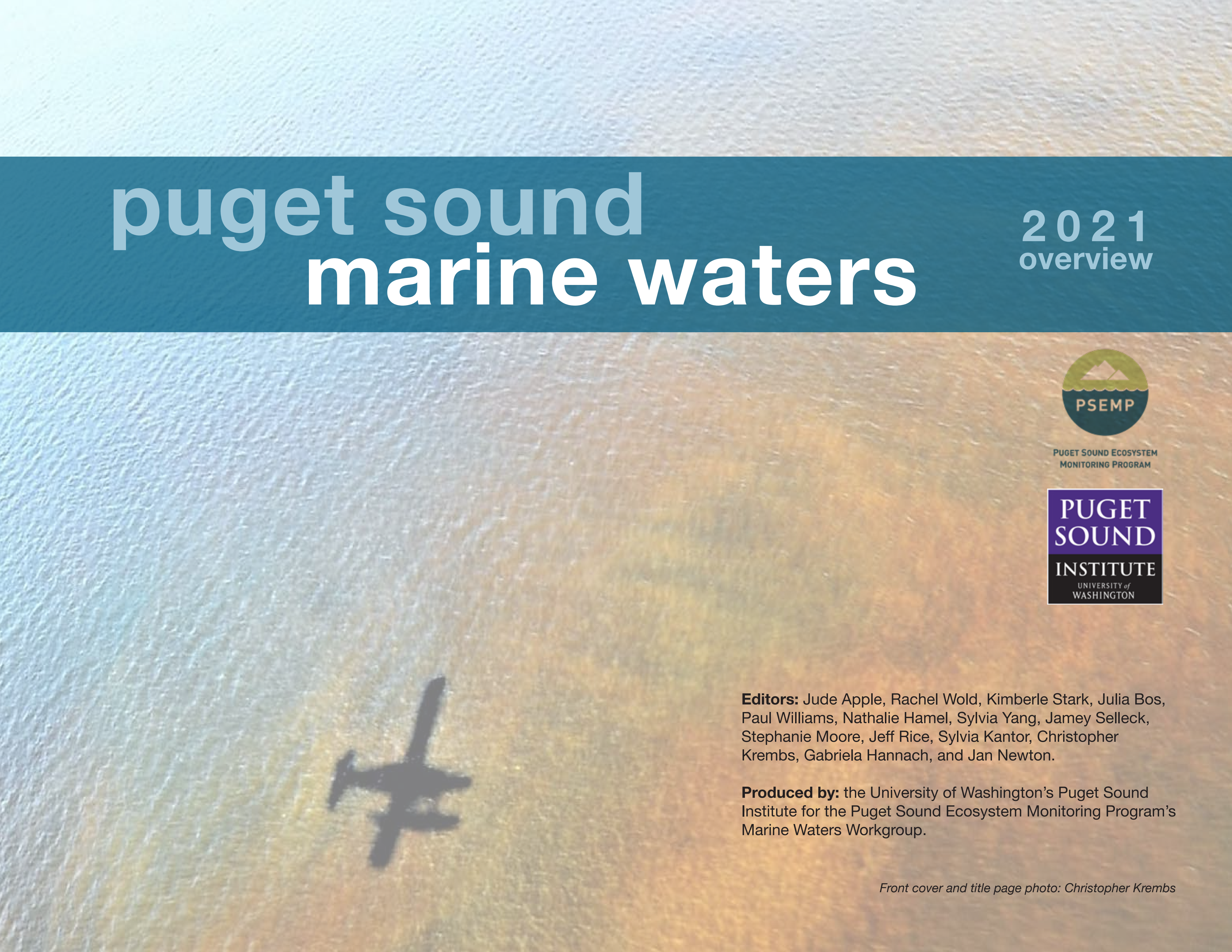
puget sound marine waters

2021 overview

Sample collection aboard R/V Carson. Photo: Jan Newton



puget sound marine waters

2021 overview

PSEMP
Puget Sound Ecosystem Monitoring Program

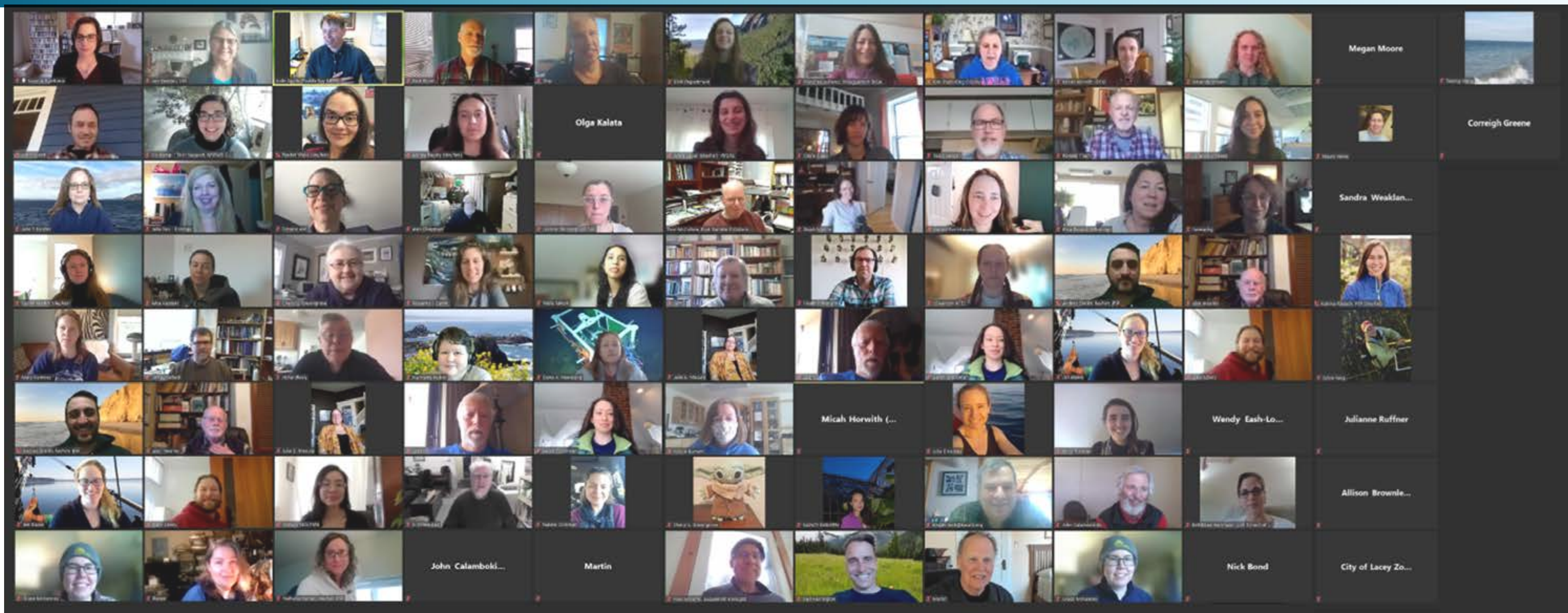
Puget Sound Institute
University of Washington

Editors: Jude Apple, Rachel Wold, Kimberle Stark, Julia Bos, Paul Williams, Nathalie Hamel, Sylvia Yang, Jamey Selleck, Stephanie Moore, Jeff Rice, Sylvia Kantor, Christopher Krembs, Gabriela Hannach, and Jan Newton.

Produced by: the University of Washington's Puget Sound Institute for the Puget Sound Ecosystem Monitoring Program's Marine Waters Workgroup.

Front cover and title page photo: Christopher Krembs

Citation and contributors



Recommended citation

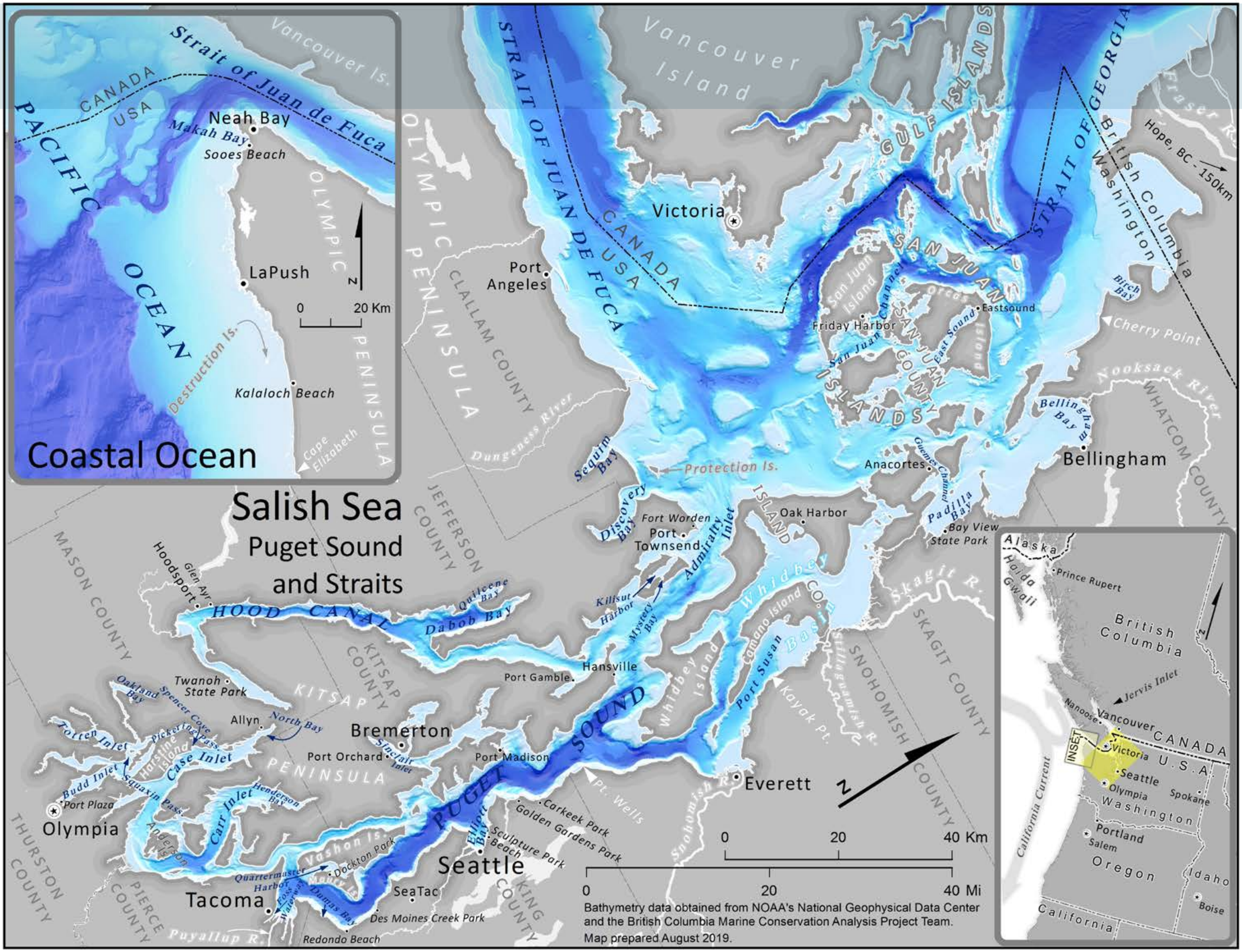
PSEMP Marine Waters Workgroup. 2022. Puget Sound marine waters: 2021 overview., J. Apple, R. Wold, K. Stark, J. Bos, P. Williams, N. Hamel, S. Yang, J. Selleck, S. K. Moore, J. Rice, S. Kantor, C. Krembs, G. Hannach, and J. Newton (Eds).

Available: www.psp.wa.gov/PSmarinewatersoverview.php

Contact email: marinewaters@psemp.org

Contributors

Adrienne Sutton
Alex Assaf
Allison Brownlee
Amanda Winans
Beth Curry
BethElLee Herrmann
Brianna Bjordahl
Bryan Murphie
Cheryl Greengrove
Christopher Krembs
Chris Sabine
Cindy Elliser
Claire Cook
Dana Manalang
David Anderson
Derek Arterburn
Emily Buckner
Emily Seubert
Emily Vierling
Erin Jaco
Franchesca Perez
Gabriela Hannach
Greg Ikeda
Heath Bohlmann
Heather Gibbs
Holly Young
Jan Newton
Jerry Borchert
Jessica Wolford
John Mickett
Joseph Evenson
Jude Apple
Julia Bos
Julianne Ruffner
Julie Keister
Julie Masura
Karin Bumbaco
Katie Olson
Katrina MacIver
Keiley Munsterman
Kimberle Stark
Laura Hermanson
Laurie Schuster
Lyndsey Swanson
Madrona Murphy
Margaret Baer
Margaret Homerding
Matthew Hamer
Melissa Miner
Micah Horwith
Michelle Lepori-Bui
Mike Sigler
Mya Keyzers
Natalie Coleman
Nicole Burnett
Nick Bond
Pete Raimondi
Phill Dionne
Roxanne Carini
Russel Barsh
Ryan Crim
Sarah Grossman
Scott Veirs
Simone Alin
Skip Albertson
Sylvia Musielewicz
Sylvia Yang
Taylor Martin
Teri King
Todd Sandell
Tracie Barry
Trevor Derie
Tyler Burks
Val Veirs
Wafa Tafesh
Wendy Eash-Loucks



Map: Damon Holzer

Table of Contents

Table of Contents (cont.)

About PSEMP

The Puget Sound Ecosystem Monitoring Program (PSEMP) is a collaboration of monitoring professionals, researchers, and data users from federal, tribal, state, and local government agencies, universities, nongovernmental organizations, watershed groups, businesses, and private and volunteer groups.

The objective of PSEMP is to create and support a collaborative, inclusive, and transparent approach to regional monitoring and assessment that builds upon and facilitates communication among the many monitoring programs and efforts operating in Puget Sound. PSEMP's fundamental goal is to assess progress toward the recovery of the health of Puget Sound.

The Marine Waters Workgroup is one of several technical workgroups operating under the PSEMP umbrella, with a specific focus on the inland marine waters of Puget Sound and the greater Salish Sea, including the oceanic, atmospheric, and terrestrial influences and drivers affecting the Sound. For more information about PSEMP and the Marine Waters Workgroup, please visit https://www.psp.wa.gov/PSEMP-overview.php

Introduction

This report provides a collective view of 2021 Puget Sound marine water quality and conditions and associated biota from comprehensive monitoring and observing programs. While the report focuses on the marine waters of greater Puget Sound, additional selected conditions are also included due to their influence on Puget Sound waters. These include large-scale climate indices and conditions along the Washington coast. It is important to document and understand regional drivers of variability and patterns on various timescales so that water quality data may be interpreted with these variations in mind, to better attribute human effects versus natural variations and change. This is the eleventh annual report produced for the PSEMP Marine Waters Workgroup. Our message to decision makers, policy makers, managers, scientists, and the public who are interested in the health of Puget Sound follows.

From the editors

Our objective is to collate and distribute the valuable physical, chemical, and biological information obtained from various marine monitoring and observing programs in Puget Sound. Based on mandate, need, opportunity, and expertise, these efforts employ different approaches and tools that cover various temporal and spatial scales. For example, surface surveys yield good horizontal spatial coverage, but lack depth information; regular station occupation over time identifies long-term trends, but can miss shorter-term variation associated with important environmental events; moorings with high temporal resolution describe shorter-term dynamics, but have limitations in their spatial coverage. However, collectively, the information representing various temporal and spatial scales can be used to connect the status, trends, and drivers of ecological variability in Puget Sound marine waters. By identifying and connecting trends, anomalies, and processes from each monitoring program, this report adds significant and timely value to the individual datasets and enhances our understanding of this complex ecosystem. We present here that collective view for the year 2021.

This report is the proceedings of an annual effort by the PSEMP Marine Waters Workgroup to compile and cross-check observations collected across the marine waters of greater Puget Sound during the previous year. Data quality assurance and documentation remains the primary responsibility of the individual contributors. All technical summaries in this report were individually authored and contact names and information are provided. The editors managed the internal cross-review process and focused on organizational structure and overall clarity. This included crafting a synopsis in the Executive Summary that is based on individual contributions and describes the overall trends and drivers of variability and change in Puget Sound's marine waters during 2021.

The larger picture that emerges from this report helps the PSEMP Marine Waters Workgroup to accomplish several goals: 1) maintain an inventory of the current monitoring programs in Puget Sound and determine how well these programs are meeting priority needs; 2) update and expand upon the monitoring results reported in the Puget Sound Vital Sign indicators (http://www.psp.wa.gov/vitalsigns/index.php); and 3) improve transparency, data sharing, and timely communication of relevant monitoring programs across participants and their organizations. The Northwest Association of Networked Ocean Observing Systems (NANOOS), the regional arm of the U.S. Integrated Ocean Observing System (IOOS) for the Pacific Northwest, is working to increase regional access to marine data. Much of the marine data presented here, as well as an inventory of monitoring assets, can be found through the NANOOS web portal (http://www.nanoos.org). The full content from each contributor, including website links to more detailed information and data, follow the executive summary.

The Canadian ecosystem report, The State of the Pacific Ocean Technical Reports (http://www.dfo-mpo.gc.ca/oceans/publications/index-eng.html), describes an area encompassing approximately 102,000 km^2 from the edge of the continental shelf east to the British Columbia mainland and includes large portions of the Salish Sea. The annual report provides information that is also relevant for Puget Sound and is a recommended source of complementary information to this report.

Puget Sound Vital Signs

Technical summaries informing the following Vital Signs are highlighted with this symbol.

Beaches
Shellfish
Local foods
Temperature
Dissolved oxygen
Nutrients
Ocean acidification
Benthic index
Sediment chemistry
Marine birds
Chinook salmon
Forage fish
Orcas
Zooplankton
Stream flow

The technical summaries presented in the Puget Sound Marine Waters: 2021 Overview span a range of topics, from water quality and climate change to marine birds and other ecosystem indicators. Their goal is to connect the status, trends, and drivers of ecological variability in Puget Sound marine waters in a way that serves Puget Sound ecosystem recovery efforts.

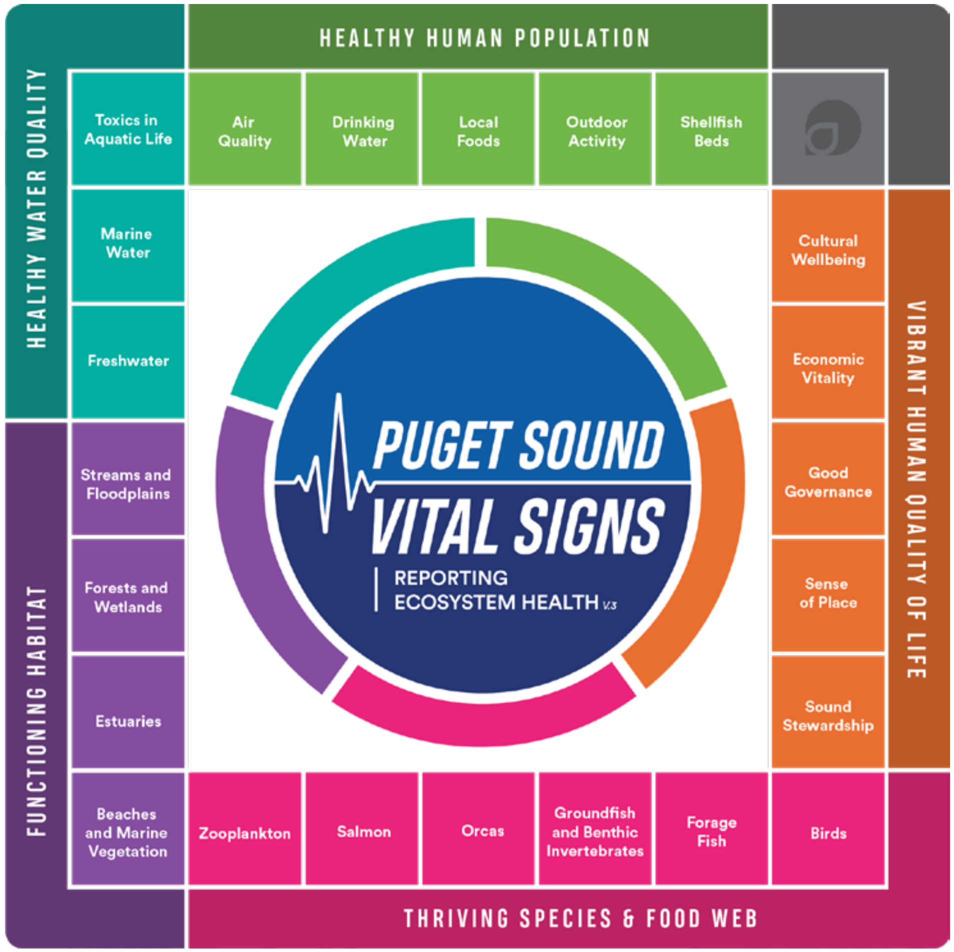


Figure VS1. Puget Sound Vital Signs revised and adopted in 2020 by the Puget Sound Partnership.

These recovery efforts are further articulated by the Puget Sound Vital Signs. The Vital Signs and their representative indicators are measures of ecosystem conditions shown in Figure VS.1.

One of the fundamental aspects of PSEMP's mission is to monitor the ecosystem in support of Vital Sign reporting. To this end, 28 of 38 technical summaries (74%) included in the 2021 Overview report provide data that collectively informs four of the five ecosystem recovery goals, including Healthy Water Quality, Healthy Human Populations, Functioning Habitat, and Thriving Species and Food Webs. Within these broad goals, data reported in this document further inform our understanding of Puget Sound Vital Signs and associated indicators. Technical summaries are considered to have informed a given recovery goal, Vital Sign and/or indicator if quantitative observations of that indicator are reported, even if these data were recorded outside of Puget Sound proper (i.e., the broader Salish Sea or outer coast). These individual technical summaries are credible and legitimate sources of information contributing to and complementing our shared understanding of progress towards recovery goals and the conditions of the Vital Signs and their indicators in Puget Sound.

The technical summaries in the 2021 Overview address four Puget Sound ecosystem recovery goals and nine Vital Signs. Many of the parameters reported in the Overview are also used as endpoints for the "Implementation Strategies"[1] designed to improve Vital Sign conditions such as the Marine Water Quality Implementation Strategy[2]. Given the Overview's focus on marine water quality conditions, it is not surprising that over half of the technical summaries reporting on Vital Sign parameters (17 out of 28; Figure VS.2) exclusively address the Marine Water Vital Sign in the Healthy Water Quality recovery goal. These summaries build from local and

[1] https://www.psp.wa.gov/implementation-strategies.php
[2] https://pspwa.box.com/s/52t8ecqbtlm7nd5juad6lu8s3uuvh9yk

regional monitoring efforts to assess metrics identified as Vital Sign indicators, including water temperature, dissolved oxygen, nutrient balance, ocean acidification, sediment chemistry, and marine benthic index. In some cases, the data presented are not part of the Vital Signs as they have been defined, but the data are relevant to the topic.

Seven of the technical summaries address Vital Signs in the Thriving Species and Food Webs recovery goal, including reports on Pacific herring biomass, marine bird populations, zooplankton biomass, and juvenile Chinook salmon. Another five summaries address the Healthy Human Populations recovery goal, reporting on the presence of harmful bacteria at recreational beaches, fecal coliform concentrations in nearshore waters, harmful algae in shellfish beds, and presence of marine biotoxins in shellfish beds. Data from these submissions also directly inform natural resource and public health management decisions. The Habitat and Abundant Water recovery goal is addressed in one technical submission on summer flows in Puget Sound streams and rivers.

Although ten of the 38 technical summaries did not directly address current Vital Signs, they represent investigations of important ecological and climatic processes in Puget Sound. Phytoplankton, a future indicator currently in development, was addressed in three technical summaries. Other summaries include reports on air temperature (to date, not a component of the Air Quality Vital Sign), precipitation, upwelling, and ocean salinity. Two technical summaries report on the abundance of humpback whales and harbor seals.

Our evaluation of the connectivity between technical summaries and Vital Signs for the 2021 edition of the Overview relied on the newly revised Vital Signs and indicators adopted in 2020 by the Puget Sound Partnership (see a related fact sheet and a full report on the subject). The scope of the revised Vital Signs has increased substantially and now includes additional ecosystem components that have historically been addressed in the annual Overview, such as zooplankton populations, water temperature, ocean acidification, and other aspects of marine food webs.

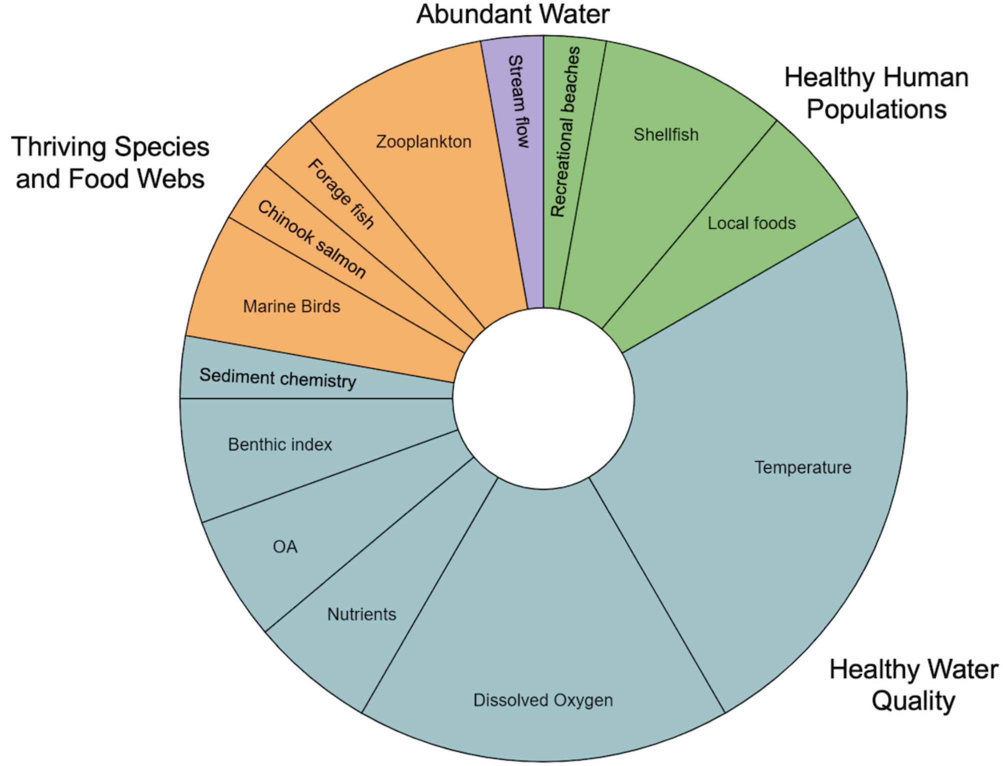


Figure VS.2. The distribution of the number of technical summaries reporting observations relevant to the Puget Sound Vital Signs, sorted by recovery goal, in this 2021 edition of the Marine Waters.

Summary of What Happened in 2021

This brief synopsis describes patterns in water quality and conditions and associated biota observed during 2021 and their association with large-scale ocean and climate variations and weather factors. The data compilation and analysis presented in the annual Puget Sound Marine Waters Overview, which began in 2011, offers the opportunity to evaluate the strength of these relationships over time and is prepared by the PSEMP Marine Waters Workgroup.

Overall, 2021 was an abnormal year in many ways, with cooler than average regional climate forcing yet warmer than average local seawater and an extreme summertime heatwave. Ecosystem responses observed were variable, with higher than normal phytoplankton abundance and more frequent harmful algal blooms, lower than normal oxygen concentrations (yet no reported fish kills), and somewhat rebounding numbers of seabirds and marine mammals but drastically low herring stocks in some areas.

Large-scale climate patterns during 2021 generally indicated cooler than average ocean conditions. The El Niño-Southern Oscillation (ENSO) index was negative (cool phase) with tropical Pacific Ocean temperatures cool enough to signify moderate La Niña conditions. The Pacific Decadal Oscillation (PDO) transitioned from weak to strongly negative (cool phase) values late in the year.

Coastal upwelling and downwelling (driven by seasonal winds) shifted predictably during the year but were stronger than average. Strong downwelling was evident in January, followed by normal conditions until July when stronger than normal upwelling occurred. Downwelling returned in September through November but was stronger than normal.

Despite the cool phase ENSO and PDO, regional air temperatures and sunlight were generally higher than normal, with an extreme heatwave beginning at the end of June. Together, these conditions resulted in an exceptionally warmer, sunnier year with extreme seasonal variability. The record-breaking atmospheric heatwave that occurred at the end of June has been described as a "once in 1,000-year event." It unfortunately coincided with seasonal low tides and resulted in high mortality of intertidal communities throughout the region. Precipitation was lower than normal early in spring, then much higher than normal in fall. Extreme head in June caused extensive melting of the snowpack, leading to below-normal streamflow and drought conditions in later summer.

Coastal deep waters, from source to the Salish Sea, were cooler than typical as recorded since 2014, and even cooler than 2020. Surface waters were also cooler than normal. Deep water oxygen was anomalously low throughout summer. Average seawater carbon dioxide (CO_2) was high and atmospheric CO_2 exhibited the typical annual increase observed in the record.

Although the coastal source waters were cooler than normal, water temperatures within the Salish Sea were generally higher than normal; however, regional and temporal differences were evident. The effect of the atmospheric heatwave on surface waters was noticeable during that event. Salinity was higher than normal throughout Puget Sound for most of the year, except a wet period in February and March and again in November and December.

Salish Sea oxygen concentrations were lower than normal throughout the region, with some seasonal and regional variation. Hypoxia was observed in South Hood Canal, but no fish kills were observed.

Seasonal phytoplankton blooms were evident in the Central Basin and total annual microphytoplankton biovolume in 2021 was somewhat higher than in previous years, with *Chaetoceros* species making up most of the diatom biomass in spring and summer. The bloom season ended early in 2021 compared to previous years in the Central Basin and Padilla Bay. Harmful algal blooms were more frequent than in 2020 and biotoxins caused 20 commercial growing area closures and 30 recreational harvest area closures. This year saw the first instance of dual toxicity (diarrhetic (DSP) and amnesic (ASP)) recorded in Washington.

Abundance and biomass of mesozooplankton were average to moderately low compared to past years, with a few elevated values.

Seabird and marine mammal populations were either stable or showed a slow increase to typical values. Pacific herring biomass decreased, with no spawn detected at Wollochett or Quartermaster Harbor. The Cherry Point stock, critically low for years, decreased again in 2021 (though surveys were limited by COVID-19), reaching critically low levels.

We record here the status and changes observed in the marine ecosystem during 2021 to aid our understanding of how climate and anthropogenic stressors may be influencing these patterns.

Highlights from 2021 Monitoring

Large-scale climate variability and wind patterns

- The El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) were both negative during the entire year. Cooler tropical Pacific Ocean temperatures early and late in the year signified moderate La Niña conditions.
- The year began with strong downwelling, followed by normal downwelling conditions through June. Stronger than normal upwelling in July was followed by strong downwelling conditions through November.

Local climate and weather

- The most recent 30-year period is warmer and wetter than the previous 1981-2010 climate normal for the Puget Sound region.
- Other than the exceptional and record breaking heat wave (heat dome) at the end of June, Puget Sound air temperatures were near-normal to slightly higher than normal in 2021. Conditions were generally sunnier than normal, especially during April, June, July, and November.
- Total annual precipitation was near-normal, but with extreame seasonal variability. Spring (March-May) was the 2nd driest on record, while fall (September-November) was the wettest on record.

Coastal ocean and Puget Sound boundary conditions

- Surface and deep ocean water temperatures were cooler than normal throughout the year. Although elevated surface water temperatures (>15°C) were observed in previous years, they were notably absent during 2021.
- Deep water dissolved oxygen concentrations were anomalously low for much of the summer, reversing a pattern of elevated deep water DO observed in 2020.

River inputs

- Freshwater inputs to the Salish Sea were generally within normal historic volumes, with peaks in river discharge following the expected pattern throughout the year. Extreme heat in June caused extensive melting of the snowpack, leading to below-normal streamflow and drought conditions in later summer.
- Abnormally high precipitation in mid-November led to severe flooding in several Salish Sea tributaries.

Water quality

- **Water temperatures** during 2021 were generally above the climatological average, continuing a general pattern of warmer conditions since the 2014-2016 marine heatwave. Periods of anomalously high and sometimes record breaking summer water temperatures were observed across the region, especially during the June 2021 heat dome. Warmer water temperatures can be linked to above-average surface heat input in 2021, which is equivalent to a +0.5°C anomaly spread over a 60 m water-column. Further, there was less heat loss than normal in Jan-Feb, and above-average heat gain during the June heat wave, which contributed significantly to the net positive heat input anomaly.
- **The atmospheric heatwave** in late June 2021 was the most extreme on record, and coincided with the lowest day-time tide series of the year. This week-long combination of extreme air temperatures and midday low tides proved to be deadly for intertidal communities in many areas of Washington, particularly those in the Salish Sea.
- **Salinity** was higher than average during much of the year. While saltier than average summers have been typically observed since 2014, the salty anomaly lasted longer into the year. The year began with above normal salinities due to low precipitation and low river flows, then salinities dropped during the spring freshet. Saltier than normal conditions returned in April through November. Heavy rainfall and elevated river flow in November and December led to a precipitous decline in salinities and significant fresh anomalies.
- **Water column structure** in Puget Sound waters has continued a general trend of increasing stratification. Stratification in some basins was reported to be exceptionally high May through June, and again in November and December after substantial rainfall. In Padilla Bay, the water column transitioned from well-mixed in winter to a spring freshening event in March, followed by moderate stratification throughout the summer. Estuarine inflow to South Sound was typical, while Hood Canal had atypically strong deep inflow in spring and early summer.
- **Nutrient concentrations** appeared to continue a long-term trend of increasing surface water nitrate concentrations and decreasing silicate concentrations. As a result, the Si:DIN ratio has been variable but generally within the long-term trend. Late spring and summer drawdown of dissolved nutrients was observed in many basins and attributed to algal blooms, as well lack of freshwater input. Following a large summer diatom bloom, Central Basin silica concentrations were below

or near detectable levels, while deep water silicate concentrations in the Central Basin remained higher than normal for most of the year

- **Chlorophyll concentrations** varied seasonally, with spring and summer blooms reported throughout the region. A mid-April phytoplankton bloom occurred in the Central Basin, followed by elevated chlorophyll levels in June due to a *Rhizosolenia* bloom. Chlorophyll-a in outer Quartermaster Harbor was unusually high in September due to a large flagellate bloom, but otherwise was low in spring and summer in both inner and outer harbors. Substantial fall blooms were not reported.
- **Dissolved oxygen (DO)** exhibited regional variability. DO in the Central Basin was generally lower than normal, especially in deeper waters, with positive anomalies in surface waters corresponding to phytoplankton blooms. Buoy data indicate a pattern of lower than average DO in South Sound and Main Basin during fall, but higher than average the rest of the year. DO concentrations in Hood Canal were much lower than average for the majority of the year, with hypoxic conditions recorded during January and May through November. Despite low DO conditions, fish kills were not observed. DO in Quartermaster Harbor was lower than normal in the late summer and fall.

Ocean and atmospheric CO_2

- Atmospheric CO_2 levels on the outer coast continued the long-term (2010–2021) upward trend of 2 ppm/year. Atmospheric CO_2 was approximately 3 ppm higher than the global average for marine surface air, except during summer when primary production in surface waters caused drawdown of CO_2. Outer coast seawater CO_2 was also relatively high compared to previous years.
- Atmospheric CO_2 at Hood Canal moorings showed a similar rate of increase to that of the coastal moorings, with more enriched concentrations (11–15 ppm) relative to globally averaged marine surface air. Atmospheric values during July–August remained enriched by as much as 6.5 ppm, despite drawdown of CO_2 by seasonal primary production during this time. In contrast, average seawater CO_2 at Dabob Bay was relatively low, ranking fourth lowest of all the years measured.

Plankton

- **Phytoplankton** varied in abundance and timing across the region. In the Central Basin, total annual microplankton biovolume was somewhat higher than previous years and SoundToxins reported a 30% increase in the number of phytoplankton blooms. The chain-forming diatoms *Chaetoceros* and *Rhizosolenia* were the dominant taxa in Central Basin and as reported by SoundToxins, with *Chaetoceros* making up most of the diatom biomass in spring and summer. In Padilla Bay, monthly average chlorophyll and phytoplankton abundance peaked earlier than in previous years.
- **Zooplankton** abundance and biomass of mesozooplankton were average to moderately low compared to past years, with a few elevated values. Patterns in the magnitude and timing of zooplankton abundance observed at stations across Puget Sound, and within Padilla Bay, were similar to patterns observed earlier in these respective time series. In San Juan Islands and Bellingham Bay, spring biomass was dominated by large oceanic copepod species, continuing a trend observed in 2019-2020. Abundance and community composition was variable throughout the year in Padilla Bay, with lower than average abundance in February, May, and December, and elevated abundance in November.
- **Larval crab** abundance was very high in Admiralty Inlet, resulting in the 4th highest biomass value on record. A similar phenomenon was observed for this station in 2015-2017 during the marine heatwave. Dungeness larval abundances in northern Washington waters were orders of magnitude greater than previous monitoring years, while South Sound and Hood Canal reported annual abundances similar to previous years. Initiation of the Dungeness larval growing season in Puget Sound was later than previous years, with the exception of southern Hood Canal where megalopae earlier than other sites in the Salish Sea.

Harmful algae and biotoxins

- *Pseudo-nitzschia* was the fourth most abundant blooming species reported in 2021, representing an increase from the previous year. In contrast, there were fewer *Alexandrium* and *Dinophysis blooms* in 2021. Mapping of *Alexandrium catenella* in Puget Sound sediments revealed cysts in Bellingham Bay, Inner Budd Inlet, and Hood Canal entrance.
- Marine biotoxins associated with paralytic, diarrhetic, and amnesic shellfish poison (PSP, DSP, and ASP) caused closure of 20 commercial growing areas and 30 recreational harvest areas. The first DSP-ASP dual toxin closure and second instance of a waterbody closure due to PSP, DSP, and ASP in a single year occurred in Sequim Bay.

Highlights from 2021 Monitoring (cont.)

Bacteria and pathogens

- Beach fecal coliform concentrations in King County were generally within the normal long-term range, while *Enterococcus* values were in the normal to high range. Offshore bacteria concentrations in Central Basin were also low, and similar to values reported for the last decade.
- The highest concentrations of fecal indicator bacteria in King County occurred in November, following a period of heavy precipitation. *Enterococcus* levels at the Carkeek Park/Piper's Creek outflow were among the highest values since 1980.
- Only three quarters (77%) of the 60 Puget Sound beaches monitored by the BEACH program met EPA's standards for safe swimming, representing an 18% decrease from 2020.

Marine birds and mammals

- Scoter species abundance is 23% below the long-term (1996-2022) average, although this group has remained generally stable since 2011. Fall seabird density in the San Juan Islands was observed to be higher than the previous two years, but still much less than 2010–2012.
- Densities of marine mammals (harbor porpoise, Steller sea lion, and harbor seal) recorded in the eastern Strait of Juan de Fuca were relatively low compared to the 15-year record, although higher than the last two years. This recent increase is associated with a higher density of harbor seals, which have also been observed in large in-water, foraging groups across the Salish Sea.
- Harbor porpoise densities have remained generally stable since 2015, after a long-term (1996-2015) gradual increase.
- Humpback vocalizations in Haro Strait increased in 2021 by a factor of four relative to the previous two years. The recent increase in humpback vocalizations continues a decadal trend, which is attributed to their increased presence in Haro Strait and Puget Sound.

Fish

- After the historically high estimated spawning biomass (ESB) for herring in 2020, the total for 2021 declined nearly 45% and approached the ten-year average of 10,500 mt. Herring stocks in south Sound remain depressed, with no spawn detected at Wollochett or Quartermaster Harbor. The Cherry Point stock decreased again in 2021 and remains at critically low levels.
- Consumption of zooplankton by unmarked juvenile Puget Sound-origin Chinook in the San Juan Islands have declined by one-fifth since the extreme ocean warming event of 2014, largely due to a 35 percent reduction in consumption of larval crabs.

Sediment and benthos

- Analysis of sediments collected as part of Ecology's Marine Sediment Monitoring Program revealed that Puget Sound sediments are of intermediate grain size and characterized as clayey sand to sandy silt. There is an inverse relationship between grain-size and total organic content, with higher organic carbon content in smaller grain sized sediments.

Technical Summaries

Golden Gardens, Seattle. Photo: Rachel Wold

1. Large-scale climate variability and wind patterns

Large-scale patterns of climate variability, such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) can strongly influence Puget Sound's marine waters. Seasonal upwelling winds on the coast, with intrusions of upwelled waters into Puget Sound, also strongly influence Puget Sound water properties, generating a signal that is similar to human-sourced eutrophication (i.e., high nutrients, low oxygen). It is important to document and understand these regional processes and patterns so that water-quality data may be interpreted with these variations in mind.

ENSO and PDO are large-scale patterns in Pacific Ocean sea surface temperatures (SST) that can also strongly influence atmospheric conditions in the Pacific Northwest, particularly in winter. For example, warm phases of ENSO (El Niño) and PDO generally produce warmer-than-usual coastal ocean temperatures and drier-than-usual winters. The opposite is generally true for cool phases of ENSO (La Niña) and PDO. ENSO events usually persist from six to 18 months, whereas phases of the PDO typically persist for 20 to 30 years. In Puget Sound, warm water temperature anomalies are produced during the winter of warm phases of ENSO and PDO, and can typically linger for two–three seasons. For PDO, these anomalously warm waters can reemerge four to five seasons later (Moore et al. 2008).

A. El Niño–Southern Oscillation (ENSO)

Source: Nick Bond (nab3met@uw.edu) and Karin Bumbaco (OWSC, UW; CICOES, UW); www.climate.atmos.washington.edu

The near-surface waters of the tropical Pacific were relatively cool in 2021, especially during the early and late parts of the year when moderate La Niña conditions were present. As is expected during La Niña conditions, these periods were accompanied by higher than normal sea level pressure (SLP) in the central North Pacific centered south of the eastern Aleutian Islands, with wind anomalies from the northwest extending from the Gulf of Alaska to the coastal waters of the Pacific Northwest. This atmospheric circulation pattern resulted in near-normal sea surface temperatures (SSTs) off the coast of the Pacific Northwest for 2021 as a whole, and greater than normal precipitation on the west side of the Cascade Mountains during both the first two and last few months of 2021.

Low tide at Golden Gardens. Photo: Rachel Wold

B. Pacific Decadal Oscillation (PDO)

Source: Nick Bond (nab3met@uw.edu) and Karin Bumbaco (OWSC; UW, CICOES); www.climate.atmos.washington.edu

The PDO ranged from weakly negative early in 2021 to strongly negative late in the year (Figure 1.1), with values lower than -2.5 during the months of October and November. During much of the year, the negative state of the PDO can be attributed to warmer than normal SSTs present in a broad band between roughly 30° and 50° N extending from the east coast of Asia into the eastern North Pacific. Temperature anomalies within this band were on the order of 1-2 °C. The fall and early winter of 2021 also featured cold anomalies in the Gulf of Alaska, and to a lesser extent, the sub-tropical Northeast Pacific from off California to the Hawaiian Islands. This horseshoe pattern of colder water, in combination with the persistence of relatively warm water in the middle latitudes of the central and western portion of the Pacific basin, contributed to the strongly negative values for the PDO that occurred near the end of the year, as noted above.

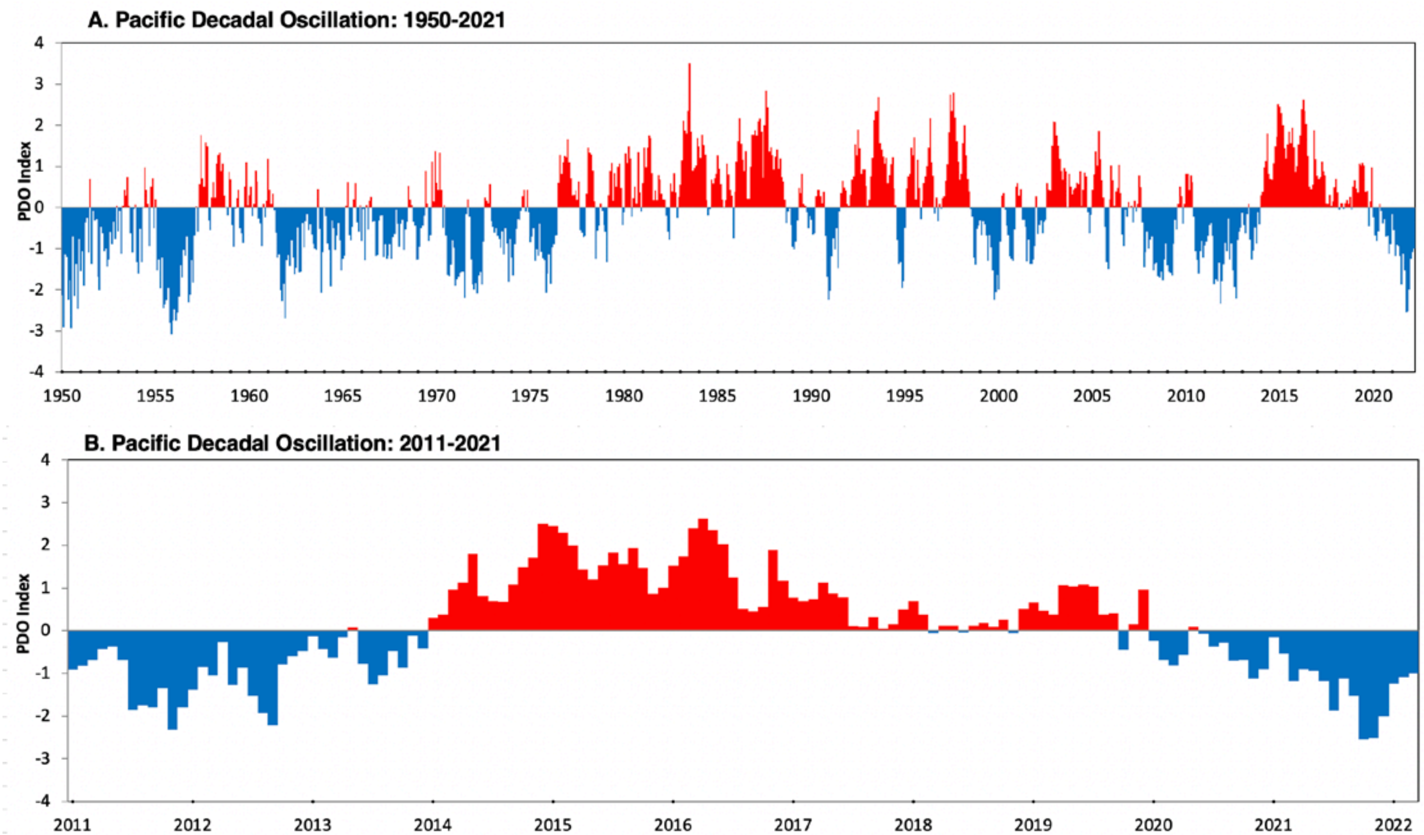


Figure 1.1. Monthly values of the Pacific Decadal Oscillation (PDO) Index from (A) 1950-2021 and (B) 2011-2022.

C. Upwelling index

Upwelling-favorable winds (i.e., winds from the north) on the Washington coast bring deep ocean water into the Strait of Juan de Fuca, and potentially into Puget Sound if other conditions are met, such as sufficient riverine discharge to drive estuarine exchange, occurring during neap tidal cycles. This upwelled water is relatively cold and salty, with low oxygen, low pH, and high nutrient concentrations. The typical upwelling season for the Pacific Northwest is from April through September, while downwelling typically occurs during the wet winter season.

Source: Skip Albertson (skip.albertson@ecy.wa.gov), Natalie Coleman, Micah Horwith, Christopher Krembs, Julianne Ruffner, and Holly Young (Ecology); https://ecology.wa.gov/Research-Data/Monitoring-assessment/Puget-Sound-and-marine-monitoring

Marine conditions in the Salish Sea are strongly influenced by the upwelling of coastal waters, which tend to be relatively cold and salty, with low oxygen, low pH, and high nutrient concentrations. Factors contributing to delivery of deeper ocean water into the Strait of Juan de Fuca and Puget Sound include sustained upwelling-favorable coastal winds (i.e. from the north), sufficient riverine input to drive estuarine exchange, and neap tides during which vigorous mixing over the Admiralty Reach sill does not occur. January showed strong downwelling conditions with somewhat weaker downwelling beginning in February, repeating a pattern first observed in 2018. Normal upwelling occurred May through June with stronger than normal upwelling in July. Downwelling-favorable winds resumed in September, which is slightly earlier than in 2020, resulting in stronger than normal downwelling during September and October.

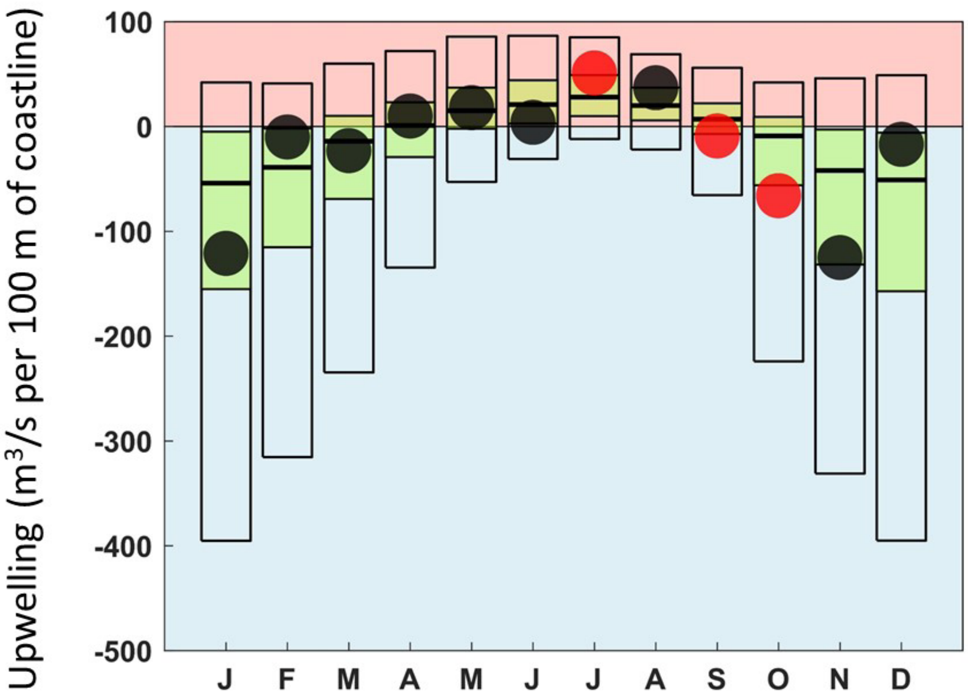


Figure 1.2. Monthly mean values of Pacific Fisheries Environmental Lab (PFEL) coastal upwelling index for 2021 (red and black dots). The box plots are based on index values at 48° N and 125° W from 1967 to 2018 and represent the 5th and 95th percentiles, with the interquartile range (shaded green) and median represented by a thick black line. Values falling outside the interquartile range are colored red. Pink- and blue-shaded areas indicate upwelling and downwelling conditions, respectively. Data source: www.pfeg.noaa.gov/products/las/docs/upwell.nc.html

2. Local climate and weather

Local climate and weather conditions can exert a strong influence on Puget Sound marine water conditions on top of the influences of longer-term, large-scale climate patterns. Variations in local air temperature best explain variations in Sound-wide water temperatures (Moore et al. 2008).

A. Regional air temperature and precipitation

Source: Karin Bumbaco (kbumbaco@uw.edu) and Nick Bond (OWSC; CICOES; UW); www.climate.washington.edu

Air temperatures and precipitation were near-normal for the 2021 calendar year in the Puget Sound area. Washington State is divided into 10 separate climate divisions based on similar average weather conditions (http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php). The following summary uses data from the Puget Sound Lowlands division that encompasses most of Puget Sound. The 2021 Puget Sound annual average air temperature (10.7°C; 51.3°F) was near the 1991-2020 normal (+0.1°F) and cooler than most of the previous 7 years. Total annual precipitation was 124.26 cm (48.92"), which was 107% of normal, and similar to annual precipitation in 2020.

Monthly values are used to illustrate the substantial variability in the weather during the year. Figure 2.1 shows monthly temperature and precipitation anomalies for the Puget Sound region relative to the 1991-2020 normal. There was a wet start to the calendar year, and January and February combined were the 22nd wettest since records began in 1895. That precipitation, in combination with the cooler than normal temperatures in February and March, helped to build and maintain the state's snowpack which was 121% of normal averaged across the state on April 1. On the other hand, March through May was very dry (49% of normal precipitation), ranking as the 2nd driest spring since 1895. Drier than normal conditions continued through the summer, and a record-breaking heat wave at the end of June accelerated drought conditions. There were three consecutive days with temperatures exceeding 100°F in parts of the central and southern Puget Sound region. June ranked as the second warmest on record with an anomaly of 2.6°C, and June and July combined ranked as the 9th warmest. In contrast to the warm and dry summer, fall was extremely wet. September through November surpassed 2016 as the wettest on record (155% of normal) and significant flooding occurred in November, particularly in the northern Puget Sound region. The year ended with below normal temperatures in December.

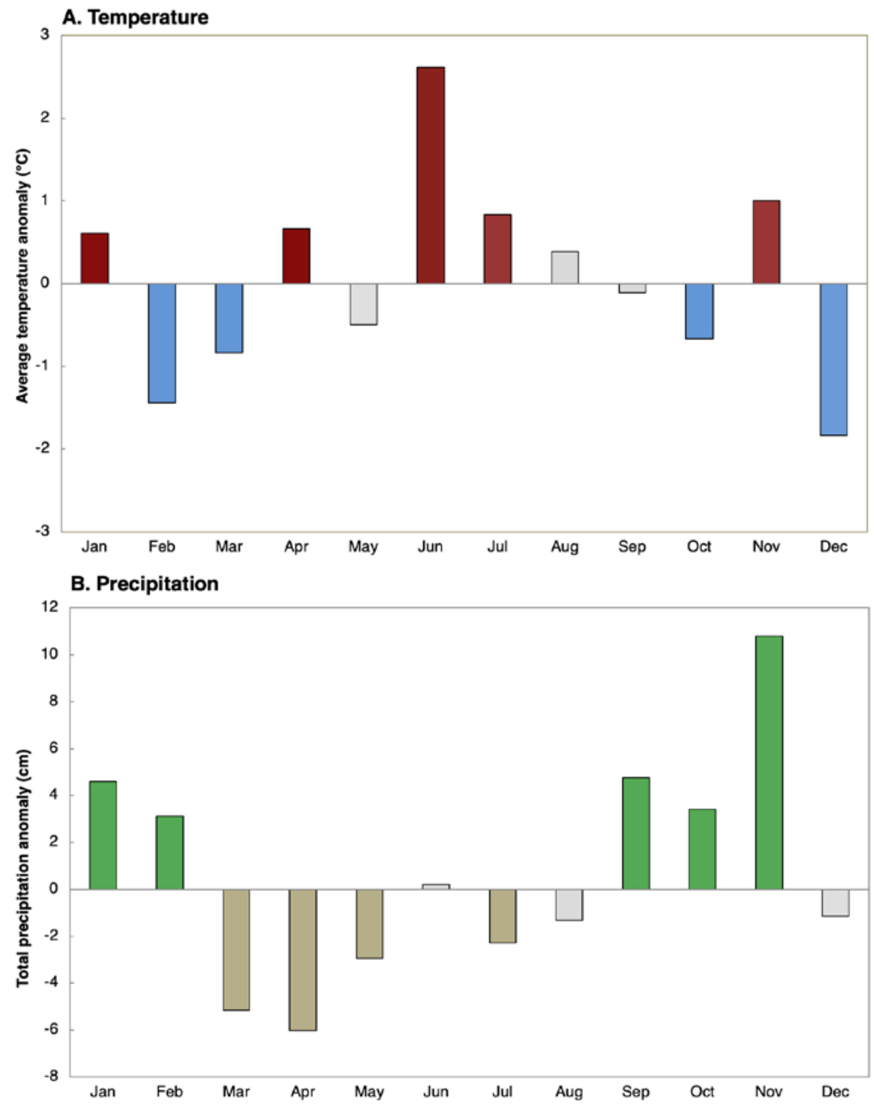


Figure 2.1. Monthly anomalies for (A) temperature (Celsius) and (B) precipitation (centimeters) for the Puget Sound Lowlands climate division in Washington State for the 2021 calendar year. Anomalies are relative to the 1991-2020 climate normal and are colored red (green) for above normal temperature (precipitation) anomalies and blue (brown) for below normal temperature (precipitation) anomalies. Temperature (precipitation) anomalies within 0.5°C (2 cm) are classified as near-normal and are colored gray.

B. Local air temperature and solar radiation

Source: Skip Albertson (skip.albertson@ecy.wa.gov), Natalie Coleman, Micah Horwith, Christopher Krembs, Julianne Ruffner, and Holly Young (Ecology); https://ecology.wa.gov/Research-Data/Monitoring-assessment/Puget-Sound-and-marine-monitoring

Air temperatures at SeaTac airport were generally warmer than normal relative to the 1971–2000 historical baseline especially during January, April, June, and November (data source: NOAA-NWS). February, September, and December were cooler than normal (Figure 2.2A). Seattle (SeaTac airport) recorded an all-time record high temperature of 42°C (108°F) on June 28, 2021, which is nearly 16°C above normal. Note that the National Weather Service (NOAA-NWS) has updated its baseline to 1991-2020, but to allow for consistency in reporting anomalies for Puget Sound boundary conditions, we continue to use 1971-2000.

Sunlight, as measured by daily surface solar energy flux, was above average during April, June, the second half of July, November corresponding to warmer air temperatures. In prior versions of this publication, which began in 2011, we lacked a sufficient statistical background for presenting the current year's data. Starting in 2021, we calculated a baseline from 2011-2020 and overlaid the 2021 results in the foreground as black (Figure 2.2B). Daily percentile ranges are calculated by using results from the same calendar day to generate the baseline. UW-Atmospheric Science sensors take a recording every minute and these data are integrated over the day and converted into energy (kW-h), taking both solar intensity and duration into account.

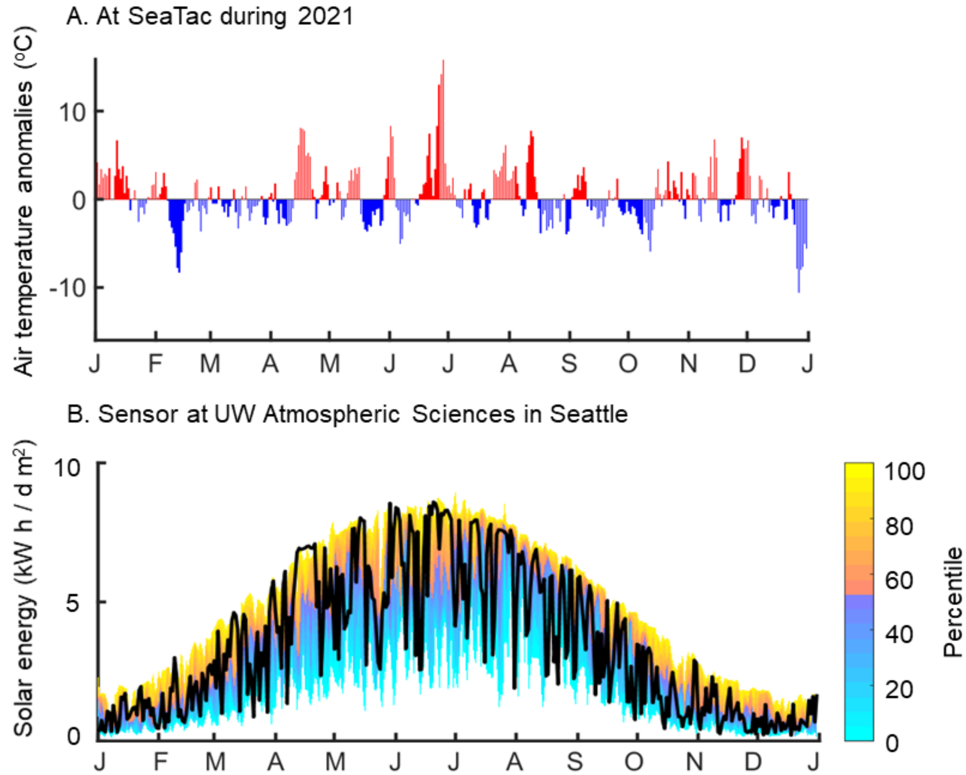


Figure 2.2. (A) Daily air temperature anomalies at SeaTac during 2021. Red and blue shading indicate warmer and cooler than average values, respectively. (B) Daily solar energy flux from the rooftop PAR sensor at the UW Atmospheric Sciences Building in Seattle. The contour color represents the various percentiles recorded from 2011-2020 on the same calendar day as in 2021. The black line shows daily values for 2021.

Zittle's Marina in Olympia. Photo: Mya Keyzers

CALL-OUT BOX: Updated 30-year Normals

In accordance with the World Meteorological Organization (WMO) recommendation, the process for using long-term averages of air temperature and precipitation to compare current versus average conditions at a particular location (i.e. climate normals) has been updated. In previous PSEMP reports, the 1981-2010 normals were used to put the local weather and climate conditions into historical perspective. The WMO requires that NOAA update the normals every decade, and NOAA released their 1991-2020 normals in early 2021. The regional air temperature and precipitation summary in this report compares 2021 temperatures and precipitation to the new 1991-2020 normals.

The latest update swaps the 1980s (1981-2010) for the 2010s (1991-2020). Figure 1 shows the difference between the 1981-2010 and 1991-2020 normals for the Puget Sound Lowlands climate division by month. While temperatures have warmed with every new normal release, the normals are not intended to be a climate change indicator. Instead, their purpose is to put the current weather into recent historical context. Also, decadal variability, rather than long-term climate change, can play a role in the comparison between the new and old normals. For example, the 1991-2020 November precipitation normal is slightly drier than the 1981-2010 normal (Figure 1), whereas a pattern of drier autumns in Washington state is not expected with climate change.

Overall, the 1991-2020 normals show a Puget Sound region that is slightly warmer and wetter. Annually, the new 30-year averages for the Puget Sound region are 0.2°C warmer and 1.83 cm wetter than before. According to Figure 1, average monthly temperatures are warmer for 10 months of the year. February and March are the exceptions, with some cold years in the 2010s causing the new normals to be colder than the previous set. Changes to the precipitation normal are more seasonal than temperature. The January-April, September-October, and December normals are all wetter in the 1991-2020 average compared to the old normal. May through August and November are drier.

There have been several summaries comparing 1991-2020 with 1981-2010 normals at a national scale and for other variables. For example, according to the NOAA Northwest River Forecast Center (https://www.nwrfc.noaa.gov/ws/docs/NWRFC_1991-2020_Normals_Update_Documentation.pdf), the natural water supply runoff for Puget Sound rivers has increased between 2-6%, depending on the river, which is consistent with annual average precipitation becoming wetter. Maps of the annual differences in temperature and precipitation are available at NOAA (https://www.ncei.noaa.gov/news/noaa-delivers-new-us-climate-normals), and while the temperatures have consistently warmed across WA for the new normal period, the precipitation changes are not spatially consistent across the state.

This shift in normal periods will be used in this and subsequent editions of the PSEMP Marine Waters report. The average annual temperature for 2021 was near-normal for the Puget Sound region with respect to our new 1991-2020 normals, but not in the longer historical context. It is tied as the 19th warmest year since records began in 1895, illustrating that we are dealing with a climate system with systematic long-term warming trends as well as decadal-scale variability.

Author: Karin Bumbaco (kbumbaco@uw.edu) (OWSC; UW, CICOES); www.climate.washington.edu

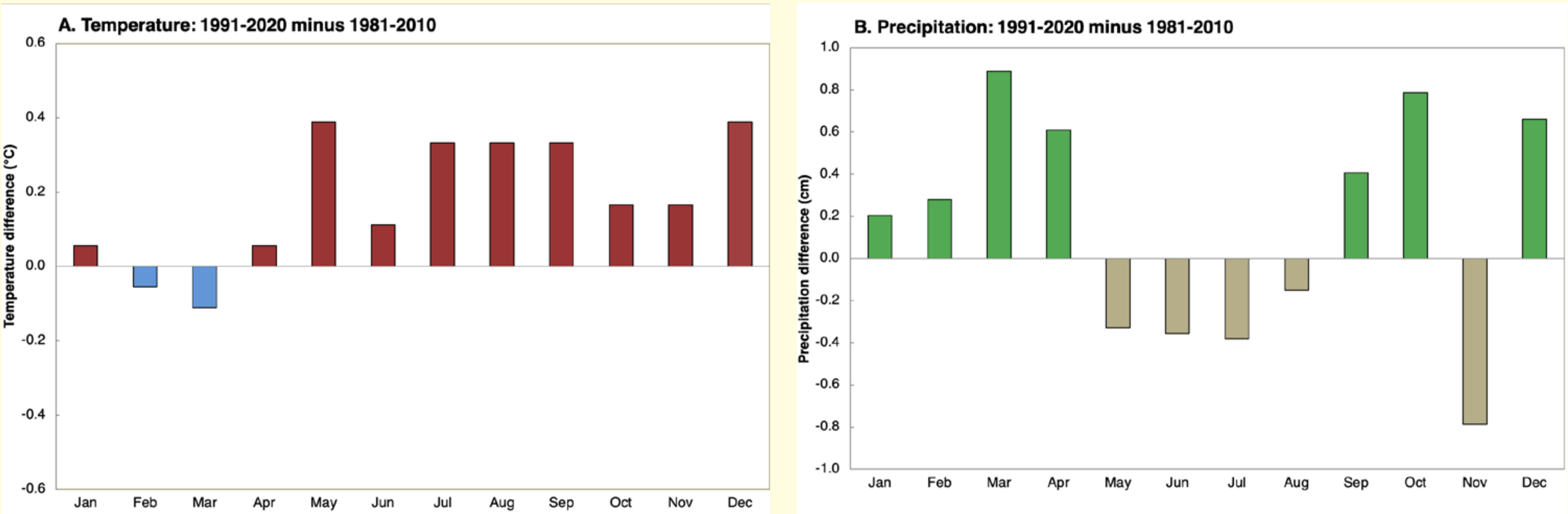


Figure 1. Monthly differences between the 1991-2020 normal period and the 1981-2020 normal period for (A) temperature (Celsius) and (B) precipitation (centimeters) for the Puget Sound Lowlands climate division in Washington State. The bars are colored red (green) for positive differences in temperature (precipitation) and blue (brown) for negative differences in temperature (precipitation).

Calm day in the Middle Channel, south of San Juan Island.
Photo: Rachel Wold.

3. Coastal ocean and Puget Sound boundary conditions

The waters of Puget Sound are a mix of coastal ocean water and river inputs. Monitoring the physical and biochemical processes occurring at the coastal ocean provides insight into this important driver of marine water conditions in Puget Sound.

A. NW Washington Coast water properties

Dissolved oxygen
Temperature

Source: John Mickett (jmickett@apl.uw.edu), Jan Newton, Beth Curry, and Dana Manalang (UW, APL); nwem.ocean.washington.edu, nvs.nanoos.org/Explorer

A large surface mooring, Chá?ba·, and an adjacent subsurface profiling mooring, NEMO-subsurface, maintained by the Northwest Association of Networked Ocean Observing Systems (NANOOS) and the University of Washington (UW), were established in 2010 and collect oceanographic and meteorological measurements on the Northwest Washington shelf. These observations give insight into boundary condition changes for Puget Sound.

The most significant observation of 2021 was that – similar to 2020 – summertime deep water (i.e. mid-depth to the bottom) continued to be cooler than other years following the 2014-2015 MHW (Marine Heat Wave). In fact, in early summer the deep water was the coldest observed for that time of year since 2013 (Figures 3.1A, 3.2). Although a strong correspondence between near-surface and deep water temperature patterns is uncommon, near-surface temperatures in August-October were also substantially cooler (~1°C) than normal. Also, although average deep water temperatures were near-normal in June and July, daily-averages lacked

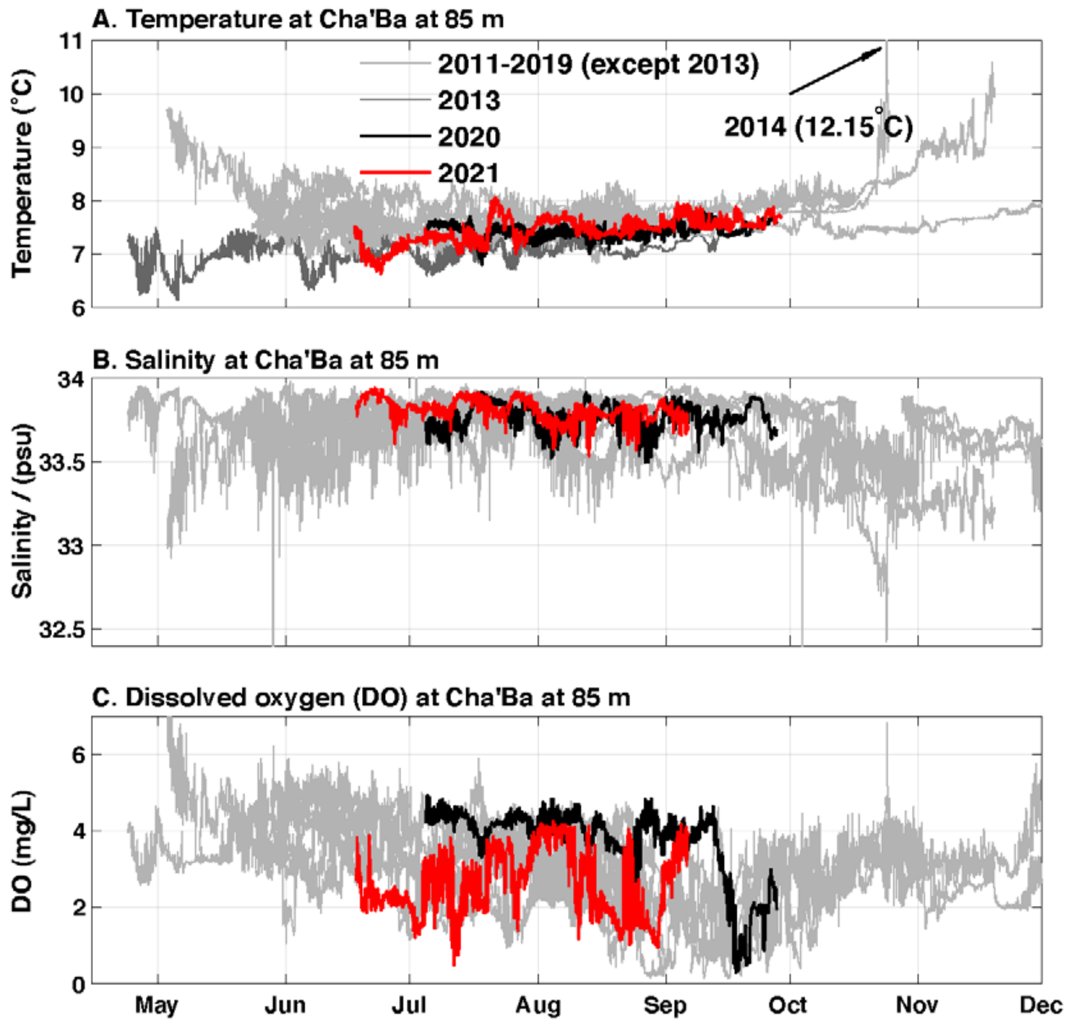


Figure 3.1. Interannual comparison of near-bottom properties (85 m). (A) temperature, (B) salinity, (C) dissolved oxygen.

peaks above 15°C. This contrasts with previous years (i.e. 2019, 2017 and the MHW) where near-surface temperatures in excess of 15°C occurred during several, week-long events each summer.

Although cooler deep water temperatures in 2021 could be explained by the continued effect of the same water that drove cooler temperatures in 2020, patterns in dissolved oxygen (DO) suggests something different. The DO values observed during 2021 were below average and were episodically hypoxic (< 2 mg/l) for periods of several days to a week (Figure 3.1C). This is unlike deep water DO values during 2020, which were among the highest yet observed for most of the summer. This difference, combined with significantly saltier deep water in 2021 versus 2020, suggests another mechanism or water mass is responsible for the cooler deep water in 2021.

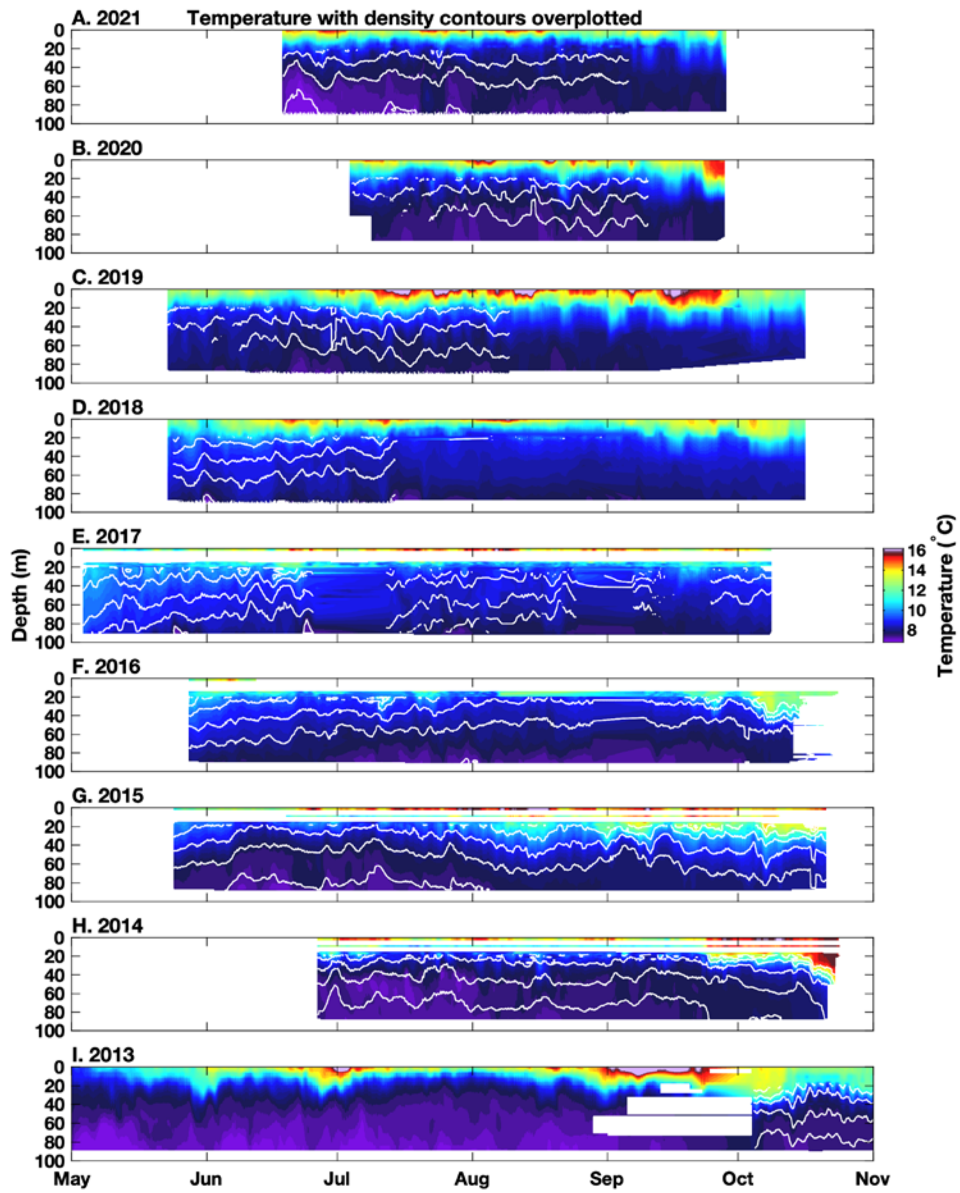


Figure 3.2. Water column temperature with density contours overplotted for 2021-2013 (A-I).

B. Ocean and atmospheric CO_2

Ocean acidification

Ocean acidification (OA) refers to the chemical changes that occur when some of the excess carbon dioxide (CO_2) in the atmosphere from human activities, an amount that grows each year, is absorbed by the surface ocean. The increasing CO_2 concentration results in declining pH and increasingly corrosive conditions for calcifying organisms like shellfish or certain plankton, like pteropods, that secrete calcium carbonate (aragonite or calcite) shells. Other organisms show metabolic responses to elevated CO_2 that affect growth or reproduction. OA in Puget Sound is of particular concern as estuarine processes, both natural and human-mediated, can also increase the CO_2 content and lower the pH of marine waters. Moreover, coastal upwelling brings deeper waters with naturally higher CO_2 concentrations upwards and into Puget Sound via the Strait of Juan de Fuca. Thus, Puget Sound is influenced by a variety of drivers that exacerbate the growing OA signal, making our waters particularly sensitive to these conditions. All of these changes have ramifications for marine food webs and are areas of active current research.

Source: Simone Alin (simone.r.alin@noaa.gov), Adrienne Sutton (NOAA, PMEL), Jan Newton, John Mickett (UW, APL), Sylvia Musielewicz (UW, CICOES), Beth Curry (UW, APL), and Chris Sabine (Univ. Hawaii); https://pmel.noaa.gov/CO2/story/Cape+Elizabeth, https://pmel.noaa.gov/CO2/story/La+Push
Website for online data: https://www.pmel.noaa.gov/CO2/timeseries/CAPEELIZABETH.txt; https://www.pmel.noaa.gov/CO2/timeseries/CHABA.txt; PMEL contribution number 5384

Carbon dioxide (CO_2) sensors have measured atmospheric and surface seawater xCO_2 (mole fraction of CO_2) on the surface Ćháʔba· mooring off La Push since 2010 and on the National Data Buoy Center mooring 46041 off Cape Elizabeth since 2006. Data collection during 2021 occurred at Ćháʔba· mid-June through early December and mid-May through December at Cape Elizabeth (Figure 3.3).

The atmospheric xCO_2 range was 401–460 parts per million (ppm) at Ćháʔba· and 401–494 ppm at Cape Elizabeth in 2021. Average 2021 atmospheric xCO_2 values for all observations at Ćháʔba· (413±6 ppm) and Cape Elizabeth (414±7 ppm) were similar to the NOAA/ESRL global average marine surface air value of 415 ppm for 2021, despite some periods of missing observations at both sites. Mean air xCO_2 values between mid-July and mid-October 2021 were the same as in 2019 at Ćháʔba· after a slight decline during 2020 (Table 3.1), but fit a linear trend of increase (slope=2.25 ppm/year; r^2=0.96). Variability in atmospheric xCO_2 at Ćháʔba·, as evidenced by standard deviation, was lower than observed in 2020, possibly due to wildfires during that year (Table 3.1).

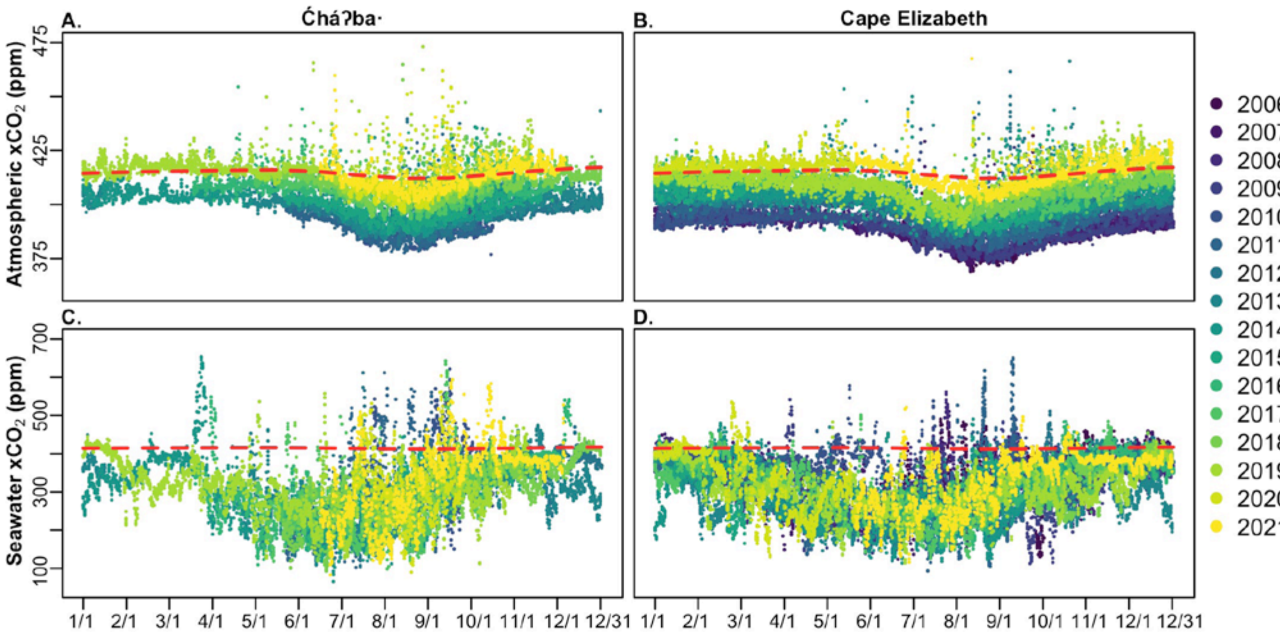


Figure 3.3. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater (A, B) and in surface seawater at 0.5 m depth (C, D) on the Ćháʔba· (A, C), and Cape Elizabeth (B, D) moorings. Typical uncertainty associated with quality-controlled measurements from these systems is <2 ppm for the 100–600 ppm range and increases for values above 600 ppm. The dashed line in each panel represents monthly mean atmospheric xCO_2 values for globally averaged marine surface air (NOAA/ESRL).

For both sites, monthly average atmospheric xCO_2 values were above globally averaged marine surface air during May–June and October–December by 0.8–5.1 ppm and fell below the global average July–September by 1.9–4.8 ppm, reflecting the effect of regional summertime primary productivity.

Surface seawater measurements spanned 83–594 ppm at Ćháʔba· and 116–522 ppm at Cape Elizabeth (Figure 3.3C and D) during 2021. Annual means at both sites were on the higher end of the record (Tables 3.1 and 3.2). Mean seawater xCO_2 values at Ćháʔba· during mid-July through mid-October were the third highest since 2010, and annual average seawater xCO_2 values at Cape Elizabeth were tied with 2016 for 4th highest (out of 16) since 2006 (Tables 3.1 and 3.2).

Table 3.1. Mean (± standard deviation) surface seawater and atmospheric xCO_2 values at Ćháʔba· during the most commonly measured period across years, mid-July to mid-October, in parts per million (ppm). Percent data return indicates how much of that period is represented by three-hourly measurements (during parts of 2012–2013, higher measurement frequency resulted in a return over 100%).

Ćháʔba·	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Atmosphere	388 ± 6	387 ± 7	392 ± 8	394 ± 7	394 ± 7	400 ± 7	N.A.	403 ± 7	406 ± 7	410 ± 7	408 ± 10	410 ± 5
Seawater	354 ± 87	332 ± 76	296 ± 54	280 ± 67	275 ± 72	298 ± 72	N.A.	273 ± 91	286 ± 66	308 ± 62	313 ± 84	327 ± 108
Data return	100	101	108	128	100	100	0	100	100	100	81	90

Table 3.2. Year-round mean (± standard deviation) surface seawater (sw) and atmospheric (atm) xCO_2 values at the Cape Elizabeth mooring in parts per million (ppm). Percent data return provides a simple metric for how much of each year is represented, at a three-hour measurement interval (during part of 2011, measurement frequency increased, resulting in a return over 100%). A note to end users: it is good practice to always use the most recent year's reports as values can change after data processing and quality control are finished.

Cape Elizabeth	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Atmosphere	386 ± 8	390 ± 7	390 ± 6	389 ± 7	393 ± 6	394 ± 8	397 ± 8	402 ± 7	403 ± 8	400 ± 8	405 ± 6	407 ± 7	407 ± 7	411 ± 7	419 ± 3	414 ± 7
Seawater	362 ± 66	323 ± 70	321 ± 68	314 ± 64	356 ± 52	306 ± 80	346 ± 55	280 ± 61	305 ± 73	317 ± 57	332 ± 69	307 ± 71	330 ± 53	306 ± 58	330 ± 80	332 ± 69
Data return	50	88	95	82	94	107	42	91	100	53	47	75	40	99	38	60

C. Puget Sound environmental metrics

Dissolved oxygen Temperature

Source: John Mickett (jmickett@apl.uw.edu), Jan Newton, Beth Curry (UW, APL), and Nick Bond (UW, CICOES); http://www.nanoos.org/products/ps_metrics/home.php

Five real-time metrics that use regional observations inform resource managers, scientists, health officials, and others on how key climate and ocean factors may influence Puget Sound water properties. The metrics include temperature changes from surface heat fluxes, salinity changes from rivers and rain, estuarine flow, water column dissolved oxygen (DO), and ocean boundary conditions.

The **temperature changes** metric showed that surface heat loss was lower than normal in the winter and surface heat gain was higher than normal during the late June/July heat wave and again in the early fall. If acting alone this excess heating would cause a 60 m thick water column to be about 0.5 °C warmer than normal (Figure 3.4). ORCA buoy warm seawater anomalies (see section 5.B.i. Puget Sound profiling: temperature on page 20) suggests this excess heating significantly contributed to above-average water column temperatures.

The **salinity changes** metric showed that Puget Sound salinity anomalies in 2021 were driven almost entirely by changes in freshwater input into Puget Sound, with a strong salty anomaly developing in spring and then a rapid switch to a fresh anomaly in November (Figure 3.4, see section 5.B.ii. Puget Sound profiling: salinity on page 22).

The **estuarine flow** metric, based on density differences driving circulation between ORCA buoy pairs, showed typical flow into South Sound but abnormally-strong and sustained inflow (~1 km/day) in the main stem of Hood Canal during the spring, when flow is typically weak or negligible. This enhanced inflow ended abruptly at the start of the June/July heat wave, suggesting the freshening of northern Hood Canal water was due to increased Skagit River flow associated with excessive snowmelt.

The **water column DO** metric showed typical seasonal patterns, but also revealed consistently greater percentage of habitat in low oxygen categories than expected at all five tracked ORCA buoy sites. The occurrence of water with DO≤2 mg/L at Hoodsport was often more than double that of the climatology values.

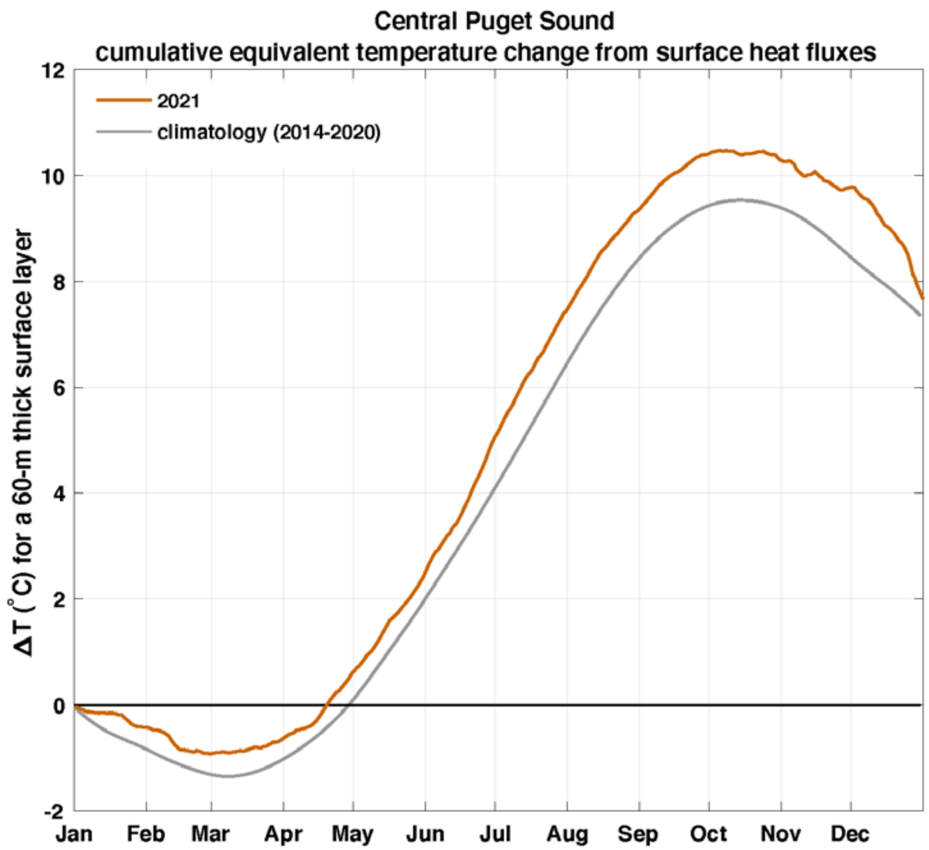


Figure 3.4. Central Sound location equivalent change in temperature from accumulated heat gain or loss over a fixed 60 m water depth starting on January 1, 2021. This depth was chosen based on sill depths and wind-mixing depths. Reducing this thickness would proportionally increase the heating (a 30m layer would warm twice as much), increasing it would proportionally decrease the cumulative heating. Observed changes in warming/cooling that are different than this would be due to differences in vertical heat distribution, the influence of lateral advection or spatial variability (or errors) in the surface heat fluxes. The deviations from the climatology in this plot are typically due to long-term (week and longer) trends and not daily differences.

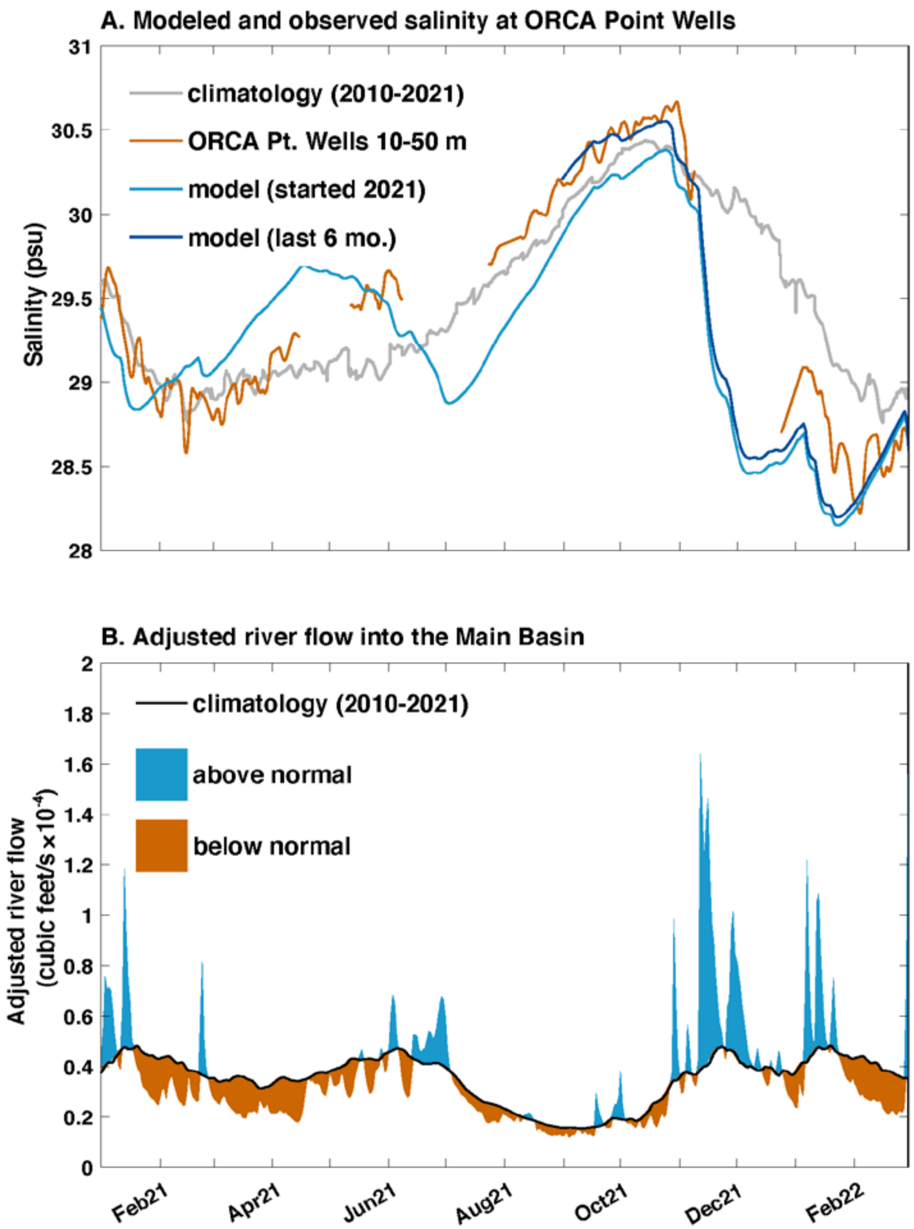


Figure 3.5. Estimate of the influence of river flow on the variability of salinity in the Main Basin (Point Wells) based on a simple box model that only uses USGS river flow for input (top panel). Compare this to daily-measured (or better) depth-averaged salinity as measured by the ORCA moorings. Near-surface values are excluded to reduce transient, short-timescale variability in the observations. Comparison to adjusted river flow anomalies for the Main Basin (lower panel) shows the influence of river flow anomalies on salinity.

4. River inputs

The waters of the Salish Sea are a mix of coastal ocean water and river inputs. The flow of rivers that discharge into the Salish Sea is strongly influenced by rainfall patterns and the elevation of mountains feeding the rivers. Freshwater inflows from rivers with high-elevation watersheds peak once annually in early summer from snowmelt. Rivers with mid-elevation watersheds peak twice annually from periods of high precipitation in winter and snowmelt in spring and summer. Low-elevation watersheds collect most of their runoff as rain, rather than mountain snowpack, and freshwater flows peak only once annually in winter due to periods of high precipitation. The salinity and density-driven circulation of Puget Sound marine waters are influenced by river inflows and can influence water quality conditions.

A. Fraser River

Summer Stream Flows

The Fraser River is the largest single supply of freshwater to the Salish Sea, contributing a total of approximately two-thirds of all river inputs. Most of this water is delivered in early summer, typical of a snowmelt-dominated flow regime.

Source: Tyler Burks (tyler.burks@ecy.wa.gov) (Ecology) and Environment and Climate Change Canada; https://wateroffice.ec.gc.ca/report/real_time_e.html?stn=08MF005

Snowpack in the Fraser River watershed was high in 2021, with a basin-wide average at 116% of normal by April. Accumulation occurred under La Niña (ENSO) conditions, which have historically created cooler temperatures across British Columbia, and elevated precipitation in the southwest (BCRFC, 2021). Above normal precipitation and below normal temperatures during late fall led to substantial snowpack accumulation prior to December 2020. After a relative mid-winter lull, accumulation resumed normal rates in February. A brief warm period in mid-April 2021 lead to a rapid melting of low and mid elevation snowpack, spurring the onset of the snowmelt runoff season and resulting in discharge well above the historical median (Figure 4.1). While the Fraser continued to rise, extremes were moderated by periodic cool and dry periods through the month of May (BCRFC, 2021). Streamflow reached peak runoff during the first week of June when warm temperatures combined with a wet storm system to rapidly melt snow at even the highest elevations in the watershed (BCRFC, 2021). The resulting peak flow was a couple weeks early, compared to the historical median, and well above the 75th percentile for a short duration (Figure 4.1). Unprecedented heat at the end of June (120°F at Lytton, BC), decimated any remaining snowpack, and generated a second, yet less strong runoff peak in early July (Figure 4.1). Streamflow quickly declined thereafter, due to lack of sustaining snowpack and precipitation, dropping below the 25th percentile and reaching near historical minimums amidst drought conditions by early September. Levels rebounded with the return of precipitation in fall and remained at or just above normal the remainder of the year, except for an intense storm event in mid-November that flooded the lower Fraser valley and exceeded historical maxima, resulting in sediment-rich plumes entering the Salish Sea.

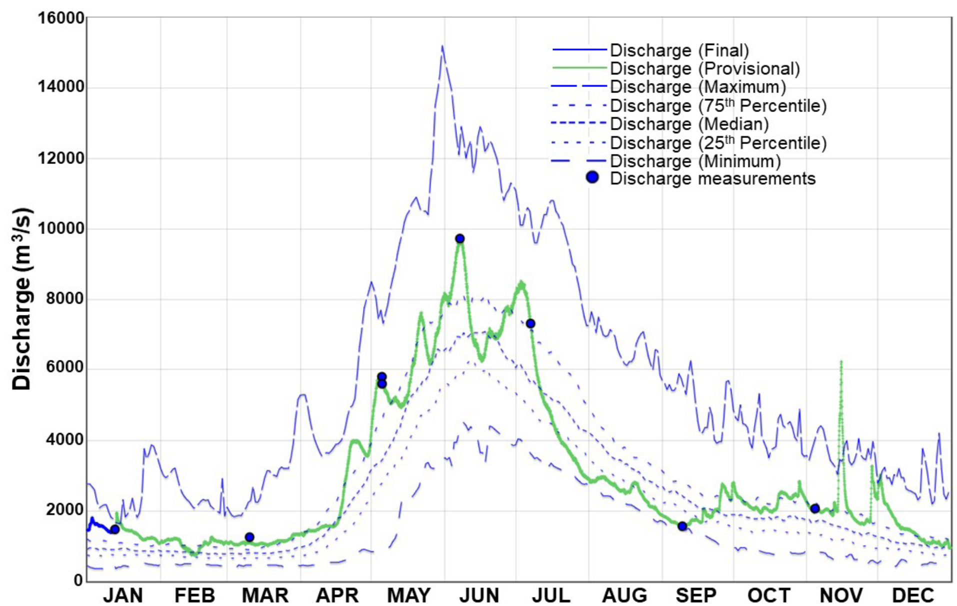


Figure 4.1. Fraser River daily discharge (m^3/s) at Hope, B.C (08MF005) for 2021, compared to the maximum, 75th percentile, median, 25th percentile, and minimum values for the period of record (1912-2021). (Note 1 m^3/s= 35.3ft^3/s).

B. Puget Sound rivers

Summer Stream Flows

One-third of the freshwater supply to the Salish Sea comes from the rivers draining to Puget Sound, particularly the Skagit, Snohomish, Puyallup, Nooksack, and Stillaguamish Rivers. In contrast to the Fraser River, the flow regime for the majority of Puget Sound rivers is characterized by dual peaks; the first is observed when snowmelt peaks in spring, and the second when rain returns in the fall.

Source: Tyler Burks (tyler.burks@ecy.wa.gov) (Ecology) and U.S. Geological Survey; https://waterdata.usgs.gov/wa/nwis/rt; https://waterwatch.usgs.gov/index.php?id=sitedur

Mountain snowpack accumulated under moderate La Niña (ENSO) conditions providing cooler and wetter weather in Washington State (OWSC, 2021). Snow accumulation in the Cascade and Olympic Mountains feeding major Puget Sound rivers had a typical start early in the season, but then lagged during December and January due to above normal temperatures. La Niña finally brought below normal temperatures and above normal precipitation during the month of February, creating a surge in snowpack, with notable lowland accumulations (OWSC, 2021). This surge was followed by a dry and cold March, which sustained an above normal snowpack (138%) into early April (OWSC, 2021). Early in 2021, streamflow levels ranged from normal to well above normal for the major rivers draining to Puget Sound (Figure 4.2), resulting in minor flooding in the south. Streamflow levels were temporarily below normal during early spring due to dry conditions, but a warm spell in mid-April initiated the snowmelt runoff season and brought streamflow back to normal levels. Peaks in runoff occurred due to above normal temperatures in early June, which were well timed and exceeded historical means. A secondary runoff peak varying in magnitude depending on the remaining snowpack occurred at the end of June during unprecedented heat. Dry spring conditions followed by exceptional summer heat caused some rivers to reach below normal streamflow by mid-July lasting into early September. A drought emergency was declared on July 14th, except for the watersheds that supply Everett, Seattle, and Tacoma (Bumbaco et. al, 2022). River levels returned to normal or above normal by mid-September, due to a series of strong precipitation events. During mid-November, an intense storm caused severe flooding in the Nooksack and Skagit watersheds. Major freshwater inputs to Puget Sound were at or near their historic median cumulative discharge at the end of 2021.

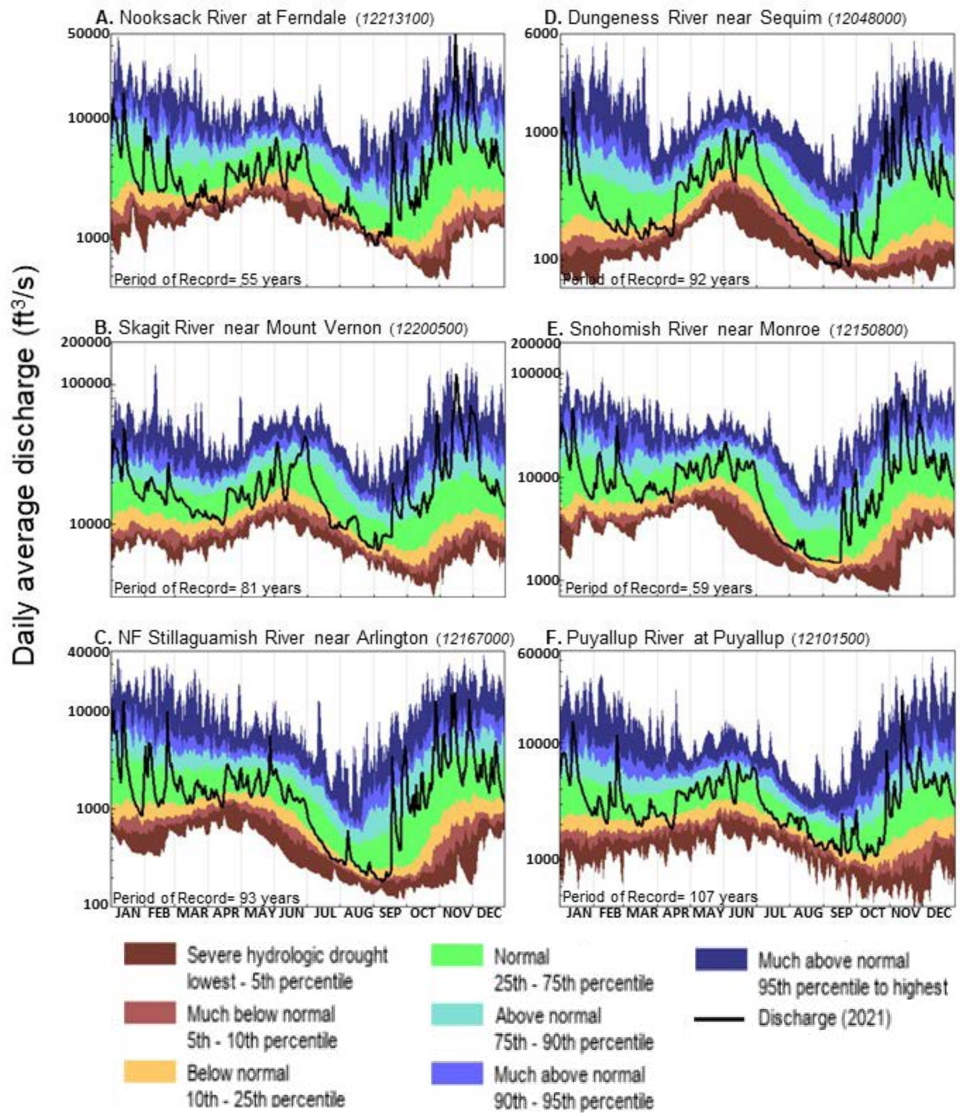


Figure 4.2 Daily average river discharge (ft^3/s) at stations on the Nooksack (A), Skagit (B), NF Stillaguamish (C), Dungeness (D), Snohomish (E), and Puyallup (F) Rivers in 2021, compared to period of record percentile classes. (Note: the period of record varies for each station and is listed in number of years on each hydrograph).

5. Water quality

Temperature and salinity are fundamental water quality measurements. They define seawater density and are important for understanding estuarine circulation and conditions favorable to Puget Sound's marine life. Many marine organisms have developed tolerances and life-cycle strategies for specific thermal and saline conditions. Nutrients and chlorophyll give insight into the production of organisms at the base of the food web. Phytoplankton are assessed by monitoring chlorophyll-*a*, their photosynthetic pigment. In Puget Sound, like most marine systems, nitrogen nutrients sometimes limit phytoplankton growth. On a mass balance, the major source of nutrients is from the ocean; however, rivers and human sources also contribute to nutrient loads. Dissolved oxygen in Puget Sound is quite variable spatially and temporally and can quickly shift in response to wind, weather patterns, local biological processes, and upwelling influence via mixing at sills. In some parts of Puget Sound, dissolved oxygen is measured intensively to understand the connectivity between hypoxia and large fish kills. Dissolved oxygen is also an indicator of biological production, respiration, and consumption of organic matter, and a component for understanding the health of the food web.

A. Puget Sound long-term stations

Ecology maintains a network of monitoring stations throughout the southern Salish Sea, including the eastern Strait of Juan de Fuca, the San Juan Islands, and Puget Sound basins. This network of stations provides the temporal coverage and precision needed to identify long-term, Sound-wide trends; https://ecology.wa.gov/Research-Data/Monitoring-assessment/Puget-Sound-and-marine-monitoring; https://apps.ecology.wa.gov/eim/search/default.aspx.

A.i. Nutrients and chlorphyll

Nutrients *Source: Christopher Krembs (christopher.krembs@ecy.wa.gov), Mya Keyzers, Skip Albertson, and Julia Bos (Ecology); Primary website: https://ecology.wa.gov/Research-Data/Monitoring-assessment/Puget-Sound-and-marine-monitoring; Website for online data: https://apps.ecology.wa.gov/eim/search/Eim/EIMSearchResults.aspx?ResultType=EIMTabs&StudySystemIds=99970619&StudySystemIds=99970618&StudyUserIdSearchType=Equals&StudyUserIds=MarineWater-P&StudyUserIds=MarineWater*

Ecology conducts monthly, full-depth CTD casts at 27 stations in Puget Sound, with discrete water samples collected at target depths of 0m, 10m, and 30m corresponding to actual depth bin ranges of 0-5m, 5-20m, 20-50m. Reported results represent conditions integrated from surface to 50m. To remove regional and seasonal variability, site-specific monthly-baselines (1999-2008) are subtracted to calculate anomalies (Krembs 2012). The annual median of the resulting anomalies across all stations reflects large-scale, inter-annual patterns and trends.

The year 2021 followed the 23-year pattern with surface water becoming increasingly more stratified (Figure 5.1A). Median nitrate concentrations in surface waters appear to be cyclical varying between 4 μM with a period of approx. 15 years (Figure 5.1B), with increasing values in recent years. The time averaged seasonality of phytoplankton biomass in Ecology's monitoring network has been changing over 22 years. Historically, two distinct peaks of phytoplankton biomass in May and August have gradually moved towards a single seasonal peak in June, (Figure 5.1C). Over the same historical period Si:DIN ratio has also declined (Figure 5.1D), albeit not to diatom-growth limiting levels. The decline in Si:DIN may reflect a combination of changing factors; ranging from human nitrogen inputs (Downing et al. 2016), weathering from land, and the hydrology of rivers responding to changing climate. While drivers of the Si:DIN ratio remain unresolved, a consistent decline in silicate concentration of 11 μM from 2005 to 2021 (Spearman Rank Coef., Rho=-0.94, $p<0.05$, $n=15$) (Figure 5.1F) indicates that delivery of silicate to the marine environment may be a factor. Water clarity (measured by light transmission) has also continued to change (Figure 5.1E) with a trend towards clearer water.

5. Water quality (cont.)

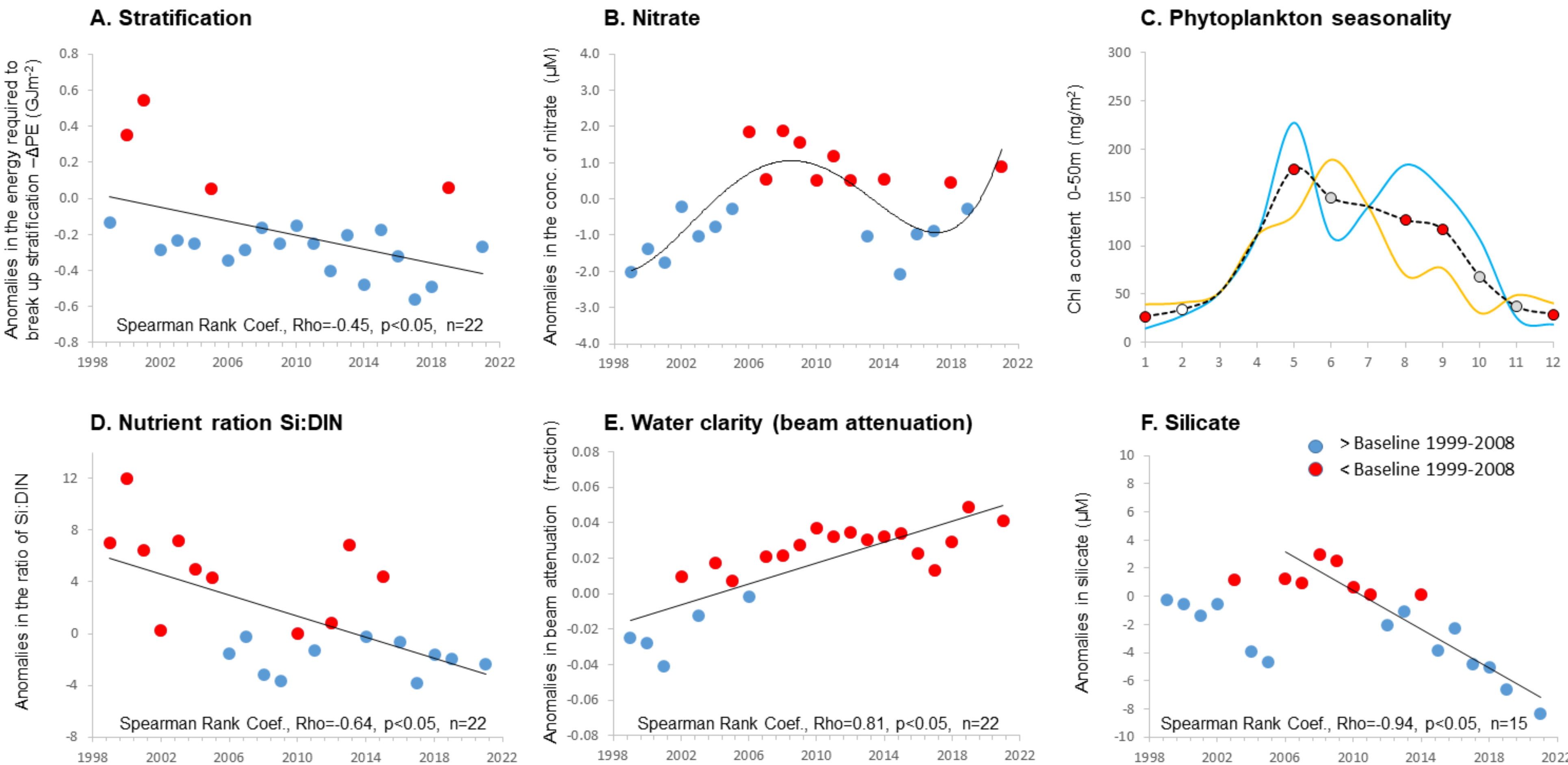


Figure 5.1. (A) Annual anomalies in density stratification of the water column from surface to 50m (reported as delta potential energy or the energy required to homogeneously mix the water column). Since Puget Sound is typically stratified at the surface due to a freshwater layer, negative values indicate that more energy is required to break up stratification while positive values mean the water column is more mixed than normal). (B) Annual median anomalies in nitrate concentration. (C) Seasonal baseline (dashed line) of chl-a from 1999-2021. Superimposed are significant monthly trends (red, grey and white dots) from 1999 (blue) to 2021 (yellow). (D) Annual anomalies in the Si:DIN ratio. (E) Yearly anomalies in beam attenuation. (F) Yearly anomalies in silicate in surface water concentrations.

5. Water quality (cont.)

A.ii. Water mass characterization

Temperature

*Source: Skip Albertson (*skip.albertson@ecy.wa.gov*), Natalie Coleman, Micah Horwith, Christopher Krembs, Julianne Ruffner, and Holly Young (Ecology);* https://ecology.wa.gov/Research-Data/Monitoring-assessment/Puget-Sound-and-marine-monitoring

Puget Sound circulation is driven by tidal currents, the surface outflow of freshwater from rivers, deep inflow of saltwater from the Pacific Ocean to replace it, and wind. Water quality in greater Puget Sound is tied closely to its source waters. Source waters (e.g. oceanic and freshwater end members) can be characterized by properties such as temperature and salinity (T-S). For example, high salinity and cold temperatures can identify Pacific Ocean water masses in the summer and rivers are characterized by low salinity. Salinity and temperature values in a basin progress through an elliptical cycle each year with the warmest and saltiest waters occurring in late summer, while cool, fresher waters are typically observed in the spring.

We present key monthly conditions within 2021 when large-scale water properties changed largely as the result of boundary conditions at play in the region. We show hydrographic data from Ecology's network as anomalies, departures from a 20-year baseline (1999-2018), along a center-channel transect from Olympia in the South to San Juan Island in the north (map not shown). 2021 began with higher-than-normal conditions of water temperature & salinity, particularly in the Central Basin and to the north. Higher precipitation and river discharge began to lower salinities by February (Figure 5.2A and B). February and March were cooler months than normal around the Puget Sound lowlands, so by April water temperature had generally decreased, although salinities were broadly on the rise and stayed high through the dry summer (Figure 5.2C and D). Water temperatures increased during July after a record hot spell at the end of June. While snowmelt discharge from rivers lowered salinity in certain adjacent locations, overall salinities remained high until November (Figure 5.2E and F). In December, salinities plummeted while temperatures remained high leading into a cold spell during the final week of the year (Figure 5.2G and H).

In Figure 5.2G, December temperature anomalies are shown relative to incoming oceanic source water, rather than a location- and depth-specific average over the baseline years. This more clearly shows that on the landward side in Puget Sound, water was about 3°C warmer relative to the ocean offering thermal refuge to some species of fish, such as anchovy (Brewer, 1976).

Whidbey Island. Photo: Rachel Wold

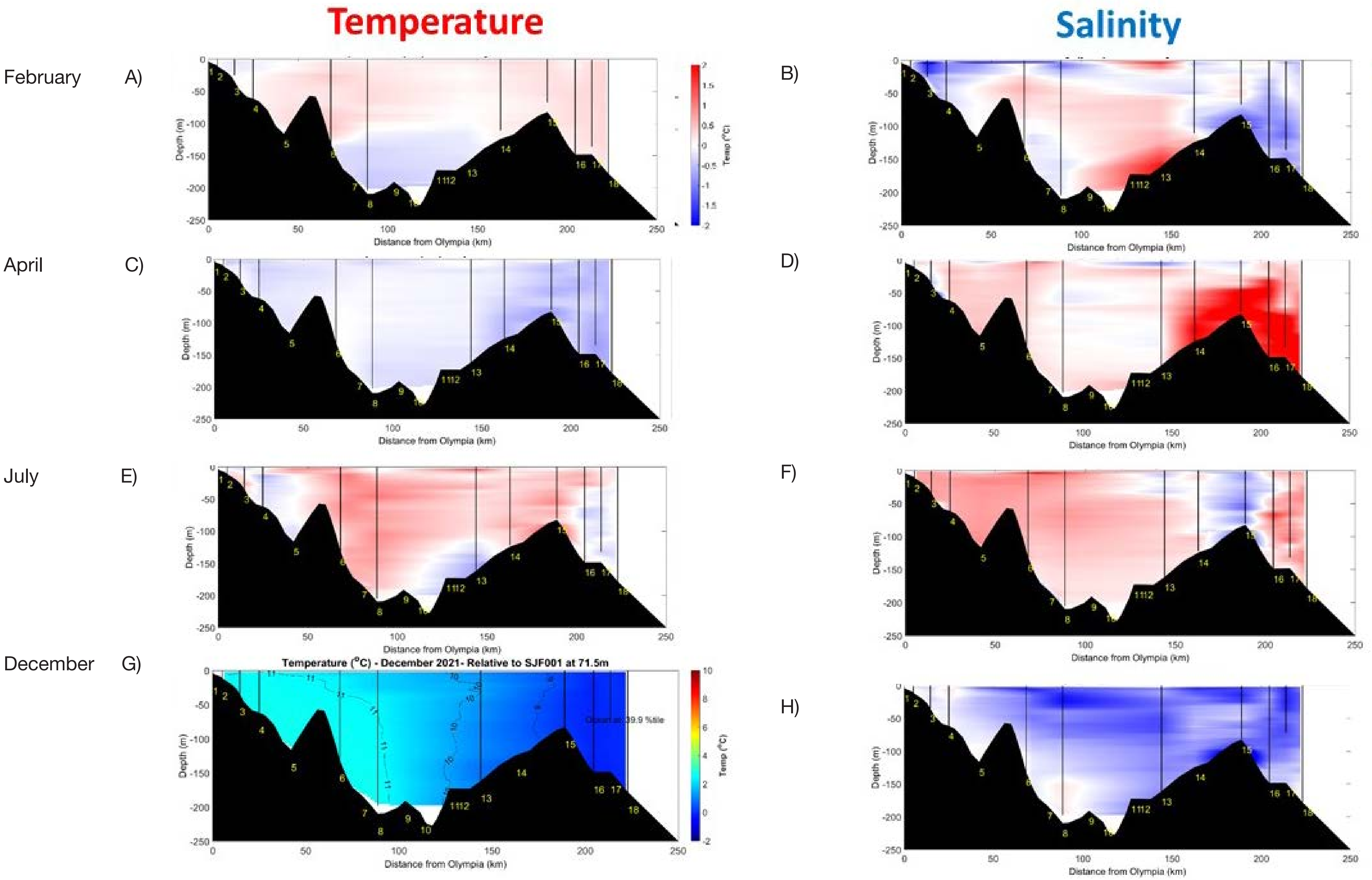


Figure 5.2. Key months of change in annual anomalies of temperature and salinity relative to a 20-year baseline (1999-2018) for February (A, B), April (C, D), July (E, F) and December (H). Red and blue shading indicate warmer and cooler than average values, respectively. All anomalies are month- and depth-specific except for (G), which is an anomaly relative to incoming oceanic water from below 70m at the outermost (seaward) station.

B. Puget Sound profiling buoys

Profiling buoys take frequent (one to four times per day) measurements of water properties over the full water column. This allows characterization of short- and long-term processes, including deep-water renewal events, surface influence of river runoff and heating, and tracking water mass properties. There are currently six ORCA (Oceanic Remote Chemical Analyzer) moorings in Puget Sound supported primarily by NANOOS and the Washington Ocean Acidification Center: South Hood Canal (Twanoh), central Hood Canal (Hoodsport), Dabob Bay, Admiralty Inlet (Hansville), Main Basin (Point Wells), and Southern Puget Sound (Carr Inlet).

B.i. Temperature

Temperature

Source: Jan Newton (janewton@uw.edu), John Mickett, Beth Curry, Dana Manalang, and Roxanne Carini (UW, APL); Primary website: http://www.nanoos.org; Website for online data: https://nwem.apl.washington.edu

Observations from the University of Washington ORCA mooring program highlight a strong difference between Puget Sound and Hood Canal water properties during 2021, especially for temperature and oxygen (see section 5.B.iii. Puget Sound profiling: dissolved oxygen on page 24). While basin-specific variation has always been noted, the difference was more pronounced in 2021 than in previous years.

All basins showed warmer temperature anomalies for much of 2021, but were stronger and lasted longer at the two Hood Canal sites (Figure 5.3). At the Main Basin and South Sound sites, the magnitude of anomalies was generally small (<1°C) – except for surface waters – and alternated seasonally over the water column, with positive (warmer) anomalies generally observed in summer (July-September) and winter (Janunary-March, December), and negative (cooler) anomalies in spring (April-June) and fall (October-November). In contrast, Hood Canal sites were generally warmer throughout the year, except for a notable cool spell driven by surface conditions in February, which were exceptionally cool (see section 3.C. Puget Sound environmental metrics on page 12). The cooler than average air and water temperatures in February also corresponded to lower than normal salinities, likely influenced by higher than normal rain in January (see section 5.B.ii. Puget Sound profiling: salinity on page 22).

The effect of the 2021 heat dome during late June was noticeable, particularly at Carr Inlet and Twanoh where much stronger positive anomalies were evident and extended all the way to depth. This underscores the strong atmospheric influence on regional marine waters. At Hoodsport, the seasonal oceanic intrusion was approximately two weeks later than normal and was anomalously warm. Intrusions are always warmer than the ambient water, and this delay in 2021 manifested as a short-lived cool anomaly, followed by rapid reversal to a warm anomaly upon the arrival of the anomalously warm intrusion.

Predominantly warmer anomalies have been more common in the last seven years since the 2014 marine heat wave, with 2017 and 2020 being the only years without predominantly warmer than average water temperatures. This indicates a pattern that may be influenced by regional climate change and warmer air temperatures.

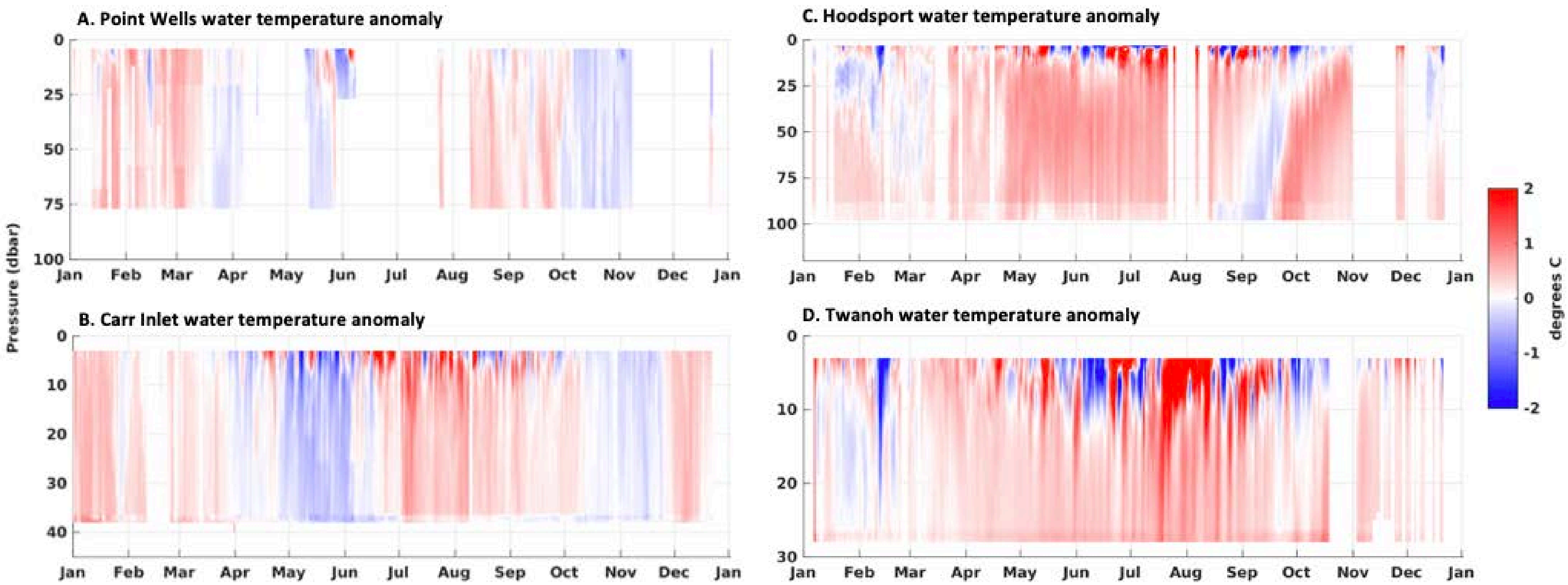


Figure 5.3. Four-panel figure showing pressure-time colormaps of water temperature anomalies in 2021 relative to the climatological average over 2005-2017. Pressure (or depth) is shown on the y-axis and time in monthly increments on the x-axis between January 2021 and December 2021 at four ORCA mooring sites: Point Wells in Main Basin (A), Carr Inlet in South Sound (B), Hoodsport in mid-Hood Canal (C) and Twanoh in South Hood Canal (D).

B.ii. Salinity

Source: Jan Newton (janewton@uw.edu), John Mickett, Beth Curry, Dana Manalang, and Roxanne Carini (UW, APL). Primary website: http://www.nanoos.org; Website for online data: https://nwem.apl.washington.edu

Observations from the University of Washington ORCA mooring program showed higher than average salinities in 2021 compared to climatological averages. This pattern held true for all basins (Main Basin, South Sound, Hood Canal) and occurred predominantly during the summer-fall months (Figure 5.4). The period of saltier than average waters was extended to November in 2021, which was longer than in most other years. While all basins showed saltier anomalies from April or May through November, the positive salinity anomalies were stronger at the two Hood Canal sites and particularly at the surface. Higher than average salinities during summer have been noted for all years since 2014, with the exception of 2017. This indicates a pattern that may be influenced by regional climate change and summer droughts.

Also notable were the fresher than average salinity anomalies during January-March, which were particularly strong at the Hood Canal sites. This is largely caused by above-average precipitation/river flow during this period (see section 3.C. Puget Sound environmental metrics on page 12). The above-average November rainfall caused the Puget Sound-wide salinity to rapidly drop and produce significant freshwater anomalies (0.5 psu) by December. As with temperature, anomalies were strongest at the surface in Hood Canal. At Hoodsport, the 1-2 week delay of the more saline, late-summer/fall intrusion had the interesting effect of briefly erasing the pre-existing salty anomaly (the light red positive salt anomaly goes to white during early September), but then, like temperature, became an even stronger positive anomaly (darker red in late September) as the intrusion was saltier than normal.

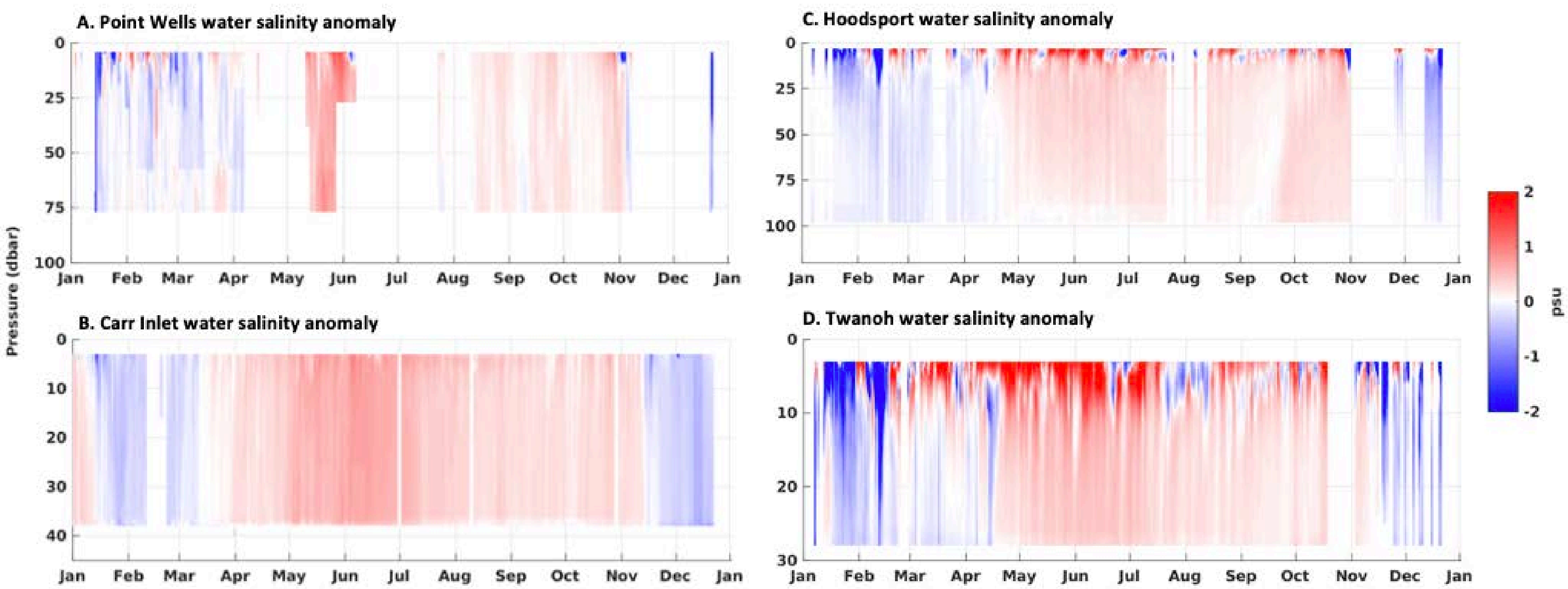


Figure 5.4. Four-panel figure showing pressure-time colormaps of salinity anomalies in 2021 relative to the climatological average over 2005-2017. Pressure (or depth) is shown on the y-axis and time in monthly increments on the x-axis between January 2021 and December 2021 at four ORCA mooring sites: Point Wells in Main Basin (A), Carr Inlet in South Sound (B), Hoodsport in mid-Hood Canal (C) and Twanoh in South Hood Canal (D).

Orcas Island. Photo: Rachel Wold

B.iii. Dissolved oxygen

Source: Jan Newton (janewton@uw.edu), John Mickett, Beth Curry, Dana Manalang, and Roxanne Carini (UW, APL); Primary website: http://www.nanoos.org. Website for online data: https://nwem.apl.washington.edu

Dissolved oxygen (DO) in Puget Sound observed from the University of Washington ORCA moorings exhibited strong variation regionally and temporally during 2021. In particular, Hood Canal DO anomalies were substantially lower than the long-term average for most of April through October than the rest of Puget Sound (Figure 5.5). Although DO anomalies varied and records have gaps, in general South Sound and Main Basin (not shown) values tended slightly lower than average during fall but higher the rest of the year. In contrast, DO at the two Hood Canal sites, Hoodsport and Twanoh, was lower than average for much of the year, though no fish kills were reported. Notably, springtime (April-June) negative anomalies were strongest at the depth associated with subsurface chlorophyll maxima (~10 m), possibly implying less photosynthetic production. The negative anomalies shifted positive during July and August. At both Hoodsport and Carr Inlet, the strongest anomalies were observed in surface waters, likely correlated with the presence or absence of phytoplankton blooms.

Unlike 2020, the seasonal oceanic intrusion into Hood Canal during mid-September had higher than average oxygen levels, as seen at Hoodsport. However, at depth this positive anomaly was erased and switched to a negative anomaly by late November.

While hypoxia was evident in South Hood Canal at Twanoh during January (Figure 5.6), it was not severe (>1 mg/L) and generally constrained to depths greater than 20 m. Hypoxia returned in May, was strongest in August and September, then was minimal by November. The termination of hypoxia is quite variable over the record. Hypoxic water shoaled to ~10 m depth in late September, and then to the surface in late October but was not strong at that time and no fish kills were reported. 2021 did not fit the pattern regarding the onset and intensity of hypoxia that has been observed in the record: early onset with strong hypoxia (e.g., 2015-16); medium onset with medium intensity (e.g., 2011 and 2018-20), and later onset with weaker hypoxia (e.g., 2012, 2014, 2017). In contrast, 2021 showed early onset with medium intensity hypoxia.

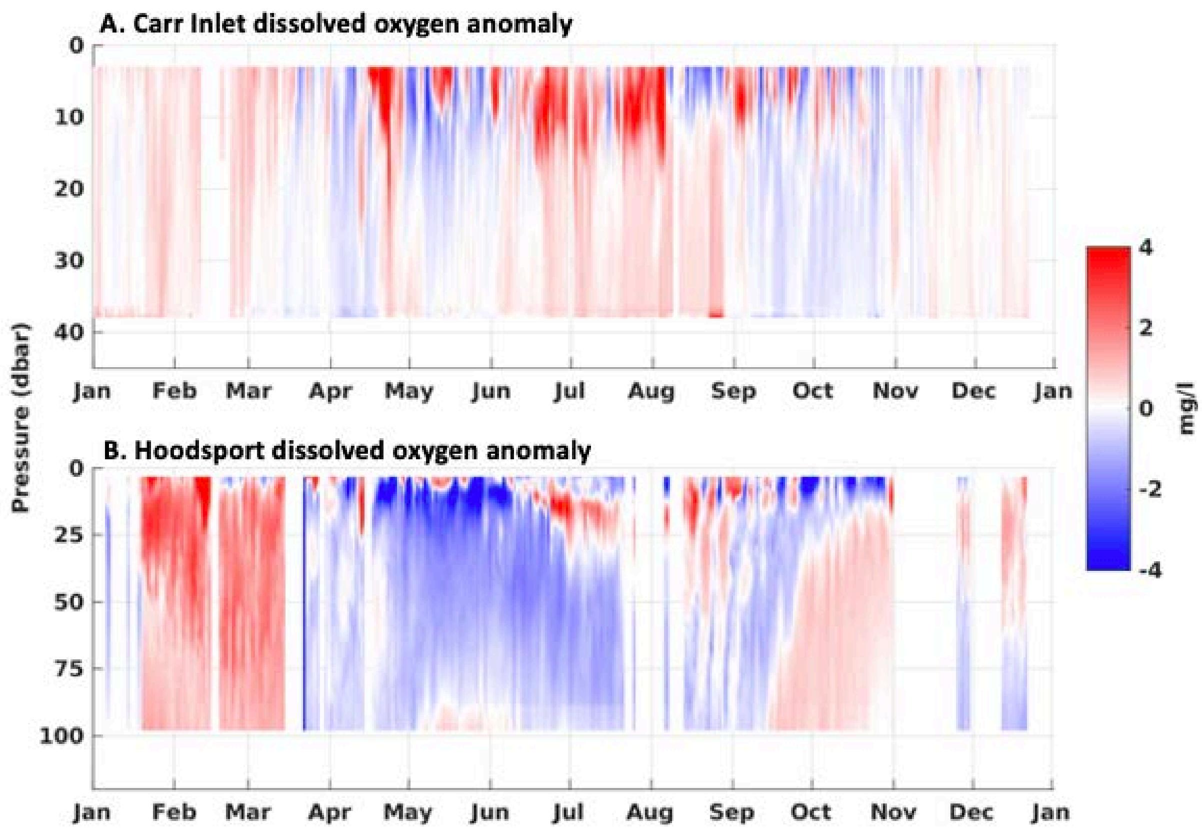


Figure 5.5. Two-panel figure showing pressure-time colormaps of dissolved oxygen anomalies in 2021 relative to the climatological average over 2005-2017. Pressure (or depth) is shown on the y-axis and time in monthly increments on the x-axis between January 2021 and December 2021 at two ORCA mooring sites: Carr Inlet in South Sound (A) and Hoodsport in mid Hood Canal (B).

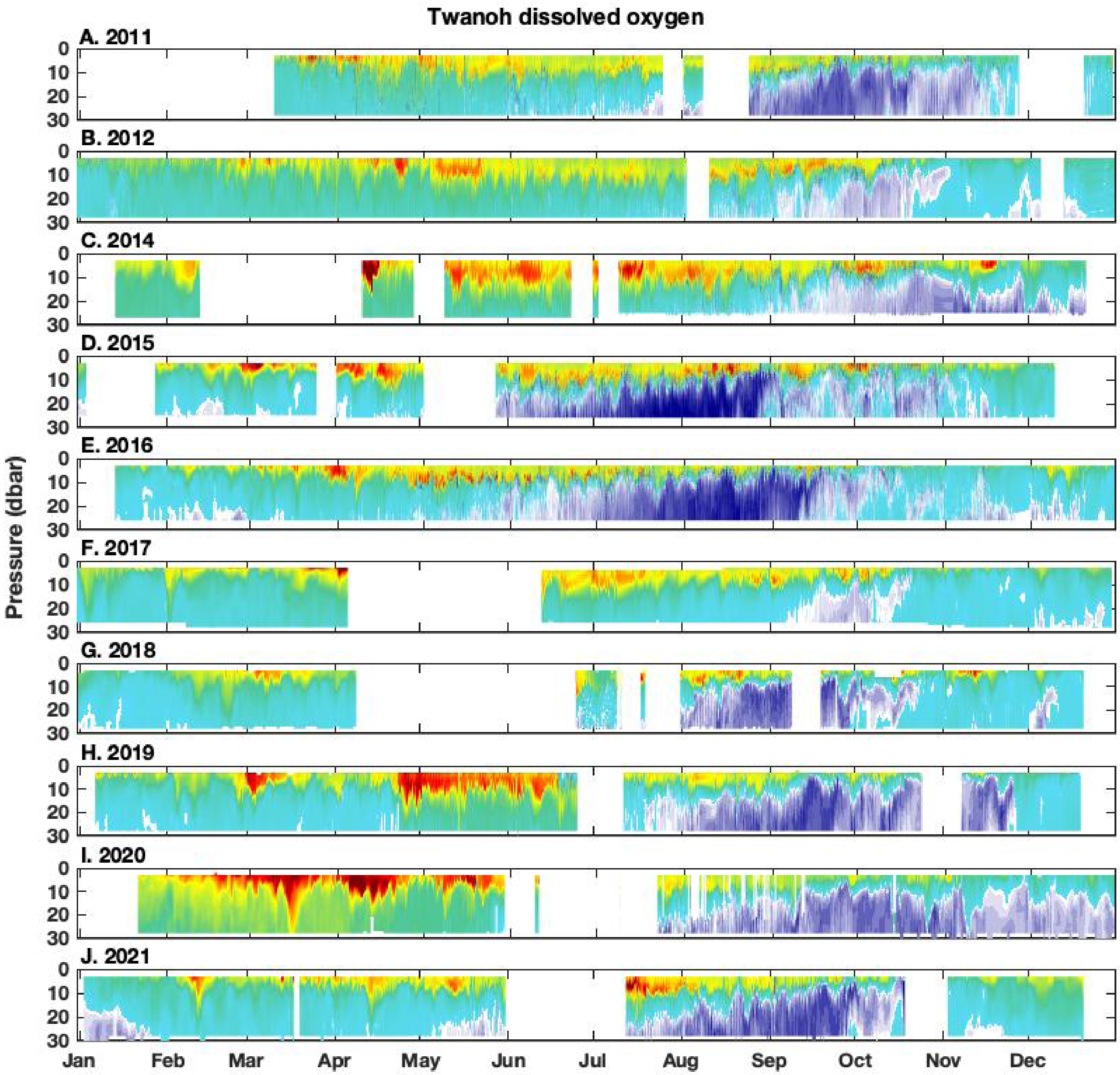


Figure 5.6. Time series of water column dissolved oxygen concentrations at the Twanoh mooring between 2011 and 2021 (not the full record, selected years to fit). Pressure (or depth) is shown on the y-axis and time in monthly increments on the x-axis between January 2021 and December 2021.

B.iv. Ocean and atmospheric CO_2

Ocean acidification

Source: Simone Alin (simone.r.alin@noaa.gov), Adrienne Sutton (NOAA, PMEL), Jan Newton, John Mickett (UW, APL), Sylvia Musielewicz (UW, CICOES), Beth Curry (UW, APL), and Chris Sabine (Univ. Hawaii); Primary website: https://pmel.noaa.gov/CO2/story/Dabob, https://pmel.noaa.gov/CO2/story/Twanoh; websites for online data: https://www.ncei.noaa.gov/data/oceans/ncei/ocads/metadata/0116715.html; https://www.ncei.noaa.gov/data/oceans/ncei/ocads/metadata/0157600.html; PMEL contribution number 5384

Atmospheric (air) and surface seawater xCO_2 (mole fraction of CO_2) have been measured on surface ORCA moorings in Dabob Bay since 2011 and at Twanoh in southern Hood Canal since 2009. Dabob and Twanoh had 84% and 52% preliminary data return in 2021, respectively, with Twanoh lacking measurements May–mid-October (Figure 5.7, Tables 5.1 and 5.2).

During 2021, atmospheric xCO_2 at Dabob spanned 400–488 ppm, with a mean of 426 ppm (Table 5.1). At Twanoh, atmospheric xCO_2 spanned 415–495 ppm, with a mean of 430 ppm (Table 5.2). Mean annual atmospheric values at both moorings were 11-15 ppm higher than the global average of 415 ppm for

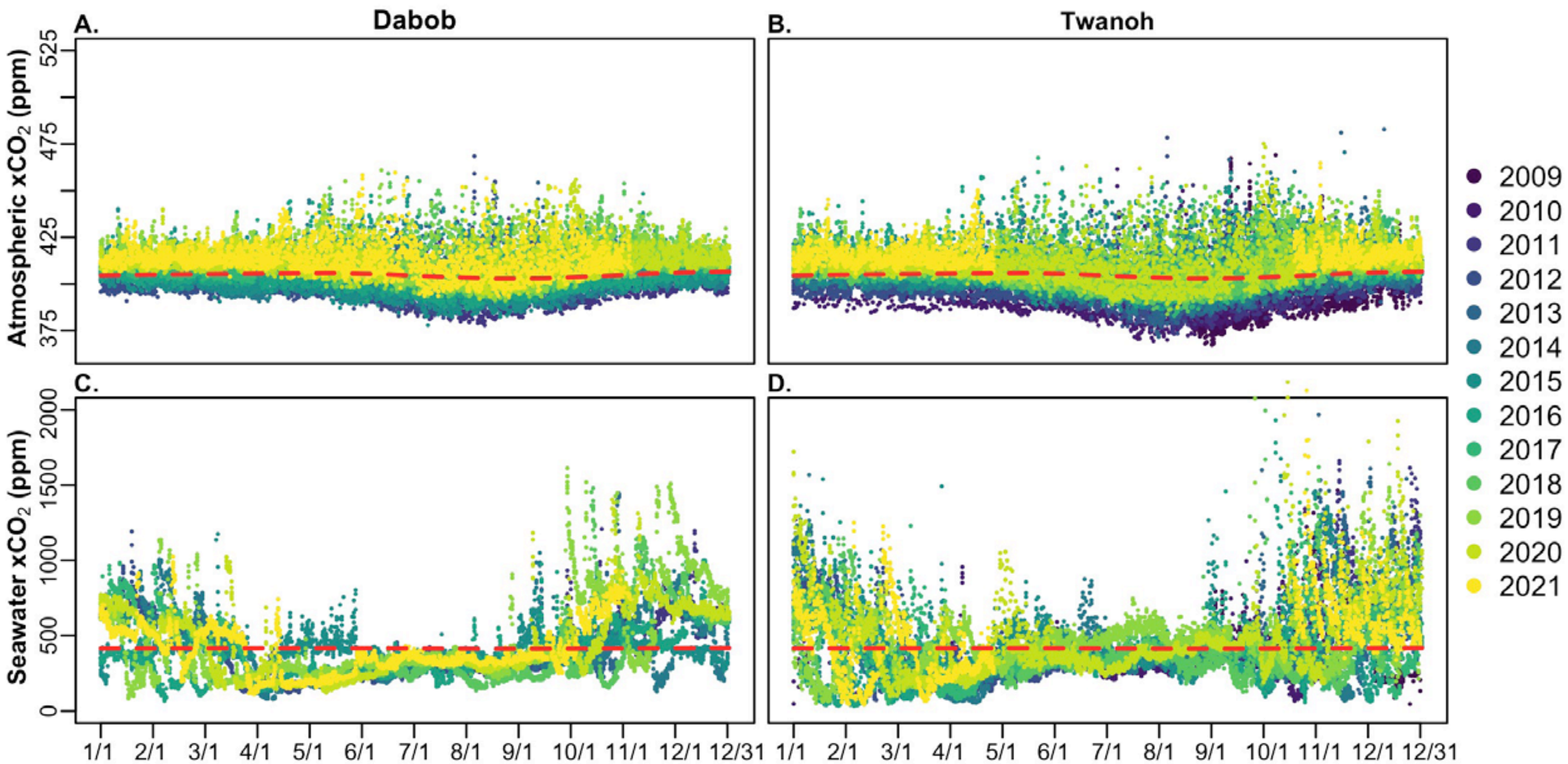


Figure 5.7. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater (A, B) and in surface seawater at 0.5 m depth (C, D) in Dabob Bay (A, C) and at Twanoh (B, D). Typical uncertainty associated with quality-controlled measurements from these systems is <2 ppm for the 100–600 ppm range, increases for values above 600 ppm, and is not well constrained above 1000 ppm. The dashed line in each panel represents monthly mean atmospheric xCO_2 values for globally averaged marine surface air (NOAA/ESRL).

marine surface air (NOAA/ESRL). Values at Dabob have remained flat since 2019, but fit a positive linear trend of increase (slope 2.05 ppm/year; r^2=0.90) when the longer time record is considered. Values at Twanoh were biased high due to the absence of summertime observations.

Similar to coastal moorings, monthly average air xCO_2 values were most enriched compared to the global marine surface air in January–June and September–December (11.6–16.9 ppm above average global values), with July–August having less enriched xCO_2 (but still 5.4–7.5 ppm above the global average) owing to primary production drawing down regional atmospheric CO_2. Using standard deviations as a metric of variability, atmospheric xCO_2 variability was the same as in past years at Dabob, but lower at Twanoh. This lower variability at Twanoh can be attributed to missing summertime observations.

Mean surface seawater xCO_2 in 2021 at Twanoh was the third highest in the time-series, after 2013 and 2011; however, we note that all three years had low data return biased toward higher late summer–fall xCO_2 conditions. In contrast, Dabob surface seawater mean xCO_2 was fourth lowest in its time-series, with much better data return. In 2021, surface seawater xCO_2 spanned 43–2128 ppm at Twanoh and 112–1025 ppm at Dabob. In 2021, surface seawater xCO_2 first declined below atmospheric values for a sustained period in late January at Twanoh and late March at Dabob.

*Table 5.1: Year-round mean surface seawater and atmospheric xCO_2 values at Dabob mooring for all available years in parts per million (ppm). Percent data return provides a simple metric for how much of each year is represented, at a three-hour measurement interval. *A note to end users: it is good practice to always use the most recent year's reports as values can change after data processing and quality control are finished.*

Dabob	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Atmosphere	407 ± 13	409 ± 12	416 ± 15	415 ± 12	413 ± 13	417 ± 11	419 ± 5	425 ± 14	427 ± 12	427 ± 12	426 ± 12
Seawater	416 ± 165	357 ± 182	415 ± 218	395 ± 190	411 ± 93	366 ± 158	579 ± 162	402 ± 253	467 ± 290	457 ± 235	398 ± 162
% data return	56	70	14	93	100	97	22*	65	100	88	84

Table 5.2: Year-round mean surface seawater and atmospheric xCO_2 values at Twanoh mooring in parts per million (ppm). Percent data return provides a simple metric for how much of each year is represented, at a three-hour measurement interval.

Twanoh	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Atmosphere	401 ± 20	401 ± 16	409 ± 16	407 ± 12	415 ± 18	417 ± 14	420 ± 14	421 ± 13	420 ± 13	421 ± 14	424 ± 13	425 ± 14	430 ± 9
Seawater	414 ± 158	342 ± 153	509 ± 283	374 ± 207	542 ± 312	424 ± 220	461 ± 242	347 ± 190	414 ± 192	442 ± 233	461 ± 203	494 ± 268	507 ± 268
% data return	53	63	39	60	43	99	100	91	90*	76*	96*	96	52

C. Central Basin long-term stations

Puget Sound's Central Basin extends southward from Whidbey Island to Commencement Bay. At its northern end it connects with Admiralty Inlet and the Whidbey Basin, and at the southern end it connects via The Narrows to the Southern Basin. King County collects physical, chemical, and biological data twice a month at 12 open-water sites and two sites in Quartermaster Harbor in addition to monthly temperature, salinity, nutrient, and bacteria data at 20 marine beach sites. Physical and biological data are also collected at four mooring locations.

C.i. Temperature, salinity, and density

Temperature

Source: Taylor Martin (taymartin@kingcounty.gov) and Greg Ikeda (King County); Primary website: https://green2.kingcounty.gov/marine Website for online data: https://green2.kingcounty.gov/marine/Download

As part of King County's routine monitoring program, monthly water column profiles were conducted at three deep water stations in Central Basin (i.e. Point Jefferson, Dolphin Point, South Plant Outfall). Water temperatures in 2021 were frequently warmer than the 1998–2013 monthly baseline mean (Figure 5.8A and D), particularly in January–February and August–December at Point Jefferson. Observations indicate that this is representative of the other mainstem Central Basin stations. Surface waters were anomalously warm in late spring and summer, which coincided with a heat dome at the end of June. At the three deeper stations, temperature anomalies ranged from +0.02 to +0.72 °C at the surface (0–35 m depth-averaged) and -0.19 to 1.70 °C at >175 m. The deep temperature anomaly was highest in December, similar to values during the 2014–2016 marine heat wave (Figure 5.8D).

Salinity throughout the water column in early 2021 started out lower than the 1998–2013 baseline and after April shifted to slightly higher than the baseline for much of the year (Figure 5.8B and E). In November, very high rainfall led to much lower salinity at the surface, which gradually propagated to deeper waters in November–December. At the three deep stations, salinity anomalies ranged from -1.36 to +0.24 PSU at the surface and -0.20 to +0.38 PSU at depth.

Deep water in 2021 was relatively dense from April–July (Figure 5.8C), which is unusual compared to previous years. Deep water was densest in September–November, corresponding to the intrusion of water from the Pacific Ocean. Surface densities were low in May–June and November–December (Figure 5.8C). Stratification, measured by standardized potential energy anomaly (Simpson and Hunter, 1974; Hamade and Kim, 2021), was also high during those periods (Figure 5.8F). Values in the spring were similar to those seen in 2017, which was another year with significant stratification. The high stratification values in November–December 2021 were some of the highest for the period of record.

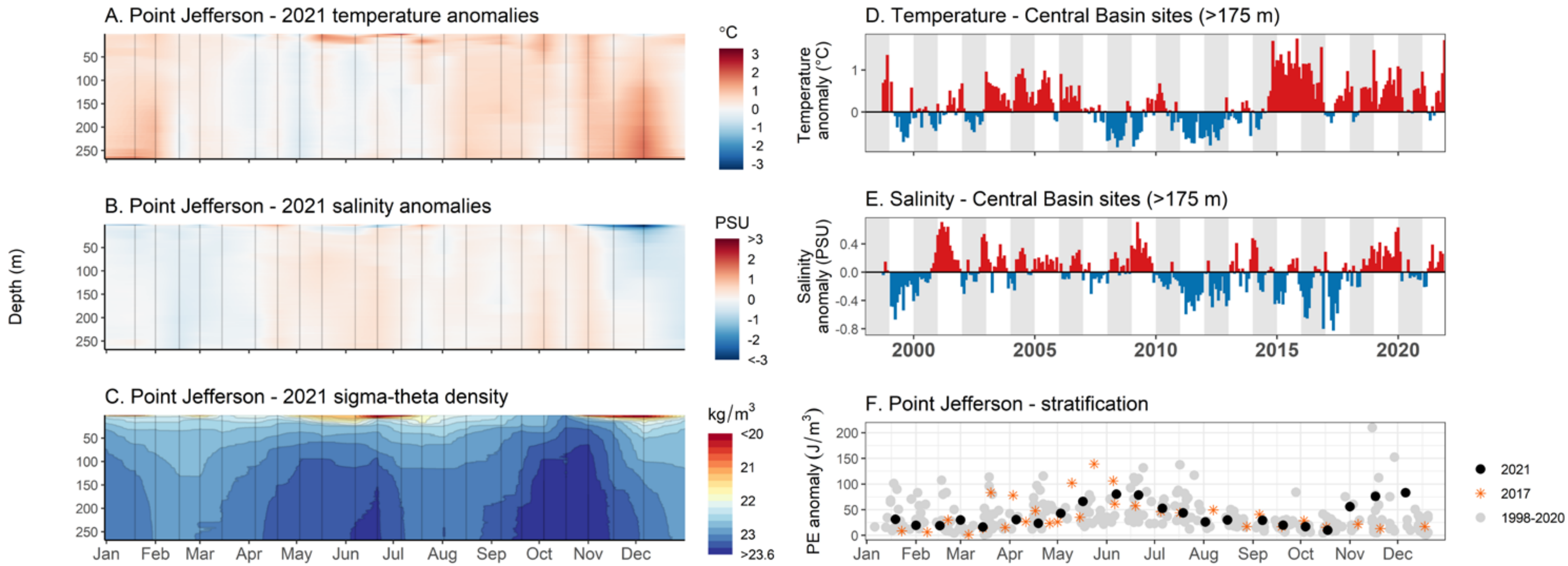


Figure 5.8. (A) Contour plot of temperature (°C) anomalies in 2021 at the deepest Central Basin station (Point Jefferson) calculated from the difference between observations and a monthly baseline mean for the period 1998–2013. Vertical lines indicate when data were collected. (B) As in A, but for salinity (PSU). (C) Contour plot of water column sigma-theta density (kg/m^3) at Point Jefferson in 2021. Contour intervals are 0.2 kg/m^3. Vertical lines as in A.

(D) Monthly mean deep water (>175 m) temperature anomalies at the three deepest Central Basin stations (Point Jefferson, Dolphin Point, and South Plant Outfall) calculated from the difference between observations and a monthly baseline mean by month for the period 1998–2013. Background shading separates individual years. Positive values (in red) indicate higher than normal temperature, and negative values (in blue) indicate lower than normal temperature. (E) As in D, but for salinity. (F) Scatter plot of Simpson's potential energy (PE) anomaly, standardized to average water column depth, at Point Jefferson. Black points are from 2021, orange stars from 2017 (a highly stratified year), and gray points from other years 1998–2020.

C.ii. Dissolved oxygen

Dissolved oxygen

Source: Taylor Martin (taymartin@kingcounty.gov) and Greg Ikeda (King County); Primary website: https://green2.kingcounty.gov/marine. *Website for online data: https://green2.kingcounty.gov/marine/Download*

Dissolved oxygen (DO) was monitored at multiple Central Basin sites, including Point Jefferson, Dolphin Point, South Plant Outfall, and the shallow and poorly flushed Quartermaster Harbor. Central Basin water column dissolved oxygen in 2021 was lower than the 1998–2013 baseline throughout most of the year at Point Jefferson (Figure 5.9A), which is representative of the pattern observed at other stations. There were large positive anomalies at the surface during the spring and summer, corresponding with phytoplankton blooms. Monthly DO anomalies at three long-term Central Basin sites ranged from -0.5 (September) to +0.5 (June) mg/L at the surface (0–35 m depth-averaged) and from -0.7 (December) to +0.2 (April) mg/L at depths greater than 175 m (Figure 5.9C and D). Deep water DO anomalies were mostly negative throughout the year, similar to 2020 and other recent years.

Dissolved oxygen in Quartermaster Harbor peaked later in the spring than in 2020 (Figure 5.9B). This initial peak occurred in early April and was lower than previous years and lower than a second peak that followed in late April. DO throughout the spring and early summer was similar to previous years. DO began to dip below 5 mg/L in August, and occasionally fell below 2 mg/L (i.e., waters were hypoxic) in September and October, more frequently than observed in 2020. DO increased through November and stayed higher than many previous years through December. Compared to the 2006–2013 baseline, DO at the surface was mostly higher than normal throughout the year with anomalies ranging from -1.8 mg/L in March to 3.6 mg/L in April (Figure 5.9E). Water column DO at 2–7 m (tide-dependent) was lower than normal in the summer and early fall, with anomalies ranging from -3.5 mg/L in August to 3.4 mg/L in April (Figure 5.9F).

Whidbey Island. Photo: Rachel Wold

5. Water quality (cont.)

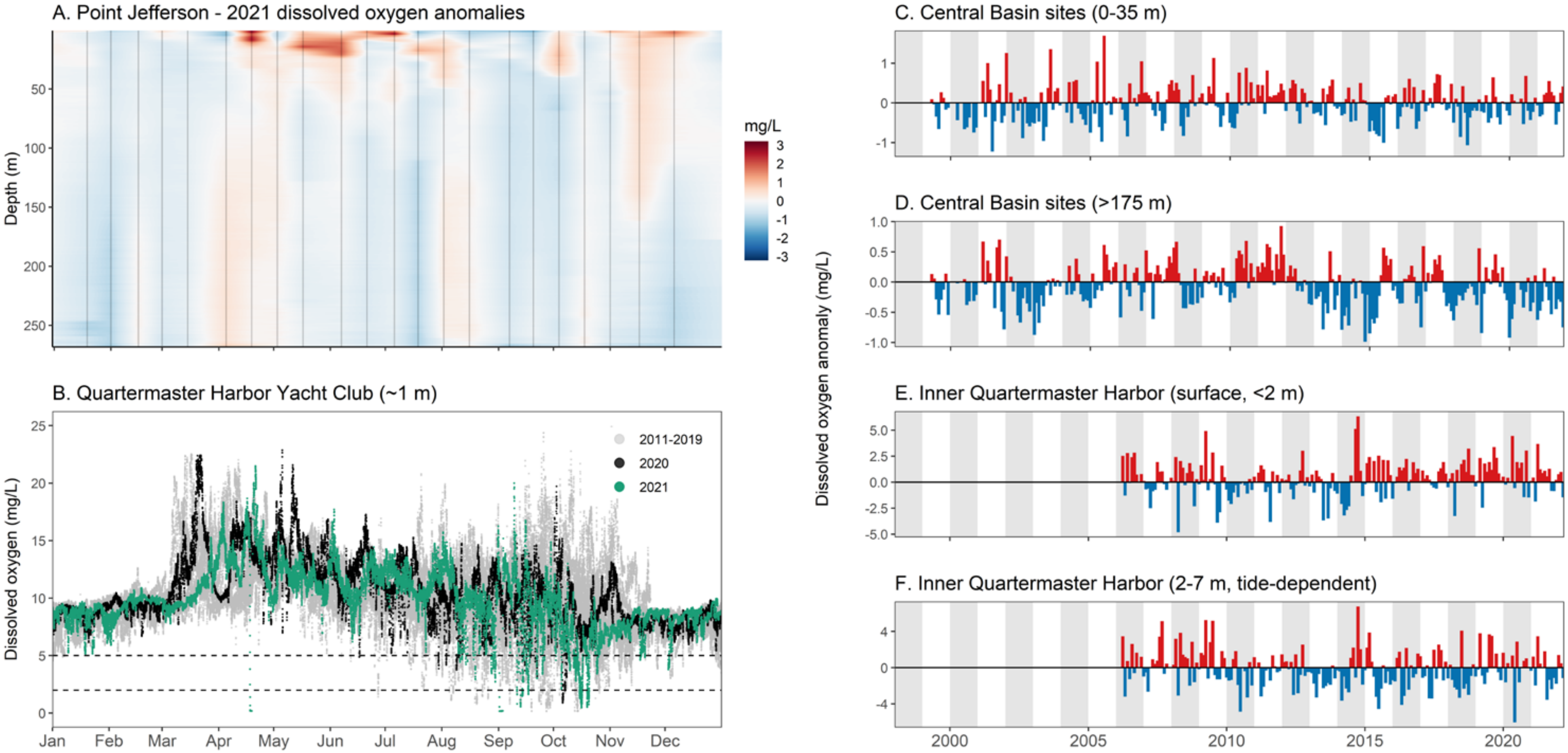


Figure 5.9. (A) Contour plot of dissolved oxygen anomalies (mg/L) in 2021 at the deepest Central Basin station (Point Jefferson) calculated from the difference between observations and a monthly baseline mean for the period 1998–2013. Vertical lines indicate when data were collected. (B) Time series of 15-minute dissolved oxygen measurements at the Quartermaster Harbor Yacht Club mooring in 2021 (green), 2020 (black) and 2011-2019 (gray). Dashed lines represent dissolved oxygen concentrations of 5 mg/L and 2 mg/L. (C) Monthly mean surface water (0–35 m) dissolved oxygen anomalies at the three deepest Central Basin stations (Point Jefferson, Dolphin Point, and South Plant Outfall) calculated from the difference between observations and a monthly baseline mean by month for the period 1998–2013. Background shading separates individual years. Positive values (in red) indicate higher than normal dissolved oxygen, and negative values (in blue) indicate lower than normal dissolved oxygen. (D) As in C, but for depths >175 m. (E) Monthly mean surface (<2 m) dissolved oxygen anomalies from samples collected in Inner Quartermaster Harbor, calculated from a difference between observations and a monthly baseline mean by month for the period 2006-2013. (F) As in E, but for subsurface (2–7 m, depending on tide) samples collected in Inner Quartermaster Harbor.

5. Water quality (cont.)

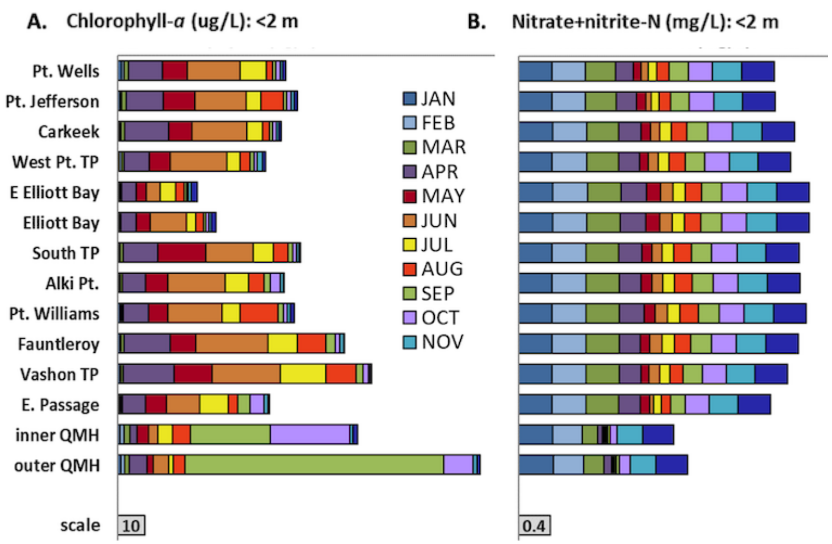
C.iii. Nutrients and chlorophyll

Nutrients *Source: Kim Stark (kimberle.stark@kingcounty.gov) (KCDNRP); Primary website: https://green2.kingcounty.gov/marine; Website for online data: https://green2.kingcounty.gov/marine*

Central Basin 2021 chlorophyll-*a* data from twice monthly sampling indicate that levels were typical of recent years (data not shown), except for decreasing levels at East Passage and in Quartermaster Harbor. This decrease in chlorophyll-a at these locations has occurred since 2018. A pronounced spatial gradient with decreasing levels from north to south was seen in 2021, which was not apparent in past years. The main spring phytoplankton bloom was evident in mid-April throughout the basin with very high June chlorophyll-*a* levels, mainly due to the diatom *Rhizosolenia* spp (Figure 5.10A). Influenced by strong density stratification, sustained chlorophyll-*a* levels occurred at some sites spring through summer, but the period of elevated productivity in the main stem ended in early August with no fall bloom. A large and unusual golden flagellate bloom occurred in outer Quartermaster Harbor in early September that resulted in very high chlorophyll-*a* levels.

Low dissolved nutrients (nitrate+nitrite-N, ammonia-N, silica, and orthophosphate-P) in surface waters corresponded to high chlorophyll levels and less freshwater input, with the lowest values of the year in June and July (Figure 5.10b). Nitrate+nitrite-N was below detectable levels in late May at north and south stations and in June through early July at most stations, which was an unusual occurrence. Nitrate+nitrite-N was below detectable levels from late April through September in Quartermaster Harbor, which is a longer period of depleted nutrient concentrations than observed in past years. Following the high chlorophyll-*a* biomass in June, silica was also below or near detectable levels at northern sites in early July, a rare occurrence. Ammonia-N and orthophosphate-P were also below or just above detectable levels during this time.

Nitrate+nitrite-N concentrations in deep waters (>150 m) remained higher than the 1997-2013 baseline throughout most of 2021 except for April, May, and August in the northern basin (Figure 5.10C) but were more variable in other areas. Silica concentrations in deep waters were higher than normal for most of the year at all sites, except spring (see Figure 5.10C).



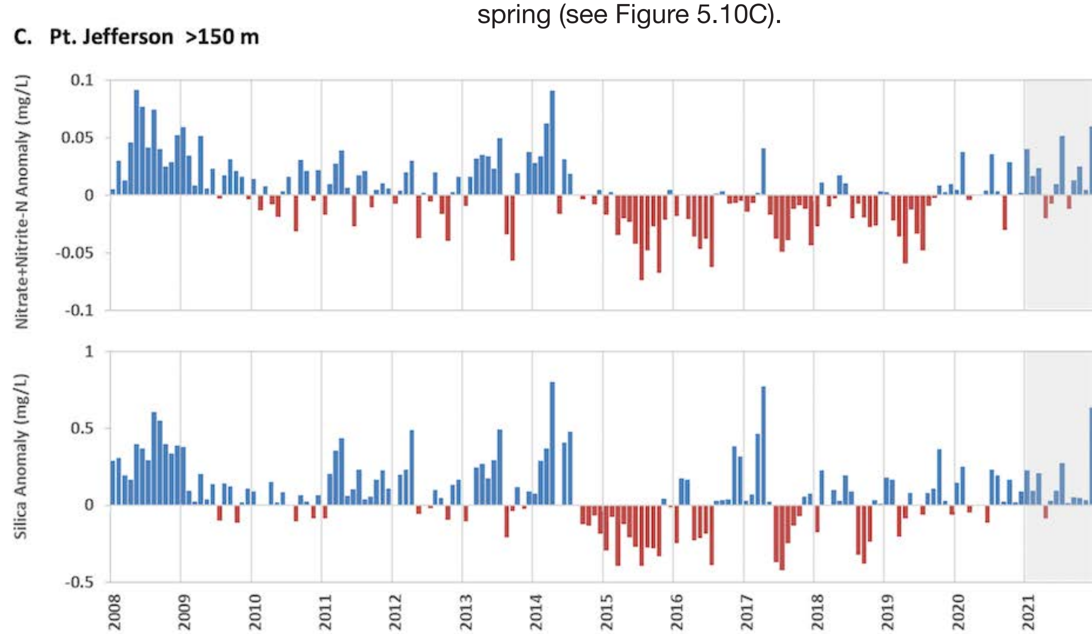


Figure 5.10 (A) 2021 chlorophyll-a monthly averages in surface waters for 14 Central Basin sites ordered north (top) to south (bottom). (B) 2021 nitrate+nitrite-N monthly averages in surface waters for 14 Central Basin sites. (C) Nitrate+nitrite-N and silica monthly anomalies (compared to 1997-2013 baseline) for deep water at Pt. Jefferson. 2021 is shaded gray.

D. North Sound surveys

D.i. Padilla Bay temperature

Temperature

Padilla Bay is a tidally influenced shallow (<5 m) embayment north of Puget Sound and part of the National Estuarine Research Reserve System (NERRS). The Reserve maintains a long-term monitoring program (>20 years) at four stations throughout the bay that represent a range of conditions and nearshore habitats, including eelgrass meadows and deeper marine-dominated open water channels. High frequency (15-minute interval) monitoring data reveal trends in water column structure, plankton community dynamics, and water-quality parameters such as dissolved oxygen, pH, salinity, and temperature.

Source: Keiley Munsterman (kmunsterman@padillabay.gov), Jude Apple, Sylvia Yang, Nicole Burnett, and Heath Bohlman (Padilla Bay NERR/Ecology)
Primary website: www.padillabay.gov
Website for online data: https://cdmo.baruch.sc.edu/dges

Continuous monitoring of nearshore surface-waters in Padilla Bay reveals temperatures ranging from -0.9 to 25.5°C throughout the year, with daily fluctuations approaching 10°C during summer months (data not shown). These large variations tend to occur in July–August during periods of high tidal exchange, where colder water of marine origin is introduced to the otherwise warm water overlying extensive eelgrass meadows and tidal flats. Mean annual water temperature (±SE) in 2021 (10.8 ± 0.2°C) was comparable to 2017 (10.8°C) and 2020 (10.9°C), and lower than 2015 (11.7°C), 2016 (11.5°C), 2018 (11.2°C), and 2019 (11.5°C). Throughout the year, water temperatures were generally well aligned with long-term daily means, with some noticeable exceptions of unseasonably low temperatures in February and December, and elevated temperatures in late June (Figure 5.11A). The combination of cooler and warmer periods resulted in an annual mean temperature anomaly for 2021 that was slightly positive (0.31°C) and similar to the previous two years (Figure 5.11B)

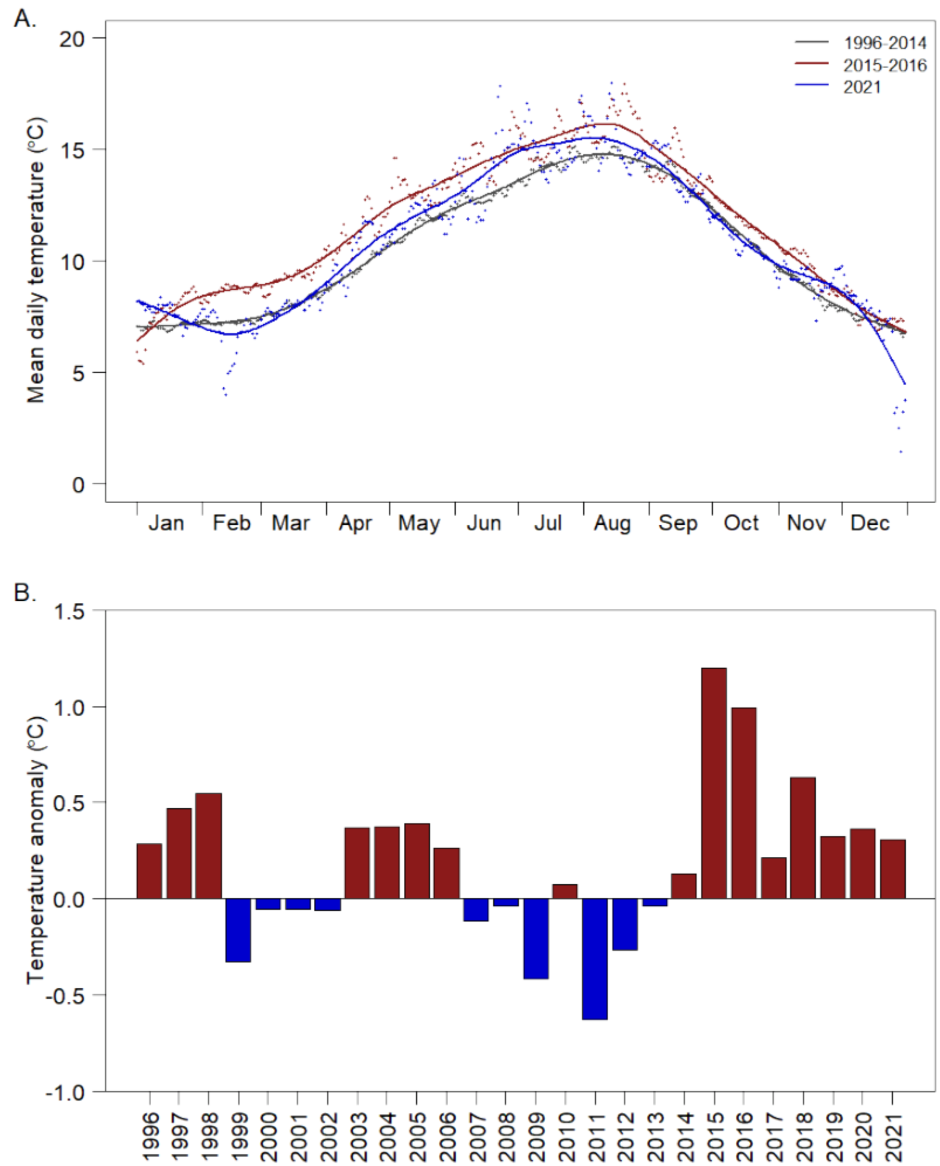


Figure 5.11. Long-term patterns in temperature in Padilla Bay, including (A) comparison of daily mean temperatures in 2015-2016, 2021 and long-term (1996-2014) daily mean, and (B) long-term annual temperature anomalies.

D.ii. Padilla Bay water column characteristics

Dissolved oxygen
Temperature

Source: Keiley Munsterman (kmunsterman@padillabay.gov), Jude Apple, Sylvia Yang, Nicole Burnett, and Heath Bohlman (Padilla Bay NERR/Ecology)
Primary website: www.padillabay.gov

Researchers at the Padilla Bay National Estuarine Research Reserve (NERR) have conducted monthly water column profiles at Gong Buoy since 2015. Gong Buoy is located in approximately 20 m of water in the northwest region of Padilla Bay. These long-term data provide an opportunity to identify interactions between water column structure, water chemistry, and biological processes throughout the year. In 2021, there were three noteworthy instances related to water column density. In March, a fresh period occurred in which salinity levels were low throughout the water column. A few months later, pronounced stratification was observed July through September (Figure 5.12A). This summer stratification occurs on an annual basis along with lower salinity levels and warmer surface temperature. A third fresh period occurred in November when salinity levels were lower than previous years and which correlated with a major local flooding event (Figure 5.12A-B). In general, summer stratification was less pronounced and exhibited a smaller range in densities than previous years, but stratification occurred more frequently than previous years due to the additional fresh period in November. These patterns in water column structure influenced biological activity and water quality parameters. Chlorophyll, dissolved oxygen, and pH were moderate in the beginning of the year and were elevated March through September (Figure 5.12D-F). See section 6.A.ii. Padilla Bay phytoplankton on page 40 for further information on chlorophyll trends. Patterns in dissolved oxygen and pH were coupled with these changes in biological activity, with higher values observed during periods of elevated chlorophyll and algal biomass (Figure 5.12E-F). Lower algal biomass in the fall (i.e. October) combined with water column mixing resulted in generally lower dissolved oxygen and pH throughout the water column. Seasonal variation reveals a strong relationship between water column structure, phytoplankton abundance and water chemistry in Padilla Bay.

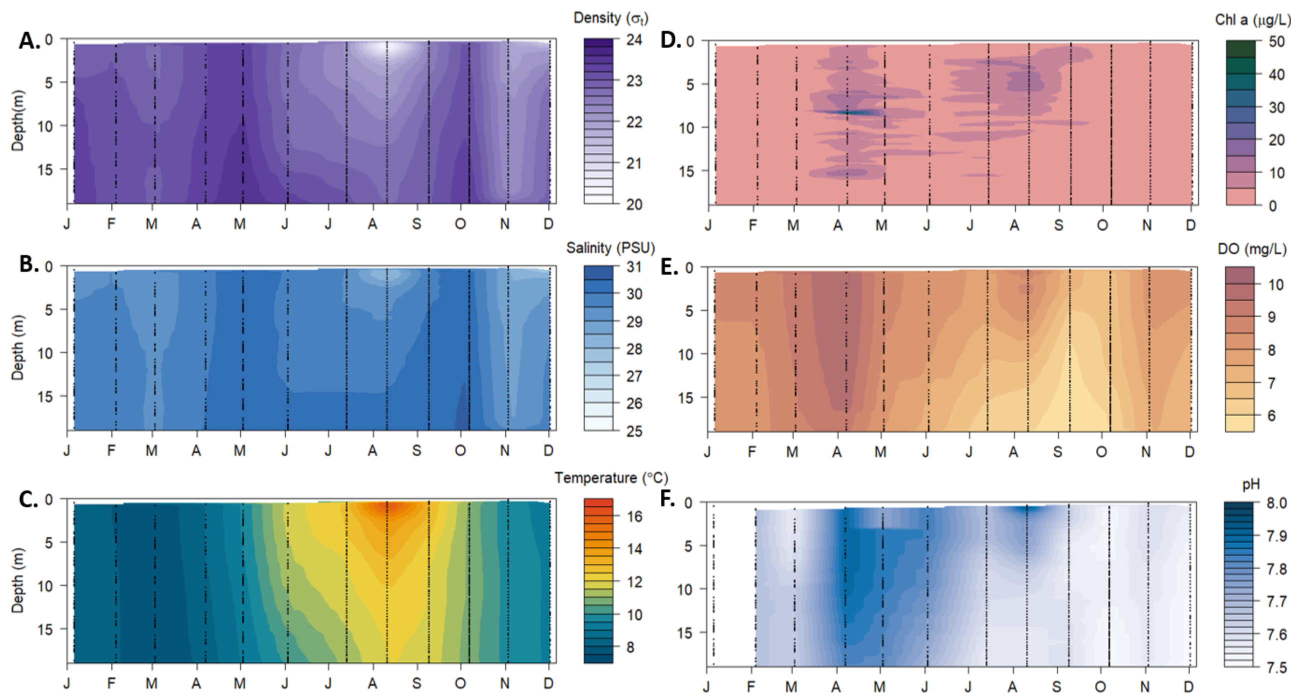


Figure 5.12. Water column profiles derived from monthly sampling at Gong Buoy illustrating patterns in (A) density, (B) salinity, (C) temperature, (D) chlorophyll fluorescence, (E) dissolved oxygen, and (F) pH.

D.iii. Port Susan buoy

Dissolved oxygen
Temperature

Source: Franchesca Perez (fperez@stillaguamish.com) and Derek Arterburn (Stillaguamish Tribe of Indians); https://www.stillaguamish.com/natural-resources

Located inside east Whidbey Basin, northern Port Susan is a shallow, semi-enclosed bay that responds rapidly to external forcing, including river inputs and mixing. This highly productive estuary supports populations of forage fish, salmon, Dungeness crab, bivalves, and marine mammals. Since 2011, the Stillaguamish Tribe has collected near-surface water quality measurements from a probe located in the northern part of the bay where it is 13m deep at Mean High Water. In 2019, researchers at the Tribe began conducting monthly water column profiles at 10 stations throughout Port Susan, including the location of the probe deployed in 2011 (Figure 5.13).

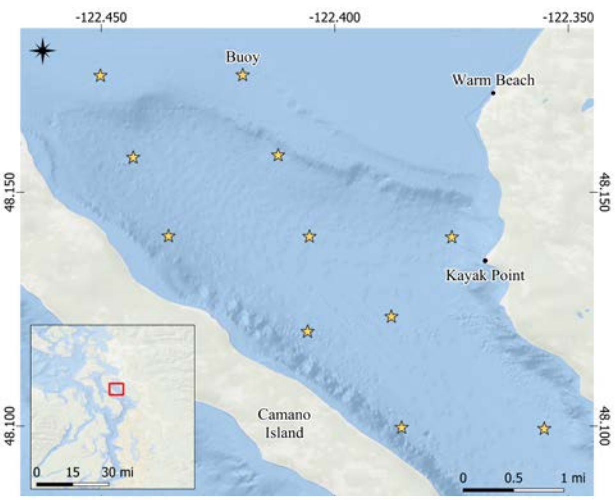


Figure 5.13. Map of Port Susan with stars marking profile stations and buoy location.

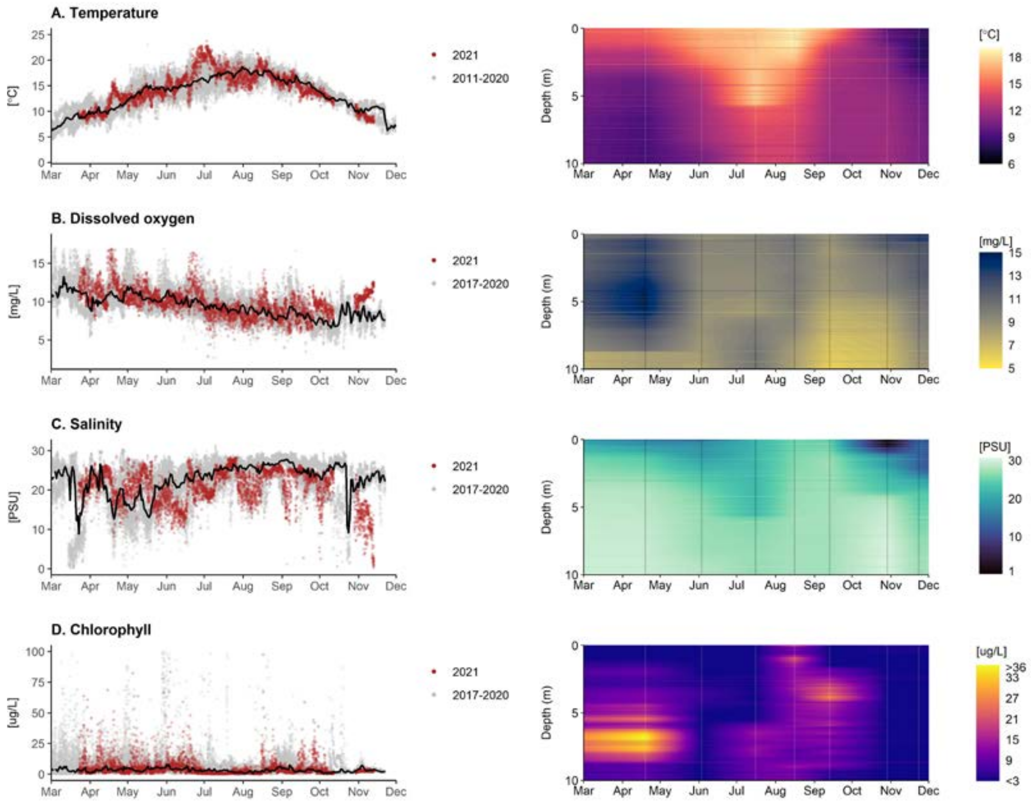


Figure 5.14. Hourly water quality data for near-surface (left panel), and 2021 water column profiles (right panel) from north-central Port Susan Bay: (A) Temperature, (B) Dissolved Oxygen, (C) Salinity, and (D) Chlorophyll. Black lines in scatter plots represent median values over the entire sampling period and black lines in profile graphs represent the day on which the profile was taken.

Salinity measurements reflect the influence of the Stillaguamish River and/or local weather conditions, with low values in late April, May, and September matching increases in river discharge (https://nwis.waterdata.usgs.gov). Water temperatures responded to the extreme heat event of late June. Surface waters reached the highest temperatures in ten years, exceeding 22°C for several days, with water over 15°C persisting in the water column through August.

Port Susan experienced a spring phytoplankton bloom that ended abruptly in late June, as well as several late summer pulses of elevated chlorophyll. The final late summer phytoplankton event consisted of a six-week bloom of the diatom *Ditylum* which persisted into late October, as observed from plankton tows off of Kayak Point Park pier. This bloom was detected at water column profile stations throughout the bay. Smaller blooms occurred in late summer and early fall after periods of wind mixing and/or elevated river discharge, either of which may have enhanced available nutrients, followed by clear, calm days (Paine Field weatherspark.com).

E. Snapshot surveys

Snapshot surveys take place over a short period of time and can provide intensive observations in select regions of interest. When interpreted in the context of more frequent long-term observations, snapshot surveys can reveal processes and variations in water conditions that would not otherwise be detected.

E.i. San Juan Channel/Juan de Fuca fall surveys

Temperature
Marine birds

The University of Washington Friday Harbor Laboratories Research Apprenticeship Program has maintained a time series of pelagic ecosystem variables during fall quarter (September–November) since 2004. Pelagic Ecosystem Function (PEF) research apprentices sample along a transect from station "North" (~100–110 m depth) in the well mixed San Juan Channel, to station "South" (~80– 90 m depth) in the Strait of Juan de Fuca, with two-layer stratification between out-flowing estuarine water and in-flowing oceanic water.

Source: Jan Newton (janewton@uw.edu); Roxanne Carini (UW, APL); Mike Sigler (UW, FHL); and Connor Trentman, Junzhe Liu, Nicole Frederick, and Aidan Cox, (FHL);
Primary website: http://courses.washington.edu/pelecofn;
Website for online data: www.nanoos.org

As part of the Pelagic Ecosystem Function (PEF) study in the San Juan Islands, temperature and salinity anomalies were calculated for both surface (0-5 m) and deep waters (10 m above seabed) at both North (120 m) and South (90 m) stations occupied on ~weekly cruises during fall (September-November) over the last 18 years (2004-2021). During fall 2021, temperature anomalies were warmer than average (Figure 5.15A). In general, since the 2014-2016 marine heatwave, most temperature anomalies have been positive except for 2020 which had several cooler than average anomalies.

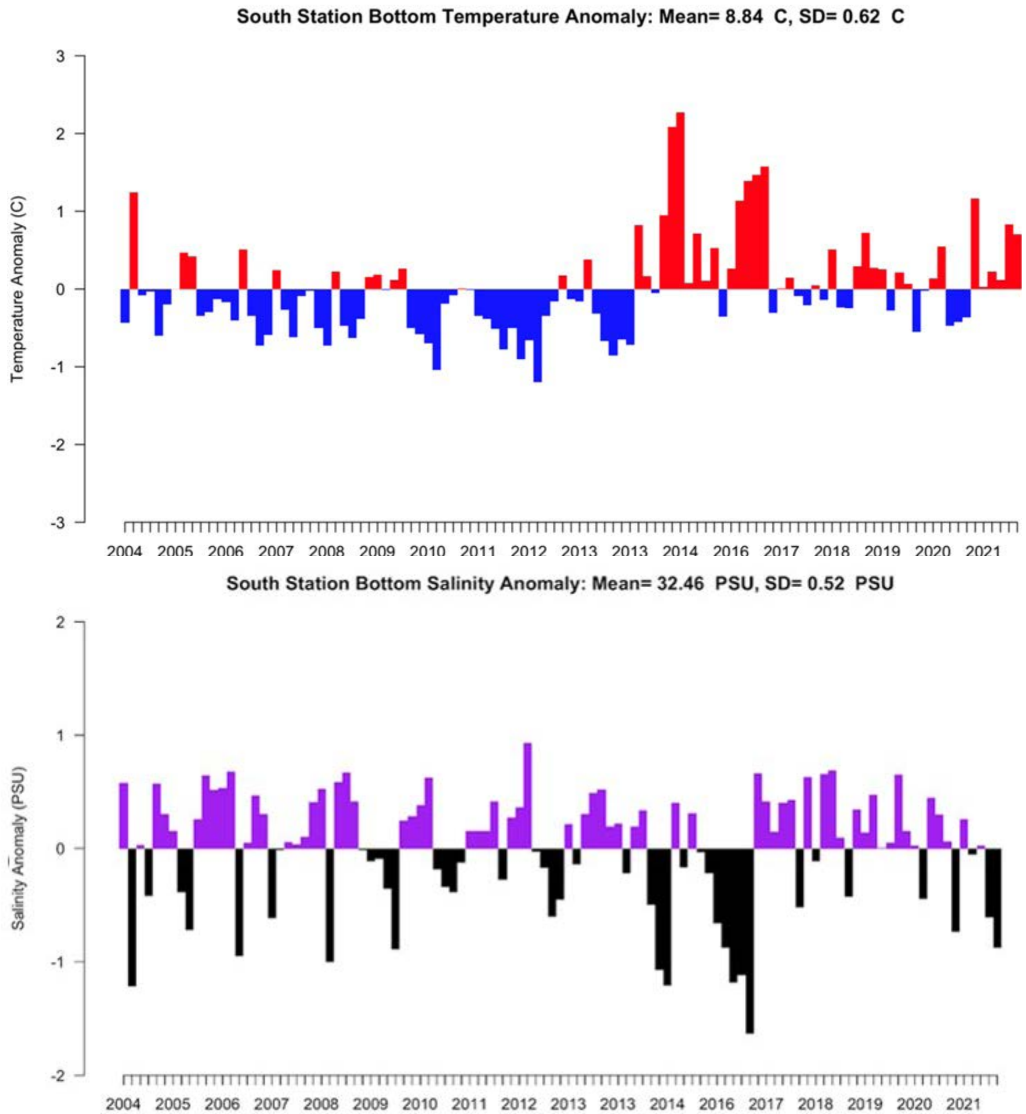


Figure 5.15. (A) Temperature anomalies taken near the bottom of the South Station during fall from 2004 to 2021. Red indicates warmer (positive) temperature anomalies and blue indicates cooler (negative) temperature anomalies. The mean and standard deviation for fall temperature from 2004-2021 was 8.84°C and 0.62°C, respectively. (B) Salinity anomalies taken near the bottom of the South Station during fall from 2004 to 2021. Purple indicates saltier (positive) salinity anomalies and black indicates fresher (negative) salinity anomalies. The mean and standard deviation for fall salinity from 2004-2021 was 32.46 and 0.52 PSU, respectively.

Fall 2021 salinity anomalies were dominated by fresher than average in the latter two cruises (Figure 5.15B). South deep waters show the 2014-2016 marine heatwave years had fresher than average waters, with saltier than average waters in 2017-2020. The 2021 record has the strongest (magnitude and duration) fresher salinity anomaly since 2016.

Fall season temperature versus salinity plots (not shown) for all the years (2004-2021) revealed a sharp difference between pre and post "Blob" marine heat wave years. A water mass defined by temperature 8-8.5°C and salinity 32.5-34 was always seen in years 2004-2013 at the South Station. However, from 2014-2021 it appeared only briefly (two cruises in 2020) and just slightly, indicating a general shift to warmer, though not saltier, fall conditions. The minimum water temperature recorded in 2021 was ~8.8°C, whereas prior to 2014, the fall minima ranged 8.0-8.4°C.

Observations of marine mammals (Harbor seals, Steller sea lions, Harbor porpoise) and seabirds (Figure 5.16) from six weekly repeated transects over fall reveal different interannual patterns. Marine mammals show relatively low densities since and including the marine heatwave year of 2014. 2021 was the lowest on record. Seabirds exhibit a different pattern; the years 2010-2012 had the higher seabird densities of the record, while densities have been consistently lower during other years (2006-2009 and 2013-2021). Seabird density in 2021 was among the higher densities since 2014.

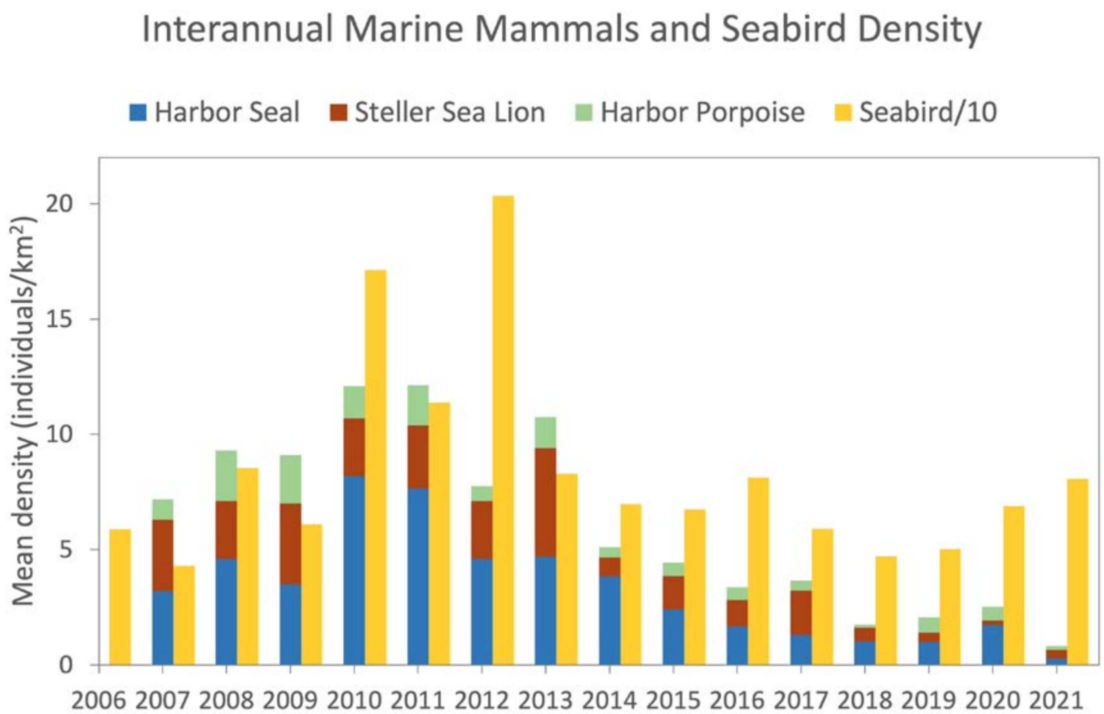


Figure 5.16. Bar graph showing mean density (individuals per square kilometer) from fall surveys conducted from 2006 to 2021 of harbor seals (blue), Steller sea lions (red), harbor porpoises (green), and seabirds (yellow). Seabird densities are scaled by 1/10.

6. Plankton

A. Marine phytoplankton

Marine phytoplankton are microscopic algae that form the base of the marine food web. They are also very sensitive indicators of ecosystem health and change. Because they respond rapidly to a range of chemical and physical conditions, phytoplankton community composition can be used as an indicator of deteriorating or changing ocean conditions that can affect entire ecosystems.

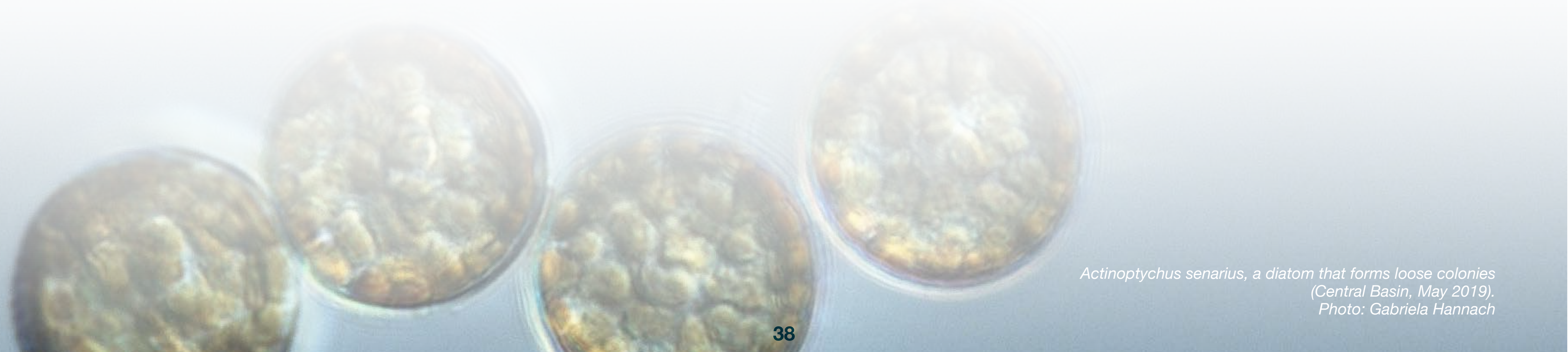
King County analyzes phytoplankton assemblages semi-monthly in the Puget Sound Central Basin. A FlowCAM® particle imaging analyzer has been used since 2014 to assess abundance, biovolume and taxonomic composition of all microplankton particles in the 10-300 µm range.

A.i. Puget Sound

Source: Gabriela Hannach (gabriela.hannach@kingcounty.gov) and Lyndsey Swanson (KCEL); Primary website: https://green2.kingcounty.gov/marine/Monitoring/Phytoplankton
Website for online data: https://data.kingcounty.gov/Environment-Waste- Management/Marine-Phytoplankton-Samples-by- Taxonomic-Group/uydm-m3ym

Ten long-term monitoring stations were sampled in 2021, including nine open water sites and one shallow embayment (Dockton in outer Quartermaster Harbor).

Seven years of biovolume data from surface samples indicate that in 2021 total microplankton biomass was higher than the previous years (Figure 6.1A). *Thalassiosira* spp. typically initiates the spring bloom in Central Basin. However, low biovolumes of *Thalassiosira* spp. were observed as early as mid-February and March (Figure 6.1B). The spring bloom developed in early April, peaked in mid-April (before the water column was fully stratified), and was dominated by *Chaetoceros*, primarily *C. debilis*. A mix of *Chaetoceros* species remained dominant until mid-July. An unusually large bloom of *Rhizosolenia* lasted from early June until mid-July, mixed in with the *Chaetoceros* population. *Rhizosolenia* blooms are common but are usually shorter, such as those recorded in 2017, 2018 and 2020. The mixotrophic dinoflagellate *Akashiwo sanguinea* bloomed briefly in early August following the crash of the diatom population (Figure 6.1C). The heterotrophic dinoflagellate *Noctiluca* was present throughout the 2021 season but in lower numbers than in the previous two years. The 2021 bloom pattern is generally consistent with observations of strong vertical density gradients from May to July (see section 5.C.i. Central Basin temperature, salinity, and density on page 28). With increased mixing, the season ended in mid-August, quite early compared to previous years. There was no fall bloom except for the presence of large single cells of *Coscinodiscus* spp. coinciding with a period of unusually low surface salinity. (Note that due to their size, these cells were not fully quantified by the FlowCAM method). *Coscinodiscus* spp. have been noted previously during the colder months.



Actinoptychus senarius, a diatom that forms loose colonies (Central Basin, May 2019). Photo: Gabriela Hannach

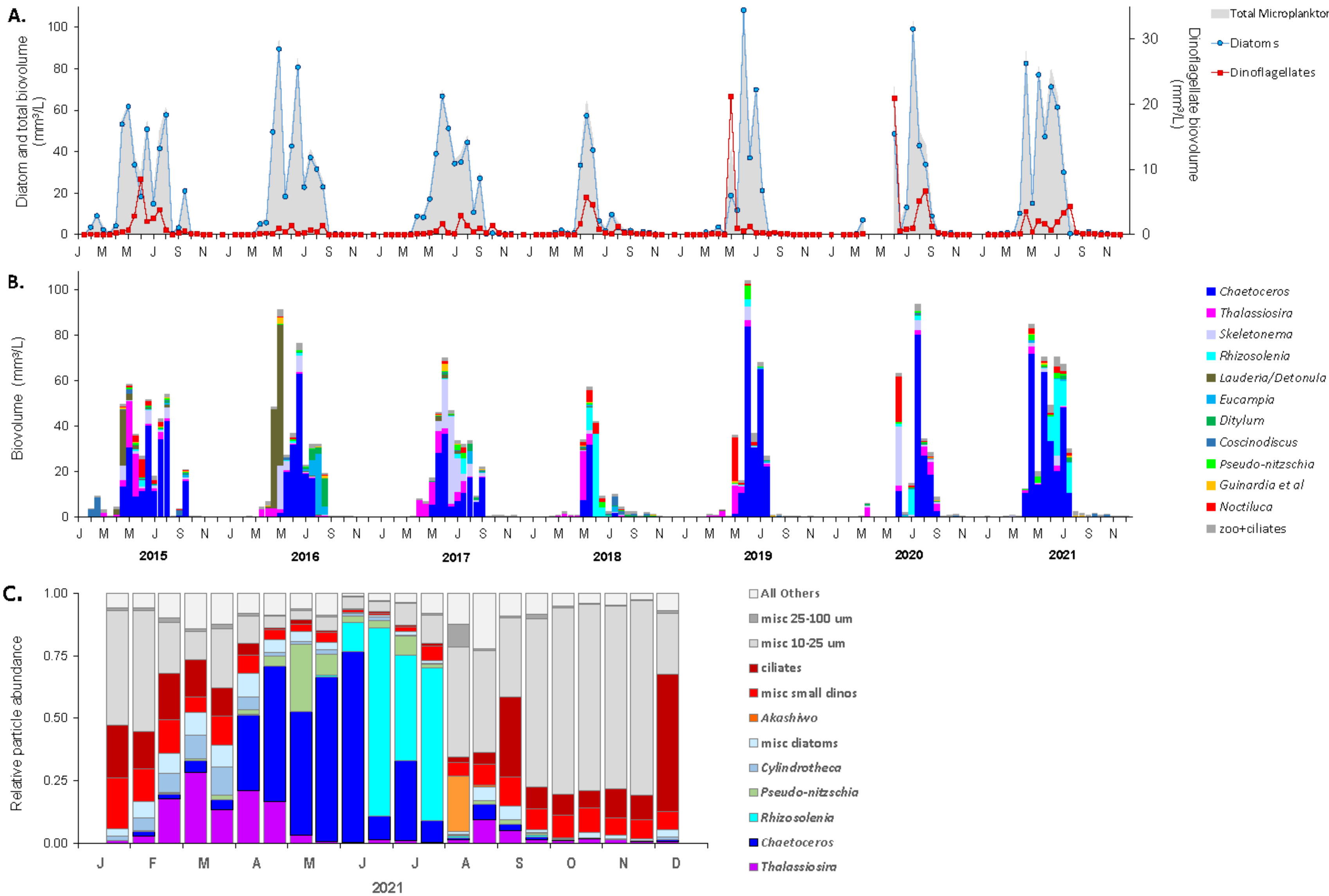


Figure 6.1. (A) Total microplankton biovolume (gray area) and biovolume of main phytoplankton groups, and (B) biovolumes of each year's top six taxa identified using FlowCAM between 2015 and 2021. (C) Relative abundance of taxonomic categories that contributed at least 10% in each sampling event during 2021. Plotted values in (A) are means for seven long term stations (Alki CSO, Vashon outfall and Dockton excluded); values in (B,C) represent nine open water sites (Dockton excluded). Note that "Particle abundance" may refer to whole chains, fragments, or individual cells, and is not indicative of cell density except for non-colonial taxa.

A.ii. Padilla Bay

Source: Keiley Munsterman (kmunsterman@padillabay.gov), Nicole Burnett, Heath Bohlmann, Jude Apple, and Sylvia Yang (Padilla Bay NERR/Ecology); www.padillabay.gov

Padilla Bay National Estuarine Research Reserve has monitored *in-situ* chlorophyll since 2016 and phytoplankton community composition since 2019. *In-situ* chlorophyll fluorescence values are recorded every 15 minutes and phytoplankton are collected monthly using whole-water surface samples. Both chlorophyll and phytoplankton monitoring are conducted in the channel east of Guemes Island, adjacent to Padilla Bay. Timing and persistence of peak chlorophyll and phytoplankton varied throughout the last five years, but typically occurred between May and August. Compared to previous years, chlorophyll levels in 2021 peaked earlier in the year in April and remained elevated through September (Figure 6.2A). April also had the highest total phytoplankton abundance in 2021 (Figure 6.2B), similar to in-situ chlorophyll patterns. In April, *Skeletonema* made up about 45% of the community composition (data not shown). Phytoplankton abundance peaked again in August, and *Chaetoceros* became dominant. *Thalassiosira* did not peak in March as it has done in previous years. *Skeletonema*, *Chaetoceros*, and *Thalassiosira* are three of the most common species found in Padilla Bay. During late fall and winter when phytoplankton abundance was at its lowest, various pennate diatoms increased in relative abundance. Abundance of other taxa, such as dinoflagellates, silicoflagellates, and ciliates remained consistently low throughout the year. In September, dinoflagellates, mostly *Protoperidinium* and *Prorocentrum*, made up over 50% of the community composition.

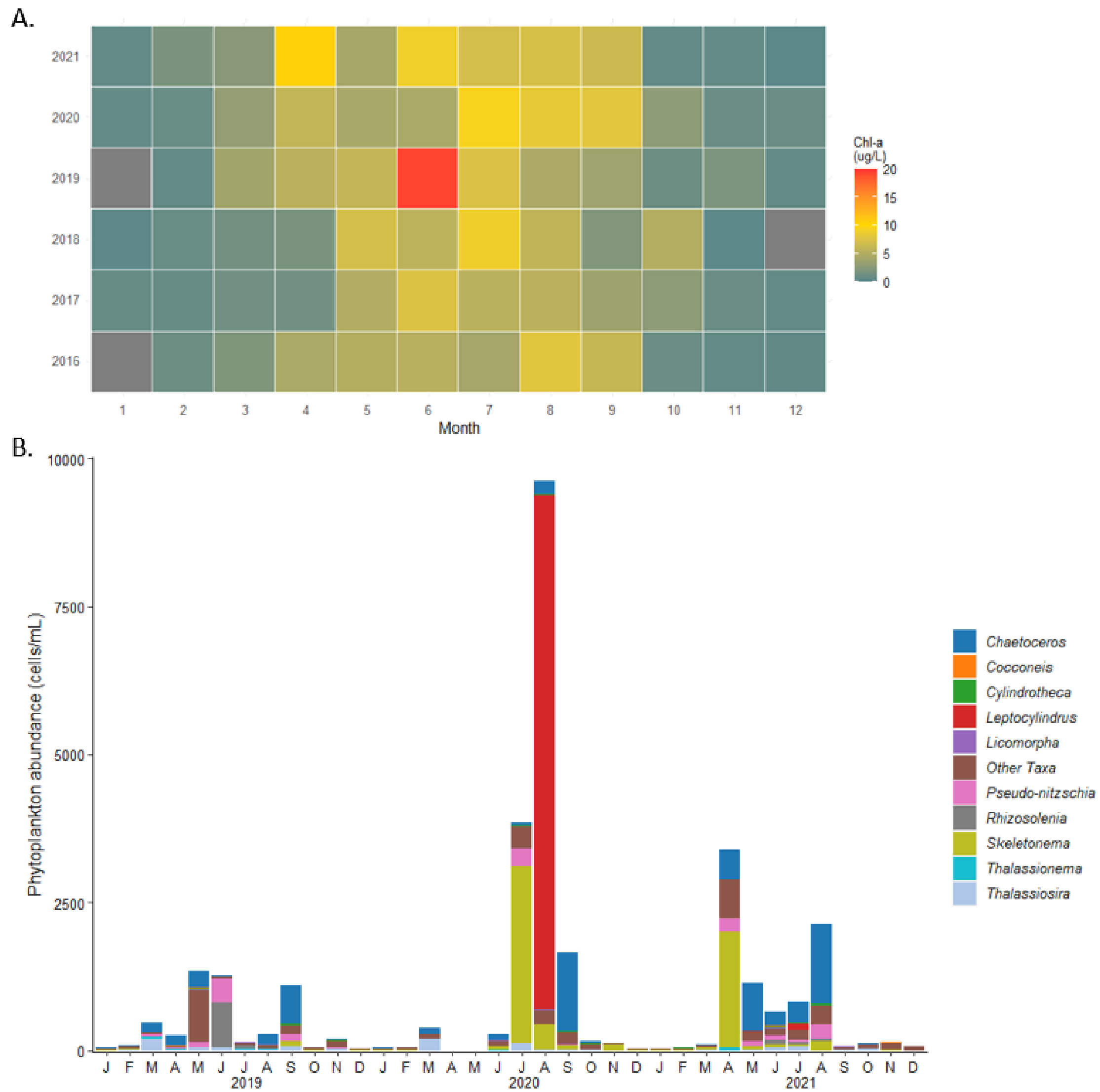


Figure 6.2. (A) Average monthly in-situ chlorophyll-a for 2016–2021. (B) Monthly phytoplankton abundance of the 10 most abundant taxa in 2019–2021. Data missing for April and May of 2020 due to COVID-19.

RV Edna Breazeale on the glassy waters of Padilla Bay.
Photo: Vanessa Jimenez, Padilla Bay NERR

B. Zooplankton

Zooplankton are the (mostly) microscopic animals of the ocean, ranging from tiny crustaceans to jellyfish. They occupy a key role in marine food webs and chemical cycling. Changes in their species diversity and abundance can be used to indicate environmental and anthropogenic changes that are important to marine ecosystems and fisheries. Little historical zooplankton data exists from Puget Sound; monitoring data are required to establish baselines and track the effects of change on Puget Sound ecosystems.

B.i. Puget Sound

Zooplankton

Source: Julie Keister (jkeister@uw.edu), Amanda Winans, and BethElLee Herrmann, (UW, School of Oceanography); Primary website: http://faculty.washington.edu/jkeister; Website for online data: https://green2.kingcounty.gov/ScienceLibrary/Document.aspx?ArticleID=556

Abundances and biomass of mesozooplankton in 2021 from the southern Salish Sea were generally average to moderately low compared to previous years, with a few elevated values (Figure 6.3A, B, C, D). Some of the elevated values extended recent trends or repeated patterns observed earlier in the time series. In the northern Washington regions of the San Juan Islands and Bellingham Bay, the 2019-2020 trend of increased biomass continued into 2021. Large oceanic copepods (*Eucalanus bungii* and *Neocalanus plumchrus*) and a boreal copepod (*Calanus marshallae*) contributed to high spring biomass, while moderately sized copepods (*Pseudocalanus* spp. and *Epilabidocera*

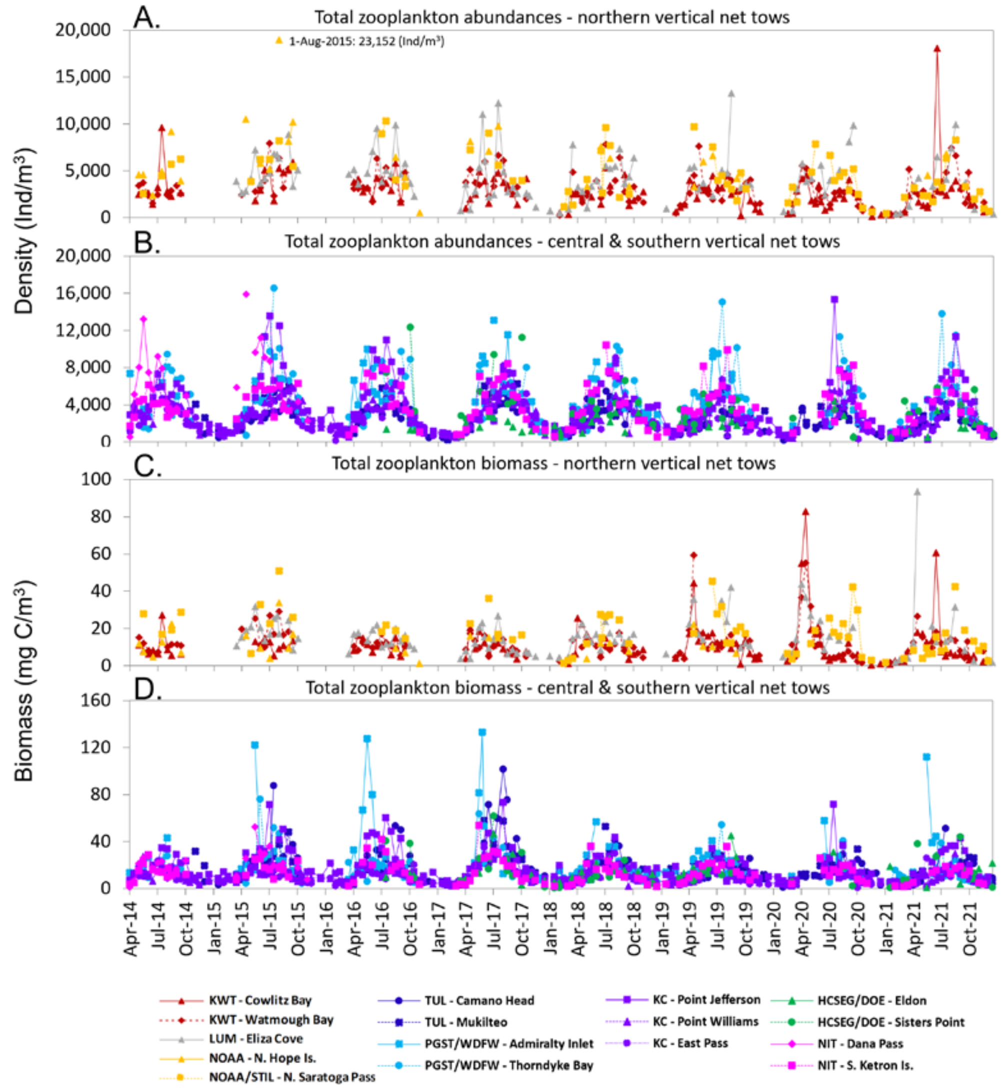


Figure 6.3. Time series of total mesozooplankton abundance (Ind/m³) at northern stations (A) and mid & southern stations (B) in 2014-2021. Note that most stations suspended sampling from mid-March to mid-June due to COVID-19. Time series of total mesozooplankton biomass (mg/m³) at northern stations (C) and southern stations (D) in 2014-2021.

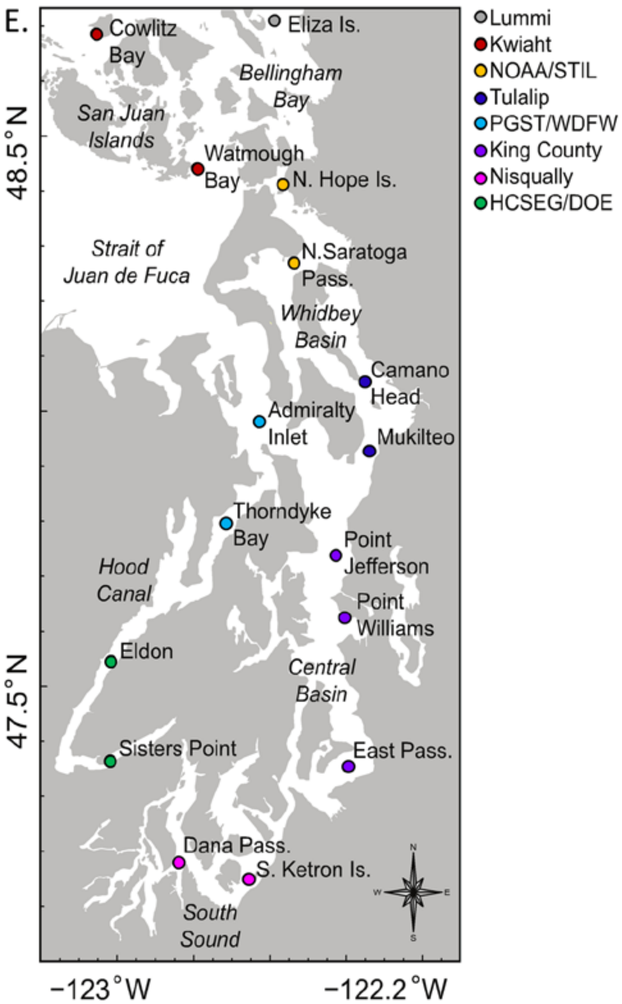


Figure 6.3 (E) Map of the sampling locations. Symbols are color-coded by sampling group and correspond to stations in panels A-D.

longipedata) were responsible for high biomass at Cowlitz Bay in June (Figure 6.3C). The peak biomass at Watmough Bay was lower than in 2019-2020, yet the mid-April biomass value in Bellingham Bay was the highest on record for that station. The high biomass sampled at Admiralty Inlet in May was driven primarily by high abundance of crab larvae, mirroring the record-high values seen in that region in the warm years of 2015-2017 (Figure 6.3D).

Zooplankton sampling was conducted by King County, Nisqually Indian Tribe, Tulalip Tribes, Kwiáht, Lummi Nation (since 2015), Port Gamble S'Klallam Tribe, WA Dept. of Fish and Wildlife (WDFW), NOAA, Hood Canal Salmon Enhancement Group with WA Dept. of Ecology (since late 2016), and Stillaguamish Tribe (since late 2019) (Figure 6.3E). Funding for 2021 sampling was provided by King County and WA DNR through WDFW.

Data shown here were collected with 60-cm diameter, 200-μm mesh plankton nets towed vertically from 5 m off the bottom (or a max. of 200 m) to the surface. Most locations were sampled bi-weekly from mid-March through October. Taxonomy by species and life stage was conducted at UW. *Noctiluca* data are not included here.

The copepod Ditrichocorycaeus anglicus *collected in the Central Basin in January 2020. Photo: Gabriela Hannach*

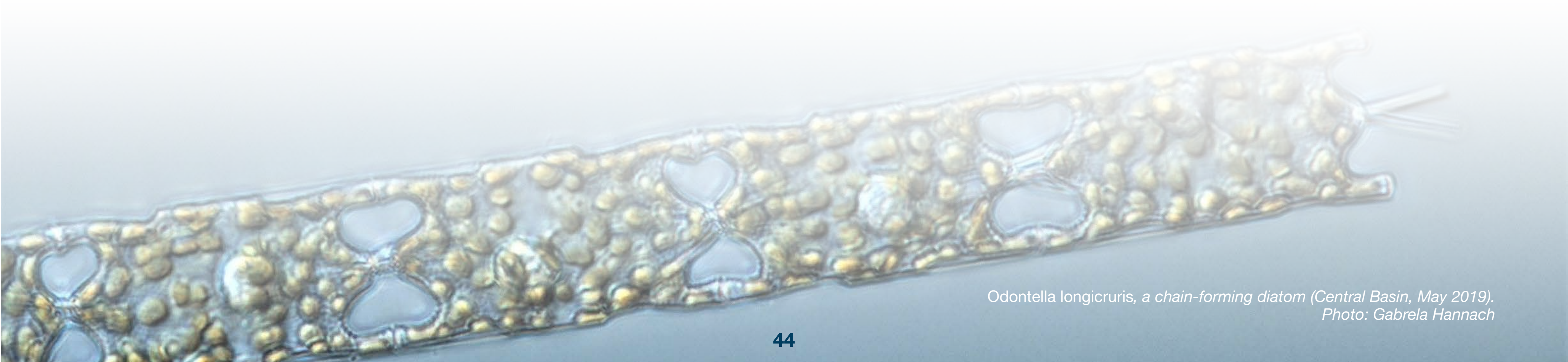
6. Plankton (cont.)

B.ii. Padilla Bay

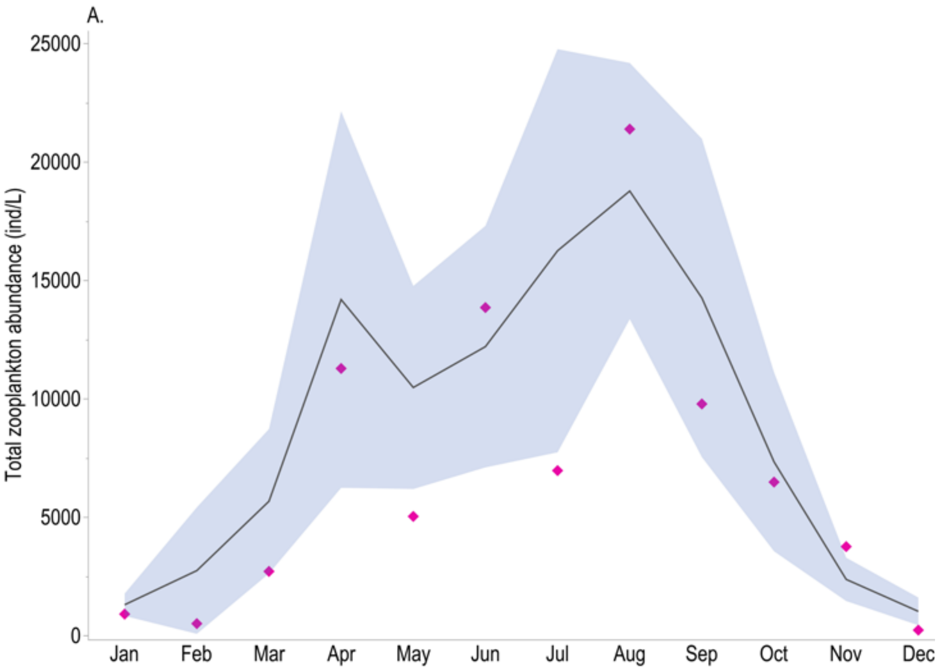
Zooplankton *Source: Nicole Burnett (nbur461@ecy.wa.gov), Jude Apple, and Sylvia Yang (Padilla Bay NERR/ Ecology); www.padillabay.gov*

Padilla Bay National Estuarine Research Reserve has been monitoring zooplankton communities since 2008 in conjunction with long-term water quality, nutrient, and meteorological data. Vertical tows to 18 m were performed at least monthly using a 153μm mesh net with a 1 ft diameter opening at an open-water site located in a large, ~20 m deep channel adjacent to Padilla Bay (Gong Station). Zooplankton abundances are consistently low during the winter and high in both the spring and mid-summer to early fall, though the timing and magnitude of these peaks vary annually (Figure 6.4A). Zooplankton community composition and abundance in Padilla Bay exhibit within-season variation, but have distinct seasonal compositions that persist annually despite environmental changes (Figure 6.4B).

The timing of the spring and summer peaks in 2021 occurred in April and August, respectively, and were similar in timing and magnitude (±1 SD) to the pattern of the 14-year mean. Monthly total zooplankton abundances were generally within 1 SD of the mean, with only May, July, November, and December having abundances outside of this range. We also observed shifts in community composition during these months, most noteworthy a consistent decrease in copepod abundance, although other zooplankton contributed to shifts in community composition (data not shown). Decreased zooplankton abundance in February and December may be linked to unseasonably colder water temperatures (see Figure 5.11 on page 33). November was the only month where there was an increase in both total abundance and a shift in community composition (aside from 2009 and 2015), which was associated with an increase in copepods, larvaceans, barnacles, and mollusks. In general, zooplankton abundance in 2021 was similar in pattern to the long-term average, with the exception of a few months where changes also



Odontella longicruris, a chain-forming diatom (Central Basin, May 2019). Photo: Gabrela Hannach



resulted in shifts to the community composition.

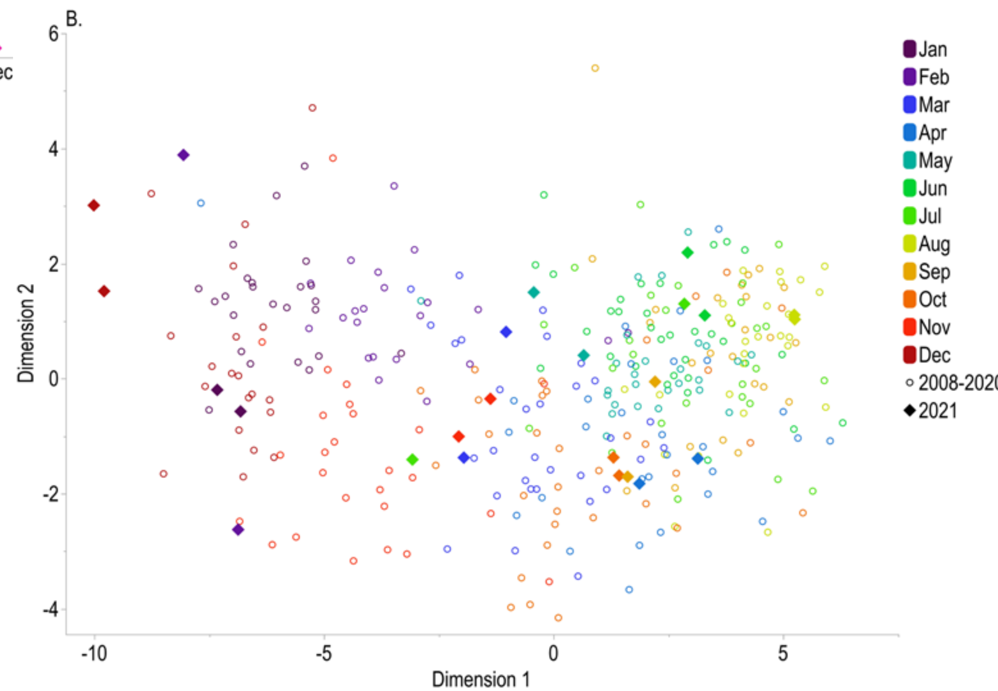


Figure 6.4. Mean monthly total zooplankton abundances (A) and non-parametric multidimensional scaling ordination (NMDS) of zooplankton community composition (B) at Gong Station, 2008-2021. Each point (open circle or diamond) in the NMDS is a single sample replicate for a given month and year.

6. Plankton (cont.)

B.iii. Larval Dungeness crab

Zooplankton

Source: Emily Buckner (pnwcrab@gmail.com), Ryan Crim (Puget Sound Restoration Fund), Allison Brownlee (WDNR), Claire Cook, Sarah Grossman (Swinomish Indian Tribal Community), Margaret Homerding (Nisqually Indian Tribe); www.pnwcrab.com

In 2019, the Puget Sound Crab Research Group (PCRG) initiated a larval Dungeness crab monitoring network to examine the temporal and spatial population dynamics of late-stage larvae (megalopae) across Salish Sea. In 2021, light traps were deployed throughout from April to September, by PCRG partners at 14 sites spanning Washington waters. The start of the 2021 larval delivery period occurred later than the previous two years. Megalopae were first observed in Hood Canal and the Pacific Coast in mid-May, followed by sites in the Strait of Juan de Fuca, San Juan, and Whidbey Basins. Central and south Puget Sound sites were the last to observe their first larval pulses. In 2020 and 2021, southern Hood Canal was the first site to observe megalopae. Generally, our assumption is that larvae arriving in April/early May are transported into the Salish Sea from Pacific coast populations and by June/July sites are catching larvae from local populations. Southern Hood Canal, however, has limited oceanic connectivity and exhibits a trend of larval development timing unlike any other site in the monitoring network. This could suggest unique population level life-history traits. Northern sites observed peak larval abundances in June while southern sites recorded peak abundance in July. Peak abundance reached record highs at northern sites, and generally abundances decreased from north to south (Figure 6.5). The largest pulse was at Birch Bay, where 52,785 larvae were captured in a single night. In contrast, the south Sound and southern Hood Canal sites continued to record low abundances of larvae with a peak of 5 megalopae in south Sound and 21 in southern Hood Canal. As the PCRG network continues to examine the annual patterns of larval inputs by region, we will begin to better understand the physical and oceanographic factors that influence larval dynamics and the strength of subsequent recruitment.

Clouds reflecting on the waters of Padilla Bay eelgrass meadows. Photo: Nicole Burnett, Padilla Bay NERR

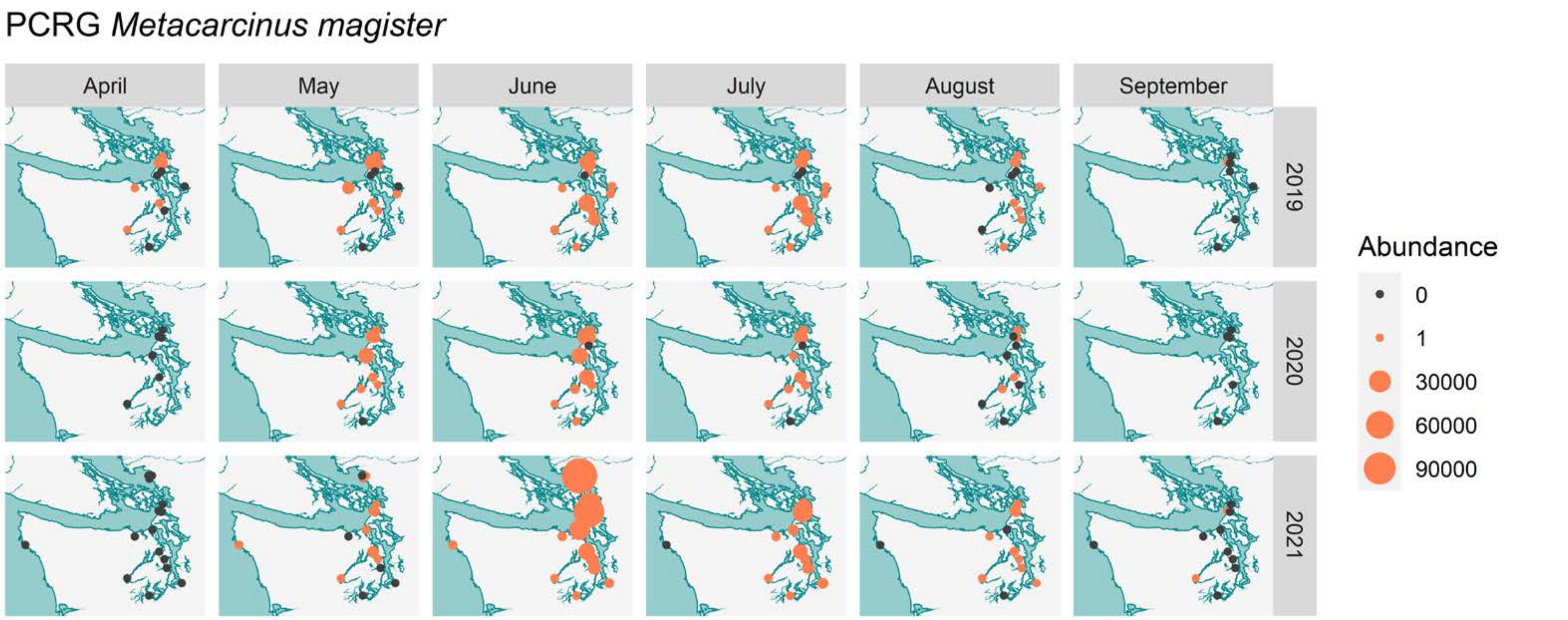


Figure 6.5. Monthly larval Dungeness crab abundance observed from April to September of 2019, 2020 and 2021. Abundance data were calculated as the sum of megalopae and instar counts per site and per month, and are represented as the orange circles on the map. Gray circles represent sites where traps were active and no Dungeness crab were collected.

CALL-OUT BOX: Impacts of the 2021 Heatwave on Rocky Intertidal Communities

The atmospheric heatwave that impacted the Pacific Northwest in late June 2021 was the most extreme on record and was perfectly timed with one of the lowest daytime tide series of the year. This unfortunate combination of extreme air temperatures and low tides proved to be deadly for intertidal communities in many areas of Washington, particularly those in the Salish Sea, where peak low tides occurred at mid-day for an entire week. While intertidal organisms are adapted to withstand the harsh conditions associated with living in the intertidal zone, the heatwave/low tide combination pushed some species beyond their physical limits. Gaping or dead mussels, dead barnacles, sea stars, and anemones, and crispy, desiccated seaweed were reported from British Columbia to south Puget Sound.

Long-term monitoring data from the Multi-Agency Rocky Intertidal Network (MARINe) were used to quantify the impacts of this heatwave event. MARINe is a consortium of organizations using standardized protocols to assess changes in rocky intertidal communities along the entire west coast of North America. Annual surveys at most MARINe sites in Washington were completed prior to the heatwave event and WA Sea Grant funding was used to resurvey 8 sites within the Salish Sea immediately following the heatwave. Resurveyed sites were located in Freshwater Bay (Strait of Juan de Fuca), Post Point (Bellingham Bay), Padilla Bay (4 sites), McDonald Cove (Hood Canal), and Manchester State Park (Central Basin).

Long-term patterns of community similarity displayed using non-metric multidimensional scaling (NMDS) plots suggest that the 2021 heatwave caused significant shifts in community structure at most MARINe sites within the Salish Sea, with increased bare rock, largely due to a decline in *Fucus* (rockweed) cover (Figure 1A, 1B and 2). At Freshwater Bay, substantial loss of the California mussel, *Mytilus californianus* occurred during the heatwave (Figure 3). Both *Fucus* and mussels are key "foundation species", providing habitat and food for many of other intertidal organisms. Populations of the ochre star, *Pisaster ochraceus*, are still recovering from massive declines that resulted from sea star wasting disease, and some were lost to desiccation during the heatwave (M. Miner, pers. obs.). However, sea stars in shaded crevices appeared healthy and counts showed only a slight dip in numbers associated with the heatwave.

The Pacific Northwest 2021 heatwave has been labeled a "once in 1,000-year event." If similar extreme events become more common with climate change, then there will be less time between events for recovery and the compounded effects will result in fewer survivors. Species that are slow-growing, such as mussels and sea stars, or those that have limited dispersal, such as *Fucus*, would likely experience the most severe declines, with consequences for the suite of species that depend on these foundation and keystone species. Recovery rates and lasting impacts of the Pacific Northwest 2021 heatwave will be assessed through continued MARINe monitoring.

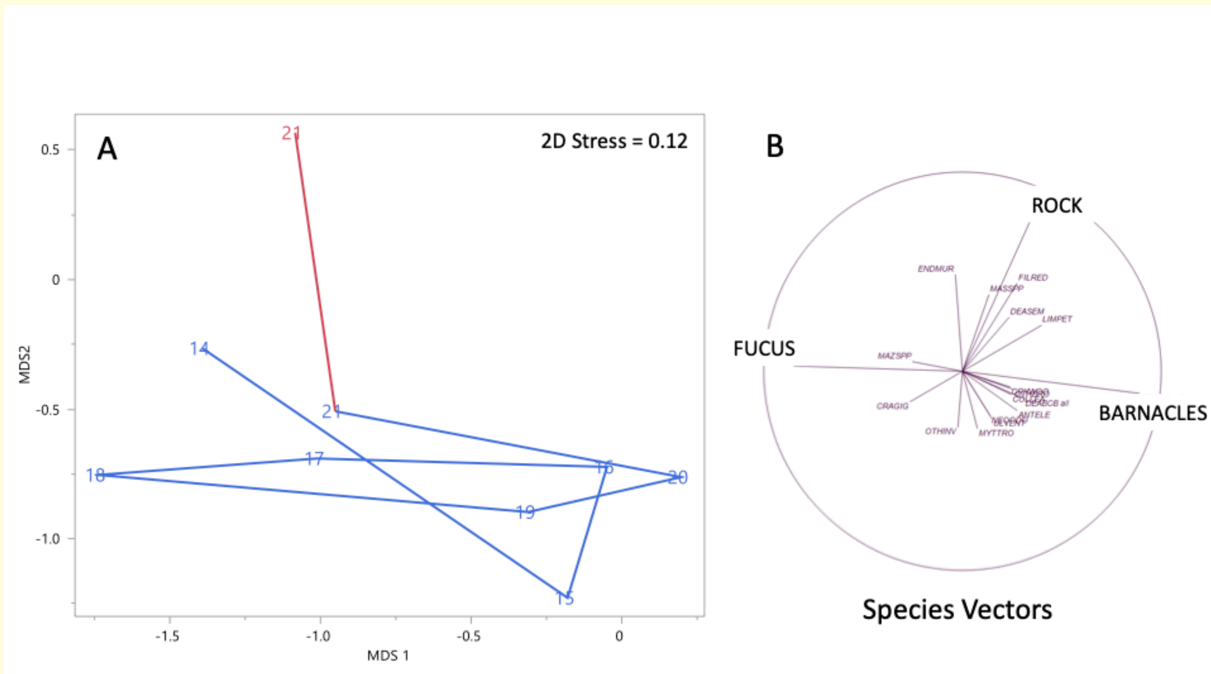


Figure 1. NMDS plot from McDonald Cove site (Hood Canal) showing (A) shifts in community similarity within barnacle and Fucus *plots over time and (B) species driving the patterns of change. Numbers shown in blue represent summer survey years (e.g. "14" = summer 2014) and the red number represents the post-June 2021 heatwave survey. Species contributing the most (longest vectors in 1B) to observed patterns in 1A are highlighted in bold.*

CALL-OUT BOX: Cont'd

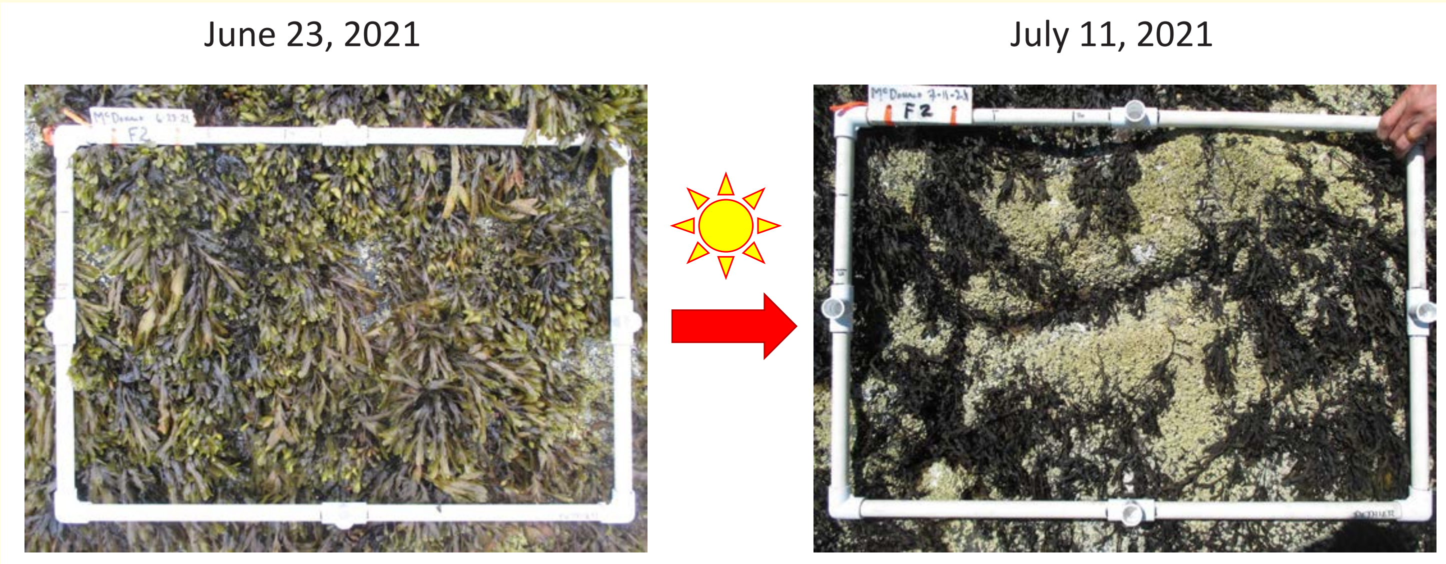


Figure 2. Example photos of a Fucus plot at McDonald Cove (Hood Canal) pre/post heatwave showing high rockweed cover just prior to the heatwave event and loss of rockweed with increased cover of barnacles and bare rock following the event.

Author: Melissa Miner (cmminer@ucsc.edu) and Pete Raimondi (UC Santa Cruz, Department of Ecology and Evolutionary Biology); www.pacificrockyintertidal.org

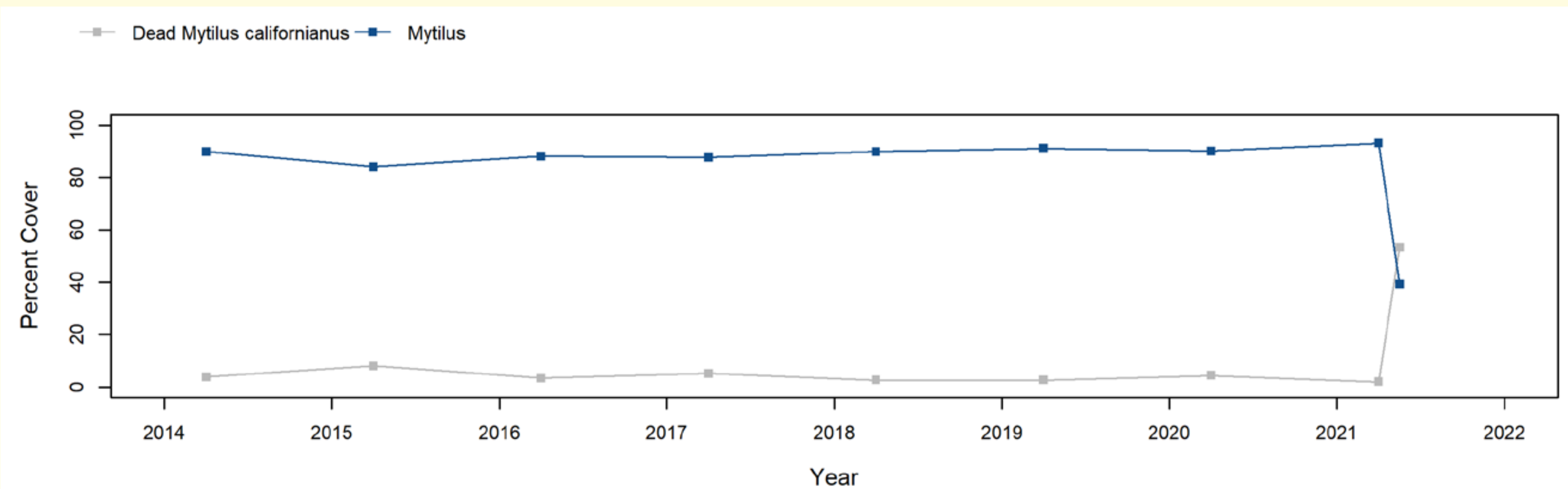


Figure 3. Mean percent cover of the mussel, Mytilus californianus *(blue line) and dead* M. californianus *(gray line) in mussel plots at Freshwater Bay showing mass mortality resulting from June 2021 heatwave event.*

6. Plankton (cont.)

Harmful algal blooms (HABs) are natural phenomena caused by the rapid growth of certain kinds of algae, resulting in damage to the environment and/or risk to human and ecosystem health. Many HAB species produce toxins that accumulate in shellfish and can cause illness or death in humans if contaminated shellfish are consumed. Other HABs can cause fish kills.

C.i. Biotoxins

Shellfish
Local foods

Biotoxins are produced by certain HABs and can accumulate in shellfish. Health authorities monitor biotoxins in commercial and recreational shellfish to protect humans from illness associated with eating contaminated shellfish. Shellfish are tested for biotoxins that cause paralytic shellfish poisoning (PSP toxins including saxitoxin), amnesic shellfish poisoning (ASP; domoic acid), and diarrhetic shellfish poisoning (DSP toxins including okadaic acid). Harvest areas are closed when toxin levels exceed regulatory limits for human consumption.

Source: Tracie Barry (tracie.barry@doh.wa.gov) and Jerry Borchert (WDOH); https://doh.wa.gov/community-and-environment/shellfish/recreational-shellfish/illnesses/biotoxins; https://doh.wa.gov/shellfishsafety

In 2021, the Washington State Public Health Laboratory analyzed 2,724 samples for paralytic shellfish poison (PSP) toxins. Atypical January PSP toxin events occurred in Clallam and Jefferson counties. Additional PSP events occurred in Clallam, Island, Jefferson, Kitsap, San Juan, Skagit, Snohomish, and Whatcom counties. PSP toxin levels peaked in September, with a maximum of 3,723 ug/100 g tissue in blue mussels from Port Susan. The FDA action level for PSP toxin is 80 µg/100 g of shellfish tissue. In 2021, PSP toxins caused 15 commercial and 21 recreational harvest area closures. Diarrhetic shellfish poison (DSP) toxin events occurred in Clallam, Jefferson, Kitsap, San Juan, and Thurston counties. The highest DSP toxin level was 39 ug/100 g tissue in blue mussels from Budd Inlet on January 6. The FDA action level for DSP is 16 µg/100 g of shellfish tissue. DSP toxins caused two commercial and seven recreational harvest closures in 2021, including the first in the Kingston area. A total of 2,740 samples were analyzed for amnesic shellfish poison (ASP) toxin. The highest level of ASP toxin was 81 ppm in Dungeness crab viscera from Grays Harbor on February 24. The FDA action level for ASP toxin is 20 ppm. ASP caused recreational and commercial closures along the Washington coast in 2020 which extended into 2021. A 2021 ASP event in Sequim Bay also caused recreational and commercial shellfish closures. The first Washington DSP/ASP dual toxin closure and second instance of a Washington waterbody closed for PSP/DSP/ASP in a single year occurred in Sequim Bay during 2021. In 2019, Sequim Bay was the first water body to be closed for PSP/DSP/ASP in the same year. Dual toxin PSP/DSP closures have occurred in Clallam, Jefferson, King, Kitsap, San Juan and Whatcom counties and PSP/ASP closures in Grays Harbor and Clallam counties.

Close-up of Chaetoceros debilis *(Central Basin, January 2020). Photo: Gabriela Hannach*

C.ii. SoundToxins

SoundToxins, a phytoplankton monitoring and research program for Puget Sound, provides real-time information to resource managers and aquaculture producers. The program is a committed diverse partnership of Native American tribes, aquatic farmers, environmental learning centers, colleges, community groups and individual volunteers. Partners collect and analyze phytoplankton and environmental data at 27 regularly sampled stations throughout Puget Sound with additional opportunistic sites weekly from March to October, and biweekly from November through February.

Source: Michelle Lepori-Bui (soundtox@uw.edu) and Teri King (WSG); https://soundtoxins.org

In addition to understanding phytoplankton abundance, distribution and documenting environmental conditions throughout Puget Sound, the SoundToxins data is used to provide early warning about harmful algal blooms (HABs) of concern to both humans and animal health. This carefully collected data allows the Washington State Department of Health (WDOH) to prioritize shellfish toxin tissue analyses, and alerts aquaculture producers and researchers to potential HAB events.

In 2021, the most frequently observed phytoplankton blooms were of *Chaetoceros* and *Rhizosolenia* (Figure 6.6). The number of blooms observed for both of these genera was about twice that observed in 2020. The third most frequently observed bloom was *Thalassiosira*, which was similar in number of observations to 2020. The first blooms observed of the season were in the last week of February and were all *Thalassiosira*.

Pseudo-nitzschia, a HAB species of human health concern, was ranked fourth most abundant species blooming overall in 2021, up from being tied for sixth in 2020. There were slightly fewer *Alexandrium* blooms than last year, and all occurred in late August to early September. Notably, there were only two reports of *Dinophysis* blooms in 2021, which occurred in late June and early July.

SoundToxins partners enabled recording of diverse phytoplankton observations and environmental conditions across Puget Sound during a challenging year. Results from this program support the needs and decision making of resource managers, farming communities, and other partners.

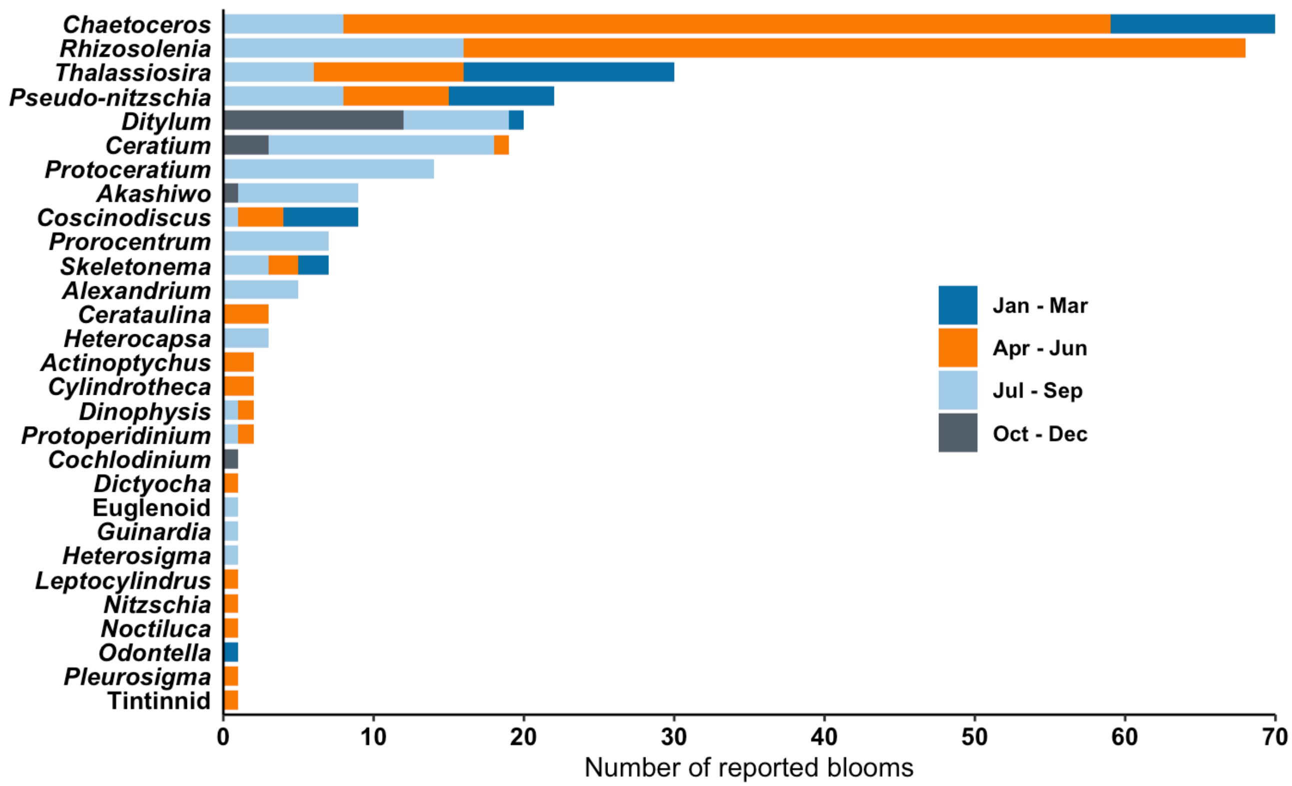


Figure 6.6. Total reported phytoplankton blooms in Puget Sound in 2021.

C.iii. *Alexandrium* species cyst mapping

Shellfish

Dinoflagellates in the genus Alexandrium *form dormant cysts that overwinter on the seafloor and can provide the inoculum for toxic blooms the following summer when conditions become favorable again for growth of the motile cell. "Seedbeds" with high cyst abundances correspond to areas where shellfish frequently attain high levels of toxin in Puget Sound. Cyst surveys are a way for managers to determine how much "seed" is available to initiate blooms, where this seed is located, and when/where this seed could germinate and grow.*

Source: Julie Masura (jmasura@uw.edu) and Cheryl Greengrove (UWT); https://www.tacoma.uw.edu

Alexandrium catenella is a dinoflagellate that produces saxitoxin, a powerful neurotoxin, known to bioaccumulate in filter-feeding shellfish. Mammals consuming these shellfish can experience paralytic shellfish poisoning, a severe toxin-induced illness. *Alexandrium* overwinters in seafloor sediments as a cyst, and in the spring and summer, when environmental conditions are right, these cysts can germinate and become vegetative cells within the water column. Identification and enumeration of cysts are used to determine regions where there is a greater potential for these harmful algae to bloom. This project identified harmful algae in sediments collected throughout the Puget Sound from 2013-2021 to create baseline observations and determine if *Alexandrium catenella* cyst concentrations in sediments have changed over time. Washington State Department of Ecology's Marine Sediment Monitoring Group has provided sediment samples to analyze for cysts since 2013. Ten long-term stations have been sampled using a 0.1 m^2 stainless steel van Veen grab sampler to recover 2-3 cm of the top sediment from the seabed. Each year the sediment samples are analyzed by undergraduate researchers for grain-size distribution, total organic content percentage, harmful algae abundance, and microplastic concentration as part of a summer research experience. *A. catenella* cysts were processed by sieving, fixing, etching, and staining the cysts for identification using a standard microscopy method. Sampling was conducted in spring and therefore results may be an underestimate of overwintering cysts, as some may have already germinated into the water column. Figure 6.7 shows a time series of cysts present in Puget Sound from 2013-2021. In 2021, cysts were found in Bellingham Bay, the entrance of Hood Canal, and Dyes Inlet southeast of Seattle. The color scale indicates changes of an order of magnitude in cyst counts. For this timeseries, *Alexandrium* cysts have been found in Bellingham Bay each year with varying magnitudes from year to year.

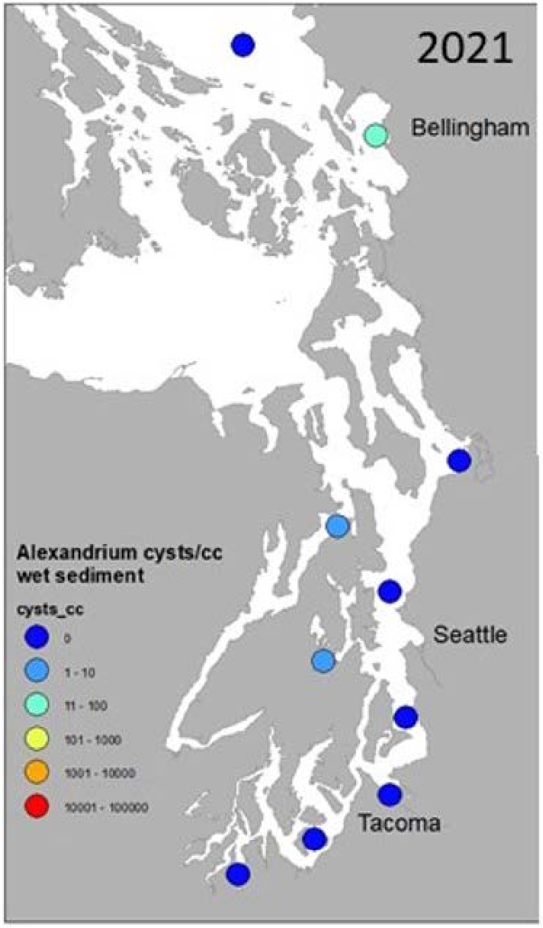
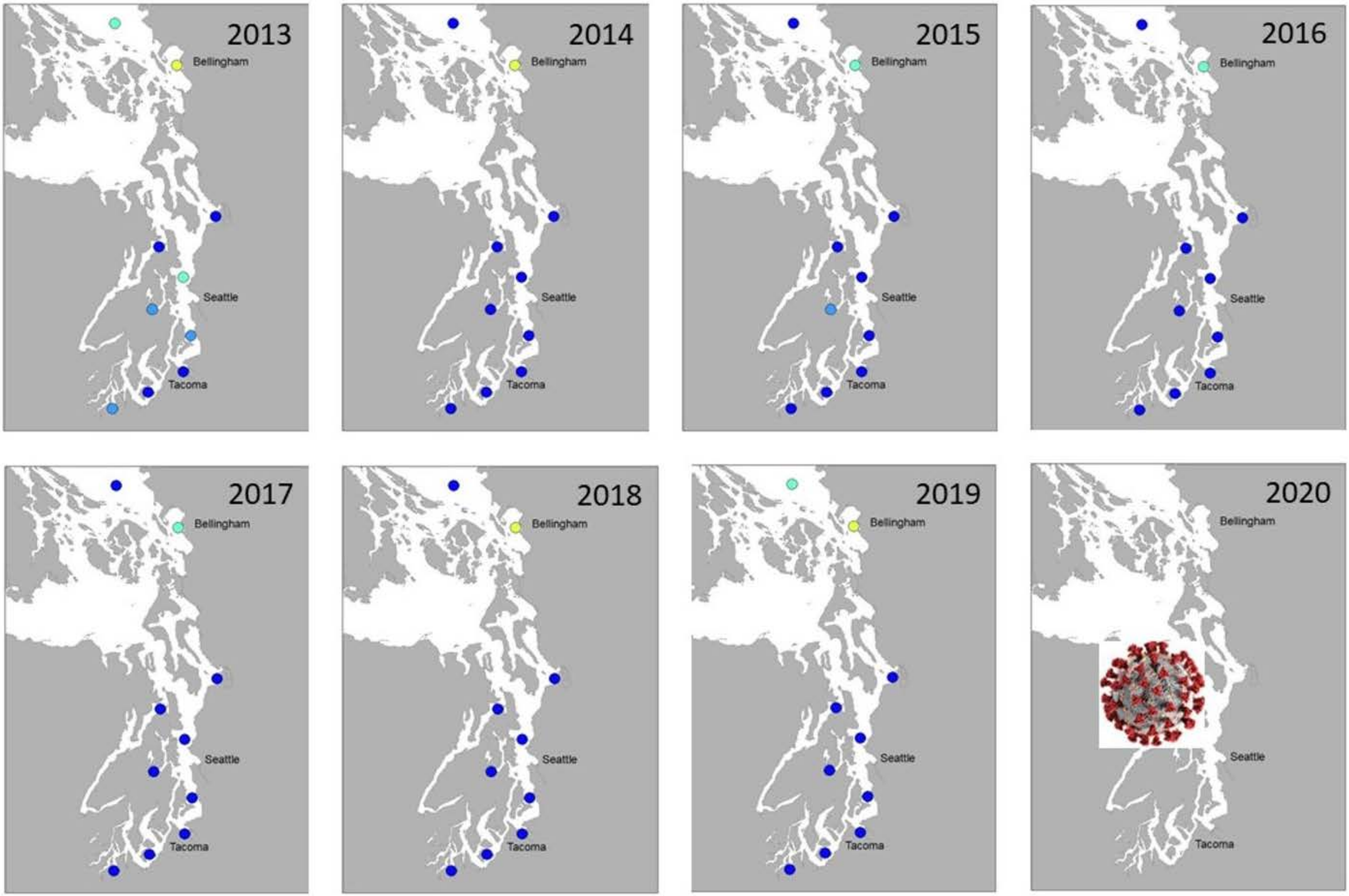


Figure 6.7. Distribution and concentration of Alexandrium catenella *cysts in Puget Sound surface sediment samples collected from 2013-2021.*


2013
Bellingham
Seattle
Tacoma
2014
Bellingham
Seattle
Tacoma
2015
Bellingham
Seattle
Tacoma
2016
Bellingham
Seattle
Tacoma
2017
Bellingham
Seattle
Tacoma
2018
Bellingham
Seattle
Tacoma
2019
Bellingham
Seattle
Tacoma
2020
Bellingham
Seattle
Tacoma

7. Bacteria and pathogens

A. Fecal indicator bacteria

Members of two bacteria groups, coliforms and fecal Streptococci, are commonly used as indicators of sewage contamination as they are found in the intestinal tracts of warm-blooded animals (humans, domestic and farm animals, and wildlife). Although they are generally not harmful themselves, they indicate the possible presence of pathogenic (disease-causing) bacteria, viruses, and protozoans. Fecal coliforms are a subset of total coliform bacteria, and *Enterococci* are a subgroup within the fecal *Streptococcus* group.

A.i. Puget Sound recreational beaches

Beaches

The Beach Environmental Assessment, Communication and Health (BEACH) Program is jointly administered by the Washington State Departments of Ecology and Health. The goal of the program is to monitor high-risk, high-use marine beaches throughout Puget Sound and the coast for fecal bacteria (enterococcus) and to notify the public when results exceed Environmental Protection Agency's (EPA) swimming standards. The program is funded by the EPA.

Source: Heather Gibbs (heather.gibbs@ecy.wa.gov) and Laura Hermanson (Ecology, WDOH); https://ecology.wa.gov/Water-Shorelines/Water-quality/Saltwater/BEACH-program

The BEACH Program coordinates weekly or biweekly monitoring from Memorial Day to Labor Day with local and county agencies, tribal nations, and volunteers. In 2021, 60 Washington beaches were sampled including 42 core beaches (sampled yearly).

During the 2021 monitoring season, 77% of beaches sampled were considered passing, meaning no more than one exceedance of the swimming standard during the sampling season. This is an 18% decrease in passing beaches from 2020. Many of the exceedances reported happened during or immediately after the record-breaking Puget Sound heatwave event (June 26th-July 2nd). These exceedances could be attributed to an increased number of beachgoers and pets making contact with the water, in addition to an increase in trash and food waste, which can attract animals. All of these factors are associated with higher fecal bacteria levels on our beaches.

The Puget Sound Partnership uses BEACH data for their Vital Sign indicator and has set a target that at least 95% of monitored core beaches meet human health standards by 2026. Details on 2021 beach sampling results can be found at: https://ecology.wa.gov/Research-Data/Monitoring-assessment/BEACH-annual-report.

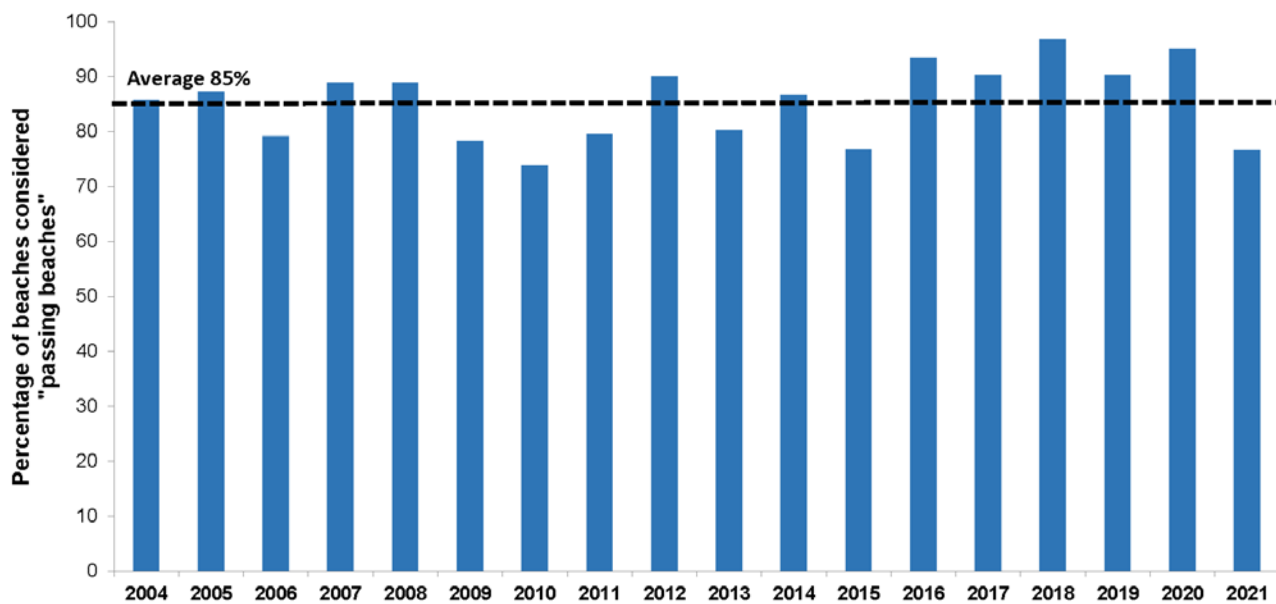


Figure 7.1. Percent of all marine beaches sampled that had no more than one swimming closure or advisory (considered "passing beaches") during 2004-2021. In 2021, 77% of sampled beaches were considered passing. The average percentage of passing beaches is 85% (black dashed line).

A.ii. Central Basin stations

Shellfish
Local foods

Source: Wendy Eash-Loucks (wendy.eash-loucks@kingcounty.gov) and Wafa Tafesh (King County); Primary website: https://green2.kingcounty.gov/marine/; *Website for online data: https://data.kingcounty.gov/Environment-Waste-Management/Water-Quality/vwmt-pvjw*

King County monitors fecal indicator bacteria monthly at 20 beach stations in Puget Sound's Central Basin. King County also monitors bacteria at 14 offshore locations, a mix of ambient and outfall stations, with samples collected from 1 m depth twice-monthly most of the year (monthly in January and December). These data are used to determine if sites have chronic bacteria problems and evaluate how concentrations are changing over time.

Annual geometric means of beach bacteria concentrations in 2021 were spatially variable. The highest *Enterococcus* concentrations occurred at the outflow of Piper's Creek at Carkeek Park, Golden Gardens, and Redondo Beach (Figure 7.2A). All three of these sites have nearby freshwater inputs, which are potential pathways for bacteria to enter the marine environment. The 2021 annual geometric means for *enterococci* and fecal coliforms were within the historic range for most stations, although most stations were on the high end of the range for *Enterococcus* (Figure 7.2B). Carkeek Park Piper's Creek outflow had its highest *Enterococcus* annual geometric mean in 2021 since monitoring began in the 1980s. That site typically has elevated bacteria concentrations due to creek discharges. The nearby Carkeek Park site, outside the immediate influence of the creek, typically has much lower bacteria levels (Figure 7.2A and 7.2B). For most beach stations, the highest bacteria concentrations in 2021 occurred in November when samples were collected after two days of 0.9 inches or more of rainfall in a day.

Similar to previous years, bacteria concentrations offshore in 2021 were much lower than those at beach stations due to their distance from various sources. The offshore stations with the highest bacteria concentrations included those located within Elliott Bay (Figure 7.2A), but even those stations had very low concentrations with annual geometric means of 3 CFU/100 mL or less for both types of indicator bacteria.

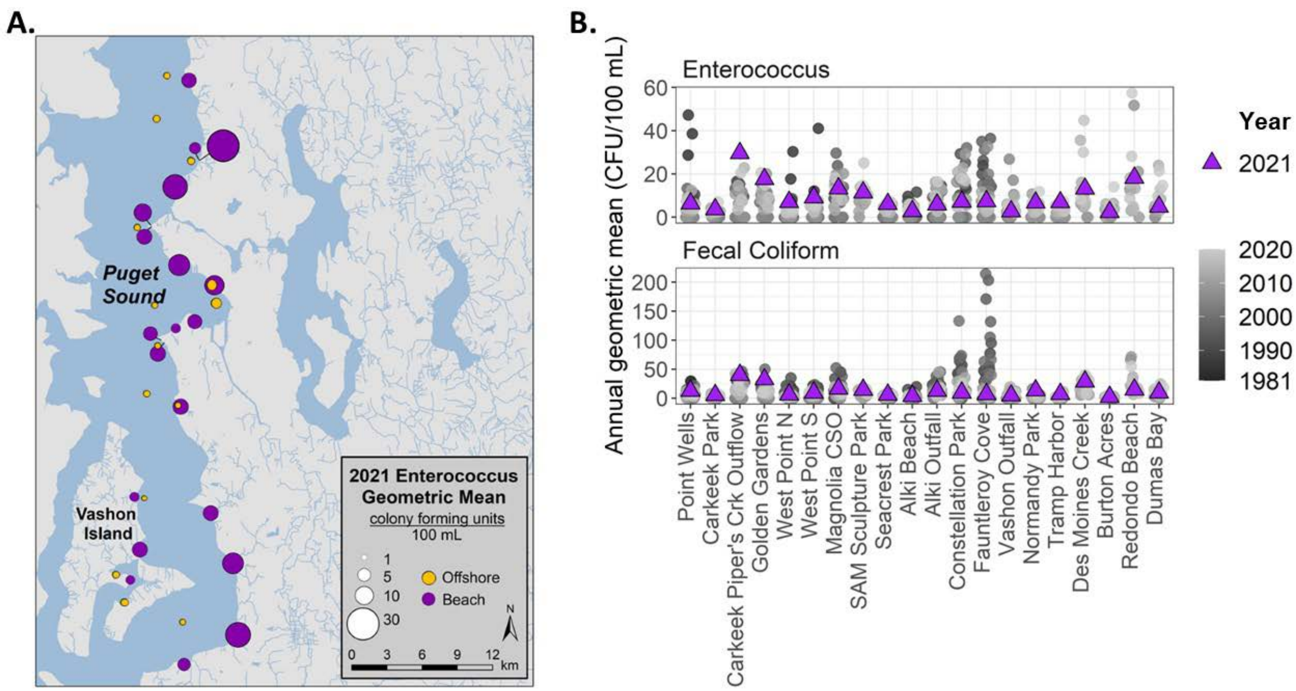


Figure 7.2. 2021 King County indicator bacteria monitoring results. (A) Map of the Enterococcus *annual geometric mean concentration at King County beach and offshore stations; (B) Annual geometric mean* Enterococcus *and fecal coliform concentrations at beach stations from 1981 to 2021. In B, 2021 values are shown in purple and older data are shown in a grayscale gradient by year. In B, beaches are listed from north (left) to south (right).*

8. Forage fish

Forage fish are a vital component of the marine food web as they are prey throughout their life history for many invertebrates, fish, birds, and mammals. Pacific Herring (*Clupea pallasii*) are the most researched forage fish; stocks are defined by spatiotemporal isolation of spawning activity, and 21 stocks are monitored annually in the southern Salish Sea (SSS).

A. Pacific herring

Forage fish

Source: Todd Sandell (todd.sandell@dfw.wa.gov), Phill Dionne, Katie Olson, Erin Jaco, and Emily Seubert (WDFW); https://wdfw.wa.gov/fishing/management/marine-beach-spawning

Forage fish are a vital component of the marine food web, as they are prey throughout their life cycle for many invertebrates, fish, birds, and mammals. Pacific herring (*Clupea pallasii*) are the best studied forage fish and are used as an indicator species of Puget Sound health. The Puget Sound metapopulation is divided into stocks, each of which have spatiotemporal isolation of spawning activity and spatially distinct dynamics. WDFW recognizes twenty-one different herring stocks in Puget Sound based primarily on the timing and location of spawning activity. However, recent research suggests that, at present, only the Cherry Point and Elliott Bay stocks are genetically unique (Petrou et al., 2021), although not all stocks have been evaluated. After the historically high estimated spawning biomass (ESB) in 2020 (18,559 metric tonnes; Figure 8.1), the total for 2021 (10,255 mt) declined nearly 45%, returning towards the ten-year average (10,500 mt). This was mainly driven by reductions in ESB for the two largest stocks, Quilcene Bay (Hood Canal; 3,491 mt, 52% decline from 2020) and Port Orchard-Port Madison (2,472 mt, 65% decline from 2020). The 2021 total was bolstered by a strong year at Semiahmoo Bay, with 2,395 mt (a 62% increase from 2020). However, the genetically distinct, late-spawning Cherry Point stock ESB was only 157 mt in 2021, down from 274 mt in 2020, though this may be an underestimate as we were unable to survey Point Roberts due to border closures. Three stocks that typically have spawning activity (i.e. Quartermaster Harbor, South Hood Canal, and Discovery Bay) had no spawn detected in 2021, and five other stocks continued to have no spawn detected (Wollochett, Fidalgo Bay, Kilisut, Interior San Juan Islands, and NW San Juan Island). This loss of diversity from the *Herring Portfolio* (Siple and Francis, 2015) undermines the stability of southern Salish Sea herring in the face of environmental uncertainty.

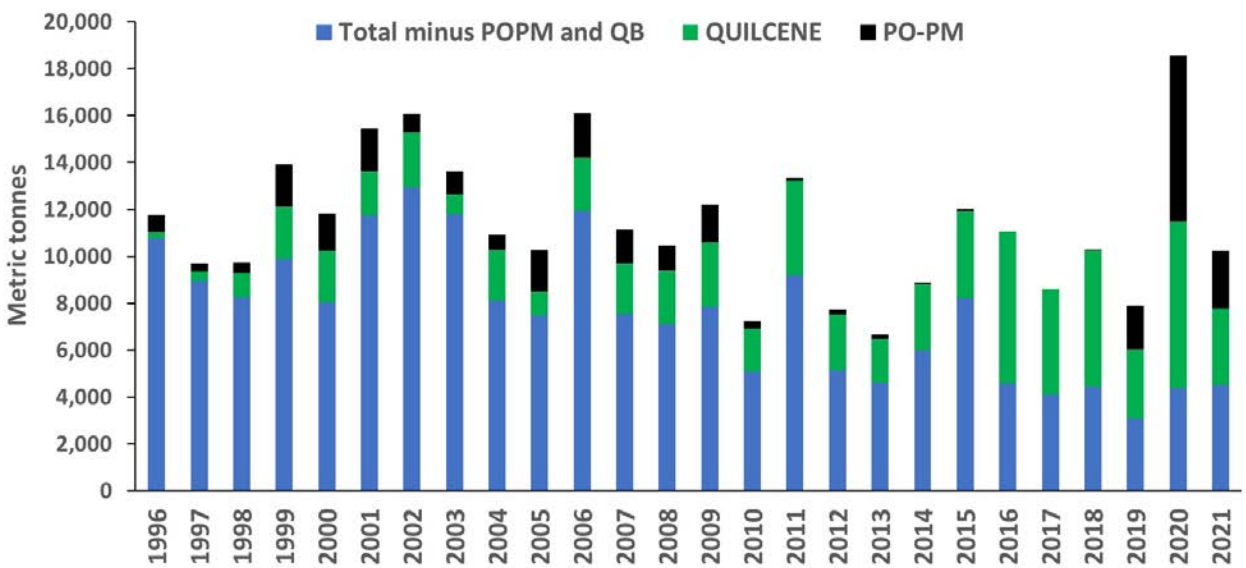


Figure 8.1. Pacific Herring spawning biomass estimates in the southern Salish Sea, 1996-2021.

B. Juvenile Chinook

Salmon Source: Russel Barsh (russel@kwiaht.org), Madrona Murphy, Alex Assaf, and Brianna Bjordahl (KWIAHT); http://www.kwiaht.org

Juvenile Chinook out-migrants have been monitored since 2009 by biweekly beach seines at two stations in the San Juan Islands: Watmough Bay (Lopez Island) and Cowlitz Bay (Waldron Island). Sampling was conducted on 10 dates from May to September on evening flood tides using a 120-foot modified Puget Sound beach seine. Puget Sound origin Chinook were more abundant at the Watmough station (Chamberlin et al., 2017), and Juvenile Chinook transiting the San Juan Islands were found to be consuming fewer forage fish (Barsh et al., 2021). On days when forage fish were not found in the gut contents of unmarked juvenile Chinook, prey were chiefly planktonic crustaceans in early to mid-summer, and detrital insects in late summer. More than 12,000 zooplankton prey items were identified in juvenile Chinook gut contents from 2009 to 2021 and their biomass was estimated from their size. Mean estimated zooplankton biomass consumed per juvenile Chinook has declined by about 20 percent since 2014, and most of this change can be attributed to reduced consumption of larval crabs. Juvenile Chinook outmigrants in the San Juan Islands were selective in their use of zooplankton, targeting four groups of relatively large crustaceans: larval crabs, euphausiids (krill), hyperiid amphipods (a free-swimming pelagic group distantly related to sand fleas), and the larger taxa of calanoid copepods. Krill and hyperiids tend to form large seasonal aggregations, making them attractive as prey. Larval crabs and the largest calanoid genera such as *Eucalanus* and *Neocalanus* are also seasonally abundant but more dispersed in the water column. When juvenile salmon and larger forage fish, such as adult Pacific herring and Pacific sand lance, co-occur at Watmough Bay and Cowlitz Bay, they compete for these larger, calorie-rich planktonic crustaceans (Barsh et al., 2022).

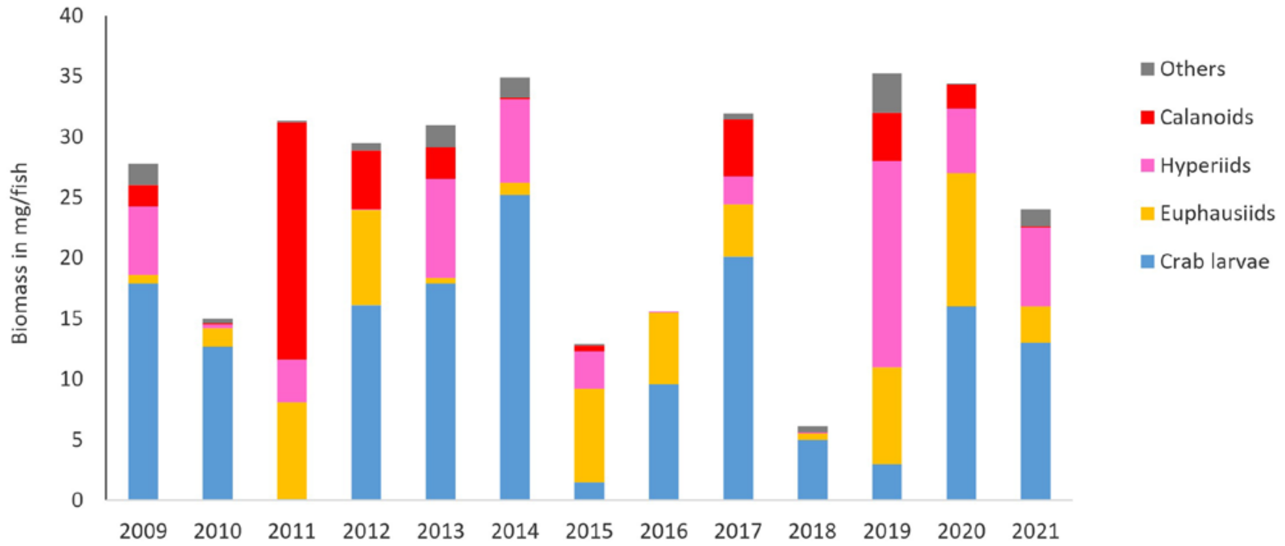


Figure 8.2. Mean zooplankton biomass consumed by unmarked juvenile Chinook from Watmough Bay in the San Juan Islands.

9. Marine birds and mammals

One hundred and seventy-two bird species rely on the Puget Sound/Salish Sea marine ecosystem either year-round or seasonally. Of the 172 species, 73 are highly dependent upon marine habitat (Gaydos and Pearson 2011). Many marine birds (seabirds such as gulls and auklets, sea ducks such as scoters and mergansers, and shorebirds such as sandpipers and plovers) are at or near the top of the food web and are an important indicator of overall ecosystem health. Marine birds need sufficient and healthy habitat and food to survive.

A. Wintering marine birds and harbor porpoise

Marine birds

Source: Joseph Evenson (joseph.evenson@dfw.wa.gov) Matthew Hamer, and Bryan Murphie (WDFW); https://wdfw.wa.gov/species-habitats/at-risk/species-recovery/seabirds/surveys-winter-aerial

Aerial surveys during the 2021-22 winter period included a total of 6,338 km of transects covering all shorelines and following two sets of fixed random offshore transects, the first within a 0-50m and the second within a >50m depth bin. The yearly survey records sighting data on all observed marine avian and mammal species, although only a select subset of species and species groupings are reported here. These include the scoter species (*Melanitta* spp.), sea ducks (*Merginae*), pigeon guillemots (*Cepphus columba*), western grebes (*Aechmophorus occidentalis*), diving forage fish specialists, all marine bird species, and harbor porpoise (*Phocoena phocoena*). All credible intervals (CrI) reported are 90% and estimates are not corrected for detection rates. Data include all survey years from winter 1995-96 through 2021-22.

The scoter species estimate was 61,352 (CrI 55,189–67,515) (Figure 9.1a). This was an increase of 3% over the previous winter survey period (PWSP) two years prior in 2020 and was 23% below the long-term average (LTA) of 79,921, with an annual rate of change (ARC) of -3.0% (1996-2022). The scoter species group has remained relatively stable since the lowest abundance estimate recorded in 2010 (53,309), from which time there has been an ARC of 1.2% (2010-2022).

The overall estimate of all sea duck species was 199,189 (CrI 186,677–212,820) (Figure 9.1b). This was 1.2% above the PWSP (196,815) and was 8.8% below the LTA with an ARC of -1.6%.

The abundance estimate for Pigeon Guillemots was 8,486 (CrI 7,610–9,239), which was the second highest winter estimate since 1996 (Figure 9.1c). This estimate was 4.2% above the PWSP, 30% above the LTA with an ARC of 3.6%.

The western grebe estimate was 12,670 (CrI 8,318–18,037) which was the third lowest estimate since 1996 (Figure 9.1d). This estimate was 15% below the PWSP, 62% below the LTA with an ARC of -6.9%.

The diving forage fish specialists include grebes, loons, alcids, cormorants, and mergansers. The estimate for this group was 105,251 (CrI 97,056–114,436), which was the second lowest recorded since 1996 (Figure 9.1e). This estimate was 21% below the PWSP, 31% below the LTA with an ARC of -3.3%.

The marine bird category comprises grebes, loons, alcids, cormorants, gulls, terns, waterfowl, and shorebirds. The estimate for all marine birds was 742,477 (CrI 668,811–825,750), which was 2.7% below the PWSP, 20% below the LTA with an ARC of -2.4% Figure 9.1f).

We do not estimate population of harbor porpoise but instead report on the observed density (animals/km^2) to measure trends. Laake et al. (1997) reported a detection rate of 0.292 by experienced aerial observers for this species when at an altitude of 183m AGL (above ground level), at an air speed of 185 km/h, cloud cover <=50%, and Beaufort <=2. Our winter survey is flown at 61m AGL, at an air speed of 157 km, in all cloud covers and at Beaufort <=3, thus likely resulting in a lower detection rate.

The statewide observed density of harbor porpoise was 0.66 porpoise/km^2 (CrI 0.54–0.78) (Figure 9.1g). This was equal to the PWSP (0.66, CrI 0.55–0.77) and 39% above the LTA with an ARC of 3.8%. Although there has been a long-term increasing trend, this increase occurred up to 2015 with an ARC of 5.6% through that period. Since 2015, densities have remained relatively flat with an average (2015-2022) density of 0.68 porpoise/km^2 (range = 0.62 – 0.78).

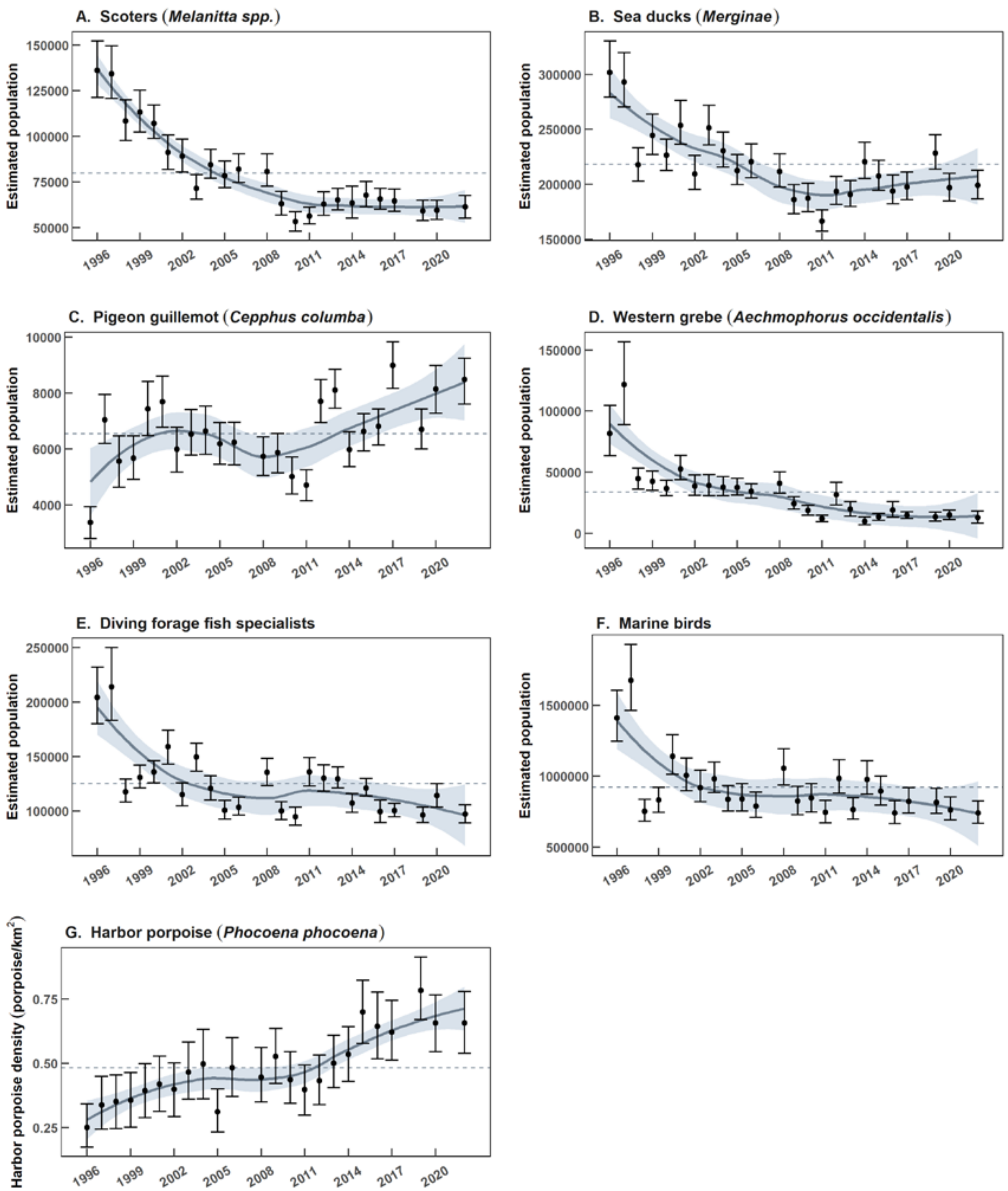


*Figure 9.1. Winter population estimates from Washington's portions of the Salish Sea by year for (A) scoters (*Melanitta spp.*), (B) sea ducks (*Merginae*), (C) pigeon guillemot (*Cepphus columba*), (D) western grebes (*Aechmophorus occidentalis*), (E) diving forage fish specialists (grebes, loons, cormorants, alcids, and mergansers), and (F) all marine bird species (grebes, loons, alcids, cormorants, gulls, terns, waterfowl, and shorebirds). (G) Harbor Porpoise (*Phocoena phocoena*) winter density estimates by year from Washington's portions of the Salish Sea.*

Shorebirds, such as this Black Oystercatcher photographed at Orcas Island, are sensitive to marine conditions that affect the health of intertidal shellfish. Photo: Russel Barsh for Kwiaht

B. Harbor seals

Source: Cindy Elliser (cindy.elliser@pacmam.org) (Pacific Mammal Research), David Anderson (Cascadia Research Collective), Trevor Derie, Katrina MacIver (Pacific Mammal Research), and Laurie Shuster (Cascadia Research Collective and Pierce College); www.pacmam.org

Harbor seals (*Phoca vitulina*) commonly form large congregations at haul-out locations during times of rest and during pupping season (Bigg, 1981; Zier & Gaydos, 2014), and are generally solitary at sea. Occasionally larger clusters of individuals can be observed swimming near haul-out sites (Scheffer & Slipp., 1944), forced bottlenecking channels (Zamon, 2001) or mouths of rivers (Marston et al., 2002) where prey is concentrated and space is restricted. Recently, isolated occurrences of mass gatherings of harbor seals have been observed in the Salish Sea that were at a distance from haul-out sites (over one kilometer away), and in forced bottlenecking regions. In April-June (but primarily May) 2019-2021, juvenile and adult harbor seals were observed in large groups (N=31) in Burrows Pass (Anacortes, WA) ranging from 6-50 individuals (mean=16.8) and within 1-2 body lengths of each other periodically diving to presumably hunt and chase prey. The likelihood of these as foraging events is corroborated by the observation that groupings primarily occurred during flood and slack high tides, and that the observed surface activity, habitat type, and specific area is used for foraging by individuals year round. Similar large groups have been documented (N=10) in South Puget Sound and Central Puget Sound, and were first observed in 2016 and officially documented in February of 2017. These groupings (ranging from 20-30 to >150 individuals) occurred throughout the year and at varied tidal states. While some sightings were obviously foraging behavior, others appeared to be resting, traveling or socializing. Open water behavior of harbor seals is not well documented, and a literature review found no other published accounts of large in-water groupings. Future investigation of ecological relationships such as prey spawning, prey abundance, or other environmental correlates, as well as observation of underwater harbor seal behavior, will aid in determining the reason for this seemingly novel behavior.

Paper published: Behaviour (2022)
DOI:10.1163/1568539X-bja10175

*Figure 9.2. Photographs of about 30 harbor seals on April 30, 2019 in Burrows Pass during slack high tide. Panel (A) shows the group as they floated together in the pass towards the bay, and panel (B) shows when they would periodically dive and swim inverted at the surface, seemingly chasing prey. Gulls (*Laridae*) and cormorants (*Phalacrocoracidae*) were also present, with one cormorant diving and observed catching a fish.*

C. Humpback whales

Source: Emily Vierling (emvierling@gmail.com), Scott Veirs, and Val Veirs (Orcasound Hydrophone Network)
Primary website: https://psemp.net/mmwg
Website for online data: https://orcasound.net

The Orcasound hydrophone network has been tracking the presence of killer whales in Haro Strait since the early 2000s. Live-streamed audio data are monitored by community scientists listening along with OrcaHello, a machine learning model trained to detect the calls of endangered Southern Resident Orcas. The last five years of recordings are archived in an open data registry hosted by Amazon.

Humpback whale populations in the North Pacific have recovered since the end of the commercial whaling era, with a corresponding increase in the number of photo-identified individuals in Washington waters (Calambokidis, 2018). A similar trend has been noted for sightings within Puget Sound, called the "humpback comeback" since the species was extirpated within the Salish Sea in the early 20th century. In 2021, humpback non-song vocalization events (bioacoustic "bouts") were detected in Haro Strait 13 times, almost exclusively during the fall months (October-December). In comparison, such sounds were heard at most once annually between 2013-2018, and only 3-4 times per year in 2019 and 2020. Since listening effort using this hydrophone network has been steady during the last decade, we attribute this ~4x increase in vocal activity to increased use of Haro Strait by humpbacks. These humpback vocalizations, probably made by males in a prelude to singing in the tropics over the winter, have been distilled into a new open access catalog of Haro Strait humpback sounds that includes 12 types of non-song vocalizations (Vierling et al., 2022). Although humpbacks are known to be opportunistic feeders, recent tag studies suggest that humpbacks foraging nearby in the central Strait of Juan de Fuca may be focusing on euphausiid prey (Calambokidis et al., 2019). Sightings in southern Puget Sound may also be associated with periods of increased anchovy abundance.

Humpback breaching in Haro Strait.
Photo: Beam Reach, Carlos Sanchez, PSEMP Marine Mammal Work Group

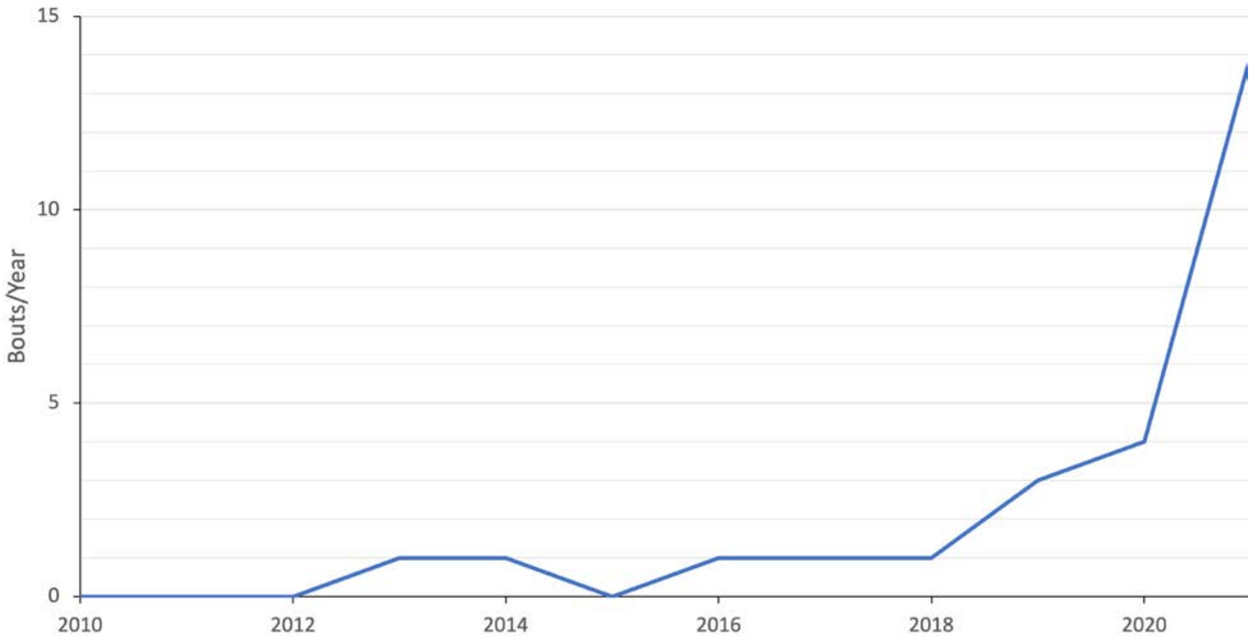


Figure 9.3. Humpback whale vocal activity in Haro Strait (2010-2021). A bioacoustic bout is a period of relatively continuous non-song vocalization separated from other bouts by extended periods of ambient noise.

10. Sediment

Sediment characteristics are important to connect environmental conditions to the seafloor and features of interest (i.e., benthic communities). Total organic carbon can represent oxygenated or reduced environments and/or biological vitality depending on water depth. Grain-size can represent high or low energy if sandy or silty, and the variability of grain-sizes (sorting) can indicate stormy conditions, landslides, or dumping. This study provides a foundation for scientists to understand and maintain environmental health.

A. Particle grain-size and total organic content analyses of surface sediment

Benthic index

Source: Julie Masura (jmasura@uw.edu), Jessica Wolford, and Cheryl Greengrove (UWT); www.tacoma.uw.edu

This project explores characteristics of sediments collected throughout the Puget Sound in spring 2021 to correlate with other measurements (i.e., harmful algae or plastic pollution). Washington State Department of Ecology's Marine Sediment Monitoring Group has provided sediment samples to analyze since 2013. For 2021, 50 long-term stations from Puget Sound were sampled using a 0.1 m^2 stainless steel van Veen grab sampler to recover 2-3 cm of the top sediment from the seabed. Each year the sediment samples were analyzed by undergraduate researchers for grain-size distribution, total organic content percentage, harmful algae abundance, and microplastic concentration as part of a summer research experience. Samples were analyzed in the lab with a Beckman-Coulter Particle Size Analyzer for sediment grain-size. The loss-on-ignition technique was used to determine the total organic content. For 2021, most of the sediments plotted in the clayey sand region to the mid-left of the diagram to sandy silt to the right, unlike previous years that also included silty sand and silt (Figure 10.1). A linear regression analysis of the median grain-size and the total organic content showed a negative correlation for both wet sediment (R2=0.5277) and dry sediment (R2=0.6707). Note: wet sediment represents the spatial distribution, whereas the dry sediment represents only the solid material.

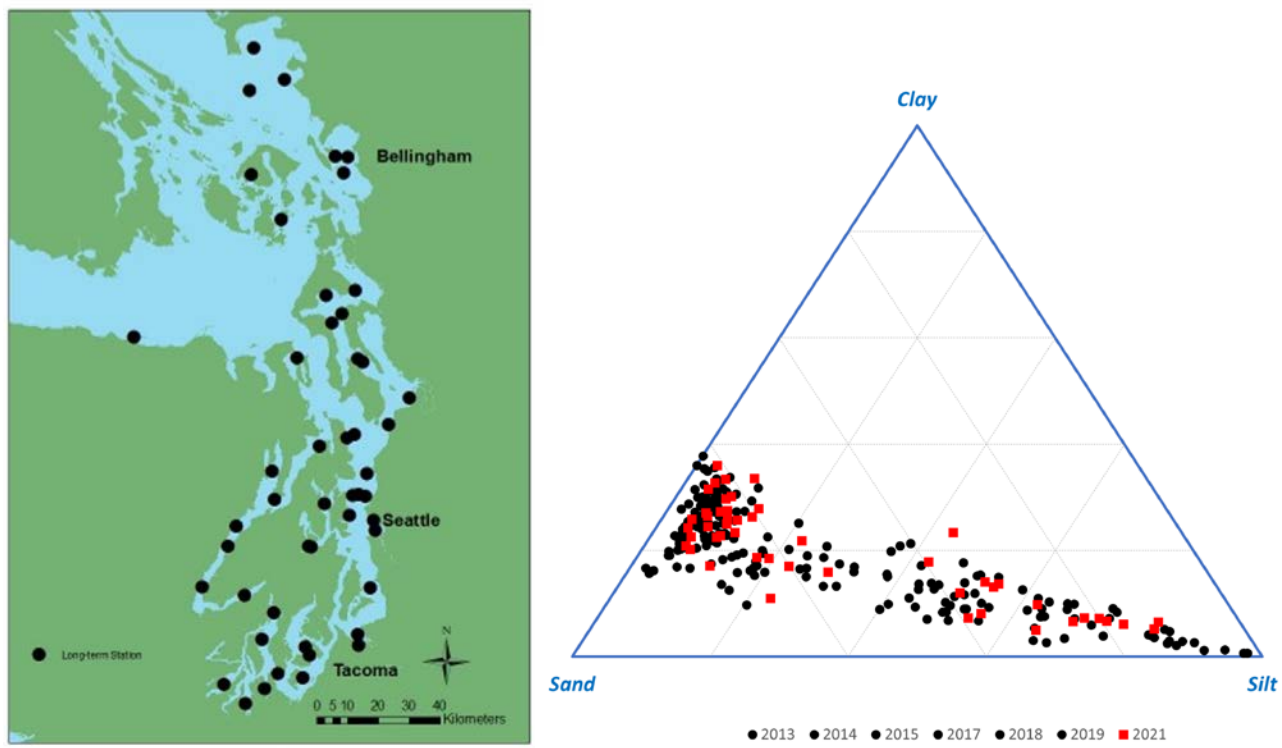


Figure 10.1. Map of Puget Sound with sampling location and ternary plot of sediment-type.

B. Plastic pollution in bed sediment

Benthic index
Sediment chemistry

Source: Julie Masura (jmasura@uw.edu), Margaret Baer, and Cheryl Greengrove (UWT); www.tacoma.uw.edu; Student contributors: Erin Campion, Celine Jolibois, Abby Deaton, Brenda Solano Jimenez, Amy Self, Roger Chang, Ashley Fowler, and Shannon Wacholz.

In 2018, 359 million tonnes of plastics were produced worldwide, with 59% common polymers (e.g., polyethylene, polypropylene, polyvinyl chloride; PlasticsEurope 2019). The rate of input of ocean plastic is estimated to be approximately 9.5 million tonnes per year. Primary plastics are those manufactured at the size for use, and secondary plastics are those that have broken down from primary plastics. Size-categories for plastics are macroplastics (> 5 mm) and microplastics (< 5 mm).

This project explored microplastics in sediments collected throughout the Puget Sound from 2014-2021 to create baseline observations and determine if plastic pollution in sediments have changed over time. Washington State Department of Ecology's Marine Sediment Monitoring Group has provided sediment samples to analyze for microplastics since 2014. Ten long-term stations have been sampled using a 0.1 m^2 stainless steel van Veen grab sampler to recover 2-3 cm of the top sediment from the seabed. Each year the sediment samples were processed by undergraduate researchers for grain-size distribution, total organic content percentage, harmful algae abundance, and microplastic concentration as part of a summer research experience. Microplastics were concentrated through a series of density separations, sieving, and picking. Each piece was characterized by type, color, and size.

For 2021, microplastics concentrations in the wet sediment decreased in the Whidbey Basin, north of Seattle, and increased from Tacoma on south each by an order of magnitude since 2019 (Figure 10.2). All other stations' concentrations stayed the same. As with previous years, except 2017, microplastics were found at all stations sampled.

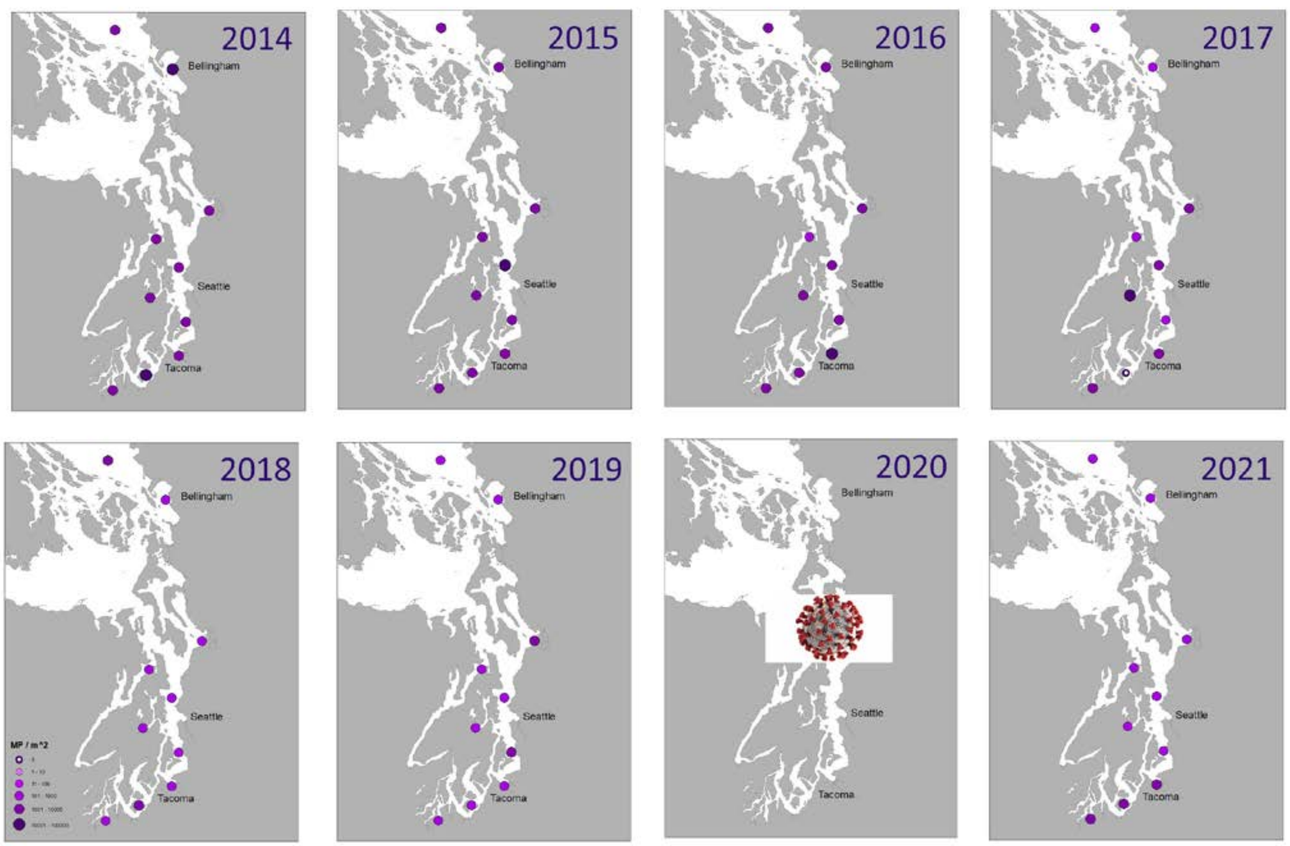


Figure 10.2. Time series of number of microplastics per square meter at 10 long-term stations in the Salish Sea from 2014-2021.

References

Barsh, R., M. Murphy, A. Assaf, and B. Bjordahl. 2022. "Foraging strategy, prey preferences, and limited competition among forage fishes in the San Juan Islands: Implications for Chinook recovery." Poster presentation, Salish Sea Ecosystem Conference, April 26, 2022.

Barsh, R., M. Murphy, M. Howard, and E. Fisher. 2021. "Juvenile Chinook" PSEMP Marine Waters Workgroup. 2021. Puget Sound marine waters: 2020 overview (J. Apple, et al., eds), p. 49.

Bigg, M.A. 1981. Harbour seal *Phoca vitulina Linnaeus*, 1758 and Phoca largha Pallas, 1811. – In: Handbook of marine mammals volume 2 seals (Ridgway, S.H. & Harrison, R.J., ed.). Academic Press, p. 1-27.

Brewer, G.D. Thermal tolerance and resistance of the northern anchovy, *Engraulis mordax*. October 1975. FISHERY BULLETIN: VOL.74. NO.2, 1976

British Columbia River Forecast Centre (BCRFC), 2021, Snow Survey and Water Supply Bulletin- January 1st to June 15th, 2021. BC Ministry of Forests, Lands, Natural Resource Operations, and Rural Development. https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/river-forecast/2021.pdf, Accessed 5/16/2022

Bumbaco, K.A., M.H. Rogers, L.W. O'Neill, D.J. Hoekema, C.L. Raymond, 2022. 2021 Pacific Northwest Water Year Impacts Assessment. A collaboration between the Office of the Washington State Climatologist, Climate Impacts Group, Oregon State Climatologist, Idaho Department of Water Resources, and NOAA National Integrated Drought Information System. https://www.drought.gov/sites/default/files/2022-02/PNW-Water-Year-Impacts-Assessment-2021.pdf. Accessed 5/18/2022

Calambokidis, J., J.A. Fahlbusch, A.R. Szesciorka, B.L. Southall, D.E. Cade, A.S. Friedlaender. 2019. "Differential Vulnerability to Ship Strikes Between Day and Night for Blue, Fin, and Humpback Whales Based on Dive and Movement Data From Medium Duration Archival Tags." Frontiers in Marine Science.

Calambokidis, J., 2018. "Update on research efforts on humpback and other endangered whales in 2018 with an emphasis on Washington waters." WDFW/NOAA contract report.

Chamberlin, J., M. Gamble, K. Connelly, J. Gardner, R. Barsh, J. Keister, D. Beauchamp, M. Schmidt, B. Beckman, and K. Warheit. 2017. Assessing early marine growth in juvenile Chinook salmon: factors affecting variability in individual growth in Northern Puget Sound. Salish Sea Marine Survival Project. Available online: https://marinesurvivalproject.com/resources/

Downing, J.A., C.T. Cherrier, R.W. Fulweiler. 2016. Low ratios of silica to dissolved nitrogen supplied to rivers arise from agriculture not reservoirs. Volume 19, Issue 12, December 2016, Pages 1414-1418, https://doi.org/10.1111/ele.12689

Gaydos, J.K., and S.F. Pearson. 2011. Birds and mammals that depend on the Salish Sea: A compilation. *Northwestern Naturalist* 92:79–94.

Hamade, T. and S. Kim. 2021. Stratification potential-energy anomaly index standardized by external tide level. Estuarine, Coastal and Shelf Science, 250, 107138.

Krembs, C., 2012. Marine Water Condition Index: Washington State Department of Ecology. Publication no. 12-03-013, May 2012. Pp.127.

Laake, J.L., J. Calambokidis, S.D. Osmek, and D.J. Rugh. 1997. Probability of detecting harbor porpoise from aerial surveys: Estimating g(0). *Journal of Wildlife Management* 61:63-75.

Marston, B.H., Willson, M.F. & Gende, S.M. (2002). Predator aggregations during eulachon *Thaleichthys pacificus* spawning runs. – Mar. Ecol. Prog. Ser. 231: 229-236.

Moore, S. K., N. J. Mantua, J. P. Kellogg, and J. A. Newton. 2008. Local and large-scale climate forcing of Puget Sound oceanographic properties on seasonal to interdecadal timescales. *Limnology and Oceanography* 53(5):1746–1758.

NOAA/ESRL website: https://www.esrl.noaa.gov/gmd/ccgg/trends/gl_data.html; accessed – May 26, 2022.

Office of the Washington State Climatologist, 2021. May 2021 Report and Outlook, Volume X, Issue 5. University of Washington. https://climate.washington.edu/wp-content/uploads/2021May.pdf, Accessed 5/18/2022

Petrou, E.L. et al. 2021. Functional genetic diversity in an exploited marine species and its relevance to fisheries management. *Proceedings of the Royal Society B* 288: 20202398. https://doi.org/10.1098/rspb.2020.2398

PSEMP Marine Waters Workgroup. 2021. Puget Sound marine waters: 2020 overview. J. Apple, R. Wold, K. Stark, J. Bos, P. Williams, N. Hamel, S. Yang, J. Selleck, S. K. Moore, J. Rice, S. Kantor, C. Krembs, G. Hannach, and J. Newton (Eds).

Sandell, T., A. Lindquist, P. Dionne, and D. Lowry. 2019. 2016 Washington State Herring Stock Status Report. Washington Department of Fish and Wildlife, Fish Program Technical Report No. FPT 19-07, Olympia, WA.

Simpson, J.H. and J.R. Hunter. 1974. Fronts in the Irish Sea. *Nature*, 250, 404-406.

Siple and Francis, 2015. Population diversity in Pacific Herring of the Puget Sound, USA. *Oecologia*, 180 (1): 111-125.

Scheffer, V.B. & Slipp, J.W. 1944. The harbor seal in Washington State. – *Amer. Mid Nat.* 32(2): 373-416.

Vierling E, S. Veirs, V. Veirs. 2022. "An open access humpback non-song vocalization catalogue for Haro Strait (WA, USA)." https://www.orcasound.net/portfolio/humpback-catalogue

Zamon, J.E. 2001. Seal predation on salmon and forage fish schools as a function of tidal currents in the San Juan Islands, Washington, USA. – *Fish. Oceano.* 10(4): 353-366.

Zier, J.C. & Gaydos, J.K. 2014. Harbor seal species profile. – Encyclopedia of Puget Sound, University of Washington Puget Sound Institute.

Acronyms

AGL	above ground level
APL	Applied Physics Laboratory
ARC	annual rate of change
BCRFC	British Columbia River Forecast Center
BEACH	Beach Environmental Assessment, Communication and Health
cc	cubic centimeter or 1 milliliter
CDOM	colored dissolved organic matter
cfs	cubic feet per second
CFU	Colony Forming Unit
Chl-*a*	chlorophyll-*a*
CICOES	UW Cooperative Institute for Climate, Ocean, and Ecosystem Studies
cms	cubic meters per second
CO_2	carbon dioxide
CrI	credible intervals
CPUE	catch per unit effort
CTD	conductivity, temperature, depth
DA	domoic acid
DFO	Fisheries and Oceans Canada
DIC	dissolved inorganic carbon
DO	dissolved oxygen
Ecology	Washington State Department of Ecology
ENSO	El Niño–Southern Oscillation
EPA	Environmental Protection Agency
ESRL	NOAA Earth System Research Laboratory
FHL	Friday Harbor Laboratories
FISH	fluorescent in situ hybridization
ft^3/s	cubic feet per second
g	gram
HAB	harmful algal bloom
HCSEG	Hood Canal Salmon Enhancement Group
IOOS	Integrated Ocean Observing System
KC	King County
KCDNRP	King County Department of Natural Resources and Parks
KCEL	King County Environmental Laboratory
KWT	Kwiáht
L	liter
LUM	Lummi Nation
m	meter
m^2	square meter
m^3/s	cubic meters per second
mg C/m^3	milligrams carbon per cubic meter
mg/L	milligrams per liter
MARINe	Multi-Agency Rocky Intertidal Network
MHW	mean high water
MPN	most probable number
mt	metric ton
NANOOS	Northwest Association of Networked Ocean Observing Systems
NERR	National Estuarine Research Reserve
NEMO	Northwest Enhanced Moored Observatory
NIT	Nisqually Indian Tribe
NMDS	non-metric multidimensional scaling
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWFSC	Northwest Fisheries Science Center
OA	ocean acidification
ORCA	Ocean Research College Academy
O_2	molecular oxygen
OM	organic matter
OWSC	Office of the Washington State Climatologist
PAR	Photosynthetically Active Radiation
pCO_2	partial pressure of carbon dioxide
PCRG	Pacific Northwest Crab Research Group
PDO	Pacific Decadal Oscillation
PGST	Port Gamble S'Klallam Tribe
PFEL	Pacific Fisheries Environmental Laboratory
PI	Protection Island
PMEL	Pacific Marine Environmental Laboratory
ppm	parts per million
PSEMP	Puget Sound Ecosystem Monitoring Program
PSI	Puget Sound Institute
PST	Paralytic Shellfish Toxin
PSU	practical salinity unit
PWSP	previous winter survey period
S	salinity
SLP	sea level pressure
SSS	southern Salish Sea
SST	sea surface temperature
STIL	Stillaguamish Tribe
Sw	sea water
T	temperature
T-S	temperature-salinity
TA	total alkalinity
TMin	minimum daily temperature
TUL	Tulalip Tribe
µatm	microatmospheres
µg	microgram
µm	micrometer
USGS	United States Geological Survey
UW	University of Washington
UWT	University of Washington-Tacoma
WB	Whidbey Basin
WDFW	Washington Department of Fish and Wildlife
WDOH	Washington State Department of Health
WDNR	Washington Department of Natural Resources
WMO	World Meteorological Organization
WSG	Washington Sea Grant
xCO_2	mole fraction of carbon dioxide
°C	degrees Celsius

View from Mt. Constitution. Photo: Rachel Wold

PSEMP

PUGET SOUND ECOSYSTEM MONITORING PROGRAM

PUGET SOUND INSTITUTE

UNIVERSITY of WASHINGTON