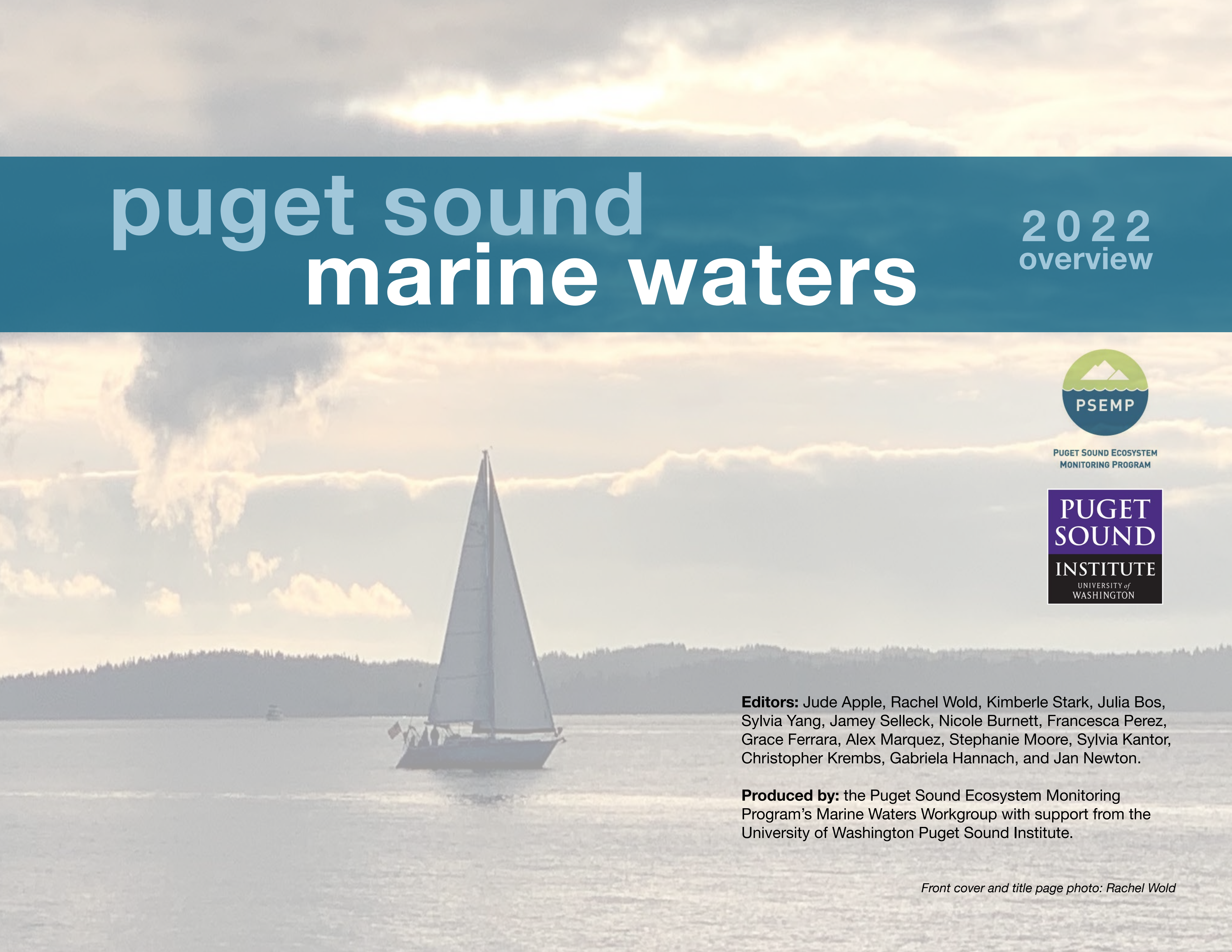
puget sound marine waters

2022 overview

Clayton David and Holly Young on board Washington Department. of Ecology R.V. Skookum.
Photo: Chris Jendrey



puget sound marine waters

2022 overview

PSEMP

PUGET SOUND ECOSYSTEM MONITORING PROGRAM

PUGET SOUND INSTITUTE UNIVERSITY of WASHINGTON

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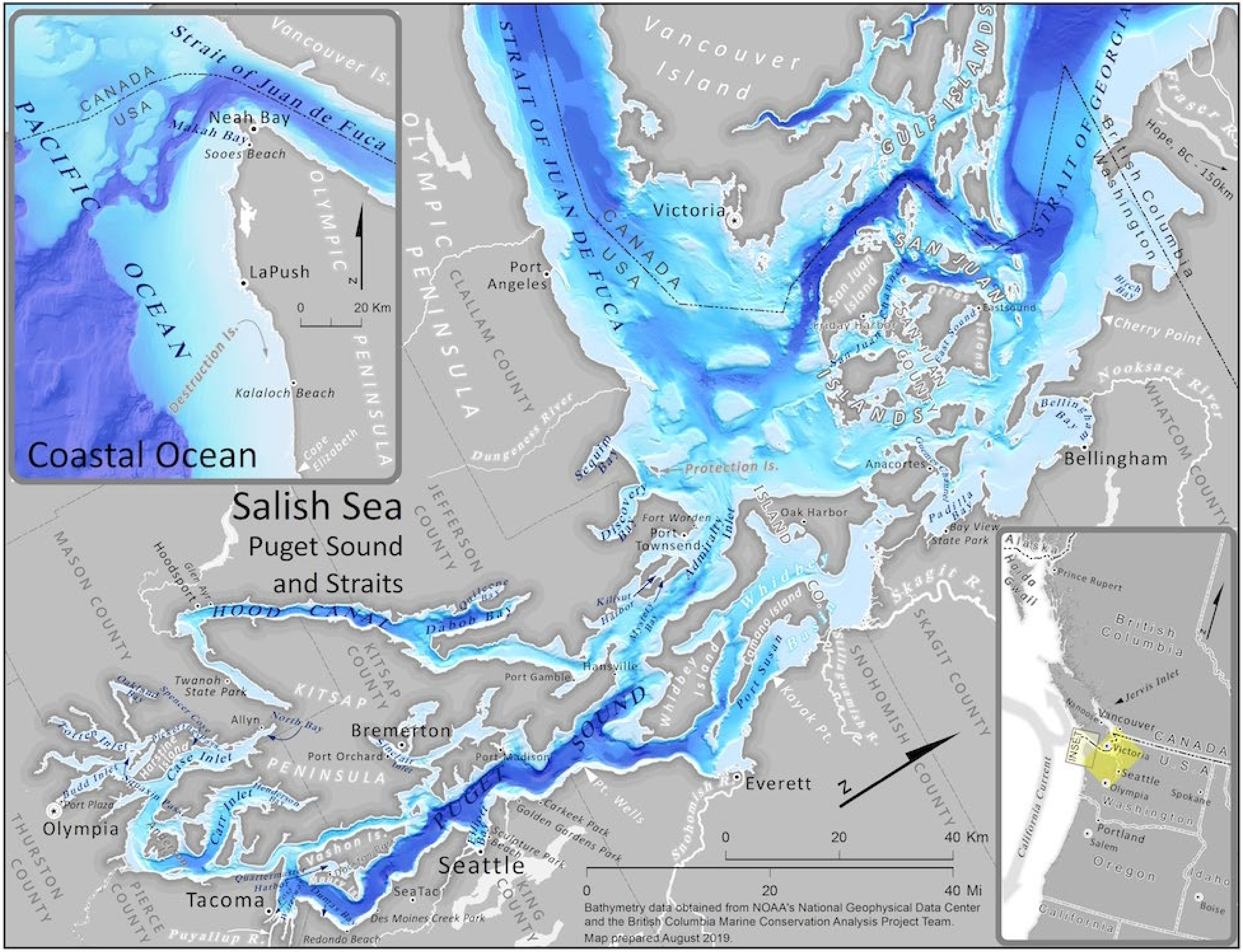

Salish Sea
Puget Sound
and Straits

Coastal Ocean

Bathymetry data obtained from NOAA's National Geophysical Data Center and the British Columbia Marine Conservation Analysis Project Team.
Map prepared August 2019.

Map: Damon Holzer

Table of Contents

Table of Contents (cont.)

About PSEMP

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

PSEMP
PUGET SOUND ECOSYSTEM MONITORING PROGRAM

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

APL
CICOES
Cornell University Founded A.D. 1865
Environment and Climate Change Canada
Environnement et Changement climatique Canada
Hakai
Science on the Coastal Margin
IOOS
Integrated Ocean Observing System

King County
KWIAHT
Lummi Nation Treaty of 1855
NANOOS
NISQUALLY INDIAN TRIBE
NOAA
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

OWSC
PMEL
pacmam
Pacific Northwest Crab Research Group
Padilla Bay
National Estuarine Research Reserve
Port Gamble S'Klallam Tribe
Natural Resource Department

PUGET SOUND PARTNERSHIP
SOUND TOXINS
STILLAGUAMISH TRIBE OF INDIANS
SWINOMISH INDIAN TRIBAL COMMUNITY
TULALIP TRIBES

United States Environmental Protection Agency
USGS
science for a changing world
UAF
UNIVERSITY OF ALASKA FAIRBANKS
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Washington Department of Natural Resources
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Introduction

This report provides a collective view of 2022 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 twelfth 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 – including but not limited to surface and water column surveys, fixed depth and profiling high temporal resolution moorings, and continuous monitoring platforms. Collectively, these methods provide information representing various temporal and spatial scales and can be used to connect the status, trends, and drivers of ecological variability in Puget Sound/ Salish Sea marine waters. In this report, the terms Puget Sound and Salish Sea are used interchangeably. 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 2022.

This report is the proceedings of an annual effort by the PSEMP Marine Waters Workgroup to compile observations collected across the marine waters of Washington State during the previous year. Data quality assurance and documentation remains the primary responsibility of the authors submitting technical summaries, whose names, contact information, and links to data are provided with each submission. The editorial team conducts an internal review of each submission, develops the organizational structure of the report, and reviews for overall clarity. The Summary and Vital Sign linkages sections are based on the individual contributions and seek to provide a high-level description of the overall trends in variability and change in marine waters during 2022 and how these contributions address Puget Sound Vital Signs.

This report helps the PSEMP Marine Waters Workgroup address three important priorities, including 1) maintain an inventory of active monitoring programs in Puget Sound and other marine waters, 2) identify and document the extent to which these monitoring efforts inform and 3) address Puget Sound Vital Sign indicators improve dissemination, transparency, data sharing, and communication of monitoring results and efforts across the marine waters monitoring network. Integral to this data sharing is the Northwest Association of Networked Ocean Observing Systems (NANOOS), which is the regional arm of the U.S. Integrated Ocean Observing System (IOOS) for the Pacific Northwest and is working to improve regional access to marine monitoring data. Much of the marine data presented in the report, as well as an inventory of monitoring assets, can be found through the NANOOS web portal.

The Canadian ecosystem report State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2022 provides a companion overview of monitoring and marine conditions in Canadian waters, covering approximately 102,000 km^2 from the edge of the continental shelf eastward to the British Columbia mainland, and includes large portions of the Salish Sea. This annual report provides information that is relevant to understanding marine conditions across the Salish Sea and is a recommended source of complementary information to the Marine Waters Overview report.

Puget Sound Vital Signs

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

- *Beaches*
- *Dissolved oxygen*
- *Forage fish*
- *Local foods*
- *Marine birds*
- *Nutrients*
- *Ocean acidification*
- *Salmon*
- *Shellfish*
- *Streams*
- *Temperature*
- *Zooplankton*

The technical summaries presented in the **Puget Sound Marine Waters: 2022 Overview** span a range of topics, from water quality and climate change to abundance of marine macrofauna and other ecosystem indicators. Their goal is to connect the status, trends, and drivers of ecological variability in Puget Sound marine waters in a way that serves Puget Sound ecosystem recovery efforts.

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

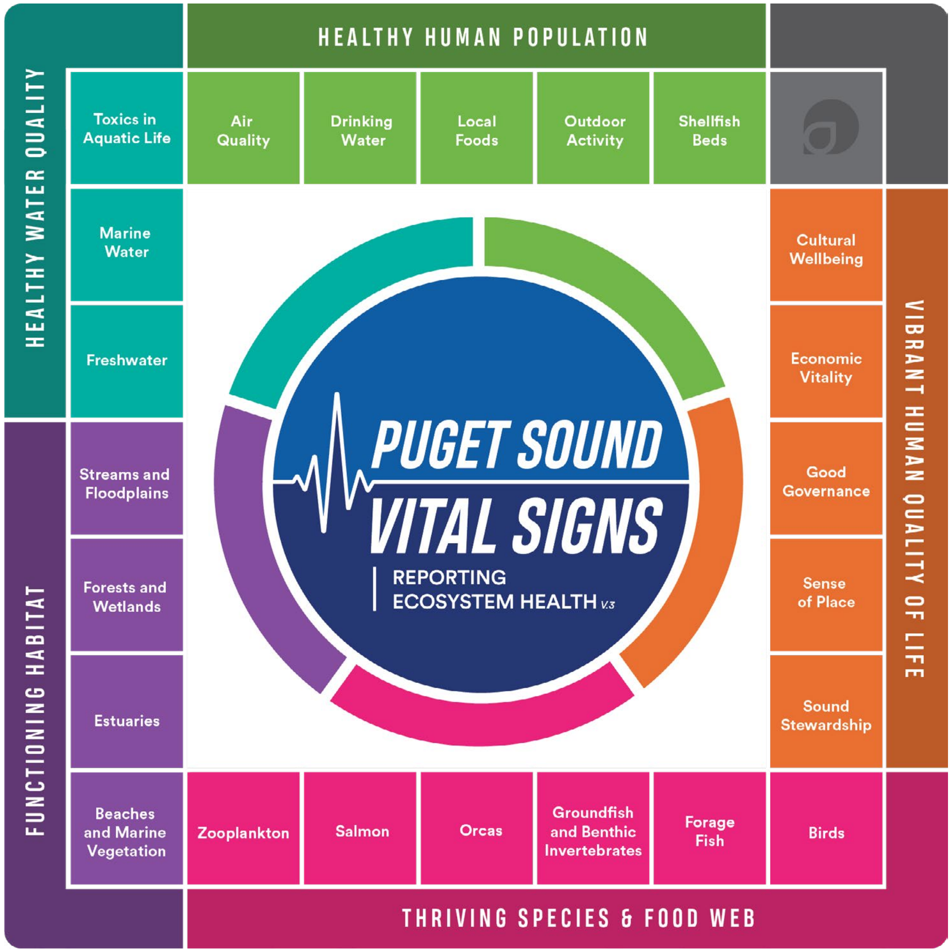

Figure VS.1. Puget Sound Vital Signs revised and adopted in 2020 by the Puget Sound Partnership.

One of the fundamental aspects of PSEMP's mission is to monitor the ecosystem in support of Vital Sign reporting. To this end, 32 of 38 technical summaries (84%) included in the 2022 Overview report provide data that collectively informs four of the five ecosystem recovery goals, including **Healthy Water Quality, Healthy Human Populations**, **Functioning Habitat**, and **Thriving Species and Food Webs**. Within these broad goals, data reported in this document further inform our understanding of Puget Sound Vital Signs and associated indicators. Technical summaries are considered to have informed a given recovery goal, Vital Sign and/or indicator if quantitative observations of that indicator are reported, even if these data were recorded outside of Puget Sound proper (i.e., the broader Salish Sea or outer coast). These individual technical summaries are credible and legitimate sources of information contributing to and complementing our shared understanding of progress towards recovery goals and the conditions of the Vital Signs and their indicators in Puget Sound.

The technical summaries in the 2022 Overview address four Puget Sound ecosystem recovery goals and fourteen Vital Sign indicators. Many of the parameters reported in the Overview are also used as endpoints for the Implementation Strategies designed to improve Vital Sign conditions such as the Marine Water Quality Implementation Strategy. Given the Overview's focus on marine water quality conditions, it is not surprising that 20 out of 32 (63%) of the technical summaries reporting on Vital Sign parameters (Figure VS.2) exclusively address the Marine Water Vital Sign in the **Healthy Water Quality** recovery goal. These summaries build from local and regional monitoring efforts to assess metrics identified as both established and emergent Vital Sign indicators, including water temperature, dissolved oxygen, nutrient balance, ocean acidification, and phytoplankton.

Vital Signs (cont.)

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

Only six of the 38 technical summaries did not directly address current Vital Signs. Nonetheless, these submissions represent important ecological and climatic processes in Puget Sound. Multiple summaries include reports on air temperature (to date, not a component of the Air Quality Vital Sign), precipitation, upwelling, and ocean salinity. Marine mammals are addressed in a submission documenting the abundance and behavior of harbor porpoises, and the health of eelgrass habitat is addressed in a submission on eelgrass wasting disease.

Our evaluation of the connectivity between technical summaries and Vital Signs for the 2022 edition of the Overview relied on the newly revised Vital Signs and indicators adopted in 2020 by the Puget Sound Partnership (see a related fact sheet and a full report on the subject). The scope of the revised Vital Signs has increased substantially and now includes additional ecosystem components that have historically been addressed in the annual Overview, such as zooplankton populations, water temperature, ocean acidification, phytoplankton, and other aspects of marine food webs.

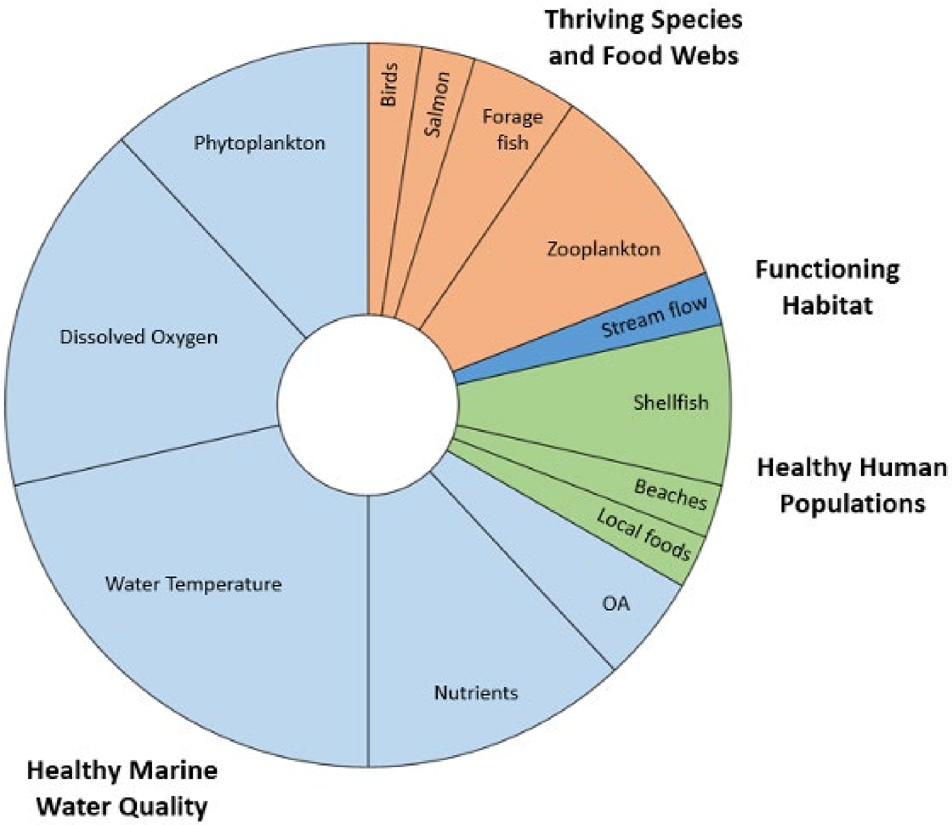

Figure VS.2. The distribution of the number of technical summaries reporting observations relevant to the Puget Sound Vital Signs, sorted by recovery goal, in this 2022 edition of the Marine Waters Overview.

Summary of what happened in 2022

This brief synopsis describes patterns in water quality and conditions and associated biota observed during 2022 and their association with large-scale ocean and climate variations and weather factors. The data compilation and analysis presented in the annual Puget Sound Marine Waters Overview, which began in 2011, offers the opportunity to evaluate the strength of these relationships over time and is prepared by the PSEMP Marine Waters Workgroup.

The year 2022 was notable, presenting as an unprecedented third consecutive La Niña year. While 2022 local weather ***annual*** *values were average, there were monthly extremes in opposite directions; thus, weather conditions were far from average. Region-specific variation in water properties and biota abundance adds to the difficulty to generalize patterns in 2022. Terms such as "flip-flop," extreme, and highly variable were common among the participants in the workshop for this report.*

The La Niña that prevailed throughout 2022 and a negative Pacific Decadal Oscillation, particularly during the second half of the year, are typically associated with cool and wet conditions. Seasonal air temperatures were quite anomalous and included the sixth coldest April-May, record warmest July-October, and sixth coldest November-December. Puget Sound precipitation was also characterized by extremes; May-June was the fifth wettest, and July-September was the driest on record. Thus, we saw a 'flip-flop' pattern of record-setting extremes: a cold and wet spring, a hot and dry summer, and a cold late fall. This was accompanied by below normal streamflow mid-September through late October due to warm and dry conditions on land. Puget Sound water temperatures were cooler than average throughout the water column for much of the year, particularly spring through summer. This could be expected given both the cooler than average ocean conditions as well as spring weather. Temperature anomalies were more variable in the fall and winter months, dependent upon location. Salinity anomalies oscillated with time, somewhat consistent with the observed pattern in precipitation and river input, but with four periods: fresh anomalies in January-March and July-October and salty

Beach seining. Photo: Aleta Elliot

anomalies during April-June and November-December.

2022 was a stand-out year in terms of upwelling/downwelling wind patterns. There was a very late transition to upwelling winds (early June 2022 vs more typical early May) then weak upwelling winds extended a month later than usual to late October. Late and weak upwelling would select for relatively lower salinity oceanic input, which also factors into the complicated salinity anomaly pattern observed.

Atmospheric CO_2 levels on the outer coast and in the Sound were generally higher than the global average. The preliminary data suggest new maximum surface seawater xCO_2 values for both Hood Canal moorings, as well as a new low minimum value at the Twanoh mooring compared to all previous years; mechanisms for the high ranges are under investigation.

Oxygen concentrations were near normal throughout the region, but with seasonal and regional variation. Main Basin and South Sound were slightly above normal, while Hood Canal was lower than average for much of the year, with hypoxic areas forming earlier in the year at Twanoh compared to prior years. Hypoxia was also observed in Quartermaster Harbor, and low oxygen in Whidbey Basin, but no signal was particularly strong this year and no fish kills observed.

Regional differences were also seen in phytoplankton abundance/biovolume and bloom timing. Although an early bloom in late February was seen throughout most of the Central Basin and was highest in the northern Central Basin, the main spring bloom was slightly late in early May. The onset of the spring bloom in Padilla Bay was also later compared to recent years. An unusually large diatom bloom was seen in the southern Central Basin August through October that coincided with atypically strong density stratification. Although fewer blooms were seen Puget Sound-wide, phytoplankton biovolume in the Central Basin was ~40% higher than previous years. Nutrients and chlorophyll varied seasonally and regionally.

Alexandrium and *Dinophysis* were observed less frequently in Puget Sound and at lower abundances than in 2021. However, the number of Pseudo-nitzschia blooms about doubled. Marine biotoxins associated with paralytic (PSP) and diarrhetic (DSP) shellfish poison caused 18 commercial and 29 recreational Puget Sound shellfish harvest area closures in 2022. A PSP illness due to the consumption of butter clams harvested in Island County in June was confirmed.

Abundances and biomass of mesozooplankton in 2022 from the southern Salish Sea were generally average to moderately low compared to past years. Admiralty Inlet had the highest biomass value in 2022, mainly due to elevated larval crab abundance. Hood Canal and South Sound showed unique temporal patterns of Dungeness crab larval delivery relative to other Salish Sea sites, potentially driven by localized conditions or distinct population level life-history traits. Peak Dungeness crab larval abundance occurred in July in most areas, which was one month later than prior years. The spring zooplankton peak abundance in Padilla Bay also occurred one month later than prior years. Eelgrass surveys throughout the San Juan Islands indicated high disease prevalence, declining eelgrass, and possible synergies between seagrass wasting disease and climate stressors in intertidal eelgrass meadows.

Seabird densities observed during fall 2022 in the San Juan Islands have steadily increased since 2018. In contrast, the same observations reveal that marine mammals (Harbor seals, Steller sea lions, Harbor porpoises) have shown relatively low densities since 2017, with 2021 the lowest on record. The 2022 density was only slightly higher than 2021, primarily due to Harbor seals. Within the Salish Sea, large aggregations of harbor porpoises (20 or more individuals) were observed 160 times during 2022. These large aggregations have generally been considered rare events but may be more common than previously thought.

Pacific herring biomass showed a slight increase from 2021 and was above the recent 10-year average, although the biomass is concentrated in a handful of stocks. No spawning was detected in South Hood Canal, Discovery Bay, Wollochet Bay, Holmes Harbor and Elliott Bay, but spawning was detected in Kilisut Harbor, Fidalgo Bay, and Quartermaster Harbor for the first time since 2019.

We conclude that although strong signals were seen in both climate state and local weather, the extreme oscillations in the weather conditions coupled with anomalous ocean upwelling timing made for a somewhat confusing year, where biological responses were spatially diverse and not consistent.

Highlights from 2022 Monitoring

1. Large-scale climate variability and wind patterns

- El Niño–Southern Oscillation (ENSO): La Niña conditions prevailed during 2022 with winter months in the weak-moderate category, accompanied by relatively high sea level pressure over the central North Pacific Ocean.
- Pacific Decadal Oscillation (PDO): The PDO was negative throughout 2022.

2. Local climate and weather

- On an annual basis, Puget Sound air temperatures were near-normal for 2022. However, seasonal temperatures for the year were quite anomalous and included the sixth coldest April-May, record warmest July-October, and sixth coldest November-December.
- Puget Sound annual total precipitation was near-normal, but the seasonal cycle was accentuated with extremes. May-June was the fifth wettest and July-September was the driest on record.
- Puget Sound seasonal precipitation extremes in 2022 were the opposite of those seen in 2021. Spring (March-May) 2021 was the second driest on record while Spring 2022 (May-June) the fifth wettest on record. Fall (September-November) 2021 was the wettest on record while summer/early fall (July-September) 2022 the driest on record.

3. Coastal ocean and Puget Sound boundary conditions

- 2022 was a stand-out year in terms of upwelling/downwelling wind patterns. There was a very late transition to upwelling winds (early June vs early May), then weak upwelling winds extended a month later than usual to late October.
- Surface dissolved oxygen (DO) showed abnormally low values, consistent with low chlorophyll and weaker-than-normal upwelling during summer. At depth, there was no deep hypoxic water (<2 mg/L) until early August, consistent with a delayed onset of upwelling (early June), then episodic deep hypoxia until the end of record (Oct 10), consistent with prolonged upwelling (through October).
- Monthly average atmospheric CO_2 at the two coastal moorings was 2–8 ppm higher than the globally averaged marine surface air, except during July–September, when it was equal to or lower than the global monthly average. This was likely a result of regional seasonal production on land that draws CO_2 down.
- Monthly average seawater xCO_2 was within the historical range during all months with observations.

4. River inputs

- Freshwater inputs to the Salish Sea were above normal historic volumes for most of the year, due to above normal snowpack accumulation that extended later into the spring.
- The timing of river discharge spring runoff peaks was generally typical in WA but of an extended duration and later in BC, although both exceeded normal magnitudes.
- Warm and dry conditions in summer through late fall led to below normal streamflows in almost all rivers mid-September through late October.

5. Water quality

Temperature

- Cooler than average conditions were seen throughout the water column for much of the year in Puget Sound, particularly spring through summer. Temperature anomalies were more variable in the fall and winter months, dependent upon location and were +0.7 °C above-normal in October in some areas.
- Below-average surface heat input from April-June likely drove large, cold anomalies in the Main Basin and South Sound that persisted until late summer. A reversal to positive heat flux anomalies from mid-July to late October steadily erased this anomaly and resulted in moderate positive (+ 0.2 °C) upper water-column anomalies in early fall. These were short-lived, however, persisting until erased by negative heat flux anomalies extending almost to the end of 2022 that once again acted to cool the water column.
- For most of the year, deep waters of Hood Canal were warmer than average. The surface waters of Hood Canal had both strong negative and positive anomalies over the year. These patterns reflect differences in flushing and stratification. Shallow stratification in Hood Canal limited temperature changes from both negative and positive anomalies to the near-surface (top 10-20 m).
- High temperatures in Port Susan were observed in late July (23.7 °C) and were warmer than 2021, which was the previous 10-year high.
- Unlike other areas, annual average temperature in Padilla Bay waters was near normal and daily mean temperatures were also near normal, with the exception of a warm summer and unseasonably cold November and December.
- Despite the third consecutive La Niña, water temperatures in San Juan Channel and the

Strait of Juan de Fuca during fall 2022 were generally warmer than average, consistent with the pattern of warmer than or average waters since 2014. An exception was the cooler than average deep waters in the Strait, which may reflect La Niña influence.

Salinity

- In all basins, salinity anomalies oscillated with time, with fresh anomalies in January-March and July-October and salty anomalies during April-June and November-December, consistent with river input.
- A wet fall to early winter in 2021 led to early 2022 fresh anomalies, but these were largely erased by a dry spring. The freshwater anomaly returned with anomalously high river flow in June and July. A dry late fall/early winter, with reduced river flow, then resulted in a positive salinity anomaly in most basins by year's end.
- Fall salinity in the deep waters of the Strait of Juan de Fuca was saltier than average. Most salinities measured were average, except an almost 2 psu fresher anomaly in the surface waters in the Northern San Juan Channel in early fall, which were likely influenced by exceptionally high Fraser River flow with a delayed peak flow.

Water column structure

- The general trend of increasing density stratification continued in 2022. Early stratification was seen in the Central Basin in February/early March as well as fairly strong stratification June-August. Strong stratification was also seen in the southern Central Basin during this time, but was extended until early October. These stratification patterns contributed to phytoplankton bloom dynamics.
- Stratification was persistent in Whidbey Basin except for the end of October where the water column was well-mixed.
- Stratification patterns in Padilla Bay were similar to previous years, with mild stratification in spring due to freshwater inputs and more pronounced thermal and salinity stratification in summer.

Nutrients

- Nitrate in Puget Sound surface waters continued an increasing trend when all basins were combined. Nitrate and silicate in deep Central Basin waters remained higher than normal until August in the northern basin, but were more variable in other areas. The silicate to dissolved inorganic nitrogen (Si:DIN) ratio for all basins combined declined in 2022, unlike previous years where it was variable but generally within the long-term trend.
- Significantly high nitrate and orthophosphate and low silicate were seen in the Strait of Juan de Fuca, whereas an extended period of low nutrients was seen in Quartermaster Harbor and Port Susan.

Chlorophyll

- Chlorophyll varied seasonally and regionally. An early bloom in late February was seen throughout most of the Central Basin, but was highest in the northern Central Basin.
- The spring phytoplankton bloom in the Central basin was evident slightly late, in early May, and was later in the season in other areas. Chlorophyll was unusually high in the southern Central Basin, with sustained high values August through October that coincided with atypical strong density stratification throughout the summer and early fall.
- Chlorophyll in Whidbey Basin peaked dramatically in late June, with smaller earlier peaks in March and April that corresponded with low nitrate concentrations.
- In Padilla Bay, weak to non-existent bloom conditions were observed in spring, with elevated sub-surface chlorophyll for a limited period in July. .

Dissolved oxygen (DO)

- High surface dissolved oxygen was seen throughout Puget Sound corresponding to phytoplankton blooms.
- While DO in the Central Basin generally had similar values and patterns, differences were seen in anomalies likely due to different baselines. Main Basin and South Sound had mostly weak positive oxygen anomalies over the water column compared to the 2010-2022 average and negative anomalies were seen throughout most of the water column in the Central Basin compared to a 1998-2013 baseline average.
- Hood Canal had lower than average oxygen for much of the year, with hypoxic areas forming earlier in the year at Twanoh compared to prior years. Quartermaster Harbor had short periods of hypoxia in September – October, which is typical.
- DO in the Whidbey Basin was generally lowest in bottom waters August-October, although some of the lowest values were also seen in Port Susan in February.

Ocean and atmospheric CO_2

- Atmospheric CO_2 levels on the outer coast was 2–8 ppm higher than the globally averaged marine surface air, except during July–September, when it was equal to or lower than the global monthly average as a result of regional seasonal production on land that draws CO_2 down.

- Surface coastal seawater xCO_2 started the year off lower than historical observations and was somewhat higher than average historical conditions during April, mostly within the range of past conditions during May–October, and experienced high variability and/or means during November–December.
- Atmospheric CO_2 in Hood Canal averaged 13 ppm higher than the globally averaged marine surface air, with larger differences in fall–winter (12–21 ppm) than spring–summer (7–13 ppm) when regional primary production reduces the offset.
- Preliminary data suggest new maximum surface seawater xCO_2 values inHood Canal, as well as a new low minimum value at Twanoh compared to all previous years.

6. Plankton

Phytoplankton

- Regional differences were seen in abundance/biovolume and bloom timing. The total 2022 annual microplankton biovolume in the Central Basin was ~40% higher than previous years, although fewer blooms were seen Puget Sound-wide.
- The spring diatom bloom developed late compared to previous years in the Central Basin and Padilla Bay. *Chaetoceros* species were abundant in early spring and summer and there were unusually large blooms of the diatoms *Stephanopyxis* in the spring and *Ditylum* in summer and fall, especially in the southern Central Basin.
- The Whidbey Basin bloom season lasted March through October and was characterized by a succession of diatom blooms (notably *Skeletonema*, *Thalassiosira* and *Pseudo-nitzschia*) and an abundance of the dinoflagellate *Noctiluca*. Total biovolume in Penn Cove was comparable to Saratoga Passage, but much less in Port Susan.
- Phytoplankton abundance in Padilla Bay in 2022 was similar to 2020, with peak abundance in August, dominated by the diatom *Leptocylindrus*. The onset of the spring bloom in Padilla Bay was also later compared to recent years.

Harmful algae and biotoxins

- *Alexandrium* and *Dinophysis* were observed less frequently in Puget Sound and at lower abundances than in 2021. The only *Dinophysis* bloom reported was in June, while the only Alexandrium bloom reported was in September. However, the number of *Pseudo-nitzschia* blooms about doubled.
- Alexandrium cyst abundances were lower in general in 2022 than prior winter observations, yet areas of higher cyst abundance were consistent with past cyst hot spots – Quartermaster Harbor, Bellingham Bay, and bays in the western Main Basin.
- Marine biotoxins associated with paralytic (PSP) and diarrhetic (DSP) shellfish poison caused 18 commercial and 29 recreational Puget Sound shellfish harvest area closures in 2022. A PSP illness due to the consumption of butter clams harvested in Island County in June was confirmed.

Zooplankton

- Abundances and biomass of mesozooplankton in 2022 from the southern Salish Sea were generally average to moderately low compared to past years. Biomass in the San Juan Islands and Bellingham Bay continued the trend from 2019-2021, with large oceanic copepod species primarily driving high biomass in the spring.
- Admiralty Inlet had the highest biomass value in 2022, mainly due to elevated larval crab abundance. Although lower in 2022, this imitated the timing and composition of the record-high biomass values that occurred at this station during the marine heatwave in 2015-2017, and in 2021.
- Sites in southern Hood Canal and south Puget Sound showed unique temporal patterns of Dungeness crab larval delivery relative to other Salish Sea sites, potentially driven by localized conditions or distinct population level life-history traits. Peak Dungeness crab larval abundance occurred in July across most of the Salish Sea, which was one month later than prior years, and was highest in the central Salish Sea.
- Padilla Bay peak zooplankton abundance in spring 2022 was similar in magnitude to average, but occurred one month later. Conversely, summer peak abundance was similar in timing but much greater in magnitude than average.

7. Bacteria and pathogens

- In 2022, 90% of the 39 Puget Sound core beaches monitored for the BEACH program met EPA’s standards for safe swimming.
- Fecal indicator bacteria values in eastern Central Basin beach waters were generally low to average compared to the historical record, with few exceptions. Overall, values were generally much lower in 2022 compared to 2021.

Highlights from 2022 Monitoring (cont.)

- Fecal indicator bacteria concentrations in Central Basin offshore waters were low, as in previous years.

8. Forage Fish

- Stock specific increases in estimated Pacific herring spawning biomass (ESB) outpaced decreases in 2022, and the 2022 ESB (12,931 metric tons [mt]) was above the 2021 ESB and recent 10-year average (10,191 mt). Most of the spawning biomass remains concentrated in a handful of stocks while other stocks have fluctuated, some to the point of being undetected.
- While no Pacific herring spawning was detected in South Hood Canal, Discovery Bay, Wollochet Bay, Holmes Harbor and Elliott Bay, spawning was detected in Kilisut Harbor, Fidalgo Bay, and Quartermaster Harbor for the first time since 2019.
- Juvenile Puget Sound origin Chinook are eating less forage fish biomass in the San Juan Islands, on average, than they did six to twelve years ago.
- This decrease is mainly due to eating fewer Pacific sand lance and smaller Pacific herring.

9. Marine mammals

- Large aggregations may be important foraging and socializing opportunities for Salish Sea harbor porpoises. In 2022, aggregations of harbor porpoises (20 or more individuals) were observed 160 times. These large aggregations have generally been considered rare events, but may be more common than previously thought
- Fall 2022 seabird densities in the San Juan Islands have steadily increased since 2018. In contrast, marine mammals (Harbor seals, Steller sea lions, Harbor porpoises) have shown relatively low densities since 2017, with 2021 the lowest on record. The 2022 density was only slightly higher than 2021, primarily due to Harbor seals.

10. Seaweed

- Eelgrass surveys throughout the San Juan Islands indicated high disease prevalence, declining eelgrass, and possible synergies between seagrass wasting disease and climate stressors in intertidal eelgrass meadows.

Golden Gardens, Seattle. Photo: Rachel Wold

Technical Summaries

Healthy Ochre sea stars (Pisaster ochraceus).
Photo: Russel Barsh for Kwiaht

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 to three seasons. For PDO, these anomalously warm waters can reemerge four to five seasons later (Moore et al. 2008).

A. El Niño–Southern Oscillation (ENSO)

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

La Niña conditions first developed in late 2020, and the winter of 2022-23 was the third consecutive winter featuring La Niña. The intensity of this extended event generally decreased in time with the winters of 2021-22 and 2022-23 in the weak-moderate category. As is typical for La Niña, these winters included higher than normal sea level pressure (SLP) in the central North Pacific south of Alaska. The winter of 2022-23 also featured lower than normal SLP over the interior of the western US, which is uncharacteristic of La Niña.

Low tide at Golden Gardens. Photo: Rachel Wold

B. Pacific Decadal Oscillation (PDO)

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

The PDO was negative during 2022, with values less than -2 during portions of the last half of the year. The negative state of the PDO can be attributed largely to warmer than normal SSTs present in a broad band between roughly 30° and 50° N, extending from the east coast of Asia across the dateline into the eastern North Pacific; the temperature anomalies within this band were on the order of +1 to 2°C. As a whole, the near-surface waters along the west coast of North America in 2022 had close to normal temperatures relative to 1991-2020 norms.

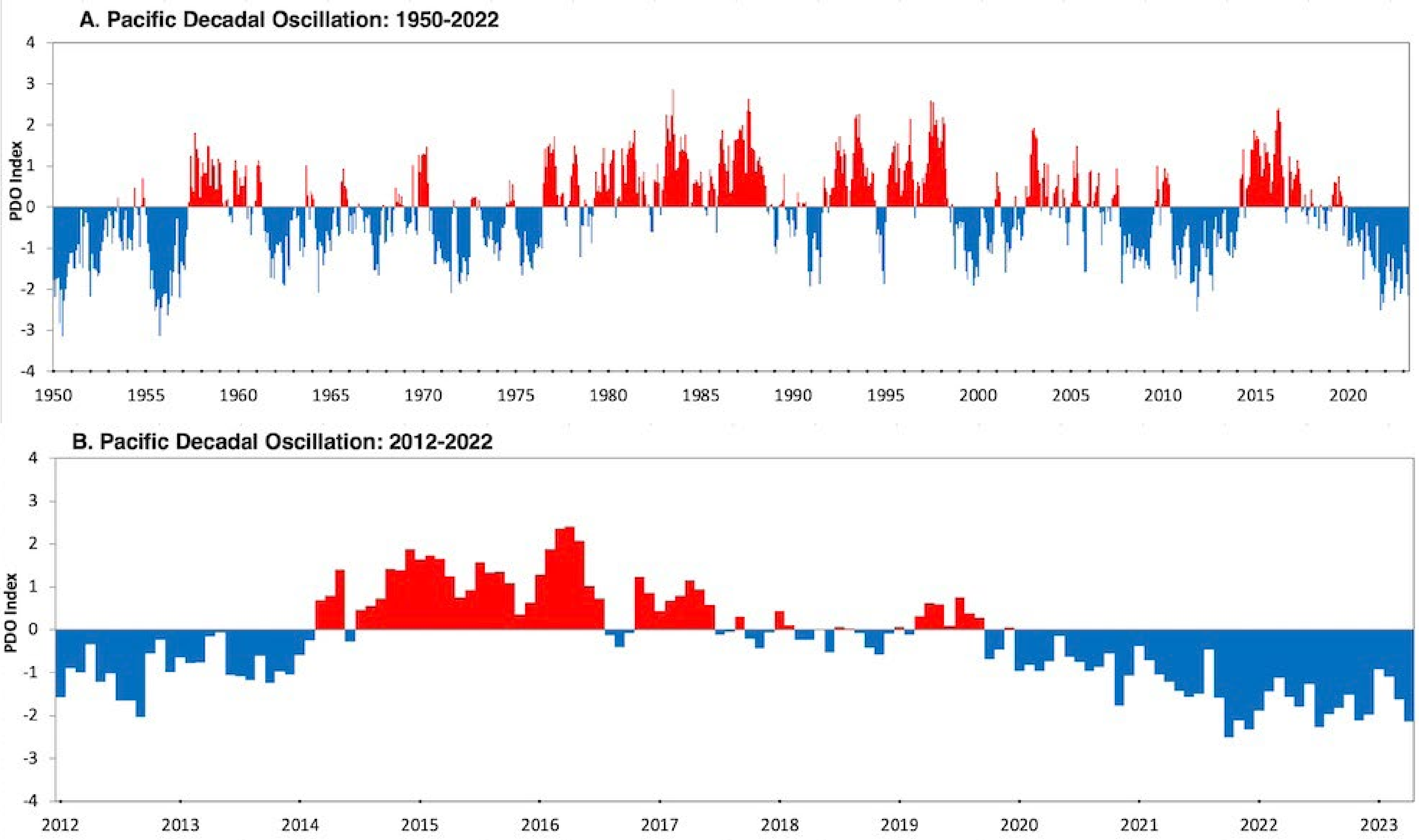

Figure 1.1. Monthly values of the Pacific Decadal Oscillation (PDO) Index from (A) 1950 through 2022 and (B) 2012 into 2023.

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. Air and water temperatures tend to be well-correlated in Puget Sound waters.

A. Regional air temperature and precipitation

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

Temperatures and precipitation were near-normal for the 2022 calendar year in the Puget Sound area. Washington is divided into 10 separate climate divisions based on similar average weather conditions. The following summary uses data from the Puget Sound Lowlands division that encompasses most of Puget Sound. The 2022 Puget Sound annual average air temperature (10.6°C; 51.1°F) was near the 1991-2020 normal (-0.1°F), similar to 2021, 2019, and 2017 but cooler than the rest of the last 8 years. Total annual precipitation was 109.9 cm (43.25"), which was 95% of normal, and drier than 2020 and 2021.

Monthly values are used to illustrate the substantial variability in the weather during the year. Figure 1 shows monthly temperature and precipitation anomalies for the Puget Sound region relative to the 1991-2020 normal. February and March were drier than normal contributing to below normal snowpack by April 1 (80% of median averaged statewide). A shift to a colder and wetter than normal spring prolonged the snow-building season, easing the overall drought concerns for the state. April-May was the 6th coldest (-1.9°C) and May-June was the 5th wettest (170% of normal) since records began in 1895. Conditions shifted rapidly as warmer and drier than normal conditions persisted from July through October. July-September was the driest on record (15% of normal) and July-October was the warmest (+1.8°C) on record. The return of the fall rains was delayed as wildfires continued to burn west of the Cascade Mountains into October. Another abrupt temperature shift occurred in November, tying as the 6th coldest on record, and the -2.2°C anomaly mirroring the +2.4°C October temperature anomaly. Colder than usual conditions continued into December, which was accompanied by near-normal precipitation, on average.

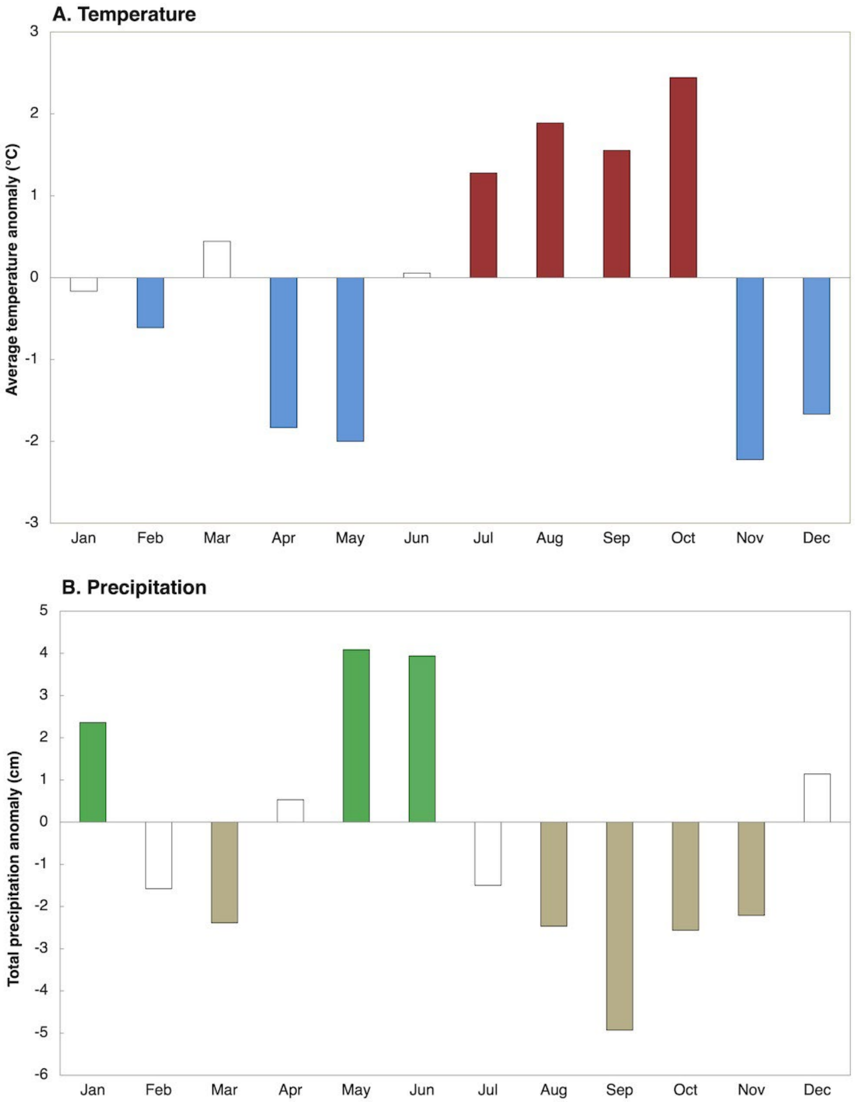

Figure 2.1. Monthly anomalies for (A) temperature (Celsius) and (B) precipitation (centimeters) for the Puget Sound Lowlands climate division in Washington State for the 2022 calendar year. Anomalies are relative to the 1991-2020 climate normal and are colored red (green) for above normal temperature (precipitation) anomalies and blue (brown) for below normal temperature (precipitation) anomalies. Temperature (precipitation) anomalies within 0.5°C (2 cm) are classified as near normal and are colored white.

CALLOUT BOX: Unusual string of La Niña events

The winter of 2022-23 represented the third in a row with La Niña conditions in the tropical Pacific. If that seems unusual to you, pat yourself on the back. Triple-header La Niña events have happened before but only twice previously in the last 50 years, namely from late 1973 into 1976 and late 1998 into 2001. Moreover, the recent extended run of La Niña has occurred during a period favoring such a state (Figure 1), with the last 30 years including 9 El Niño and 13 or 14 La Niña winters (depending how they are counted). The climate community has taken notice and is looking into whether this difference is merely a fluke or perhaps related to overall changes taking place in the climate system (e.g., Wills et al. 2022). This is not just of academic interest in that the tropical Pacific is a key driver of the global climate, with implications for the waters of the Pacific Northwest.

La Niña has a systematic if not guaranteed impact on one type of water important to Puget Sound and that is the snowpack in the surrounding mountains, and ultimately the timing and magnitude of freshwater inflows. This effect is illustrated in Figure 2 in terms of a 60-year time series for the April 1 snow water equivalent (SWE) at Stampede Pass in the central Cascades, with the larger blue squares highlighting the winters featuring La Niña. There is considerable variability among the individual events. Nevertheless, the April 1 SWE does tend to be greater when La Niña prevailed the previous winter. The recent preponderance of La Niña has served to counteract snowpack loss due to overall warming trends to some extent. If there is a transition to a regime with a lower frequency of La Niña, there would certainly be implications for Puget Sound.

La Niña, and for that matter, the El Niño-Southern Oscillation (ENSO) cycle tends to have significant influences on snowpack and ocean properties along the US West Coast. Swings in this cycle are associated with changes in wind patterns, and ultimately the sense and strength of coastal downwelling/upwelling. In addition, ENSO produces temperature and other perturbations in the coastal ocean originating in the tropical Pacific that can propagate all the way to the Pacific Northwest and beyond. These connections have been documented by the

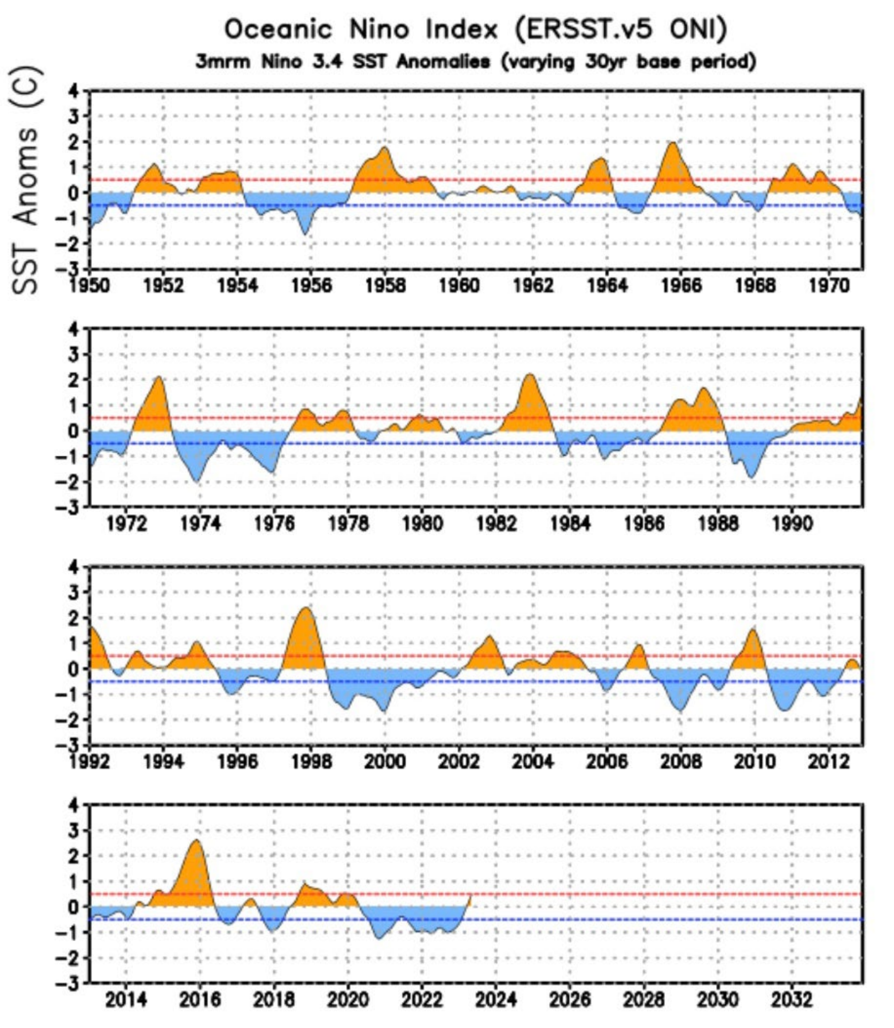

Figure 1. Time series of Oceanic Nino Index (ONI) representing sea surface temperature anomalies in the NINO3.4 region of the tropical Pacific for the period of 1950 through May 2023. Orange values above the dashed red line signify El Nino; blue values below the dashed blue line signify La Nina. [Reproduced from a website maintained by NOAA/Climate Prediction Center (https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/enso_evolution-status-fcsts-web.pdf).*

**The Oceanic Nino Index is a large-scale index used to tract sea surface temperatures (the ocean part of ENSO) in the tropical Pacific Ocean. The ONI is calculated comparing the 3-month rolling average to the 30-year baseline average.*

CALLOUT BOX (cont.)

Fish Ecology group of NOAA's *Northwest Fisheries Science Center (NWFSC)*, among others, for a variety of physical and biological variables off the coast of the Pacific Northwest that influence juvenile salmon growth and survival. The linkages between the tropical Pacific and Washington's coastal ocean are important from a local perspective, in that the latter represents a source for the estuarine circulation through which Puget Sound is ventilated.

Author: Nick Bond (nab3met@uw.edu) (OWSC; UW, CICOES); www.climate.washington.edu

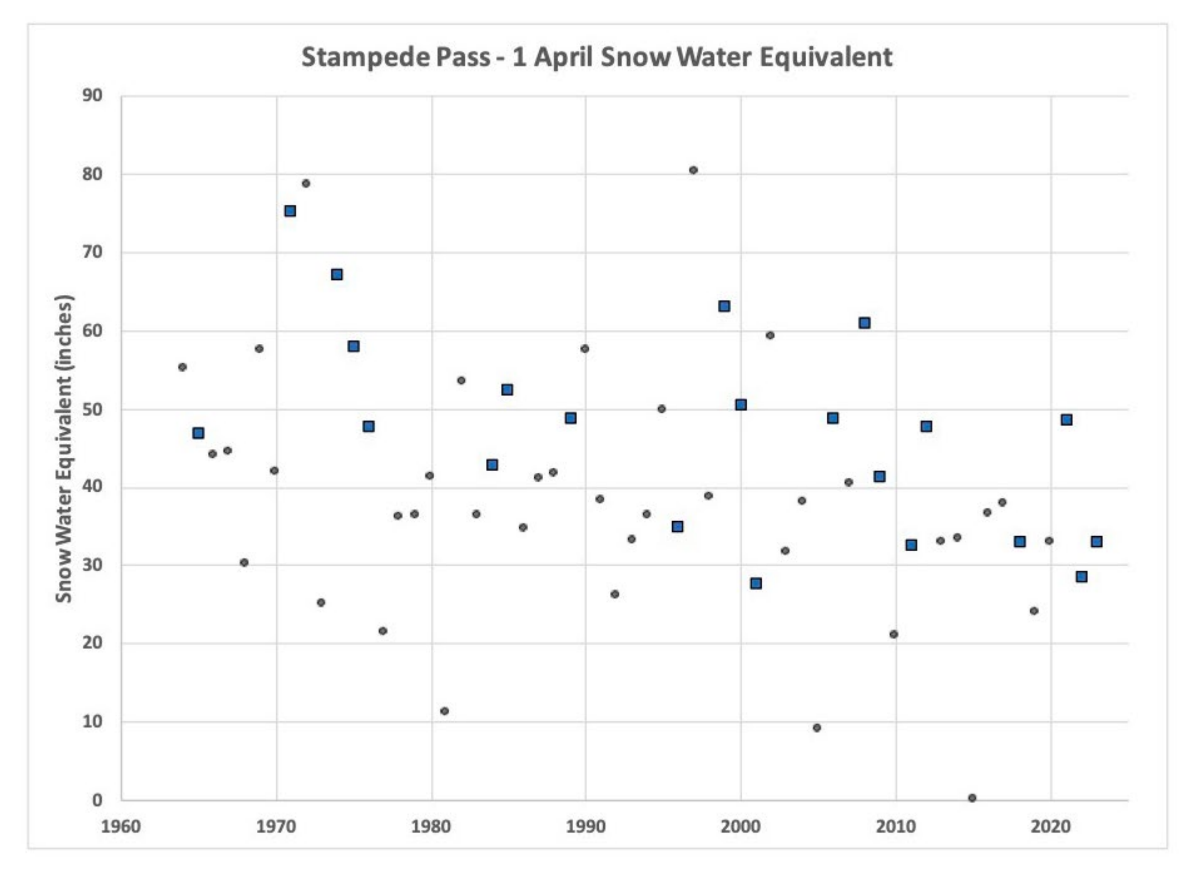

Figure 2. Values of April 1 snow water equivalent (SWE) in inches at Stampede Pass, Washington (elevation 3,860 feet) for the years of 1960 through 2023. The blue squares indicate years during which La Nina was present during the previous winter.

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

3. Coastal ocean and Puget Sound boundary conditions

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

A. NW Washington Coast water properties

Dissolved oxygen
Nutrients
Temperature

Source: John Mickett (jmickett@apl.uw.edu), Jan Newton, and Dana Manalang (UW, APL);

Websites: nanoos.org, nwem.ocean.washington.edu

The surface mooring Chá?ba· 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). These moorings were established in 2010 and collect oceanographic and meteorological measurements on the Northwest Washington shelf and give insight into boundary condition changes for Puget Sound.

The most defining characteristic of the spring-to-fall conditions on the shelf in 2022 was the significantly delayed transition to upwelling-favorable (southward) winds followed by the persistence of abnormally weak upwelling winds roughly a month longer than typical. In 2022, persistent upwelling winds commenced in early to mid-June compared to the typical transition period of early to mid-May, and this wind pattern held until the end of October—a month or so longer than usual (Figure 3.1). When comparing ten years of time-integrated (summed) along-shelf wind velocity, an indication of upwelling vs. downwelling persistence and strength, 2022 is a stand-out year.

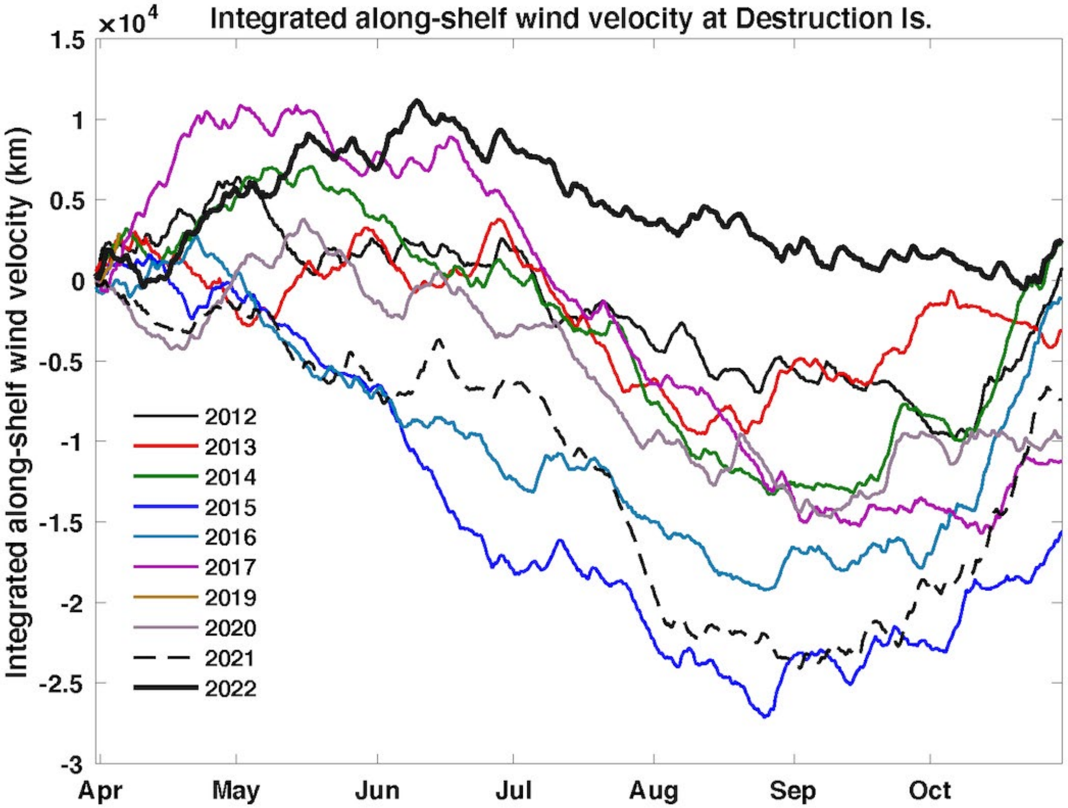

Figure 3.1. Time-integrated (April-October) along-shelf wind velocity at Destruction Island, 2012-2022. Positive (upward) slopes indicate downwelling-favorable conditions, negative (downward) slopes upwelling-favorable wind conditions.

The delayed upwelling followed by atypically weak upwelling winds likely led to the below-average, near-surface chlorophyll levels from May through September (data not shown) with no strong (>10 μg/L) bloom events measured. This was likely the reason for the atypically low near-surface dissolved oxygen (DO) concentrations over this period. Additionally, as persistent, upwelling-favorable winds are a primary driver of deep low-DO events on the mid-shelf (< 2 mg/L) as Ekman processes draw up cold, salty, low-DO slope water, the abnormal 2022 wind conditions led to higher-than-average deep DO in the spring to early summer and then abnormally low deep DO levels in late summer and early fall (Figure 3.2).

Deep salinity and temperature were roughly typical in 2022, except for lower than normal salinity in May and June. This anomaly is potentially due to the extended downwelling winds. Full-water column temperature profiles were near average but warmed from 2021 in the early summer (Figure 3.3).

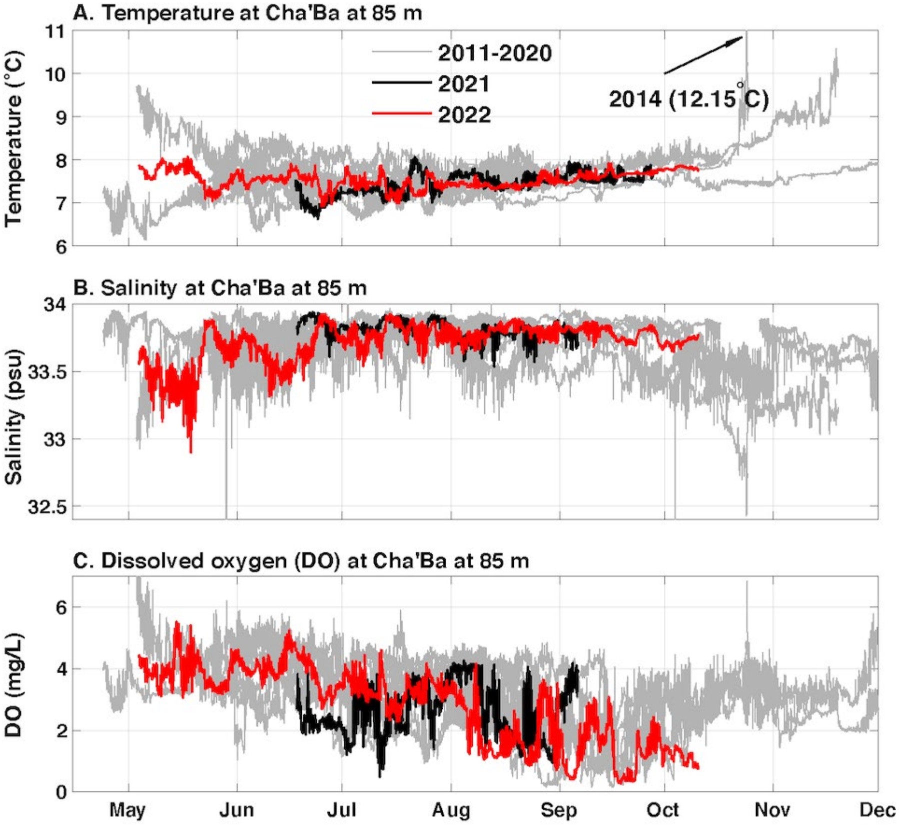

Figure 3.2. Interannual comparison of near-bottom properties (85 m). (A) temperature, (B) salinity, (C) dissolved oxygen.

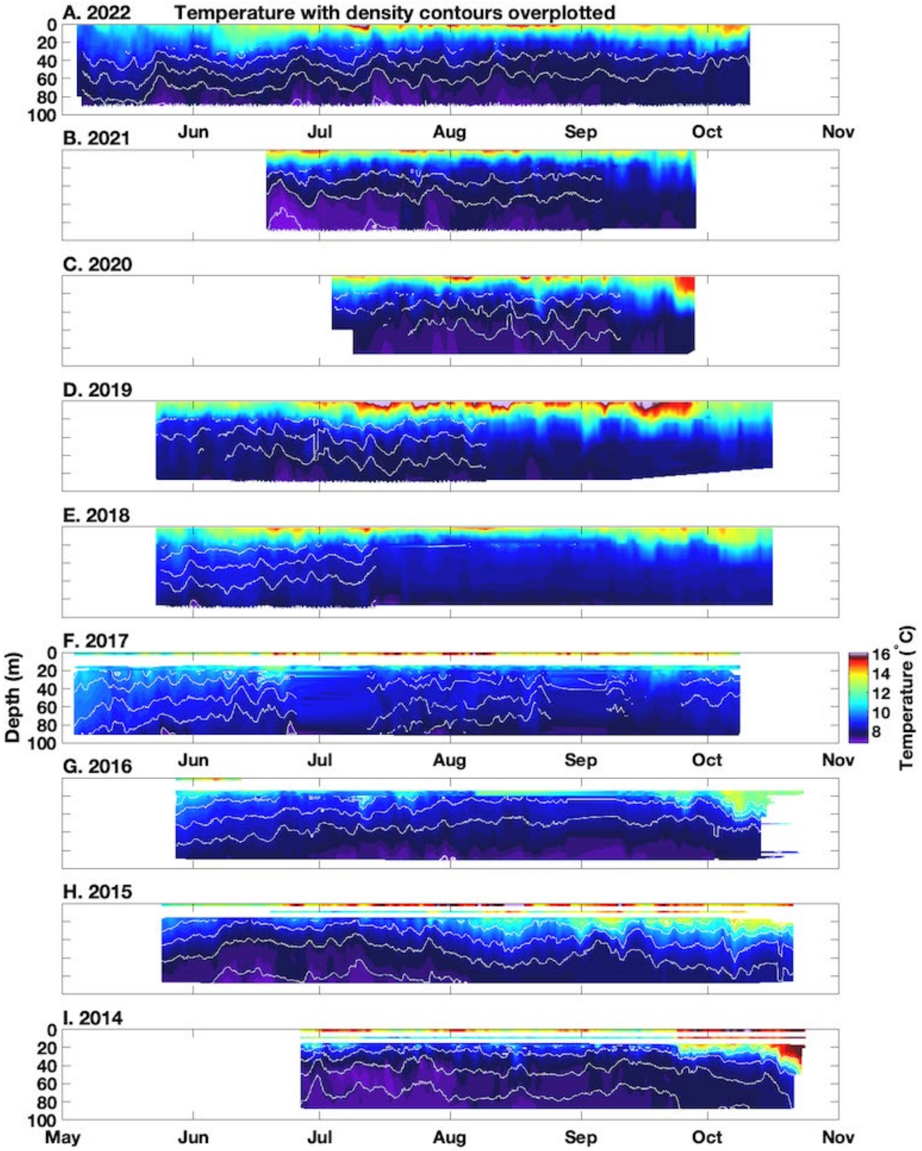

Figure 3.3. Water column temperature with density contours over-plotted for 2014-2022 (A-I).

B. Ocean and atmospheric CO_2

Ocean acidification

Ocean acidification (OA) refers to the chemical changes that occur when some of the excess carbon dioxide (CO_2) in the atmosphere from human activities, an amount that grows each year, is absorbed by the surface ocean. The increasing CO_2 concentration results in declining pH and increasingly corrosive conditions for calcifying organisms like shellfish or certain plankton, like pteropods, 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 its waters particularly sensitive to these conditions. All these changes have ramifications for marine food webs and are areas of active current research.

Source: Simone Alin (simone.r.alin@noaa.gov), Adrienne Sutton (NOAA, PMEL), Jan Newton, John Mickett (UW, APL), Sylvia Musielewicz (UW, CICOES), Beth Curry (UW, APL), and Chris Sabine (Univ. Hawaii); https://pmel.noaa.gov/CO2/story/Cape+Elizabeth, https://pmel.noaa.gov/CO2/story/La+Push Website for online data: https://www.pmel.noaa.gov/CO2/timeseries/CAPEELIZABETH.txt; https://www.pmel.noaa.gov/CO2/timeseries/CHABA.txt; PMEL contribution number 5552

Carbon dioxide (CO_2) sensors have measured atmospheric and surface seawater mole fraction of CO_2 (xCO_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. Preliminary data returns during 2022 spanned January 1–30 and May 3–November 1 at Ćháʔba· (58% of the year) and January 1–February 22 at Cape Elizabeth (14%, Figure 3.4, Table 3.1).

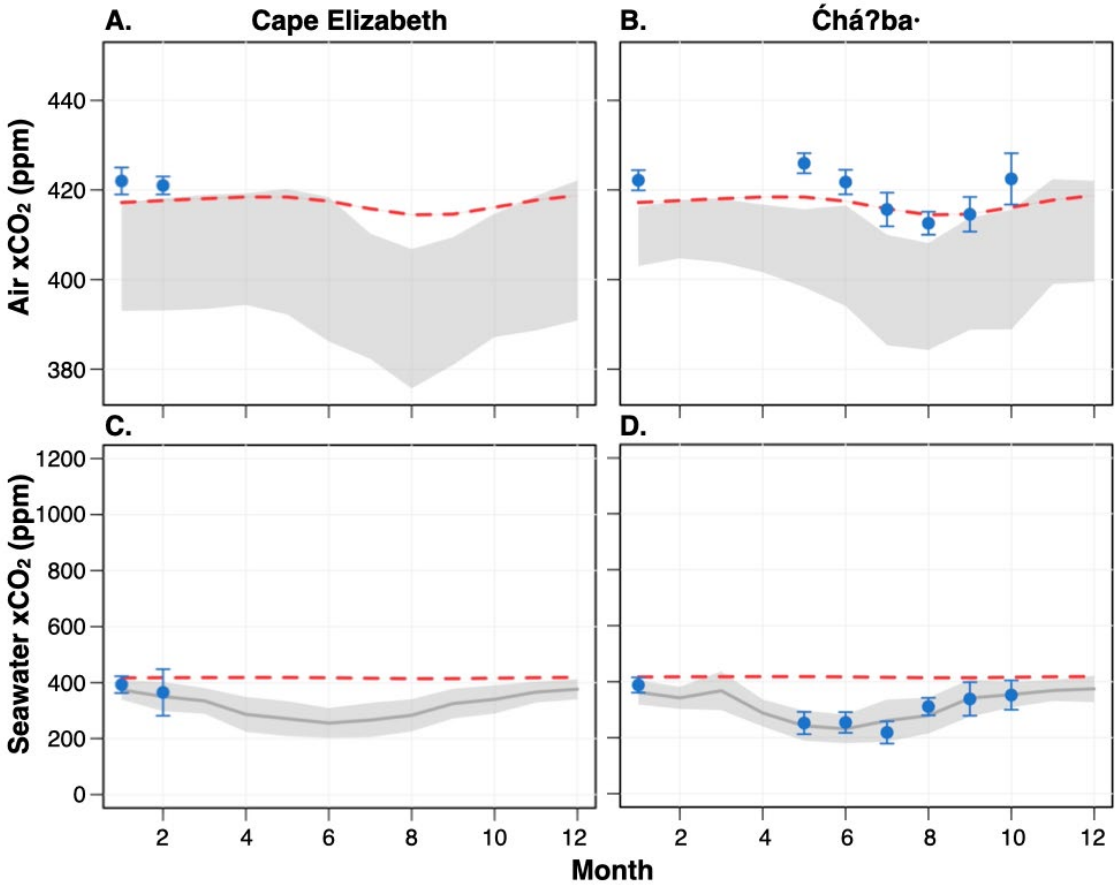

Figure 3.4. Atmospheric xCO_2 in air at 1.5 m above seawater (A, B) and in surface seawater at 0.5 m depth (C, D) on the Cape Elizabeth (2006–present, A, C), and Ćháʔba· (2010–present, B, D) moorings. Gray shading in atmospheric panels represents the range of monthly mean values across the time-series preceding the current year (i.e., 2022). In the seawater panels, the darker gray line reflects the monthly mean value across the time-series, with the lighter gray shading representing natural variability as one standard deviation (1SD) around the mean. Means ± 1SD for all 2022 months with ≥50% data return for 3-hourly atmospheric and seawater measurements are shown in blue symbols and error bars. The dashed red line in each panel represents monthly mean atmospheric xCO_2 values for globally averaged marine surface air (NOAA/ESRL).

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

The atmospheric xCO_2 range was 403–468 parts per million (ppm) at Ćhá?ba· and 416–435 ppm at Cape Elizabeth in 2022. Monthly average atmospheric xCO_2 values for months with ≥50% of data return across both sites were 2–8 ppm higher than the monthly globally averaged marine surface air values (NOAA/ESRL), except during July–September when coastal atmospheric xCO_2 was equal to or as much as 2 ppm lower than the global monthly average. Lower values during the summer likely reflect summertime productivity of regional forests. Compared to 2021[1], atmospheric xCO_2 averages were 1–6 ppm higher in 2022 across months, with larger differences observed across May–October than in January–February and November. Atmospheric xCO_2 variability within months, reflected in one standard deviation (1SD) error bars, was similar across all months with data.

Surface seawater xCO_2 measurements spanned 118–478 ppm at Ćhá?ba· and 173–600 ppm at Cape Elizabeth during 2022. Monthly means at both sites were within the historical range for all months with ≥50% data return. The historical range is defined as the monthly mean ± 1SD of all data prior to the current year for each site, where the standard deviation reflects natural variability rather than measurement error. All monthly coastal seawater xCO_2 means for 2022, and most 1SD bars, fell below the monthly 2022 globally averaged marine surface air xCO_2 values, suggesting local CO_2 drawdown in seawater through marine primary production.

Table 3.1 Atmospheric and surface seawater xCO_2 at the coastal Ćhá?ba· (A) and Cape Elizabeth (B) moorings in parts per million (ppm). Monthly means ± 1SD for 2022 are compared to monthly statistics for the historical time-series at each location. Because atmospheric CO_2 increases year after year, the past statistics used for comparison to the current year are the minimum and maximum monthly means observed across the full time-series at each mooring, such that the lower bound represents earlier years and the upper bound represents more recent years. For seawater measurements, historic monthly statistics used for comparison are means ± 1SD, because the variability (reflected by the 1SD) at Washington mooring sites is sufficiently high to prevent detection of long-term trends at this time (Sutton et al. 2019).*

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ćhá?ba· ATM												
2022	422 ± 2	n.a.	n.a.	n.a.	426 ± 2	422 ± 3	416 ± 4	413 ± 3	415 ± 4	422 ± 6	n.a.	n.a.
2010–2021*	403–416	405–418	404–418	402–417	398–416	394–417	385–410	384–408	389–414	389–416	399–422	400–422
Ćhá?ba· SW												
2022	388 ± 27	n.a.	n.a.	n.a.	252 ± 40	254 ± 37	219 ± 40	311 ± 31	338 ± 60	352 ± 52	n.a.	n.a.
2010–2021*	362 ± 44	342 ± 40	368 ± 69	288 ± 48	242 ± 54	231 ± 51	261 ± 75	279 ± 64	341 ± 67	354 ± 46	368 ± 37	374 ± 47
Cape Elizabeth ATM												
2022	422 ± 3	421 ± 2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2006–2021	393–417	393–418	393–419	394–419	392–420	386–418	382–410	376–407	381–409	387–415	389–419	391–422
Cape Elizabeth SW												
2022	393 ± 30	365 ± 83	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2006–2021	374 ± 35	350 ± 52	335 ± 46	287 ± 62	271 ± 63	256 ± 54	266 ± 61	283 ± 57	325 ± 53	340 ± 50	366 ± 37	376 ± 36

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[1] For months in 2021 without sufficient atmospheric data, 2021 monthly averages were estimated by adding the annual increase in xCO_2 observed at these moorings off the Washington coast (1.9 ppm/yr) to 2019 or 2020 data, multiplied by the number of years.

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

C. Puget Sound environmental metrics

Dissolved oxygen
Temperature

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

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

In 2022, the combined surface heat fluxes, which can warm or cool the water column, swung dramatically between extended periods of exceptionally negative and positive anomalies (Figure 3.5A). Surface heat fluxes were anomalously low from April to July, anomalously high from July through October, then flipped to negative anomalies almost through the end of the year. The negative anomalies were associated with less warming due to reduced sunshine (shortwave radiation) and more cooling predominantly due to increased latent (evaporative) and infrared (longwave) heat losses. The opposite is the case for the positive anomalies. For the Central Puget Sound region, the equivalent water column temperature changes that would result from the surface heat flux anomalies acting alone are mostly cold water-column anomalies (Figure 3.5B). The exception is two short periods (1–2 months) of projected warm water anomalies in spring and late October, both following anomalously sunny weather. This pattern closely follows the observed upper water column temperature anomalies at the Point Wells ORCA mooring (Main Basin) and the Carr Inlet ORCA mooring (South Sound), strongly suggesting that the observed temperature anomalies are largely due to local surface heat flux anomalies. In Hood Canal (Hoodsport and Twanoh

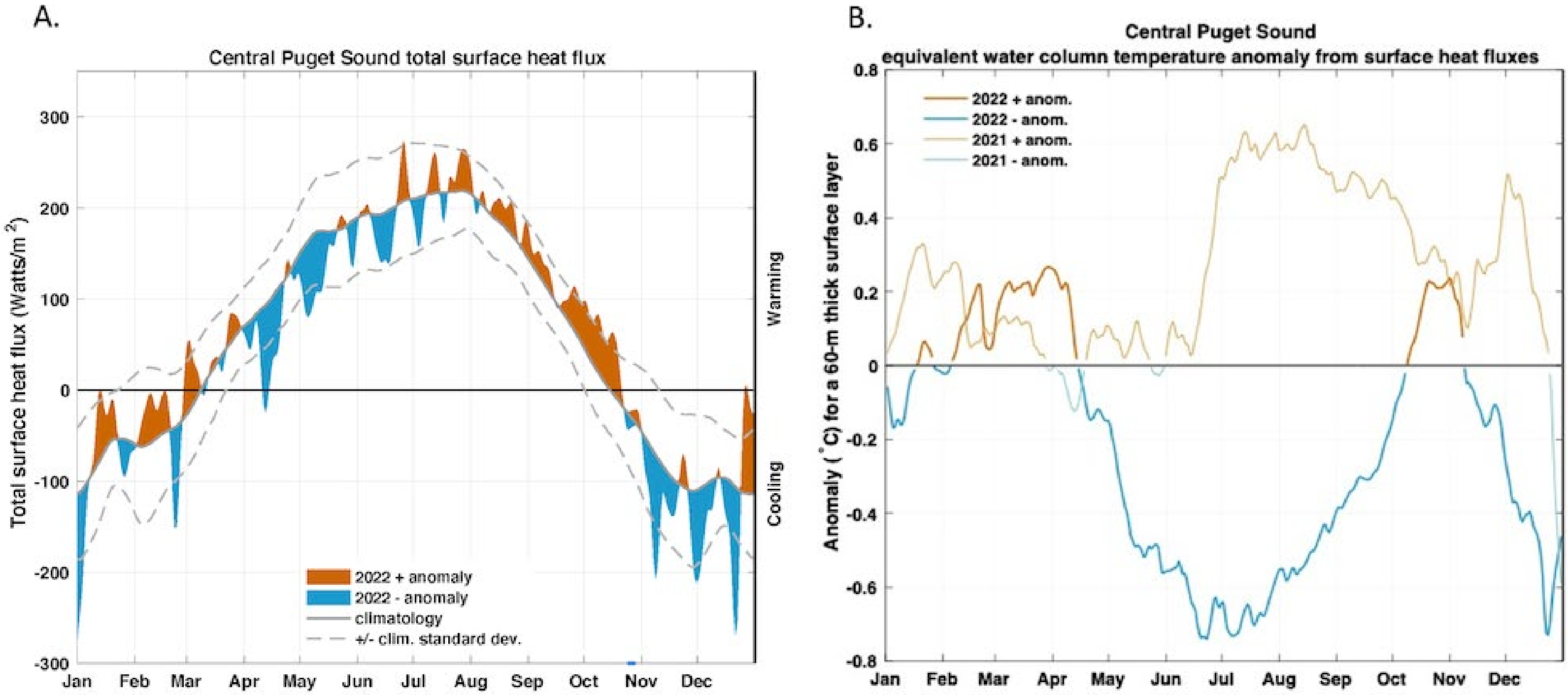


Figure 3.5. (A) Central Puget Sound total surface heat fluxes for 2022. Positive anomalies are shown in orange and negative anomalies are shown in blue. (B) Central Sound equivalent change in temperature from accumulated heat gain or loss over a fixed 60 m mixing depth starting on January 1 (for 2021 and 2022). The line plots show the departure from climatology (the anomaly).

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

ORCA buoys), these anomalies were likely confined to the near-surface due to the strong, shallow stratification (see section B5.B.i. Puget Sound profiling: temperature on page 20).

The salinity changes metric showed that dominant patterns of Puget Sound salinity anomalies in 2022 were almost entirely due to changes in freshwater input into Puget Sound. A freshwater-conserving box model largely reproduced depth-averaged ORCA buoy salinity observations that showed a fresh-salty-fresh-salty anomaly pattern over 2022 (Figure 3.6A, B, see section 5.B.ii. Puget Sound profiling: salinity on page 21). Anomalously high river flow late in 2021 led to negative salinity anomalies early in 2022 that persisted until offset by anomalously low river flow from February–May. Elevated river flow June–July resulted in a second period of anomalously low salinity that persisted until October, when reduced river flow led to a salty anomaly through the end of the year (see section 5.B.ii. Puget Sound profiling: salinity on page 21).

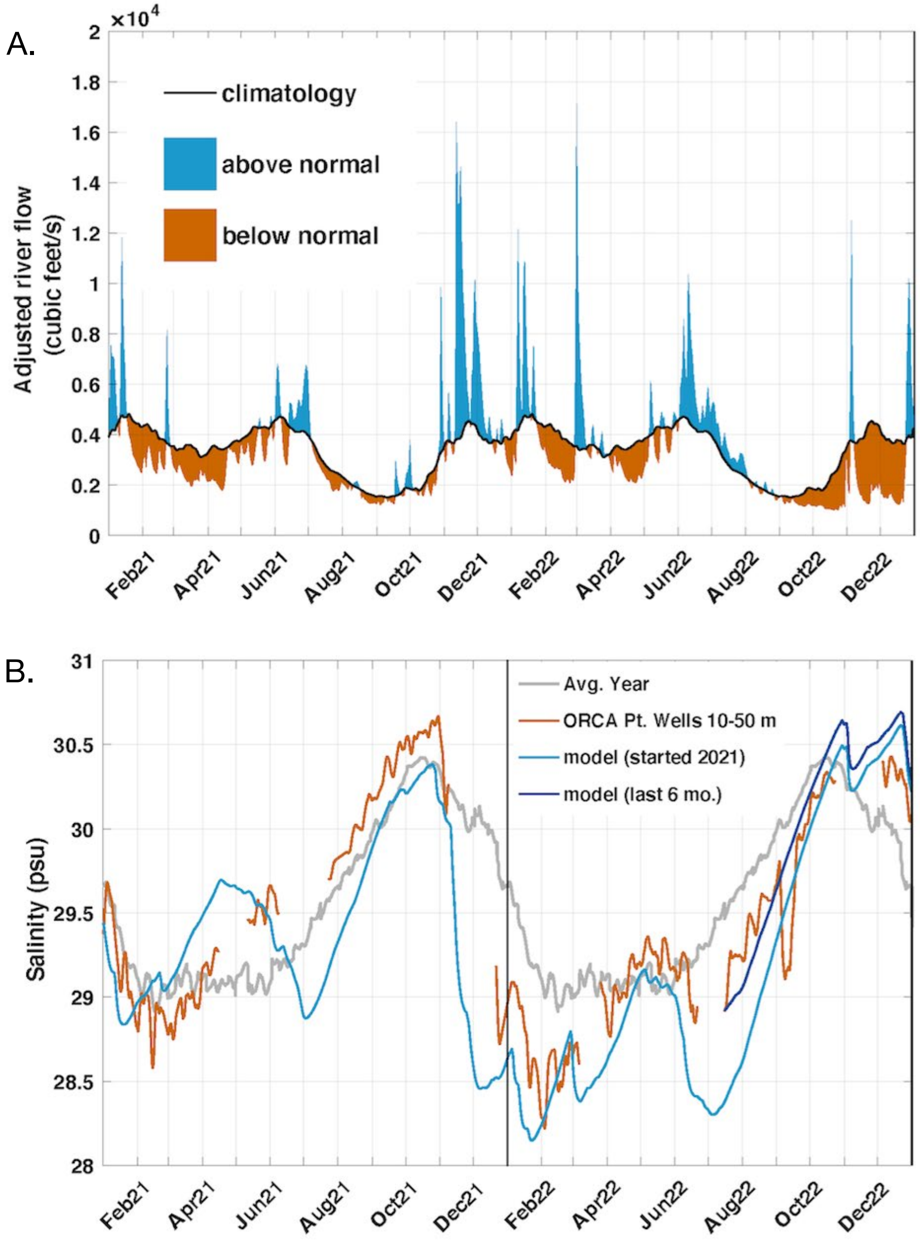


Figure 3.6. (A) Adjusted river flow anomalies for the Main Basin from January 2021 through December 2022. The vertical black line indicates the start of 2022. (B) Depth-averaged salinity climatology (gray), ORCA measurements (orange) and freshwater box-model estimates (blue). Near-surface values are excluded to reduce transient, short-timescale variability in the observations. Close correlation between the model and ORCA observations (blue and orange) indicates salinity changes are mostly due to changes in river flow input to Puget Sound. The vertical black line indicates the start of 2022.

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 in watersheds 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 precipitation as rain, rather than mountain snowpack, and freshwater flows peak only once annually in winter due to periods of high rainfall. 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

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 above normal in 2022, with a basin-wide average at 102% by early April. Accumulation occurred under La Niña (ENSO) conditions, for a second consecutive year, which have historically created cooler temperatures across British Columbia (BCRFC, 2022). Conditions at the end of 2021 were erratic; summer drought was followed closely by historic fall flooding. However, in December below normal temperatures and a continued series of precipitation events coincided to produce a robust early winter snowpack. Despite moderate conditions through early spring, snowpack continued to build through April and May at higher elevations due to periods of cold and wet conditions. Though some limited snowmelt had occurred, the Fraser River watershed still held a snowpack of 129% on May 15th, which posed a significant flood risk if conditions were to change rapidly (BCRFC, 2022). These conditions caused a delayed onset of significant snowmelt, resulting in periods of below normal streamflow during April and May (Figure 4.1). Warmer (but not extreme) temperatures returned in June, and coupled with periods of heavy precipitation, streamflow reached peak runoff during the last week of June. The resulting peak flow was a couple weeks later than the historical median, and well above the 75th percentile (Figure 4.1). The duration of peak runoff extended further into July than recent years and the historical maximum was exceeded during the first week. During the first week of July, moderate flooding occurred in many low-lying areas resulting in evacuations of some communities. Streamflow quickly declined, due to lack of sustaining snowpack and precipitation, dropping below normal by mid-September amidst drought concerns. Warm and dry conditions persisted later into the fall intensifying drought conditions, while streamflow dropped below historical minimums in mid-November. Though precipitation returned later in November, streamflow did not rebound to normal until late December.

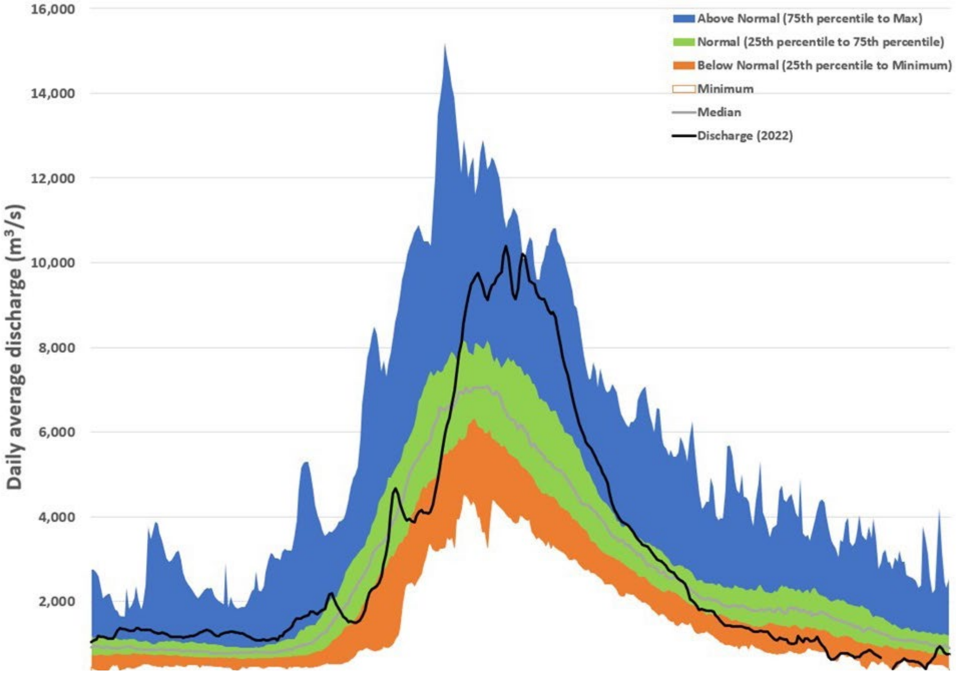


Figure 4.1. Fraser River daily discharge (m^3/s) at Hope, B.C (08MF005) for 2022, compared to the maximum, 75th percentile, median, 25th percentile, and minimum values for the period of record (1912-2022). (Note 1 m^3/s= 35.3ft3/s).

Fraser River, British Columbia. Photo: Drew Brayshaw (CC BY-NC 2.0)

4. River inputs (cont.)

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. Snowmelt-dominated rivers usually have peak flows in the late spring and rainfall-dominated rivers have peak flows in winter months. Although seasonal peaks in flows are evident, the Skagit, Green, Cedar, Nisqually, and Skokomish River flows are regulated by dams, typically in their upper watersheds.

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

As observed in the Fraser River watershed, mountain snowpack accumulated under La Niña (ENSO) conditions, providing cooler and wetter weather in Washington State for the second consecutive year. Snow accumulation in the Cascade and Olympic Mountains feeding major Puget Sound rivers, had a slow start, but grew substantially during December and early January due to below normal temperatures and above normal precipitation. This surge was followed by an extended period of below normal precipitation through the end of March, which delayed snowpack development (Bumbaco et. al, 2023; see section 2.A on page 3. Regional air temperature and precipitation). By April 1, snowpack was 82% of normal, which continued drought concerns that carried over from 2021. However, conditions shifted dramatically in April and snowpack continued to build later into spring and reached 118% by May 1 with limited snowmelt (OWSC, 2022). Early in 2022, streamflow levels ranged from normal to well above normal for major rivers draining to Puget Sound (Figure 4.2), with some flooding in the South Sound in early January. Streamflow levels were temporarily below normal during April due to dry conditions in March and then cool conditions delaying the onset of typical snowmelt. Mild temperatures began gradually melting snow through May, while precipitation events assisted in keeping streamflow conditions in the normal range (Figure 4.2), lifting drought declarations in Puget Sound (Bumbaco et. al, 2023). Spring runoff peaked in early June, driven primarily by the arrival of unseasonably intense atmospheric river precipitation. This event was in addition to typical snowmelt runoff and brought streamflow above normal, which coincided with the timing of historical peaks. The duration of snowmelt runoff extended later into the season, due to mild conditions, until streamflow began to decline in early July following a shift to warm temperatures that likely depleted remaining snowpack. Below normal precipitation and above normal temperatures persisted much later into the fall, leading to streamflow deficits. Below normal streamflow began to occur by mid-September, with only periodic recovery through the end of the year due to precipitation events.

Skagit River delta. Photo: Image modified from the Washington Geological Survey (Washington State DNR)

4. River inputs (cont.)

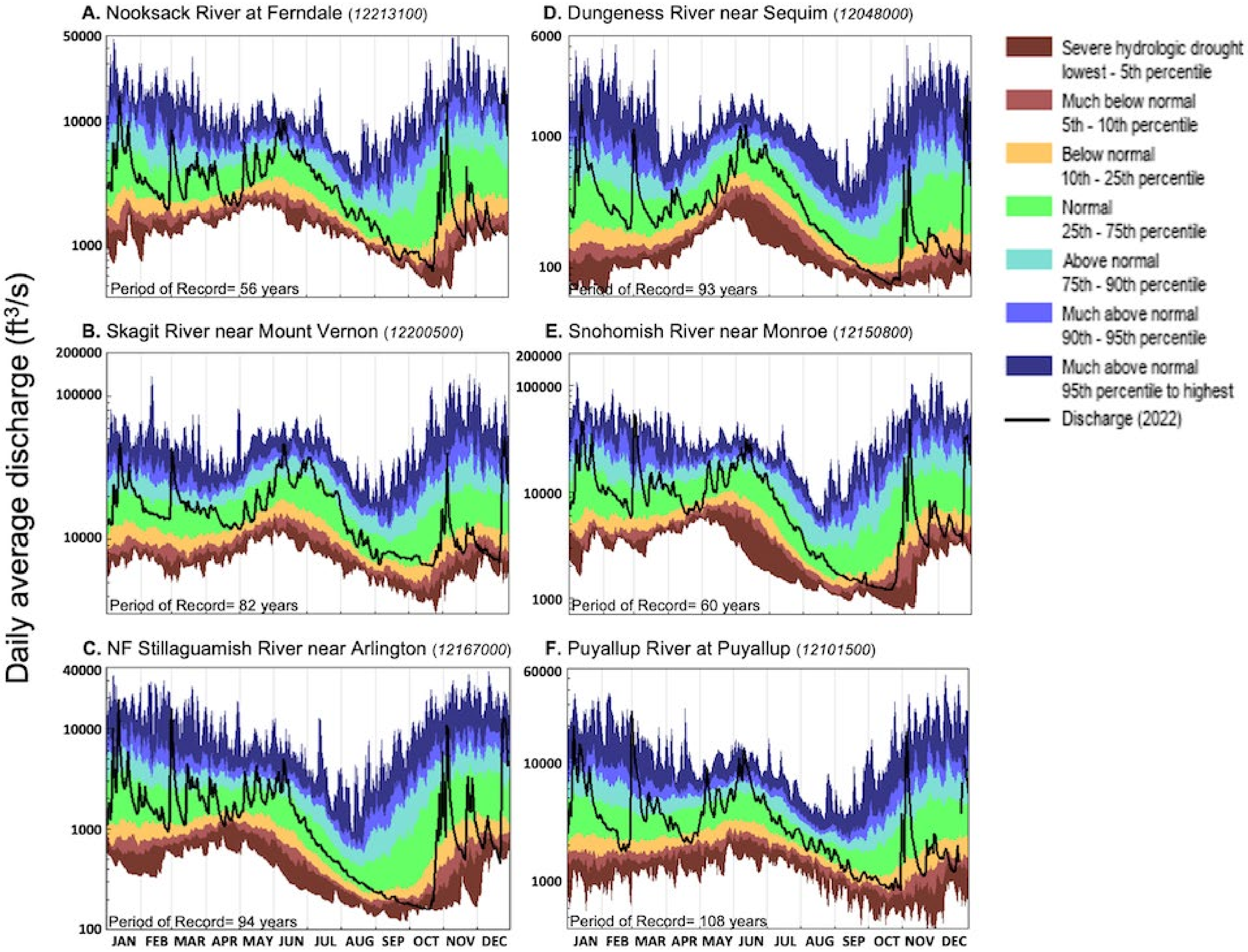


Figure 4.2 Daily average river discharge (ft3/s) at stations on the Nooksack (A), Skagit (B), NF Stillaguamish (C), Dungeness (D), Snohomish (E), and Puyallup (F) Rivers in 2022, compared to period of record percentile classes. (Note: the period of record varies for each station and is listed in number 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 marine life. Many marine organisms have developed tolerances and life-cycle strategies for specific thermal and saline conditions. Phytoplankton, organisms at the base of the food web, are assessed by monitoring chlorophyll, their main photosynthetic pigment. Like in most marine systems, nutrients (nitrogen in particular), 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 is a component for understanding the health of the food web and CO_2 dynamics.

A. Puget Sound long-term stations

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

A.i. Temperature and salinity

Temperature

Source: Suzan Pool (suzan.pool@ecy.wa.gov), Christopher Krembs, Natalie Coleman, (Washington State Department of Ecology), Micah Horwith, Holly Young, and Christopher Jendrey (Ecology); Primary website: https://ecology.wa.gov/Research-Data/Monitoring-assessment/Puget-Sound-and-marine-monitoring; Website for online data: 2022 data available upon request

Water temperature and salinity were assessed in the 0 to 50 m layer at Ecology's long-term Puget Sound marine water monitoring stations. Data from this depth range were averaged for 18 stations in 2022, then compared to monthly, site-specific baselines from 1999 to 2008. Monthly anomalies for Puget Sound were averaged across all stations by month.

Temperature transitioned from an initially cooler than normal phase to a warmer phase in August (Figure 5.1A). The warm temperature anomalies reached +0.7°C in October before cooling. Low salinity anomalies in January were a carry-over effect of a wet fall in 2021 and extended into 2022 (Figure 5.1A). A stronger than normal freshet of major snow-fed rivers (Fraser, Skagit, Puyallup, and Nisqually; data not shown) contributed to a second low salinity anomaly of 0.6 PSU in August. Salinity anomalies were fresher than normal until December.

Spatial differences were evident in temperature and salinity anomalies. Unusual fall conditions were seen in September, with pronounced temperature and salinity anomalies in bays of Central and South Puget Sound, particularly Sinclair Inlet, Elliott Bay, and Oakland Bay (Figure 5.1B). Unusual results for discrete parameters, high chlorophyll-a and ammonium in particular, were also seen in September. Although physical conditions did not explain September's unusually high chlorophyll-a concentrations in Central Sound or the high concentration of ammonium in South Sound (see section 5.A.ii. Puget Sound long-term: nutrients and chlorophyll on page 18), other monitoring programs did observe a connection between high chlorophyll-a and atypical density stratification in Central Sound.

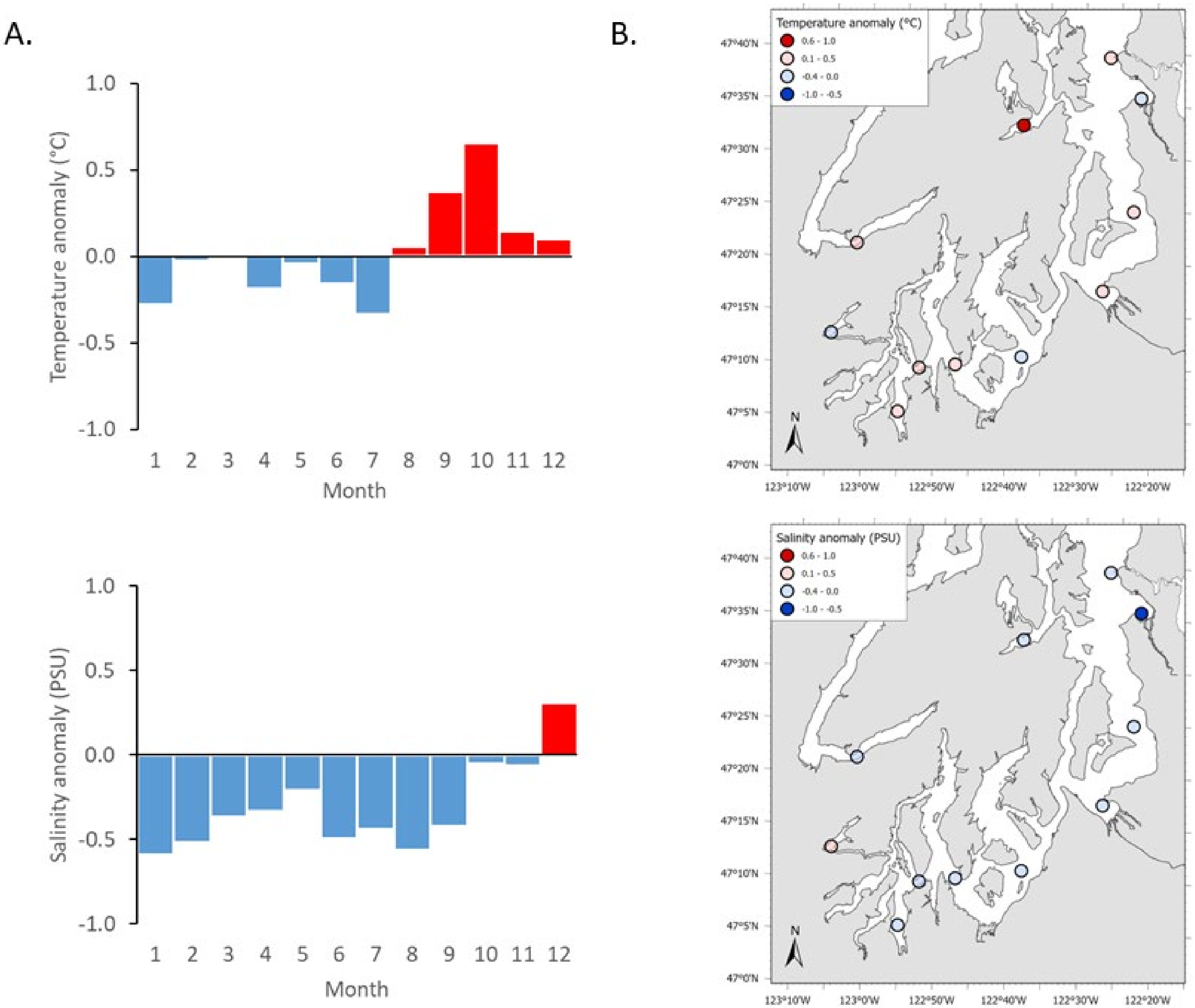


Figure 5.1. (A) Average monthly anomalies in 2022 for water temperature and salinity in the 0 to 50 m layer in Puget Sound compared to the 1999 to 2008 baseline. Anomalies were calculated from sensor profiles at 18 long-term monitoring stations. (B) September 2022 anomalies of water temperature and salinity at 11 long-term monitoring stations in Central and South Puget Sound.

A.ii. Nutrients and chlorophyll

Nutrients

Source: Christopher Krembs (christopher.krembs@ecy.wa.gov), Holly Young, Natalie Coleman, Christopher Jendrey, and Suzan Pool (Ecology); https://ecology.wa.gov/Research-Data/Monitoring-assessment/Puget-Sound-and-marine-monitoring; Website for online data: https://apps.ecology.wa.gov/eim/search/Eim/EIMSearchResults.aspx?ResultType=EIMStudyTab&StudySystemIds=99970619&StudySystemIds=99970618&StudyUserIds=MarineWater-P&StudyUserIds=MarineWater&StudyUserIdSearchType=Equals

Ecology's marine water monitoring program covers a large geographic area, enabling analyses with a focus on long-term, large-scale patterns in the southern Salish Sea. Critical to the analysis is removing variability from the depth, regional, and seasonal signals. Data are treated as follows: 1) monthly samples from 27 stations (target depths of 0 m, 10 m, and 30 m) are reduced to medians; 2) regional and seasonal variability are removed by subtracting site-specific monthly-baselines (1999–2008) based on depth-integrated medians; and 3) the 324 normally-distributed anomalies (when sampling monthly all stations, Krembs, 2012) are averaged to reflect trends of the entire system. This approach is not intended to describe regional or higher-frequency variability. Please refer to regional monitoring and mooring program summaries in this report for such information.

In 2022, the trend continued of surface waters becoming more stratified (Figure 5.2A) and clearer (Figure 5.2B). In contrast, nitrate concentrations in surface waters continued a cyclical trend over 15 years with an amplitude of about 4 μM (Figure 5.2C). Since 2016, nitrate has generally been increasing.

The silicon to dissolved inorganic nitrogen (Si:DIN) ratio, which is an important indicator of nutrient balance for the marine ecosystem, has continued to decline (Figure 5.2D). The cause of this change is not clear. In 2022, significantly high nitrate and phosphate concentrations were observed, and significantly lower than normal (outside 50 percent (IQR) of observations from 1999–2021) silicate concentrations for most of the year in the Strait of Juan de Fuca (data not shown). In September, a 5.4-times-stronger but spatially separated bloom and 2.8-times-higher ammonium concentrations appeared in Central and South Sound (Figure 5.2E).

Whidbey Island. Photo: Rachel Wold

5. Water quality (cont.)

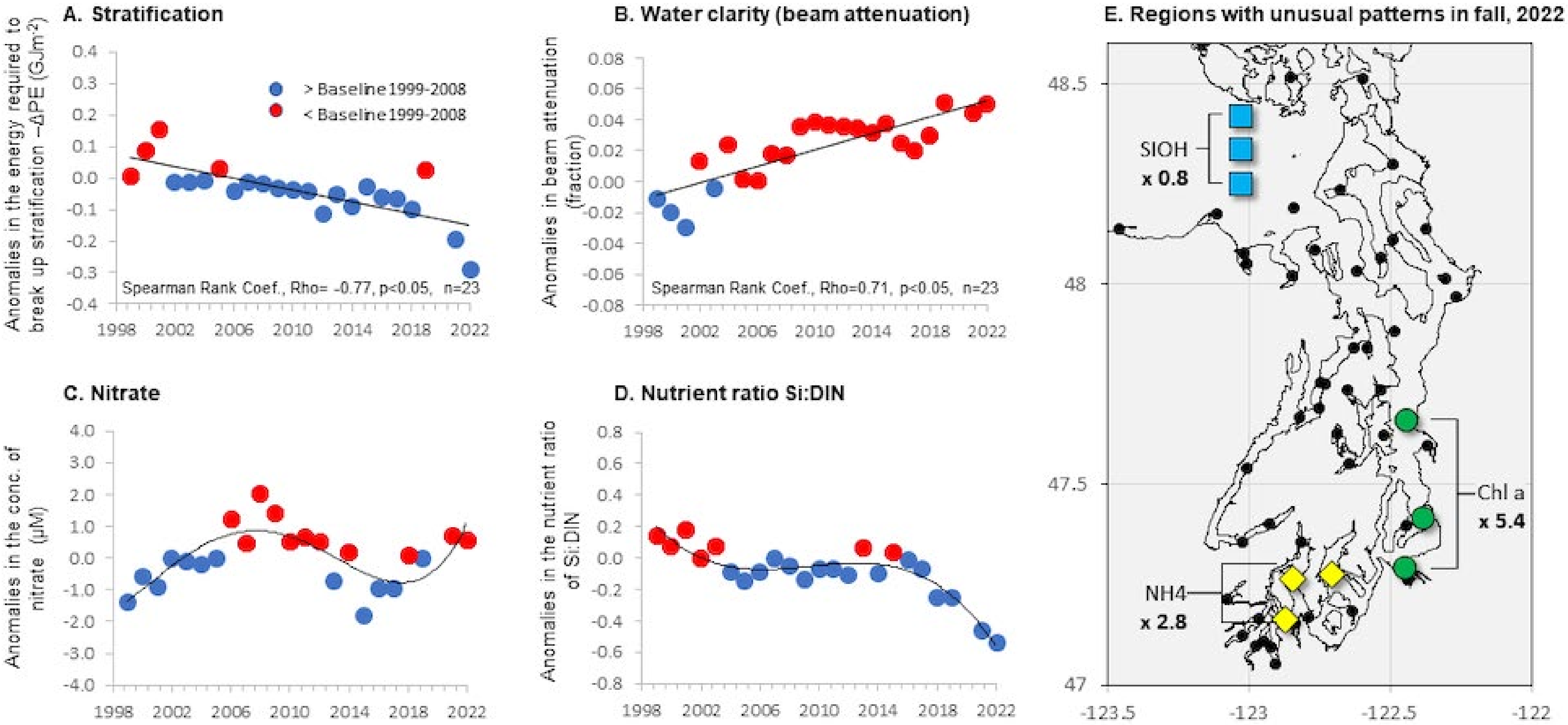


Figure 5.2. (A) Annual anomalies and significant trend in density stratification of the water column from surface to 50m (reported as delta potential energy difference or the energy required to mix the water column). Since Puget Sound is typically stratified at the surface due to a freshwater layer, increasingly negative values indicate that more energy is required to break up stratification relative to a baseline 1999–2008 while positive values mean the water column is more mixed than normal). (B) Beam attenuation measures the attenuation of an active light source by the water relative to clear water and is inversely related to water clarity. Increasing values and significant trend indicate that water is getting clearer. (C) Annual median anomalies in nitrate concentration fitted by a third-degree polynomial shows cyclical pattern over 15 years. (D) Annual anomalies in the Si:DIN ratio fitted by third degree polynomial is pointing to a continued decrease over time. (E) Ecology's station map depicting regions with unusual seasonal patterns. The average factor relative to the baseline for September is presented for silicate (blue square), Chlorophyll-a (green circle) and ammonium (yellow diamond).

B. Puget Sound profiling buoys

Profiling buoys take frequent (one to four times per day) measurements of water properties over the full water column. This allows characterization of short and long-term processes, including deep-water renewal events, surface influence of river runoff and heating, and tracking water mass properties. There are currently six ORCA (Oceanic Remote Chemical Analyzer) moorings in Puget Sound supported primarily by NANOOS and the Washington Ocean Acidification Center: South Hood Canal (Twanoh), central Hood Canal (Hoodsport), Dabob Bay, Admiralty Inlet (Hansville), Main Basin (Point Wells), and southern Puget Sound (Carr Inlet). Climatologies are based upon the data record available at all buoy sites, being the years of 2010–2011, and 2014–2022. In total, 10 years of data were available for use in creating the climatologies.

B.i. Temperature

Temperature

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

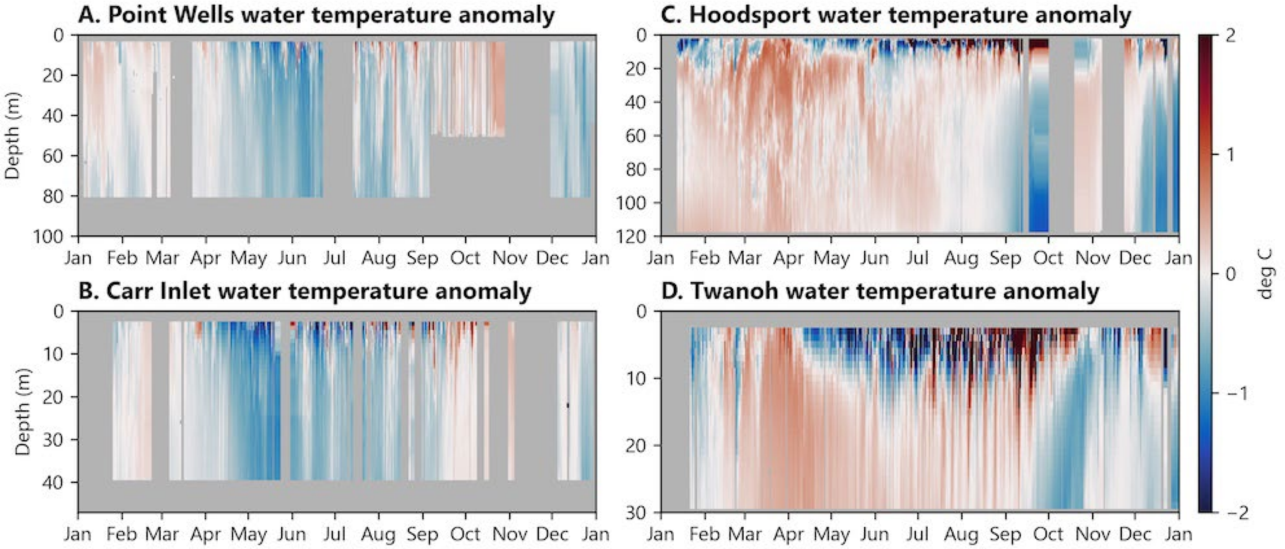


Figure 5.3. Four-panel figure showing depth-time color maps of water temperature anomalies in 2022 relative to the climatological averages (years included in the climatologies: 2010–2011 and 2014–2022). Depth is shown on the y-axis and time in monthly increments on the x-axis between January 2022 and December 2022 at four ORCA mooring sites: Point Wells in Main Basin (A), Carr Inlet in South Sound (B), Hoodsport in mid-Hood Canal (C) and Twanoh in South Hood Canal (D).

Temperature observations from the University of Washington ORCA mooring program highlight a strong difference between Main Basin and South Sound versus Hood Canal water properties during 2022, especially for temperature and oxygen. Compared to climatologies from the full buoy record, the basins showed different patterns likely linked to stronger stratification and slower residence times in Hood Canal. In the Main Basin and South Sound, cool anomalies were mixed through the water column throughout the entire year, while in Hood Canal, the cooler anomalies were mainly confined to the surface layer (~upper 10 m) with warm anomalies below. The pattern of upper water column temperature anomalies is consistent with that expected solely from surface heat flux anomalies (see section 3.C. Puget Sound environmental metrics on page 10). For Hood Canal, deeper waters were broadly warmer during 2022, with temperature anomalies regularly at or exceeding 1°C. In the surface waters, weakly cooler anomalies (<1°C colder) existed at the beginning of the year and persisted until a period of warmer surface waters (>1°C warmer) during late March and early April. Following this warm event, strongly cooler anomalies (>1°C colder) were present throughout the late spring and summer, and were periodically interrupted by strong, short-lived warm temperature anomalies. During this same period, waters at depth were consistently warmer than normal, with temperature anomalies of ~1–2°C. Beginning in October, weak, cool temperature anomalies developed, before alternating between warm and cold anomalies over the rest of the year. While there are missing data, the pattern during October suggests later than normal intrusion timing.

For the Main Basin and South Sound, in contrast to Hood Canal, cool anomalies persisted throughout the entire water column for most of the year. The beginning of the year (January–March) featured weak temperature anomalies of +/- 0.5°C, and beginning in the spring (late April), anomalies become more consistently strong cold anomalies (>1°C colder) throughout the spring and summer, with periodic warm periods in the upper 25 m during August and September. Early fall (late September/early October) showed a weakening of the cold anomalies (<1°C colder), before strengthening again in December.

B.ii. Salinity

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

Salinity observations from the University of Washington ORCA mooring program showed oscillating positive and negative salinity anomalies during 2022 compared to climatological averages. This pattern held true for all basins (Main Basin, South Sound, Hood Canal). This pattern of all basins co-varying is in stark contrast to the pattern for temperature and oxygen, which showed opposite trends for the Hood Canal buoys versus Main Basin and South Sound. The pattern of these anomalies is largely due to anomalies in freshwater input into Puget Sound (see section 3.C. Puget Sound environmental metrics on page 10), which had oscillating high and low flows. All basins showed fresher anomalies to start the year, from January through April, with salinity values 0.5–1 PSU fresher than normal for much of the water column. Beginning in the spring, all basins began to show salty anomalies, switching to anomalies of ~0.5 PSU saltier. The anomalies started approximately two weeks earlier in Hood Canal, during the middle of March, compared to early April for the Main Basin. The summer and fall saw a return of fresher anomalies in all basins, which persisted until late November/early December. As with temperature, the salinity anomalies were the strongest at the surface in Hood Canal, while the Main Basin and South Sound had more uniform anomalies with respect to depth, following the degree of stratification within these basins.

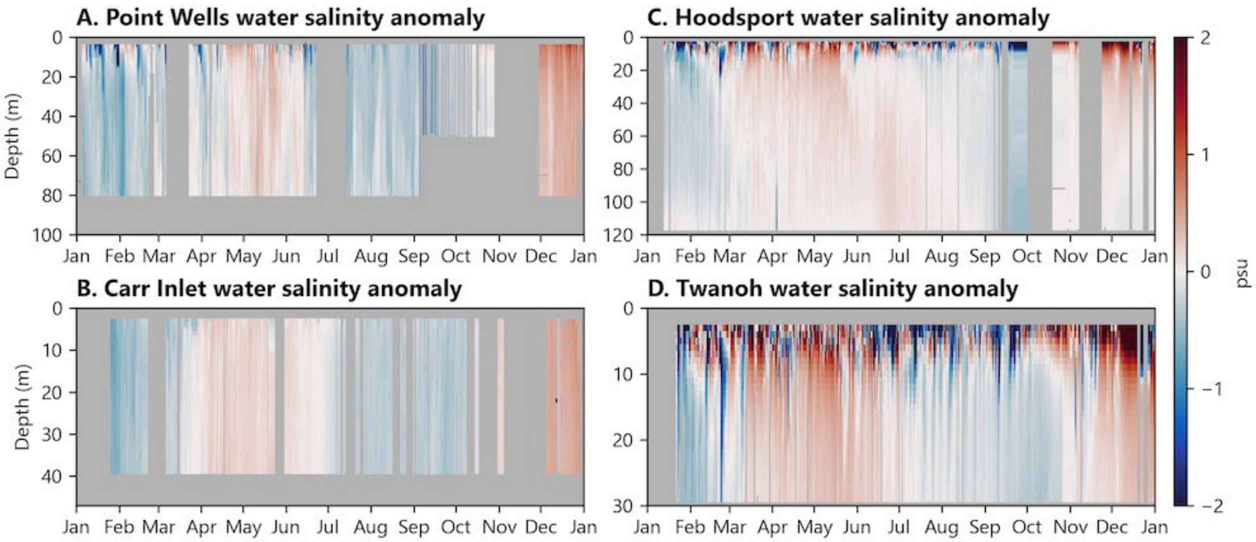


Figure 5.4. Four-panel figure showing depth-time color maps of water salinity anomalies in 2022 relative to the climatological averages (years included in the climatologies: 2010–2011 and 2014–2022). Depth is shown on the y-axis and time in monthly increments on the x-axis between January 2022 and December 2022 at four ORCA mooring sites: Point Wells in Main Basin (A), Carr Inlet in South Sound (B), Hoodsport in mid-Hood Canal (C) and Twanoh in South Hood Canal (D).

B.iii. Dissolved oxygen

Dissolved oxygen

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

Dissolved oxygen (DO) in Puget Sound observed from the University of Washington ORCA moorings exhibited strong variation regionally and temporally during 2022. The Main Basin and South Sound showed alternating patterns of positive and negative DO anomalies throughout the year but were generally positive. In contrast, Hood Canal DO was substantially lower than the long-term average for most of the year (DO anomalies exceed -2 mg/L at Twanoh), and more intense than those seen in the rest of Puget Sound. The oxygen signal in Hood Canal also showed some coherence with the temperature anomalies seen at those locations. In the Main Basin, DO was broadly positive across the year, with episodic periods of negative anomalies lasting a few weeks at a time. At most depths, the DO anomalies were +/- 1 mg/L, with the strongest anomalies occurring in the upper 20 m and are likely associated with the presence or absence of phytoplankton blooms. A similar pattern is observed in the South Sound at Carr Inlet with the notable difference of an extended negative anomaly period occurring throughout the water column from late March through June. This period has negative DO anomalies (~ -1 mg/L) and is only periodically interrupted by short, positive anomaly events likely related to short-lived phytoplankton blooms. In Hood Canal, hypoxic areas formed earlier in the year at Twanoh compared to prior years, with mildly hypoxic areas (>1 mg/L) developing at depths greater than 10 mbeginning in April. These mildly hypoxic areas persisted into the summer, when the hypoxic regions deepened to greater than 20 m, but intensified to less oxygenated waters (<1 mg/L). From July to November, the hypoxic waters shoaled to 10 mdepth, and became more hypoxic, with extended periods of waters with <0.5 mg/L oxygen occurring during September and October. The termination of these strongly hypoxic waters occurred in early November, with sporadic, weakly hypoxic events (>1.5 mg/L) occurring during the rest of the year.

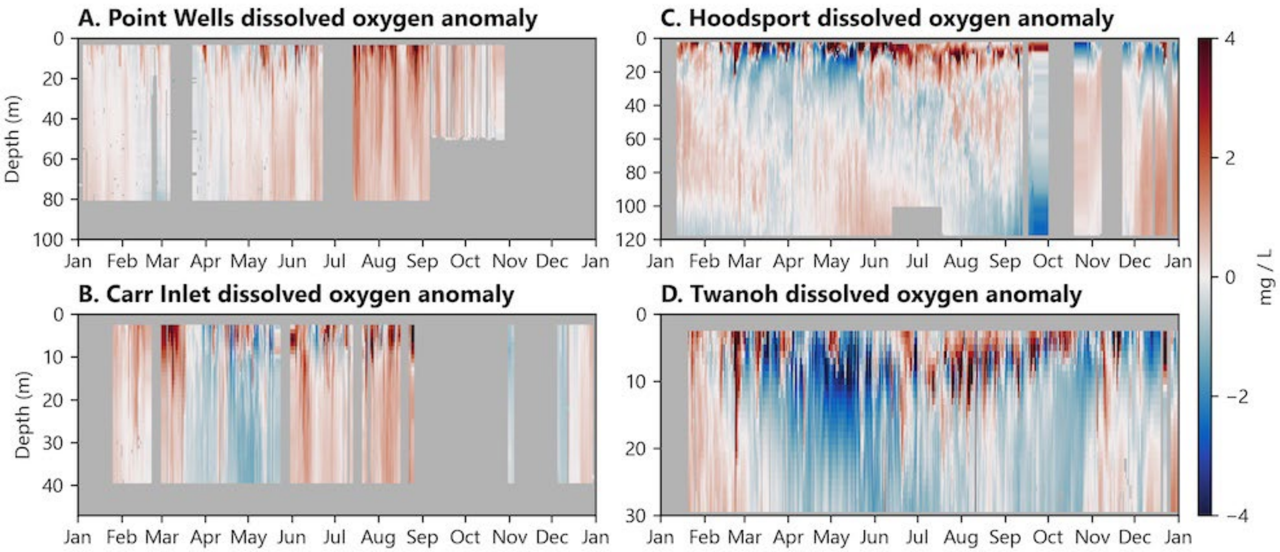


Figure 5.5. Four-panel figure showing depth-time color maps of dissolved oxygen anomalies in 2022 relative to the climatological averages (years included in the climatologies: 2010-2011 and 2014-2022). Depth is shown on the y-axis and time in monthly increments on the x-axis between January 2022 and December 2022 at four ORCA mooring sites: Point Wells in Main Basin (A), Carr Inlet in South Sound (B), Hoodsport in mid-Hood Canal (C) and Twanoh in South Hood Canal (D).

5. Water quality (cont.)

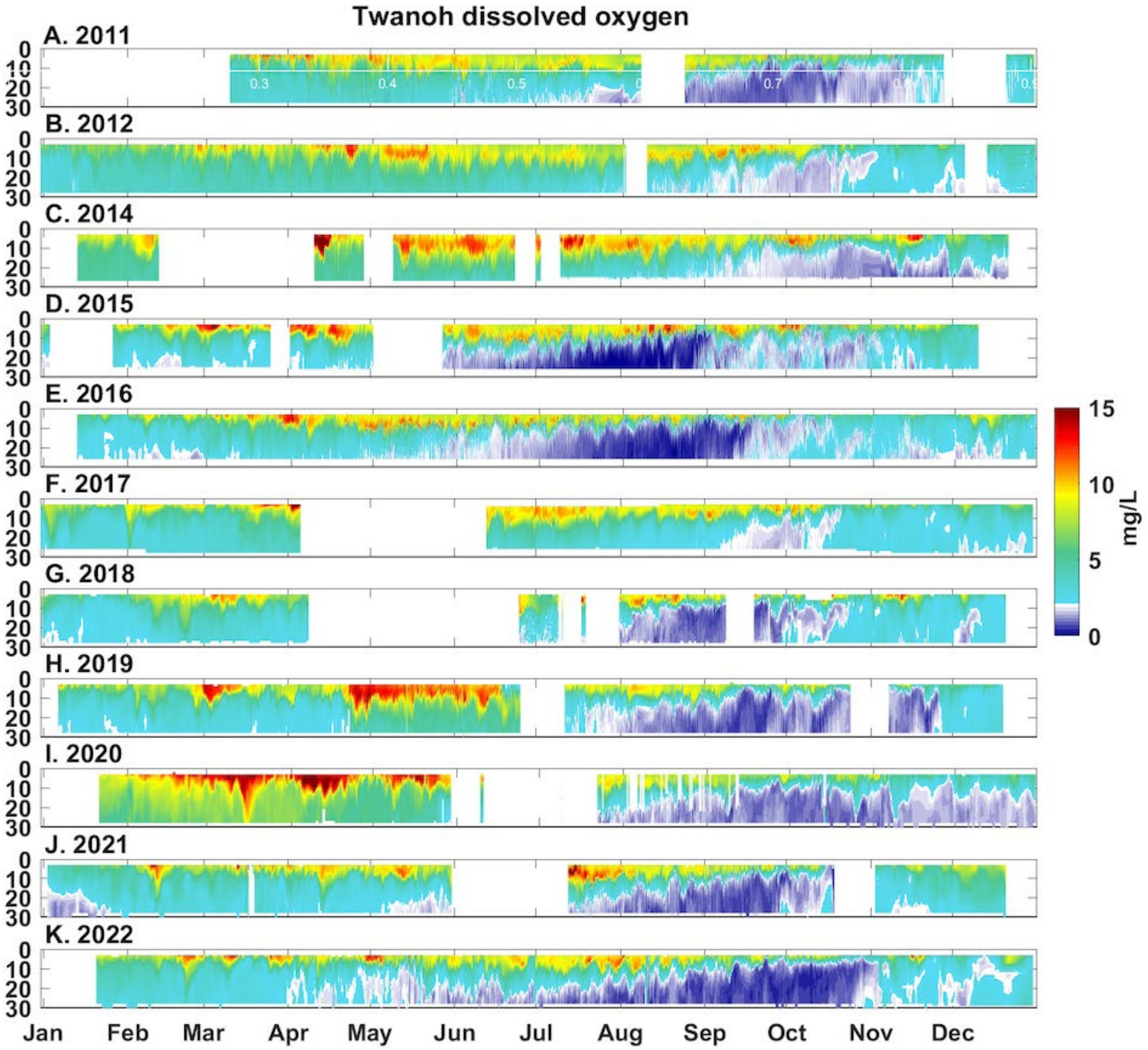


Figure 5.6. Time series of water column dissolved oxygen concentrations at the Twanoh mooring between 2011 and 2022 (not the full record, selected years to fit). Pressure (or depth) is shown on the y-axis and time in monthly increments on the x-axis between January and December.

B.iv. Ocean and atmospheric CO_2

Ocean acidification

Source: Simone Alin (simone.r.alin@noaa.gov), Adrienne Sutton (NOAA, PMEL), Jan Newton, John Mickett (UW, APL), Sylvia Musielewski (UW, CICOES), and Chris Sabine (Univ. Hawaii);
Primary website: https://pmel.noaa.gov/co2/story/Dabob, https://pmel.noaa.gov/co2/story/Twanoh; Website for online data: https://www.ncei.noaa.gov/data/oceans/ncei/ocads/metadata/0116715.html, https://www.ncei.noaa.gov/data/oceans/ncei/ocads/metadata/0157600.html
PMEL contribution number 5552

Atmospheric (air) and surface seawater xCO_2 (mole fraction of CO_2) have been measured on surface ORCA moorings in Dabob Bay since 2011 and at Twanoh in southern Hood Canal since 2009. Preliminary 2022 data returns at Dabob spanned April 16–December 31 (72% of the year) and January 1–December 31 at Twanoh (100% of the year; Figure 5.7, Table 5.1).

The 2022 atmospheric xCO_2 range was 402–582 ppm at Dabob and 398–504 ppm at Twanoh. Monthly average atmospheric xCO_2 at both Hood Canal moorings averaged 13 ppm higher than the globally averaged marine surface air, presumably the result of regional emissions. However, larger differences were observed in winter and fall months (12–21 ppm) than spring and summer months (7–13 ppm). Seasonal production of regional forests likely explains the smaller offset between regional and global average atmospheric xCO_2 values during spring and summer. Atmospheric xCO_2 variability, which is represented by the one standard deviation (1SD) error bars rather than measurement error, was larger during June–November than other months (Figure Y, Table 2). However, as suggested in recent PSEMP reports, regional atmospheric minimum values appear to be shifting later than the historical time-series at both Hood Canal sites, presumably due to changes in the phenology of terrestrial productivity in the region.

During 2022, surface seawater xCO_2 measurements spanned 151–1737 ppm at Dabob Bay and 16–2236 ppm at Twanoh. If these preliminary spans prove correct after final quality control, these values will represent new highest maxima at both sites and a new lowest minimum at Twanoh. Spring and summer months in 2022 had average (±1SD) surface seawater xCO_2 conditions that fell mostly within the long-term ranges (defined here as mean ± 1SD) representing natural variability at each site. During spring and summer

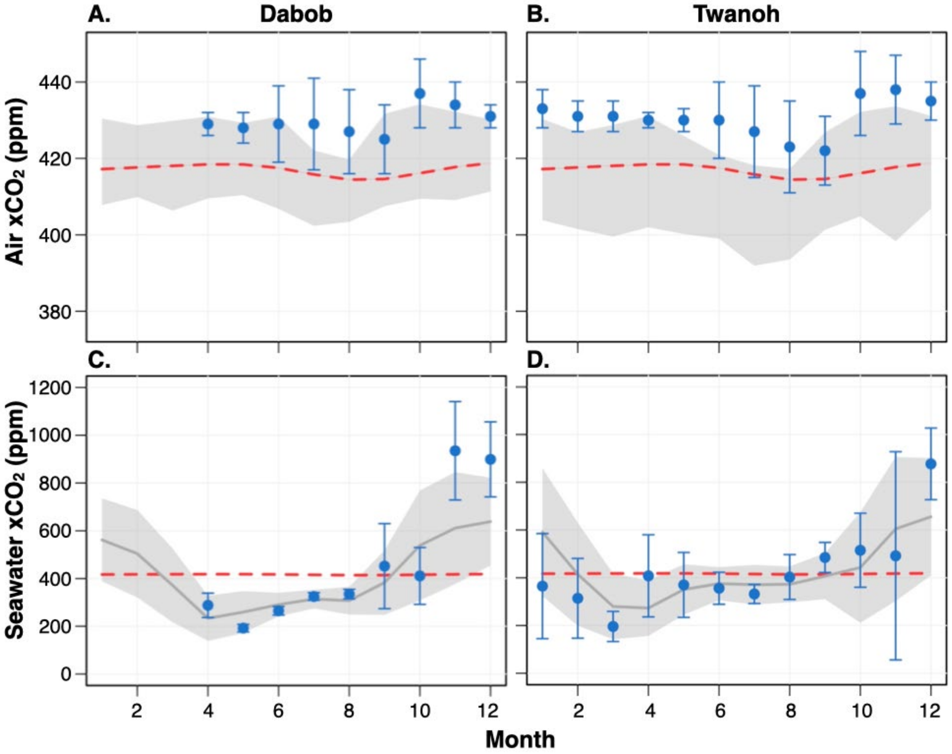


Figure 5.7. Atmospheric xCO_2 in air at 1.5 m above seawater (A, B) and in surface seawater at 0.5 m depth (C, D) on the Dabob Bay (2011–present, A, C), and Twanoh (2009–present, B, D) moorings. Gray shading in atmospheric panels represents the range of monthly mean values across the time-series preceding the current year (i.e., 2022). In the seawater panels, the darker gray line reflects the monthly mean value across the time-series, with the lighter gray shading representing natural variability as one standard deviation (1SD) around the mean. Means ± 1SD for all 2022 months with at least 50% data return for 3-hourly atmospheric and seawater measurements are shown in blue symbols and error bars. The dashed red line in each panel represents monthly mean atmospheric xCO_2 values for globally averaged marine surface air (NOAA/ESRL).

at the Hood Canal moorings, surface xCO_2 typically falls below atmospheric saturation values, reflecting surface primary productivity. Specifically, these conditions were seen April–August at Dabob Bay and March and May–August at Twanoh. However, early 2022 conditions were somewhat below the long-term mean at Twanoh, which may suggest an early-onset spring bloom, and were higher than average there by April. At both sites, September seawater xCO_2 values skewed toward the higher end of the historical range but were more within the historical range in October. November and December seawater mean xCO_2 values were outside the historical range at Dabob Bay. At Twanoh, November had an anomalously wide range of surface xCO_2 conditions with a relatively low mean, while the mean was on the high end of the historical range with a relatively small range in December.

Table 5.1: Atmospheric and surface seawater xCO_2 (in parts per million, ppm) at the Dabob Bay (A) and Twanoh (B) moorings in Hood Canal. Monthly means ± 1SD for 2022 are compared to monthly statistics for the historical time-series at each location. Because atmospheric CO_2 increases year after year, the past statistics used for comparison to the current year are the minimum and maximum monthly means observed across the full time-series at each mooring, such that the lower bound represents earlier years and the upper bound represents more recent years. For seawater measurements, historic monthly statistics used for comparison are means ± 1SD because the variability (reflected by the 1SD) at Washington mooring sites is sufficiently high to prevent detection of long-term trends at this time (Sutton et al. 2019).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dabob ATM												
2022	n.a.	n.a.	n.a.	429 ± 3	428 ± 4	429 ± 10	429 ± 12	427 ± 11	425 ± 9	437 ± 9	434 ± 6	431 ± 3
2010–2021*	408–430	410–429	406–430	410–431	410–429	407–431	402–422	403–420	407–432	409–434	409–432	411–430
Dabob SW												
2022	n.a.	n.a.	n.a.	288 ± 51	192 ± 16	265 ± 18	325 ± 16	335 ± 20	452 ± 178	411 ± 119	935 ± 206	899 ± 157
2010–2021*	562 ± 174	504 ± 183	371 ± 154	233 ± 95	260 ± 88	291 ± 49	314 ± 39	308 ± 58	383 ± 135	538 ± 230	611 ± 234	638 ± 193
Twanoh ATM												
2022	433 ± 5	431 ± 4	431 ± 4	430 ± 2	430 ± 3	430 ± 10	427 ± 12	423 ± 12	422 ± 9	437 ± 11	438 ± 9	435 ± 5
2006–2021	404–430	402–427	400–429	402–431	400–426	399–421	392–418	394–417	401–427	405–432	398434	407–431
Twanoh SW												
2022	365 ± 220	314 ± 167	196 ± 63	408 ± 172	370 ± 136	356 ± 67	332 ± 40	403 ± 94	485 ± 63	515 ± 155	492 ± 436	877 ± 150
2006–2021	591 ± 268	415± 216	280 ± 137	273 ± 116	351 ± 106	375 ± 69	371 ± 83	372 ± 75	407 ± 96	443 ± 232	604 ± 302	655 ± 246

C. Central Basin long-term stations

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

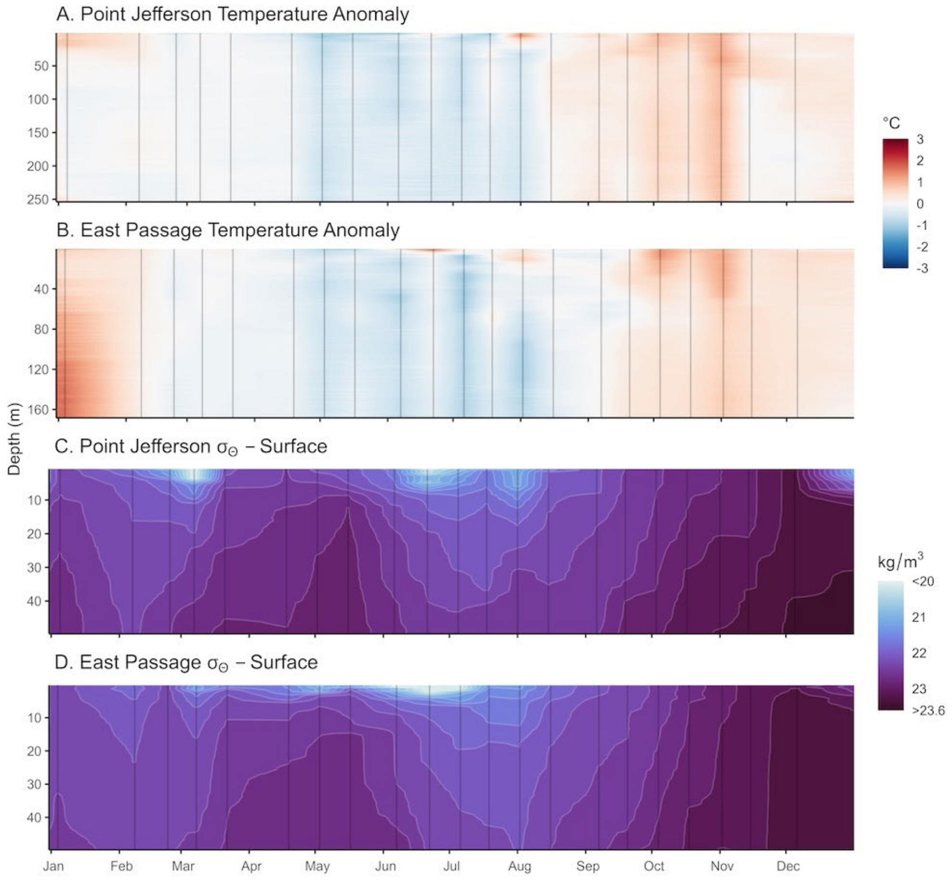
C.i. Temperature, salinity, and density

Temperature

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

Water temperatures in Central Basin in early January were warmer than the monthly 1998–2013 baseline average then were consistently cooler from late winter until early fall, when a delayed warming led to higher than baseline temperatures through December (Figure 5.8A, B). Cooler temperatures persisted longest at southern sites in Central Basin (e.g. East Passage, Figure 5.8B). These negative anomalies were mostly consistent throughout the entire water column in the spring and early summer, with brief positive anomalies at the surface in June and August. Despite these extended periods of cool and warm temperatures, there were few large anomalies compared to the previous five years.

High precipitation in late 2021 led to low salinity that was below the 1998–2013 baseline throughout the beginning of 2022, with brief positive surface anomalies in spring and in fall (not pictured). Low precipitation in summer increased salinity from July onwards, which stayed above the baseline throughout the Central Basin from October into 2023. In northern Central Basin (e.g. Pt. Jefferson), higher salinity deep water reached the surface in late spring, separating low surface salinity into two major periods of density stratification: one in February–April and again in June–August (Figure 5.8C). In contrast, southern stations retained low salinity in the top 10 m throughout spring, resulting in sustained stratification from February to August (Figure 5.8D), likely leading to an extended phytoplankton bloom (see section 6.A.i. Puget Sound phytoplankton on page 38) in the southern Central Basin that did not occur in the northern stations. Mooring data exhibited the same pattern of low salinity throughout the first half of the year, with the effect of major rainfall events evident, particularly in Quartermaster Harbor where three major drops in salinity occurred in January, March, and June (Figure 5.8 E-H), followed by high salinity for the remainder of the dry season.



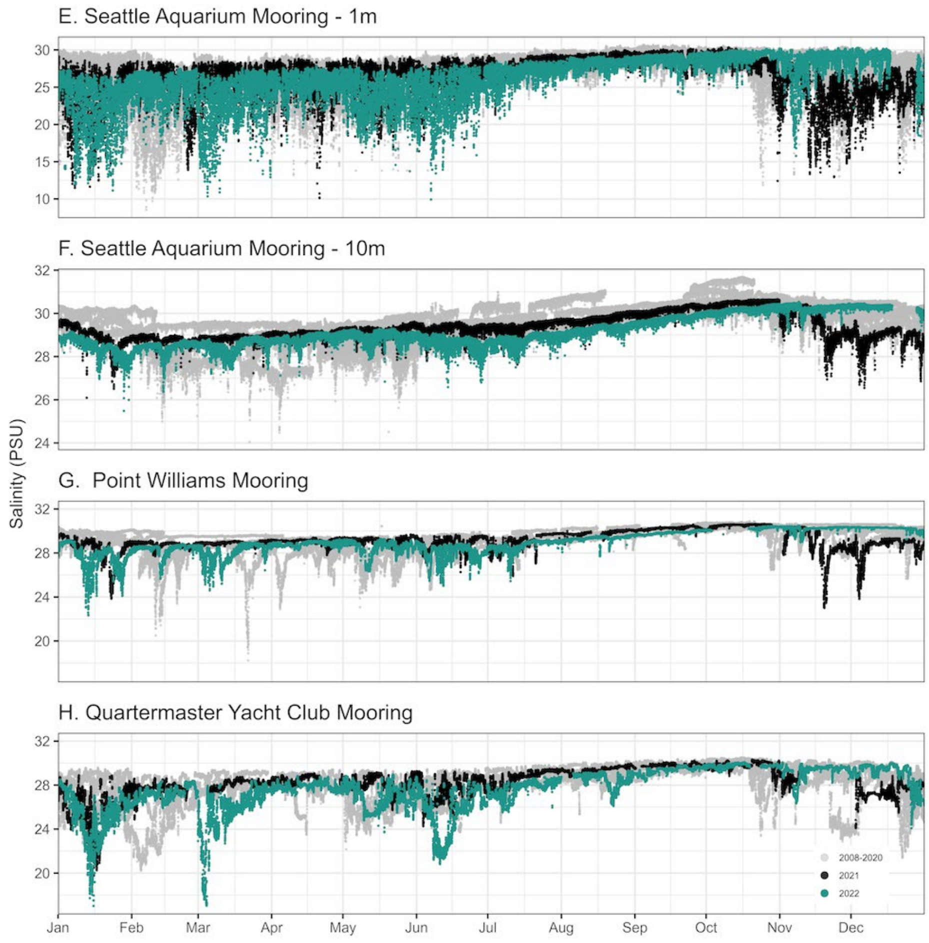


Figure 5.8. (A, B) Contour plots of temperature anomalies (°C) at the northernmost (Point Jefferson) and southernmost (East Passage) Central Basin stations calculated from the difference between observations and a monthly baseline mean for the period 1998–2013. (C, D) Contour plots of water column sigma-theta density (kg/m^3) in the top 50 m at Point Jefferson and East Passage. Vertical lines indicate when data were collected. (E, F, G, H) Salinity data from moorings in 2022 (green), 2021 (black), and 2011 – 2019 (gray) at the Seattle Aquarium (E, 1 m; F, 10 m), Point Williams (G) and Inner Quartermaster Harbor (H). Each mooring collects data on a 15-minute interval.

C.ii. Dissolved oxygen

Dissolved oxygen

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

Dissolved oxygen (DO) in the Central Basin was below the 1998–2013 monthly baseline average for most of the year, with periods of high surface DO corresponding with phytoplankton blooms. Delayed springtime productivity throughout the Central Basin coincided with anomalously low surface DO from March to May, followed by periods of elevated surface DO throughout summer and fall. The timing and magnitude of high surface DO varied between sites. Point Jefferson in northern Central Basin had brief and isolated increases in surface DO in June–September (Figure 5.9 A), while East Passage in the southern Central Basin had more consistent high surface DO in May–November, with DO up to 4.1 mg/L higher than the baseline (Figure 5.9B). Sustained phytoplankton blooms in East Passage, likely driven by stratification throughout spring and summer, contributed to higher surface DO and DO anomalies than the northern stations. The lowest DO at deep stations (>100 m) ranged from 5.0 mg/L (Point Jefferson) to 4.6 mg/L (East Passage) and occurred in October and November, respectively.

Quartermaster Harbor, a shallow poorly flushed embayment which consistently has the lowest observed DO in the Central Basin, had earlier increases in DO than other sites due to earlier phytoplankton blooms (Figure 5.9C). In the inner harbor, a brief rise in DO in February corresponded with increased chlorophyll fluorescence but DO decreased in March after an influx of freshwater and a reduction in chlorophyll. Peak DO in the inner harbor occurred in April, which was earlier than the rest of the Central Basin but later than prior years. DO at the inner Quartermaster Harbor mooring exhibited high variability throughout the year, particularly in the late summer and early fall, and periodically dropped below 2 mg/L in September and October which is typical at this location.

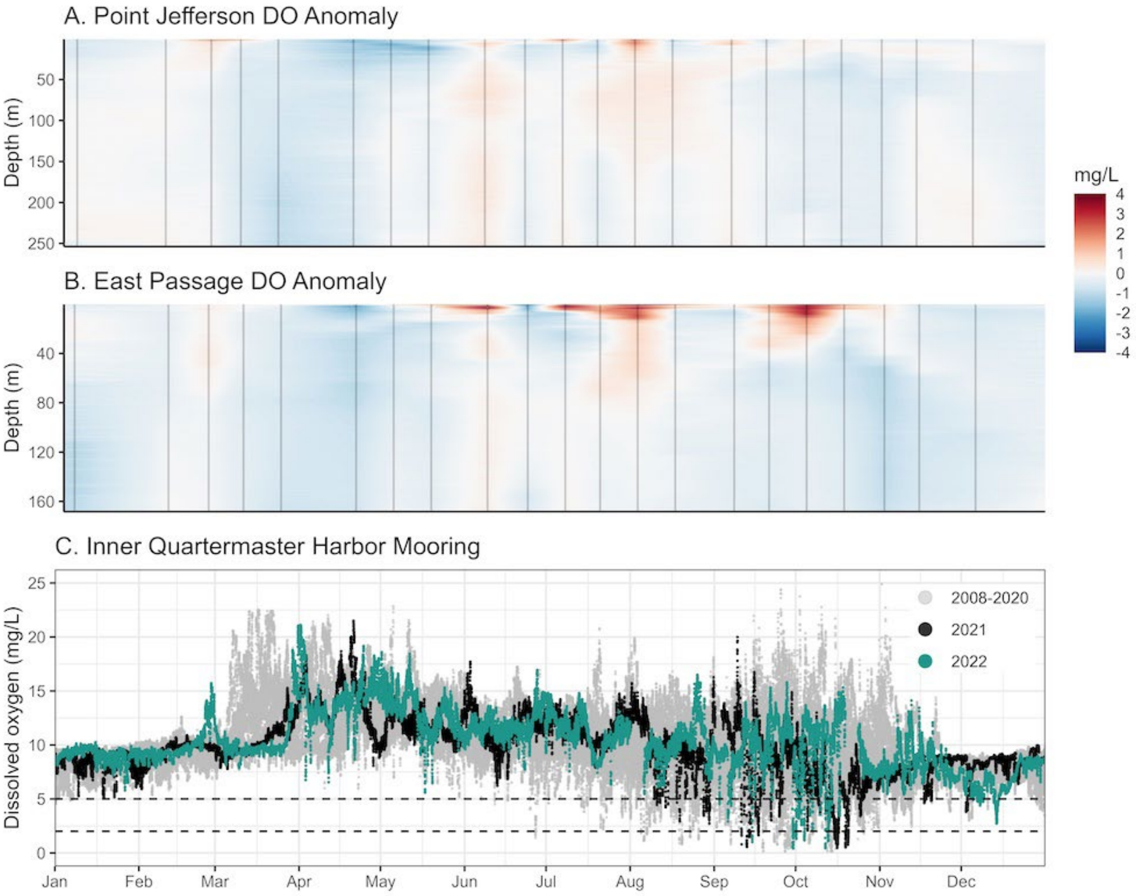


Figure 5.9. (A, B) Dissolved oxygen water column anomalies (mg/L) at Point Jefferson (A) and East Passage (B) calculated from the difference between observations and a monthly baseline average for the period 1998–2013. (C) Dissolved oxygen mooring data from 2022 (green), 2021 (black), and 2011 – 2019 (gray) collected in inner Quartermaster Harbor. Data are collected on a 15-minute interval. The top dashed line corresponds with 5 mg/L and the bottom dashed line corresponds with 2 mg/L.

Whidbey Island. Photo: Rachel Wold

C.iii. Nutrients and chlorophyll

Nutrients
Phytoplankton

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

Central Basin chlorophyll-a data from twice monthly sampling in 2022 indicated an early bloom at most sites the third week in February that was highest in the north (Pt. Jefferson), corresponding to strong density stratification (Figure 5.10A). The trend of earlier than normal blooms at Pt. Jefferson continued in 2022, but overall, the spring bloom was not evident until early May at most sites. Chlorophyll-a levels declined the first week in June at all sites following the record June rain event and fall chlorophyll levels were relatively low in the northern and mid-basin. However, chlorophyll-a levels were unusually high compared to prior years in the southern basin, especially at East Passage, with sustained high values August through October that coincided with atypical strong density stratification throughout the summer and early fall. High temporal resolution data (15-minute intervals) in inner Quartermaster Harbor showed that the trend of lower chlorophyll levels in late February through March and late summer/fall continued in 2022.

Low dissolved nutrients (nitrate+nitrite-N, silica, and orthophosphate-P) in surface waters corresponded to high chlorophyll-a levels and less freshwater input, with the lowest values of the year June-August (Figure 10B). In Quartermaster Harbor, nitrate+nitrite-N was below detectable levels from April through October and orthophosphate-P below detectable levels April-July, which is a longer period than past years. This extended period of low nutrients likely contributed to less chlorophyll (phytoplankton) in the summer and fall.

Nitrate+nitrite-N and silica concentrations in deep waters (> 150m) remained higher than the monthly baseline (1997-2013) average until August in the northern basin, but were more variable in other areas. Deep water silica concentrations at East Passage have been mostly higher than normal since mid-2019 (Figure 5.10C).

A. Central Basin chlorophyll-*a*

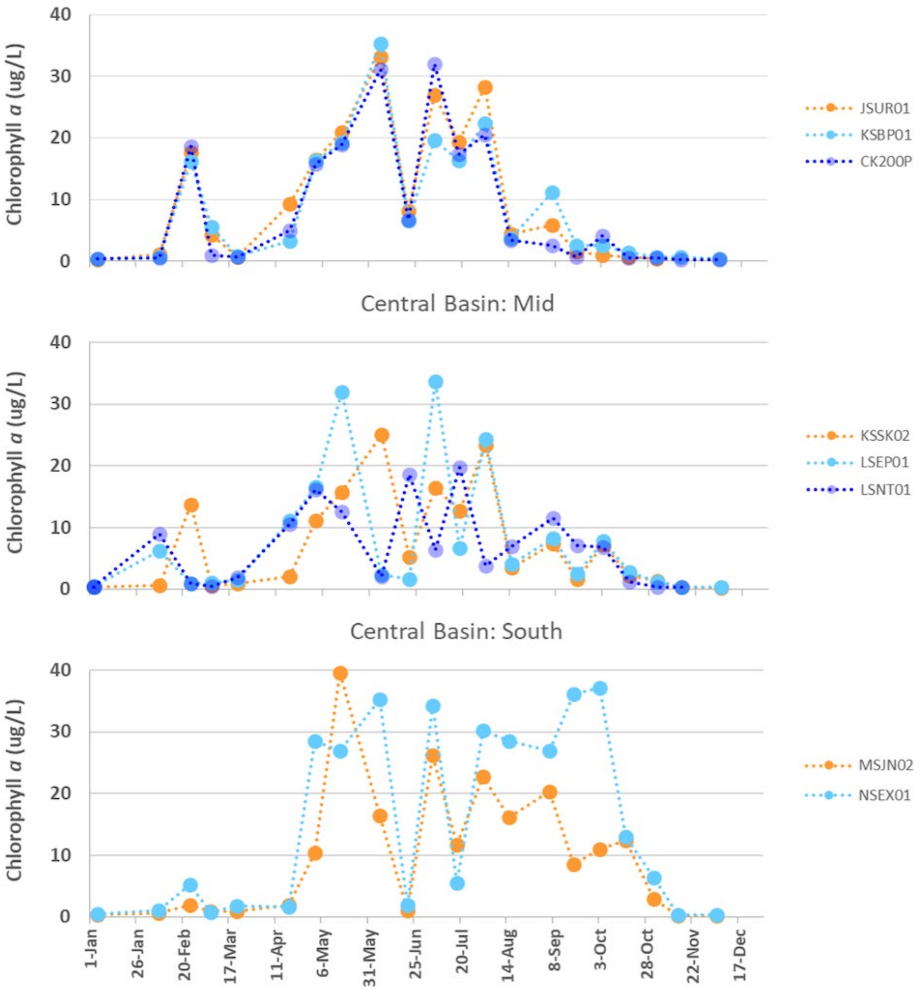


Figure 5.10 (A) 2022 chlorophyll-a in surface waters (<2m) for Central Basin sites.

5. Water quality (cont.)

B. Central Basin monthly nitrate

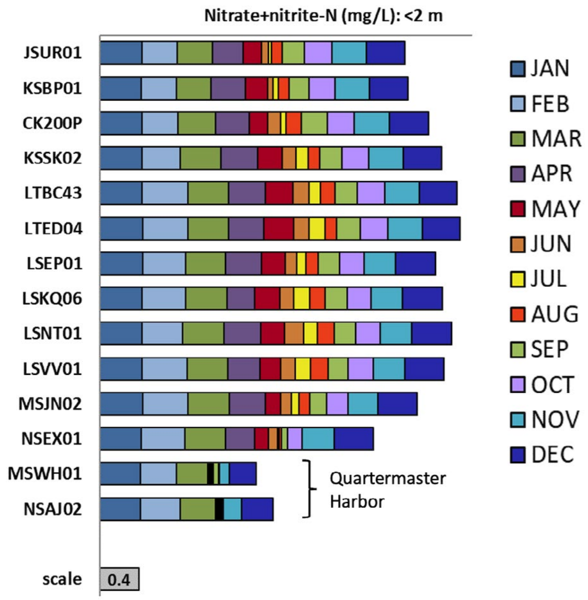


Figure 5.10 (B) 2022 nitrate+nitrite-N monthly averages in surface waters for 14 Central Basin sites ordered north to south.

C. Monthly silica anomolies

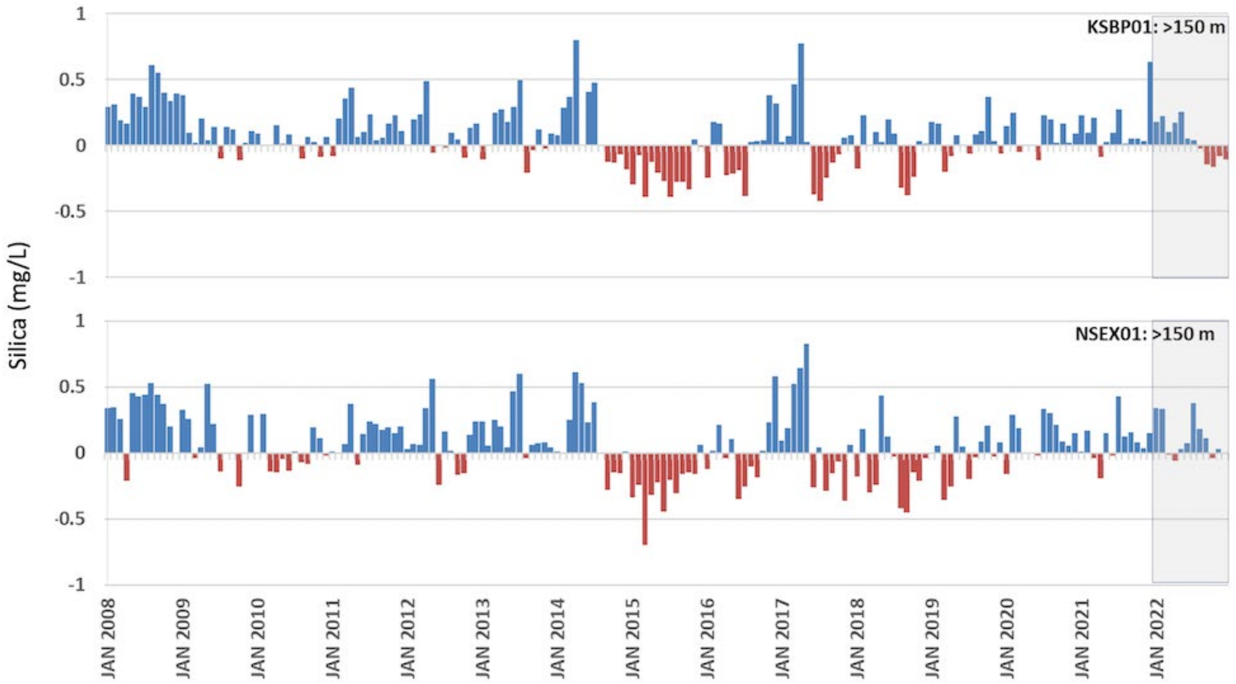


Figure 5.10 (C) Silica monthly anomalies (compared to 1997-2013 baseline) for deep water at Pt. Jefferson (top) and East Passage (bottom). 2022 is shaded gray.

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

D. North Sound surveys

D.i. Padilla Bay temperature

Temperature

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

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

Continuous monitoring of nearshore surface waters in Padilla Bay revealed temperatures in 2022 ranged from -1.7 to 23.3°C throughout the year, with daily fluctuations approaching 10°C during summer months (data not shown). These large variations tend to occur July through 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 2022 (10.5 ± 0.2°C) was comparable to 2013 (10.5°C) and 2008 (10.5°C), and lower than 2015 (11.7°C), 2016 (11.5°C), 2018 (11.2°C), and 2019 (11.5°C). Throughout the year, water temperatures were generally well aligned with long-term daily means, with some noticeable exceptions of unseasonably low temperatures in November and December and elevated temperatures in late July through October (Figure 5.11A). The combination of cooler and warmer periods resulted in an annual mean temperature anomaly of -0.04°C for 2022 that was similar to the long-term average anomaly and lower when compared to the previous eight years (2014–2021) where positive anomalies were recorded (Figure 5.11B).

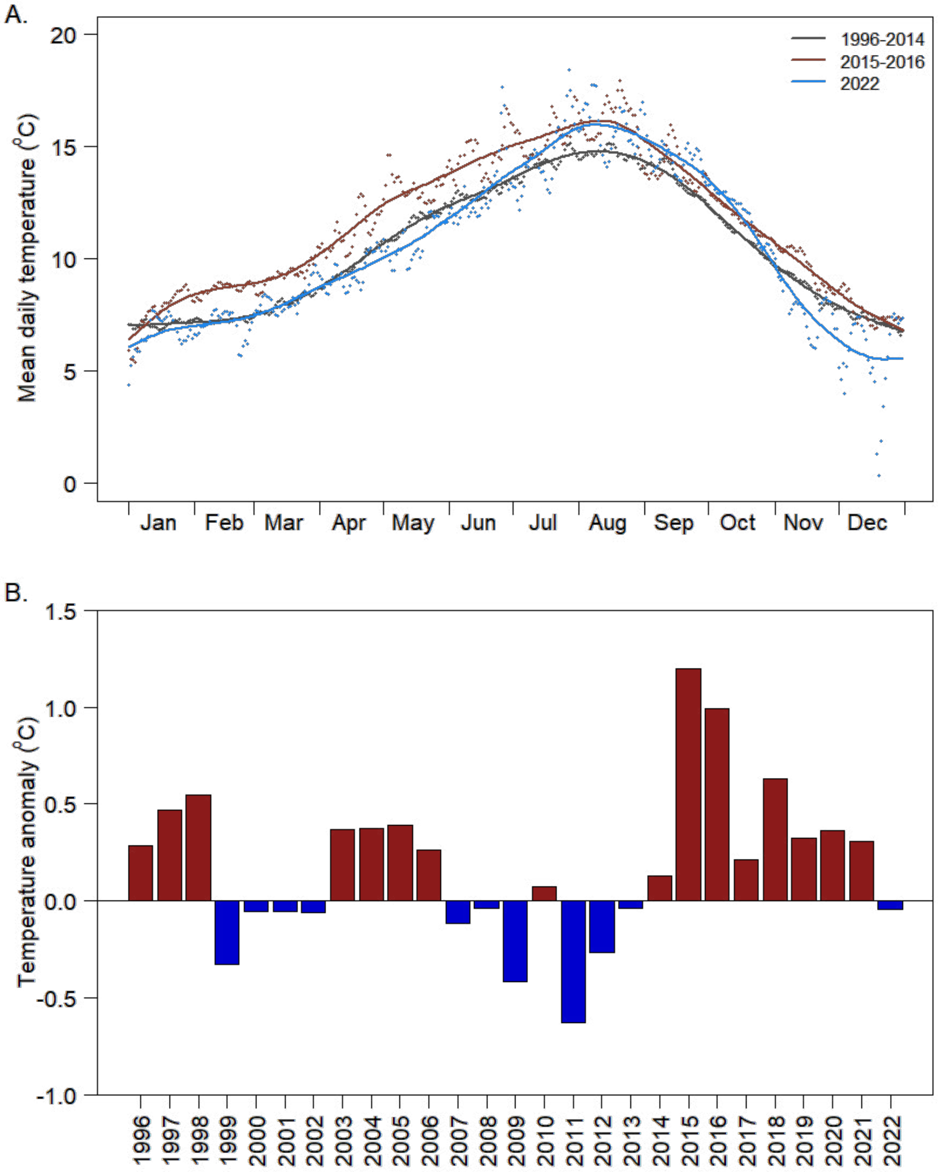


Figure 5.11. Long-term patterns in temperature in Padilla Bay, including (A) comparison of daily mean temperatures in 2015–2016, 2022 and long-term (1996–2014) daily mean, and (B) long-term annual temperature anomalies.

D.ii. Padilla Bay water column characteristics

Dissolved oxygen
Temperature

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

Researchers at the Padilla Bay National Estuarine Research Reserve (NERR) have conducted monthly water column profiles at Gong Buoy since 2015. Gong Buoy is located in approximately 20 m of water in the northwest region of Padilla Bay. The long-term data from these profiles provide an opportunity to identify interactions between water column structure, water chemistry, and biological processes throughout the year. In 2022, patterns in these metrics were relatively muted. Water column density remained moderate through most of the spring, with evidence of fresher surface waters, until a warming of the water column in July and August (Fig. 5.12A-C). In general, summer stratification was less pronounced than previous years. These patterns in water column structure influenced biological activity and water quality parameters. Chlorophyll fluorescence, dissolved oxygen, and pH were moderate with no distinctive patterns in the beginning of the year and were not elevated until May (Fig. 5.12D-F). Patterns in dissolved oxygen and pH were generally coupled with apparent changes in biological activity, with higher values observed during periods of elevated chlorophyll and algal biomass (Figure 5.12E-F). Historically, fall in Padilla Bay is a time of water column mixing and lower dissolved oxygen and pH throughout the water column, but the absence of data from this period makes it difficult to determine if a similar pattern existed in 2022.

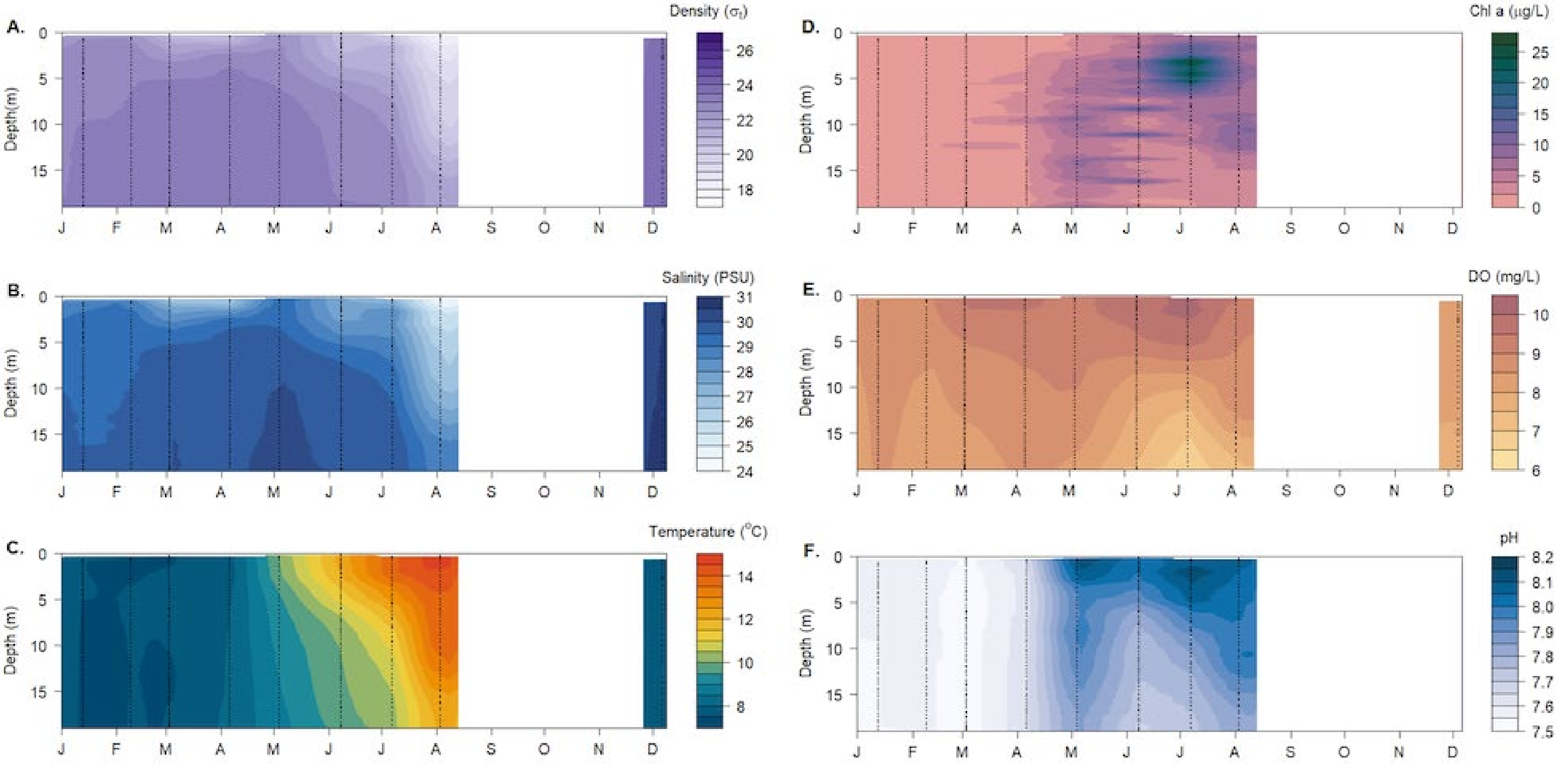


Figure 5.12. Water column profiles derived from monthly sampling at Gong Buoy illustrating patterns in (A) density, (B) salinity, (C) temperature, (D) chlorophyll fluorescence, (E) dissolved oxygen, and (F) pH. Profiles were not conducted September through December 2022.

D.iii. Port Susan buoy

Dissolved oxygen
Nutrients
Temperature

Source: Taylor Martin (taymartin@kingcounty.gov, King County) and Franchesca Perez (Stillaguamish Tribe of Indians); Primary websites: http://green2.kingcounty.gov/marine; http://www.stillaguamish.com/natural-resources; Website for online data: https://kingcounty.gov/services/environment/water-and-land/puget-sound-marine/whidbey-basin-sensor-data.aspx

Port Susan is a shallow, semi-enclosed bay located on the east side of Camano Island within the Whidbey Basin. The Stillaguamish River mouth is at the north end of the bay and is a major influence on water quality parameters. The Stillaguamish Tribe of Indians has collected surface (1 m) data every 30 minutes via sensors suspended from a buoy at the north-central part of the bay since 2011. The Tribe also collected water column profile data at 10 stations in Port Susan, including the buoy location. King County co-deployed sensors collecting data every 15 minutes from the buoy, collected water column profile data once–twice monthly at three stations in Port Susan, and collected data from specific depths (1 m, 5 m, and bottom) at the buoy starting in February 2022.

Figure 5.13 panels A–E show water column profile data, panels F–I data from moored instruments, and panel J data from surface samples. Temperature at the buoy was highest in late July (Figure 5.13A & F). This was the warmest period of record in the mooring data (2011–2022), with a maximum temperature of 23.7°C. These high temperatures occurred during a period with no rainfall and minimal river flows, which also led to high salinities July–late October (Figure 5.13B & G). High river flows in late February corresponded with the lowest surface salinity. Dissolved oxygen (DO) was highest in spring (Figure 5.13C & H), aligning with high chlorophyll fluorescence (Figure 5.13D & I) and low nitrate+nitrite (N) values (Figure 5.13E & J). Chlorophyll was highest in March, April, and June. There was a period of low chlorophyll in May, which was accompanied by high N, low DO, and low surface salinity. There was significant river input during May and early June that may have contributed to the brief reduction of phytoplankton production (see section B. Puget Sound rivers on page 14). Two late summer/early fall periods of increased chlorophyll corresponded to observations of increased phytoplankton (see section 6.A.ii. Whidbey basin phytoplankton on page 40).

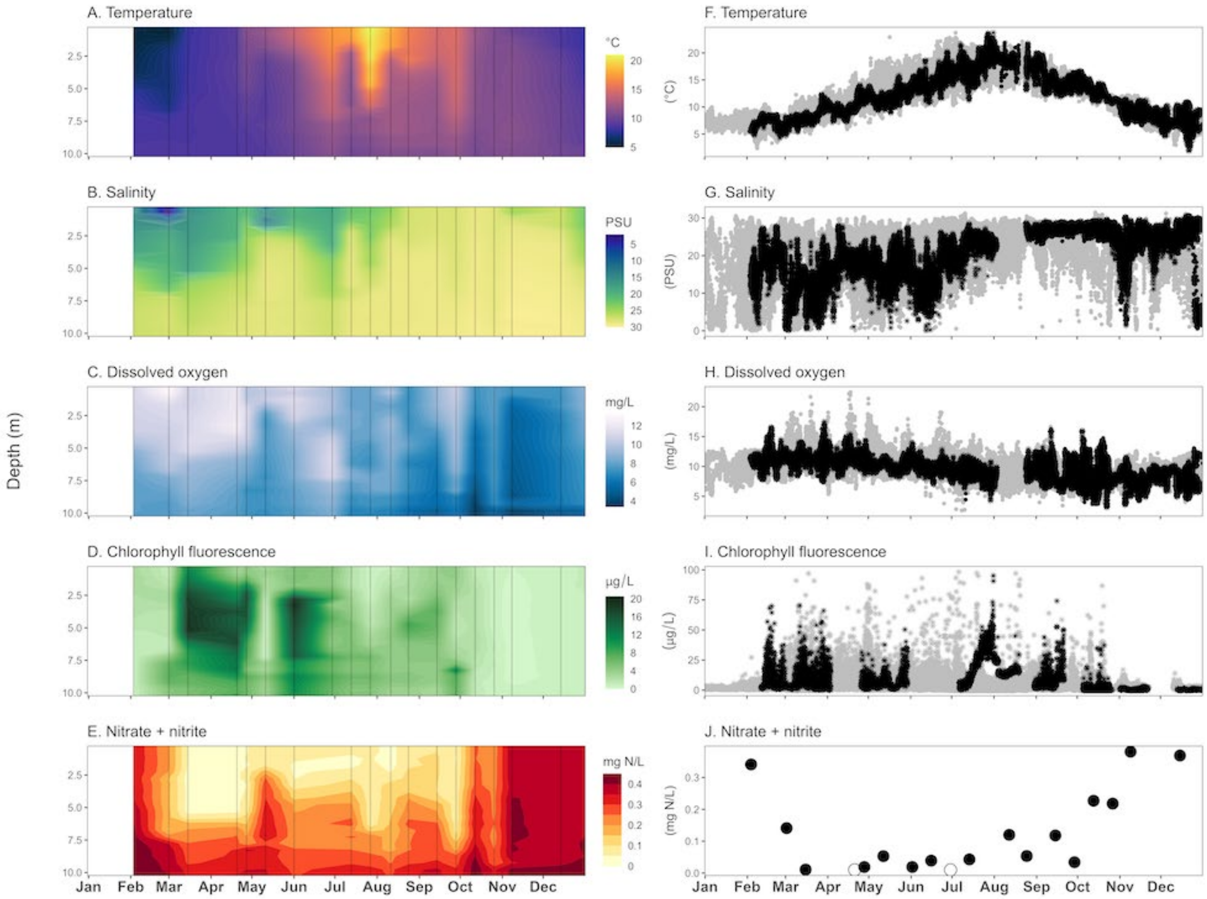


Figure 5.13. Data from north-central Port Susan in 2022. (A–E) Water column profile data for multiple parameters. Black lines indicate dates when casts were performed. (F–I) Time series plots of 15- and 30-minute mooring data collected at the surface (1 m). Black dots are 2022 data and gray dots are 2011–2021 data. (J) Time series of surface (1 m) nitrate+nitrite data. Empty circles represent concentrations below the method detection limit.

D.iv. Whidbey Basin

Dissolved oxygen
Nutrientes

Source: Taylor Martin (taymartin@kingcounty.gov, King County); Primary website: http://green2.kingcounty.gov/marine; Website for online data: https://kingcounty.gov/services/environment/water-and-land/puget-sound-marine/whidbey-basin-sensor-data.aspx

King County began water quality sampling in Whidbey Basin in February 2022. Vertical profiles were collected at 10 sites once–twice monthly, and samples at specific depths were also collected at five of those sites. All the sites were consistently stratified throughout the year, with a 5–10 m layer of fresher water at the surface and a steep density gradient directly below. A density water column plot from Camano Head in Saratoga Passage is shown as an example (Figure 5.14A). Substantial mixing occurred at the end of October, likely wind-driven, which led to a single sampling event of unstratified water columns. Bottom water density increased in September at Saratoga Passage stations and October at Port Susan and Penn Cove stations. Surface nitrate+nitrite concentrations were low, corresponding with phytoplankton growth March–September (Figure 5.14B). Some values were below the detection limit at all stations, but nitrate+nitrite was only persistently depleted at the Penn Cove stations in the late spring.

Minimum dissolved oxygen (DO) was highest March–April during the spring bloom and lowest August–October (Figure 5.14C). The minimum DO usually occurred at the bottom, though there were some mid-water column minima at the deeper Possession Sound and Saratoga Passage stations in the summer. The Port Susan stations had the lowest DO of the deep stations (>50 m), with minimum DO <3 mg/L in February and August. The other deep stations followed similar patterns to each other, but with a DO gradient that decreased northward across the four stations (i.e, Poss DO-2 > SARATOGACH > SARATOGAOP > SARATOGARP). Depth-integrated chlorophyll fluorescence (1–50 m) was exceptionally high in late June (400–600 mg/m^2) and coincided with a pronounced ~20 m thick chlorophyll peak at most stations (Figure 5.14D). There were smaller peaks in March and April. Saratoga Passage stations also had a peak in September following the crash after the late June peak.

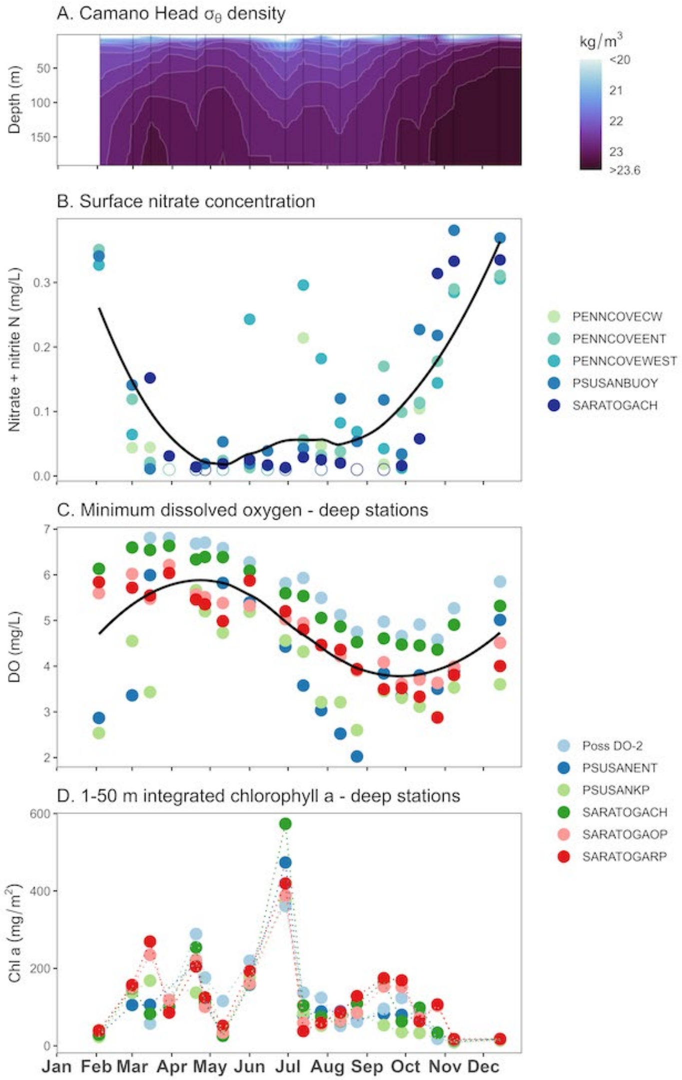


Figure 5.14. Data from Whidbey Basin in 2022. A) Sigma-theta density at Camano Head (SARATOGACH). Black lines indicate dates when casts were performed. B–D) time series plots of B) surface nitrate+nitrite, C) dissolved oxygen, and D) 1–50 m integrated chlorophyll. See King County website for map. Open symbols indicate concentrations below the method detection limit. Black lines represent averages of B) five sites or C) six sites (max. depth >50 m).

E. Snapshot surveys

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

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

Temperature
Marine birds

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

Source: Jan Newton (janewton@uw.edu); Roxanne Carini (UW, APL), Becca Guenther, Fred Wang, Evan Carroll (UW, FHL), and Mike Sigler (NOAA, ret.)
Primary website: http://courses.washington.edu/pelecofn;
Website for online data: www.nanoos.org

As part of the PEF study in the San Juan Islands, temperature and salinity anomalies were calculated for both surface (0–5 m) and deep waters (10 m above seabed) at both "North" (North San Juan Channel, 120 m depth) and "South" (Strait of Juan de Fuca, 90 m depth) stations occupied on ~weekly cruises during fall (September–November) over the last 19 years (2004–2022).

During fall 2022, seawater temperature anomalies were mixed, with warmer than average conditions at North (both deep and surface) and South (surface only) stations, while South deep waters showed several negative anomalies (0.2–0.5°C, Figure

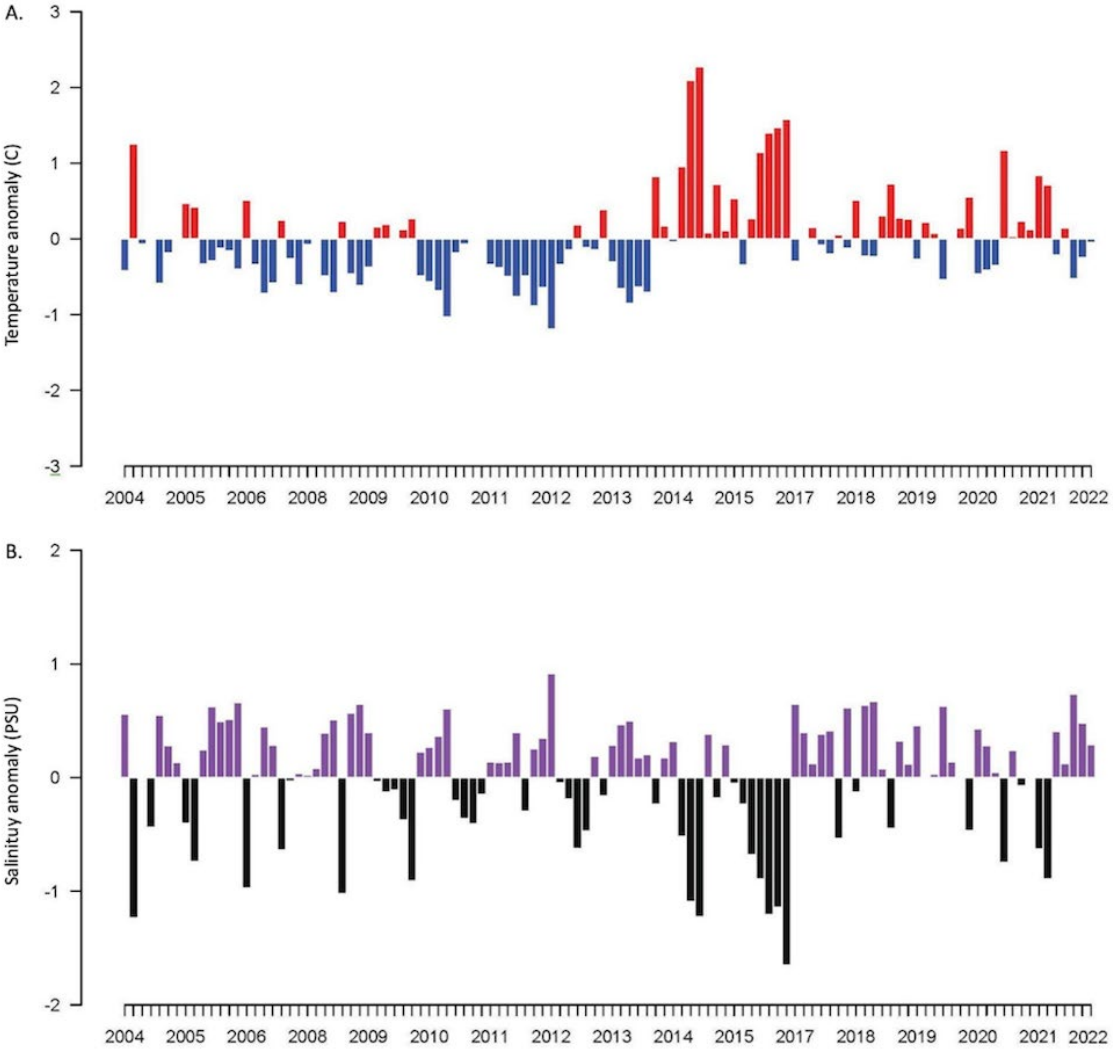


Figure 5.15. (A) Temperature anomalies taken near the bottom of the South Station during fall from 2004 to 2022. Red indicates warmer (positive) temperature anomalies and blue indicates cooler (negative) temperature anomalies. The mean and standard deviation for fall temperature from 2004–2022 was 8.83°C and 0.61°C, respectively. (B) Salinity anomalies taken near the bottom of the South Station during fall from 2004 to 2022. Purple indicates saltier (positive) salinity anomalies and black indicates fresher (negative) salinity anomalies. The mean and standard deviation for fall salinity from 2004–2022 was 32.48 and 0.52 PSU, respectively.

5. Water quality (cont.)

5.15A, last five bars) though one slightly positive (0.1) and the last cruise was zero. In general, since the 2014–2016 marine heatwave, most temperature anomalies in South deep waters have been positive except for 2020 which had several cooler than average anomalies, and 2022. These cool anomalies may reflect La Niña influence from 2020–2022.

Fall 2022 salinity anomalies were mostly average with two exceptions. Salinity in South station deep waters was saltier than average (Figure 5.15B), which accompanied cooler than average temperature anomalies and may reflect La Niña influence. The other exception was an almost 2 PSU fresher anomaly in the surface waters at North during early fall. This signal was likely influenced by exceptionally high Fraser River flow with a delayed peak flow during 2022.

Observations of marine mammals (harbor seals, Steller sea lions, harbor porpoise) and seabirds (Figure 5.16) from six weekly repeated transects over fall reveal different interannual patterns. Marine mammals show relatively low and decreasing densities since, and including, the marine heatwave of 2014. While 2021 was the lowest on record, the 2022 density was only slightly higher, primarily due to harbor seals. Seabird density exhibited a different pattern, with a steady increase since 2018. The fall 2022 seabird density was the highest since 2012, the fourth highest in the record since 2006.

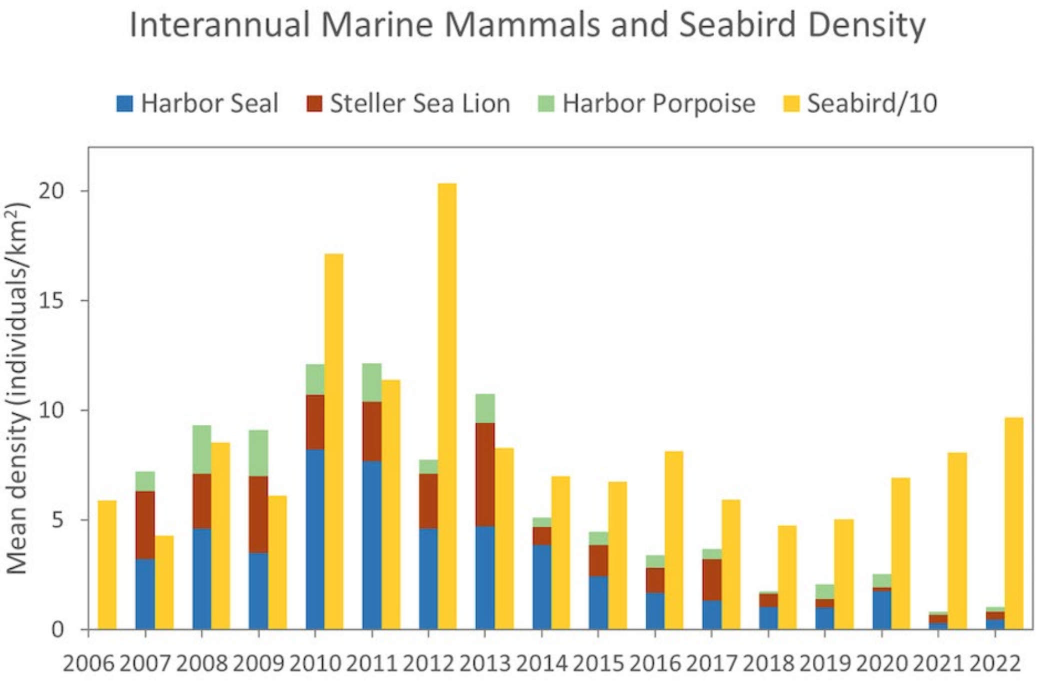
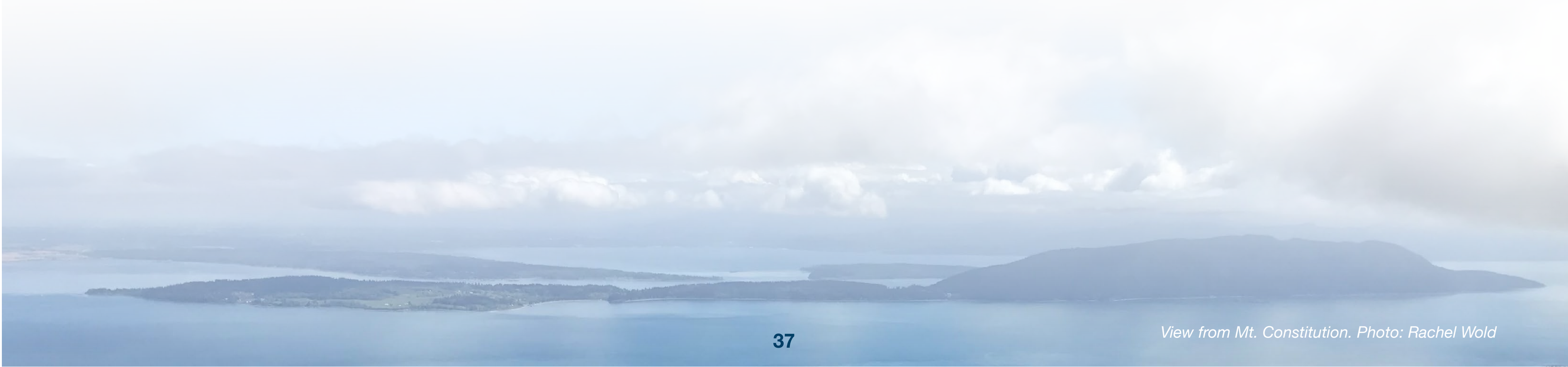
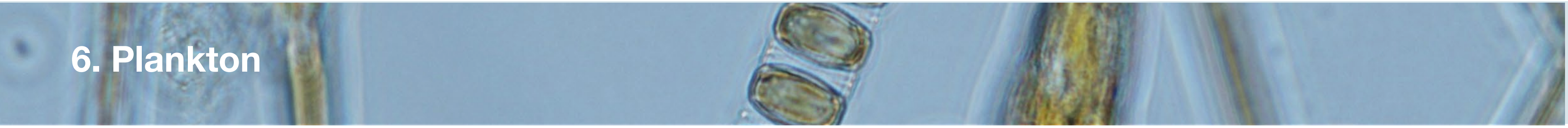


Figure 5.16. Bar graph showing mean density (individuals per square kilometer) from fall surveys conducted from 2006 to 2022 of harbor seals (blue), Steller sea lions (red), harbor porpoises (green), and seabirds (yellow). Seabird densities are scaled by 1/10.



View from Mt. Constitution. Photo: Rachel Wold



6. Plankton

A. Marine phytoplankton

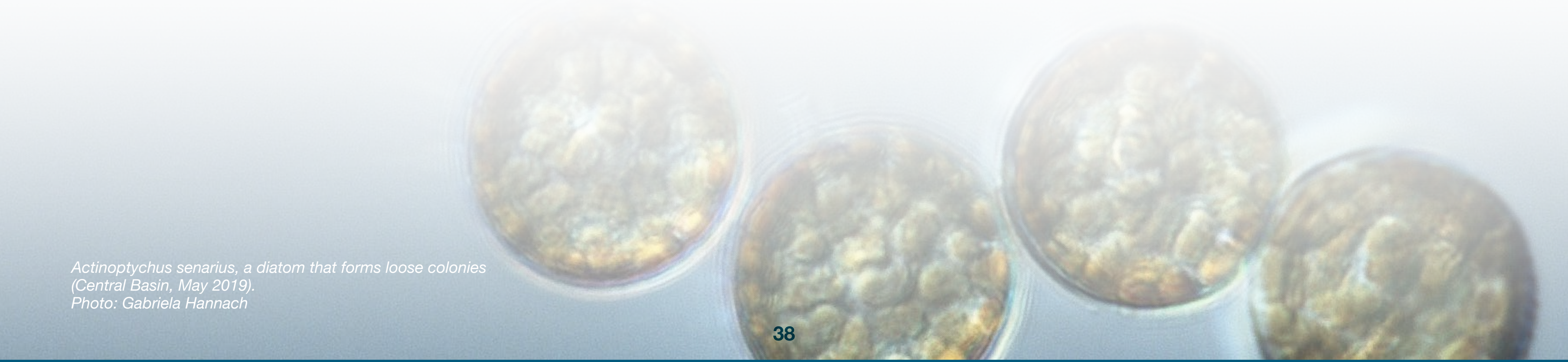
Marine phytoplankton are microscopic algae that form the base of the marine food web. They are also very sensitive indicators of ecosystem health and change. Because they respond rapidly to a range of chemical and physical conditions, phytoplankton community composition can be used as an indicator of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

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

Ten long-term monitoring stations were sampled in 2022, including nine open water sites and one shallow embayment (Dockton in outer Quartermaster Harbor). Eight years of biovolume data from surface samples indicate that in 2022 total microplankton biomass was higher than any previous year and ~40% higher than the previous 7-yr average (data not shown). A small, transient mixed diatom bloom was observed in mid-February. The spring bloom developed late, reaching its first peak in early June (Figure 6.1), presumably due to cooler than normal temperatures. Similar to 2021, the diatom *Thalassiosira* spp. did not dominate the early spring bloom as in some previous years (e.g., 2016–2019). Instead, it was initially dominated by species of the diverse diatom genus *Chaetoceros*, which was soon succeeded by a large bloom dominated by the diatoms *Stephanopyxis* and *Pseudo-nitzschia*. In mid-June, while the water column was still well stratified, this population disappeared, possibly due to nutrient depletion or the effects of heavy rains (see section 5.C.i. Temperature, salinity, and density on page 26). Additional blooms quickly followed. These were first dominated by *Chaetoceros* with an abundance of *Asterionellopsis*, and then in late summer and fall by an unusually large and persistent bloom of the large-celled diatom *Ditylum*. The 2022 blooms of *Stephanopyxis*, *Pseudo-nitzschia*, *Asterionellopsis* and *Ditylum* were larger than any blooms recorded for these taxa over the last eight years. *Stephanopyxis* and *Ditylum* populations were particularly abundant at the southernmost station, East Passage. The heterotrophic dinoflagellate *Noctiluca* was present from July to early August but never reached high numbers. The season ended late, with an unusually persistent *Ditylum* bloom lingering until early November.



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

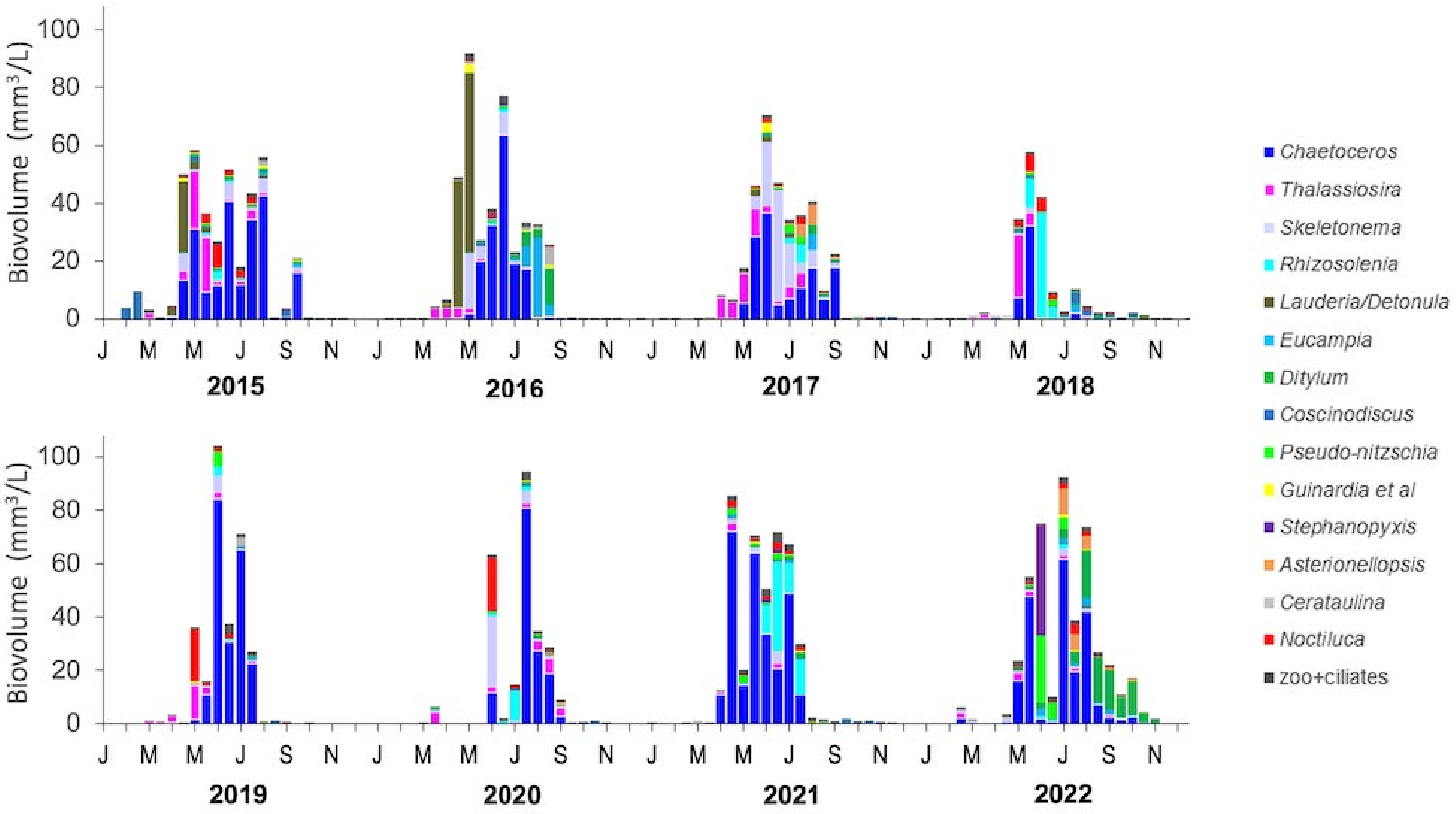


Figure 6.1. Biovolumes of top 15 taxa identified using FlowCAM between 2015 and 2022. Values are means for nine open water sites (Dockton excluded). No data collected April–May 2020 and early April 2022.

A.ii. Whidbey Basin

Phytoplankton
Zooplankton

Source: Gabriela Hannach (gabriela.hannach@kingcounty.gov), Lyndsey Swanson (KCEL), and Franchesca Perez (Stillaguamish Tribe of Indians)
Primary website: https://green2.kingcounty.gov/marine/Monitoring/Phytoplankton;
Website for online data: https://data.kingcounty.gov/Environment-Waste-Management/Marine-Phytoplankton-Samples-by-Taxonomic-Group/uydm-m3ym; https://www.stillaguamish.com/natural-resources/data-resources

In 2022, King County began analyzing phytoplankton assemblages twice a month in the Whidbey Basin. A FlowCAM® particle imaging analyzer is used to assess abundance, biovolume, and community composition of all microplankton particles in the 10–300 µm range. Five stations were sampled for surface phytoplankton, including two open water sites (Saratoga Channel near Camano Head and Port Susan at the Stillaguamish buoy in the north-central part of the bay) and three in Penn Cove, a shallow embayment. This first year of data suggests that in 2022, total microplankton biovolume in Penn Cove was comparable to Saratoga Passage, but less than half of that was measured in Port Susan, where the Stillaguamish River influence on salinity was evident throughout the season (see section 5.D.iii. Port Susan buoy on page 34). Early and persistent water column stratification throughout the basin (see section 5.D.iv. Whidbey basin on page 35) led to the start of the growth season in March, which continued well into October. The season started with a mixed bloom dominated by the chain diatoms *Skeletonema* and *Thalassiosira* (Figure 6.2). This was followed in early June by a bloom of *Pseudo-nitzschia*, which in turn was followed by a mixed diatom bloom (notably *Chaetoceros*, *Rhizosolenia* and *Pleurosigma*) and an abundance of *Noctiluca*, a large heterotrophic dinoflagellate. *Noctiluca* was present throughout the season and was most abundant in Penn Cove, where densities ranged from 400 to 2,100 cells/L between July and September (not shown). *Noctiluca* was mostly absent from Port Susan, where it is only common every several years (F. Perez personal obs.) Stillaguamish Tribe historical records for Port Susan indicate that the observed 2022 bloom pattern was generally typical, both in timing and in species succession (data not shown). Annual biovolumes in the Saratoga Channel were higher than at Central Basin open water stations (see section 6.A.i. Puget Sound phytoplankton on page 38) and the season started earlier. The main taxa observed in Whidbey Basin are also common in the Central Basin, yet there were marked differences in bloom composition and seasonal succession between these two basins.

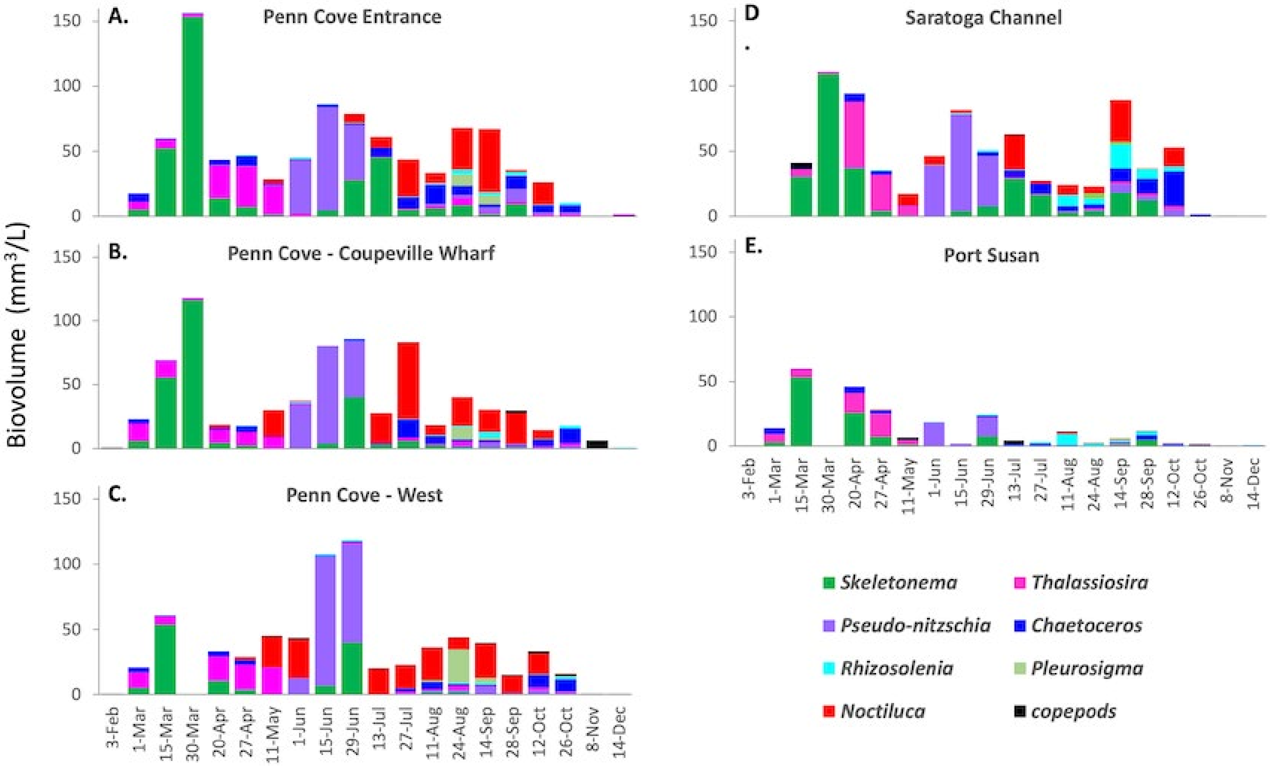


Figure 6.2 Biovolumes (mm^3/L) of top eight taxa identified using FlowCAM in 2022. No sampling occurred in late May. (A) Saratoga Channel near Camano Head (no samples Feb 3 and Mar 1). (B) Port Susan buoy (no samples Feb 3 and Mar 30). (C) Entrance to Penn Cove. (D) Coupeville Wharf. (E) Penn Cove West (no samples Mar 30).

A.iii. Padilla Bay

Phytoplankton

Source: Cameron Sokoloski (csok461@ecy.wa.gov), Sylvia Yang, Nicole Burnett, and Heath Bohlman (Padilla Bay NERR/ Ecology);Primary website: www.padillabay.gov

Padilla Bay National Estuarine Research Reserve has monitored in-situ chlorophyll since 2016 and phytoplankton community composition since 2019. In-situ chlorophyll fluorescence values are recorded every 15 minutes and phytoplankton are collected monthly using whole-water surface samples. Whole-water samples represent an instantaneous snapshot of phytoplankton abundance and community composition whereas daily in-situ chlorophyll is averaged from continuous measurements. Both chlorophyll and phytoplankton monitoring are conducted in the channel east of Guemes Island, adjacent to Padilla Bay.

Timing and persistence of chlorophyll and phytoplankton varied throughout the last seven years, but typically occurred between May and August. In 2022, the onset of the spring bloom occurred in early May, similar to 2017 and 2018, compared to more recent years (2019–2021) when the spring bloom occurred earlier (Figure 6.3A). In 2022, chlorophyll was highest in the summer months starting in July (Figure 6.3A). The trend in phytoplankton abundance and composition was similar to 2020, with peak abundance in August dominated by *Leptocylindrus* followed by *Skeletonema* (Figure 6.3B). The diatoms *Chaetoceros*, *Skeletonema*, and *Thalassiosira* continue to be three of the most common species found in Padilla Bay (Figure 6.3B). In July, *Chaetoceros* was the dominant taxon, making up 44% of the community composition. In August, when phytoplankton abundance peaked, the dominant taxa were the diatoms *Leptocylindrus* and *Skeletonema*, which totaled 90% of the community composition when combined. Similar to previous years, phytoplankton abundance declined in fall, starting in September, and pennate diatoms increased in relative abundance. Abundance of other taxa like dinoflagellates, silicoflagellates, and ciliates remained consistently low throughout the year.

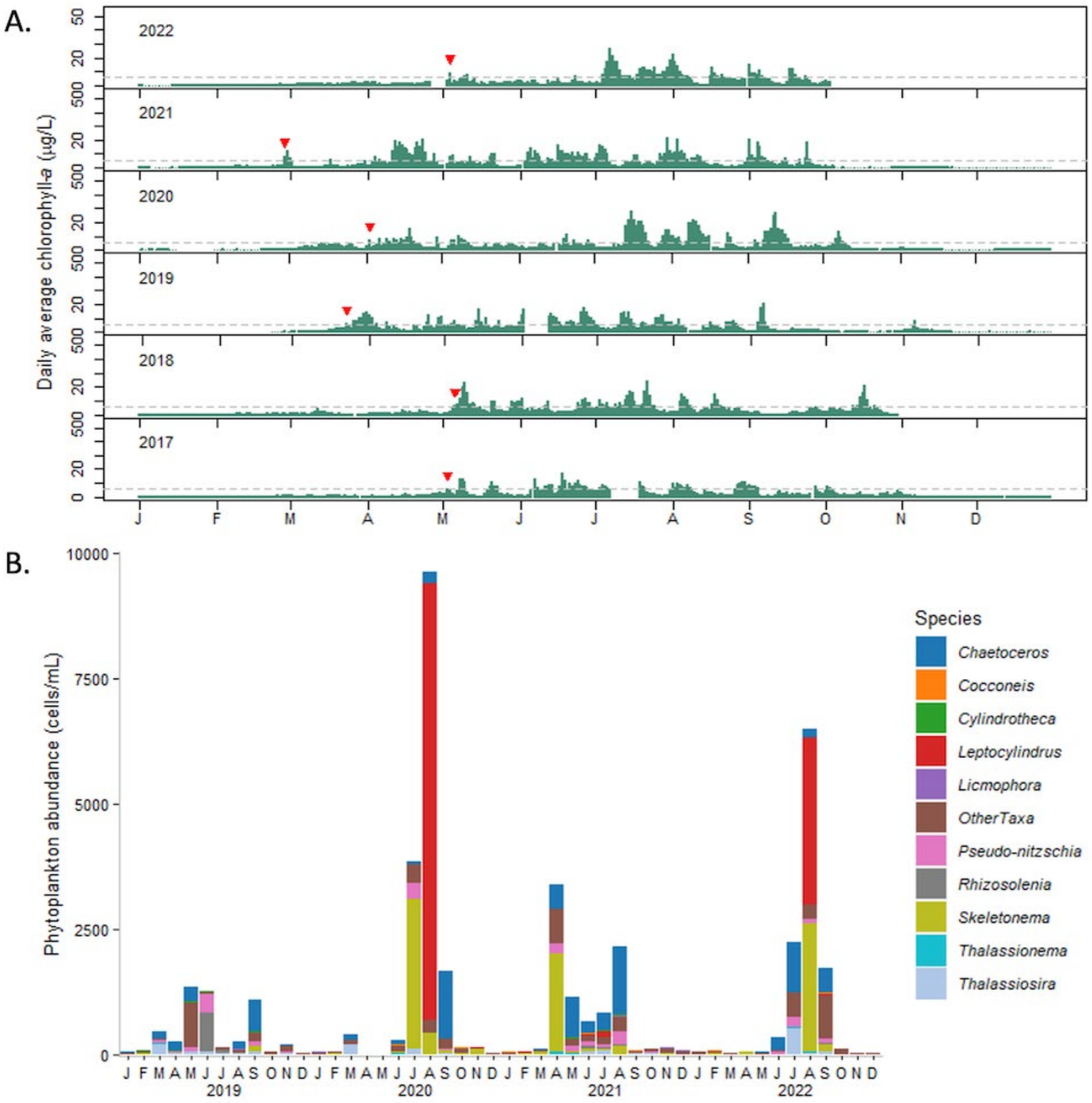


Figure 6.3. (A) Average daily in-situ chlorophyll fluorescence from 2017 through 2022 and monthly phytoplankton abundance of the 10 most abundant taxa plus all other taxa combined in 2019 through 2022. Horizontal dashed line in (A) represents the spring bloom threshold (5.6 ug/L), as calculated by multiplying daily average chlorophyll concentration from 2017–2022 by 1.5 as per Tommasi et al. 2013. Red triangles indicate the start of the spring bloom. (B) Taller bars represent greater abundance and colors correspond to different phytoplankton taxa.

CALLOUT BOX: Phytoplankton & primary production Vital Sign indicators

The Phytoplankton & Primary Production Vital Sign Indicator Project was funded by the Puget Sound Partnership to better track changes to the base of the Puget Sound marine food web. The project consisted of a core team and a science advisory team that included individuals from multiple organizations. The first phase of the project was implemented in 2022 in four stages that focused on (1) assembling an inventory of phytoplankton-related monitoring programs and data available in Puget Sound, (2) examining the process used to create other Puget Sound vital sign indicators, (3) learning from regional and international experts about characteristics of a good phytoplankton-related indicator, and (4) using this information to guide the creation of a phytoplankton-related vital sign indicator for Puget Sound. This was achieved through a series of five workshops involving more than 90 researchers and stakeholders over the course of a year from June 2022 to June 2023 (Figure 1).

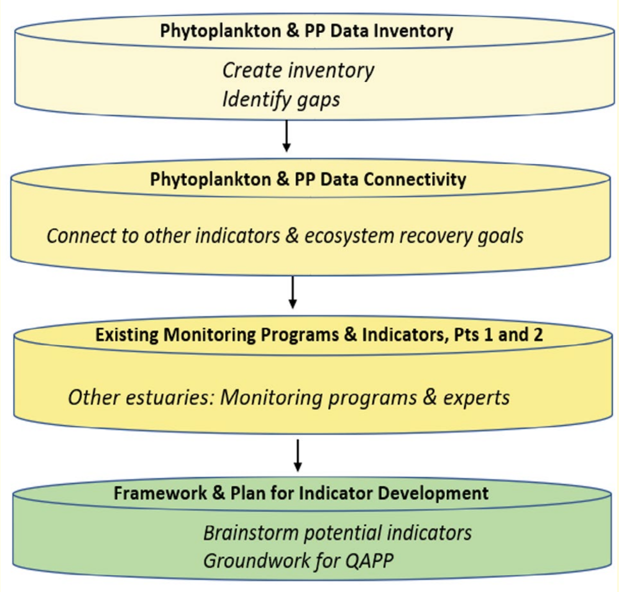


Figure 1. Schematic showing the four stages of the Phytoplankton & Primary Production Vital Sign Indicator Project.

From the first workshop and monitoring inventory survey, ~20 different monitoring programs/studies conducted by 18 different organizations were identified in Puget Sound (Figure 2). Of these, five have been in existence since the 1990s or early 2000s, and most programs are ongoing. Five of the programs monitor harmful algal blooms. Sampling mostly focuses on the size of the phytoplankton community though measures of abundance, biomass, biovolume, chlorophyll-a extractions, or in-situ chlorophyll fluorescence and/or species composition. A key take-away is that no state-wide, long-term funded, coordinated, and ongoing phytoplankton monitoring program exists to provide routine phytoplankton assessments (status and trends) although there are many regional efforts that could be leveraged to develop a broader program. During the second workshop, three fundamental metrics of phytoplankton communities that could be connected to other Puget Sound indicators, such as zooplankton were identified. These are phytoplankton community composition and abundance, chlorophyll-a, and rates of primary production.

During workshops three and four, regional and international experts provided guidance on the characteristics of a good indicator, gave examples of operational indicators, and highlighted the issues and challenges that should be considered for using each of these operational indicators. From these discussions, four potential metrics to consider for inclusion in an indicator were identified including chlorophyll-a, in-situ chlorophyll fluorescence, phytoplankton community composition, and primary production.

The final workshop focused on how the four metrics listed above could be used for a phytoplankton-based indicator and planning for the next phase of the project. Phase 2 of the project, which will begin in late 2023, will focus on compiling and analyzing the data from the Phase 1 user-generated inventory and identifying and recommending potential metrics to be included in a phytoplankton-based indicator for Puget Sound.

The results of the Phase 1 project are publicly available, as a final summary report and as individual workshop reports. These can be accessed, along with presentations, agendas and workshop recordings, at: Phase 1: Workshops and Inventory.

Authors: Cheryl Greengrove (cgreen@uw.edu, UWT), Julia Bos (King County), Jude Apple (Padilla Bay NERR/Ecology

CALLOUT Box (cont.)

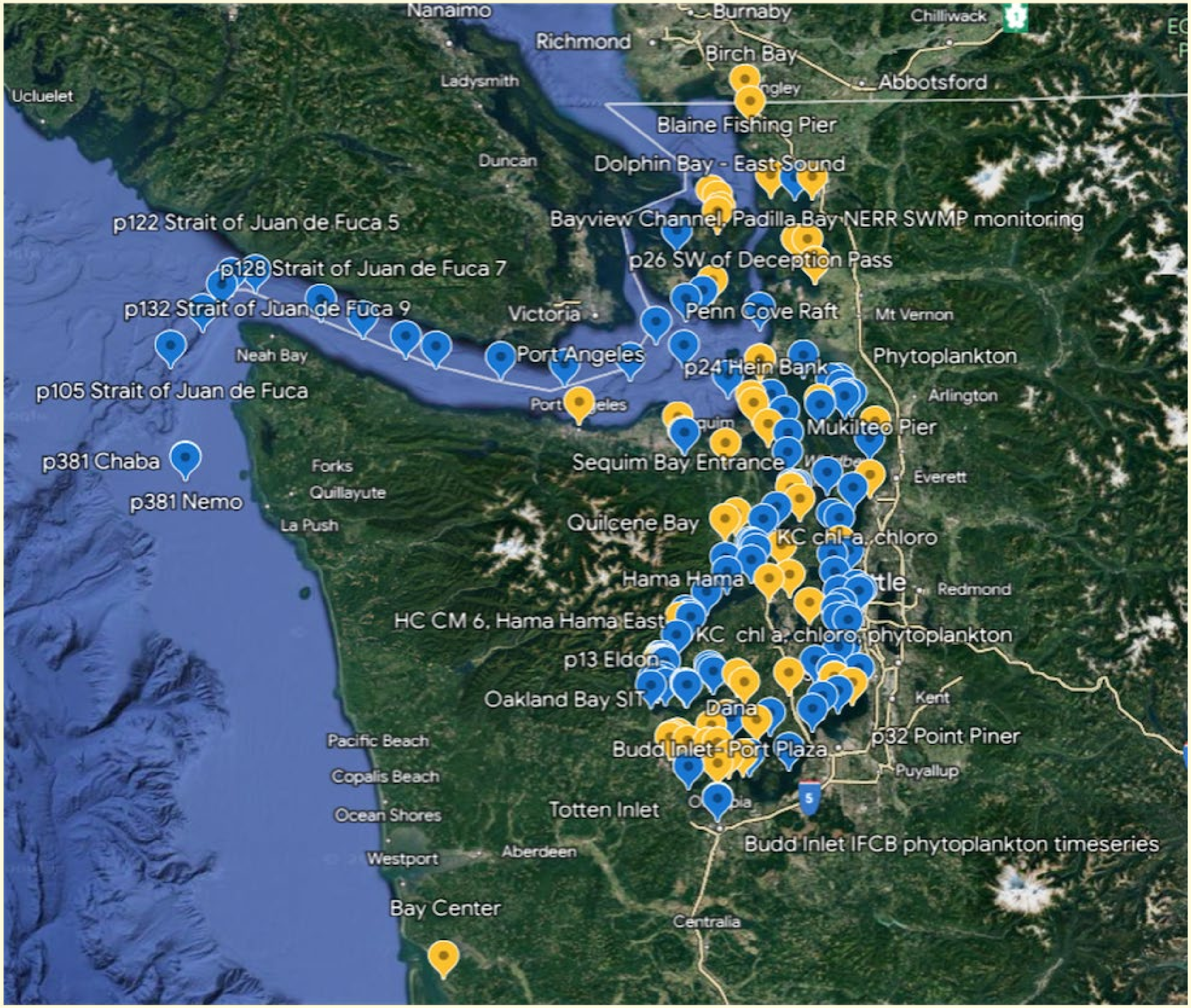


Figure 2. Map of phytoplankton data locations in Puget Sound; user-generated inventory assembled as part of the project in a geospatial platform.

CALLOUT BOX: IFBC provides an unprecedented glimpse into the base of Puget Sound's food web

The Imaging FlowCytobot (IFCB) is an imaging-in-flow cytometer that makes it technically feasible to continuously monitor phytoplankton communities in the marine environment. It collects nominal 5-ml water samples every ~20 minutes and captures high-resolution images of individual phytoplankton cells and colonies (Figure 1). When the IFCB is paired with a machine learning image classifier, this system can count and identify phytoplankton (~10–150 microns) to the genus-level and sometimes species-level from images. Regularly programmed self-cleaning cycles enable extended deployments in the field that can last up to several months. For the past several years, two teams have been using IFCB with co-located physical and chemical sensors to observe the phytoplankton community of Puget Sound in relation to environmental factors.

The first is a UW Oceanography team led by Evelyn Lessard, who deployed an IFCB on a dock at Friday Harbor Laboratories. These IFCB data are being used for a variety of purposes including monitoring harmful algal blooms and investigating the impacts of climate change on the phytoplankton community of the Salish Sea.

The second is a NOAA Northwest Fisheries Science Center team (Alexis Fischer, Stephanie Moore, and Brian Bill) who have deployed an IFCB underwater in Budd Inlet. Their objective is to use this IFCB time-series to understand the environmental factors driving harmful algal blooms of *Dinophysis* spp. that commonly occur in the area. These toxic blooms can cause diarrhetic shellfish poisoning in humans who consume contaminated shellfish. Those who are curious to see what's underwater in Budd Inlet can view this IFCB's live datastream.

Both teams are now hard at work optimizing machine learning image classifiers that will be used to successfully identify IFCB images of their local phytoplankton communities. These high temporal resolution, long-term monitoring datasets will be incredibly valuable to many other future ecological research projects.

Authors: Alexis Fischer (alexis.fischer@noaa.gov) (UCAR) and Evelyn Lessard (UW); https://habon-ifcb.whoi.edu/timeline?dataset=buddinlet

Brian Bill (left) and Alexis Fischer (right) secure IFCB to the winch line before lowering it underwater at Budd Inlet. Credit: Vera Trainer.

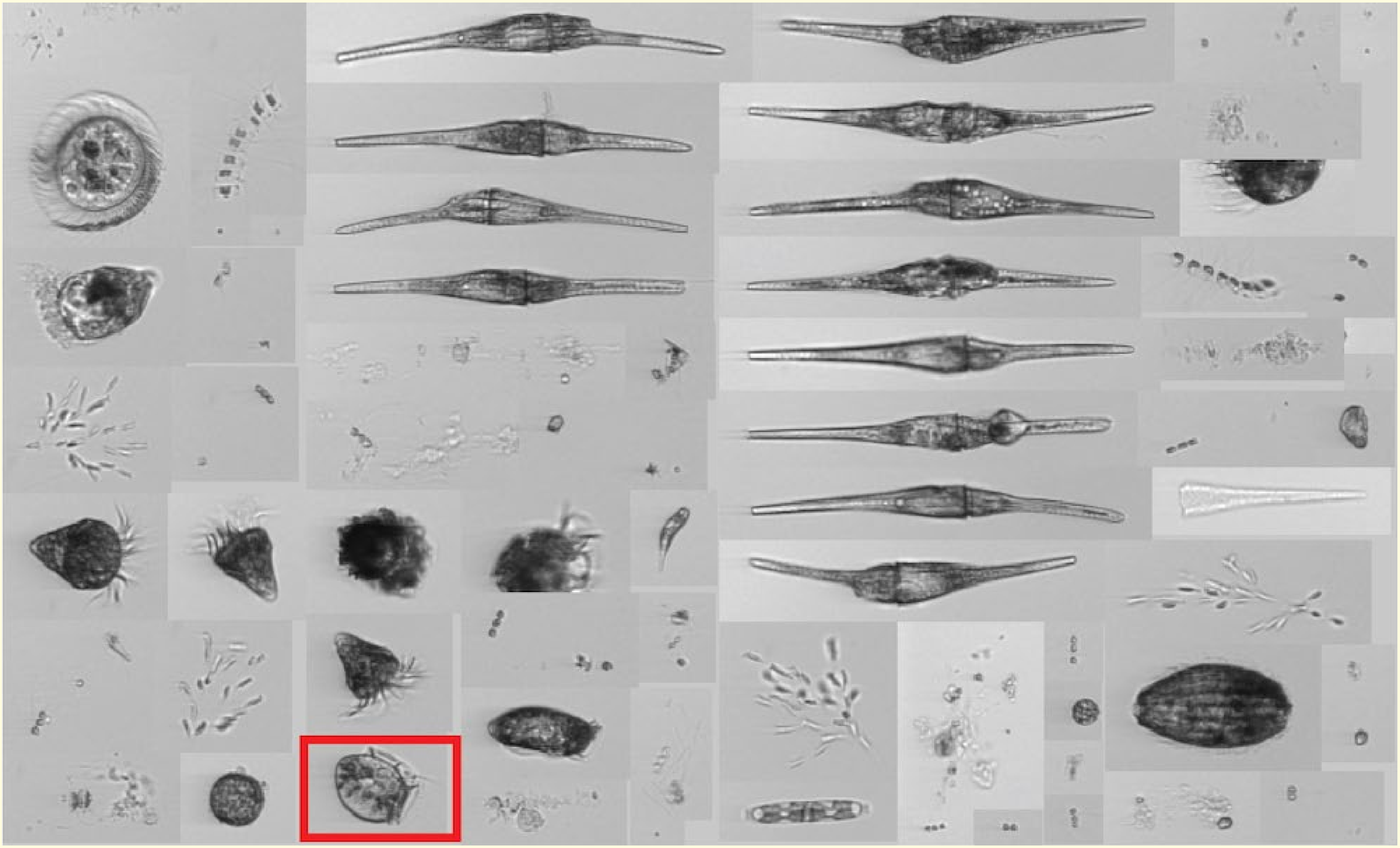


Figure 1. Example of IFCB data collected at Budd Inlet. The red box indicates a cell of the target genus: Dinophysis.

6. Plankton (cont.)

B. Zooplankton

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

B.i. Puget Sound

Zooplankton

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

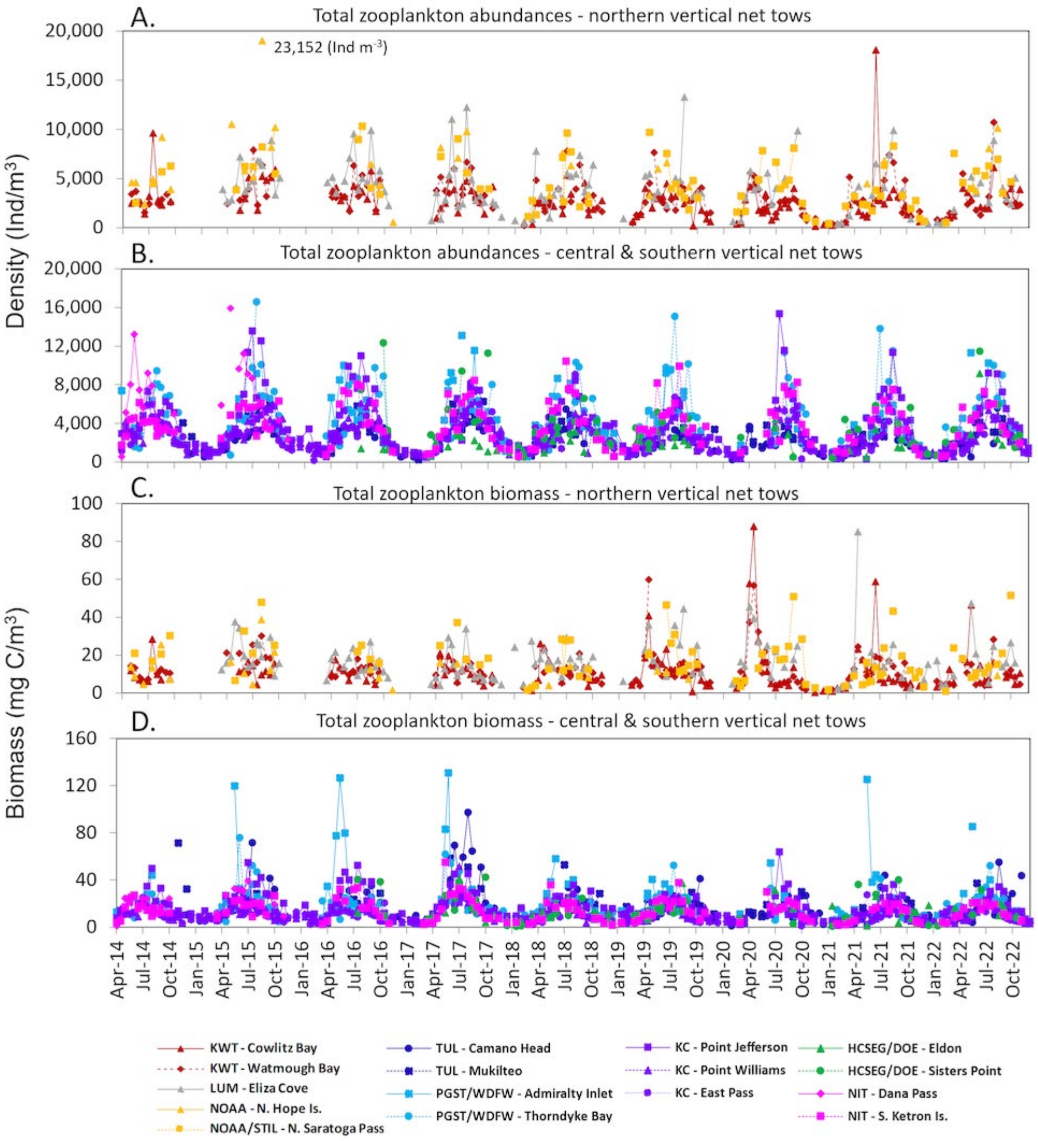
Abundances and biomass of mesozooplankton from the southern Salish Sea in 2022 were overall average to moderately low compared to past years, with later average peak biomass timing for many stations (Figure 6.4A, B, C, D). Some of the higher biomass values demonstrated continuations of patterns already observed in the time series. In the northern Washington regions of the San Juan Islands and Bellingham Bay, the springtime appearance of large oceanic copepods (*Eucalanus bungii* and *Neocalanus plumchrus*) continued to have a notable effect on biomass, a trend which has endured since 2019. *E. bungii* appeared in moderate (Bellingham Bay and Watmough Bay) or high (Cowlitz Bay) biomass in May, while *N. plumchrus* dominated in Bellingham Bay. The medium-sized copepod *Pseudocalanus spp.* also contributed moderately to biomass in Bellingham bay (Figure 6.4C), where peak total biomass was lower than in 2021.

The highest annual biomass value was observed at Admiralty Inlet in May and driven primarily by high abundance of crab larvae. Although lower in 2022, the timing and composition were similar to the record-high values seen in that region in the warm years of 2015–2017 and in 2021 (Figure 6.4D).

Zooplankton sampling was conducted by King County, Nisqually Indian Tribe, Tulalip Tribes, Kwiáht, Lummi Nation (since 2015), Port Gamble S'Klallam Tribe, WA Dept. of Fish and Wildlife (WDFW), NOAA, Hood Canal Salmon Enhancement Group with WA Dept. of Ecology (since late 2016), and Stillaguamish Tribe (since late 2019) (Figure 6.4E).

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

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



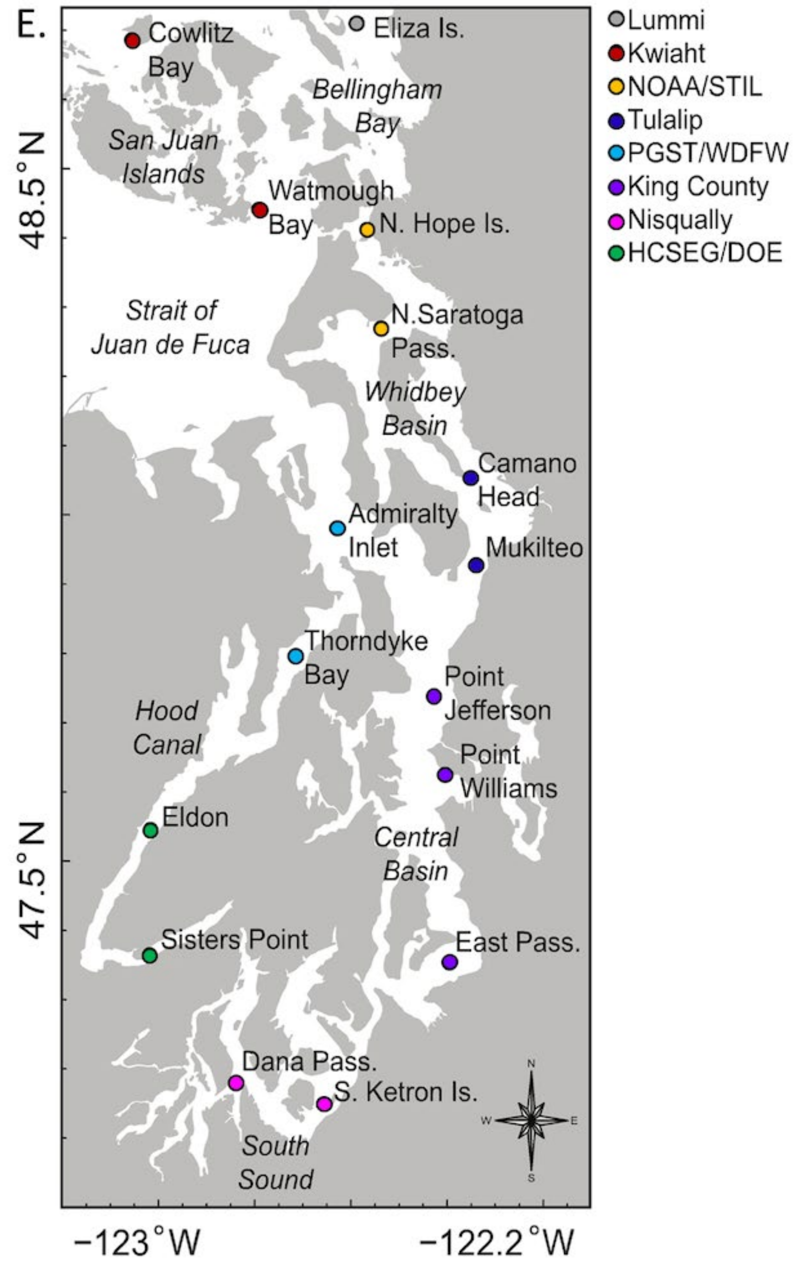


Figure 6.4. Time series of total mesozooplankton abundance (Ind/m^3) at northern stations (A) and central & southern stations (B) in 2014-2022. Time series of total mesozooplankton biomass (mg C/m^3) at northern stations (C) and central & southern stations (D) in 2014-2022. (E) Map of the sampling locations. Symbols are color-coded by sampling group and correspond to stations in panels A–D. Note that most stations suspended sampling from mid-March to mid-June 2020 due to COVID-19.

6. Plankton (cont.)

B.ii. Padilla Bay

Zooplankton *Source: Nicole Burnett (nbur461@ecy.wa.gov), Colleen Ebright, 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 collection of 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 6.5A). Zooplankton community composition and abundance in Padilla Bay exhibit within-season variation but have distinct seasonal compositions that persist annually despite environmental changes (Figure 6.5B). The total zooplankton abundance April 2022 was less than the average abundance for April from 2008–2021, but the abundance in May was higher than the average abundance for May indicating that the timing of the spring peak which normally occurs in April was delayed to May.

The summer peak showed the typical timing, occurring in August, but had higher abundance than the average summer peak. August 2022 had the most zooplankton of any month or year except July 2014, which occurred during the marine heat wave. The daily average water temperatures mid-July through August 2022 were similar to those for the same period in 2015 and 2016 (see section 5.D.ii. Padilla Bay water column on page 33, Figure 5.12 on page 33). The increase of total zooplankton abundance in August was due to increased abundances of copepods, larvaceans (*Appendicularia*, *Oikopleura* spp.), and cladocerans (data not shown). However, the observed shifts in spring and summer total abundance peaks did not result in shifts to the overall community composition. January was the only month in 2022 that had a shift in community composition and was due to less zooplankton overall (January 2022 had the least zooplankton since sampling began) as well as less abundance in each of the identified groups. In general, 2022 exhibited typical monthly patterns except the timing of the spring peak and magnitude of the summer peak.

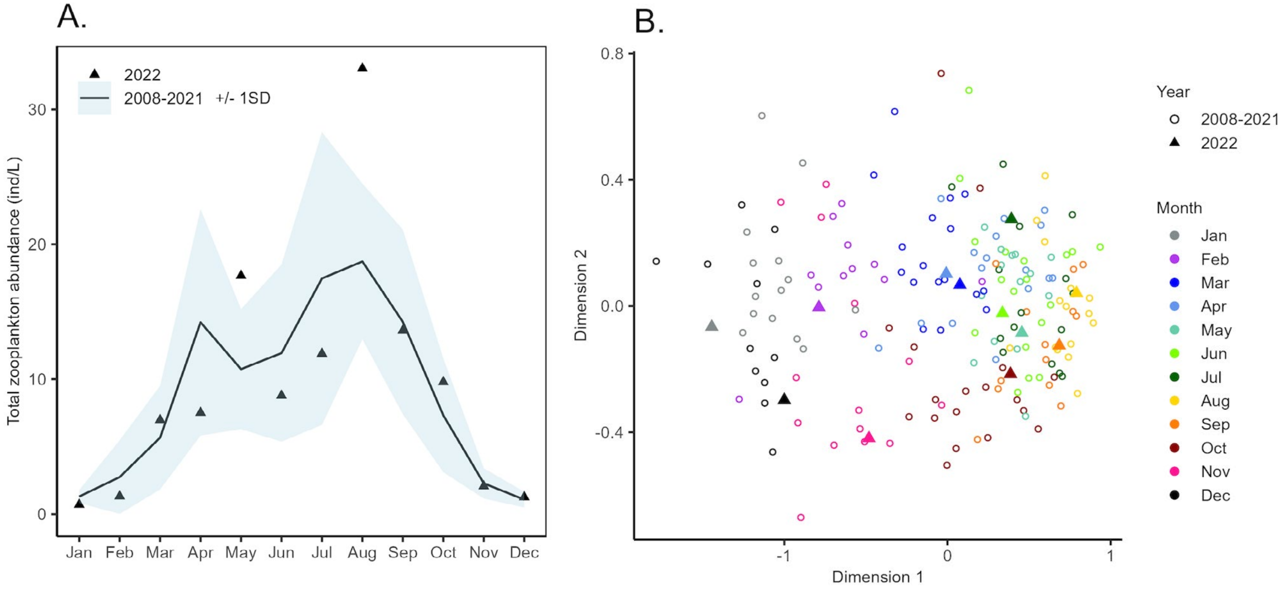


Figure 6.5. Mean monthly total zooplankton abundances (A) and non-parametric multidimensional scaling ordination (NMDS) of zooplankton community composition (B) at Gong Station, 2008-2022. The black line in (A) is the monthly mean of total zooplankton from 2008–2021 and the gray band is +/- 1 SD. Each point (open circle or diamond) in the NMDS is the mean of replicates for a sample month in a given year. Erratum: The units for zooplankton abundance for the annual review years of 2019-2021 were incorrectly labeled as ind/ L, instead the correct label for those years is ind/ m³.

6. Plankton (cont.)

B.iii. Larval Dungeness crab

Zooplankton

Source: Ally Galiotto (pnwcrab@gmail.com) (Puget Sound Restoration Fund), Allison Brownlee (WA DNR), Emily Buckner (Puget Sound Restoration Fund), Claire Cook, Sarah Grossman (Swinomish Indian Tribal Community), Heather Earle (Hakai Institute), Margaret Homerding (Nisqually Indian Tribe); www.pnwcrab.com

In 2019, the Pacific Northwest Crab Research Group (PCRG) initiated a continuous late-stage larval (megalopae) Dungeness crab monitoring network to explore the factors that influence local larval dynamics and the strength of subsequent recruitment. In 2022, PCRG and Hakai Institute partners deployed light traps from April to September at 39 sites spanning Washington and British Columbia.

The first megalopae were captured in northern Whidbey basin and southern Hood Canal in late-April. First observations occurred progressively later at sites with increasing distance from the Strait of Juan de Fuca. A notable exception being south Puget Sound which, along with southern Hood Canal, may exhibit unique larval delivery patterns due to relatively warmer surface water temperatures in early spring. By June, Dungeness crab megalopae were present at all sites. For a majority of the Salish Sea, peak abundance occurred in July—one month later than the previous three years of monitoring (Figure 6.6). Overall cooler than average spring temperatures may have delayed larval phenology. Dungeness crab megalopae delivery was highest in the central Salish Sea region with the largest single pulse event of 14,208 larvae and the largest seasonal total of 112,305 megalopae. In contrast, larval abundance in the far north and south were orders of magnitude lower, with seasonal totals as low as 11. Interannual trends consistently show the highest overall abundance in San Juan, Whidbey, and Admiralty basins, with diminishing numbers to the north and south. Recent fishery closures coupled with the low larval counts from these regions are concerning, as Dungeness crab serve vital ecological, cultural, and economic roles in the Salish Sea.

Gaining a more detailed understanding of the oceanographic drivers that influence larval delivery and recruitment limitations in these regions is a priority of PCRG and could have significant consequences for fisheries management and human livelihoods.

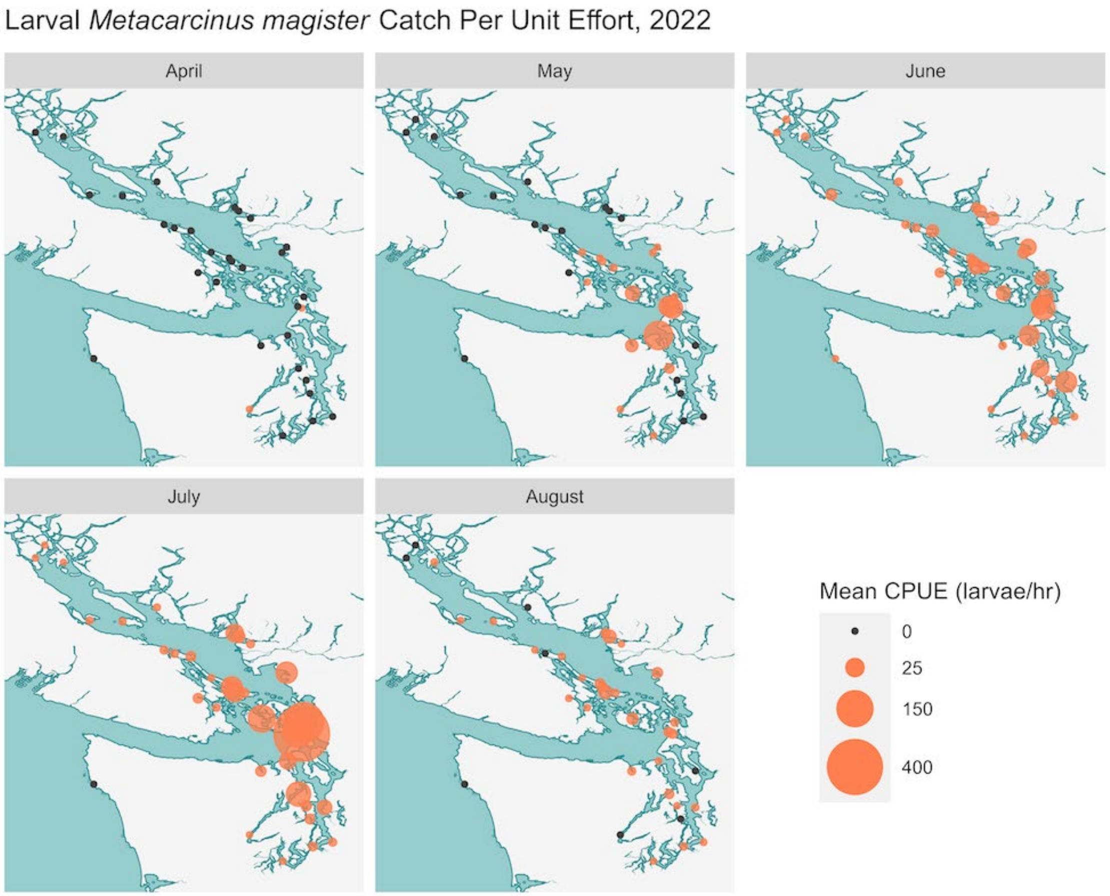


Figure 6.6. Monthly mean larval Dungeness crab catch per unit effort (CPUE) observed from April to August of 2022. CPUE was calculated as catch per hour for each trapping period (typically every two nights) for each light trap location. Monthly means are represented as orange circles on the map. Dark gray circles represent sites where traps were active and no Dungeness crab were collected.

CALLOUT BOX: Zooplankton Vital Sign indicators

The newly developed Puget Sound Zooplankton Vital Sign Indicators provide status and trends for the Thriving Species and Food Web component of the Puget Sound Ecosystem Recovery Goals. The indicators fill long-standing data gaps for fishery managers and ecosystem modelers that will enable them to monitor changes in the southern Salish Sea at this critical level of the marine food web and assess changes in the availability of prey for fish and other organisms. The indicators are calculated from the Puget Sound Zooplankton Monitoring Program's ongoing dataset, initiated in 2014. Biomass data collected bi-weekly from 15 stations are grouped into two distinct hydrodynamic regions to calculate the indicators: Northern Washington and Puget Sound.

Three indicators are calculated: (1) an annual average zooplankton biomass, (2) a seasonal average zooplankton biomass, and (3) a zooplankton index. For each indicator, zooplankton taxonomic groups that are highly sensitive to environmental changes (e.g., temperature, circulation, and nutrient availability) are shown on the Vital Signs *website* in addition to the total biomass shown in the figures below. Included in the zooplankton index are total zooplankton biomass, two size classes of crustacean zooplankton (copepods, amphipods, shrimp, crab larvae, krill, etc.), gelatinous zooplankton (jellyfish and ctenophores), and crab larvae.

The annual average zooplankton biomass indicator captures broad variability in zooplankton biomass among years related to environmental changes (e.g., heatwaves). This indicator showed that total zooplankton biomass was higher in Puget Sound than in Northern Washington during warmer years (2014–2017), yet similar or lower in cool years (2018–2022) (Figure 1).

*Sea nettle ellyfish (*Chrysaora fuscescens*). Photo: Kim Stark*

The seasonal average zooplankton biomass indicator shows changes across years within each season and helps to understand linkages to other organisms/processes, such as whether changes in seasonal peak timing of zooplankton relates to changes in abundance of forage fish or juvenile salmon. This indicator showed that biomass in Puget Sound regions typically peaks in summer, whereas Northern Washington peaks in spring (Figure 2), especially for crabs (see online figures). Gelatinous zooplankton biomass peaked in summer in Puget Sound and was anomalously high in 2014 compared to other years, with the second highest year in 2015, during the Pacific marine heatwave that entered Puget Sound (see online figures).

The zooplankton index indicator highlights increases and decreases in biomass relative to the overall average. This indicator showed that total zooplankton biomass in Northern Washington was well above average in 2015 and 2019, and moderately below average in 2017 and 2021 (Figure 3). It was also very high in the Puget Sound region in 2015, but remained above average through 2017, and moderately high in 2019. Conversely, 2020 and 2021 were low biomass years in Puget Sound with 2018 and 2022 being unremarkable.

Target levels are not defined for any of these indicators because, while high biomass of any group would indicate high prey availability for their predators, decreased biomass could have resulted from sustained predation prior to sampling and does not necessarily indicate that the system is in an unhealthier state. Long-term patterns may provide insight into the unique, complex ecosystems of the Salish Sea as more data are collected. These data will enable ecosystem modelers to assess predator-prey relationships and model energy flow using realistic zooplankton biomass levels. This is the first time zooplankton have been monitored in the Southern Salish Sea at this resolution and scale, providing new opportunities for comparisons with other trophic levels and climate variables.

Author: BethElLee Herrmann (blh1975@uw.edu), Amanda Winans (UW, School of Oceanography), and Julie Keister (UW, School of Oceanography; NOAA, Alaska Fisheries Science Center); https://vitalsigns.pugetsoundinfo.wa.gov/VitalSign/Detail/35

CALLOUT BOX (Cont.)

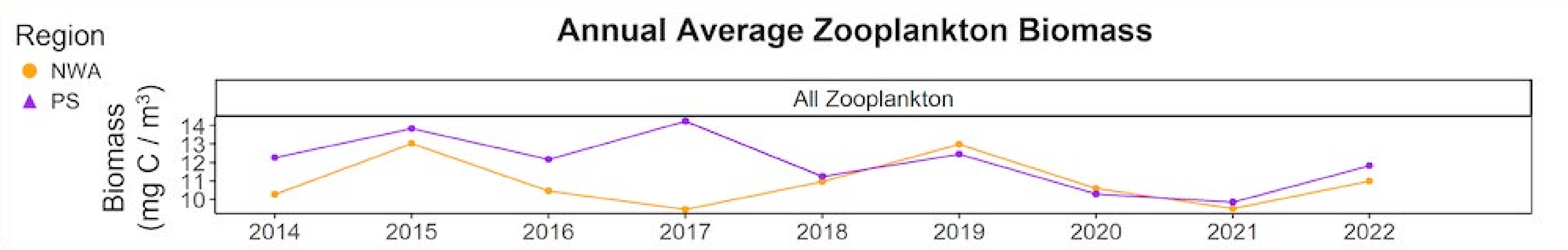


Figure 1. Annual average zooplankton biomass (mg C/m³) integrated annually from 2014–2022 across multiple locations for all zooplankton at two regions, Northern Washington (NWA – yellow line) and Puget Sound (PS – purple line).

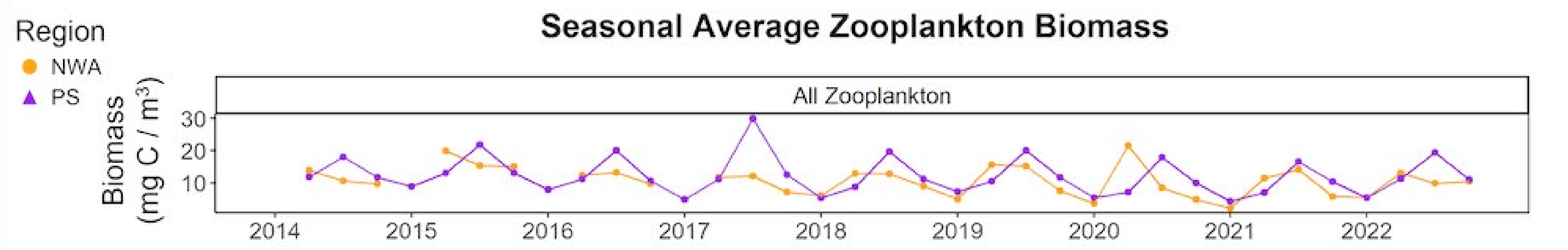
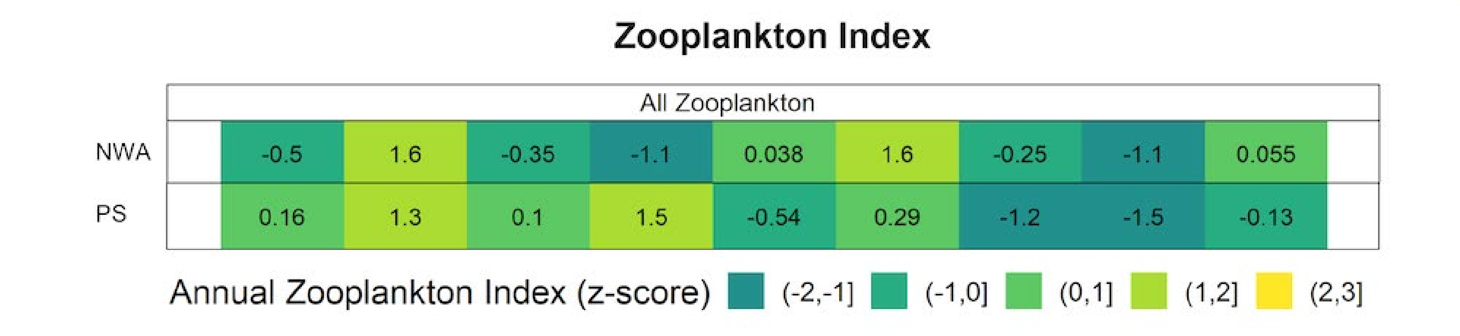


Figure 2. Seasonal average zooplankton biomass (mg C/m³) integrated seasonally from 2014–2022 across multiple locations for all zooplankton at two regions, Northern Washington (NWA – yellow line) and Puget Sound (PS – purple line). The x-axis is aggregated continuously for seasons from winter through fall for each year. Seasons represent months chronologically aggregated for winter (Dec–Feb), spring (Mar–May), summer (Jun–Aug), and fall (Sep–Nov). Note that winter was not sampled for NWA in 2014–2017.



Zooplankton Index

All Zooplankton

NWA	-0.5	1.6	-0.35	-1.1	0.038	1.6	-0.25	-1.1	0.055
PS	0.16	1.3	0.1	1.5	-0.54	0.29	-1.2	-1.5	-0.13

Annual Zooplankton Index (z-score) ■ (-2,-1] ■ (-1,0] ■ (0,1] ■ (1,2] ■ (2,3]

Figure 3. Zooplankton Index reports as z-scores from 2014–2022 for all zooplankton at two regions, Northern Washington (NWA) and Puget Sound (PS). Colors indicate whether the annual average biomass is 1–3 standard deviations (SD) above (positive) or below (negative) the mean. Values are relative within the calculated means of each region and taxon.

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.

Year-old juvenile Pacific oyster, Crassostrea gigas, *in a newly constructed "living breakwater" protecting eroding salt marshes in Fisherman Bay, Lopez Island. Photo: Ken Kortge for Kwiaht*

C.i. Biotoxins

Local foods Shellfish

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

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

In 2022, the Washington State Department of Health, Public Health Laboratory (PHL) analyzed 2,846 shellfish samples for PSP toxins. PSP toxin events occurred in North and Central Puget Sound, Hood Canal, Strait of Juan de Fuca, and Pacific Coast (Figure 6.7A). Blue mussels from East Sound, San Juan County contained the highest PSP toxin levels in 2022 with 1,715 µg/100g tissue on July 27. In 2022, PSP toxins caused 13 commercial (5 geoduck clam, 8 general growing area) and 18 recreational shellfish closures. In June, a PSP illness was confirmed due to the consumption of butter clams harvested from a closed area in Island County. PSP in butter clams exceeded the regulatory action level of 80 ug/100g shellfish tissue in the Whidbey Basin due to a 2021 PSP event, but no new PSP events were detected in 2022. Butter and varnish clams are known to retain PSP toxins for long periods of time.

The PHL tested 2,260 samples for DSP toxins. DSP toxins reached the regulatory action level of 16 µg/100g of shellfish tissue in North, Central and South Puget Sound, Hood Canal, Strait of Juan de Fuca, and Pacific Coast (Figure 6.7B). The highest DSP level measured of 98 µg/100g shellfish tissue was detected in the July 27 blue mussel sample from East Sound which had the highest PSP level of 2022. DSP toxins caused 5 commercial (2 geoduck clam and 3 general growing area) and 9 recreational shellfish closures.

ASP toxins did not exceed the regulatory action level of 20 ppm in Puget Sound in 2022 but reached 14 ppm in blue mussels from the Whidbey Basin. Fall and winter coastal razor clam harvests were interrupted with ASP toxin levels reaching 37 ppm in razor clams from the Long Beach Peninsula on December 20. A total of 2,166 shellfish samples were tested for ASP toxin (Figure 6.7C).

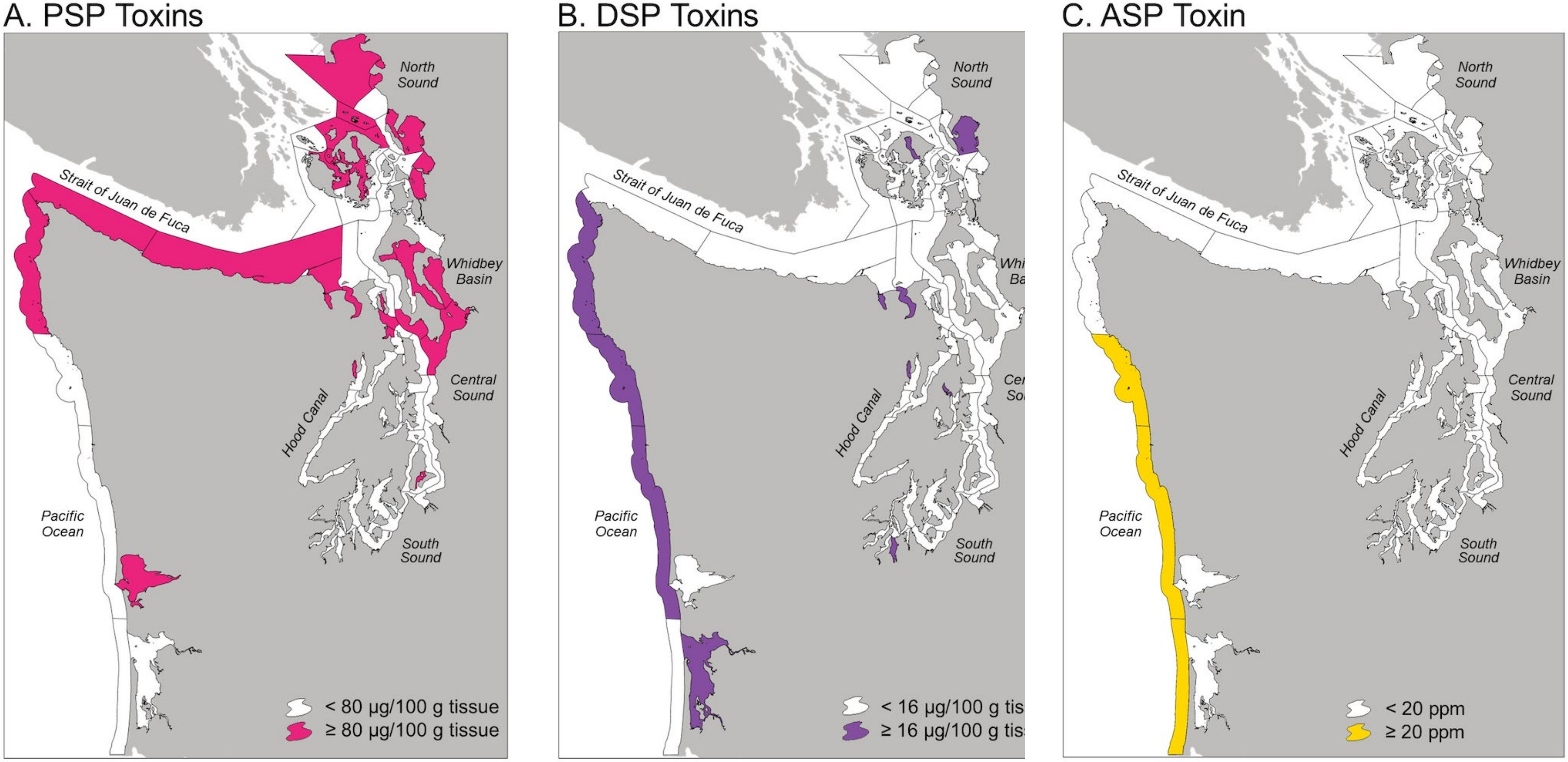


Figure 6.7. Distribution of Washington marine waterbodies where biotoxins in shellfish tissues were above regulatory action levels. (A) PSP toxins. (B) DSP toxins. (C) ASP toxin. Shellfish may not be collected from every waterbody and waterbodies may be closed for shellfish harvesting based on nearby biotoxin results.

C.ii. SoundToxins

Phytoplankton

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

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

In addition to phytoplankton abundance and distribution, and documenting environmental conditions throughout Puget Sound, SoundToxins data are used to provide early warning about algal blooms of concern to humans and animal health. These data allow the Washington State Department of Health (WDOH) to prioritize shellfish toxin tissue analyses, and alert aquaculturists and natural resource managers to current conditions. In 2022, fewer phytoplankton blooms were reported than in 2021. The most frequently observed blooms were diatoms in the genera *Chaetoceros*, *Pseudo-nitzschia*, and *Rhizosolenia*, with most of these blooms occurring between April and June (Figure 6.8). Though the number of *Chaetoceros* and *Rhizosolenia* blooms observed decreased from the previous year, the number of *Pseudo-nitzschia* (a species of human health concern) blooms approximately doubled. The diatom *Ditylum*, was the fourth most frequently observed bloom, and most common October to December. The first blooms observed of the season started in February and included the diatoms *Thalassiosira* and some *Chaetoceros* species. *Alexandrium* and *Dinophysis*, two dinoflagellates of human health concern, were observed less frequently and at lower abundances than the previous year. The only *Dinophysis* bloom reported was in June, while the only *Alexandrium* bloom reported was in September. SoundToxins partners enabled recording of diverse phytoplankton observations and environmental conditions across Puget Sound during 2022. Results from this program support the decision-making needs of resource managers, farming communities, and other partners.

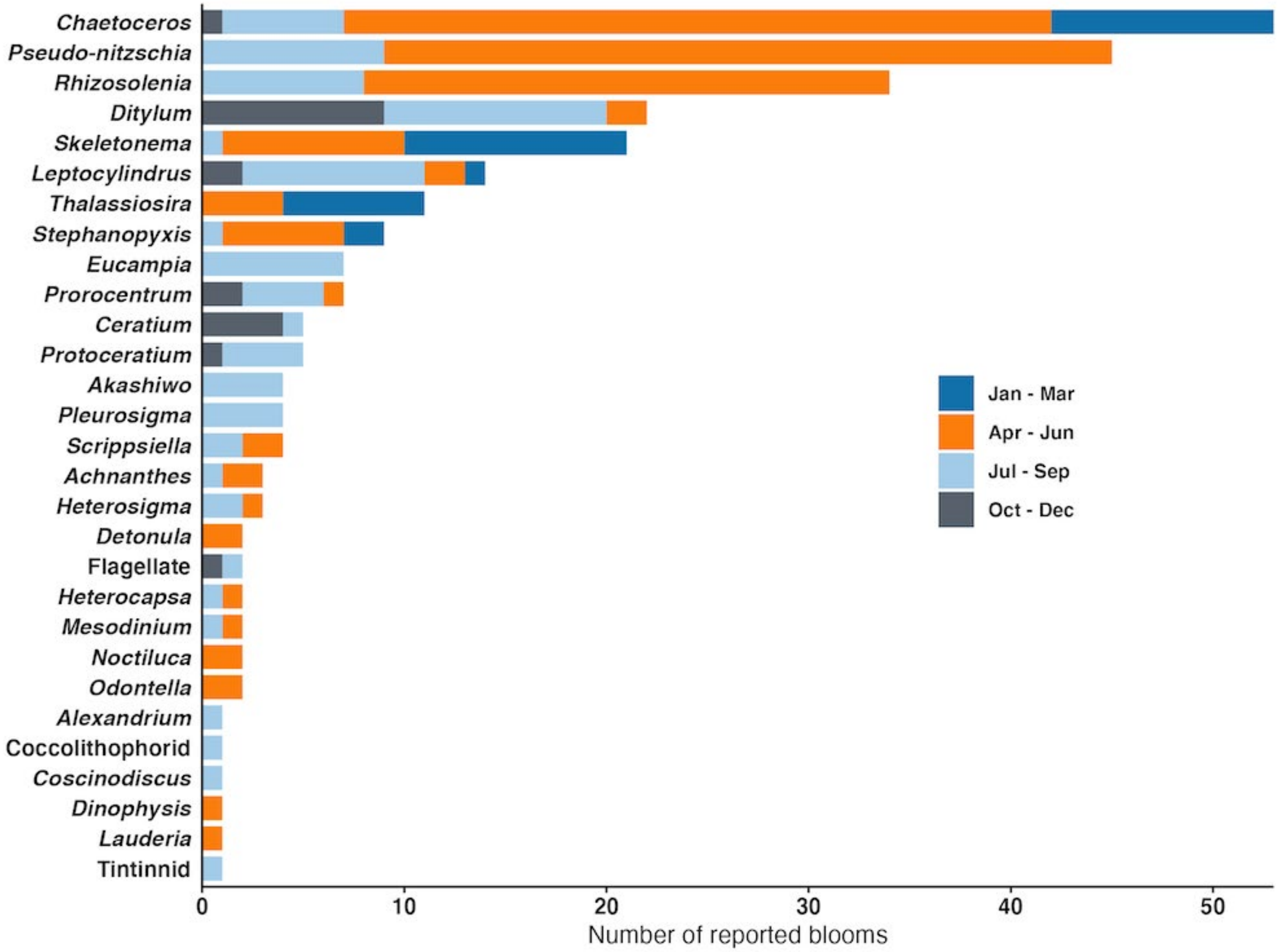


Figure 6.8. Total reported phytoplankton blooms in Puget Sound in 2022.

C.iii. *Alexandrium* species cyst mapping

Shellfish

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

Source: Julie Masura (jmasura@uw.edu) and Cheryl Greengrove (UWT); Steve Kibler (NOAA Beaufort Laboratory), Julie Matweyou and Courtney Hart (University of Alaska Fairbanks); https://www.tacoma.uw.edu

Alexandrium catenella is a dinoflagellate known to produce saxitoxin, which is potentially harmful to mammals that consume shellfish that bioaccumulate the toxin through filter feeding. *Alexandrium* exists in two phases, as a vegetative swimming cell and as 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, which is the optimal time to sample to determine potential cyst beds that could produce algal blooms after excysting during warmer times of the year. Predicting potential locations for *Alexandrium* blooms is useful to commercial and recreational shellfish harvesters. Researchers at the University of Washington Tacoma have been mapping *Alexandrium* cysts and reporting to stakeholders since the early 2000's. A NOAA NCCOS 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. Surface sediment samples were collected in the field, prepared for analysis, and manually counted for cysts using an epifluorescence microscope. New methods using qPCR molecular analytical procedures were developed with the goal of potentially lessening the labor for cyst identification and counting. Field work included collecting samples annually (2020–2022) from the Gulf of Maine, Gulf of Alaska, and Puget Sound. No Puget Sound samples were collected in 2021 or in South Sound in 2022 due to restrictions associated with the COVID pandemic. In 2022, a total of 29 samples were collected in Puget Sound. The findings from the 2022 survey microscope enumeration are highlighted below. 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).

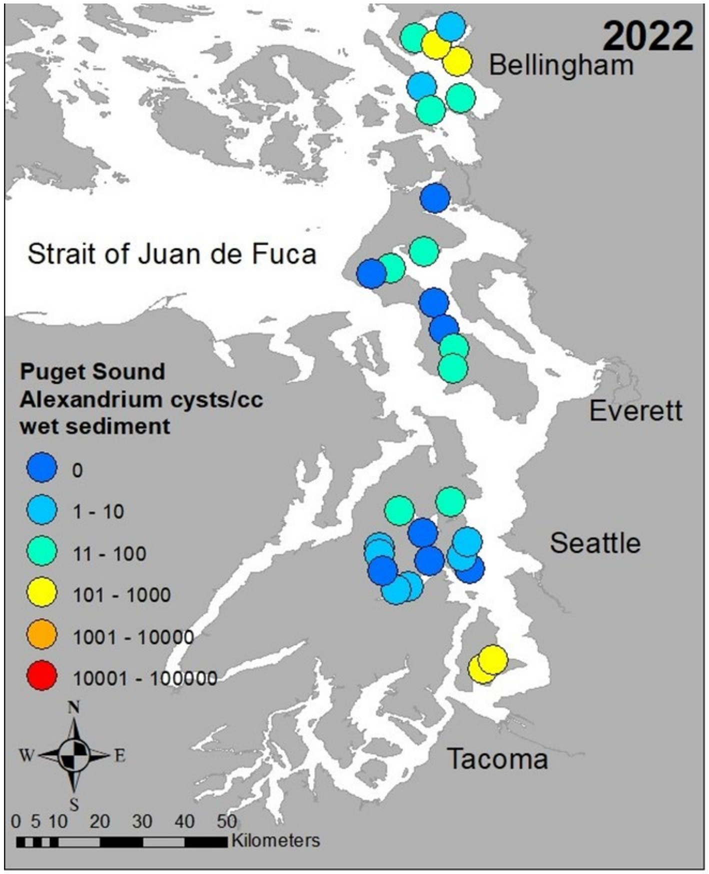


Figure 6.9. Distribution and concentration of Alexandrium catenella *cysts in Puget Sound surface sediment samples collected in winter 2022.*

7. Bacteria and pathogens

A. Fecal indicator bacteria

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

A.i. Puget Sound recreational beaches

Beaches

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

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

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

In 2022, 60 Washington beaches were sampled including 39 core beaches (sampled yearly). Beginning in 2022, only core beaches were used to calculate the percentage of passing beaches due to their long-term monitoring results which also reflects improvements made at beaches by BEACH partners. During the 2022 monitoring season, 90% of the routinely sampled (i.e. core) beaches were considered passing, meaning no more than one exceedance of the swimming standard occurred during the sampling season (Figure 7.1). This is a 12% increase in passing beaches from 2021, however, all monitored beaches were used in the calculations in 2021. The Puget Sound Partnership uses BEACH data for their Vital Sign indicator and has set a target that at least 95% of monitored core beaches meet human health standards by 2026. Details on 2022 beach sampling results can be found at: https://ecology.wa.gov/Research-Data/Monitoring-assessment/BEACH-annual-report.

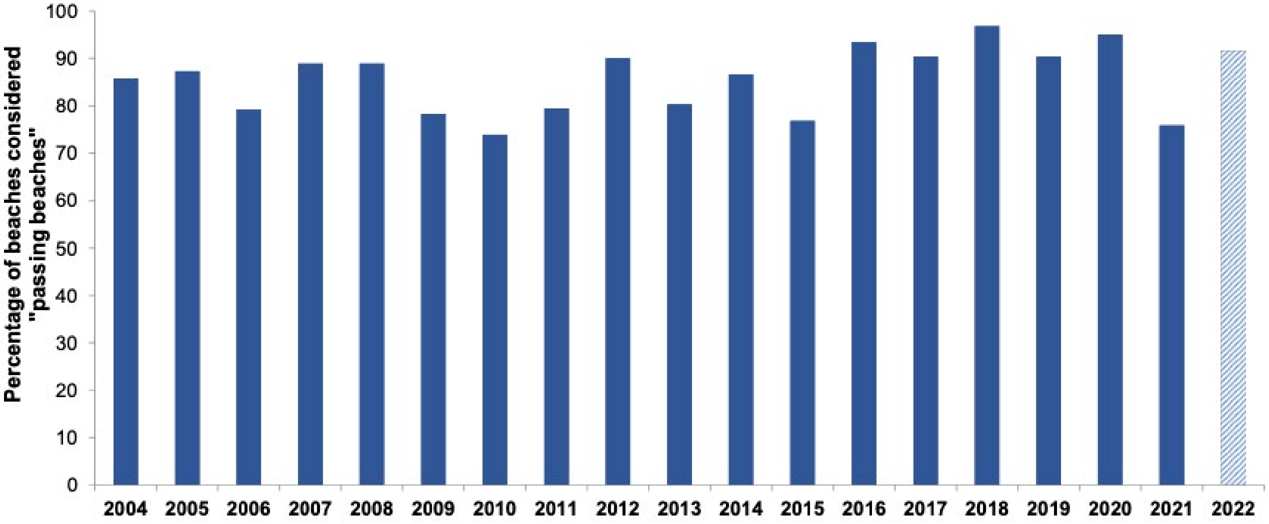


Figure 7.1.The percentage of Puget Sound core beaches that have no more than one exceedance event of the swimming standard during the summer (considered "passing beaches"). Core beaches are a subset of all monitored beaches that are sampled every year. The method for calculating an exceedance of the swimming standard changed in 2022 and therefore these results are differentiated on the chart from earlier years. Beginning in 2022, an exceedance is now recorded over a 7-day period and is called an exceedance event rather than counting each individual closure or advisory. Results from only core beaches are used in the percentage calculations.

A.ii. Central Basin stations

Beaches *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 monitored fecal indicator bacteria monthly at 20 beach stations in Puget Sound's Central Basin in 2022. Bacteria were also monitored at 14 offshore locations, a mix of ambient and outfall stations, with samples collected from the 1 m depth twice-monthly most of the year (monthly in January and December). These data are used to determine if sites have chronic bacteria problems and evaluate how concentrations are changing over time.

Annual geometric mean beach bacteria concentrations were spatially variable in 2022 (Figure 7.2A). However, both *Enterococcus* and fecal coliform geometric mean values were below average to average at all beach monitoring sites with two exceptions (Figure 7.2B). Fecal indicator values were slightly elevated at Dumas Bay but were still within the historical range of that site. The annual geometric mean for both types of bacteria at the Des Moines Creek beach site was the highest of that site's monitoring record. Bacteria at Carkeek Park near the outlet of Piper's Creek were high compared to most beach sites, but typical for that site. All three of these sites are located near freshwater inputs, which are potential pathways for bacteria to enter the marine environment. Unlike in previous years, these sites had some of the highest bacteria in 2022 during warm periods (mid-Spring to early fall) often when there was little to no rainfall.

The timing of high bacteria concentrations at other beach sites was more variable.

Like previous years, 2022 bacteria concentrations offshore were much lower than those at beach stations due to their distance from various sources. The offshore stations with the highest bacteria concentrations were those located within Elliott Bay (influenced by the Duwamish River outflow) (Figure 7.2A), but both types of indicator bacteria at these stations were low. The highest bacteria concentrations in offshore waters tended to occur in the late fall and winter when rainfall was the highest.

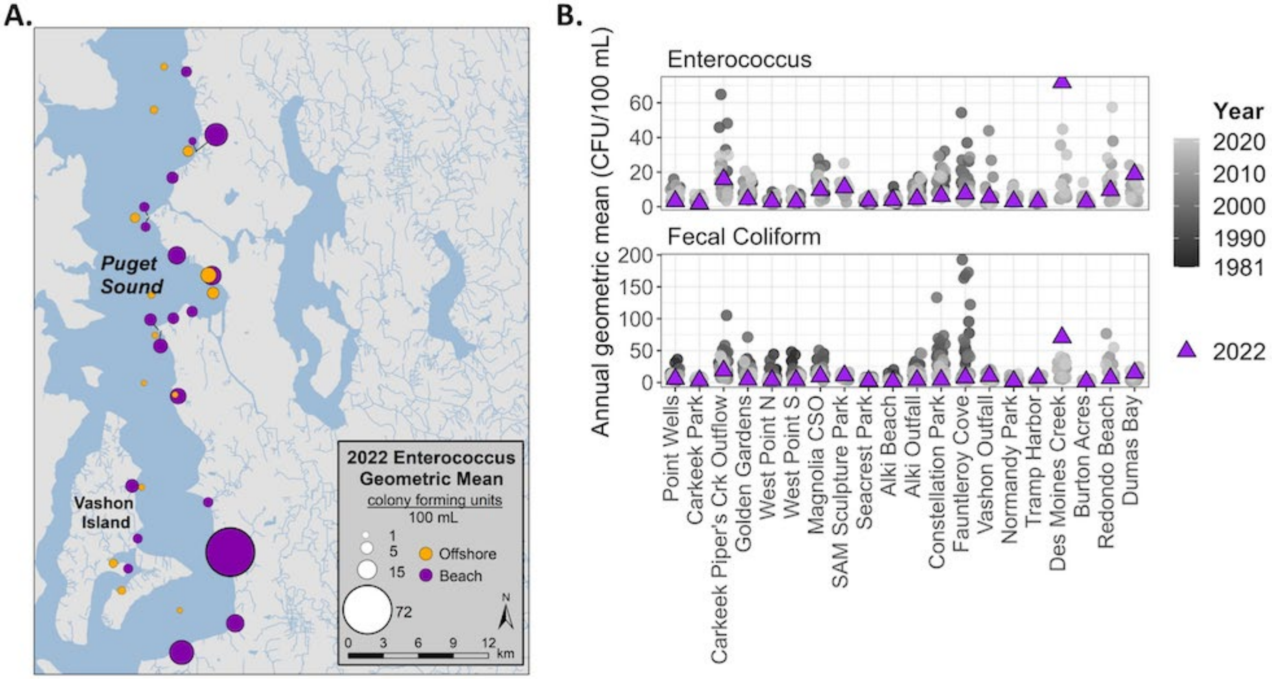


Figure 7.2. 2022 King County indicator bacteria monitoring results. (A) Map of Enterococcus *annual geometric mean concentrations at beach and offshore stations; (B) Annual geometric mean Enterococcus and fecal coliform concentrations at beach stations from 1981 to 2022. 2022 values in B are shown in purple and older data are shown in a grayscale gradient by year. In B, beaches are listed from north (left) to south (right). Note the different scales.*

B. *Vibrio parahaemolyticus*

Shellfish

Vibrio *is a genus of bacteria that occurs naturally in marine and estuarine environments and are generally present in higher concentrations as water temperatures increase. In the United States,* Vibrio *species are responsible for the majority of seafood-borne gastrointestinal illnesses from consumption of raw or undercooked seafood, specifically oysters. Because* Vibrio *populations grow faster at higher temperatures, most infections occur between May and October. In Washington,* Vibrio parahaemolyticus *(Vp) and* Vibrio vulnificus *(Vv) levels are monitored in oyster tissue during warmer months. Currently, the Washington State Department of Health employs three regulatory strategies to control* Vibrio*-related illnesses: (1) require the commercial industry to cool oysters to 50°F after harvest; (2) set temperature thresholds to limit harvest on the hottest days; and (3) close growing areas to oyster harvest when illnesses occur.*

Source: Elizabeth Lorence (elizabeth.lorence@doh.wa.gov) (WDOH); https://doh.wa.gov/about-us/programs-and-services/environmental-public-health/environmental-health-and-safety/shellfish-program

From May to September 2022, WDOH collected 122 samples from 18 sites and analyzed them for the presence of *Vibrio parahaemolyticus* (Vp) and *Vibrio vulnificus* (Vv). Six samples from three different sites had detectable levels of Vv, beginning in July. The maximum level of Vp was 24,000 MPN/g, recorded at the Hood Canal 5 site. Three additional sites had Vp levels exceeding 4,300 MPN/g tissue. During *Vibrio* sampling, weather conditions, air, shore and surface water, tissue temperatures, and salinity were recorded. In 2022, there were 18 laboratory-confirmed and epidemiologically-linked commercial, single-source illnesses from consumption of oysters contaminated with Vp. There were 24 multi-source illnesses: 14 were traced back to multiple Washington growing areas and 10 were traced back to multiple Washington growing areas, other states and/or countries (Figure 7.3). There were no closures, as Vp illnesses were not concentrated in any specific growing areas. Forty-eight confirmed illnesses were from commercially harvested oysters.

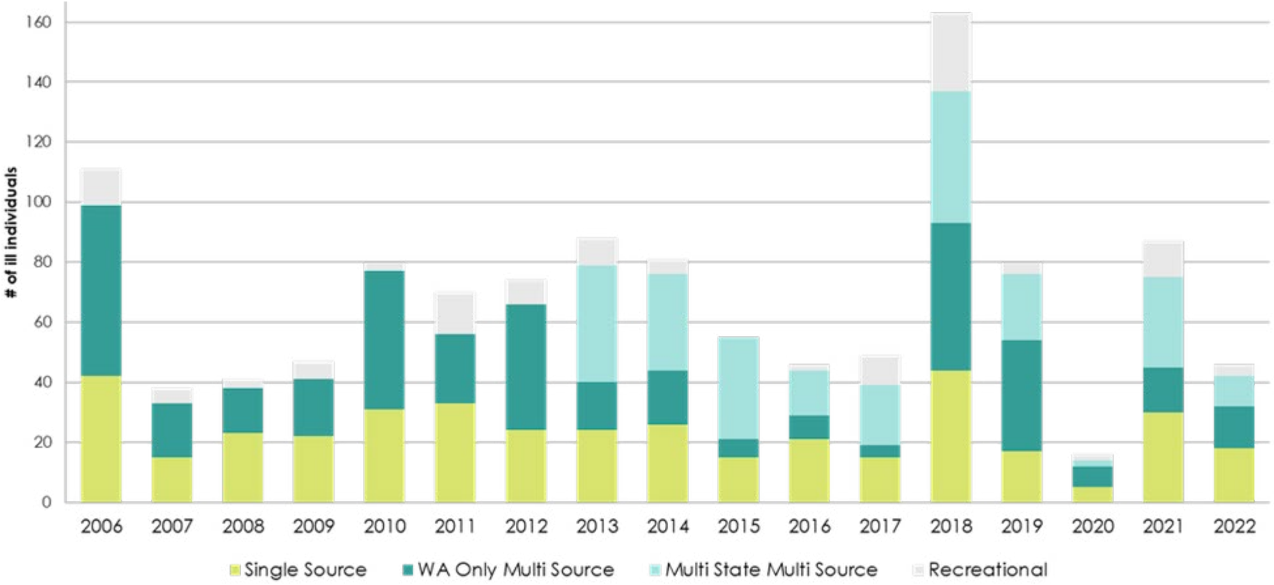


Figure 7.3. Confirmed Vibrio parahaemolyticus *(Vp) illnesses from oyster consumption, for both commercially and non-commercially harvested oysters. Confirmed illnesses include Vp positive culture confirmed illnesses. Description of illness types: single-source—illnesses that can be traced back to a single commercial growing area; multi-source—illnesses that cannot be traced back a single commercial growing area; recreational—illnesses from shellfish harvested and consumed by that member of the public, not offered for sale or barter.*

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 (including humans). Pacific herring (*Clupea pallasii*) are the most researched forage fish but Pacific sand lance (*Ammodytes hexapterus*) and surf smelt (*Hypomesus pretiosus*) populations and spawning activity are also monitored. Forage fish spawn along shorelines, making them vulnerable to shoreline development activities and impacts. Biomass of spawning Pacific herring is a Puget Sound Vital Sign Indicator.

A. Pacific herring

Forage fish

Source: Phill Dionne (phillip.dionne@dfw.wa.gov), Todd Sandell, Erin Jaco, and Emily Seubert (WDFW)

Primary website: https://wdfw.wa.gov/

Website for online data: https://pspwa.app.box.com/s/jogxmuw51h2wghaow1kywpguek1u4epe

Forage fish are a vital component of the marine food web, as they are prey throughout their life cycle for many invertebrates, fish, birds, and mammals. Pacific herring (*Clupea pallasii*) are the most studied forage fish in Puget Sound and an indicator species of Puget Sound health. The Puget Sound metapopulation is divided into "stocks" defined by spatiotemporal isolation of spawning activity, each having spatially distinct dynamics. The Washington Department of Fish and Wildlife (WDFW) recognizes 21 different herring stocks in Puget Sound based primarily on the timing and location of spawning activity. Though not all stocks have been sufficiently researched, some stocks, such as the Cherry Point stock, have also been identified as genetically unique (Petrou et al., 2021). Though the 2022 estimated spawning biomass (ESB) of 12,931 metric tons (mt) was below the recent 2020 high ESB (18,559 mt), it was still higher that the 2021 ESB (10,255 mt) and the recent 10-year average. The Port Orchard/Port Madison and Quilcene Bay spawning stocks again accounted for more than half of the total ESB in Puget Sound, and though the Quilcene Bay ESB (1,688 mt) was the lowest observed for this stock in over a decade, it remained one of the two largest stocks in Puget Sound. The Dungeness/Sequim Bay and Interior San Juan Islands stocks both had ESBs over 1,000 mt, which is a new high for both stocks. It is also notable that spawning was observed in 2022 at Kilisut Harbor, Fidalgo Bay, and Quartermaster Harbor, all of which had at least two consecutive years with no spawning observed prior to 2022. While increases outpaced decreases in 2022, South Hood Canal, Discovery Bay, and Wollochet Bay all had no spawning detected for at least the second year in a row, and Holmes Harbor and Elliott Bay both had no spawning detected as well.

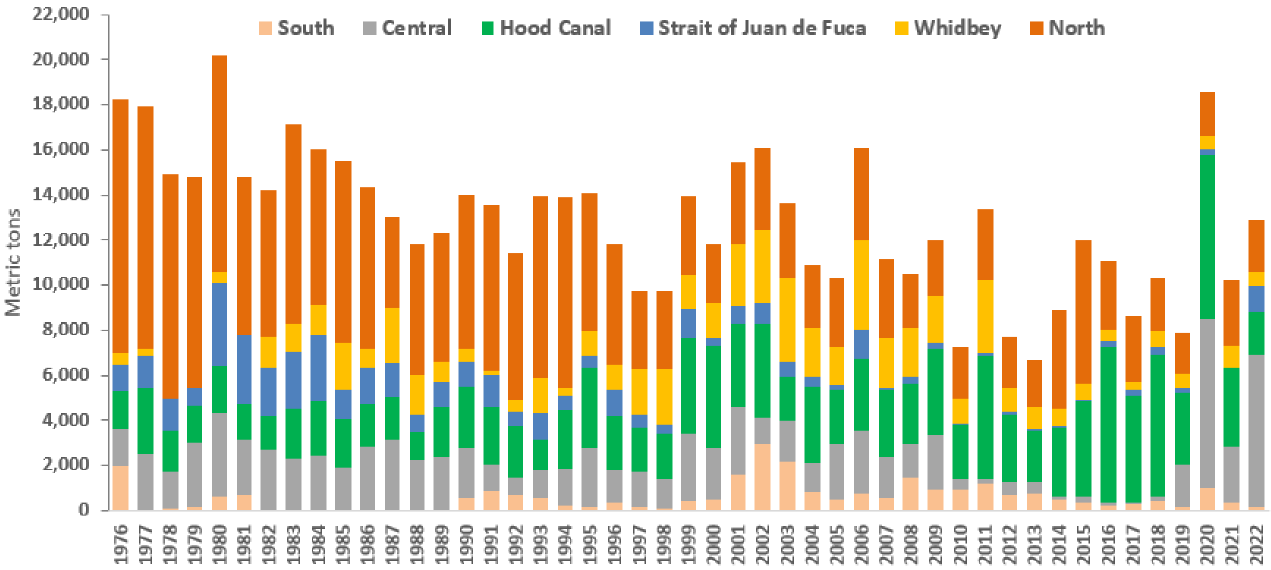


Figure 8.1. Pacific herring spawning biomass estimates by basin in the southern Salish Sea, 1976-2022.

B. Juvenile Chinook Salmon

Forage fish
Salmon

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

Juvenile Chinook salmon outmigrants have been monitored since 2009 by biweekly beach seines at two stations in the San Juan Islands: Watmough Bay (Lopez Island) and Cowlitz Bay (Waldron Island). Puget Sound origin Chinook are best represented at the Watmough station, which is close to Admiralty Inlet, whereas Fraser origin salmon dominate samples from Cowlitz (Chamberlin et al., 2017), making it possible to compare the health of these two populations. Sampling is conducted each year from May to September (ten 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; total annual sets per station have varied from 16 to 18. A subsample of juvenile Chinook brought to hand are subjected to non-lethal gut lavage, expressing the contents of their stomachs for study without harming the fish. Juvenile Chinook abundance peaked 2011–2013, coinciding with relatively cool waters, then returned to significantly lower levels that have persisted through 2022. On average since 2009, the diet of unmarked juvenile Chinook has consistently been dominated by fish (80.6%), chiefly Pacific herring (43.0%) and Pacific sand lance (35.8%). The remainder has been crustaceans such as krill and larval crabs (10.6%), insects such as midges and ants (6.7%), and other prey such as marine worms (2.1%); based on the gut contents of 4,241 juvenile Chinook salmon. Since 2017, juvenile Chinook transiting the San Juan Islands have been eating significantly less forage fish biomass (Figure 8.2A). This change has been greatest for unmarked Chinook sampled at Watmough Bay through 2022, and has been associated with (1) a decrease in the number of Pacific sand lance eaten on average by each juvenile Chinook; and (2) a decrease in the size of the Pacific herring eaten by juvenile Chinook.

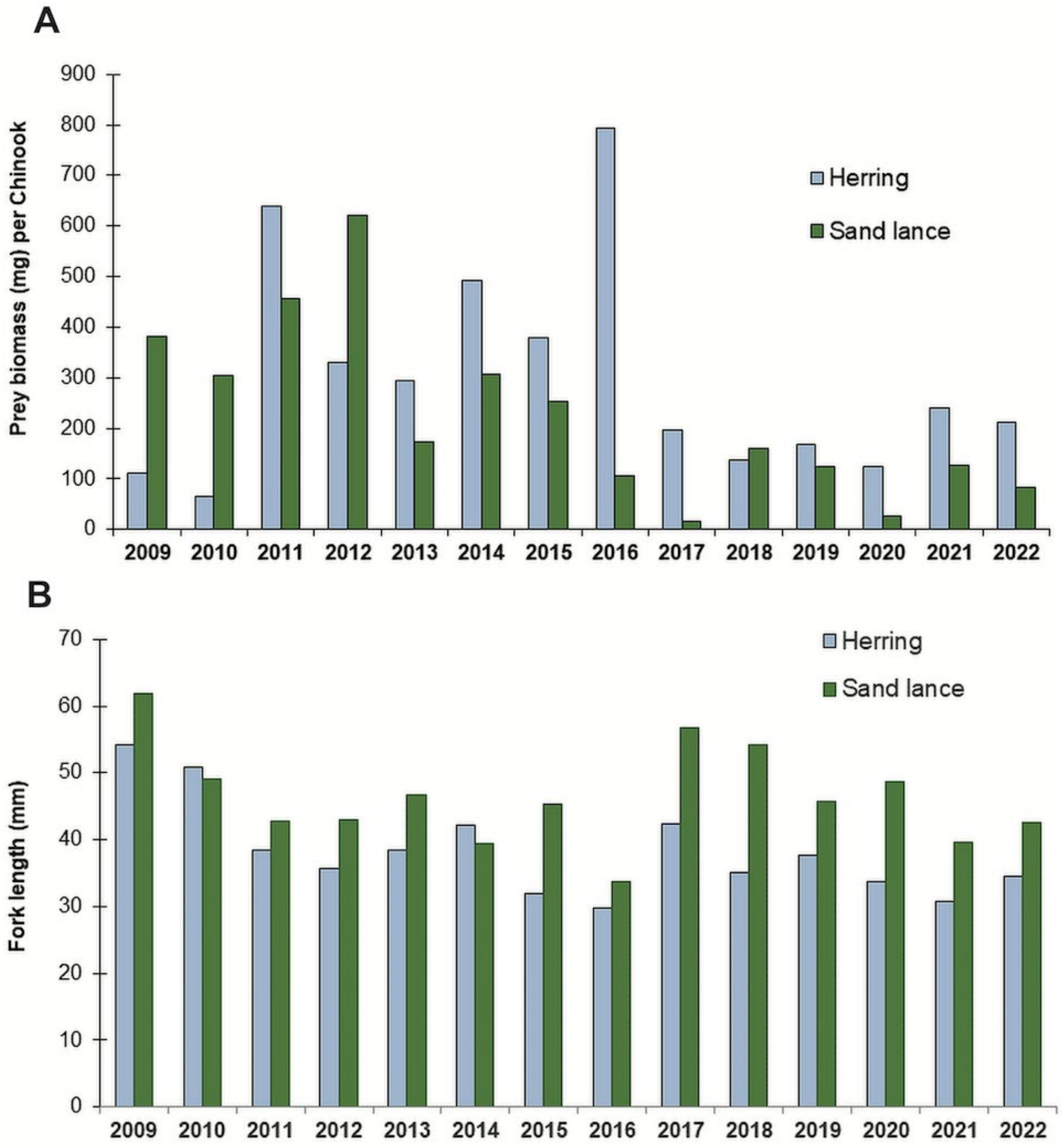


Figure 8.2. (A) Mean annual consumption of forage fish biomass by unmarked juvenile Chinook outmigrants at stations in the San Juan Islands 2009–2022. (B) Mean length of Pacific herring and Pacific sand lance eaten by unmarked juvenile Chinook outmigrants at stations in the San Juan Islands 2009–2022.

9. Marine mammals

A. Harbor porpoise

Source: Cindy Elliser (cindy.elliser@pacmam.org) (Pacific Mammal Research), Dave Anderson (Cascadia Research Collective), Laurie Shuster (Pierce College), Katrina MacIver (Pacific Mammal Research), Anna Hall (Sea View Marine Sciences), Erin Johns Gless, and Johannes Krieger (Pacific Whale Watch Association); www.pacmam.org

The Salish Sea harbor porpoise (*Phocoena phocoena*) has seen a significant recovery since the 1990s (Jefferson et al. 2016). Group sizes are typically less than three individuals (Raum-Suryan et al. 1998; Jefferson et al. 2016; Elliser et al. 2018). However, small groups occasionally come together to form larger aggregations, sometimes numbering over 100 individuals. These are generally considered rare events, although recent observations indicate that these large groupings may be more common than previously thought. To investigate the frequency of these events, observational data from United States and Canadian research organizations, community scientists, and whale watch captains or naturalists were combined. Contributors included Pacific Mammal Research, Cascadia Research Collective, Sea View Marine Sciences, the public, and whale watch companies affiliated with the Pacific Whale Watch Association via sighting apps beginning in early 2021.

In 2022, short-term (over a few hours/days) and long-term (at least a week) aggregations of harbor porpoises (20 or more individuals) were observed 160 times. Behavioral data indicated that foraging is likely a primary driver of these events; however, social behaviors, like mating, were common and seen more often during these encounters compared to small groups. In addition, other behaviors that are considered rare or unknown were also observed during these encounters, including cooperative foraging and vessel approach. These aggregations are likely important foraging and social gatherings for harbor porpoises and may be important aspects of their social structure. This holistic approach integrating data from two countries and multiple sources provides an ecosystem-level assessment that emphasizes the importance of these aggregations to harbor porpoise populations throughout the Salish Sea. Further research is needed to fully understand the role of these aggregations in harbor porpoise society, and what prey species may be driving them.

Group of harbor porpoises from a large aggregation of over 100 individuals on Feb 24, 2021 near Lawson Reef, Salish Sea, photo by Trevor Derie, Pacific Mammal Research (from Anderson et al. 2023).

CALLOUT BOX: Environmental DNA (eDNA): Using molecules to monitor

Because all living things make DNA, and because the sequence of this DNA makes species distinguishable from one another, individual cells contain a vast storehouse of biological information that can be recovered from water, soil, or air samples. This residual genetic information that is left behind from the living parts of an ecosystem is called eDNA. It is a potential goldmine of information for environmental management, since eDNA data make it possible to measure and monitor biodiversity at unprecedented resolution and scale.

Maya Garber-Yonts collects eDNA for an analysis of salmon response to culvert replacement in Bellingham, Washington. Photo: Eily Allan

Within Puget Sound, researchers have used eDNA to track killer whales (Baker et al. 2018), count endangered salmon (Shelton et al. 2019), and map different harmful algal species across space and time (Jacobs-Palmer et al. 2021). Two recent high-profile uses of eDNA from the Pacific Northwest show the very different spatial scales at which molecular data are beginning to inform management: three-dimensional mapping of hake (*Merluccius productus*) eDNA from bottle samples along the US west coast (Shelton et al. 2022), and a survey of invasive European Green Crab eDNA within Washington waters (Keller et al. 2022). In each case, eDNA provided data that would not have otherwise been available—in the hake case since other survey methods average over depths, and in the green crab case, because traditional traps don't capture the larval stage by which the crabs disperse. These are just a few of many real-world applications for eDNA that researchers have developed over the past several years. Broader examples include measuring the effect of urbanization on nearshore ecosystems (Kelly et al. 2016) and predicting ecological shifts in phytoplankton as a consequence of ocean warming and acidification (Gallego et al. 2020).

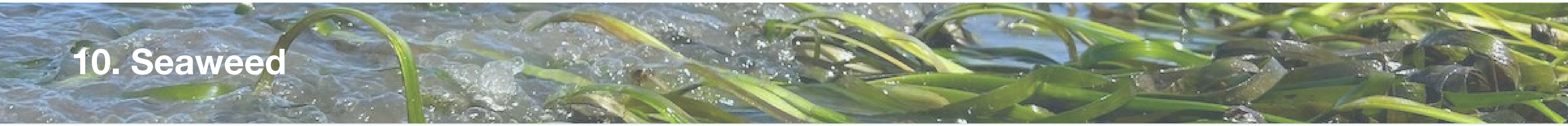
These examples all show the power of eDNA: a jar of water contains massive amounts of information about the surrounding ecosystem, and scientists are just now learning to put that information to good use. Responsible management requires understanding species distributions, how their abundances change over space and time, and how they adapt to pollution, harvesting, and large-scale stressors such as climate change—all of which is reflected in the genetic signals species leave behind in their environments.

eDNA data have become increasingly accessible as technology has matured, throughput has grown, and costs have declined—sequencing one megabase of DNA cost nearly $5,300 in 2001 and was less than $0.006 in 2021 (Wetterstrand, 2021). Large numbers of samples can now be analyzed quickly and cheaply. Widespread methods of analyzing eDNA currently include single-species assays using quantitative PCR (qPCR) or digital PCR (dPCR), and multi-species amplicon sequencing (metabarcoding).

Emily Grason and Abby Keller collect eDNA for an analysis of invasive European Green Crab. Photo: Ryan Kelly

As efforts intensify to strengthen the scientific basis for the restoration of Puget Sound, eDNA data is likely to play an increasingly important role.

Author: Ryan Kelly (rpkelly@uw.edu) (UW); https://www.ednacollab.org



10. Seaweed

A. Eelgrass

Source: Olivia Graham (ojg5@cornell.edu), Drew Harvell (Cornell University, University of Washington Friday Harbor Labs), Lillian Aoki (University of Oregon), Eliza Heery (University of Washington Tacoma), Brendan Rappazzo, and Carla Gomes (Cornell University)

Eelgrass (*Zostera marina*) creates essential marine habitats throughout the Salish Sea and is widely considered a sentinel of coastal health. However, climate and pathogenic stressors threaten the health of eelgrass meadows. Throughout the San Juan Islands, recent surveys indicate significant declines in eelgrass meadow densities (Christiaen et al. 2022) coinciding with warm temperatures and high levels of seagrass wasting disease (SWD), caused by the protist *Labyrinthula zosterae* (Figure 10.1A; Aoki et al. 2022, 2023; Groner et al. 2021; Graham et al. 2023). In particular, 2021 and 2022 summer disease surveys indicated the near-total loss of the shallow, intertidal eelgrass meadow at Beach Haven, Orcas Island, with shoot densities less than one shoot per m^2 in the intertidal zone (Figure 10.1B). Preliminary results from summer 2022 disease surveys indicate high disease prevalence (percent infected eelgrass plants) at all sites; mean, site-level prevalence ranged from 66.5% +/- 11.7% to 90% +/- 5.8% (mean +/- SE). Highest disease prevalence was recorded at Beach Haven in the small, remaining intertidal meadow (Figure 10.1C). These results are consistent with previous surveys of intertidal eelgrass in the San Juan Islands that indicated high disease levels with considerable between-site variability. Additional analyses will provide insights into inter-annual variation in disease severity and eelgrass biometrics, potentially highlighting ecosystem-scale impacts of this climate-fueled pathogen.

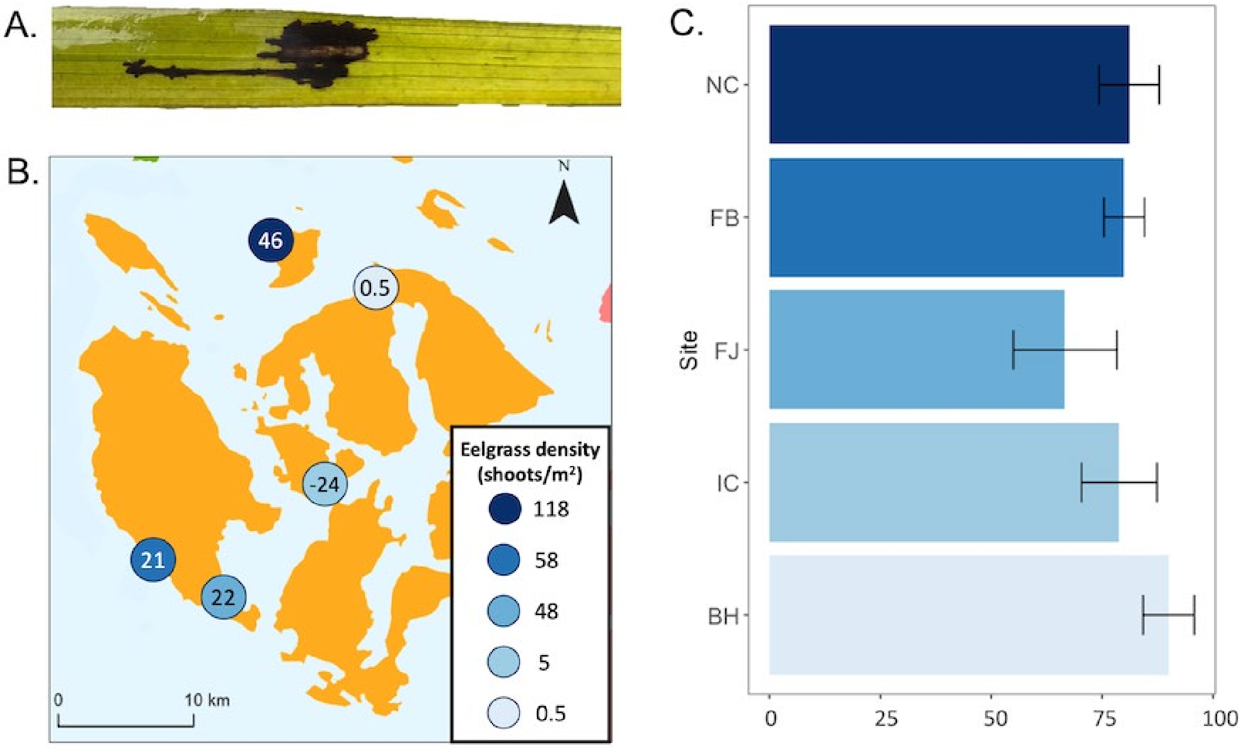


Figure 10.1. (A) Labyrinthula zosterae, *a protist, causes seagrass wasting disease, which creates dark lesions that can compromise eelgrass health. (B) Intertidal eelgrass densities during summer surveys. Circle colors correspond to mean densities (shoots per m^2) in summer 2022; numbers inside circles indicate the change in eelgrass densities from summer 2021 to summer 2022 (shoots per m^2). (C) Disease prevalence at all sites in summer 2022; bars represent mean +/- SE. Site names and abbreviations: North Cove (NC), Indian Cove (IC), Fourth of July Beach (FJ), False Bay (FB), Beach Haven (BH).*

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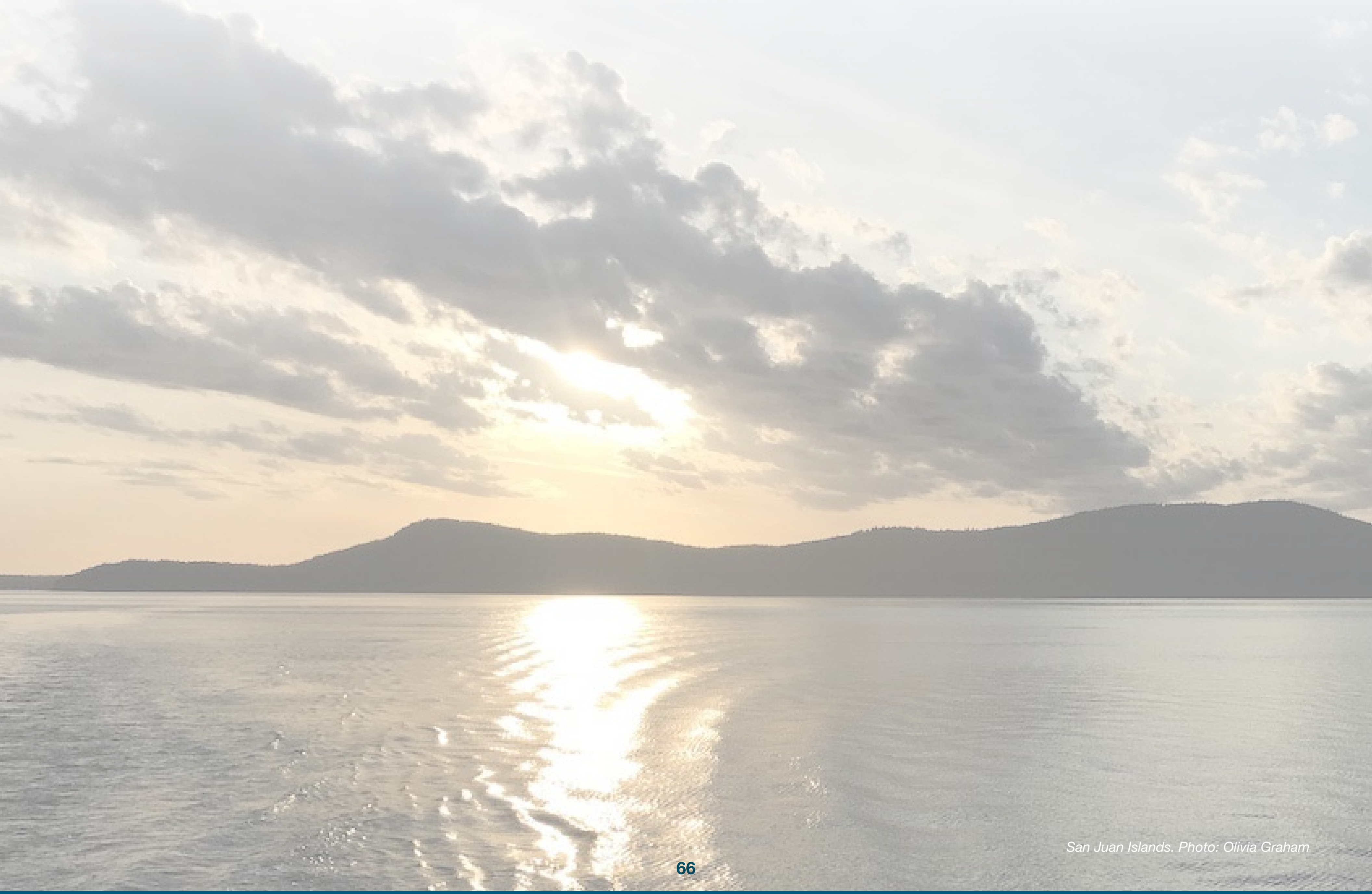

San Juan Islands. Photo: Olivia Graham

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