puget sound marine waters

2020 overview

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

Puget Sound Ecosystem Monitoring Program

Puget Sound Institute University of Washington

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

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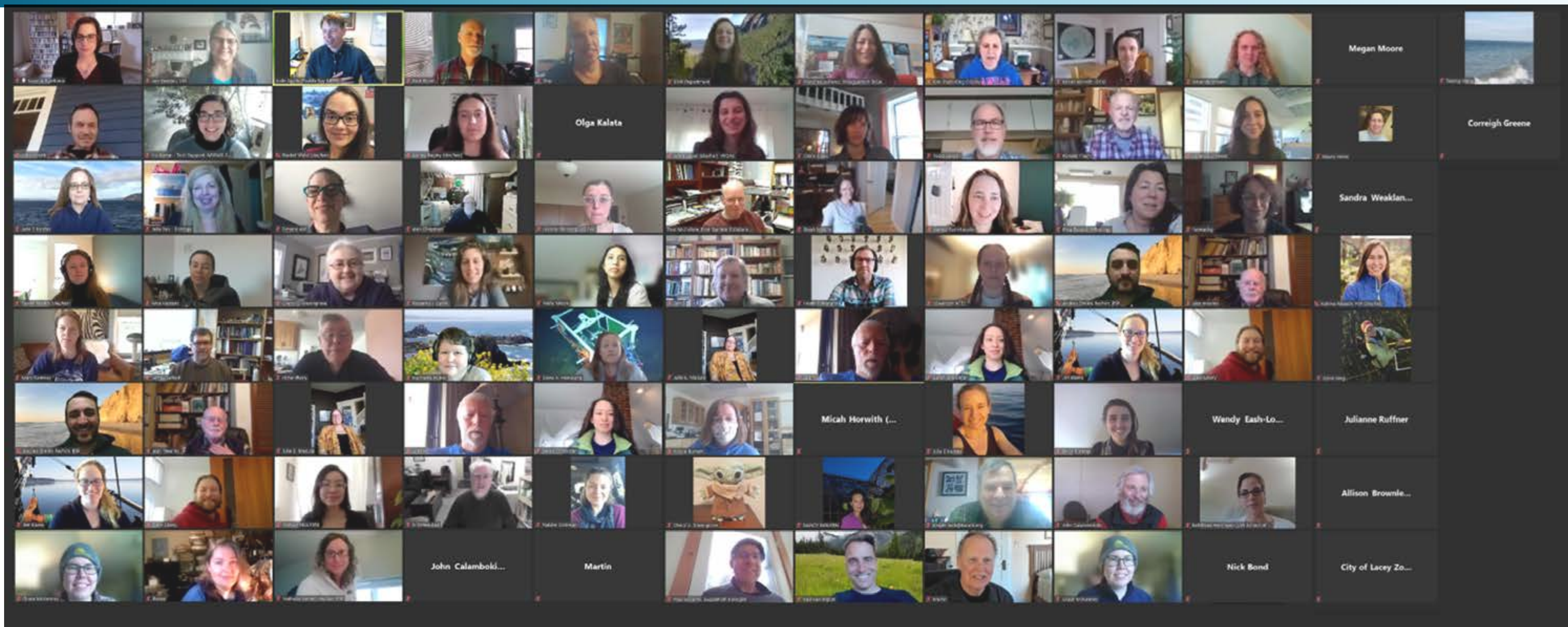
Mukilteo-Clinton ferry terminal
Front cover and title page photo: Rachel Wold

Citation and contributors



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

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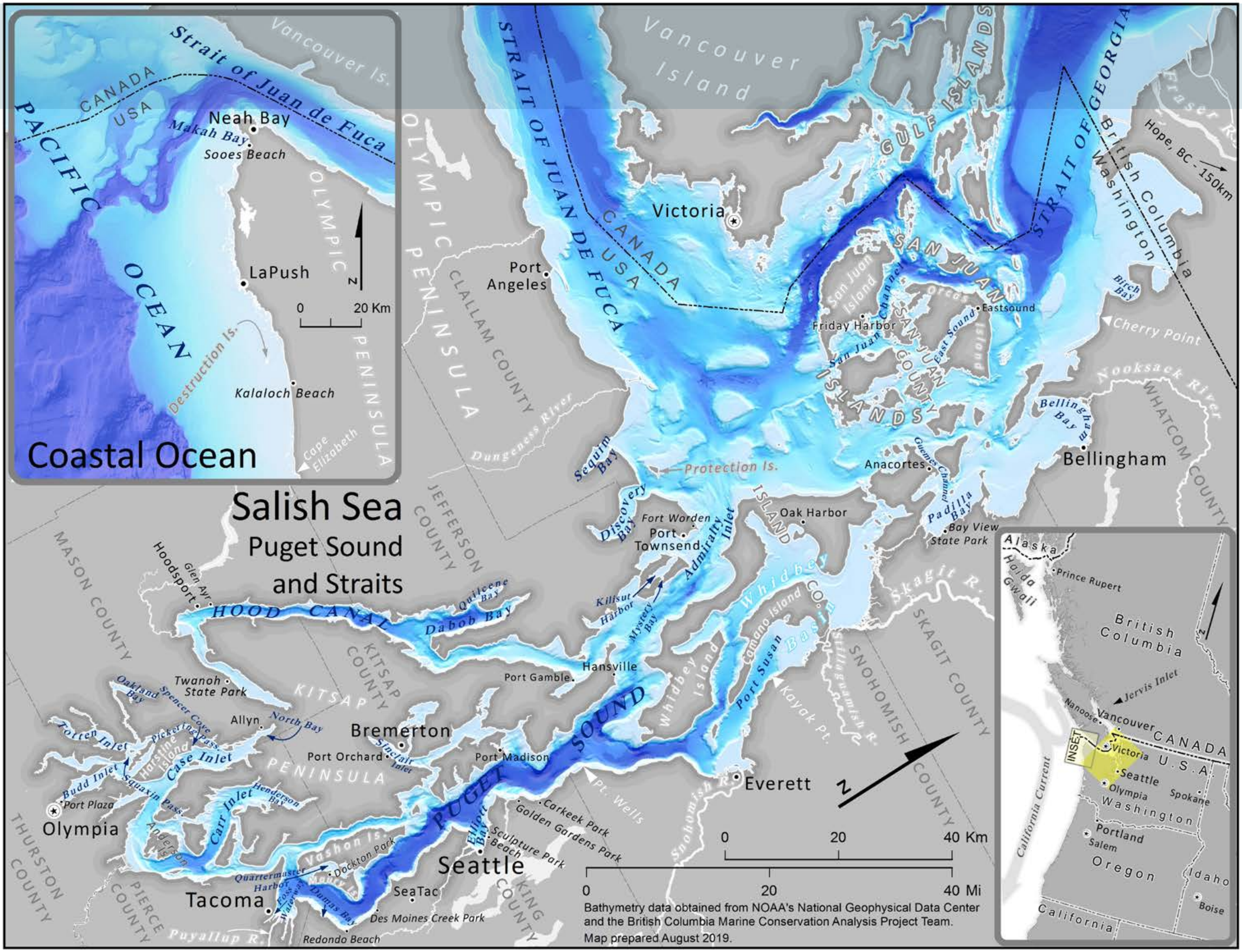

Map: Damon Holzer

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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 2020 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 tenth 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 2020.

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 sections of 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 all of the individual contributions and describes the overall trends and drivers of variability and change in Puget Sound's marine waters during 2020.

The larger picture that emerges from this report helps the PSEMP Marine Waters Workgroup to:
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 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 participating entities. 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). Full content from each contributor can be found after the executive summary, including website links to more detailed information and data.

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.

Birds
Chinook Salmon
Marine Water Quality
Outdoor Activity
Pacific Herring
Summer Stream Flows

The technical summaries presented in the Puget Sound Marine Waters: 2020 Overview span a range of topics, from marine water quality and climate to marine birds and other ecosystem indicators. The goal of the Marine Waters Annual Overview report is to connect the status, trends, and drivers of ecological variability in Puget Sound marine waters and do so in a way that serves Puget Sound ecosystem recovery efforts.

At the core of these efforts are six goals, further articulated by the Puget Sound Vital Signs. The Vital Signs and their representative indicators are measures of ecosystem conditions. They also help to better define and gauge progress toward the six goals for ecosystem recovery, shown in the outer ring of Figure VS.1.

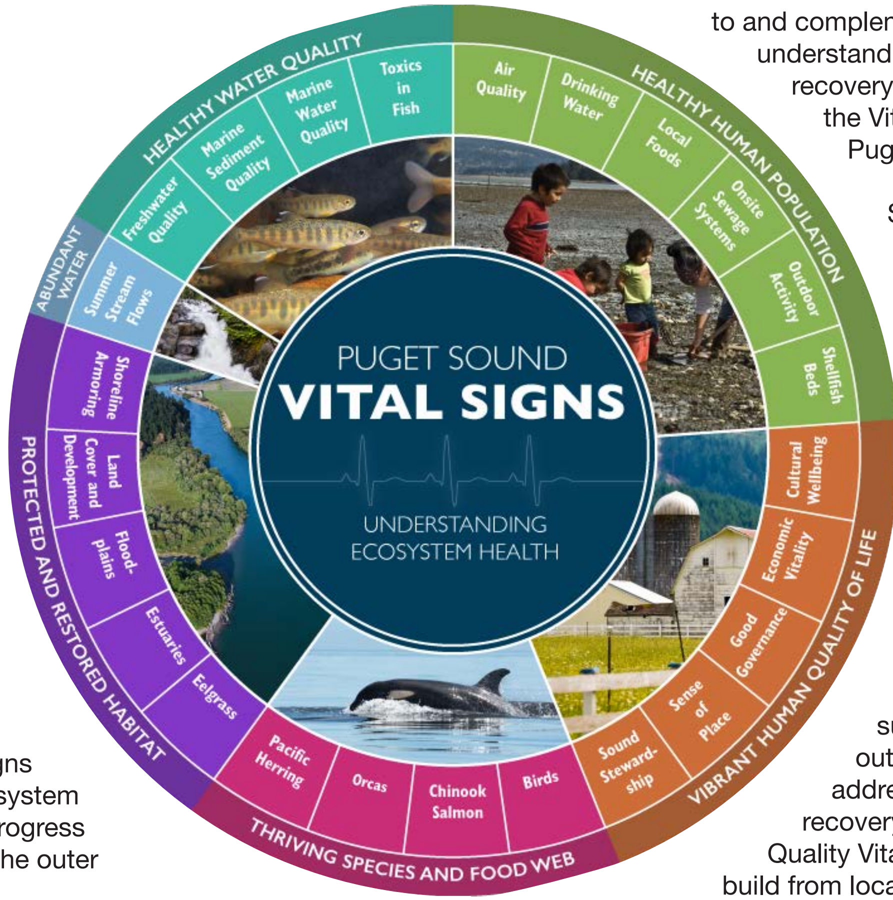


Figure VS.1. Puget Sound Vital Signs adopted in 2010 and 2015 by the Puget Sound Partnership.

One of the fundamental aspects of PSEMP's mission is to monitor the ecosystem in support of Vital Sign reporting. To this end, 26 of the 30 technical summaries (87%) included in the 2020 Overview report collectively inform four ecosystem recovery goals and six of the Vital Signs adopted by the Puget Sound Partnership in 2010 and 2015 (Figure VS.1 and VS.2). Technical summaries are considered to have informed a given recovery goal and/or Vital Sign if quantitative observations of that Vital Sign 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.

Six Vital Signs are addressed in the technical summaries of the 2020 Overview — fewer than the nine covered in 2019. We attribute this to the effect of the COVID-19 pandemic on monitoring programs across the state, which resulted in a lower number of overall submissions for the 2020 Overview. Given the focus of the Annual Overview on marine water quality conditions, it is not surprising that most technical summaries in this edition (19 out of 30; Figure VS.2) exclusively address the Healthy Water Quality recovery goal and Marine Water Quality Vital Sign. Those summaries build from local and regional monitoring efforts to assess water temperature, dissolved oxygen, nutrient balance, phytoplankton, ocean acidification and other important parameters. Some of these parameters 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]

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

Vital Signs (cont.)

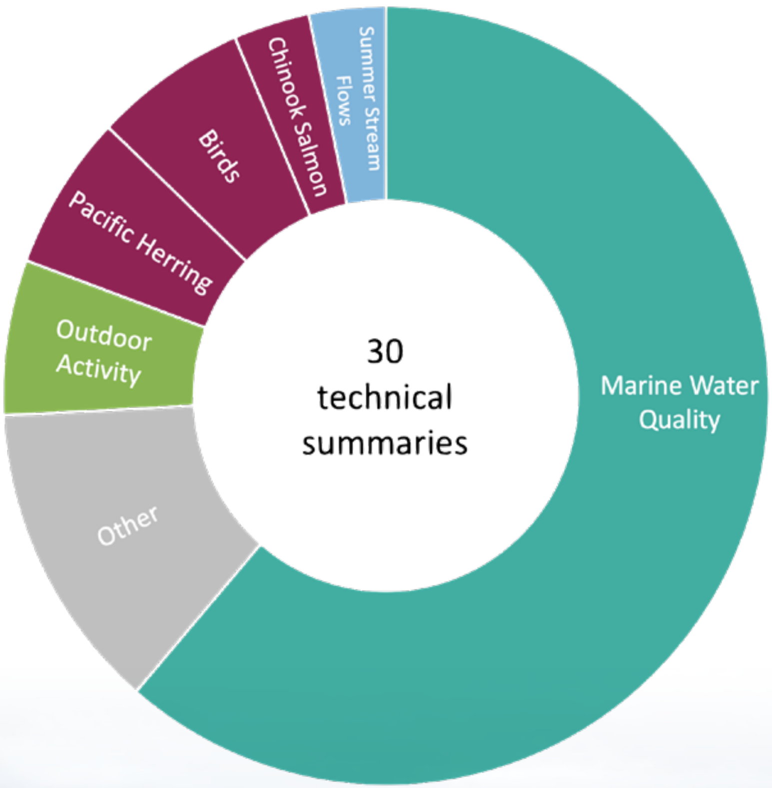


Figure VS.2. The distribution of the number of technical summaries informing Vital Signs, sorted by recovery goal. The number at center is the total number of technical summaries in this 2020 edition of the Marine Waters Annual Overview, some of which inform more than one Vital Sign. The "Other Topics" category covers ecosystem components not currently addressed by the Vital Signs.

Seven of the 30 technical summaries inform three other recovery goals and five other Vital Signs (Figure VS.2). These include studies of Pacific herring, birds, and salmon, which address Vital Signs in the Species and Food Webs goal, and data on streamflow which address the Abundant Water goal. Two summaries report the presence of harmful bacteria at swimming beaches and are therefore tied to the Human Wellbeing goal for Healthy Human Populations, directly informing natural resource and public health management.

Four technical summaries did not directly connect to current Vital Signs (Figure VS.2), although they represent important ecological and climatic processes in Puget Sound. These summaries focused on air temperature (to date, not a component of the Air Quality Vital Sign) and zooplankton. Our evaluation of the connectivity between technical summaries and Vital Signs for the 2020 edition of the Overview relied on the Vital Signs and indicators adopted by the Puget Sound Partnership between 2010 and 2015. More recently, the Partnership revised the Vital Signs (see a related fact sheet[1] and a full report[2] on the subject) and anticipates reporting on these new metrics beginning in 2022. The scope of the revised Vital Signs has increased and includes ecosystem components typically addressed in the annual Overview, such as zooplankton and groundfish. We expect that even more technical summaries will inform Vital Signs in future editions of the Annual Overview report.

1 https://pspwa.box.com/s/10utqrjbcj138nf5oejl1ogjxihvky4a
2 https://pspwa.box.com/s/rqn16bdt9gr6r7gypb399ugv5mlrmidi

Whidbey Island. Photo: Rachel Wold

A Summary of What Happened in 2020

This brief synopsis describes patterns in water quality and conditions and associated biota observed during 2020 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 a goal of the PSEMP Marine Waters Workgroup.

While the year 2020 presented many challenges to the human population due to the COVID-19 pandemic, it was somewhat typical in terms of Puget Sound water properties and biota, with only a few extremes observed. We acknowledge the efforts of those who were able to safely secure the data presented in this volume, a testament to human dedication and effective procedures. In particular, volunteer-based monitoring efforts and autonomous sampling instruments deployed in Salish Sea waters allowed us to overcome barriers and maintain data collection, which otherwise would have been lost. This Overview edition is a tribute to the resilience of the scientists and institutions producing it.

External climate forcing was not strong during 2020; El Niño-Southern Oscillation was near neutral with only moderate La Niña conditions in fall and the Pacific Decadal Oscillation was weakly to moderately negative. Coastal upwelling was typical but transitioned earlier in the year than usual. The annual average of air temperature was above normal although there was variability, with months mostly near-normal to above normal, but a cooler than normal March and a very warm September. Sunlight was generally above normal, though occluded by wildfire smoke in September. The annual average of precipitation was above normal, with a notable 6th wettest January on record accompanied by river flooding. River discharge peaks were typical except that their duration into the year was longer, especially for the Fraser River. Together, these conditions indicate a generally warmer, sunnier, and wetter year, but not extreme.

Human effects were evident in Hood Canal. While the annual average atmospheric carbon dioxide (CO_2) values over Hood Canal were more enriched in CO_2 than globally averaged marine surface air, these were at the same level as in 2019 rather than showing the typical annual increase observed in the record, possibly reflecting reduced regional emissions due to COVID-19 impacts. However, west coast wildfires put a definite mark on conditions in 2020, with not only reduced sunlight, but also increased atmospheric CO_2 levels on the coast and in Puget Sound during September.

Coastal deep waters, source waters to the Salish Sea, were cooler than typical as recorded since 2014 and may have been influenced by La Nina conditions. Surface waters returned to near normal, signaling the end of the 2019 marine heat wave. Deep water oxygen was anomalously high but then dropped rapidly to hypoxia in mid-September.

How this translated to Puget Sound is intriguing. Water temperatures were generally close to average, though with many regional and temporal differences. The cooler coastal waters may have tempered Puget Sound waters that have been warmer than average for many years, primarily due to marine heat waves in 2015-16 and 2019. Buoy data indicated that 2020 and 2017 are the only years since the 2015-16 marine heat wave when sea temperatures were not predominantly above normal. Though runoff and precipitation were somewhat above normal, salinity in Puget Sound was generally higher than average, suggesting that the longer period of upwelling of cool and salty waters had the predominant influence. Both Puget Sound's temperature and salinity conditions during 2020 highlight the strong controlling influence of the coastal ocean on these inland waters.

There were no fish kills nor reports of strong hypoxia reported in 2020. Oxygen concentrations, which are influenced by regional photosynthesis, producing oxygen in surface waters, and its ultimate respiration at depth, as well as the input of upwelled waters with low oxygen, showed highly variable conditions though not particularly high or low values compared to long-term averages. Seasonal blooms and hypoxia were seen in isolated areas like south Hood Canal, Quartermaster Harbor, and Port Susan, but not were extreme.

Plankton monitoring efforts were somewhat impacted by COVID restrictions; the limited interpretations of general patterns noted here do not show patterns out of the ordinary. Seasonal phytoplankton blooms were evident in the Main Basin of Puget Sound, with diatoms predominating as usual and transitioning to flagellates in summer, including a large *Heterosigma* bloom in the Central Basin. In general, harmful algal blooms were variable but not notable. Zooplankton were relatively typical but with higher abundance and biomass in northern Puget Sound and Padilla Bay. Species differences are important for interpreting biomass. Modest abundances of a large oceanic copepod in the north yielded high biomass,

yet record high abundance of a smaller resident copepod in the south did not translate to high biomass. Bacterial contamination of beaches and waters were low to typical, with most of the contamination in September through December in association with rainfall.

Farther up the marine food web, there was a mix of good news and bad. 2020 was a banner year for Pacific herring, with the highest estimated biomass since 1984; however, this is skewed by only two successful stocks, indicating a loss in diversity of the herring stock portfolio. Analysis of consumption of forage fish by other fish species in the San Juan Islands shows less feeding by juvenile Chinook salmon on Pacific sand lance, relative to Pacific herring. Marine birds showed typical (for scoters) to low (for fish-eating species) abundances. An encouraging observation is that the rhinoceros auklet breeding effort and reproductive success that, after three consecutive years of anomalously poor conditions had returned to long-term average values in 2019, were stable in 2020. Fall densities of harbor porpoise, Steller sea lion, and harbor seal in the eastern Strait of Juan de Fuca were relatively low compared to the 15-year record but slightly above the last two years with a higher density of harbor seals.

In summary, 2020 was not exceptional in its oceanographic properties, which is a potential reprieve from the marine heat wave and summer drought influences that have been so strong in recent years. Plankton indicated a relatively abundant, though regionally variable, population. Whether, or how quickly, these conditions may translate up the food web, is not known. This underscores the value of sustained long-term observations and the importance of synthesis of the data, as we collectively present here.

State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Salish Sea Marine Ecosystem in 2020

This summary of Salish Sea marine water conditions is based on a subset of the Fisheries and Oceans Canada report, The State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2020.

Every year the Pacific region of Fisheries and Oceans Canada (DFO) convenes a meeting of the marine science community to present the results of the most recent year's monitoring in the context of previous observations and expected future conditions. The results, which are published annually in a Departmental Technical Report (http://waves-vagues.dfo-mpo.gc.ca/Library/4098297x.pdf), provide fundamental information to assess the status of Pacific ecosystems and to develop a picture of how the ocean is changing. While several monitoring programs were cancelled due to the COVID-19 pandemic, there were other surveys that were able to proceed at least partially.

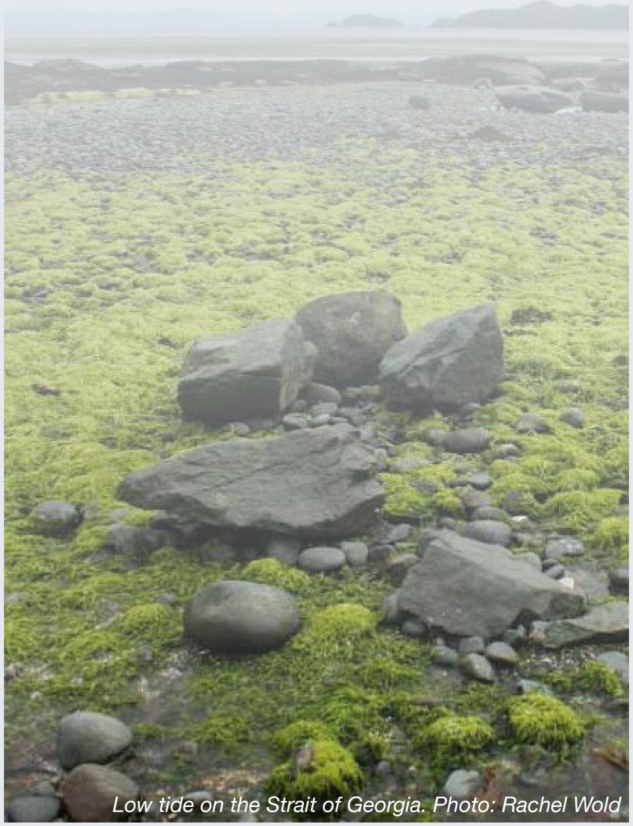
Climate change is a dominant pressure acting on North Pacific marine ecosystems. A marine heatwave in the NE Pacific was observed in 2019-2020; the cooling influences of a La Niña that emerged in the latter half of 2020 kept extreme warm ocean temperatures away from coastal B.C. waters. During 2020 in the Strait of Georgia (SoG), summer water temperatures and salinity conditions were near normal, but oxygen concentrations in the upper 100 m were lower than normal (Chandler 2021). The fall survey captured an intrusion of cooler, saltier and poorly oxygenated water from the Pacific Ocean (Chandler 2021). Fraser River discharge was significantly higher than normal in 2020 (about 30% greater than the 100-year average) (Chandler 2021). Severely acidic conditions were again observed in the Northern Salish Sea and Fitz Hugh Sound, but the duration of these events was shorter in 2020 than in 2019; however, ocean acidification will continue to intensify as anthropogenic carbon input increases (Evans et al. 2021).

In 2020, blooms of the harmful algae, *Heterosigma akashiwo*, were more abundant than in 2015-2017 and 2019, but less than in 2018 (Esenkulova et al. 2021). European green crab, an Aquatic Invasive Species, have been found in low numbers in the Salish Sea (Howard and Therriault 2021) and, in 2020, detected for the first time on Haida Gwaii. Marine vessel traffic intensity, which is a source of multiple pressures, such as oil, noise, and shipstrikes, increased in the Salish Sea from 2015-2017 for nearly all types of vessels (O'Hara et al. 2021).

In the SoG, the spring bloom timing was similar to the long-term average (Allen et al. 2021; Dewey et al. 2021) and the zooplankton biomass was above the long-term average (Young et al. 2021) – which implies good feeding conditions for juvenile fish. In 2020, the SoG Pacific herring spawning biomass was relatively high compared to historic levels (Cleary et al., 2021). The index of Fraser River eulachon spawning stock biomass was relatively high (~624 tonnes), approximately equal to the 2001 index and higher than all years since 2001 (Flostrand 2021).

In the SoG, fall juvenile Chinook and Coho salmon abundances were the highest and fourth highest observed in the time series, respectively (Neville 2021). Adult returns of most Sockeye, Chinook, and Chum salmon stocks, however, were low in 2020, while returns of Coho and Pink salmon varied by stock (Grant et al. 2021). Fraser River Sockeye salmon that matured in odd-numbered years were generally smaller than those that matured in even-numbered years (Latham et al. 2021).

Assembled by Jennifer Boldt (Fisheries and Oceans Canada, Pacific Biological Station) and Peter Chandler ((Fisheries and Oceans Canada, Institute of Ocean Sciences); https://www.dfo-mpo.gc.ca/oceans/publications/index-eng.html



Low tide on the Strait of Georgia. Photo: Rachel Wold

Highlights from 2020 Monitoring

Large-scale climate variability and wind patterns

- A near-neutral El Niño–Southern Oscillation (ENSO) state in early 2020 was followed by moderate La Niña conditions in autumn 2020 that persisted into 2021.
- The Pacific Decadal Oscillation (PDO) was weakly negative from February through April 2020, and moderately negative from September through December.
- Exceptionally strong downwelling occurred in January, followed by an early transition towards upwelling conditions in February of 2020.

Local climate and weather

- Puget Sound air temperatures were generally higher than normal in 2020, with September the warmest on record. All months (except March) had near-normal to above normal temperatures
- Sunlight levels were higher than normal in 2020, but diminished by wildfire smoke in September. Total precipitation for Puget Sound was also above normal. January was the 6th wettest on record, resulting in minor to moderate river flooding.

Coastal ocean and Puget Sound boundary conditions

- Deep water was cooler with elevated dissolved oxygen (DO) relative to previous years, with deep water DO dropping to hypoxic conditions in fall. During summer to early fall, deep water was the coolest since 2014, with water less than 8°C spanning more than half of the water column.
- Surface seawater temperatures were normal, recovering from the 2019 marine heat wave.
- Atmospheric and surface seawater CO_2 levels were comparable to previous years.
- Elevated levels of atmospheric CO_2 were observed in September and October at all mooring sites, coincident with extensive forest fires on the U.S. West Coast.

River inputs

- Freshwater inputs to the Salish Sea were generally above historic volumes, attributed to above normal snowpack accumulation in January and February.
- Peaks in river discharge were generally as expected, with some smaller variability throughout the year. Summer flows on the Fraser remained high and did not drop below the historical median, while Puget Sound rivers reached below normal levels during mid-August though for a shorter duration than previous years

Water quality

- Temperature
  - Puget Sound water temperatures were closer to the climatological average than recent years.
- Salinity and density
  - Salinities across Puget Sound exhibited a high degree of spatial and temporal variability.
  - Buoy data indicate that summer salinities were saltier than long-term averages, although salinities in Central Basin were near normal after elevated salinities in 2019 – resulting in a more stratified water column.
  - Fresher than average surface salinities and saltier than average deep waters were observed in San Juan Islands during fall.
  - Water column stratification during summer months in Padilla Bay was driven initially by freshwater input, then warming of the upper water column. The strongest period of stratification was delayed relative to previous years and persisted longer into the fall.
- Nutrients and chlorophyll
  - During spring and summer, higher than normal chlorophyll-*a* levels were observed in Port Susan and Central Basin. In Padilla Bay, elevated chlorophyll-*a* concentrations were higher than the previous five years and persisted longer into the year than in 2019. Elevated chlorophyll-*a* levels in Central Basin and Padilla Bay are attributed to strong density stratification of the upper water column.
  - Nutrient concentrations in surface waters of Central Basin were near normal throughout the year. Silica concentrations in surface and deep waters were higher than normal and attributed to riverine inputs.
- Dissolved oxygen (DO)
  - Dissolved oxygen concentrations in Puget Sound waters were near normal to above normal, with strong spatial and temporal variability. Elevated surface water DO during summer months was reported for Hood Canal (Twanoh), Central Basin, and Quartermaster Harbor.
  - Low to hypoxic conditions were observed in late summer through fall in South Hood Canal (Twanoh), Central Basin deep waters, and Port Susan. In contrast to previous years, late summer hypoxia was not observed in Quartermaster Harbor

- Ocean and atmospheric CO_2
  - » Annual average surface seawater CO_2 concentrations at moorings in Hood Canal were among the highest recorded in over a decade of monitoring.
  - » Average atmospheric CO_2 values over Hood Canal did not exhibit the expected annual increase associated with global fossil fuel emissions and were similar to 2019, yet remained enriched relative to globally averaged marine surface air values.

Plankton

- Phytoplankton
  - » Phytoplankton biovolume and abundance were greater than 2019 in Central Basin and Padilla Bay, respectively.
  - » The most frequent blooms in 2020 across Puget Sound were diatoms, including *Thalassiosira*, *Rhizsolenia*, and *Chaetoceros*. In Central Basin, chain-forming diatoms were the dominant taxa by biovolume, with *Chaetoceros* dominating biomass in late spring and summer. A mid-summer crash of the diatom population led to a bloom of the harmful dinoflagellate *Heterosigma* across the Central Basin.
  - » Composition of the phytoplankton community in Padilla Bay during summer 2020 was very different than that in 2019.
- Zooplankton
  - » Zooplankton abundance and biomass were generally similar to 2019, with spatial and temporal differences.
  - » Higher biomass and abundance was reported for northern regions of Puget Sound, including San Juan Islands, Bellingham Bay, and Padilla Bay. Abundance in Padilla Bay was the third highest since 2008 and indicated a rebound from lows observed during summer and fall 2019. High biomass in the San Juan Islands and Bellingham Bay was due to modest abundances of large oceanic copepod species.
  - » Lower biomass was generally observed in central and southern regions of Puget Sound. Although record high zooplankton abundance was observed in Central Basin, this was mainly due to smaller resident copepod species that did not translate to elevated biomass.
- Harmful algae and biotoxins
  - » Levels and frequencies of harmful phytoplankton that pose a threat to human health, including *Alexandrium*, *Dinophysis*, and *Pseudo-nitzschia* were variable in Puget Sound.
  - » *Alexandrium catenella* cyst abundances were generally lower than prior observations, yet areas of higher cyst abundance are consistent with past cyst hot spots, such as Quartermaster Harbor, Bellingham Bay, and bays in the western Main Basin of Puget Sound. Increased cyst abundances were also observed in Penn Cove, which has historically experienced paralytic shellfish toxin (PST) events.

Bacteria and pathogens

- Overall, there was a small increase in the number of beaches that met swimming standards in 2020 relative to 2019.
- In King County beaches, fecal indicator bacteria were generally within the normal range, while *Enterococcus* values were in the normal to high range for 2020. The highest fecal bacteria concentrations occurred in September through December, associated with increased rainfall
- Offshore bacteria concentrations in Central Basin were low in 2020, similar to previous years.

Fish

- Pacific Herring populations were strong in 2020, with the highest estimated biomass since 1984. Despite this success, herring populations in Puget Sound are increasingly reliant on two stocks (Hood Canal and Port Orchard/Port Madison), suggesting a loss of diversity.
- Juvenile Puget Sound-origin Chinook migrating through the San Juan Islands have been eating less forage fish than in 2011-2014. The decrease in forage fish consumption has been more pronounced in Pacific sand lance than Pacific Herring.

Marine birds and mammals

- Wintering marine birds showed typical (for scoters) to low (for fish-eating species) abundances during the 2019/2020 season.
- Abundance of forage fish specialists throughout the year was low compared to long-term monthly records going back as far as 2008.
- The number of scoters, a Puget Sound Vital Sign indicator, was relatively stable from November to February, with mean numbers within the range of the previous five years.
- Rhinoceros auklet breeding effort and reproductive success returned to long-term average values in 2019 and stabilized in 2020.

Highlights from 2020 Monitoring (cont.)

- Seabird density in the San Juan Islands was slightly higher than the previous two years, but much less than earlier in the long-term time series.
- As with seabirds in San Juan Islands, fall densities of marine mammals in the eastern Strait of Juan de Fuca were relatively low compared to the 15-year record but slightly above the last two years.

Healthy Ochre sea stars (Pisaster ochraceus) at Indian Island in East Sound, San Juan Islands, a monitoring site for Seastar Wasting Syndrome. Photo: Russel Barsh for Kwiaht

Technical Summaries

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

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)

Marine Water Quality

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

The tropical Pacific was slightly warmer than normal in early 2020, with the weak magnitude of the anomalies meaning ENSO was in the neutral category. Cooling occurred during the spring and summer of 2020 resulting in a moderate La Niña by fall. This transition was accompanied by anomalous winds from the east in the central equatorial Pacific and suppressed cumulus convection near the dateline. The remote atmospheric response to La Niña included higher than normal sea level pressure (SLP) over the Northeast Pacific centered near 40˚ N, 140˚ W during fall 2020. During that time of year, previous cool ENSO events have tended to be accompanied by positive SLP anomalies that are most prominent about 10˚ farther north and 25˚ farther west. A consequence of the atmospheric circulation pattern that prevailed in the latter portion of 2020 was wind anomalies of about 1 m/s from the northwest along the coast of the Pacific Northwest.

Low tide at Golden Gardens. Photo: Rachel Wold

1. Large-scale climate variability and wind patterns (cont.)

B. Pacific Decadal Oscillation (PDO)

Marine Water Quality

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

The PDO was in a negative state through most of 2020, with the exception of May and June, during which it had a value close to zero. This index had a value of about -1 at the end of 2020; this value is consistent with the La Niña that was occurring at the time, based on the historical correspondence between ENSO and the PDO. The PDO was negative largely due to relatively warm sea surface temperatures (SSTs) in the western and central North Pacific; the SST anomalies along the West Coast of North America were generally weak. The negative state of the PDO during 2020 occurred after a period of positive values for the PDO from 2014 through most of 2019. The early portion of that interval featured the major Northeast Pacific marine heat wave known as the “Blob.”

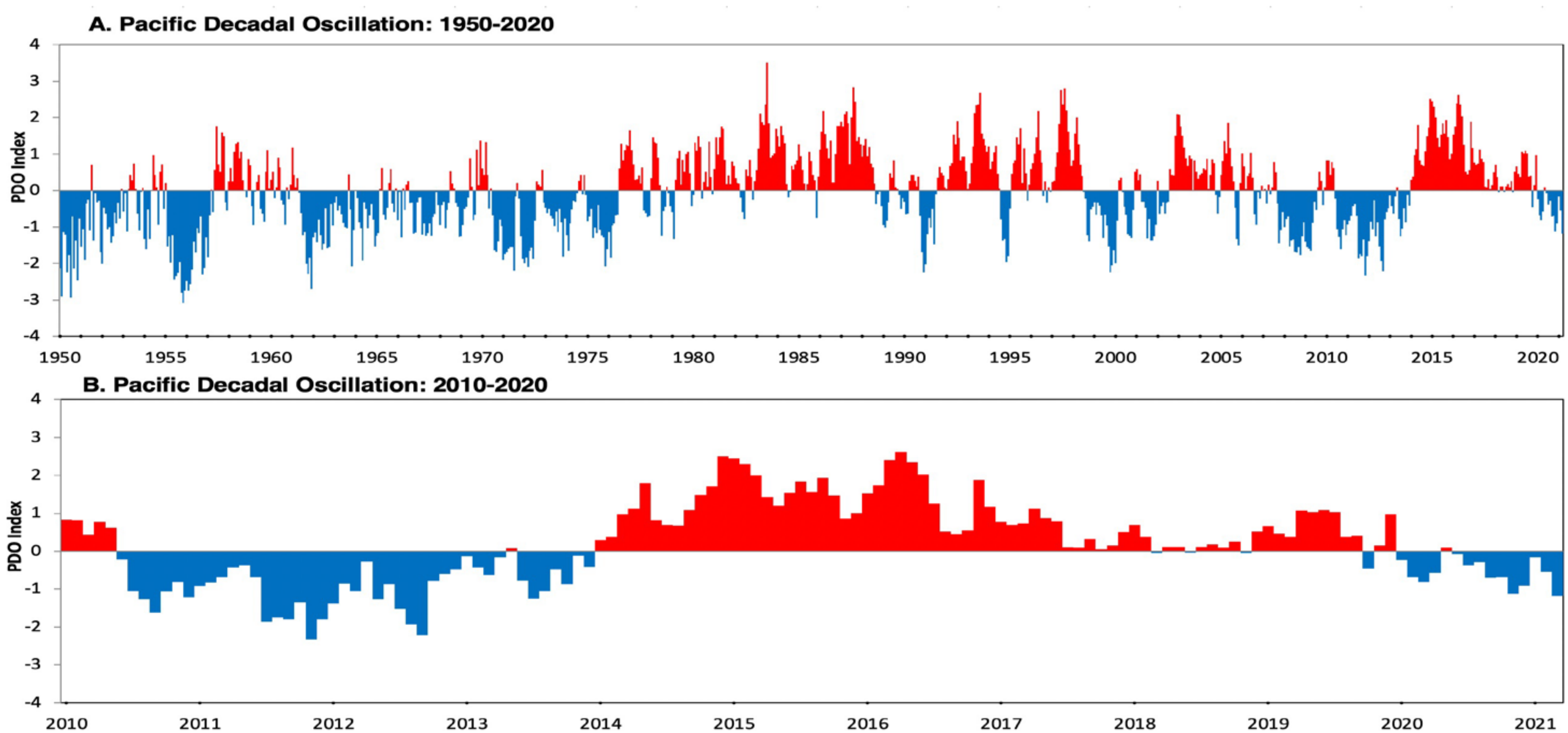


Figure 1.1. Monthly values of the Pacific Decadal Oscillation (PDO) Index from (A) 1950-2020 and (B) 2010-2020.

C. Upwelling index

Marine Water Quality

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 such as sufficient riverine input are met. 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), Christopher Krembs, Julia Bos, Mya Keyzers, Micah Horwith, and Natalie Coleman (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 Washington coastal waters, as these waters 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. The typical upwelling season for the Pacific Northwest is from April through September, while downwelling typically occurs during the wet winter months. This pattern was generally observed during 2020 (Figure 1.2). Strong downwelling occurred in January, followed by weaker downwelling again in February, repeating a pattern observed in 2018 and 2019. Strong downwelling-favorable winds did not resume again until November, which is slightly earlier than in 2019.

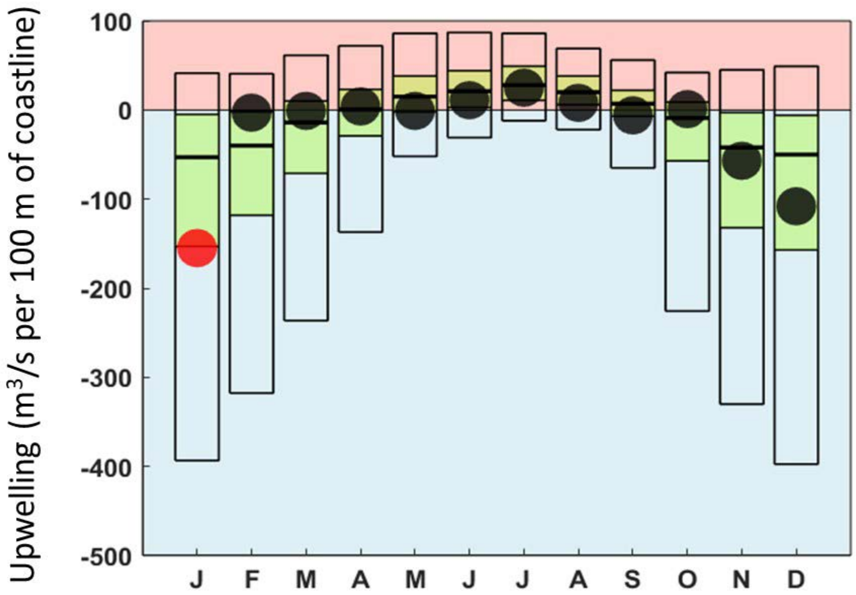


Figure 1.2. Monthly mean values of Pacific Fisheries Environmental Lab (PFEL) coastal upwelling index for 2020 (red and black dots). The box plots are based on index values at 48° N and 125° W from 1967 to 2018 and represent 5th and 95th percentiles, with the interquartile range (shaded green) and median 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

The 2020 calendar year was warmer and wetter than normal for the Puget Sound area, and the state as a whole. 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 2020 Puget Sound annual average air temperature (10.9°C; 51.7°F) was 0.8°F warmer than the 1981-2010 normal and 0.7°F warmer than 2019. Total annual precipitation was 124.03 cm (48.83”), which was 109% of normal, and wetter than the last two years.

Monthly values are used to illustrate the variability in the weather during the year. Figure 2.1 shows monthly temperature and precipitation anomalies for the Puget Sound region relative to the 1981-2010 normal. The year began warm and wet, with January ranking as the 6th wettest on record (since 1895), resulting in intermittent moderate river flooding through the first half of February. March was the only month that was substantially colder than normal. March and April were drier than normal and ranked as the 22nd driest combined, although this did not appear to affect snowpack which was relatively normal as of April 1. A shift occurred in May, which was the 18th wettest and 18th warmest on record. Wet conditions continued into June, but July and August were drier than normal. It is notable that the June, July, and August temperatures were near-normal. An east wind event in early September fanned multiple fires in the West Coast states, resulting in high concentrations of wildfire smoke in the Puget Sound region. Despite the cooling effect of the smoke, September ranked as the warmest on record. October, November, and the first half of December were drier than normal. Based on observations at the end of the year, warmer and dryer than normal conditions during fall did not appear to affect snowpack.

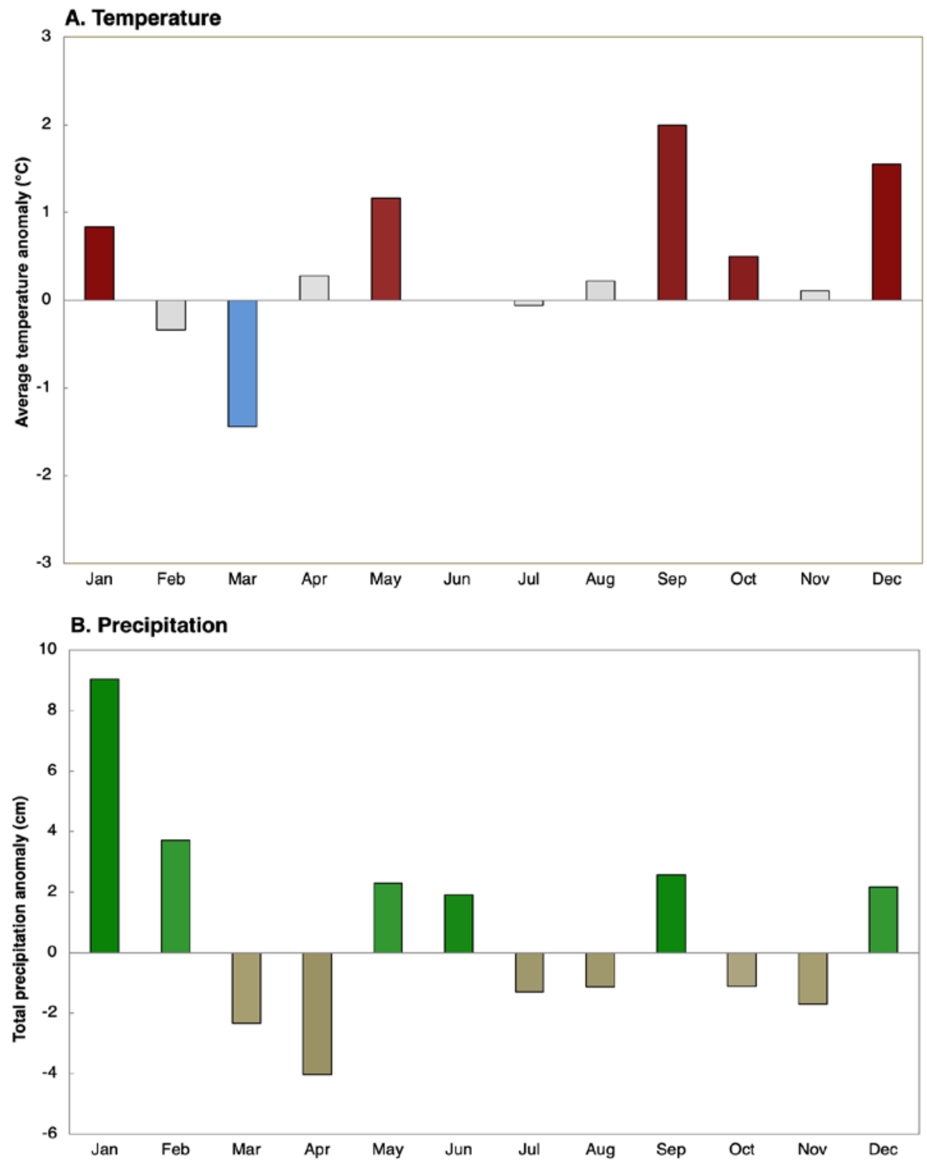


Figure 2.1. Monthly anomalies for (A) temperature (Celsius) and (B) precipitation (centimeters) for the Puget Sound Lowlands climate division in Washington State for the 2020 calendar year. Anomalies are relative to the 1981-2010 climate normal and are colored red (green) for above normal temperature (precipitation) anomalies and blue (brown) for below normal temperature (precipitation) anomalies.

B. Local air temperature and solar radiation

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

Air temperatures at SeaTac airport were mostly warmer than normal relative to the 1971–2000 historical baseline, especially during January, August, September, and December. March was the only month in 2020 that was cooler than normal (Figure 2.2A). Much of the summer was characterized by above average overnight temperatures (TMin). Sunlight, as measured by daily surface solar energy flux, was above average in April, July, and August (Figure 2.2B). Sunlight was lower in September, partially the result of wildfire smoke that was broadly distributed throughout the Puget Sound region for over a week (September 7-18). Lower sunlight levels in January, October, November, and December were attributed to cloudier than normal conditions. The effect of cloud cover on regional air temperature varies throughout the year. In the winter, clouds tend to retain heat and boost air temperatures, while they block surface heating during the summer. Integrated through the entire year, solar energy flux was the highest it has been since 2015.

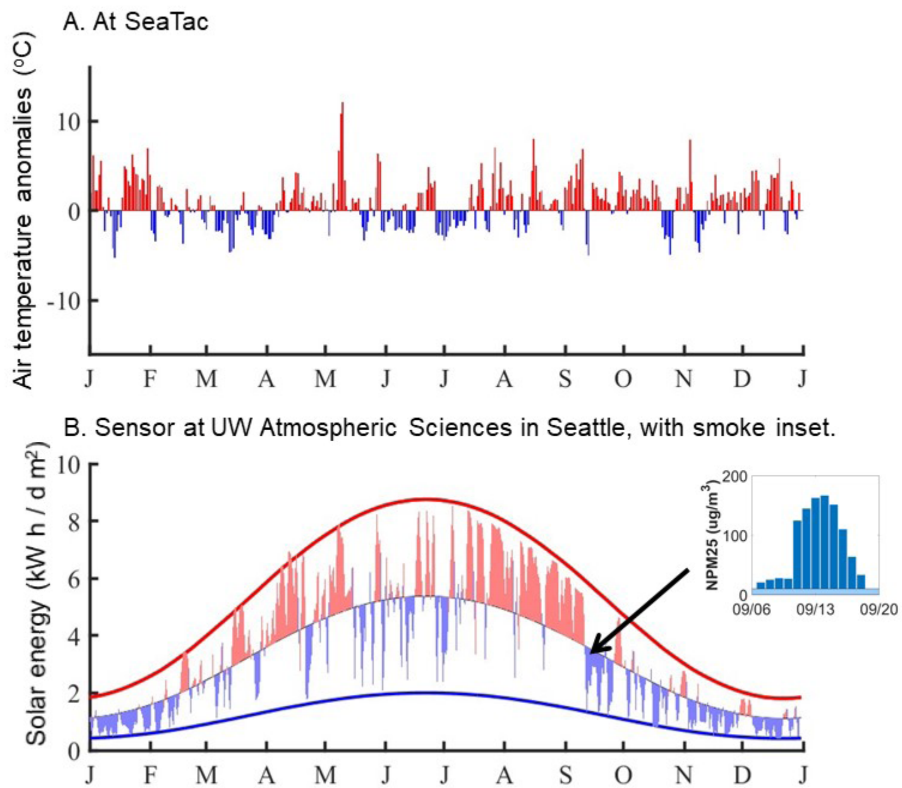
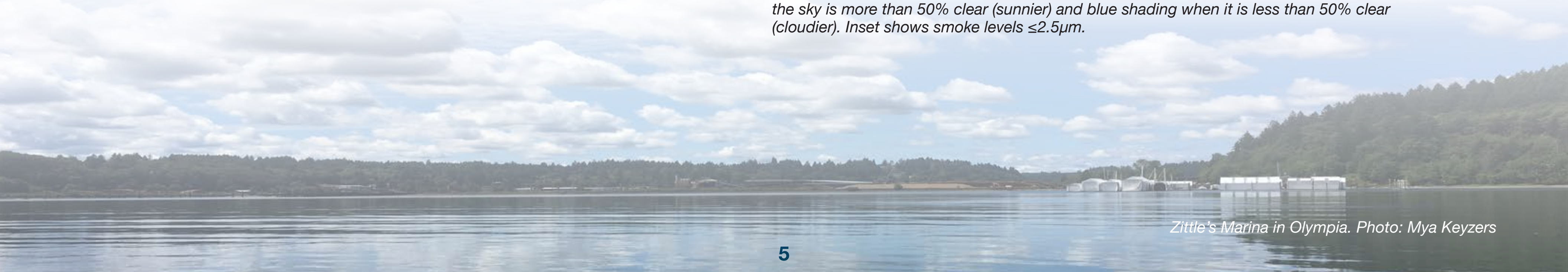


Figure 2.2. (A) Daily air temperature anomalies at SeaTac during 2020. Red and blue shading indicate warmer and cooler than average values, respectively. (B) Daily solar energy flux from the rooftop PAR sensor at the UW Atmospheric Sciences Building in Seattle. The solid red line indicates the highest theoretical solar energy for the latitude and the solid blue line indicates when the sky is fully overcast. The black line represents a 50% reduction of the total theoretical solar energy, with red shading occurring when the sky is more than 50% clear (sunnier) and blue shading when it is less than 50% clear (cloudier). Inset shows smoke levels ≤2.5μm.



Zittle's Marina in Olympia. Photo: Mya Keyzers

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

Marine Water Quality

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, Ćháʔba·, and an adjacent subsurface profiling mooring, NEMO-subsurface, are maintained by the Northwest Association of Networked Ocean Observing Systems (NANOOS) and the University of Washington (UW) 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 characteristic of the 2020 observations is that water spanning mid-depth to the bottom (~100 m) was the coolest observed during the summer and early fall since 2014. Consistent with the dissipation of the 2019 marine heat wave (MHW), near-surface water was cooler than in 2019 and similar to non-MHW years. The cooler deep waters in 2019 and 2020 marked the end of a deep-water warming trend from 2014 to 2018, which likely was affected by the 2014-2016 MHW (Figure 3.1). In warmer years like 2017 and 2018, water cooler than 8° C was only found deeper than 30 m above the bottom. However, in 2020 this water extended up to 60 m above the

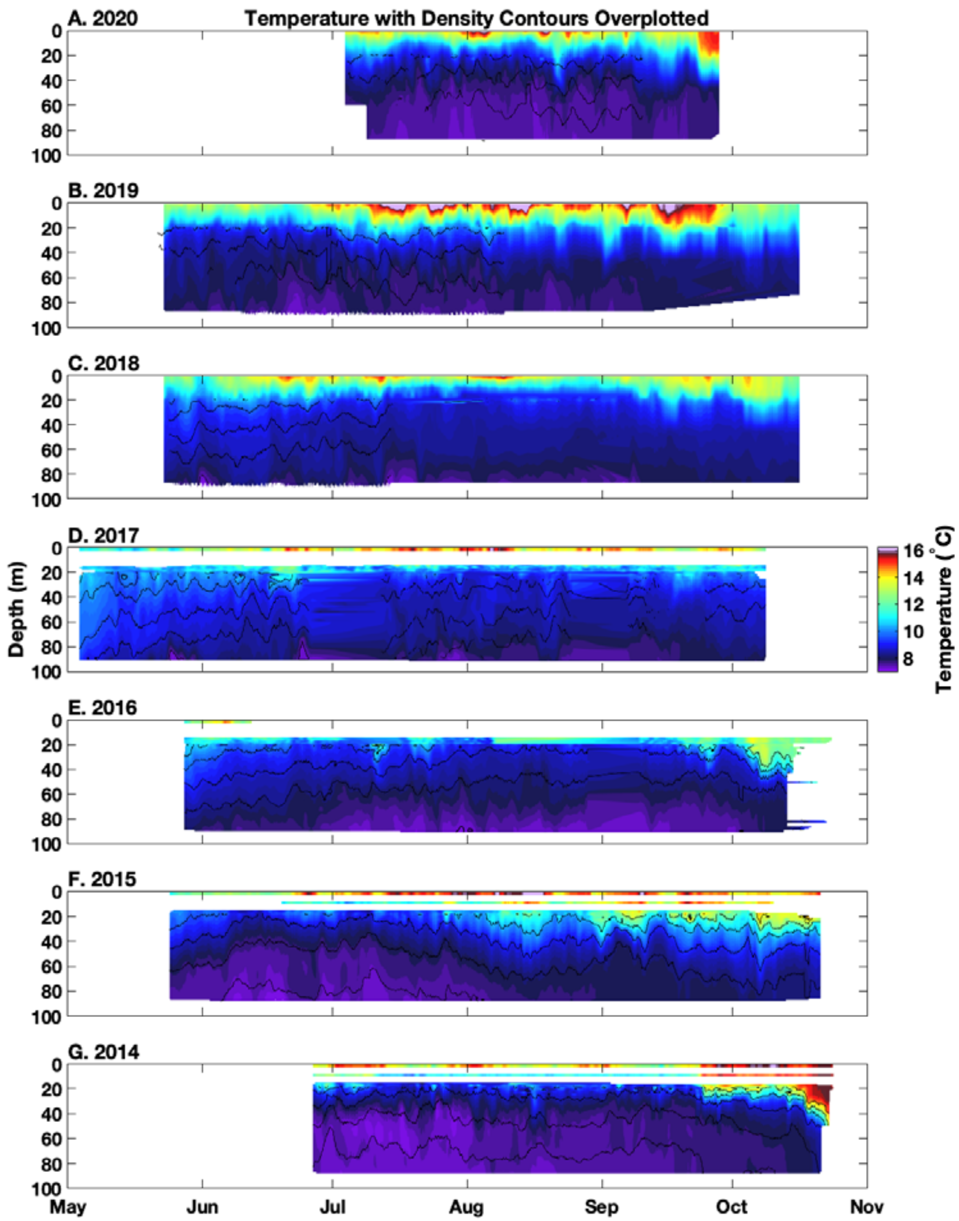


Figure 3.1. Water column temperature with density contours overplotted for 2020-2014 (A-G).

bottom. As previously discussed (PSEMP 2019), cooler deep water on the Washington shelf can result from large scale, wind-driven anomalies of along-shelf transport (e.g. Kosro 2003, Freeland et al. 2003). However, local wind observations indicate that upwelling-favorable winds, which could drive greater transport of water from the north, were not anomalously strong for 2020.

Other deep water properties (Figure 3.2) show that although salinity was roughly normal for this same summer-to-fall period, dissolved oxygen (DO) was above normal at ~4 mg/l until a rapid drop to hypoxic conditions (<2 mg/l) that started on September 12th. Consistent with observations from other years (e.g., PSEMP 2018 Call-Out), this was associated with a wind reversal from upwelling to downwelling-favorable winds.

As has been observed before, pH closely mirrored DO both at mid-depth (46 m) and deep pH (85 m). However, mid-depth pH and DO observations in 2020 do not typically match the changes in the deep water; there was strong one to two week variability in mid-depth DO and pH that was only weakly apparent in the deep observations. Mid-depth variation may indicate the influence of internal waves. High mid-depth pH values in mid-September 2020 occurred when deep water DO and pH were at the lowest values of the 2020 record. This observation highlights the need to measure pH and DO throughout the water column to fully understand the ecological impacts of these variables.

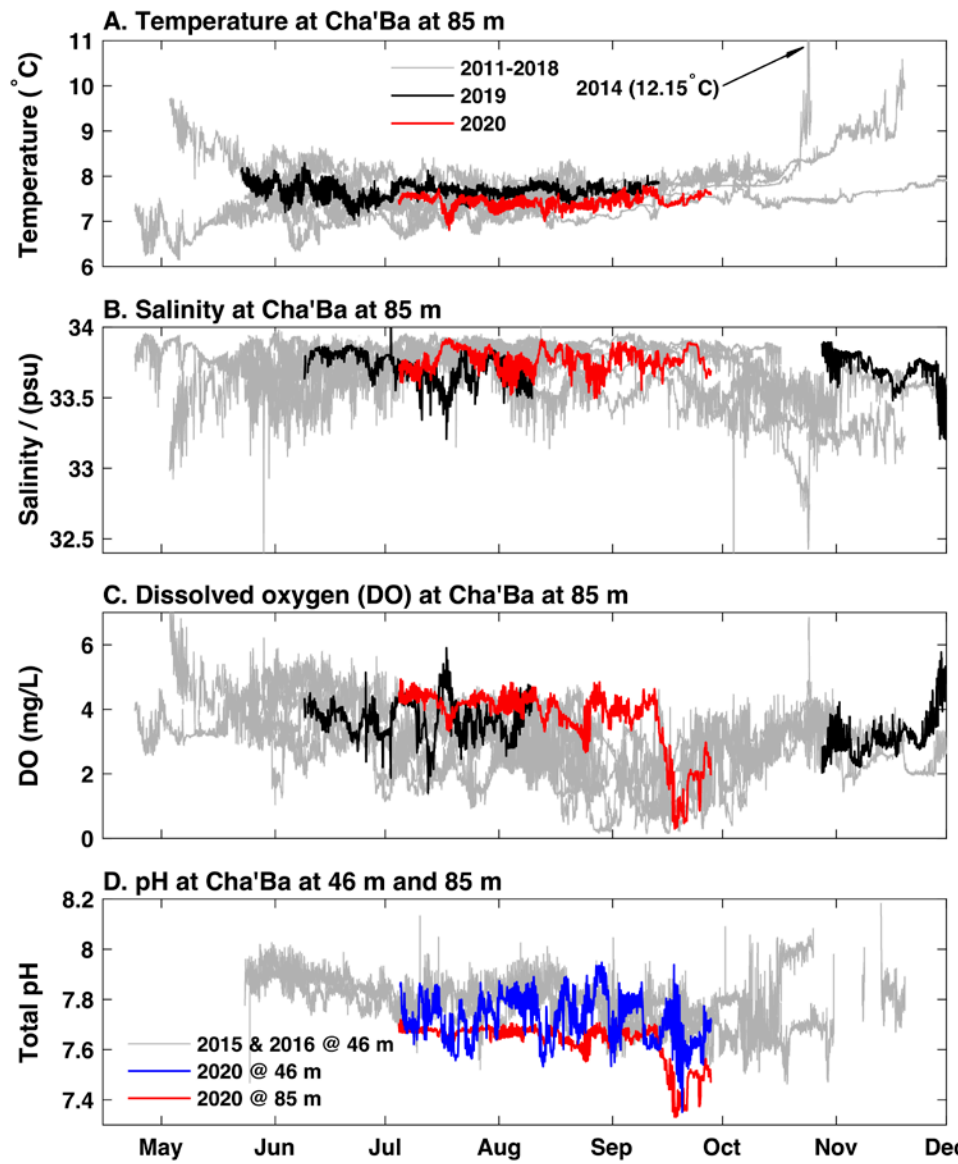


Figure 3.2. Interannual comparison of near-bottom properties (85 m; A-C) and pH at both mid-depth (46 m) and near-bottom (85 m) (D) at Ćháʔba·: (A) temperature, (B) salinity, (C) dissolved oxygen, (D) pH. 2020 is the first year that 85 m pH has been measured.

3. Coastal ocean and Puget Sound boundary conditions (cont.)

B. Ocean and atmospheric CO_2

Marine Water Quality

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, who 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 Musielewski (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 5267

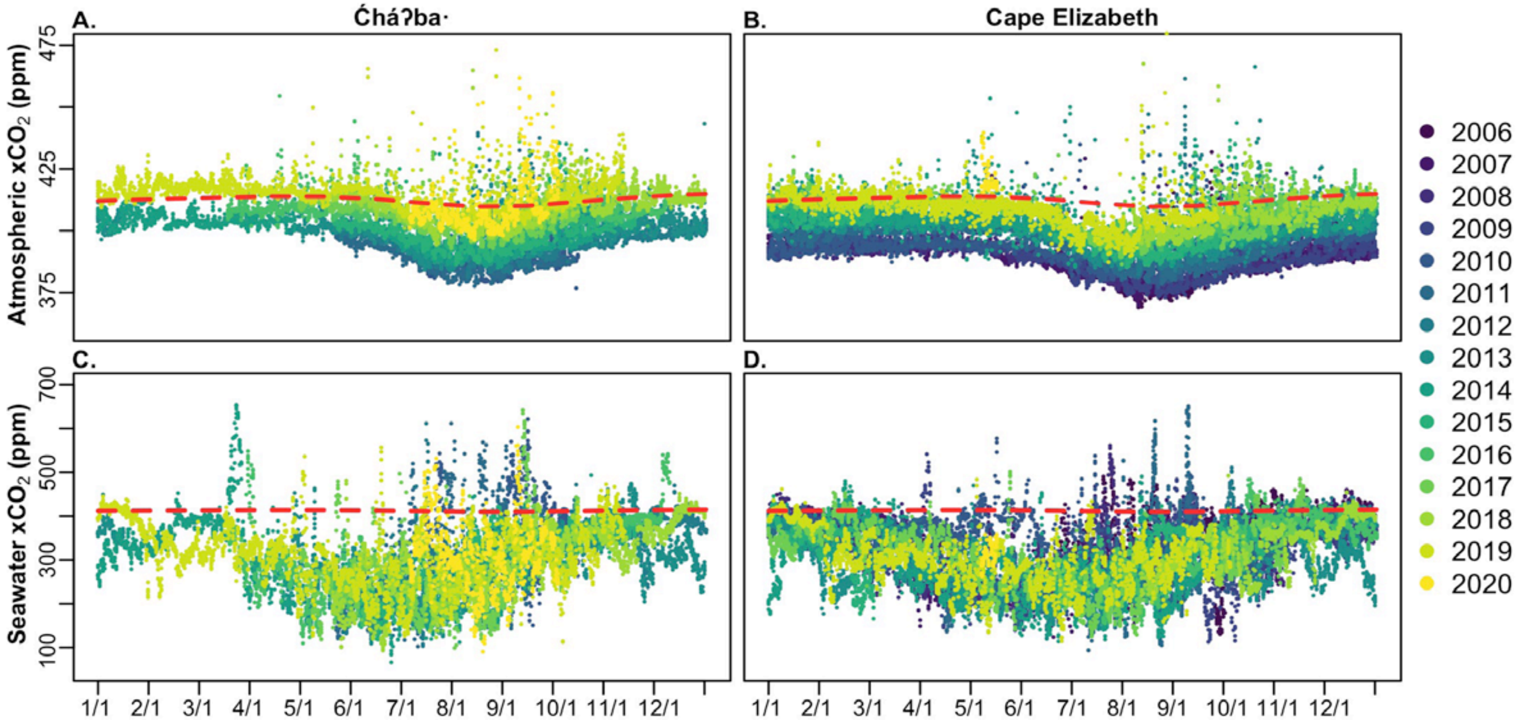


Figure 3.3. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater (A, B) and in surface seawater at 0.5 m depth (C, D) on the Ćháʔba· (A, C), and Cape Elizabeth (B, D) moorings. Typical uncertainty associated with quality-controlled measurements from these systems is <2 ppm for the 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).

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 2020 occurred at Ćháʔba· early July–mid-December; communication and calibration challenges limited remote data return from Cape Elizabeth to 3% for 2020 so meaningful comparison cannot be made with previous years (Figure 3.3, Table 3.1). Atmospheric xCO_2 ranges were 396–462 ppm (parts per million) at Ćháʔba· in 2020. Average values for atmospheric xCO_2 were lower than the globally averaged marine surface air of 412 ppm for 2020 (NOAA/ESRL), at 409±10 ppm for Ćháʔba·, based on all 2020 observations (24% data return for the full year). The mid-July–mid-October mean air xCO_2 in 2020 was the same as in 2019. The gap in observations during January–June, when atmospheric xCO_2 values are higher, suggest that atmospheric xCO_2 at Ćháʔba· would likely have been closer to the global average without the data gap. Variability in atmospheric xCO_2—as reflected by standard deviation—was 50% higher than usual in 2020, though still only a small fraction of the variability in seawater xCO_2 (Table 3.2). The higher atmospheric variability in 2020 may reflect the record-setting West Coast fire season driving up regional atmospheric xCO_2 during September and October. October 2020 had the second highest monthly average atmospheric xCO_2 in the entire time series. Surface seawater measurements spanned 90–604 ppm at Ćháʔba· (Figure 3.3C) during 2020. Mid-July–mid-October mean 2020 seawater xCO_2 values at Ćháʔba· were very close to 2019 values and fell in the middle-to-upper end of the historical range of mean values (Table 3.2).

Table 3.1. 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%).

Cape Elizabeth	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
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	409 ± 7	n.a.
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 ± 54	298 ± 61	n.a.
Data return	50	89	96	82	94	107	42	90	100	69	59	73	94_{atm}, 58_{sw}	74	3

Table 3.2. Mean (± standard deviation) surface seawater and atmospheric xCO2 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
Atmosphere	388 ± 6	387 ± 7	392 ± 8	394 ± 7	394 ± 7	397 ± 7	n.a.	403 ± 7	406 ± 7	410 ± 7	410 ± 11
Seawater	354 ± 87	332 ± 76	298 ± 53	280 ± 67	275 ± 72	323 ± 50	n.a.	273 ± 91	286 ± 66	308 ± 62	311 ± 81
Data return	100	102	108	128	100	100	0	100	100	100	85

CALL-OUT BOX: Puget Sound Metrics

A team of ocean and atmospheric scientists at the University of Washington (UW) have produced a dashboard of metrics to inform resource managers, scientists, health officials, and others on how key climate and ocean factors may influence the present state of Puget Sound and to put current conditions in the context of past observations. This project was funded by the Puget Sound Partnership and has been conducted with input from the Puget Sound Ecosystem Monitoring Program (PSEMP) and its Marine Waters Work Group, as well as a Technical Advisory Group composed of leaders from modeling, oceanographic, fisheries, and tribal resource communities.

Puget Sound Estuarine Flow Estimates tell us how fast Puget Sound's waters are moving. Estuarine circulation determines flushing times (or residence times) of Puget Sound's many basins. This in turn influences how long or how much suspended or dissolved particles (e.g., larvae or contaminants) is retained or flushed out. Yet the timing of the estuarine exchange can vary dramatically, seasonally and between basins.

Robert Daniels, Chris Archer and Ryan Newell preparing for the deployment of the UW/NANOOS Cha'Ba buoy on the Washington Shelf in July 2020. Photo: John Mickett

Salinity Changes from Rivers and Rain tell us what causes salinity to change. Changes in Puget Sound salinity can affect estuarine circulation as well as water column stratification, both of which can drive ecological processes. For instance, the strength of stratification can influence when or whether phytoplankton bloom. Since salinity in Puget Sound can change due to its oceanic source water or from freshwater input from rivers, precipitation, and groundwater, there is often uncertainty what causes salinity to change.

Water Column Dissolved Oxygen tells us how much of the water column habitat is deficient in oxygen. The amount of oxygen available to organisms varies by location and time. This metric quantifies the amount of water column habitat for two different oxygen ranges: hypoxic (DO <2 mg/l), and potentially stressful (DO <5 mg/l). Tracking this metric can illuminate when and where in Puget Sound potential ecological impacts may occur due to low dissolved oxygen.

Ocean Boundary Condition Changes tell us how the ocean affects Puget Sound. Puget Sound water properties are influenced by changes in ocean source waters. This metric tracks water properties on the northwest Washington shelf, presenting departures from long-term averages for temperature, salinity, dissolved oxygen, and chlorophyll. Coastal ocean changes that precede similar changes in Puget Sound are a potential indicator that source water may be driving Puget Sound variability.

Temperature Anomalies due to Local Heating and Cooling tell us how weather affects Puget Sound temperature. Water temperature changes in Puget Sound can be driven by both source water changes and changes in the local input of solar heat. This metric tracks anomalies in the heat that enters or leaves Puget Sound through the water's surface. Many PSEMP groups observe seawater temperatures and calculate anomalies, but drivers of these anomalies are not always apparent. With this metric, we aim to evaluate the cause of seawater temperature changes.

The Puget Sound Metrics were designed to evaluate how changes in temperature, circulation, salinity, dissolved oxygen, and boundary conditions may be connected to observed ecological and/or water quality changes and offer insights on what drives observed change. The metrics will be automatically updated weekly using real-time measurements available from buoys and other sources. The metrics will be hosted on the Northwest Association of Networked Ocean Observing Systems (NANOOS) website (www.nanoos.org), to be launched in 2021.

Authors: John Mickett (jmickett@apl.washington.edu), Beth Curry, Jan Newton (UW, APL), and Nick Bond (UW, CICOES); http://www.nanoos.org

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 2020, with a basin-wide average at 116% of normal by April. Accumulation occurred under neutral El Niño–Southern Oscillation (ENSO) conditions, which have a less defined association with snowpack and weather conditions in British Columbia (BC) in comparison to El Niño and La Niña conditions (BCRFC, 2020). Above normal precipitation and mostly below normal temperatures, primarily in January and February, led to the notable accumulations. In addition, key large tributaries (mostly unregulated by dams) that originate in BC's mountainous interior, received well above normal accumulations simultaneously, which has historically only occurred during three other years (BCRFC, 2020). Air temperature in recent years has been high in April and May, which led to earlier than normal peaks in spring runoff. A brief warm spell in April 2020 did lead to the melting of low elevation snow, spurring the rapid onset of the snowmelt runoff season and bringing discharge above the historical median (Figure 4.1), causing some localized tributary flooding. However, temperatures were near to below normal for the remainder of spring and early summer overall. These mild conditions resulted in an extended period of snowmelt runoff with an initial peak in Fraser River discharge in early June followed by a larger atypical secondary discharge peak in early July (Figure 4.1). Streamflow typically peaks in mid-June. In 2020, remaining high elevation snowmelt and above normal precipitation led to a peak on July 6 that set a new maximum value for the date and year. For the remainder of the year, streamflow levels declined as expected. Contrary to recent years however, discharge in 2020 was substantially higher than the historical median throughout much of the year.

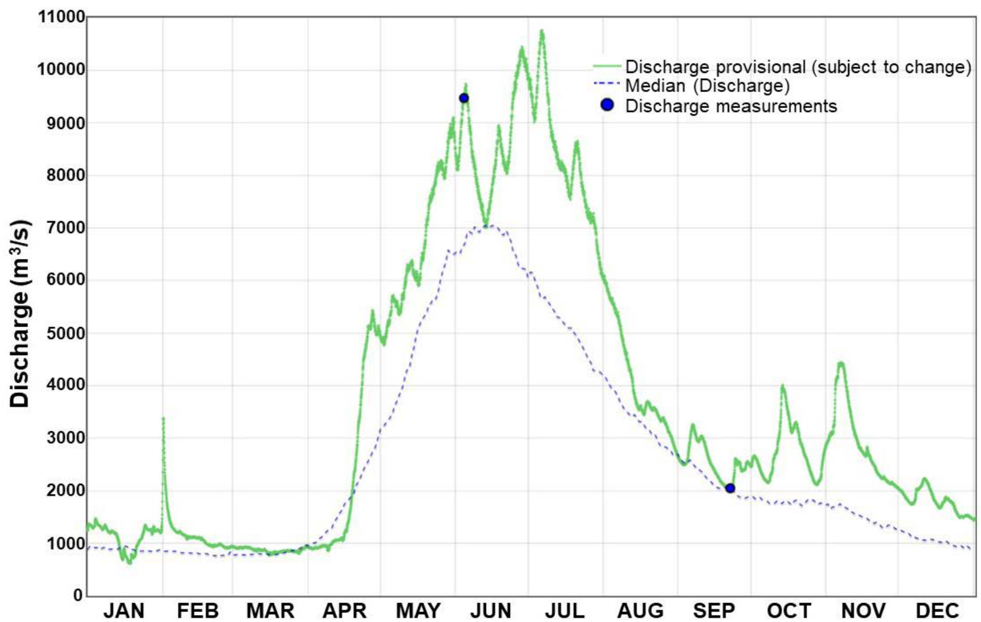


Figure 4.1. Fraser River daily discharge (m^3/s) at Hope, BC (08MF005) for 2020, compared to the median value for the period of record (1912-2020). (Note 1 m^3/s = 35.3 ft^3/s).

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

Conditions in Puget Sound watersheds during 2020 were similar to those of the Fraser River watershed in British Columbia. Mountain snowpack accumulated under neutral El Niño–Southern Oscillation (ENSO) conditions, which have limited influence on weather conditions in Washington State. Snow accumulation surged in the Cascade and Olympic Mountains during January and February due to above normal precipitation, despite a slow start due to below normal precipitation in November and December. This surge was followed by a dry and cold March, which sustained an above normal snowpack (114%) into early April (OWSC, 2020). Early in the year, streamflow levels ranged from normal to well above normal for the major rivers that drain to Puget Sound (Figure 4.2). The Snohomish and Puyallup watersheds, for example, experienced lowland flooding, which led to the Governor issuing a multi-county emergency proclamation in February. Streamflow levels were temporarily below normal during March and April due to dry conditions but seasonal warming later in April initiated the snowmelt runoff season and brought streamflow back to normal levels. Though some variability existed depending on location, multiple peaks in runoff occurred due to above normal precipitation and generally above normal temperatures in May and June, which coincided well with historical means. Snowpack depleted normally (NRCS, 2020), and subsequently streamflow levels began to decline in mid-June but remained at normal levels. Below normal precipitation in July and August eventually led to some rivers reaching below normal streamflow by mid-August and early September but for a shorter duration than recent years. All river levels returned to normal or above normal due to above-normal precipitation in September and were further augmented by strong precipitation events the remainder of the year. Though some variability existed, freshwater inputs to Puget Sound were at or above their historic median cumulative discharge at the end of 2020.

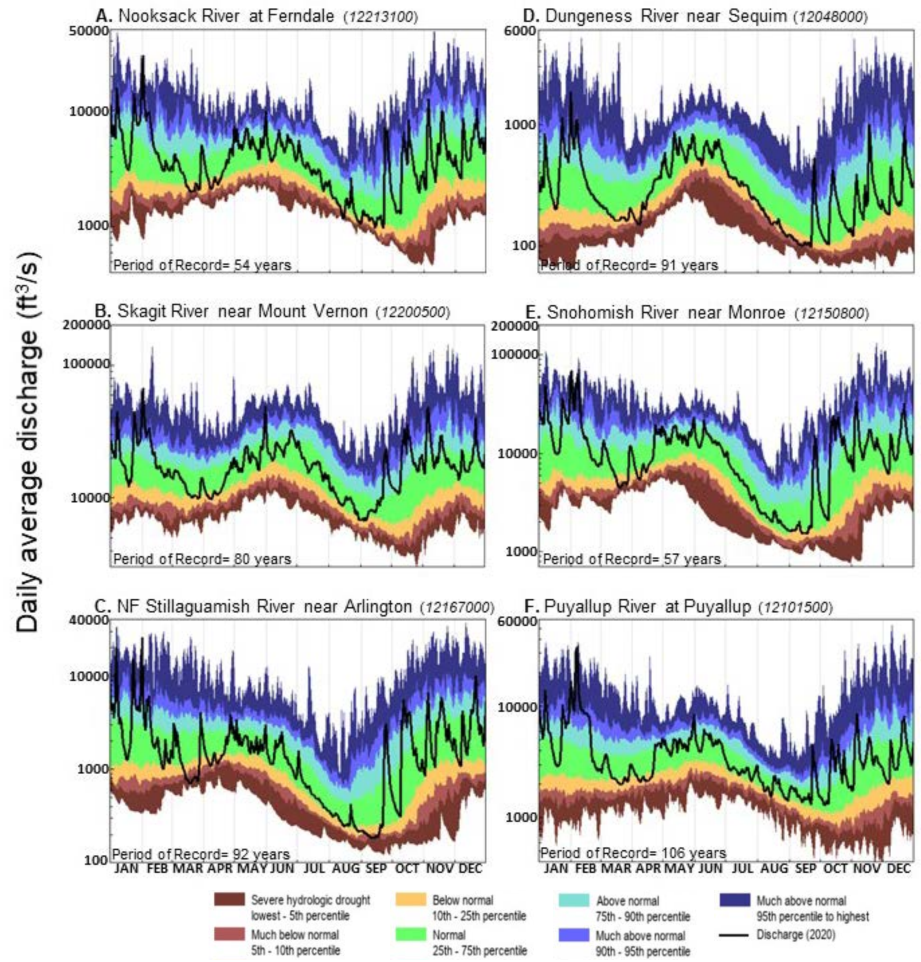


Figure 4.2. Daily average river discharge (ft^3/s) at stations on the Nooksack (A), Skagit (B), NF Stillaguamish (C), Dungeness (D), Snohomish (E), and Puyallup (F) Rivers in 2020, compared to period of record percentile classes. (Note: the period of record varies for each station and is listed in number 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 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).

A.i. Temperature

Marine Water Quality

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 show that Puget Sound temperatures during 2020 were fairly close to the climatological average (2005-2017), though there were regional and temporal differences. In the last six years, only 2020 and 2017 did not have predominantly warmer than average seawater temperatures.

The three basins represented here, Main Basin, South Sound, and Hood Canal, showed three different anomaly patterns (Figure 5.1). Point Wells in the Main Basin had generally muted and variable temperature anomalies throughout the year. Carr Inlet in South Sound showed generally more positive temperature anomalies, especially mid-May through mid-October and below a narrow surface layer, which at times was much cooler than normal. Hoodsport in Hood Canal was somewhat similar to Carr Inlet, but transitioned from cooler than average January-May, then warmer than average May-September, then a cooler than average rest of the year marked by a seasonal oceanic intrusion at depth starting in September that shoals with time. Both Hood Canal moorings, Hoodsport and Twanoh (not shown), tended toward larger temperature anomalies compared to the other basins.

These temperature variations reflect the diverse oceanographic characteristics of Puget Sound's sub-basins. Hood Canal, with strongly stratified waters, slow circulation, and deep water flushed by annual renewal, responds to atmospheric forcing differently than the Main Basin, which has stronger mixing that intensifies as this water feeds South Sound.

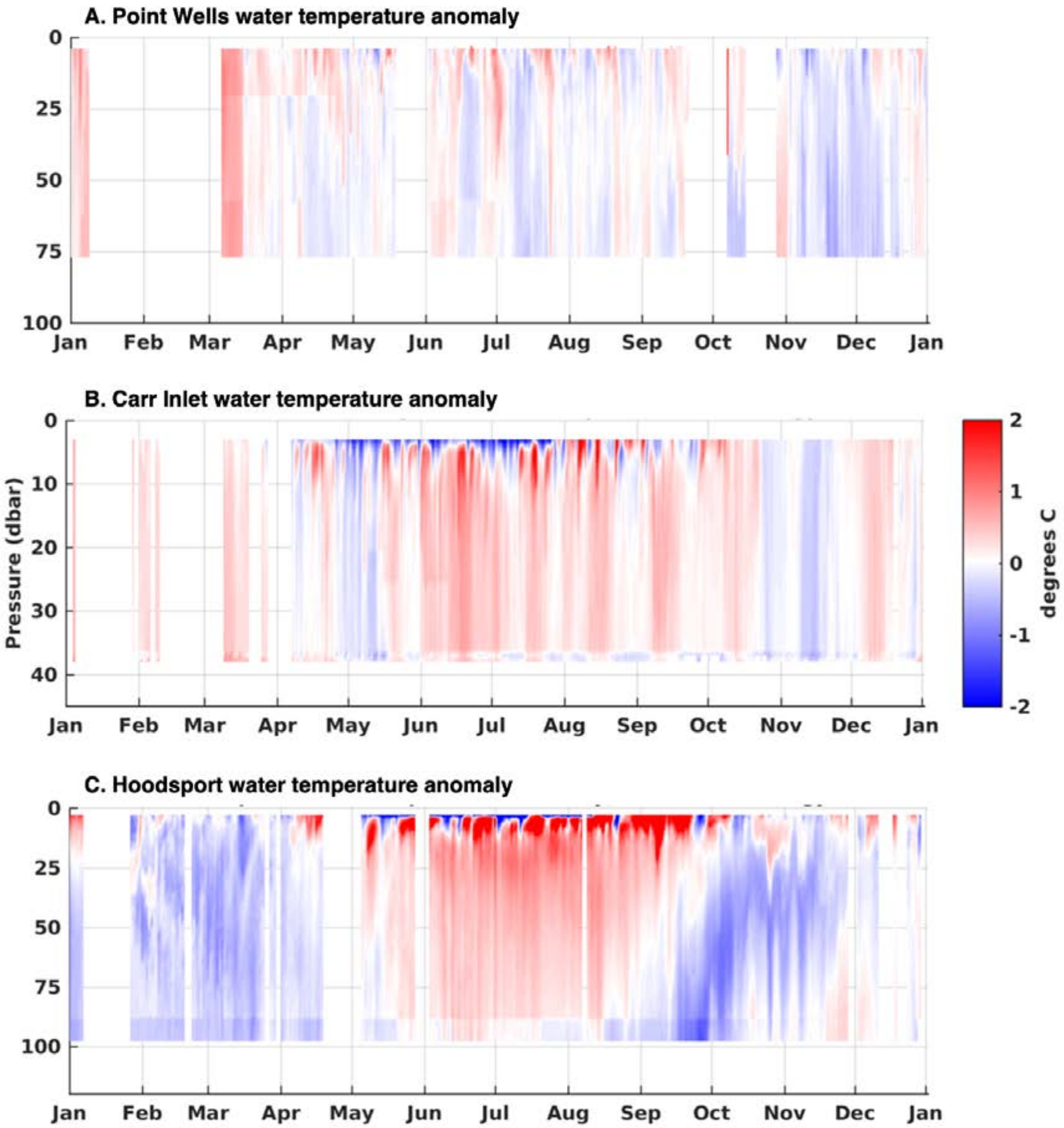


Figure 5.1. Water temperature anomalies in 2020 relative to the climatological average over 2005-2017. Pressure (or depth) is shown on the y-axis and time on the x-axis at three ORCA mooring sites: Point Wells in Main Basin (A), Carr Inlet in South Basin (B), and Hoodsport in South Hood Canal (C).

Christopher Barnes recovering discarded balloons in Puget Sound aboard the R/V SoundGuardian. Please remind your friends and family to not release helium balloons. They end up as trash and can cause serious problems for marine wildlife. Photo: Bob Kruger

A.ii. Salinity

Marine Water Quality

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 show that Puget Sound salinities during 2020 had a variable to weak anomaly pattern, but all sites showed saltier than climatological averages (2005-2017) during April through August. Higher than average salinities during summer have been noted for all years since 2014, except 2017.

Again, as with seawater temperature, the three basins, Main Basin, South Sound, and Hood Canal, showed three different salinity anomaly patterns (Figure 5.2). In general, Point Wells showed variable and small salinity anomalies, Carr Inlet showed consistent and moderate saltier anomalies, and Hoodsport showed alternating periods of positive and negative salinity anomalies and differences between surface values and the rest of the water column. At Point Wells, saltier than average anomalies were strongest from April through June and observed over the full water-column. From July through the rest of the year, anomalies tended toward fresher than average values, though these were fairly weak in magnitude. In Carr Inlet, the strongest anomalies were also saltier than average over the full water column and seen April through June. However, in contrast to Point Wells, saltier anomalies at Carr Inlet lingered the rest of the year, though were weaker than observed there earlier in the year. Hoodsport showed a different pattern from these two, which bore some similarities to its temperature pattern: The year started with saltier (and cooler) anomalies, switching to fresher (and cooler) in February, then back to saltier (and warmer) during April through August, then back to fresher (and cooler) starting with the oceanic intrusion in September. Also, in Hood Canal, surface salinity anomalies that were either fresher than average or saltier than the rest of the water column were observed. The mechanism driving this surface phenomenon is not known, but also shows in the temperature anomalies.

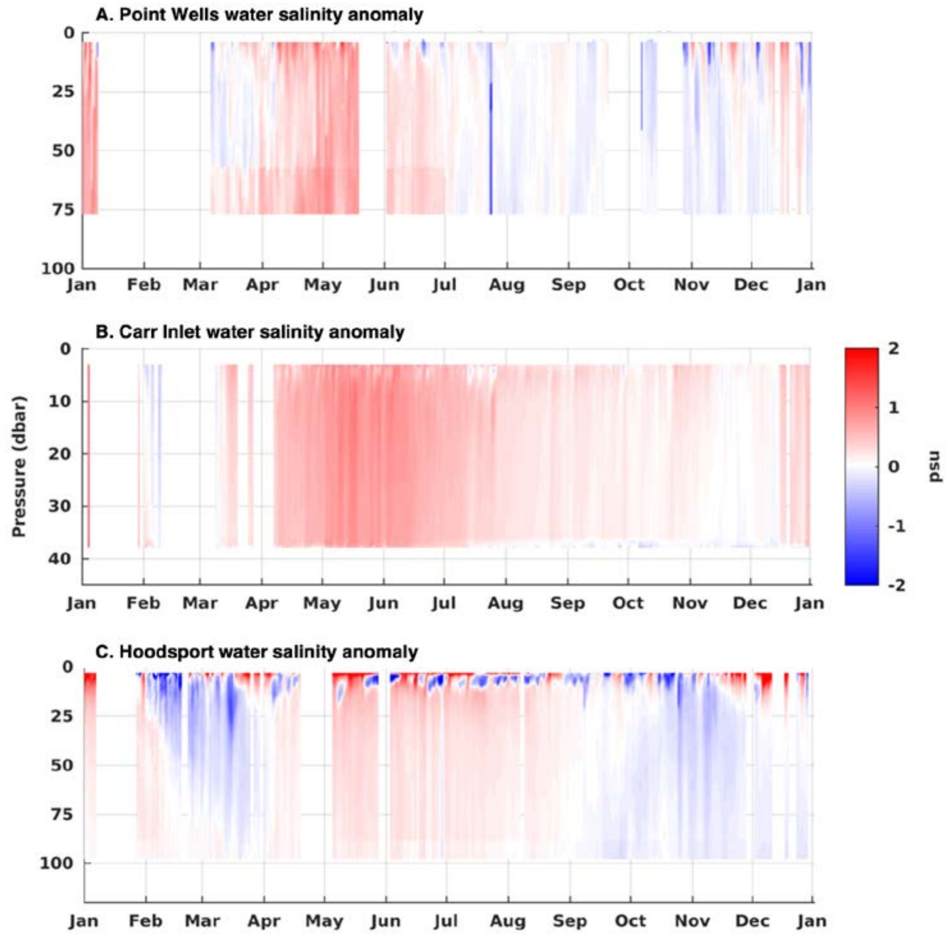


Figure 5.2. Salinity anomalies in 2020 relative to the climatological average over 2005-2017. Pressure (or depth) is shown on the y-axis and time on the x-axis at three ORCA mooring sites: Point Wells in Main Basin (A), Carr Inlet in South Basin (B), and Hoodsport in South Hood Canal (C).

A.iii. Dissolved oxygen

Marine Water Quality

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. In general, anomalies were less than 1 mg/L above or below the long-term average (2005-2017) throughout the water column, except for surface values and for Twanoh, which showed large blooms March-May that increased DO throughout much of the water column. For the majority of the year, Carr Inlet had higher than average values, while Hoodsport had lower than average values, though much variation was evident (Figure 5.3). Carr Inlet had an alternating pattern with one to two month duration: in April, values were above average, in May, below average, then in June, above, and in July, below again. From mid-July through mid-November, surface and subsurface anomalies were opposite, with a negative anomaly in surface waters (0- ~10 m) and a positive anomaly below that. Prior to July, the anomaly was consistent over the water column. At Hoodsport, there were higher than average anomalies January through April, lower than average anomalies May through August, then patches of moderately higher than average anomalies August through October. The seasonal oceanic intrusion that started at depth in September had lower than average oxygen; those conditions lasted through December. Cooler than average waters (see Figure 5.1) had higher than average oxygen (spring) and vice versa (summer), but the fall intrusion was cooler than average with lower than average oxygen. At both stations, the strongest anomalies were observed in surface waters, likely correlated with the presence and/or absence of phytoplankton blooms.

Hypoxia was observed in South Hood Canal at Twanoh from late July through the end of the year (Figure 5.4). Hypoxic water shoaled to ~10 m depth by mid-September, and its upper reach fluctuated between 5-15 m for the most part with two significant dips to 25-30 m in late October and early November. Hypoxia exhibited medium onset and intensity in 2020, as was observed in 2011 and 2018-19. Early onset years (2015-16) have stronger hypoxia and later onset years (2012, 2014, 2017) have weaker hypoxia. No fish kills were reported during 2020.

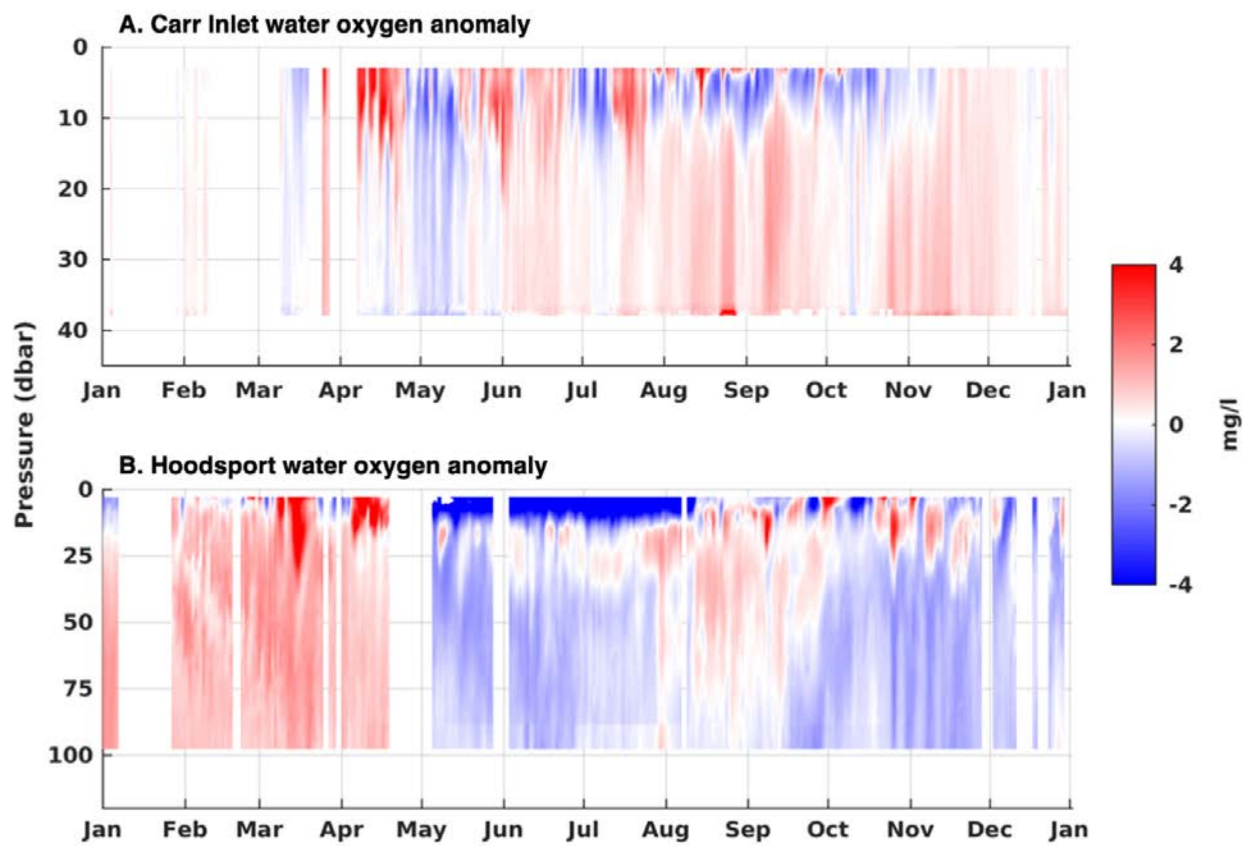


Figure 5.3. Dissolved oxygen anomalies in 2020 relative to the climatological average over 2005-2017. Pressure (or depth) is shown on the y-axis and months on the x-axis at two ORCA mooring sites: Carr Inlet in South Basin (A) and Hoodsport in South Hood Canal (B).

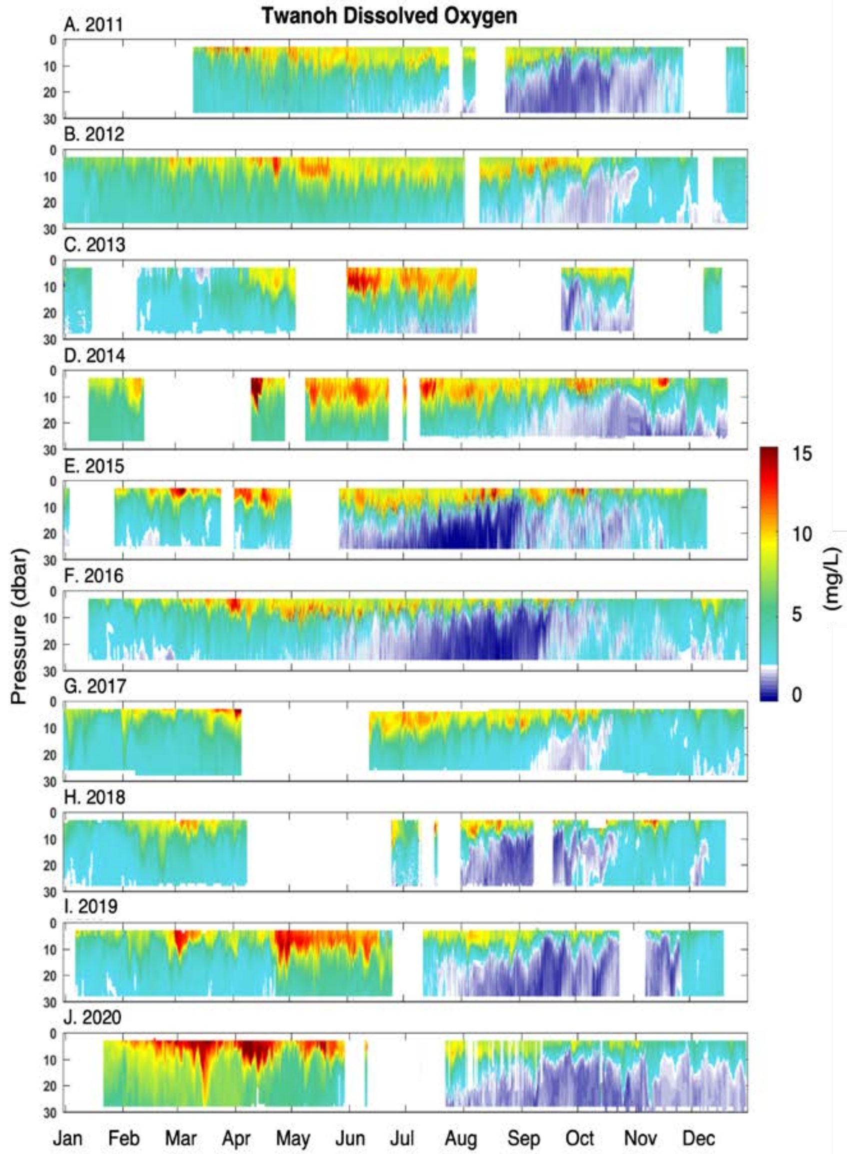


Figure 5.4. Time series of water column dissolved oxygen concentrations at the Twanoh mooring between 2011 and 2020. Pressure (or depth) is shown on the y-axis and months on the x-axis between January 2020 and December 2020.

Jim Devereaux and Christopher Barnes maintain King County's Point Williams buoy on the back deck of the R/V SoundGuardian. Routine cleaning, calibration, and maintenance is required to ensure high quality water quality and meterological data continues to be collected every 15 minutes, 24 hours a day and 365 days a year. Photo: Bob Kruger

A.iv. Ocean and atmospheric CO_2

Marine Water Quality

Source: Simone Alin (simone.r.alin@noaa.gov), Adrienne Sutton (NOAA, PMEL), Jan Newton, John Mickett (UW, APL), Sylvia Musielewski (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; 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 5267

Atmospheric 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 88% and 98% preliminary data return in 2020, respectively (Figure 5.5). During 2020, atmospheric xCO_2 at Dabob spanned 397–502 ppm, with a mean of 427 ppm (Table 5.1). At Twanoh, atmospheric xCO_2 spanned 371–651 ppm (mean = 425 ppm; Table 5.2). Mean atmospheric values at both Hood Canal moorings tend to be more enriched than global averages due to regional anthropogenic emissions. This pattern continued to be observed in 2020, with both moorings higher than the global average for marine surface air (412 ppm, per NOAA/ESRL) by 13–15 ppm. However, relative to 2019, atmospheric values in Hood Canal did not increase to the extent expected, possibly reflecting a regional reduction in emissions due to COVID-19. Twin peaks in atmospheric xCO_2 in September and October may reflect the unprecedented fire season in the western U.S. in 2020 (Figure 5.5A,B). Average atmospheric xCO_2 values for October 2020 were in the highest and third highest of any month at Dabob and Twanoh, respectively, and September 2020 was also the third highest at Dabob. Using standard deviations as a metric of variability, atmospheric xCO_2 variability was similar to past years.

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.

Dabob	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Atmosphere	407 ± 13	409 ± 12	416 ± 15	415 ± 12	413 ± 13	417 ± 11	418 ± 11	424 ± 13	427 ± 12	427 ± 12
Seawater	416 ± 165	357 ± 182	415 ± 218	395 ± 190	411 ± 93	366 ± 158	385 ± 194	424 ± 250	467 ± 290	457 ± 235
% data return	56	70	14	93	100	97	97	72	100	88

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
Atmosphere	401 ± 20	401 ± 16	409 ± 16	407 ± 12	415 ± 18	417 ± 14	420 ± 14	421 ± 13	420 ± 13	422 ± 15	425 ± 17	425 ± 18
Seawater	414 ± 158	342 ± 153	509 ± 283	374 ± 207	542 ± 312	424 ± 220	461 ± 242	347 ± 190	414 ± 192	442 ± 233	463 ± 204	494 ± 277
% data return	53	63	39	60	43	99	97	73	98	74	97	98

Mean 2020 surface seawater xCO_2 at Twanoh was the third highest in the time series, after 2013 and 2011; given the high data return, we are confident that this accurately captures 2020 conditions at the mooring location. Dabob surface seawater median xCO_2 was also second highest in its time series, with 88% data return, after 2019. In 2020, surface seawater xCO_2 spanned 46–2862 ppm at Twanoh and 122–1408 ppm at Dabob. 2020 surface seawater xCO_2 remained above atmospheric values until late February at Twanoh and early March at Dabob, when rapidly declining values suggested the onset of phytoplankton blooms. We interpret this as a return to more normal timing of the spring bloom than in marine heatwave years of 2016, when biological drawdown appeared to be particularly early and prolonged at both sites, and 2019 with a more episodic early drawdown at both sites. The early drawdown during heatwave years is not without precedent: average surface seawater xCO_2 in January–February 2010 was also below atmospheric values.

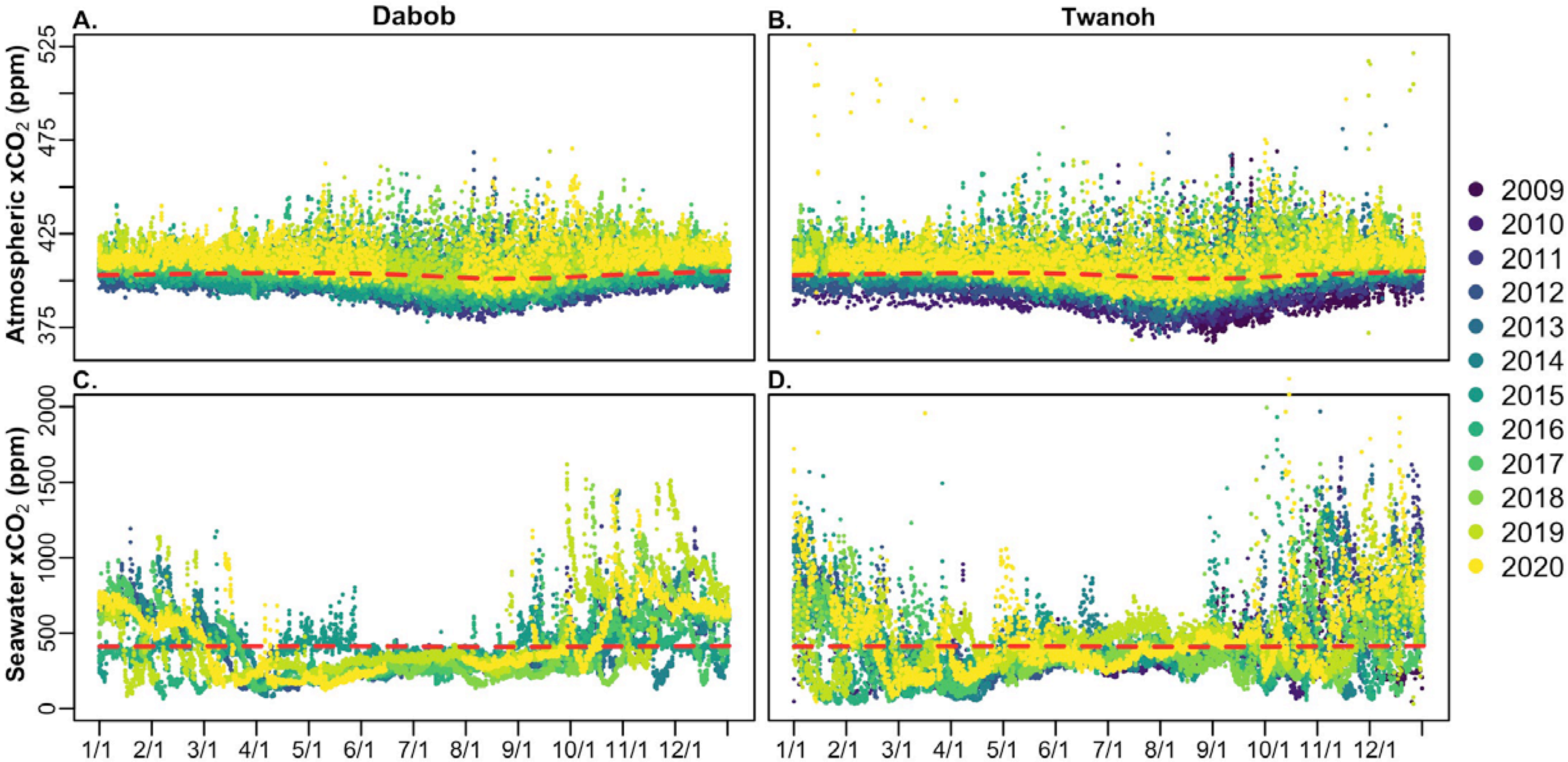


Figure 5.5. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater (A, B) and in surface seawater at 0.5 m depth (C, D) in Dabob Bay (A, C) and at Twanoh (B, D). Typical uncertainty associated with quality-controlled measurements from these systems is <2 ppm for the 100–600 ppm range, 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).

B. 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.

B.i. Temperature, salinity, and density

Marine Water Quality

Source: Taylor Martin (taymartin@kingcounty.gov) (KCWLRD); Primary website: https://green2.kingcounty.gov/marine; website for online data: https://green2.kingcounty.gov/marine/Download

Water temperatures in the Central Basin in 2020 tended to be warmer than the 1998-2013 monthly baseline mean for most of the year (Figure 5.6A,D). Figure 5.6A shows temperature anomalies at Point Jefferson, which is representative of the other Central Basin stations. At three long-term Central Basin sites, the monthly mean temperature anomalies ranged from +0.1 to +0.9°C at the surface (0-35 m depth-averaged) and from 0 to +1.1°C at depth (>175 m). Anomalies were positive in deeper waters in January and February. Temperatures were close to those observed in 2019, but not as high as those observed during the marine heatwave in 2014-2016 (Figure 5.6D). CTD data were not collected during April and May due to the COVID-19

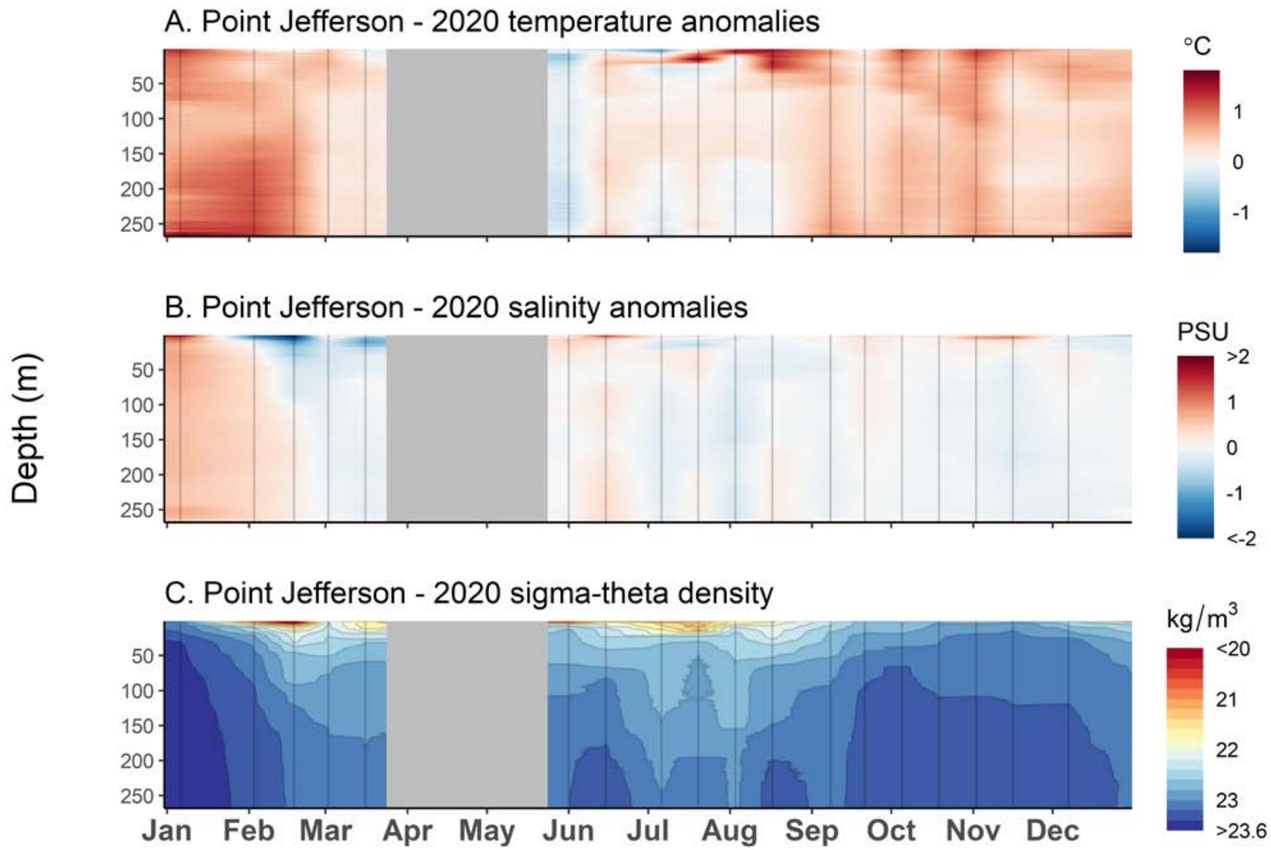


Figure 5.6 (A-C). (A) Contour plot of temperature anomalies in 2020 at the deepest Central Basin station (Point Jefferson) calculated from the difference between observations and a monthly baseline mean for the period 1998-2013. Vertical lines indicate when data were collected. The gray box represents the timeframe of no data collection due to COVID-19. (B) As in A, but for salinity. (C) Contour plot of water column sigma-theta density at Point Jefferson in 2020. Contour intervals are 0.2 kg/m3. Vertical lines and gray box as in A.

pandemic, but temperatures recorded at the Point Williams mooring revealed steadily increasing water temperatures during April, cooling in the first half of May, and a rapid temperature increase in mid-May to values similar to those observed in 2019 (data not shown).

Salinity in the Central Basin in 2020 was higher than usual at the beginning of the year, although waters became less salty and closer to average in late February (Figure 5.6B and E) as a result of high river discharge and an unusually rainy January when over 10” of cumulative precipitation was recorded at the King County Dockton mooring. Salinity remained close to normal for the remainder of the year, in contrast with the high salinities observed throughout 2019 (Figure 5.6E). Monthly mean salinity anomalies were small, ranging from -0.5 to +0.8 PSU at the surface and from -0.1 to +0.6 PSU at depth. Salinity data from the 10 m depth at the Seattle Aquarium mooring, which is influenced by the Duwamish River outflow, indicated increasing salinity through April, a slight decrease through May, followed by a larger decrease at the beginning of June corresponding with prolonged rainfall.

The return to near-normal or lower salinities coincided with moderately strong surface density gradients in February, March, and July (Figure 5.6C). The early stratification may or may not have continued in April and May since CTD data were not collected. It is difficult to draw conclusions about how stratification during that time may have contributed to the anomalously high chlorophyll observed at some sites in June (see section 5.B.iii. Nutrients and chlorophyll on page 24).

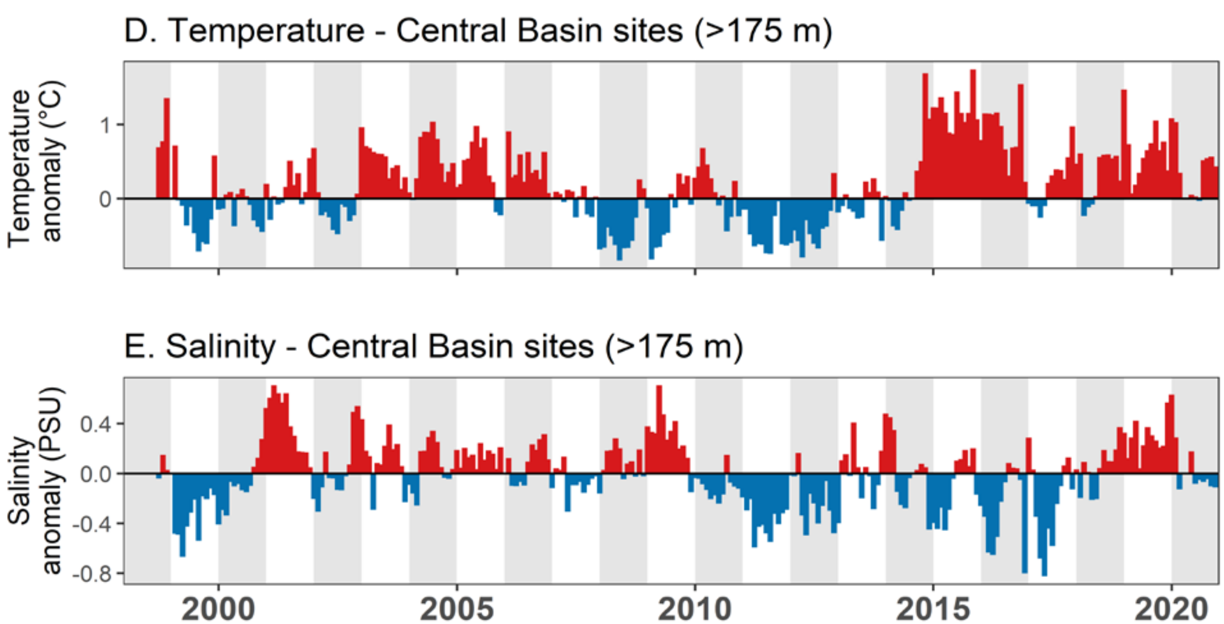


Figure 5.6 (D-E). (D) Monthly mean deep water (>175 m) temperature anomalies at the three deepest Central Basin stations (Point Jefferson, Dolphin Point, and South Plant Outfall) calculated from the difference between observations and a monthly baseline mean by month for the period 1998-2013. Background 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.

B.ii. Dissolved oxygen

Marine Water Quality

Source: Taylor Martin (taymartin@kingcounty.gov) (KCWLRD); Primary website: https://green2.kingcounty.gov/marine; website for online data: https://green2.kingcounty.gov/marine/Download

Central Basin surface layer dissolved oxygen (DO) concentrations were close to normal and deeper concentrations were lower than normal in 2020 relative to the 1998-2013 baseline. Figure 5.7 A shows DO anomalies over 2020 at Point Jefferson, which is generally representative of other Central Basin stations in our study area. Monthly surface anomalies at three long-term Central Basin sites ranged from -0.6 mg/L (July) to +1.1 mg/L (August) (Figure 5.7 C), with the highest concentrations observed in June and the lowest concentrations observed in October. Low biovolume in mid-June through early July, a large *Heterosigma* bloom in mid-June, and high phytoplankton biovolume in mid-July likely contributed to the observed changes in DO (see phytoplankton section 6.A.i. Puget Sound on page 34). Monthly deep water anomalies ranged from -0.8 mg/L in January to +0.3 in December (Figure 5.7D), with the highest concentrations observed in January through March and the lowest concentrations observed in October. The low concentrations through the late summer and fall likely coincided with the seasonal intrusion of low-DO water from the Pacific Ocean.

In contrast to the Central Basin, DO in the shallow, poorly-flushed Quartermaster Harbor was higher than normal at the surface (<2 m) and showed no clear trend in the subsurface relative to the 2006-2013 baseline (Figure 5.7 E-F). Annual mean DO

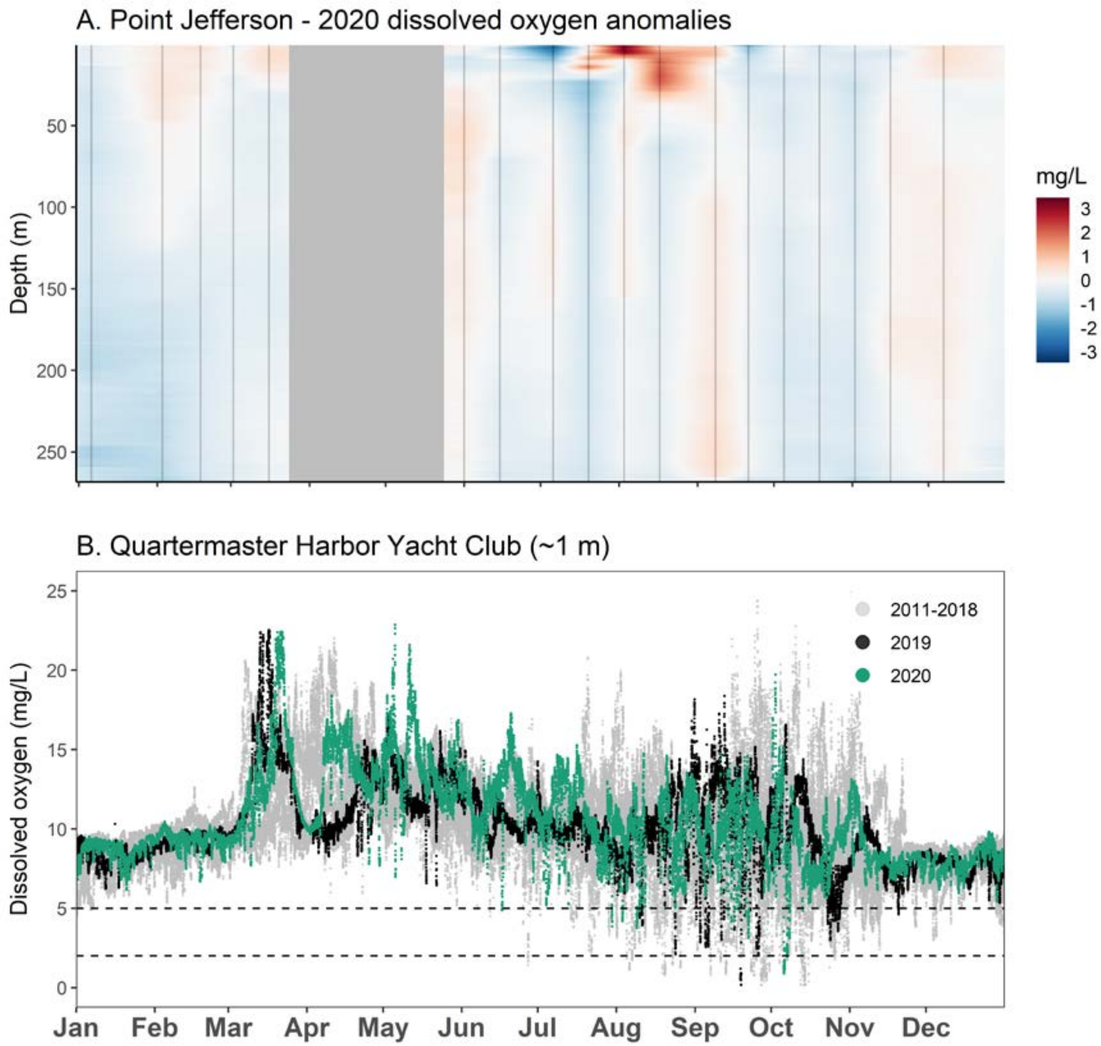


Figure 5.7 (A-B). (A) Contour plot of dissolved oxygen anomalies in 2020 at the deepest Central Basin station (Point Jefferson) calculated from the difference between observations and a monthly baseline mean for the period 1998-2013. Vertical lines indicate when data were collected. The gray box represents the timeframe of no data collection due to COVID-19. (B) Time series of 15-minute dissolved oxygen measurements at the Quartermaster Harbor Yacht Club mooring in 2020 (green), 2019 (black) and 2011-2018 (gray). Dashed lines represent dissolved oxygen concentrations of 5 mg/L and 2 mg/L.

surface anomalies were +1.2 mg/L in the outer harbor (data not shown) and +0.9 mg/L in the inner harbor, with mean subsurface anomalies of +0.1 mg/L in the outer harbor and 0.2 mg/L in the inner harbor. The range of monthly DO anomalies was greater in Quartermaster Harbor compared to the Central Basin (Figure 5.7C-F), which is similar to observations from previous years. Higher than average DO of inner harbor surface waters is consistent with observations from 15-minute mooring data collected at the same location (Figure 5.7B). DO concentrations were high through the spring and early summer, but did not get as low as previous years during the late summer and early fall when there is typically high daily variability.

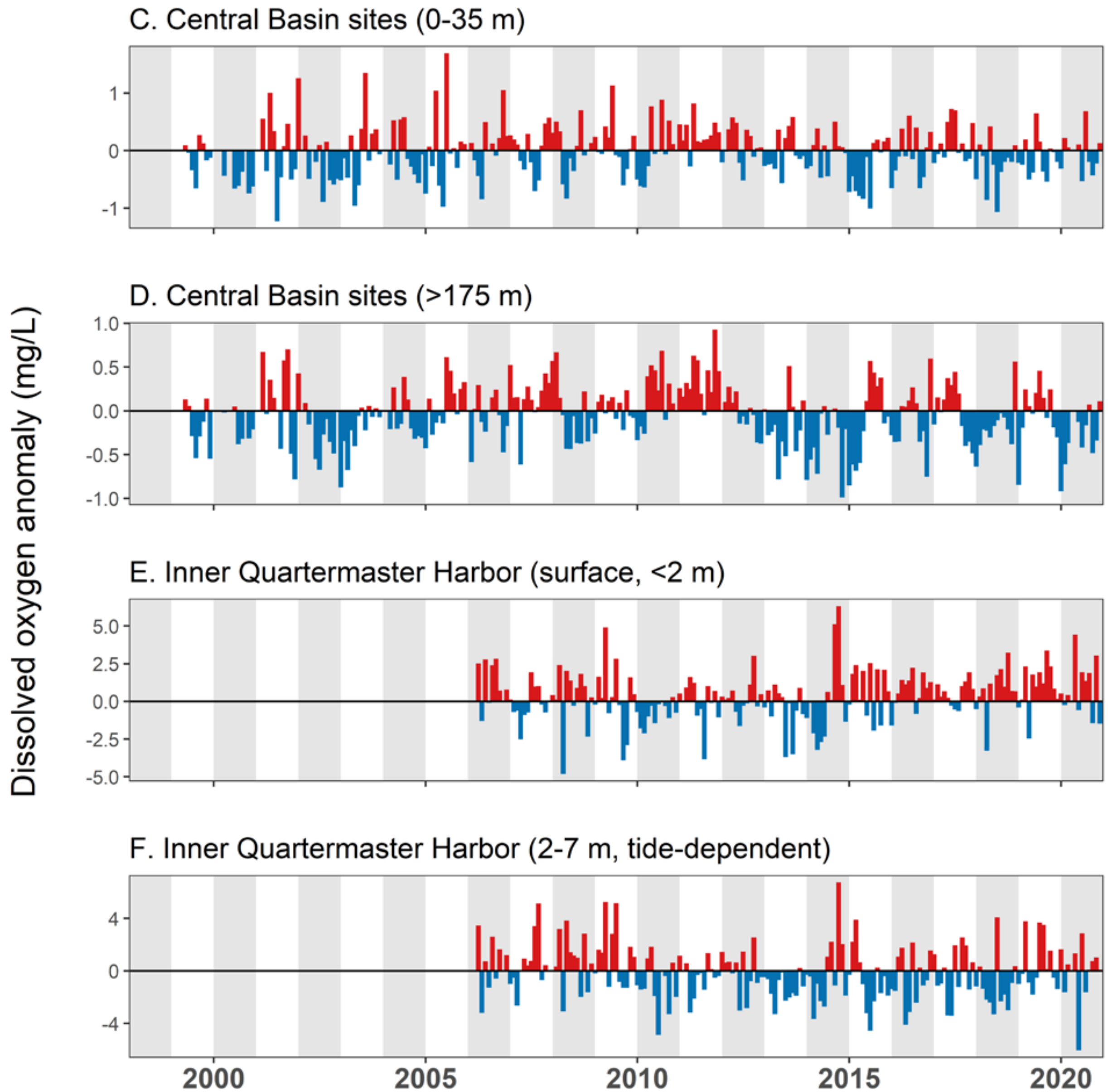


Figure 5.7 (C-F). (C) Monthly mean surface water (0-35 m) dissolved oxygen anomalies at the three deepest Central Basin stations (Point Jefferson, Dolphin Point, and South Plant Outfall) calculated from the difference between observations and a monthly baseline mean by month for the period 1998-2013. 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) As in C, but for surface (<2 m) samples collected in Inner Quartermaster Harbor. (F) As in C, but for subsurface (2-7 m, depending on tide) samples collected in Inner Quartermaster Harbor.

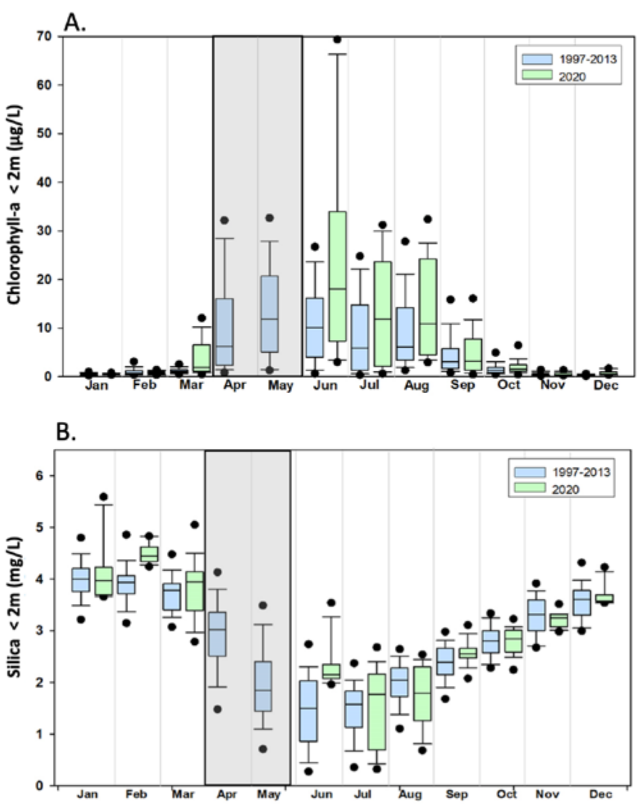
B.iii. Nutrients and chlorophyll

Marine Water Quality

Source: Kim Stark (kimberle.stark@kingcounty.gov), Gabriela Hannach, and Wafa Tafesh (KCDNRP); https://green2.kingcounty.gov/marine

Central Basin chlorophyll-*a* observations in 2020 indicate a small phytoplankton bloom occurred in mid-March. COVID-19 restrictions prevented boat sampling April through mid-June; however, the Pt. Williams mooring data indicated the main spring bloom occurred in mid-May in this area. Overall, chlorophyll-*a* levels were higher than normal in March and then June through August (Figure 5.8 A), particularly in June in the northern Central Basin during the large *Heterosigma bloom* (see plankton section 6.A.i. Puget Sound on page 34). The early small March bloom and high summer values were likely influenced by the strong density stratification in the upper water column (see water quality section 5.B.i. Temperature, salinity, and density on page 20). Chlorophyll levels in inner Quartermaster Harbor were lower than historical values for most months, continuing a two-year decreasing trend.

Surface (<2 m) silica in February and June were much higher than normal as a result of rainfall events and increased freshwater input (Figure 5.8B). Silica in deep waters was higher than normal for almost all months in 2020. With the exception of silica, surface nutrients—including orthophosphate—were near normal in 2020 and showed spatial variation between the northern and southern areas of the Central Basin. Figure 5.8C shows the seasonal and spatial variation for surface nitrate+nitrite-N. While there was little spatial variation in the winter months, June through August values were generally lower in the northern area of the Central Basin and at East Passage, consistent with spatial differences in chlorophyll levels. Nitrate+nitrite-N was below detectable levels in Quartermaster Harbor May through September for all but one sampling event in the inner harbor and two in the outer harbor. Nitrate levels in deep waters (>100 m) were higher than normal early in the year but near normal for the remainder of the year.



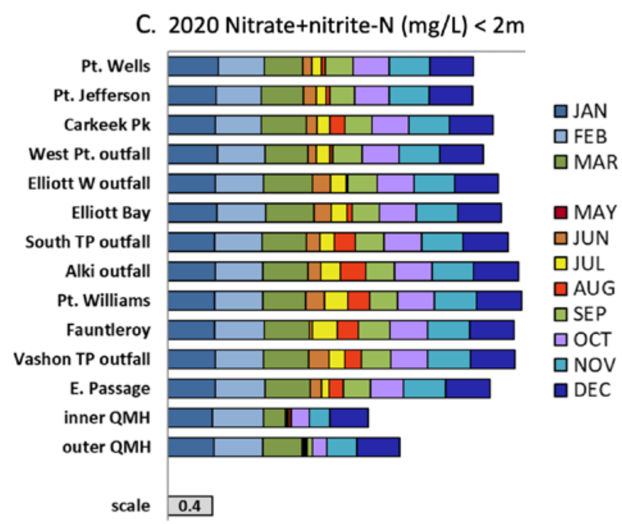


Figure 5.8. (A) Chlorophyll-a and (B) silica surface water combined monthly averages for 12 Central Basin sites compared to a long-term baseline. The box boundaries are 25th & 75th percentiles and the line within the box denotes the median (50th percentile), and the whiskers show the 10th & 90th percentiles. (C) Monthly average nitrate+nitrite-N in surface waters at all sites (north to south from top). Note there are no April results and May results exist for only the two Quartermaster Harbor sites.

C. North Sound surveys

C.i. Padilla Bay temperature

Marine Water Quality

Padilla Bay is a tidally influenced shallow (<5 m) embayment north of Puget Sound and part of the National Estuarine Research Reserve System. 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: Jude Apple (japple@padillabay.gov), Vanessa Jimenez, Sylvia Yang, Nicole Burnett, and Heath Bohlman (Padilla Bay NERR/Ecology)
Primary website: https://ecology.wa.gov/water-shorelines/shoreline-coastal-management/padilla-bay-reserve; website for online data: https://cdmo.baruch.sc.edu

Continuous monitoring of nearshore surface-waters in Padilla Bay reveals temperatures ranging from 2.3 to 23.2°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 2020 (10.9±0.01°C) was comparable to 2017 (10.8°C), and lower than 2015 (11.7°C), 2016 (11.5°C) and 2018 (11.2°C). Throughout the year, water temperatures were generally well aligned with long-term daily means, with the exception of elevated water temperatures in late summer (July-September) and short periods in January, October and November when temperatures were unseasonably low (Figure 5.9A). Despite these cooler periods, the annual mean temperature anomaly for 2020 was slightly positive (0.37°C) but still cooler than most of the previous five years (Figure 5.9B). Over the long term, warmer and cooler periods were well correlated with large-scale climatic cycles, specifically the PDO.

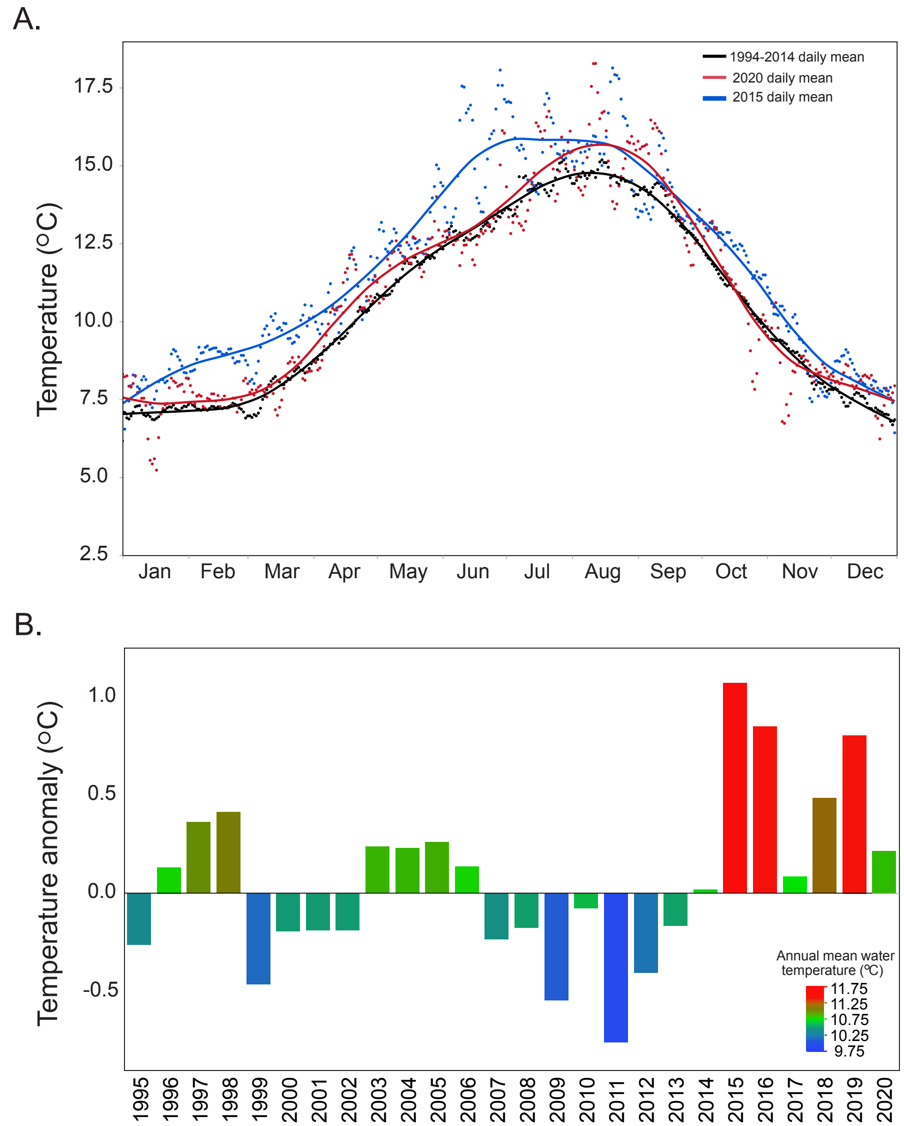


Figure 5.9. Long-term patterns in temperature in Padilla Bay, including (A) comparison of daily mean temperatures in 2015, 2020 and long-term (1995-2014) daily mean, and (B) long-term annual temperature anomalies, with bar colors representing annual mean temperature for each year.

C.ii. Padilla Bay water column characteristics

Marine Water Quality

Source: Jude Apple (japple@padillabay.gov), Vanessa Jimenez, Sylvia Yang, Nicole Burnett, and Heath Bohlman (Padilla Bay NERR/Ecology)
Primary website: https://ecology.wa.gov/water-shorelines/shoreline-coastal-management/padilla-bay-reserve; website for online data: https://cdmo.baruch.sc.edu

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 and biological processes throughout the year. 2020 began with a well-mixed water column that eventually transitioned to more stratified conditions in July (Figure 5.10A), although the precise timing and nature of this transition is difficult to define based on COVID-related restrictions on field work in spring 2020. Pronounced stratification was observed in July through September and associated with both lower salinity and elevated surface water temperature (Figure 5.10B-C) and was followed by more moderate stratification that persisted into October. The water column returned to well-mixed conditions in November. In general, stratification was delayed in the spring and ended later in the fall than in 2018 and 2019. It is important to note that COVID restrictions on field sampling prevented routine water column profiles in April - June 2020, which may compromise the ability of these data visualizations to fully describe patterns in salinity, temperature, pH, dissolved oxygen and chlorophyll throughout the year. Stratification influenced biological activity and water quality parameters. Moderate levels of chlorophyll, dissolved oxygen, and pH were observed throughout the water column in March, then transitioned to elevated chlorophyll concentrations in mid-July during the period of pronounced water column stratification (Figure 5.10D). Elevated chlorophyll concentrations persisted well into September. Patterns in dissolved oxygen and pH were coupled with these changes in biological activity, with higher values observed during the period of elevated algal biomass/fluorescence (Figure 5.10E-F). Lower algal biomass in late fall (i.e. November), combined with input of marine waters at depth and 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.

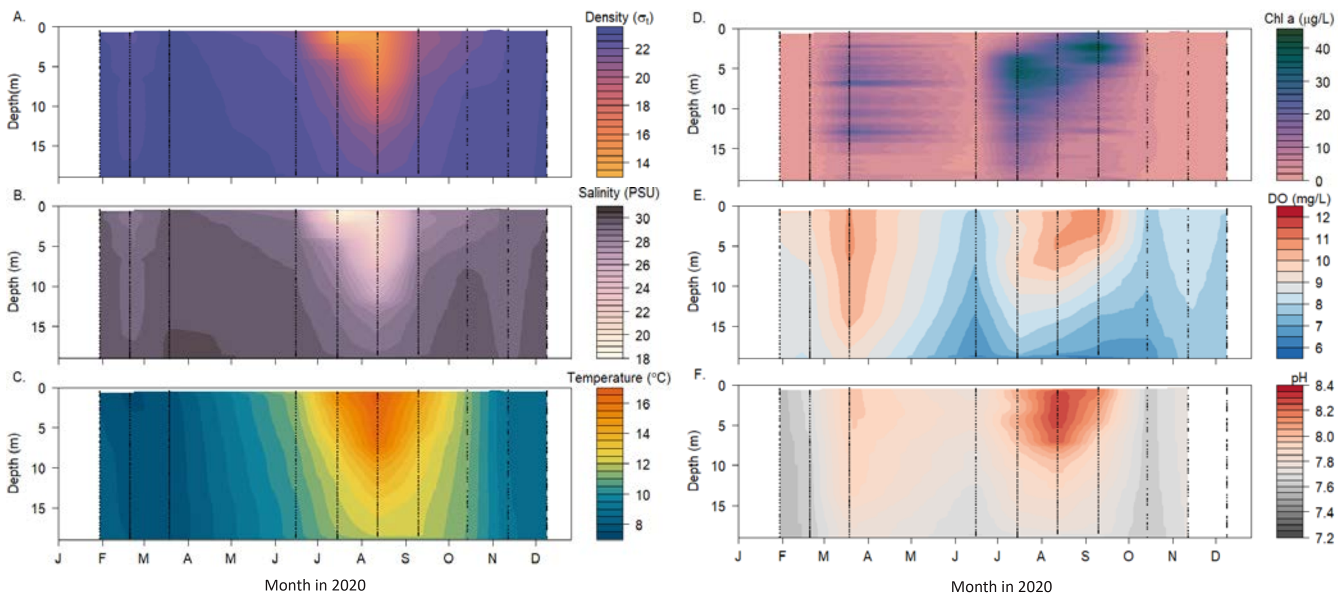


Figure 5.10. Water column profiles derived from monthly sampling at Gong Buoy illustrating patterns in (A) density, (B) salinity, (C) temperature, (D) chlorophyll, (E) dissolved oxygen, and (F) pH. NOTE: Due to COVID-based restrictions on field work, routine water column profiles were not conducted in April and May 2020. Visual interpolation of water column conditions between these sampling dates may not fully represent in situ conditions.

C.iii. Bellingham Bay

Marine Water Quality

The mooring in Bellingham Bay called Se'lhaem, installed in 2016, is maintained through a partnership between the University of Washington, Northwest Indian College, Lummi Indian Nation, and Western Washington University, with data served over NANOOS.

Source: Jan Newton (janewton@uw.edu), John Mickett, Beth Curry, Dana Manalang (UW, APL), Misty Peacock (NWIC), and Erika McPhee-Shaw (WWU); Primary website: http://www.nanoos.org; website for online data: https://nwem.apl.washington.edu

The Se'lhaem buoy is equipped with meteorological sensors at 2 m above sea level and oceanographic sensors at 0.5 m and 18 m (~7 m above the seabed). Unfortunately, there were some malfunctions that limited the time series within the first half of the year for 2020. We present the full time series for this buoy, which started in 2016 (Figure 5.11). Comparisons of such a short (and in some years incomplete) time series limits interpretation, but maximum surface temperatures during 2020 were less than observed in 2016, 2018, and 2019. Minimum surface salinities during 2020 were possibly saltier than 2016 and 2018. Over the full time series, low surface salinity and CDOM appeared to co-vary and this could imply that river waters flowing into the bay had high CDOM content, although this relationship between salinity and CDOM was not observed in 2018. Our observations suggest phytoplankton blooms were moderate in 2020, although data were missing during the time of year when phytoplankton blooms typically occur and incomplete or non-comparable records prohibit further interpretation. Surface DO dropped to 2 mg/L twice during 2020 (August and early October), which is similar to conditions observed during June 2019, though the cause of these events is not known.

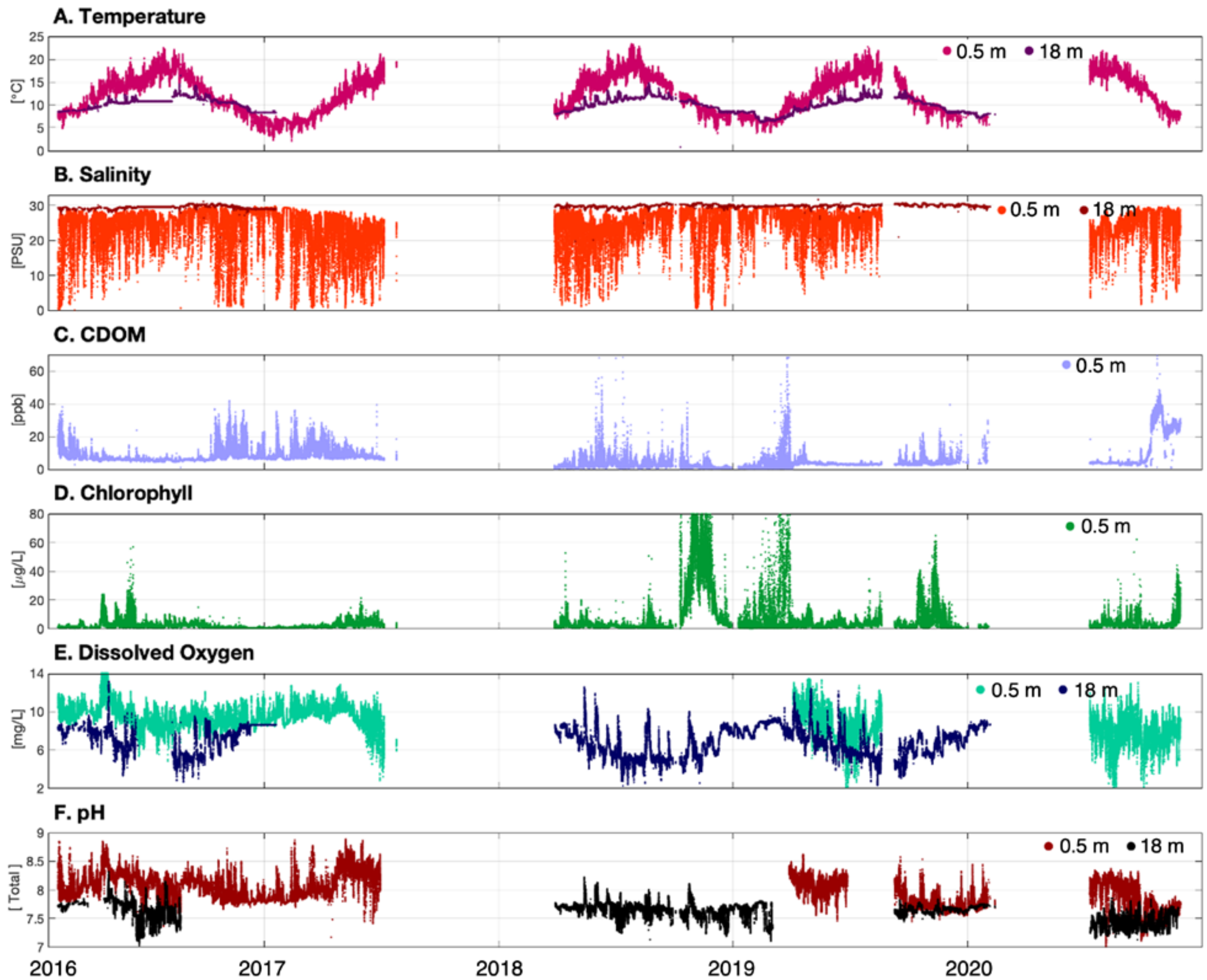


Figure 5.11. Water properties in Bellingham Bay from 2016 through 2020. Shown are (A) temperature, (B) salinity, (C) colored dissolved organic matter (CDOM), (D) chlorophyll, (E) dissolved oxygen, and (F) pH at either 0.5 m or 18 m.

C.iv. Port Susan Bay

Marine Water Quality

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 semi-enclosed estuary heavily influenced by the Stillaguamish River. This highly productive bay supports populations of surf smelt, sand lance, herring, and Dungeness crab. In 2020, researchers at the Stillaguamish Tribe conducted routine water column profiles at 10 stations throughout the bay between March and December to measure water chemistry in central Port Susan. Station 5 at 122 m depth is centrally located in the bay and is generally representative of deep waters of the basin. The Tribe also maintains a buoy in the center of the northern bay in 11 m of water, approximately two miles north of Station 5. The buoy has an autonomous probe that collects hourly data at 0.8 m below the surface.

Data from Station 5 in mid-March reveals a well-mixed water column and the coolest water of all remaining sampling events (Figure 5.12A). Highest chlorophyll concentrations were observed in April, with a chlorophyll max around 10 m deep. Elevated chlorophyll-a levels coincided with high concentrations of the diatom *Thalassosira* and elevated values of oxygen and pH. Stratification associated with low surface salinities was detected in May and June (Figure 5.12D), likely due to unusually high rainfall and river discharge during these months. Warm surface temperatures in July and August reinforced this stratification. A near-surface rise of chlorophyll-*a* in early October

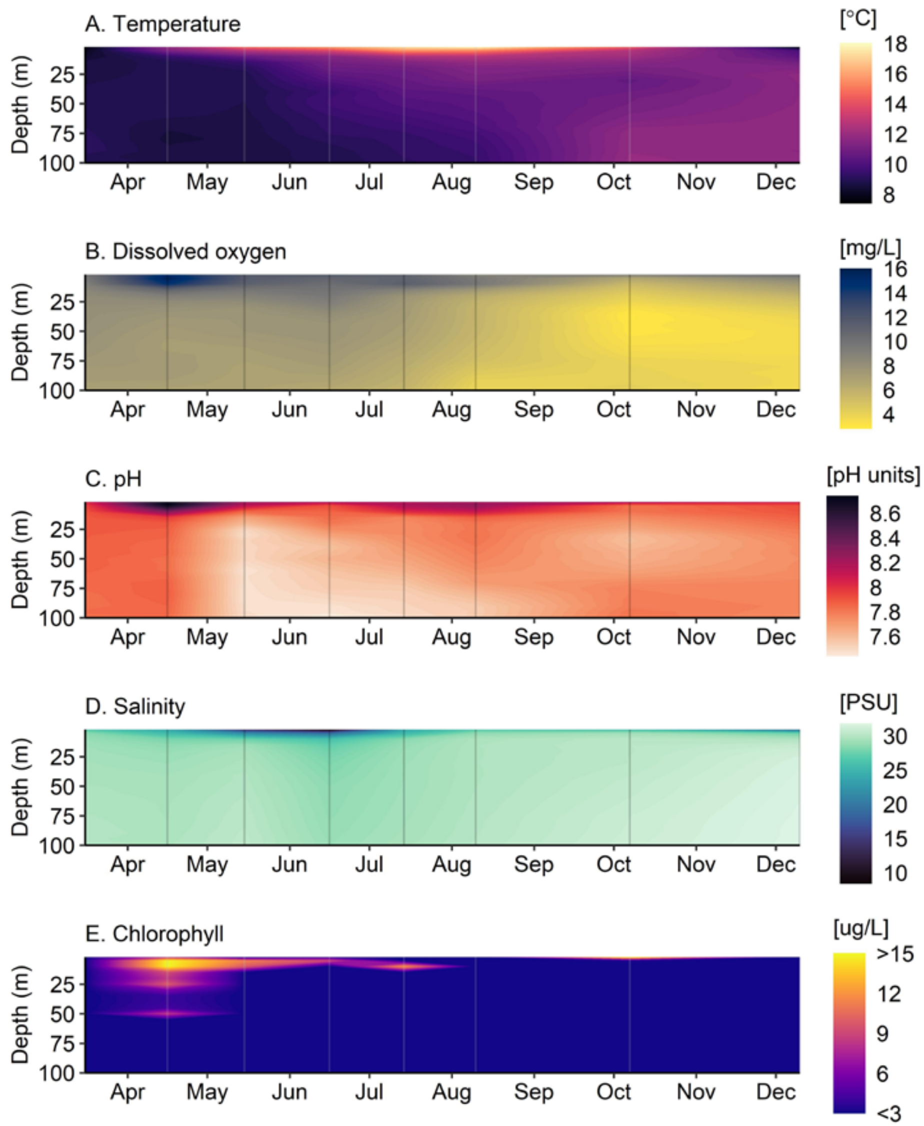


Figure 5.12. Water column profiles derived from routine sampling in central Port Susan Bay (Station 5), illustrating patterns in (A) temperature, (B) dissolved oxygen, (C) pH, (D) salinity, and (E) chlorophyll. Vertical lines on the contour plots represent the day of month on which water column profiles were conducted. Profiles were not conducted in September and November.

5. Water quality (cont.)

(Figure 5.12E) is corroborated by buoy station data (data not shown) and observations of elevated phytoplankton collected at Kayak Point Park pier. This rise in phytoplankton abundance may have been brought on by an increase in river flow discharge in late September and the consequent increase in nutrient inputs. Dissolved oxygen reached its lowest levels in October around 40 m, as subsurface salinity increased, but oxygen levels stayed at or above 3 mg/L at all stations throughout the year. These values are very similar to historical values reported in 1952-1954 (Collias, 1978). Maximum water temperatures detected were 18°C near-surface and over 11°C at 100 m. This moderate deep water temperature persisted into December.

Padilla Bay GIS specialist Suzanne Shull and AmeriCorps members Madi McKay and Holly Young at the Swinomish Channel boat launch heading out for intertidal monitoring. Photo: Madison McKay, Padilla Bay NERR

D. 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.

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

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

Marine Water Quality

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.

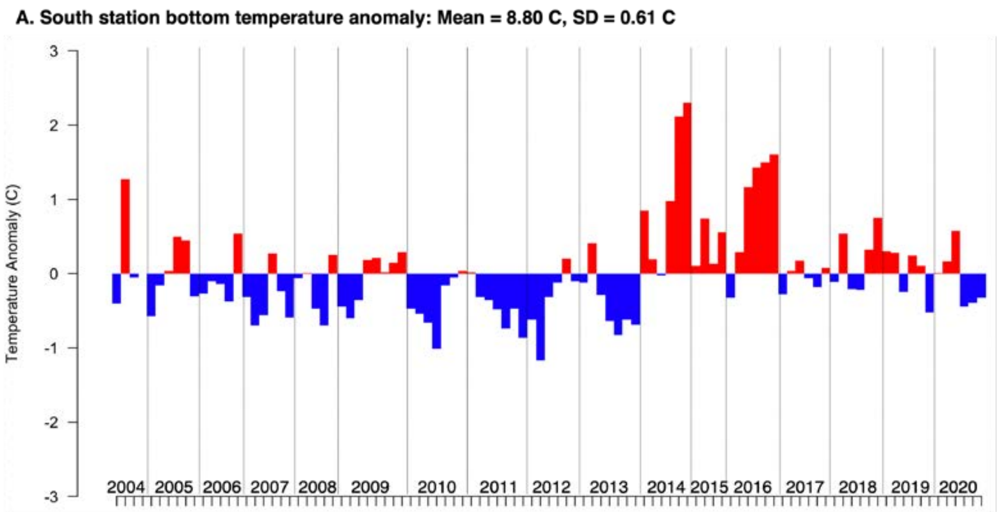
Source: Jan Newton (janewton@uw.edu) (UW, APL), Rebecca Guenther, Kayla Troske, Alex Islas, and Kate Mayer (UW, FHL);
Primary website: http://courses.washington.edu/pelecofn; website for online data: www.nanoos.org

Temperature and salinity anomalies were calculated for both surface (0-5 m) and deep waters (10 m above seabed) at both North (depth of 120 m) and South (depth of 90 m) stations occupied on ~weekly cruises during fall over the last 17 years (2004-2020). During fall 2020, seawater conditions at North and South stations showed mixed conditions relative to the long-term average. Temperature anomalies were warmer than average for the first three cruises (6-20 October) and cooler than average for the last three cruises (26 Oct-10 November), with most anomalies between +/-0.5 and 1°C. The pattern for South deep waters (Figure 5.13A) is representative of the other stations and depths. In general, since the 2014-2016 marine heatwave, most temperature anomalies have been positive.

Based on PEF records, fall 2020 was mostly fresher than average (data not shown) except for the South deep waters (Figure 5.13B), which tended saltier than average. South deep waters show the 2014-2016 marine heatwave years had fresher than average waters, with saltier than average waters in 2017-2020. However, surface waters at South station and surface and deep waters at North station all showed predominantly fresher than average waters in fall 2020, although anomalies were of varying magnitude (-0.4 PSU at North deep; -1.8 PSU at North surface; -0.9 PSU at South surface).

The magnitude and direction of temperature anomalies over the fall season were consistent across North and South stations and surface and bottom depths. In contrast, deep water salinity anomalies at South station (Figure 5.13B), which represents oceanic input, were different from the other stations and depths, which all have more riverine freshwater influence. Based on PEF and Environment Canada data, we have observed that surface salinity at North station generally correlates with Fraser River flow (PSEMP, 2019) and this station, which is well-mixed, carries this signal to depth.

During 2020, marine mammal (harbor porpoise, Steller sea lion, and harbor seal) and seabird (all species combined) abundance (as density) were relatively low compared to the 15-year record (Figure 5.14). Seabird density was higher than the previous two years and similar to 2017, but much less than 2010–2012 which had notably cool seawater temperatures. Total marine mammal densities were slightly above the last two years, with a higher density of harbor seals.



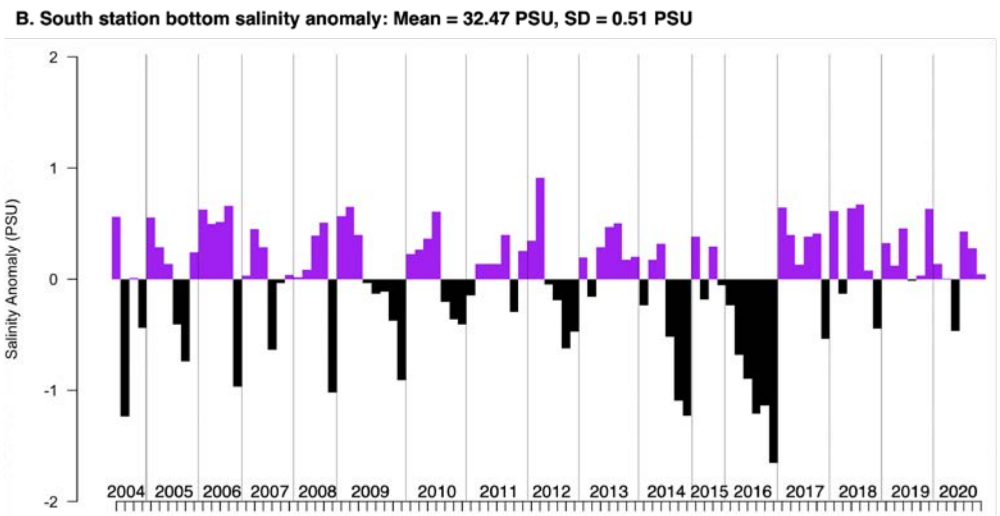


Figure 5.13. (A) Temperature anomalies (relative to full record) taken near the bottom of the South Station during fall from 2004 to 2020. Red indicates warmer (positive) temperature anomalies and blue indicates cooler (negative) temperature anomalies. The mean and standard deviation for fall temperature from 2004-2020 was 8.80°C and 0.61°C, respectively. (B) Salinity anomalies taken near the bottom of the South Station during fall from 2004 to 2020. Purple indicates saltier (positive) salinity anomalies and black indicates fresher (negative) salinity anomalies. The mean and standard deviation for fall salinity from 2004-2020 was 32.47 PSU and 0.51 PSU, respectively.

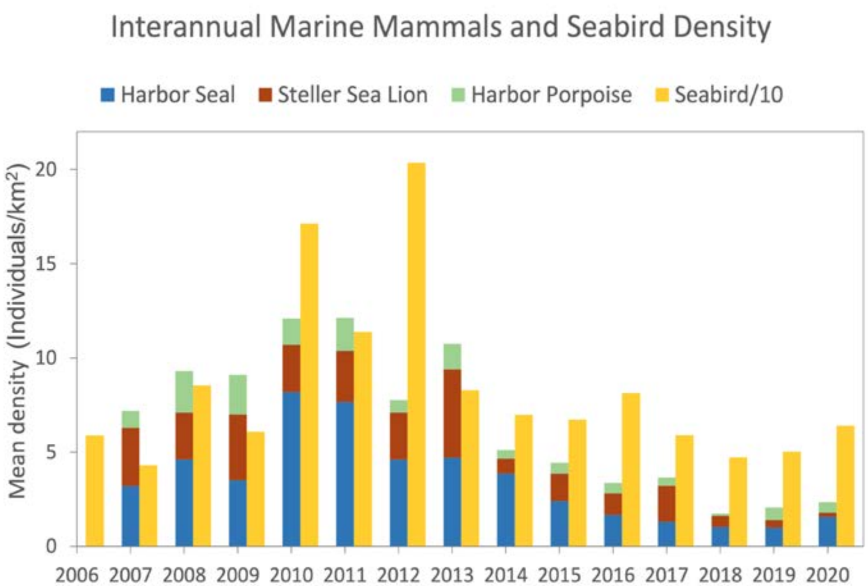


Figure 5.14. Bar graph showing mean density (individuals per square kilometer) from fall surveys conducted from 2006 to 2020 of harbor seals (blue), Stellar sea lions (red), harbor porpoises (green), and seabirds (yellow). Seabird densities are scaled by 1/10.

CALLOUT BOX: Student research at the Ocean Research College Academy

The Ocean Research College Academy (ORCA) is a two-year Running Start program at Everett Community College specializing in the marine sciences. In the first year of the program, students engage in field research by collecting biogeochemical samples from the Snohomish River Estuary onboard ORCA's research vessel, the *Phocoena*. In collaboration with their peers, students use these data to develop hypotheses and write three scientific briefs throughout their first year. In their second year, students choose their own topic for their senior research project, which culminates in a final research paper. This gives students flexibility to pursue their interests, possibly outside of the marine sciences.

One research opportunity for students in their final year is GEOPATHS, a three-quarter-long program funded by the National Science Foundation. Students in this program learn how to manage and graph "big data" using RStudio and ArcGIS, and practice communicating their research through various opportunities such as presenting at undergraduate research symposia.

Nicole and Jasmin are GEOPATHS students at ORCA. They both heard of ORCA when they were in middle school and decided they would apply. Nicole was drawn to the program because of the supportive faculty and peer community, while Jasmin was drawn because of the program's academic prowess and the research opportunities.

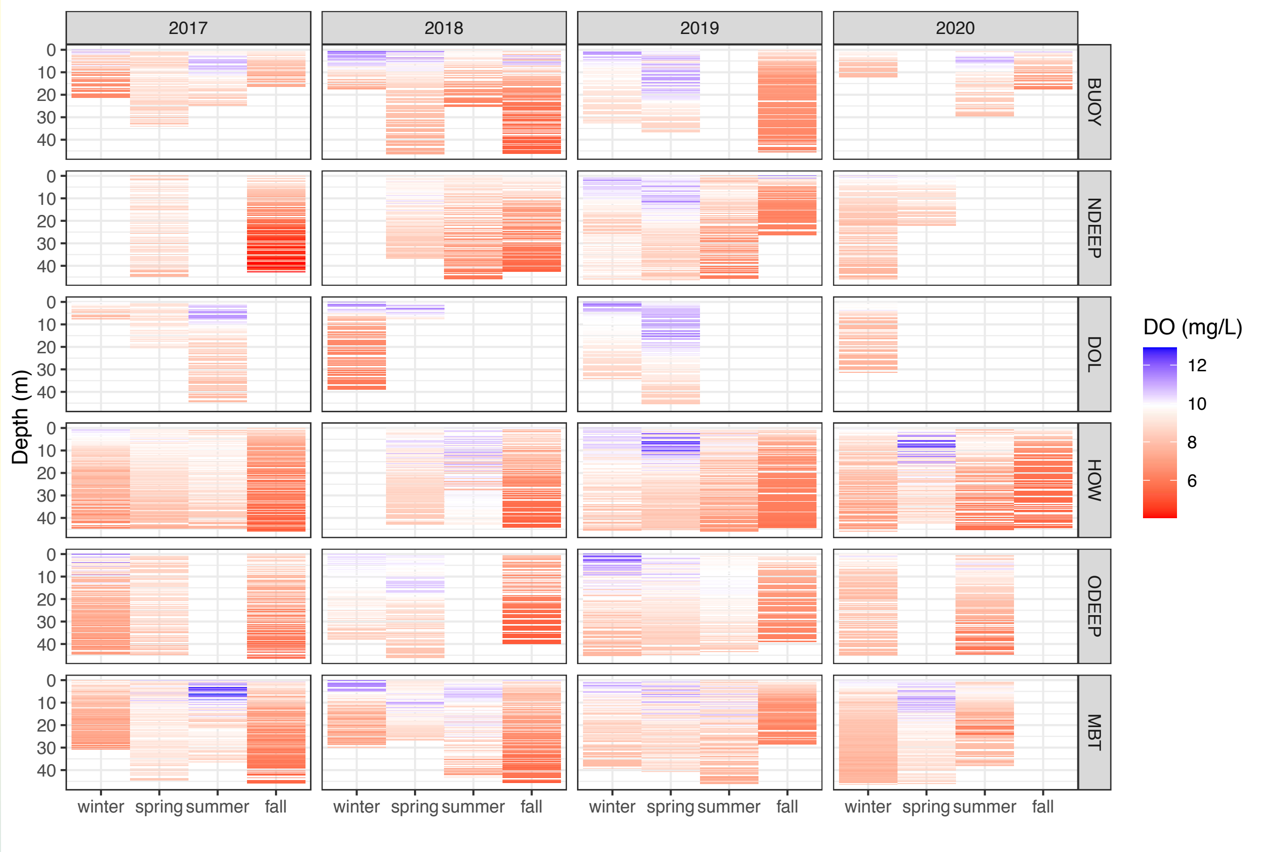


Figure 1. (A) DO concentration over depth at every study site and year (2017-2020). Concentrations were averaged over every 0.1 meter of depth for data visualization purposes. The position of the white on the color scale represents the median of DO concentration data.

CALLOUT BOX (cont.)

Attending ORCA was so important to Jasmin that she committed to commuting the three hours it took her to get to school every day.

Before attending ORCA, Jasmin was already confident in her career path and knew that ORCA would help her prepare for her future as a biological researcher. In contrast, Nicole found her career pathway at ORCA. She was able to explore different fields of marine science in the ORCA curriculum and discovered that she was interested in marine biology and oceanography and will major in those disciplines at her university.

Despite their different pathways, both took an interest in dissolved oxygen due to its ecological importance and studied its patterns in the Snohomish River Estuary for their senior research. Through the GEOPATHS program and support from the fantastic faculty, Nicole and Jasmin were able to do quality research and present their projects at the National Conference of Undergraduate Research, the University of Washington's Undergraduate Research Symposium, and the Possession Sound Student Showcase and Talks. Jasmin's research focused on influences of water temperature and chlorophyll content on DO (dissolved oxygen) from a spatiotemporal perspective; she found that there were no substantial fluctuations of DO spatially or temporally and that chlorophyll showed a larger influence on DO concentrations (Figure 1A). Nicole studied hypoxia and oxycline depths; she found that all hypoxic events (seven across 2014-2021) occurred during an El Niño period (2014-2016) and the oxycline changed over time: it was shallower in 2016-2017, deeper in 2018-2020, and shallower again in 2021 (Figure 1B). Their research is important because the Snohomish River hosts a diverse ecosystem and Puget Sound is susceptible to hypoxia, making it critical to monitor DO concentrations to protect precious marine communities. ORCA may even add oxycline measurements to its regular data collection as a result of Nicole's work.

Authors: Jasmin Graner and Nicole Reynolds (orca@everettcc.edu) (Everett Community College); www.everettcc.edu/orca

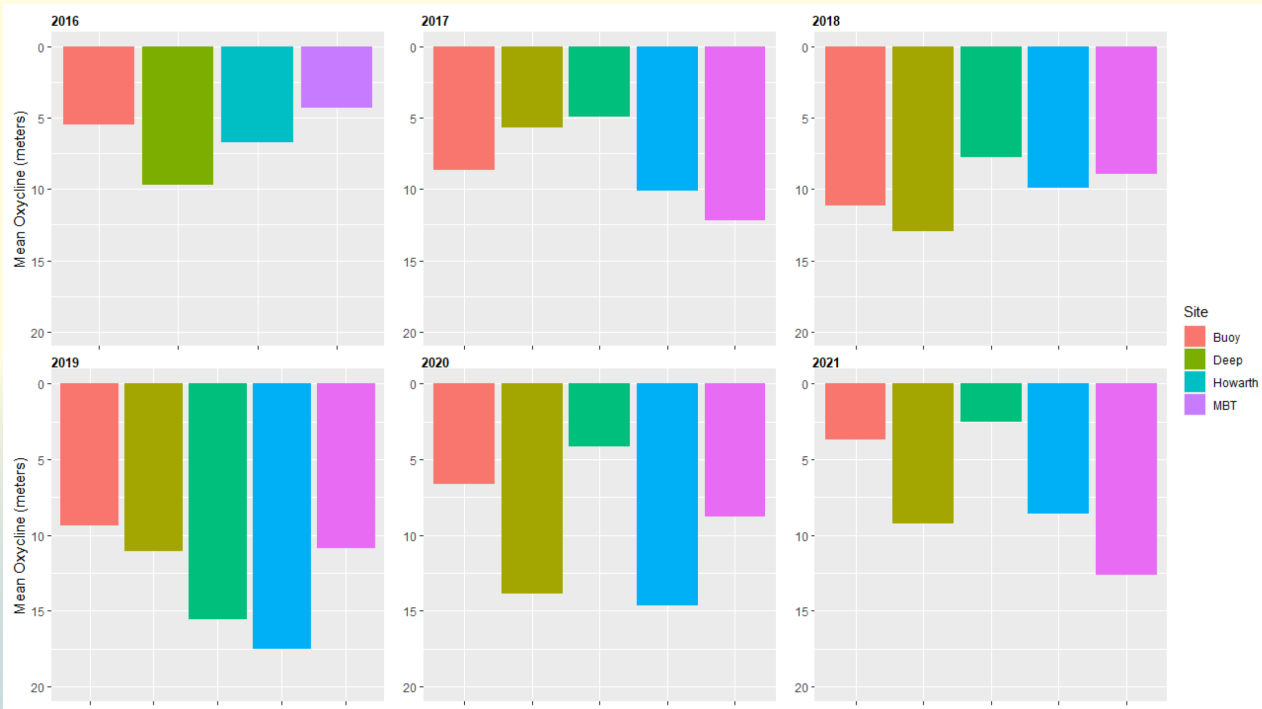
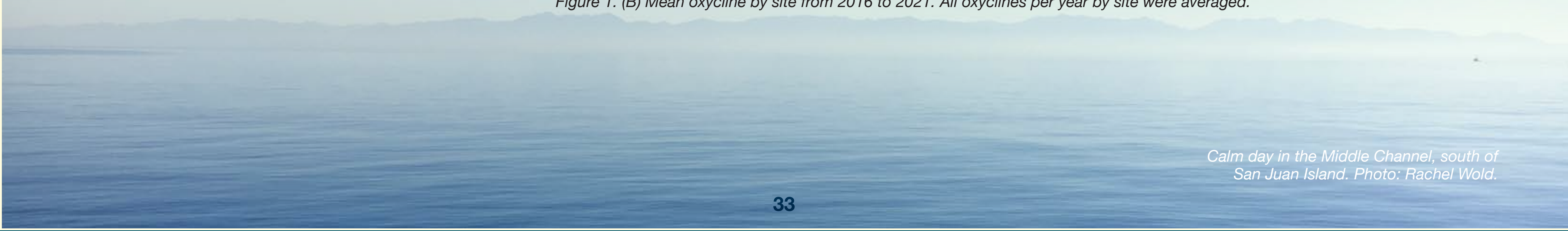
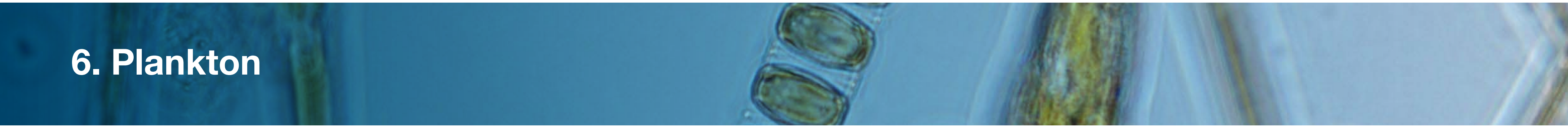


Figure 1. (B) Mean oxycline by site from 2016 to 2021. All oxyclines per year by site were averaged.



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



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

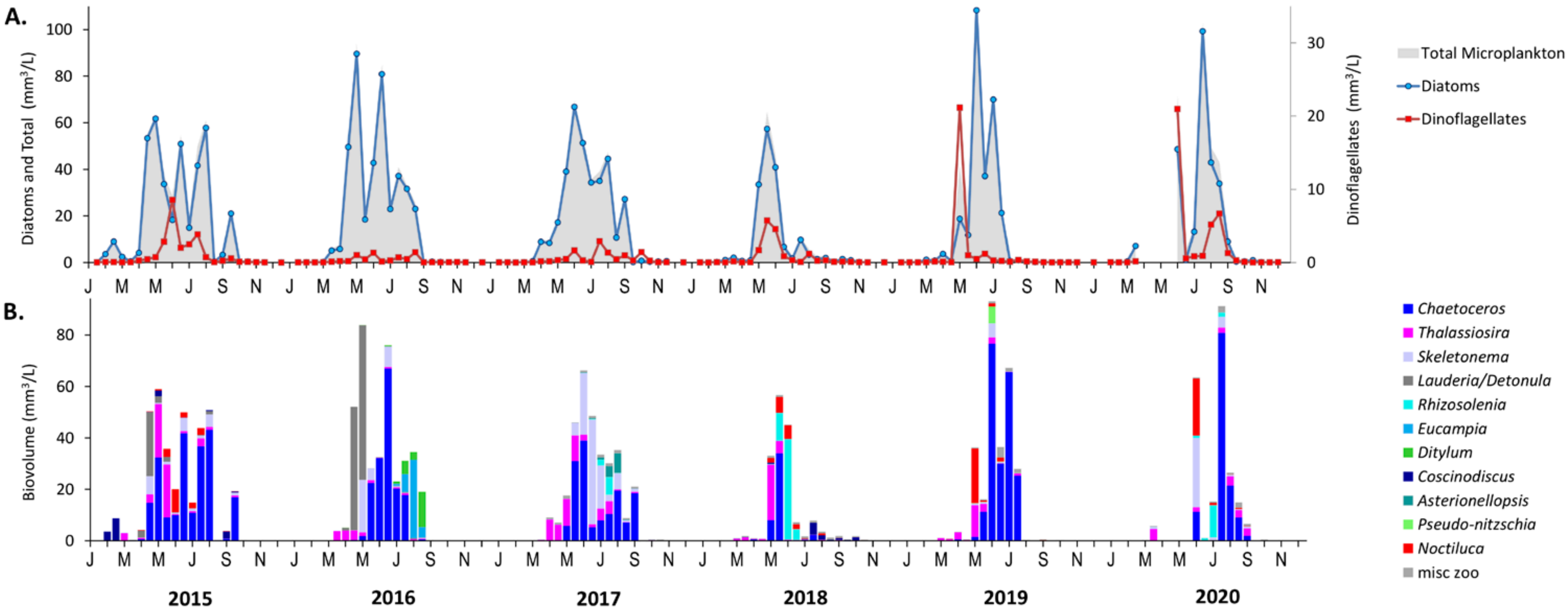
Marine Water Quality

Source: Gabriela Hannach (gabriela.hannach@kingcounty.gov) and Lyndsey Swanson (KCEL);

Primary website: http://green2.kingcounty.gov/marine/Monitoring; 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 2020, including nine open water sites and one shallow embayment (Dockton in outer Quartermaster Harbor). Six-years of biovolume data are reported in Figure 6.1A. Although total microplankton biomass in 2019 and 2020 appears similar, data that would have captured the April/May spring bloom are missing. We suspect that cumulative biomass in 2020 was higher than 2019, given evidence of an average to above-average bloom captured by continuous monitoring data collected at the Point Williams mooring (data not shown). As in past years, *Thalassiosira* species were already present in late March, indicating the beginning of a typical Central Basin succession pattern. Point Williams mooring chlorophyll data show a spring peak in May (see water quality section 5.B.iii. Nutrients and chlorophyll on page 24), most likely representing a *Thalassiosira* bloom that was gradually replaced by a mix of *Chaetoceros* species, both chain-forming diatoms (Figures 6.1B and C). *Skeletonema* was present in March and still abundant in early June after the sampling gap, and cell numbers of the large heterotrophic dinoflagellate Noctiluca peaked in June. In mid-June the *Chaetoceros* population experienced a sharp decline, and an unusually dense *Heterosigma akashiwo* bloom was observed throughout the Central Basin. The bloom (average 1.4 x 10^6 cells/L across all open water stations) reached a maximum density of 4.4 x 10^6 cells/L at the northernmost station, Point Wells, and was reflected in chlorophyll but not in biovolume values. *Heterosigma* was followed by a short bloom of *Rhizosolenia* before a return of *Chaetoceros* to form a large second bloom in July. This bloom pattern is consistent with observations of moderately strong surface density gradients in March and July (see section 5.B.i: Central Basin temperature, salinity, and density). With increased mixing, the bloom season ended in early September without an additional fall peak.

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



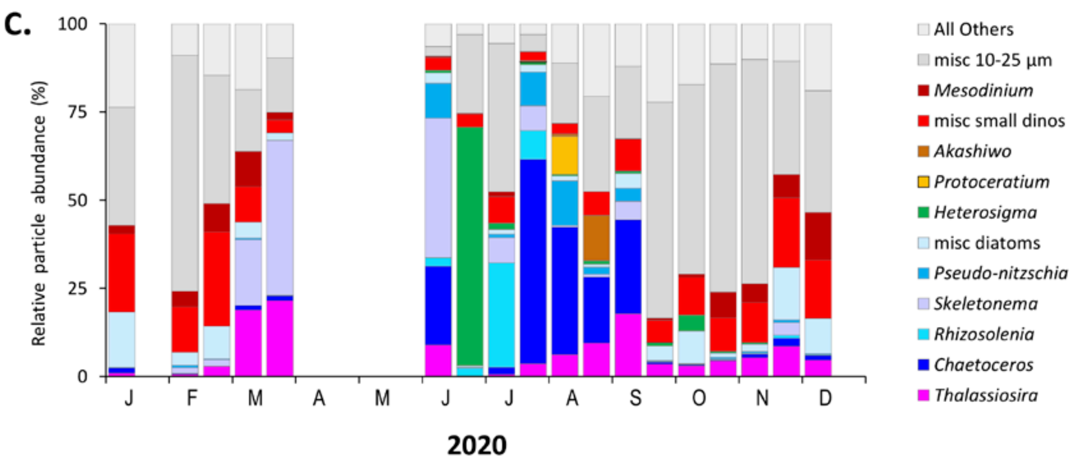


Figure 6.1. (A) Total microplankton biovolume (gray area) and biovolume of main phytoplankton groups, and (B) biovolumes of each year's top six taxa identified using FlowCAM between 2015 and 2020. (C) Relative abundance of taxonomic categories that contributed at least 10% in each sampling event during 2020. Plotted values in (A) are means for seven long term stations (Alki CSO, Vashon outfall and Dockton excluded); values in (B,C) represent eight open water sites (Elliott Bay and Dockton excluded). There was no data during April and May. Note that "particle abundance" may refer to whole chains, fragments, or individual cells, and is not indicative of biomass or cell density.

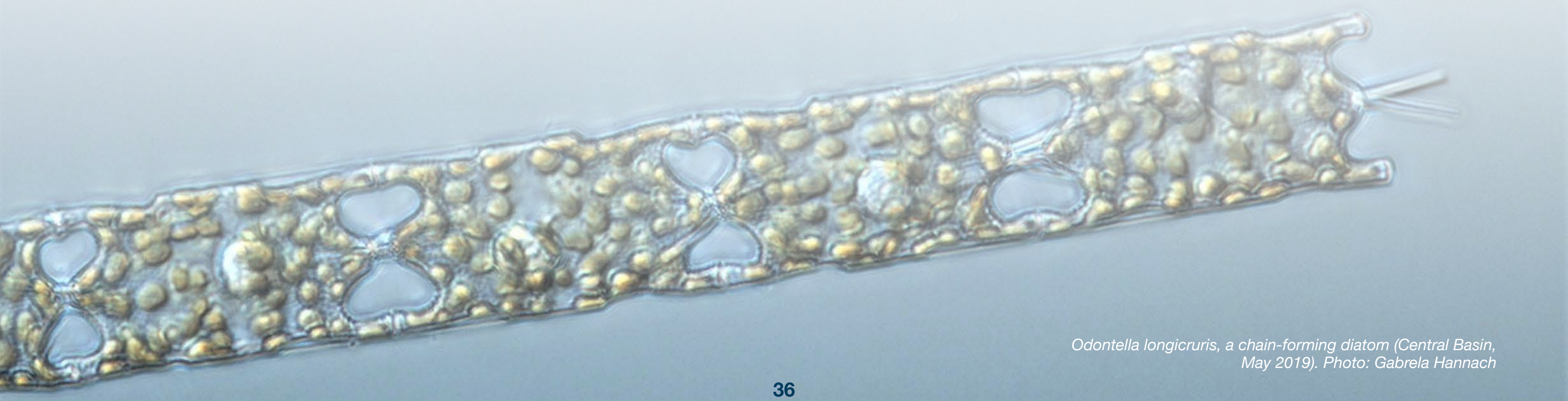
6. Plankton (cont.)

A.ii. Padilla Bay

Source: Vanessa Jimenez (vjimenez@padillabay.gov), Nicole Burnett, and Sylvia Yang (Padilla Bay NERR/ Ecology); https://ecology.wa.gov/water-shorelines/shoreline-coastal-management/padilla-bay-reserve

Marine Water Quality

Padilla Bay National Estuarine Research Reserve has been monitoring 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 (Figure 6.2A). In 2020, monthly average in situ chlorophyll was greatest from July-September and low May-June compared to the previous 3 years. July-September also had the highest phytoplankton abundances (Figure 6.2B), following in situ chlorophyll patterns. The August sample had the highest abundance of phytoplankton in 2020, *Leptocylindrus* making up 90% of the species composition. Although late summer phytoplankton abundances were greater in 2020, June 2019 had the highest monthly average in situ chlorophyll concentrations in the last five years. This may be due to the small size of the dominating chain-forming diatom species in 2020, *Skeletonema* (2-21µm) and *Leptocylindrus* (3-15µm), compared to the large solitary diatom *Rhizosolenia* (13-230µm) seen in June 2019. However, phytoplankton samples are only collected once a month and are not always indicative of monthly community composition and variation. Phytoplankton and chlorophyll dropped by the end of October, signaling the end of the fall bloom. Water column density stratification in 2020 also shows this similar pattern, with highest levels of stratification July-September and returning to a well-mixed water column by mid-October (see Figure 5.10 on page 26). Overall, phytoplankton species composition varied between months, but *Chaetoceros*, *Skeletonema*, *Thalassiosira*, and *Leptocylindrus* were dominant in 2020. *Skeletonema*, *Chaetoceros* and pennate diatoms were also present in every sample, especially in fall/winter when chlorophyll and phytoplankton abundances were low.



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

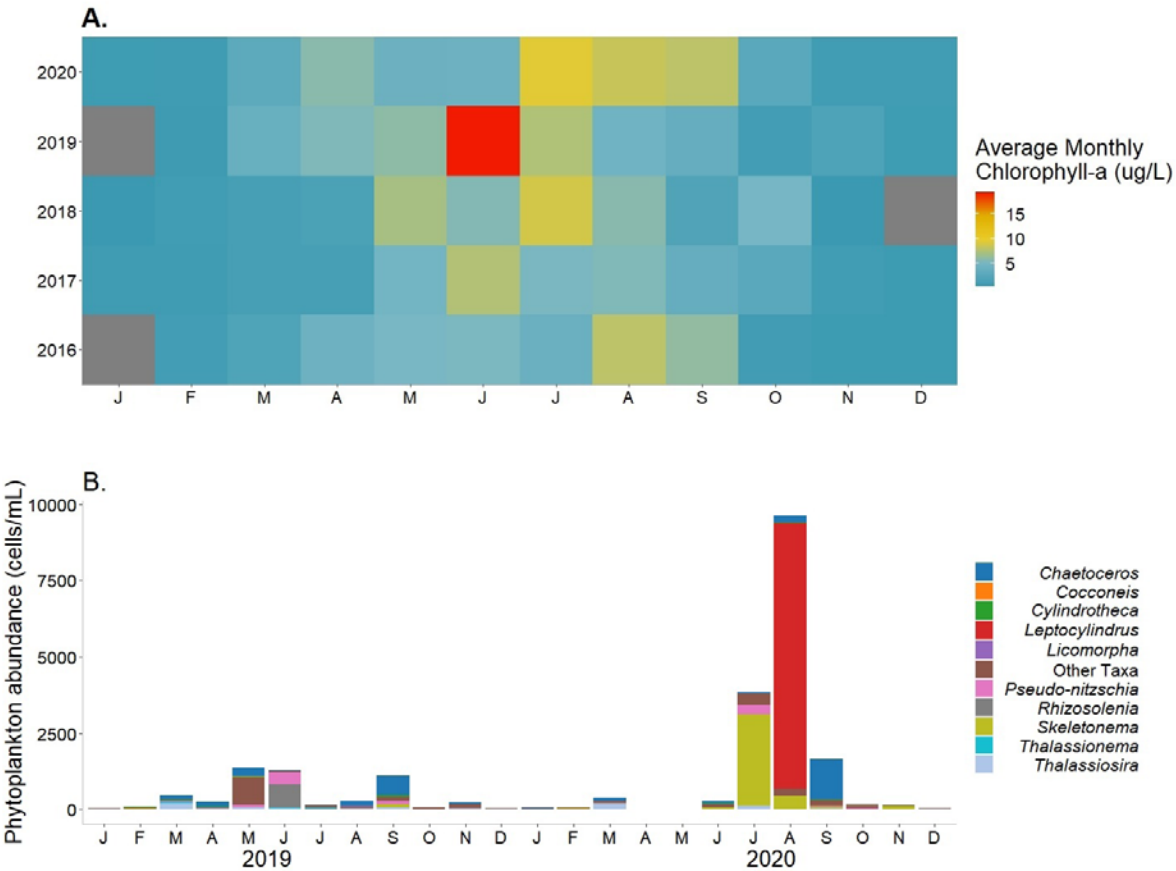


Figure 6.2. (A) Average monthly in-situ chlorophyll-a for 2016-2020. (B) Monthly phytoplankton abundance of the 10 most abundant taxa in 2019-2020. April and May 2020 were blank due to missed sampling events.

View from Mt. Constitution, Orcas Island. Photo: Simone Alin

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

Marine Water Quality

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

Overall, abundances of mesozooplankton in 2020 seemed to reflect those of 2019 (Figure 6.3A, B). However, biomass reached record highs for some of the northernmost stations, while central & southern stations remained low compared to the elevated biomass in marine heatwave years (Figure 6.3C, D). Most central & southern stations suspended spring sampling due to COVID-19, which may bias conclusions.

A notable trend that continued from 2019 was a substantial increase in spring biomass in the San Juan Islands (SJI) and Bellingham Bay driven by the large oceanic copepods *Eucalanus bungii* and *Neocalanus plumchrus* (Figure 6.3C). *E. bungii* constituted ~50-70% of the highest biomass values at SJI stations in 2020, resulting in the highest northern biomass values to date.

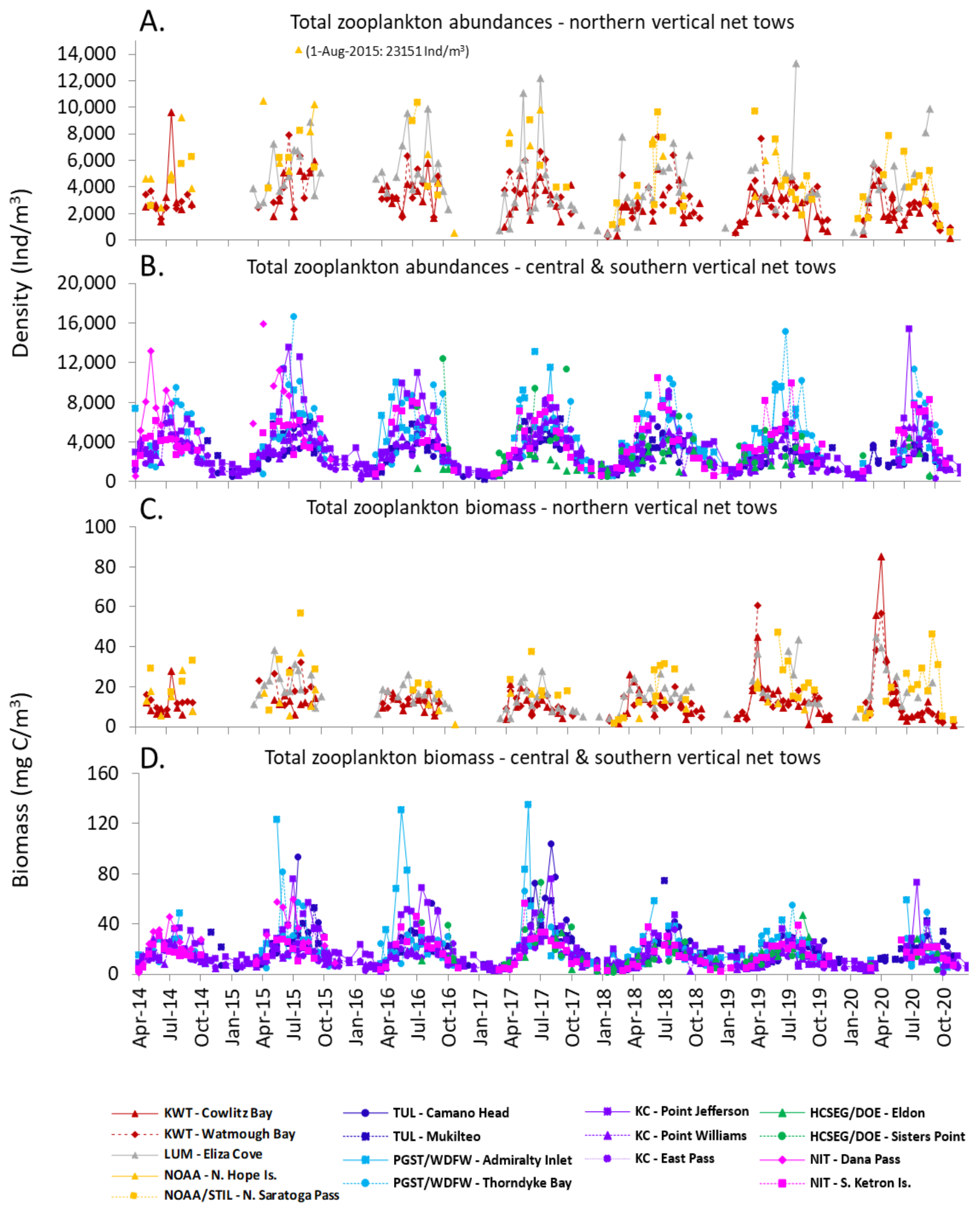
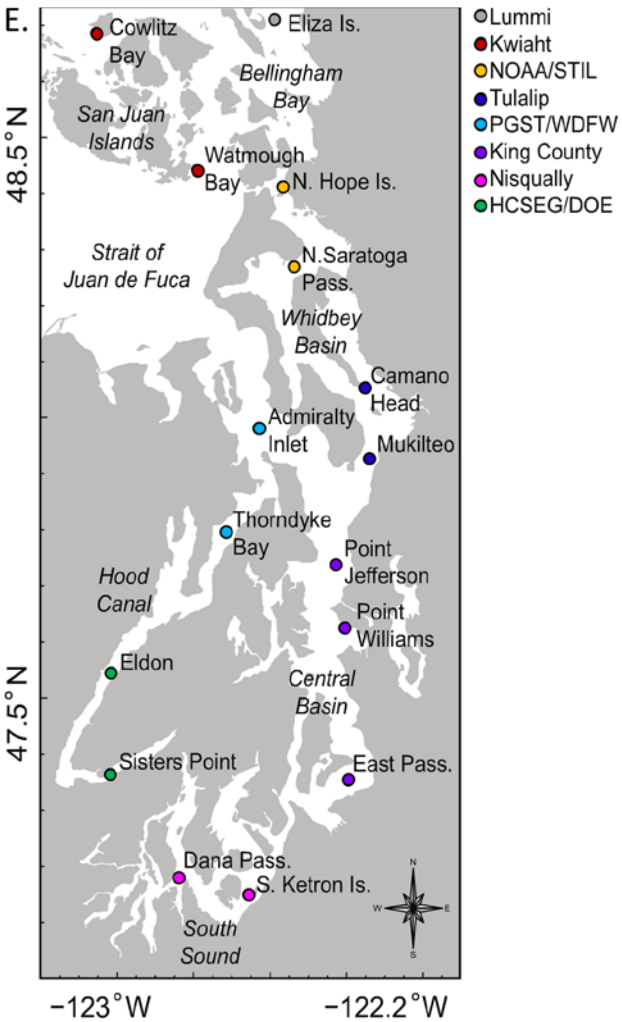


Figure 6.3. Time series of total mesozooplankton abundance (Ind/m^3) at northern stations (A) and southern stations (B) in 2014-2020. Note that most stations suspended sampling from mid-March to mid-June due to COVID-19. Time series of total mesozooplankton biomass (mg C/m^3) at northern stations (C) and southern stations (D) in 2014-2020. (E) Map of the sampling locations. Symbols are color-coded by sampling group and correspond to stations in panels A-D.



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

In contrast to other central & southern stations, Point Jefferson reached its record-high abundance and moderately high biomass in July (Figure 6.3B, D), comprised of Puget Sound resident copepods (*Microcalanus* spp., *Ditrichocorycaeus anglicus*, *Paracalanus* spp., and *Calanus pacificus*). These, along with chaetognaths and amphipods, composed 90% of the biomass, the highest value recorded at the central & southern stations in 2020.

Zooplankton sampling was conducted by King County, Nisqually Indian Tribe, Tulalip Tribe, 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 2020 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 in deep water) 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

B.ii. Padilla Bay

Marine Water Quality

Source: Nicole Burnett (nbur461@ecy.wa.gov), Jude Apple, and Sylvia Yang (Padilla Bay NERR/Ecology); https://ecology.wa.gov/water-shorelines/shoreline-coastal-management/padilla-bay-reserve

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 153 µm 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). Total zooplankton abundance started and ended below average in 2020 but was higher than average July through September. The low zooplankton abundance during winter (January, February, December) was approximately half the 10-year average (2008-2017) and was a result of decreased copepod abundance. Spring zooplankton abundances from 2020 are not directly comparable to other years because of missed samples for the months of April and May, but March 2020 abundance was the second highest since 2008. Summer 2020 zooplankton abundances were higher than the ten-year summer average (~15,000 ind/L) with more than 19,000 individuals/L. Higher than average copepod, larvacean, and other/unknown zooplankton all contribute to this trend. Similarly, fall 2020 total abundance (~10,000 ind/L) was higher than 10-year average fall abundance (~7000 ind/L) as a result of more copepods and larvaceans. Compared to 2019, 2020 summer and fall zooplankton have rebounded and are more similar to 2015-2018 abundances. The differences between 2019 and 2020 in summer and fall may be in part due to higher-than-normal chlorophyll during the corresponding months in 2020 (Figure 6.2A).

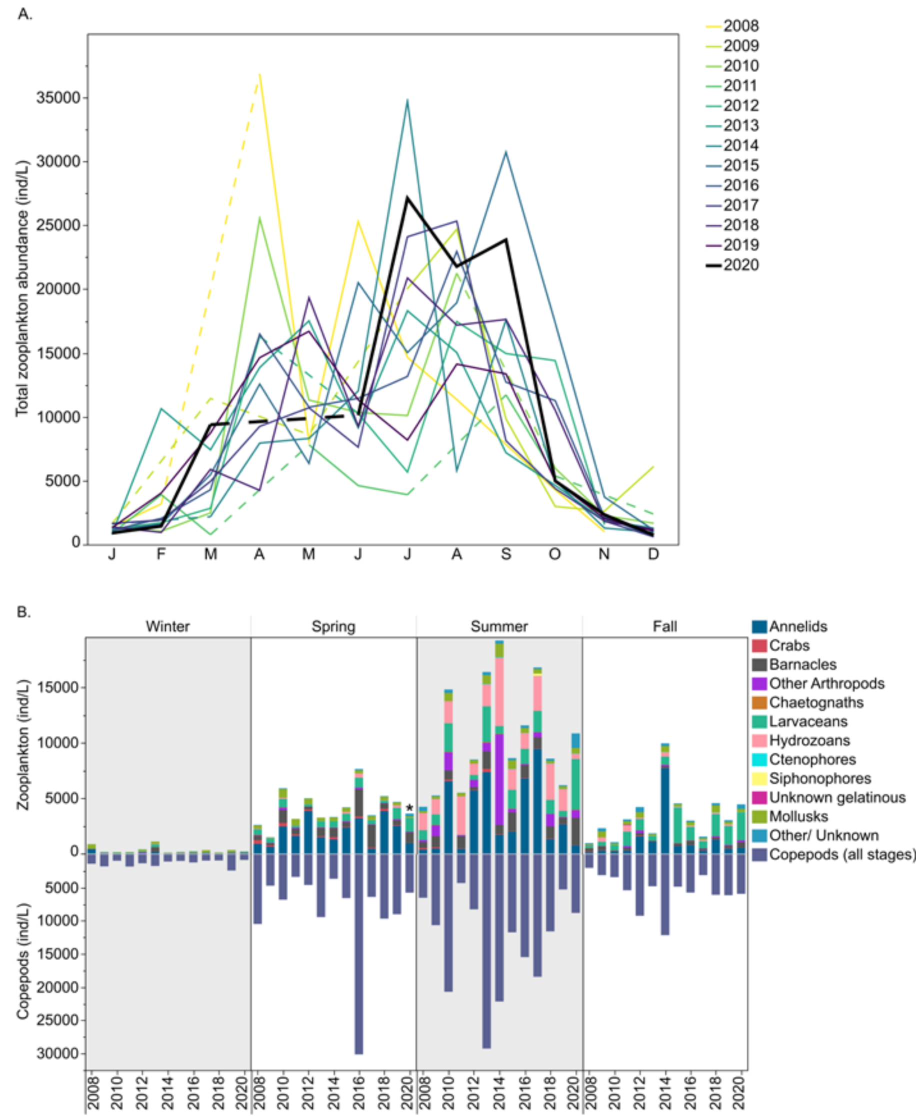


*Figure 6.4. Total zooplankton abundance monthly means from 2008-2020 (A) and seasonal mean abundances for zooplankton groups (B) at Gong Station, 2008-2020. Dashed lines indicate missed sampling events. * indicates spring mean = March only*

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

CALL-OUT BOX: Pacific Northwest Crab Research Group–Investigating spatial and temporal dynamics of larval Dungeness crab

Dungeness crab (*Metacarcinus magister*) is one of the most iconic and important marine resources in the Pacific Northwest. Despite this species' importance to coastal and tribal communities, many questions regarding how Dungeness crab populations vary and their ecological role within Washington's inland waters remain largely unknown. These knowledge gaps have become particularly evident as populations in South Puget Sound and southern Hood Canal have declined sharply in recent years, resulting in the closure of what were once productive fishing areas. The uncertainty around what is driving these population declines has raised concerns regarding the sustainability of the Dungeness crab fishery. In 2018, representatives from tribal, state and federal governments, academia, nonprofits and industry formed the Pacific Northwest Crab Research Group (PCRG) to address data gaps surrounding Dungeness crab through collaborative research.

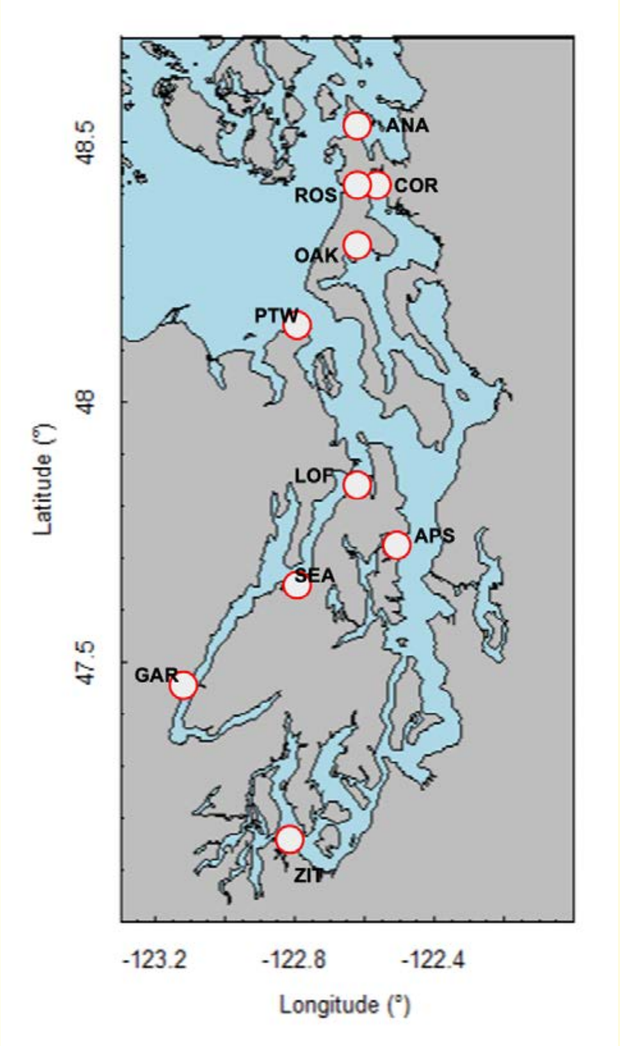
In 2019, the PCRG initiated a larval Dungeness crab monitoring network to quantify the temporal and spatial dynamics of late-stage (megalopal) larvae to evaluate potential source/sink population dynamics between and within Salish Sea sub-basins. In 2020, traps were deployed from Anacortes to Olympia, Washington by PCRG partners (Port Gamble S'Klallam Tribe, Port Townsend Marine Science Center, Skokomish Tribe, Nisqually Indian Tribe, Pacific Shellfish Institute, WA Department of Natural Resources, Suquamish Indian Tribe, and the Swinomish Indian Tribal Community) from April to September.

The 2020 results show that megalopae were present across the region from May to August, with greatest abundances observed in June for most sites. The first observed megalopae were found in southern Hood Canal in early May, nine days earlier than any other location. The Strait of Juan de Fuca complex and northern Hood Canal sites had the highest total abundances of megalopae of all monitoring sites, potentially because these waters have multiple sources for larval delivery (i.e., coastal and/or multiple Salish Sea populations). The lowest larval abundances were recorded in South Sound and southern Hood Canal, sites with limited oceanographic connectivity and sub-optimal environmental conditions (e.g. low DO levels, warmer water temperatures) that may be responsible for restricting population connectivity or inhibiting survival.

Sites within the Strait of Juan de Fuca complex and Deception Pass showed similar larval abundance and timing, with initial pulses occurring in late-May and again in late-June. The northern Hood Canal and central Sound sites exhibited a more condensed larval delivery period, with pulses occurring roughly every 10 days from June to mid-July. South Sound peak abundance occurred during this period in mid-June, albeit in much smaller numbers. Northern Hood Canal sites recorded dissimilar larval abundances overall, potentially due to diminished circulation between the two locations. Larval pulse timing in southern Hood Canal was unlike any other site, capturing both the earliest and latest-arriving larvae.

Overall, total abundances varied inter-annually and between sub-basins. PCRG partners aim to determine whether differences in timing of larval delivery are driven by genetically-based life history traits. Continuing research will look into whether these differences persist over time and how physical and oceanographic factors such as circulation, river flow, and water temperatures impact the timing and abundance of larval crab across the Salish Sea.

Authors: Claire Cook, Sarah Grossman, Emily Buckner (pnwcrab@gmail.com), Margaret Homerding, and Ryan Crim (PCRG); www.pnwcrab.com



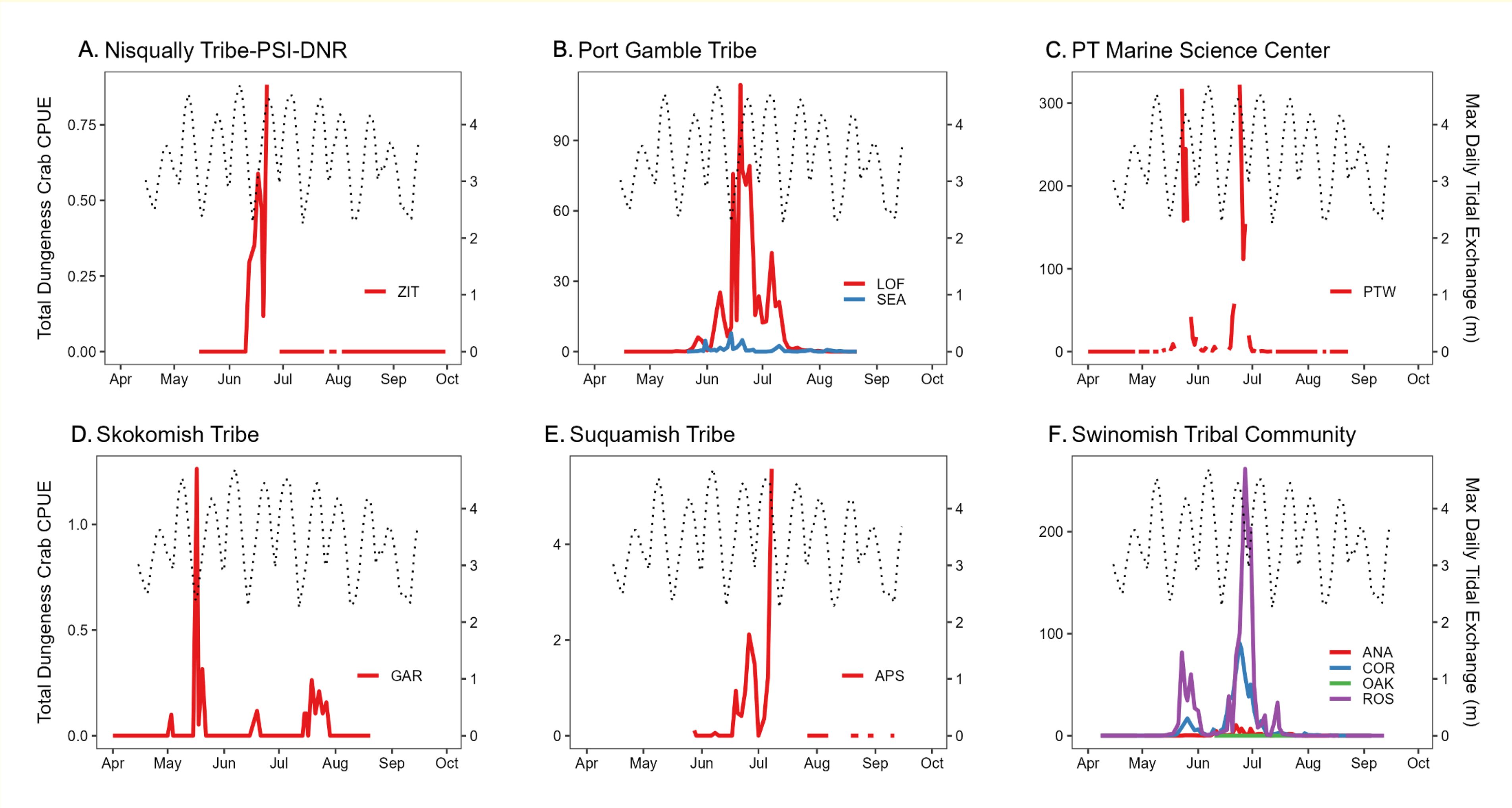


Figure 1. Larval crab catch per unit effort (CPUE) for 2020 monitoring season participants. Location of light trap stations indicated on map. Note location abbreviations in individual partner graphs and that the CPUE scale is distinct for each graph given the variability in catch across stations.

C. Harmful algae

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. Sound Toxins

Marine Water Quality

The SoundToxins program is a partnership of shellfish and fish farmers, environmental learning centers, local health jurisdictions, colleges, Native American tribes, and volunteers. Partners collect and analyze phytoplankton at 28 sampling stations throughout Puget Sound, providing an early warning system of HABs. This information allows the Washington State Department of Health to prioritize shellfish toxin analyses, and alerts shellfish and finfish producers, and researchers to potential HAB events. Stations are monitored weekly from March to October, and biweekly from November through February.

Source: Nancy Nguyen (soundtox@uw.edu) and Teri King (WSG); https://soundtoxins.org

SoundToxins, a phytoplankton monitoring and research program for Puget Sound, has 30 sentinel sites that provide key information to resource managers and aquaculture producers and notification to the Washington State Dept. of Health (WDOH) about harmful phytoplankton concentrations that threaten public health. The program documents phytoplankton and environmental parameters (e.g., temperature, salinity, weather, tide and wind conditions) occurring at its nearshore monitoring sites. The program is made possible by diverse and committed partnerships. In 2020, the most frequent blooms observed were *Thalassiosira*, *Rhizosolenia*, and *Chaetoceros* (Figure 6.5), primarily occurring from April through June. Monitors reported the first blooms of the year during the first week of March; most of these blooms were *Chaetoceros* and *Thalassiosira*. SoundToxins partners continued to document *Pseudo-nitzschia*, *Alexandrium*, and *Dinophysis*, which are three phytoplankton recognized by WDOH to be historically problematic for the safe consumption of seafood. *Pseudo-nitzschia* ranked sixth most abundant species blooming overall in 2020. Sequim Bay had the first and last reported *Pseudo-nitzschia* blooms of the year, in April and October. All but one reported Alexandrium bloom occurred in August, the other was in October. The most concentrated *Alexandrium* bloom was at Fairhaven (Bellingham) at 6,584,000 cells/L in early August. This concentration of cells greatly exceeded SoundToxins action level of ≥ 1 cells/L triggering an alert to the WDOH. The frequency of *Dinophysis* blooms decreased from 2019, with only one bloom reported in 2020 in late July at Budd Inlet, a common *Dinophysis* location. SoundToxins partners enabled recording of diverse phytoplankton observations and environmental

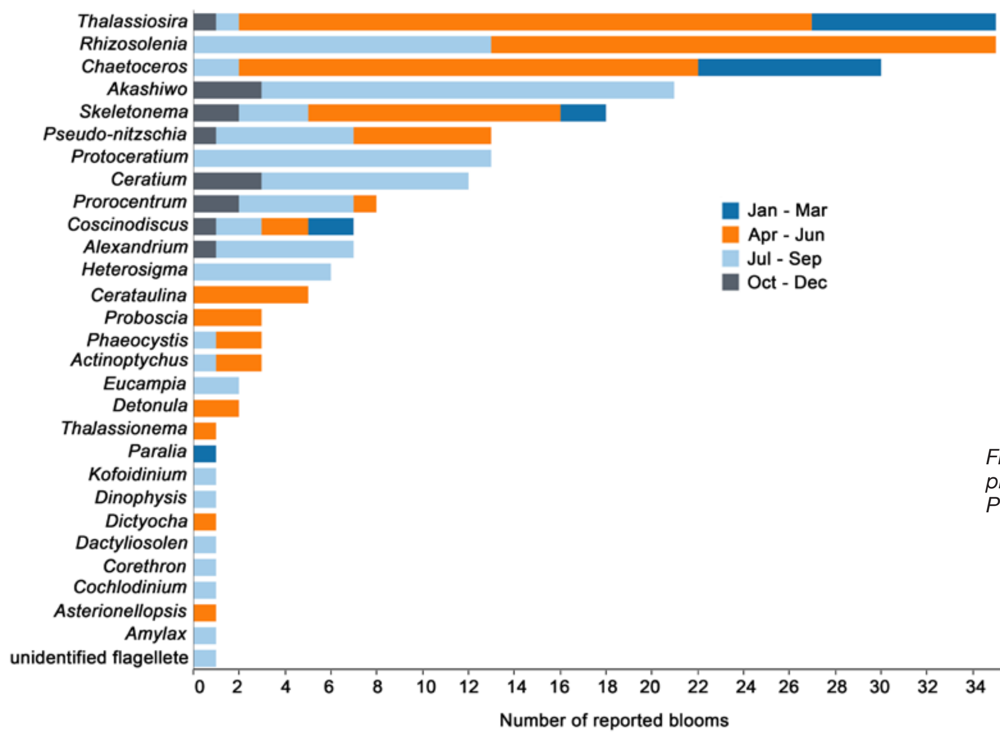


Figure 6.5. Total reported phytoplankton blooms in Puget Sound in 2020.

conditions across Puget Sound during a challenging year. Results from this program support the needs and decision making of researchers, WDOH, farming communities, and other partners.

C.ii. *Alexandrium* species cyst mapping

Marine Water Quality

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), Cheryl Greengrove (UWT), Steve Kibler (NOAA, Beaufort Laboratory), Julie Matweyou, and Courtney Hart (University of Alaska Fairbanks); https://coastalscience.noaa.gov/project/application-of-quantitative-molecular-methods-to-characterize-abundance-and-distribution-of-alexandrium-cysts-for-noaas-hab-forecasting

Alexandrium catenella is a dinoflagellate known to produce saxitoxin, which can bioaccumulate in filter feeding shellfish and is potentially harmful to mammals when consumed. *Alexandrium* exists in two phases: a vegetative swimming cell and a dormant resting cyst. *A. catenella* is most abundant in the spring and late summer after germinating from the sediment. The organism overwinters in the sediment as a cyst, making winter the optimal time to sample to determine cyst beds that could produce algal blooms after excysting during warmer times of the year. Researchers at the University of Washington Tacoma have been mapping *Alexandrium* cysts and reporting to stakeholders since the early 2000's. Predicting potential locations for *Alexandrium* blooms is useful to commercial and recreational shellfish harvesters.

Findings from the 2020 survey using microscope enumeration of cysts are highlighted in Figure 6.6. Cyst abundances were lower than prior winter observations. Consistent with past work, higher cyst concentrations were found in Quartermaster Harbor (north of Tacoma), Bellingham Bay, & bays in the western Main Basin (west of Seattle). One area of increased cyst abundance was Penn Cove (northeast of Everett), which has historically been a site with Paralytic Shellfish Toxin occurrences in shellfish.

A NOAA-MERHAB-sponsored project (NA19NOS4780188) with NOAA's Beaufort Lab, University of Alaska Fairbanks, and the University of Washington Tacoma involves the development of techniques to reduce the time and effort needed to monitor this toxic alga. Presently, surface sediment samples are collected in the field, prepared for analysis, and manually counted for cysts via epifluorescence microscopy. New methods would use molecular analytical procedures such as qPCR and FISH to lessen the effort for cyst identification and counting. Field work for this project includes collecting annual samples from Gulf of Main, Gulf of Alaska, and Puget Sound. Samples will be analyzed manually and through molecular analysis.

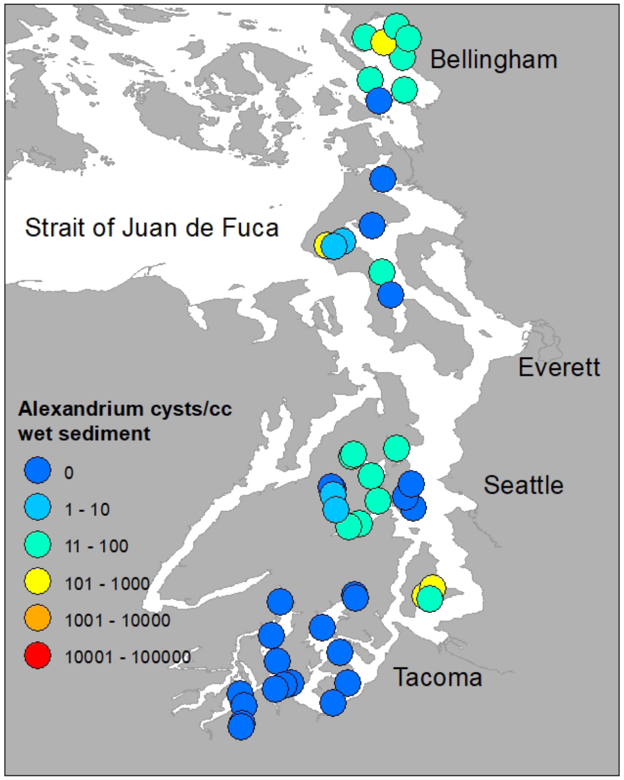


Figure 6.6. Distribution and concentration of Alexandrium catenella *cysts in Puget Sound surface sediment samples collected in winter 2020.*

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

Outdoor Activity

*The Beach Environmental Assessment, Communication, and Health (BEACH) Program is jointly administered by the 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 the Environmental Protection Agency's swimming standards. The program is funded by the Environmental Protection Agency.*

Source: Laura Hermanson (laura.hermanson@ecy.wa.gov) and Julianne Ruffner (Ecology, WDOH); Primary website: https://ecology.wa.gov; website for online data: https://ecology.wa.gov/Research-Data/Monitoring-assessment/BEACH-annual-report

The BEACH Program coordinates weekly or bi-weekly monitoring from Memorial Day to Labor Day with local and county agencies, tribal nations, and volunteers. In 2020, 63 Washington beaches were sampled, including 42 core beaches (sampled yearly). Figure 7.1 represents the percentage of all monitored beaches that had less than two swimming advisories or closures during the swimming season from 2004–2020. During the 2020 monitoring season, three beaches had more than one exceedance of the swimming standard and were therefore not considered passing beaches. Freeland County Park had two sampling events that exceeded the safe swimming standard. A permanent swimming advisory was in place from June 1 through September 15 due to sporadic, high bacteria levels during months when accumulation of beach wrack (i.e. decaying marine vegetation along the shoreline) was observed. During the summer, north winds cause wrack to accumulate along the shoreline. High bacteria levels during summer months may be a natural condition at this beach. Four sampling events at Little Squalicum Park beach exceeded the safe swimming standard. Although this beach typically has consistently low to moderate bacteria levels, occasional spikes in fecal bacteria have resulted in a permanent swimming advisory for this beach Elevated bacteria may be due to high freshwater inputs from the Nooksack River, the beach's urban location, or a nearby dog park. Two sampling events at Arness County Park each exceeded the swimming standard, but subsequent sampling resulted in safe bacteria levels, so an advisory was not issued. This beach usually has good water quality and sources of elevated bacteria remain unknown.

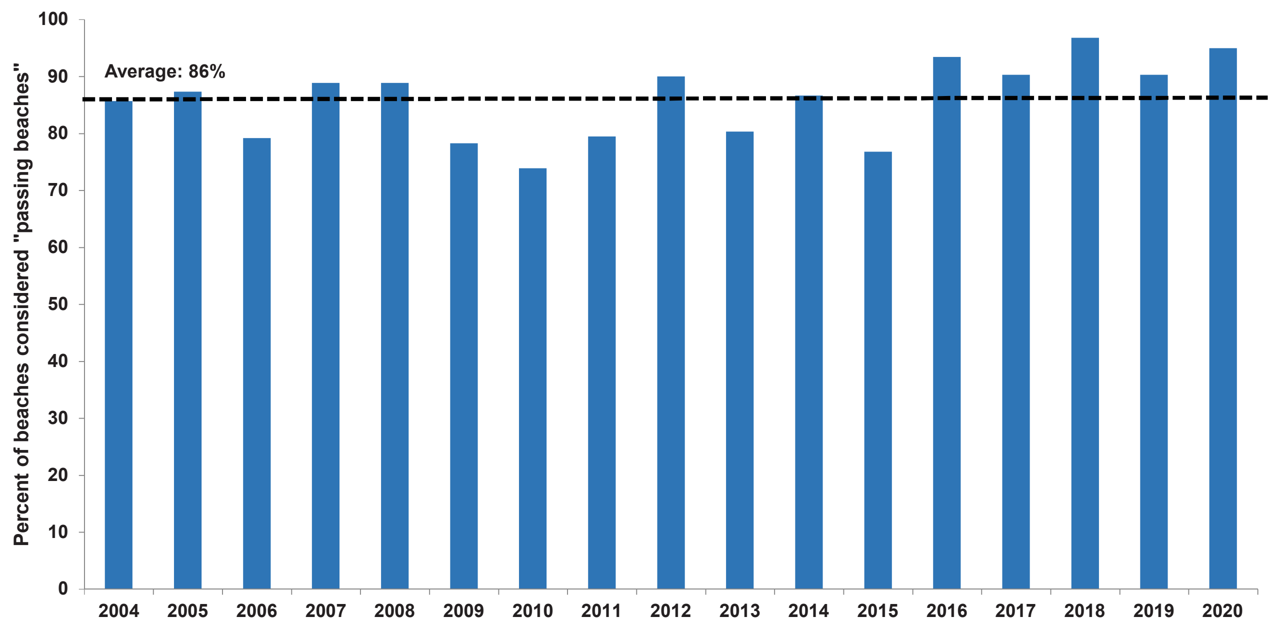


Figure 7.1. Percent of all marine beaches sampled that had no more than one swimming closure or advisory (considered "passing beaches") during 2004-2020. The average percentage of passing beaches is 86% (black dashed line).

A.ii. Central Basin stations

Outdoor Activity

Source: Wendy Eash-Loucks (wendy.eash-loucks@kingcounty.gov) (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. No beach samples were collected in April 2020 due to the COVID-19 pandemic. King County also monitors bacteria at 14 offshore locations that include a mix of ambient and outfall stations. Samples from 1 m depth were collected twice monthly most of the year (monthly in January and December; no samples were collected April to mid-June 2020). These data are used to determine if waters have chronic bacteria problems and evaluate how concentrations are changing over time.

Beach bacteria annual geometric mean concentrations in 2020 were spatially variable. The highest annual geometric mean *Enterococcus* concentrations occurred at Redondo Beach and Carkeek Park near the Piper's Creek outflow and the lowest concentrations occurred at Alki and West Point's North and South beaches (Figure 7.2A). The 2020 annual geometric means for *Enterococcus* and fecal coliform were generally within the historic spread but were on the higher end of that spread for *Enterococcus*. Exceptions were for *Enterococcus* at Redondo Beach where 2020 was the highest geometric mean, and for fecal coliforms at Constellation Park and Fauntleroy Cove, where concentrations were much lower than those in the 1980s and 1990s (Figure 7.2B). For most stations, the highest bacteria concentrations occurred September through December. The earliest months of the rainy season typically correspond to the highest bacteria concentrations. September 2020 samples, collected after several months of dry weather, generally had the highest bacteria concentrations.

Similar to previous years, 2020 bacteria concentrations offshore were much lower than those at beach stations (Figure 7.2A). The offshore stations with the highest bacteria concentrations included those located within the embayments of Quartermaster Harbor and Elliott Bay (Figure 7.2A), but even those stations had geometric means of less than 4 CFU/100 mL for both types of indicator bacteria.

A. **B.**

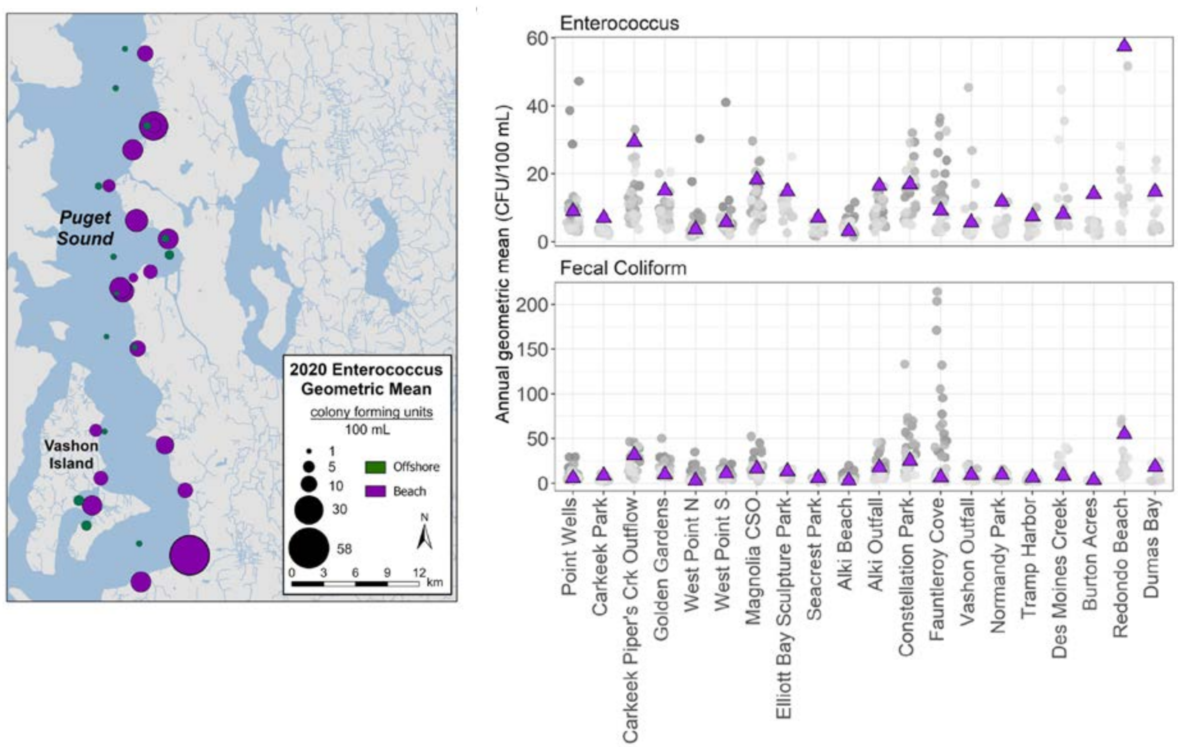


Figure 7.2. 2020 King County indicator bacteria monitoring results. (A) Map of the Enterococcus *annual geometric mean concentration at King County beach and offshore stations; (B) Annual geometric mean* Enterococcus *and fecal coliform concentrations at beach stations from 1981 to 2020. 2020 values in B 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

Pacific Herring

Source: Todd Sandell (todd.sandell@dfw.wa.gov), Adam Lindquist, Patrick Biondo, Katie Olson, Eric Bruestle, and Phill Dionne (WDFW); https://wdfw.wa.gov/fishing/commercial/puget-sound-herring

The estimate for herring spawning biomass in 2020 was 18,559 metric tonnes (mt), the highest since 1980. In comparison, the average estimated spawning biomass (ESB) over the previous ten years was 9,350 mt. Given the COVID-19 shutdown, which severely limited our herring survey efforts, it is likely that this ESB value for 2020 is an underestimate and actual biomass is much higher. Full sampling coverage (i.e. rake surveys) during the spawning period only occurred in six out of 20 stocks during 2020. Another six stocks had only moderate coverage, and eight stocks had inadequate or no coverage (i.e. Fidalgo Bay, Samish Bay, Kilisut Harbor, Sequim Bay, NW San Juan Islands, Interior San Juan Islands, Cherry Point, Point Roberts). The biggest increases in spawning biomass occurred at Purdy (884 mt; South Sound), Quilcene Bay (7,118 mt; Hood Canal) and Port Orchard-Port Madison (7,077 mt; Central Basin); these were the largest spawning events ever recorded at these sites. The genetically unique Cherry Point stock increased slightly (5%) from 2019, with an ESB of 1,925 mt. Despite all the good news, herring stocks in South Puget Sound (other than Purdy) continue to do poorly, with no spawn detected at two sites even with moderate survey coverage (Wollochett and Quartermaster Harbor). Concerns persist regarding declines in herring biomass in the southern Salish Sea and the resultant ecosystem-wide impacts of this reduction in prey abundance. 2020 may reflect deferred effects of the anomalous warm water period from 2014-2016 ("the Blob"), which saw an increase in zooplankton biomass, but it is unclear why only three stocks increased.

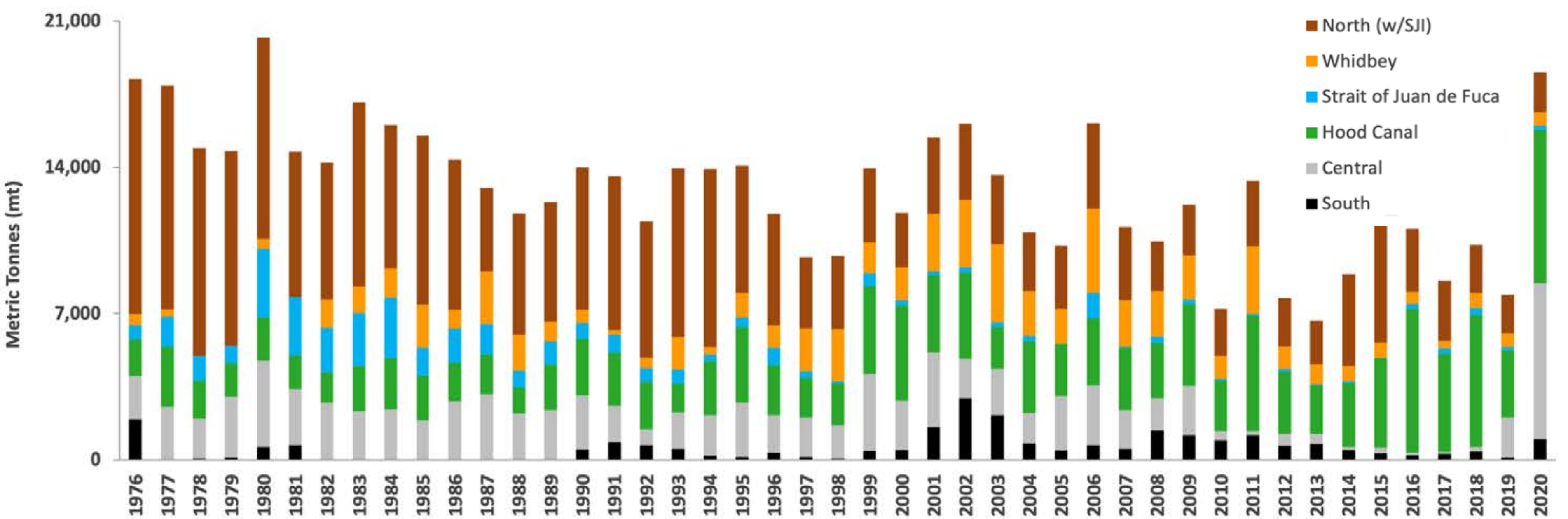


Figure 8.1. Herring estimated spawning biomass by region, 1976-2020.

B. Juvenile Chinook

Chinook Salmon

Source: Russel Barsh (russel@kwiaht.org), Madrona Murphy, Meghan Howard, and Ed Fisher (KWIAHT); http://www.kwiaht.org

Juvenile Chinook outmigrants have been monitored since 2009 at two stations in the San Juan Islands: Watmough Bay (Lopez Island) and Cowlitz Bay (Waldron Island). Sampling is conducted biweekly each year from May to September (10 dates at each station) on evening flood tides using a 120-foot modified Puget Sound beach seine. A set may be repeated to confirm whether juvenile Chinook are present, and total annual sets per station have varied from 16 to 18. Juvenile Chinook outmigrants peak between mid-May and mid-July, although they are present from early May to early September. Puget Sound origin Chinook are most abundant at the Watmough station, which is close to Admiralty Inlet, whereas Fraser origin Chinook dominate samples from Cowlitz (Chamberlin et al., 2017), making it possible to estimate relative contributions of these two watersheds to the total annual production of Chinook smolts migrating seaward through the central Salish Sea. Juvenile Chinook abundance peaked in 2011-2013, coinciding with relatively cool waters, then returned to significantly lower levels that remained through 2020.

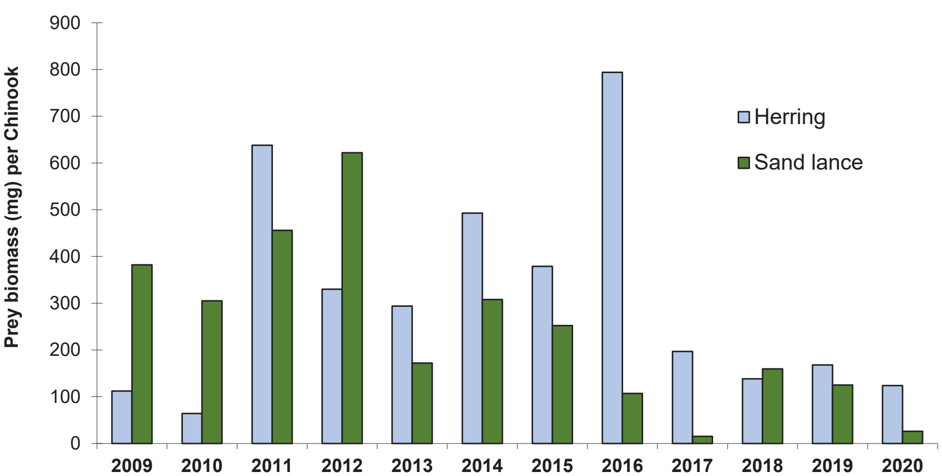


Figure 8.2. Mean annual consumption of forage fish by unmarked juvenile Chinook outmigrants at stations in the San Juan Islands 2009-2020.

Gut contents were sampled by non-lethal gut lavage of 1,587 Chinook over the course of this study. In addition to a decline in annual abundance, juvenile Chinook transiting the San Juan Islands are also eating less forage fish. This trend is strongest for unmarked Chinook sampled at Watmough Bay, and greater for Pacific Sand Lance than Pacific Herring. It remains unclear whether the observed decrease in forage fish consumption was due to a decline in forage fish presence in the central Salish Sea, or desynchronization of Chinook and forage fish migrations (Duguid et al., 2021). Mean fork length of juvenile Chinook declined 14.6 percent in the Watmough sample during the study period and 1.8 percent in the Cowlitz sample.

Juvenile Lingcod from a research beach seine in the San Juan Islands. A voracious predator and prized sport fish, it can grow to several feet in length. Photo: Russel Barsh for Kwiaht

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. Rhinoceros auklet: Long-term reproductive success

Birds

Source: Peter Hodum (phodum@pugetsound.edu) (University of Puget Sound), Scott Pearson (WDFW), Thomas Good (NOAA, NWFSC), and Eric Wagner (UW, Center for Ecosystem Sentinels); https://wdfw.wa.gov/species-habitats/at-risk/species-recovery/seabirds#monitoring

The effectiveness of using seabirds as indicators of marine conditions is a function of their sensitivity to changing environmental conditions, with changes in reproductive parameters reflective of variability in the marine environment. Since 2006, we have been monitoring the breeding season of rhinoceros auklets (*Cerorhinca monocerata*) on Protection Island, Washington, in the Salish Sea. Prior to a highly anomalous breeding season in 2016, rhinoceros auklet focal breeding parameters, including burrow occupancy (the proportion of burrows that were reproductively active) and hatching and fledging success, exhibited little inter-annual variability. However, fledging success in 2016 was the lowest recorded in our time series, as a consequence of a large-scale adult mortality event. Reproductive parameters finally returned to the long-term mean values in 2019. In 2020, burrow occupancy (0.70) was comparable to the long-term mean of 0.72 (Figure 9.1A). Hatching success, unaffected throughout the anomalous seasons, continued to be relatively consistent

Glaucous-winged Gull with an unfledged chick in a nest on a ferry dock in the San Juan Islands. Photo: Russel Barsh for Kwiaht

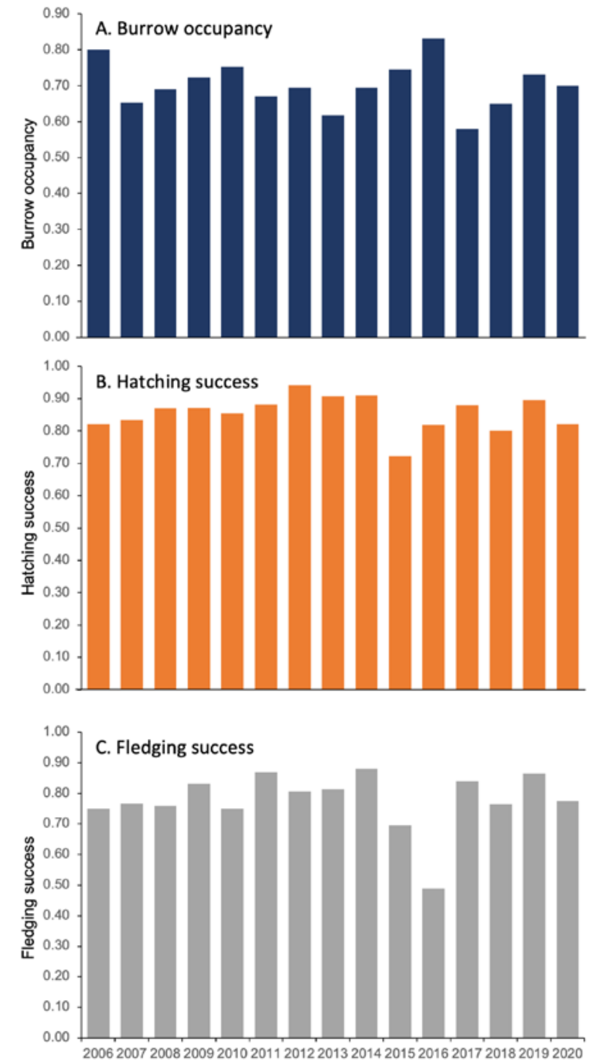


Figure 9.1. The proportion of rhinoceros auklet (A) breeding burrows that were reproductively active (burrow occupancy) and, for those that were active, the (B) proportion of burrows that successfully hatched their egg (hatching success) and (C) fledged their chick (fledging success) on Protection Island, Washington from 2006-2020.

in 2020 (0.82 vs. long-term mean of 0.86; Figure 9.1B). Fledging success in 2020 (0.78) matched the long-term mean value of 0.79 (Figure 9.1C). Nestling provisioning on the island in all four years following the 2016 perturbation (2017-2020) was comparable to long-term values, as measured by fish per bill load and bill load weight. The principal fish prey species in the diet is Pacific sand lance (*Ammodytes hexapterus*), and this did not vary between years. Results from the 2020 breeding season, both in terms of reproductive parameters and nestling provisioning, suggest that the rhinoceros auklet breeding population on Protection Island has recovered and stabilized following the multi-year impacts of the 2016 breeding failure.

B. Wintering marine birds

Birds

Seattle Audubon's Puget Sound Seabird Survey (PSSS) is a community science program that uses trained volunteer observers to identify and count marine birds from shore using standardized protocols. Surveys are conducted monthly from October to April on wintering seabird populations when abundance and diversity are highest in Puget Sound. The program began in 2007 and has since expanded to include all Puget Sound basins except Hood Canal.

Source: Peter Hodum (phodum@pugetsound.edu) (University of Puget Sound), Toby Ross, and Joshua Morris (Seattle Audubon); https://seattleaudubon.org/sas

During the 2019-2020 survey season, a total of 154 volunteers conducted 904 surveys at 155 sites across the Puget Sound/Southern Salish Sea. The number of birds counted per survey ranged from 1-1,063 (median=32). Monthly averages were similar to the previous five seasons, but represented six-year lows in December, January, February, and March (Figure 9.2A). A total of 59 species were detected, including diverse foraging guilds and both resident and migratory species. Diving forage fish specialists, which include alcids and grebes, have been identified as a foraging guild that is vulnerable and declining in the Salish Sea (Vilchis et al., 2014). As is typical for birds in this system, we expected bird numbers to increase over the year and stabilize in the mid-winter months, reflecting migration and settlement into the system. However, in the 2019-2020 season, counts of forage fish specialists peaked in October and declined steadily through March (Figure 9.2B). Counts of forage fish specialists in December, January, and February of the 2019-2020 season were the lowest of the last six seasons, and February and April were the lowest since PSSS began in the winter of 2008. Still, no clear seasonal pattern in forage fish specialist numbers emerges from year to year, possibly reflecting the dynamic and local variability in forage fish distribution and abundance. As is the case for previous seasons, scoter counts were relatively stable from November to February, with mean numbers generally within the range of the previous five years (Figure 9.2C).

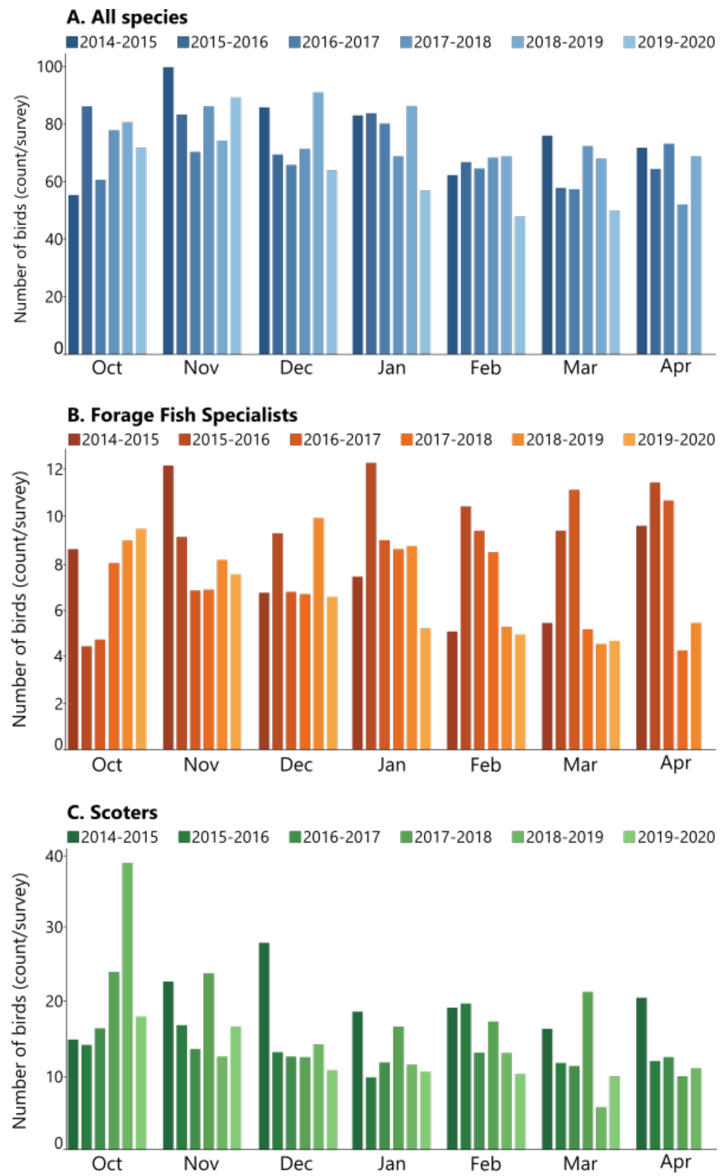


Figure 9.2. Numbers of birds counted per survey by month for (A) all species pooled, (B) diving forage-fish specialists (alcids and grebes), and (C) scoter species (surf, whitewinged, and black).

CALL-OUT BOX: Using cast-offs–Noninvasive samples for Southern Resident killer whale health assessments

Evaluating the health of Southern Resident killer whales (SRKW) is constrained by the low number of animals (74, as of 12/31/2020), changes in areas they occupy, and a prohibition on collecting invasive samples such as biopsies. This puts emphasis on extracting information from noninvasive samples, such as feces, expelled mucus, exhaled breath, and shed skin. Feces have already been used to detect hormone levels (Ayres et al. 2012, Wasser et al. 2017), and to construct pedigrees (Ford et al. 2018) for SRKW. All animals carry specialized bacterial communities, or microbiomes, on tissues that interface with the environment, and these microbiomes are shed into cast-off samples. Microbiomes are specialized for the tissue and contain species that are beneficial or benign to the host animal. Pathogenic bacteria can be present, but a healthy host and its microbiome are effective in preventing and managing infection. SRKW microbiomes provide a health assessment tool using cast-offs.

Exhaled respiratory vapor ("breath") can provide information about respiratory tract health, which is crucial for diving marine mammals. Breath collection requires positioning a sampling container in the plume of exhaled vapor (Figure 1). The initial study relied on culture-based methods (Raverty et al. 2017), while recent efforts use 16S ribosomal DNA sequencing to identify bacteria and their relative abundances. Breath microbiomes are distinctly different from seawater microbiomes, even though seawater is expected to be part of the exhaled plume (Figure 1). Using breath microbiomes from multiple animals, including repeat samples for individuals, we can learn to recognize normal from unhealthy microbiomes. For example, the breath sample from J50 during her last summer alive in 2018 is distinctly different from the other SRKW samples (Figure 1). Although no known bacterial pathogens were detected, the less complex microbiome might have been related to her poor health condition. Because respiratory microbiomes might change as an animal ages or due to shifts in reproductive status, better representative sampling is needed.

Pole-based breath sampler in use. Photo: Pete Schroeder.

Mucus is another source of microbiome information. These cast-offs are dipped from seawater, typically absorbed onto sterile gauze. In spite of the seawater contact, mucus microbiomes are also very different from seawater microbiomes.

To date, we have analyzed 62 mucus samples collected from 2010 through 2017. The bacterial families found in mucus are found in oral cavities and blowhole swabs of other cetaceans, representing both the upper gastrointestinal and respiratory tracts. Genotyping to assign samples to individual whales will aide to determine age and/or gender patterns in mucus microbiomes.

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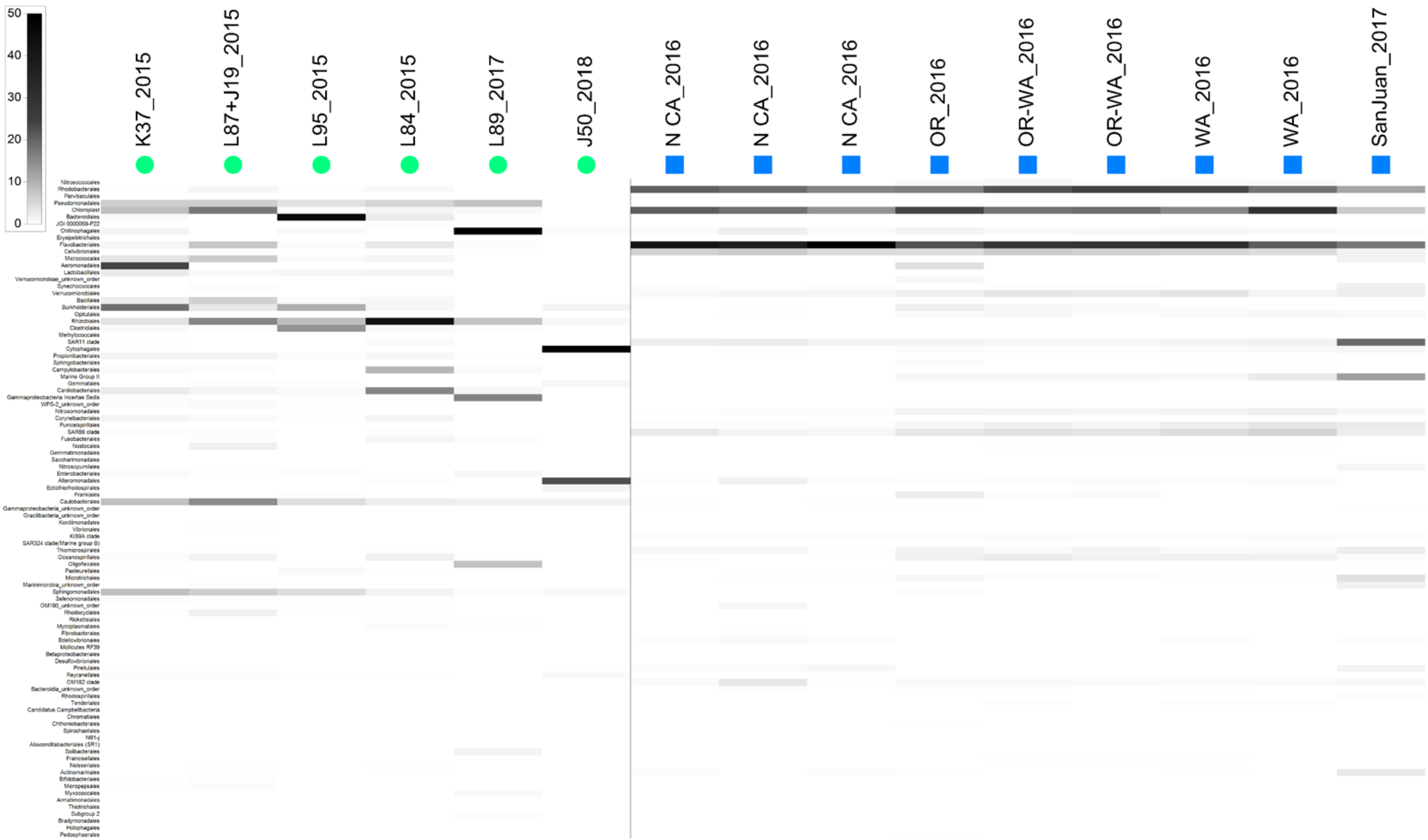
Figure 1. Shade plot of relative abundances of bacterial orders from SRKW cast-off samples compared to seawater from areas occupied by SRKW. Each column represents a sample from breath (circles) or seawater (squares). Sample labels show individual animal origin and sampling year for breath, and geographic locations and sampling year for seawater (N CA, northern California coast; OR, Oregon coast; OR-WA, Columbia River plume; WA, WA coast; SanJuan, San Juan Island). Each row corresponds to a bacterial order. The darkness of each cell represents the relative abundance of the order in that sample (scale legend on left side).

CALL-OUT BOX (cont.)



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Acronyms

APL	Applied Physics Laboratory
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
CPUE	catch per unit effort
CTD	conductivity, temperature,depth
DA	Domoic Acid
DFO	Fisheries and Oceans Canada
DIC	dissolved inorganic carbon
DO	dissolved oxygen
DFO	Fisheries and Oceans Canada
Ecology	Washington State Department of Ecology
ENSO	El Niño–Southern Oscillation
EPA	Environmental Protection Agency
ESM	Estimated Spawning Biomass
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	meter squared
m^3/s	cubic meters per second
mg C/m^3	milligrams carbon per meter cubed
mg/L	milligrams per liter
mL	milliliter
mm	millimeter
MB-SS	Main Basin to South Sound
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
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWFSC	Northwest Fisheries Science Center
NWIC	Northwest Indian College
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
pCO_2	partial pressure of carbon dioxide
PSEMP	Puget Sound Ecosystem Monitoring Program
PSI	Puget Sound Institute
PSSS	Puget Sound Seabird Survey
PST	Paralytic Shellfish Toxin
PSU	practical salinity unit
qPCR	quantitative polymerase chain reaction
S	salinity
SLP	sea level pressure
SOPO	State of the Pacific Ocean
SRKWs	Southern Resident killer whales
SSS	southern Salish Sea
SST	sea surface temperature
STIL	Stillaguamish Tribe
SoG	Strait of Georgia
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

Acronyms (cont.)

WDFW	Washington Department of Fish and Wildlife
WDOH	Washington State Department of Health
WDNR	Washington Department of Natural Resources
WSG	Washington Sea Grant
WWU	Western Washington University
xCO_2	mole fraction of carbon dioxide
ºC	degrees Celsius

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

PSEMP

Puget Sound Ecosystem Monitoring Program

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