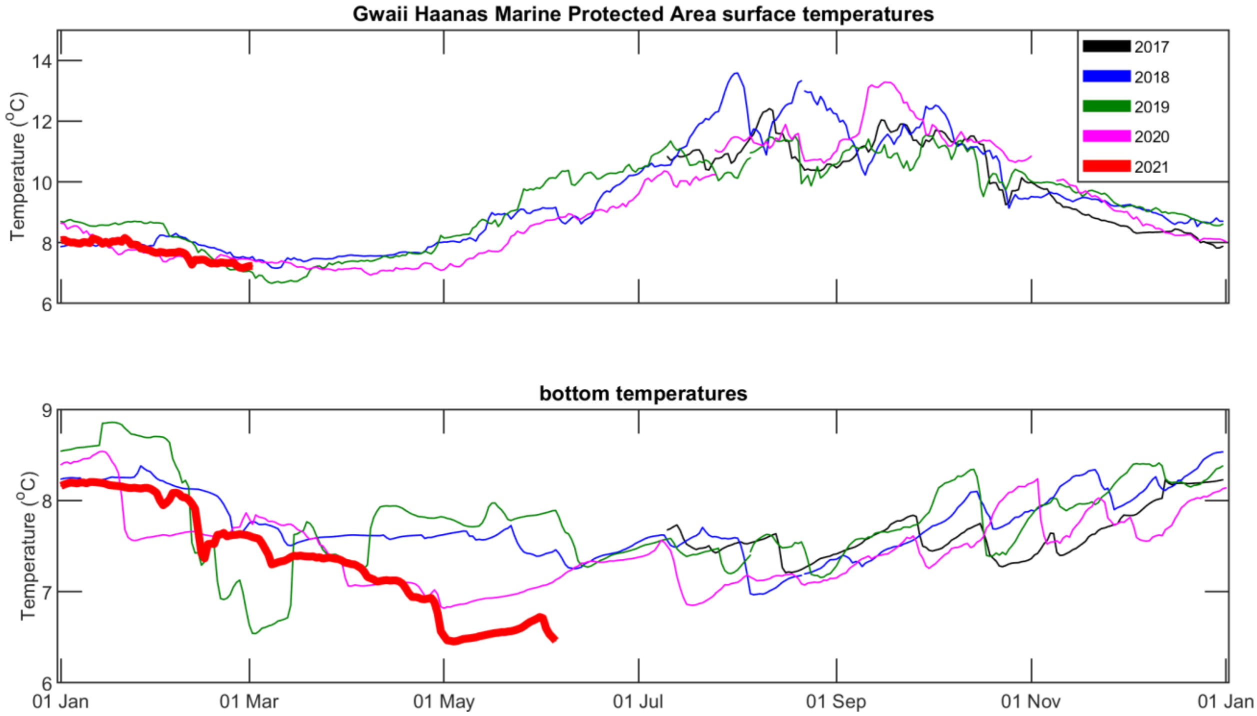


Figure 47-1. Annual variability of near surface and bottom temperatures.

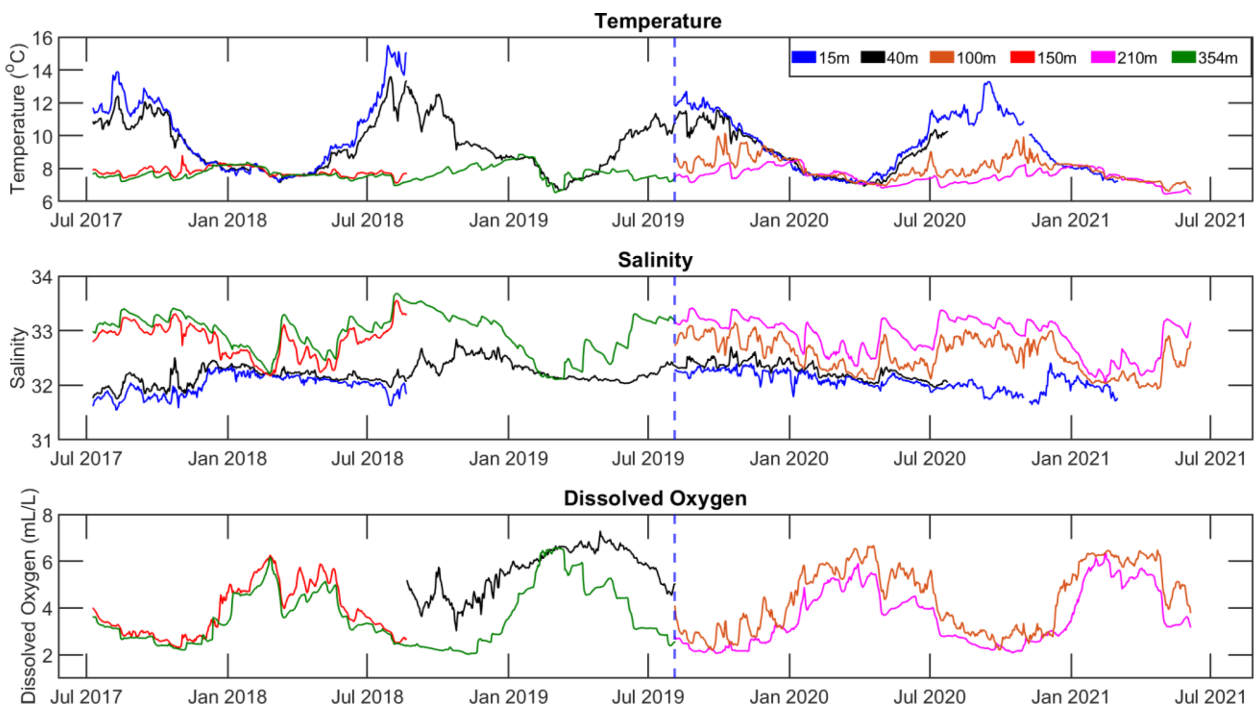


Figure 47-2. Four-year time series of temperature, salinity and oxygen at several depths from the Juan Perez Sound instrumented mooring.

Appendix 2 - Meeting Agenda

SOPO DAY 1 - Tuesday March 8, 2022		
P#	Name	Title
1	Tucker/Gauthier/Boldt	Introduction
2	Elder Naalthwiik	First Nation Welcome
3	Andy Thomson	Welcome from DFO
4	Faron Anslow	Land temperature and hydrological conditions in 2021
5	Tetjana Ross	Review of temperature, salinity and density of the North Eastern Pacific in 2021 using Argo, glider, satellite and Line P data
6	Roy Hourston	Wind-driven upwelling along the Northwest coast of North America: timing and magnitude
7	Peter Chandler	Sea surface temperature and salinity observed at shore stations and weather buoys along the B.C. coast in 2021
8	Andrea Hilborn	Sea Surface Temperature during 2021: heat waves and heat domes
	Lunch	
9	Guoqi Han	Circulation and transport variability off the west coast of Canada over 1993-2021
10	Jennifer Jackson	Rivers Inlet, Burke Channel, and Bute Inlet water properties in 2021 compared to a historical time series
11	Wiley Evans	Coastal marine CO2 observations in British Columbia during 2021
12	Akash Sastri	Oceanographic conditions off the West Coast of Vancouver Island: 2021
13	Hayley Dosser/Khush Jhugroo	C-PROOF 2021- ocean glider data from Line P and Queen Charlotte Sound
14	Ana Franco	Extremely unusual hypoxia in the shelf of British Columbia in late summer 2021
15	Akash Sastri/Moira Galbraith	West coast zooplankton: annual anomaly time series
16	Tucker/Gauthier/Boldt	Summary discussion
SOPO DAY 2 - Wednesday March 9, 2022		
17	Tucker/Gauthier/Boldt	Summary
18	Clare Ostle	Lower Trophic Levels in the Northeast Pacific, from Continuous Plankton Recorder sampling
19	Erin Herder	Surveys for Olympia Oysters (Ostrea lurida Carpenter, 1864) at six index sites in British Columbia – 2010-2021
20	Jennifer Boldt/Jaclyn Cleary	Pelagic fish: an update on status and trends
21	Howard Stiff	Sockeye Index Stock Recruitment in 2021
22	Steve Latham	Size trends of mature Fraser River Sockeye and Pink Salmon
23	Sean Anderson	Pacific Canadian groundfish stock status and surveys in 2021
24	Stéphane Gauthier	Distribution and abundance of Pacific Hake (Merluccius productus) from the 2021 Joint U.S.-Canada Acoustic-Trawl Survey

	Lunch	
25	Mark Hipfner	Observations on seabirds along the B.C. coast
26	Katie Gale	Update on the distribution of aquatic invasive species and monitoring activities in the Pacific Region
27	Cherisse Du Preez, Skil Jáada (Vanessa Zahner), Laís Chaves, Heidi Gartner	A proposed monitoring framework for the SGaan Kinghlas-Bowie Seamount Marine Protected Area: research document
28	Peter Chandler	Salish Sea temperature, salinity and oxygen observations in 2021
29	Richard Dewey	Ocean observatory contributions to assessing 2021 B.C. coastal conditions
30	Susan Allen	Spring phytoplankton bloom timing, interannual summer productivity in the Strait of Georgia
31	Rich Pawlowicz/ Svetlana Esenkulova	Harmful algal blooms and oceanographic conditions in the Strait of Georgia 2021
32	Tucker/Gauthier/Boldt	Summary discussion
SOPO DAY 3 - Thursday March 10, 2022		
33	Tucker/Gauthier/Boldt	Summary
34	Linnea Flostrand	Eulachon status and trends in Southern British Columbia
35	Christian Marchese/ Maycira Costa	Marine bioregions of British Columbia using Sentinel-3 Chlorophyll-a data: spatial-temporal dynamics 2016-present
36	Kelly Young	Zooplankton status and trends in the Central and Northern Strait of Georgia, 2021
37	Jennifer Boldt/Chrys Neville	Juvenile salmon in the SoG
38	Will Duguid	British Columbia coastal ecosystem structure through the lens of adult Chinook Salmon diets
39	Jackson Chu	The Saanich Inlet ROV transect 2021: recovery of a cold-water coral community
40	Thomas Doniol-Valcroze	Abundance, distribution and density of cetaceans from ship-based surveys in Pacific Canadian waters
	Lunch	
41	Patrick O'Hara	Recent trends in marine traffic and associated threats in the Salish Sea based on Automatic Identification System for Ships (AIS)
42	Svein Vagle	What we have learnt about the soundscape in the Salish Sea since February 2018
43	Jennifer Boldt	Unusual occurrences in 2021
44	Poster highlights	Summary highlights of posters
45	Kat Middleton	Canada's Oceans Now: Pacific Ecosystems, 2021 - State of the Pacific Ocean Public Report
46	Elder Naalthwiik	First Nation Closing
47	Tucker/Gauthier/Boldt	Summary discussion

Appendix 3 - Meeting Participants (Zoom Sign-in names and affiliations)

First Name	Last Name	Organization
Dilumie	Abeysirigunawardena	Ocean Networks Canada
Selina	Agbayani	Fisheries and Oceans Canada
Philip	Akins	Marine Plan Partnership (MaPP), Central Coast
Hussein	Alidina	WWF-Canada
Susan	Allen	University of British Columbia
Alicia	Andersen	University of British Columbia
Sean	Anderson	Fisheries and Oceans Canada
Susan	Anderson Behn	Semiahmoo First Nation
Faron	Anslow	Pacific Climate Impacts Consortium
Chris	Apps	Kitselas First Nation
William	Atlas	Wild Salmon Center
Lenore	Baker	Spuzzum
Sarah	Bartnik	Environment and Climate Change Canada
Cynthia	Barwell	Kitselas First Nation
Sonia	Batten	North Pacific Marine Science Organization
Adam	Batty	BC Government
Kohen	Bauer	Ocean Networks Canada
Bruce	Baxter	Fisheries and Oceans Canada
Kathryn	Berry	Fisheries and Oceans Canada
Rebecca	Beutel	University of British Columbia
Laura	Bianucci	Fisheries and Oceans Canada
Michelle	Bigg	Fisheries and Oceans Canada
Jennifer	Boldt	Fisheries and Oceans Canada
Sean	Boyd	Science & Technology Branch, Environment & Climate Change Canada
Hannah	Bregulla	Council of the Haida Nation
Norah	Brown	Fisheries and Oceans Canada

Nick	Brown	Fisheries and Oceans Canada
Alice	Bui	Ocean Networks Canada
Desiree	Bulger	Malahat Nation
Dominique	Bureau	Fisheries and Oceans Canada
Rianna	Burnham	Fisheries and Oceans Canada
Wendy	Callendar	Fisheries and Oceans Canada
Chelsey	Cameron	Environment and Climate Change Canada
Karalea	Cantera	Fisheries and Oceans Canada
Irene	Carrasco	Fisheries and Oceans Canada
Tyson	Carswell	BC Ministry of Agriculture, Food & Fisheries
Kristina	Castle	Fisheries and Oceans Canada
Peter	Chandler	Fisheries and Oceans Canada
Michelle	Charbonneau	Fisheries and Oceans Canada
Katherine	Charles	Fisheries and Oceans Canada
Lais	Chaves	Council of the Haida Nation (CHN)
Sean	Cheesman	BC Ministry of Agriculture, Food and Fisheries
Elly	Chmelnitsky	Fisheries and Oceans Canada
Nicole	Christiansen	Pacific Salmon Foundation
Jackson	Chu	Fisheries and Oceans Canada
Chris	Clarke	Fisheries and Oceans Canada
Stephanie	Clay	Fisheries and Oceans Canada
Jaclyn	Cleary	Fisheries and Oceans Canada
Brendan	Connors	Fisheries and Oceans Canada
Wendi	Contois	Fisheries and Oceans Canada
Maycira	Costa	University of Victoria
William	Crawford	Fisheries and Oceans Canada
Stu	Crawford	Council of the Haida Nation
Rebecca	Croke	Fisheries and Oceans Canada
Quinn	Cunningham	Fisheries and Oceans Canada
Terry	Curran	Pacific Salmon Foundation
Neil	Dangerfield	Fisheries and Oceans Canada

Katie	Davidson	Fisheries and Oceans Canada
Lindsay	Davidson	Fisheries and Oceans Canada
Shaun	Davies	Fisheries and Oceans Canada
Sarah	Davies	Fisheries and Oceans Canada
Hailey	Davies	University of Victoria
Justin	Del Bel Belluz	Hakai Institute
Roanan	DeMeyer	University of Victoria
Siobhan	Demulder	Fisheries and Oceans Canada
Jeff	Denison	Fisheries and Oceans Canada
Danielle	Denley	Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD), Province of British Columbia
Danielle	Derrick	Fisheries and Oceans Canada
Emmanuel	Devred	Fisheries and Oceans Canada
Richard	Dewey	Ocean Networks Canada
Ariane	Dilay	Fisheries and Oceans Canada
Jake	Dingwall	Pacific Salmon Foundation
Thomas	Doniol-Valcroze	Fisheries and Oceans Canada
Hayley	Dosser	Fisheries and Oceans Canada
Kelsey	Dougan	Fisheries and Oceans Canada
Nicole	Drewitz	Fisheries and Oceans Canada
Cherisse	Du Preez	Fisheries and Oceans Canada
Will	Duguid	University of Victoria
Katarina	Duke	KC First Nations
Kristy	Durst	
Wendy	Eash-Loucks	King County
Andrew	Edwards	Fisheries and Oceans Canada
Philina	English	Fisheries and Oceans Canada
Wiley	Evans	Tula Foundation / Hakai Institute
Isaak	Fain	Fisheries and Oceans Canada
Julia	Fast	University of British Columbia
Bridget	Ferriss	NOAA Fisheries Alaska Fisheries Science Center

Hannah	Fiegenbaum	TBuck Suzuki Foundation
Linnea	Flostrand	Fisheries and Oceans Canada
Michael	Folkes	Fisheries and Oceans Canada
Ian	Forster	Fisheries and Oceans Canada
Marie	Fournier	Fisheries and Oceans Canada
Fiona	Francis	Fisheries and Oceans Canada
Ana	Franco	University of British Columbia
Tamara	Fraser	Fisheries and Oceans Canada
Nicole	Frederickson	Island Marine Aquatic Working Group
Howard	Freeland	Fisheries and Oceans Canada, Retired
Caihong	Fu	Fisheries and Oceans Canada
Lindsay	Galbraith	Fisheries and Oceans Canada
Catherine	Galbrand	Transport Canada
Katie	Gale	Fisheries and Oceans Canada
Gadwyn	Gan	Musqueam
Heidi	Gartner	Fisheries and Oceans Canada
Germaine	Gatien	Fisheries and Oceans Canada
Stephane	Gauthier	Fisheries and Oceans Canada
Jennifer	Gavriel	Province of British Columbia government
Kayleigh	Gillespie	Fisheries and Oceans Canada
Iria	Gimenez	Hakai/ University of British Columbia
Dylan	Glaser	Fisheries and Oceans Canada
Lyse	Godbout	Fisheries and Oceans Canada
Stefania	Gorgopa	Malahat Nation
Caroline	Graham	North Pacific Anadromous Fish Commission (NPAFC)
Chris	Grandin	Fisheries and Oceans Canada
Sue	Grant	Fisheries and Oceans Canada
Dan	Greenberg	Fisheries and Oceans Canada
Lu	Guan	Fisheries and Oceans Canada
Rebecca	Gunderson	Fisheries and Oceans Canada

Guoqi	Han	Fisheries and Oceans Canada
Gabriela	Hannach	King County, Seattle
Lucie	Hannah	Fisheries and Oceans Canada
James	Hannah	Fisheries and Oceans Canada
Charles	Hannnah	Fisheries and Oceans Canada
Ovi	Haque	Cermaq Canada
Melanie	Hardy	Fisheries and Oceans Canada
Alex	Hare	Hakai Institute
Cassandra	Harper	Kwikwetlem First Nation
Sarah	Hawkshaw	Fisheries and Oceans Canada
Doug	Hay	Fisheries and Oceans Canada, Emeritus
Steve	Healy	Fisheries and Oceans Canada
Martin	Heesemann	Ocean Networks Canada
Melissa	Hennekes	Fisheries and Oceans Canada
Erin	Herder	Fisheries and Oceans Canada
BethElLee	Herrmann	University of Washington, School of Oceanography
Marc-Andre	Hervieux	Musqueam Indian Band
Margot	Hessing-Lewis	Hakai Institute
Andrea	Hilborn	Fisheries and Oceans Canada
Mark	Hipfner	Environment and Climate Change Canada
James	Hobart	Spuzzum
Stacey	Hobson	Fisheries and Oceans Canada
Amber	Holdsworth	Fisheries And Oceans Canada
John	Holmes	Fisheries and Oceans Canada
Carrie	Holt	Fisheries and Oceans Canada
Roy	Hourston	Fisheries and Oceans Canada
Kim	Houston	Fisheries and Oceans Canada
Brett	Howard	Fisheries and Oceans Canada
Ann-Marie	Huang	Fisheries and Oceans Canada
Brian	Hunt	University of British Columbia
Samantha	Huntington	Fisheries and Oceans Canada

Debby	Ianson	Fisheries and Oceans Canada
Katie	Innes	University of Victoria
Jen	Jackson	Hakai Institute
Marlene	Jeffries	Canadian Hydrographic Service
Brittany	Jenewein	Fisheries and Oceans Canada
Khushboo	Jhugroo	Hakai Institute/ University of British Columbia
Gregory	Jones	Fisheries and Oceans Canada
Simon	Jones	Fisheries and Oceans Canada
Elizabeth	Joyce	SOPO organizer
Francis	Juanes	University of Victoria
Olga	Kalata	University of Washington
Julie	Keister	University of Washington
Colleen	Kellogg	Hakai Institute
Jonathan	Kellogg	Canadian Integrated Ocean Observing System (CIOOS) Pacific
Jessica	Kennedy	University of British Columbia
Hongsik	Kim	University of British Columbia
Brian	Kingzett	BC Salmon Farmers
March	Klaver	Fisheries and Oceans Canada
Marta	Konik	University of Victoria
Christine	Konrad Clarke	Fisheries and Oceans Canada
Maxim	Krassovski	Fisheries and Oceans Canada
Brianne	Kucharski	Fisheries and Oceans Canada
Cher	Lacoste	Fisheries and Oceans Canada
Kim	Lagimodiere	Cowichan Tribes First Nation
Cody	Lai	Fisheries and Oceans Canada
Bernette	Laliberte	Cowichan Tribes
Steve	Latham	Pacific Salmon Commission
Doug	Latornell	Earth, Ocean & Atmospheric Sciences, University of British Columbia
Madeline	Lavery	Fisheries and Oceans Canada
Brian	Leaf	Fisheries and Oceans Canada

Derek	LeBoeuf	A-Tlegay Fisheries Society
Lynn	Lee	Parks Canada
Stuart	LePage	Fisheries and Oceans Canada
Jacob	Lerner	University of British Columbia
Joanne	Lessard	Fisheries and Oceans Canada
Roanna	Leung	Environment and Climate Change Canada
Yuehua (Andy)	Lin	Fisheries and Oceans Canada
Gwyn	Lintern	Fisheries and Oceans Canada
Qi	Liu	Fisheries and Oceans Canada Stock Assessment
Andrea	Locke	Fisheries and Oceans Canada
F	Loro	Fisheries and Oceans Canada
Daniella	LoScerbo	Fisheries and Oceans Canada
Martin	Louis	Pauquachin first nation
Raisha	Lovindeer	University of British Columbia, Vancouver
Sean	MacConnachie	Fisheries and Oceans Canada
Bronwyn	MacDonald	Fisheries and Oceans Canada
Clara	Mackenzie	Fisheries And Oceans Canada
Jody	Mackenzie-Grieve	Fisheries and Oceans Canada
Madelaine	MacLock	Fisheries and Oceans Canada - North Island Stock Assessment
Shaun	MacNeill	Fisheries and Oceans Canada
Michaela	Maier	University of Victoria
Christian	Marchese	University of British Columbia/University of Victoria
Andrea	Markiewicz	Fisheries and Oceans Canada
Taylor	Martin	King County
Jonathan	Martin	Fisheries and Oceans Canada
Edward	Mason	University of British Columbia
Kiana	Matwichuk	Fisheries and Oceans Canada
Mackenzie	Mazur	Fisheries and Oceans Canada
Madeleine	McGreer	Central Coast Indigenous Resource Alliance
Jim	McIsaac	Tbuck Suzuki

Skip	McKinnell	Salmoforsk International
Rebecca	McMurray	Fisheries and Oceans Canada
Patrick	McNeill	Canadian Hydrographic Service - Pacific Region
Stefanie	Mellon	Ocean Networks Canada
Kat	Middleton	Fisheries and Oceans Canada
Steve	Mihaly	Ocean Networks Canada
Matthew	Miller	University of Victoria
Andrea	Moore	Fisheries and Oceans Canada
Ken	Morgan	Environment and Climate Change Canada
Mike	Morley	Fisheries and Oceans Canada
James	Mortimor	Fisheries and Oceans Canada
Hem Nalini	Morzaria-Luna	Long Live the Kings
Bennit	Mueller	Ocean Networks Canada
Kelsie	Murchy	University of Victoria
Cathryn	Murray	Fisheries and Oceans Canada
Lanfranco	Muzi	Ocean Networks Canada, University of Victoria
Bruce	Nairn	King County Wastewater Treatment Division
Martin	Nantel	Fisheries and Oceans Canada
Larry	Neilson	Ministry of Agriculture, Food and Fisheries
Jocelyn	Nelson	Fisheries and Oceans Canada
R John	Nelson	Fisheries and Oceans Canada
Erika	Nielsen	Fisheries and Oceans Canada
Virginia	Noble	Fisheries and Oceans Canada
Chad	Nordstrom	Fisheries and Oceans Canada
Tammy	Norgard	Fisheries and Oceans Canada
Damon	Nowosad	Q'ul-lhanumutsun Aquatic Resources Society (QARS)
Kirstyn	Nygren	Grieg Seafood BC Ltd.
Miriam	O	Fisheries and Oceans Canada
Ben	O'Connor	University of British Columbia
Athena	Ogden	Fisheries and Oceans Canada

Patrick	O'Hara	Canadian Wildlife Service - Environment and Climate Change Canada
Greig	Oldford	Fisheries and Oceans Canada
Norm	Olsen	Fisheries and Oceans Canada
Clare	Ostle	Marine Biological Association
Sachiko	Ouchi	Kitselas First Nation
Vishnu	P Suseelan	
Stephen	Page	Fisheries and Oceans Canada
Ashley	Park	Fisheries And Oceans Canada
Sam	Pascoe	Nuxalk Nation
Patrick	Pata	University of British Columbia
Vivian	Pattison	Environment and Climate Change Canada
Rich	Pawlowicz	University of British Columbia
Kylee	Pawluk	Marine Plan Partnership
Isobel	Pearsall	Pacific Salmon Foundation
Angelica	Pena	Fisheries and Oceans Canada
Ian	Perry	Fisheries and Oceans Canada
Lynn	Pinnell	Musqueam Indian Band
Erin	Pippus	Fisheries and Oceans Canada
Katie	Pocock	Hakai Institute
Chenoa	Point	SNUNEYMUXW
Corinne	Pomerleau	Department of National Defence
Lauren	Portner	University of British Columbia
Sarah	Power	Fisheries and Oceans Canada
Tanya	Prinzing	Fisheries and Oceans Canada
Beatrice	Proudfoot	Fisheries and Oceans Canada
Julia	Putko	Fisheries and Oceans Canada
Jessica	Qualley	University of Victoria
Sid	Quinn	Shishalh Nation
Monique	Raap	Fisheries and Oceans Canada
Lynn	Rannankari	University of Victoria

Elisa	Rauschl	Washington State Department of Ecology
Erin	Rechisky	Fisheries and Oceans Canada
Natasha	Ridenour	Fisheries and Oceans Canada
Carrie	Robb	Fisheries and Oceans Canada
Devin	Robichaux	King County
Cliff	Robinson	Fisheries and Oceans Canada
Luke	Rogers	Fisheries and Oceans Canada
Stephen	Romaine	Fisheries and Oceans Canada
Kevin	Romanin	B.C. Ministry of Agriculture, Food and Fisheries
Chris	Rooper	Fisheries and Oceans Canada
Tetjana	Ross	Fisheries and Oceans Canada
Andrew	Ross	Fisheries and Oceans Canada
Alberto	Rovellini	University of Washington
Emily	Rubidge	Fisheries and Oceans Canada
Marie	Rupisan	Fisheries and Oceans Canada
Christa	Rusel	A-Tlegay Fisheries Society
Krysten	Rutherford	Fisheries and Oceans Canada
Veronica	Ryu	Fisheries and Oceans Canada
Vicki	Sahanatien	Central Coast Indigenous Resource Alliance
Saurav	Sahu	Ocean Networks Canada
Natasha	Salter	Fisheries and Oceans Canada
Tammy	Sam	Tseycum Marine Stewardship
Todd	Sandell	Washington Department of Fish and Wildlife
Zoe	Sandwith	Hakai Institute
Akash	Sastri	Fisheries and Oceans Canada
Alejandro	Schmill	University of Victoria
Shannon	Schmunk	Fisheries and Oceans Canada
Steven	Schut	Fisheries and Oceans Canada
Emilia	Schwarz	Fisheries and Oceans Canada - Fisheries Management Branch (Co-op student)
Jake	Schweigert	Fisheries and Oceans Canada

Craig	Schweitzer	Fisheries and Oceans Canada
Norma	Serra-Sogas	Fisheries and Oceans Canada
Jade	Shiller	Environment and Climate Change Canada
Miki	Shimomura	Fisheries and Oceans Canada
Cailyn	Siider	T Buck Suzuki Environmental Foundation
Eleanor	Simpson	Fisheries and Oceans Canada, Simon Fraser University
Kyle	Simpson	Fisheries and Oceans Canada
Rob	Skelly	Fisheries and Oceans Canada
Ben	Skinner	Pacific Salmon Foundation
Drew	Snauffer	Ocean Networks Canada
David	Spear	Fisheries and Oceans Canada
Chelsea	Stanley	Fisheries and Oceans Canada
Kimberle	Stark	King County
Kilian	Stehfest	David Suzuki Foundation
Catherine	Stevens	University of Victoria
Howard	Stiff	Fisheries and Oceans Canada
Karyn	Suchy	University of British Columbia
Joe	Tadey	Canadian Department of Fisheries and Oceans
Wafa	Tafesh	King County Water and Land Resources
Nigel	Tan	Fisheries and Oceans Canada
Eric	Taylor	Pacific Salmon Commission
Kathryn	Temple	Fisheries and Oceans Canada
Laura	Tessier	Fisheries and Oceans Canada
Thomas	Therriault	Fisheries and Oceans Canada
Stephanie	Thomas	Snuneymuxw elder
Patrick	Thompson	Fisheries and Oceans Canada
Andrew	Thomson	Fisheries and Oceans Canada
Pramod	Thupaki	Hakai Institute
Amanda	Timmerman	Georgia Tech
Scott	Toews	Fisheries and Oceans Canada

Meghan	Tomlin	Malahat Nation
Matthew	Townsend	Fisheries and Oceans Canada
Matt	Tradewell	Ocean Networks Canada
Nicole	Trouton	Fisheries and Oceans Canada, Fraser & Interior Area Chinook & Coho Stock Assessment
Strahan	Tucker	Fisheries and Oceans Canada
Lenora	Turcotte	Fisheries and Oceans Canada
Ryan	Uslu	Fisheries and Oceans Canada
Svein	Vagle	Fisheries and Oceans Canada
Jose	Valenti	University of British Columbia
Heidi	Van Vliet	Fisheries and Oceans Canada
Pieter	Van Will	Fisheries And Oceans Canada
Stacey	Verrin	Fisheries and Oceans Canada -Canadian Hydrographic Service
Di	Wan	Fisheries and Oceans Canada
Devon	Warawa	Fisheries and Oceans Canada
Rebecca	Wardle	Ministry of Agriculture Food and Fisheries
Teagan	Wardrop	Fisheries and Oceans Canada
Luke	Warkentin	Fisheries and Oceans Canada
Joe	Watson	Fisheries and Oceans Canada
Colin	Webber	Fisheries and Oceans Canada
Carrie	Weekes	Hakai Institute
Jacob	Weil	Fisheries and Oceans Canada
Bethany	Welsh	Environment and Climate Change Canada
Kristen	Wilson	Fisheries and Oceans Canada
Amanda	Winans	University of Washington
Cecilia	Wong	Environment and Climate Change Canada
Malcolm	Wyeth	Fisheries and Oceans Canada
Yi	Xu	Fisheries and Oceans Canada
Jaasaljuus	Yakgujanaas	Secretariat of the Haida Nation
Jennifer	Yakimishyn	Parks Canada
Bernard	Yang	University of Victoria

Kelly	Young	Fisheries and Oceans Canada
Vanessa	Zahner	Council of the Haida Nation