puget sound marine waters

2018 overview

puget sound

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Produced by: NOAA's Northwest Fisheries Science Center for the Puget Sound Ecosystem Monitoring Program's Marine Waters Workgroup.

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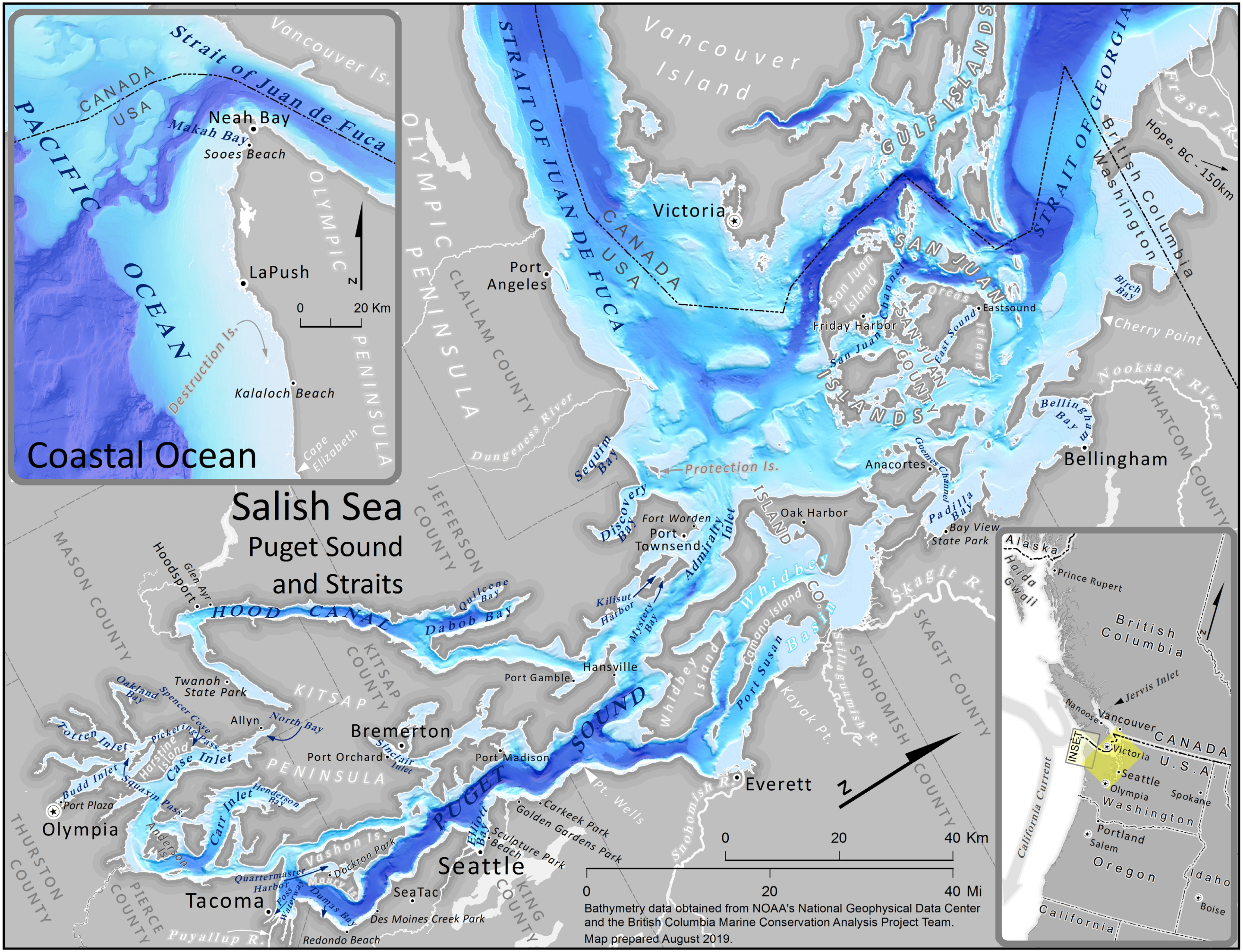

Map: Damon Holzer.

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About PSEMP

The Puget Sound Ecosystem Monitoring Program (PSEMP) is a collaborative network of subject matter experts who organize, synthesize, and communicate scientific information from many monitoring organizations and different parts of the ecosystem to directly address foundational management and science questions critical to recovery of the ecosystem.

PSEMP's objectives are to increase *collaboration* across monitoring programs, support *adaptive management* of recovery efforts, and improve *communication* within the monitoring and assessment community and to targeted audiences.

The Marine Waters Work Group is one of several PSEMP technical work groups. The group brings together people and organizations that monitor and report on physical, chemical, and biological properties of marine waters, including plankton, bacteria, and shellfish. The group's focus is on the inland marine waters of Puget Sound within the Salish Sea, including the oceanic, atmospheric, and terrestrial influences and drivers affecting the Sound.

For more information about PSEMP and the Marine Waters Work Group, please visit https://www.psp.wa.gov/PSEMP-overview.php.

Introduction

This report provides a collective view of the quality and conditions of Puget Sound's marine waters and associated biota in 2018, 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 patterns of variability and trends on various timescales so that water-quality data may be interpreted with these variations in mind, and to better distinguish human effects from natural variations and change. This is the eighth annual report produced for the PSEMP Marine Waters Workgroup.

While our primary audience for the entire report is the scientific community, our message to decision-makers, policymakers, managers, scientists, and the public who are interested in the health of Puget Sound follows.

From the editors

Our objective is to collate and share the valuable physical, chemical, and biological information obtained from various marine monitoring and observing programs to better characterize and understand Puget Sound water quality. Based on mandate, need, opportunity, and expertise, these efforts employ different approaches and tools that cover various temporal and spatial scales. For example, sampling at the surface along a transect yields good horizontal coverage, but lacks depth information; regularly sampling the same stations at set time intervals identifies long-term trends, but can miss shorter-term variation associated with important environmental events; moorings equipped with ocean-measuring instruments with high temporal resolution describe shorter-term dynamics, but have limitations in their spatial coverage.

Collectively, the information representing various temporal and spatial scales can be used to connect the status, trends, and drivers of ecological variability in Puget Sound marine waters. By identifying and connecting trends, anomalies, and processes from each monitoring program, this report adds significant and timely value to the individual datasets, and enhances our understanding of this complex ecosystem. We present here that collective view for the year 2018.

This report is the result of an annual effort by the PSEMP Marine Waters Work Group to compile and cross-check observations collected across the marine waters of greater Puget Sound during the previous year. Data quality assurance and documentation remains the primary responsibility of the individual contributors. All sections of this report were individually authored, and contact names and information are provided. The editors managed the internal cross-review process and focused on organizational structure and overall clarity. This included crafting the "summary of what happened" section that is based on all of the individual contributions and describes the overall trends and drivers of variability and change in Puget Sound's marine waters during 2018.

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

The Canadian ecosystem report, State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018 (https://www.dfo-mpo.gc.ca/oceans/publications/index-eng.html#state-ocean), describes an area encompassing approximately 102,000 km² from the edge of the continental shelf east to the British Columbia mainland, and includes large portions of the Salish Sea. The annual report provides information that is also relevant for Puget Sound and is a recommended source of complementary information to this report. To help connect these two efforts and better understand patterns and trends across the broader Salish Sea, the editors of the Canadian ecosystem report have provided a summary of their findings to complement this report of marine water conditions in Puget Sound. This summary is provided on page x.

A Summary of What Happened in 2018

This brief synopsis describes patterns in water quality and conditions and associated biota observed during 2018 and their association with large-scale ocean and climate variations and weather factors. The data compilations and analyses presented in the annual Puget Sound marine waters: Overview reports, which began in 2011, offer the opportunity to evaluate the strength of these relationships over time—one of the goals of the PSEMP Marine Waters Work Group.

Introduction

2018 Overview

In 2018, Puget Sound's marine waters most closely resembled 2017—though with a few startling differences. Water **temperatures** were mostly warmer than average, except for a cold spell in February–March. They were warmer than in 2017, though not as hot as during the years of "the Blob" (the marine heatwave of 2014–16). The Sound's **salinity** (saltiness) in 2018 followed a similar pattern to that observed in 2017, responding to a near-record-setting wet spring (fresher) followed by a record-setting summer drought (saltier). Salinity went up everywhere through the summer and fall, with some exceptional values recorded. Earlier runoff and summer droughts is what we would expect based on climate-change predictions for the region.[1] Hypoxia (a lack of **oxygen**) was more apparent in 2018 than previous years, though no fish kills were reported.

Marine populations had differing responses during this post-Blob year that was still generally warmer-than-normal. The most notable differences were at the base of the food web; the spring **phytoplankton** bloom was delayed and large, but overall, chlorophyll values and phytoplankton biovolume were greatly reduced in 2018 compared to previous years. There was a marked increase in *Vibrio* **bacteria**-related illnesses in 2018, with illness counts exceeding those during the last major outbreak in 2006. **Zooplankton** abundances were similar to or lower than in 2017, and lower than the warm Blob years. Pacific herring, a **forage fish**, showed both increases and decreases (depending on region within the Sound), while the number of **seabirds** was similar to or down from recent years (depending on the species). A fall survey showed some of the lowest abundances of **marine mammals** on record, and apex predator **Southern Resident killer whales** continued their population decline, apparently related in part to lack of food.

Detailed Summaries

Water temperatures

Warmer-than-average waters (positive temperature anomalies) were generally observed in Puget Sound during 2018, despite only weak influence from El Niño-Southern Oscillation and Pacific Decadal Oscillation conditions. This could indicate a strong role for local atmospheric heating in causing the warmer-than-average waters, since the Puget Sound region experienced warmer-than-normal air temperatures and below normal cloud cover, resulting in more sunny days. Upwelling was active during 2018. Circulation brings these typically cooler waters into Puget Sound, yet deep waters on the Washington shelf continued to show a warming trend of roughly 1°C from 2014 to 2018.

Salinity

Salinity varied in accordance with weather forcing. Fresher-than-normal waters were associated with cold and wet conditions early in 2018. While snowpack was above normal and peak river flows were unusually high, these conditions were relatively short-lived compared to normal. A record-setting summer drought, with summer river flows well below normal, was associated with saltier-than-normal waters, some well outside of typical ranges. This seasonal sequence resulted in water-column density gradients (primarily determined by salinity) that were fairly strong in spring (leading to stratification and prone to less mixing), then weaker than normal during summer and fall. Thus, weather conditions were a major factor driving water-property variation during 2018. Summer droughts and positive salinity anomalies have been observed since 2015.

Oxygen and Phytoplankton

The strong springtime water-column density stratification may have led to better conditions for spring blooms in 2018. In the Central Basin, the spring phytoplankton bloom was larger than normal, but was delayed from the typical April timeframe to early May. Chlorophyll levels were lower than previous years and there is evidence that phytoplanton size and community composition may have been different as well. Nitrate levels were higher than during the last five years. This may indicate that the lack of stratification favored mixing and led to fewer phytoplankton blooms with less nitrate uptake. It also suggests the influence of the

[1]Mauger, G. S., J. H. Casola, H. A. Morgan, R. L. Strauch, B. Jones, B. Curry, T. M. Busch Isaksen, L. Whitely Binder, M. B. Krosby, and A. K. Snover. 2015. State of Knowledge: Climate Change in Puget Sound. Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration. Climate Impacts Group, University of Washington, Seattle. DOI: 10.7915/CIG93777D.

North Pacific Gyre Oscillation, which is associated with weakened primary production in the California Current system. Despite the lack of strong density stratification during summer, in general, Puget Sound waters had lower-than-normal dissolved oxygen (DO) levels during 2018. Notably, there were more favorable periods in 2018 for intrusions of lower-oxygen upwelled oceanic water to spill over Admiralty Sill than in any year since 2013. Oxygen values on the outer NW coast were also unusually low, and upwelling began early, which may have contributed to the lower-than-normal DO values observed in Puget Sound. However, basin-scale dynamics were evident: in the Main Basin, outer Quartermaster Harbor had more-frequent short hypoxic periods than normal; while in Hood Canal, hypoxia at the southern end was more extensive than observed in 2017, though not nearly as severe as during 2015–16. These results indicate that weather, ocean dynamics, and local processes are all involved with the expression of blooms and hypoxia.

Ocean acidification

Atmospheric carbon dioxide (CO_2) measured off the coast and in Puget Sound continued its annual increase, with coastal values near the global average and Puget Sound values in excess. In stratified basins, CO_2 concentrations in surface seawater are quite different from those measured at depth. Levels potentially conducive to hypercapnia (harmfully high CO_2) were present in the deep waters of Whidbey Basin and Hood Canal during 2018.

Harmful algae and bacteria

Paralytic shellfish poisoning, amnesic shellfish poisoning, and diarrhetic shellfish poisoning toxins resulted in 18 commercial and 30 recreational harvest area closures, but caused no illnesses in 2018—both numbers substantially down from 2017. However, there were 70 alerts when action thresholds were exceeded for harmful algae that can cause shellfish toxicity. Harmful algae that can cause shellfish die-offs were observed at 28 stations. Marine beach closures due to pathogens increased slightly (up 5%) from last year, but *Vibrio* bacteria-related illnesses from the consumption of raw oysters increased from 59 in 2017 to 163 in 2018, a number that exceeded the previous major outbreak in 2006.

Zooplankton

Soundwide, zooplankton biomass in 2018 was similar to 2017, particularly for the northern regions of Puget Sound, whereas biomass decreased in central and southern regions to levels closer to 2014, potentially indicating a return to “normal” conditions after the warm period of 2015–16. In Padilla Bay, 2018 summer zooplankton community composition fell within the overlap of pre-Blob (2008–13) and Blob/post-Blob (2014–17) years, indicating a shift toward normal summer compositions—though not a full return.

Forage fish

Basin differences were very evident for pelagic forage fish. Overall, Pacific herring biomass rebounded in 2018 relative to the 10-year average (2008–17). Central, Whidbey, and Hood Canal basin stocks were up, northern stocks were down sharply, and South Sound and Strait of Juan de Fuca stocks were mixed. Large schools of anchovies continued to be seen throughout the Salish Sea.

Seabirds and marine mammals

Overwintering marine bird populations continued to fluctuate in early 2018, but with spatial, temporal, and species-specific differences. Abundances of forage-fish specialist seabirds were lower in the 2017–18 season than in the previous three seasons, particularly later in the year. Scoter species abundances fluctuated, but were generally in the range observed during the previous three seasons. Rhinoceros auklet breeding effort was slightly low but improved in 2018, suggesting that the population is recovering from a high breeding failure with unprecedented adult mortality in 2016 and a low breeding effort in 2017. A 15-year Salish Sea time series showed some of the lowest fall abundances of marine mammals on record. Finally, the whole region was saddened by the deaths of more Southern Resident killer whales. Their decline is likely due in part to a lack of available prey exacerbating a whale population already stressed from factors such as contaminants and vessel interactions.

In Conclusion

This year, like the others in this Marine Waters Overview series since 2011, shows strong linkages between observed water properties and ocean, climate, and local weather drivers. Since the Overview began pulling in results from more food-web components (circa 2014), we have found variable-to-declining biological abundances in general, although the time period mostly coincides with the influence of the Blob. Our continued synthesis efforts aim to aid a better-informed understanding of conditions and causes.

What About Up North?
A Summary of What Happened in Canadian Salish Sea Waters in 2018

This summary of Salish Sea marine water conditions is based on a subset of the *Fisheries and Oceans Canada report*, The State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018.

Every year, Fisheries and Oceans Canada (DFO), Pacific Region, conducts a review of the data collected from its programs monitoring the physical, chemical, and biological conditions in the ocean. These reviews take the form of a two-day meeting, usually held in February or March of the year following the year under review. The results, which are published annually in a Departmental Technical Report, provide fundamental information to assess the status of Pacific ecosystems and to develop a picture of how the ocean is changing.

In 2018, based on ship surveys carried out in the Strait of Georgia (SoG), temperature and salinity at the 80 stations monitored were near-normal in spring (mid-April) and summer (mid-June). As the year progressed, temperatures at all depths became warmer than normal (Chandler 2019). During the fall (early October) and winter (mid-November), lower-than-normal oxygen levels were widespread, with the exception of the deep waters of the SoG. There was an early, rapid, and high-volume Fraser River freshet. The semi-monthly collection of temperature–salinity profiles in the central SoG (by the Department of National Defence at its Maritime Experimental and Test Range near Nanoose) showed depth-averaged temperatures were similar to conditions in 2017, with three periods of warm-water anomalies extending to 40-m depths; although the long-term freshening trend continued, conditions in 2018 were saltier than expected by this trend (Chandler 2019).

After a three-year absence from the SoG, a harmful alga (*Heterosigma akashiwo*) bloomed in early June, resulting in high aquaculture fish mortality in Jervis Inlet (Esenkulova and Pearsall 2019, Haigh and Johnson 2019, Nemcek et al 2019). This bloom was linked to the early and high Fraser River freshet and hot weather in May–June (Esenkulova and Pearsall 2019, Haigh and Johnson 2019, Nemcek et al. 2019).

SoG zooplankton biomass was near the long-term average in 2017 and 2018, with peaks in May and June for the North and Central SoG, respectively (Young et al. 2019). In 2018, euphausiid abundance (the preferred food for juvenile salmon) peaked in the spring, but not in the fall as it did in 2017 (Young et al. 2019).

In the SoG, the spring bloom timing and duration was comparable to the long-term average (Allen et al. 2019, Costa 2019, Gower and King 2019, Sastri et al. 2019), which implies good feeding conditions for juvenile fish. For example, the timing of the spring phytoplankton and subsequent zooplankton blooms in the SoG is linked to the survival of herring (Boldt et al. 2019).

Over the last eight years, Pacific herring biomass estimates increased in the SoG; however, over the last two to five years, the biomass of other B.C. stocks was either stable (West Coast of Vancouver Island) or decreased (Central Coast, Haida Gwaii, Prince Rupert; Cleary et al. 2019). Other forage fish show varied trends. For example, northern anchovy consume zooplankton and have been abundant in SoG survey catches during the last three years (Neville 2019). An index of eulachon spawning stock biomass in the Fraser River was estimated to be at a moderately high level (similar to 2015) compared with most other years from 2004–17, which were relatively low (Flostrand 2019).

In the SoG, juvenile salmon species survey catches were average or better-than-average (Neville 2019). Recent warming in the ocean and freshwater, early river freshets, and summer drought, however, have led to changes in the food web and low survival and productivity of sockeye salmon coastwide (Grant et al. 2019, Hyatt et al. 2019, Xu et al. 2019).

Assembled by Jennifer Boldt and Peter Chandler.

Highlights from 2018 Monitoring

Large-scale climate variability and wind patterns

- El Niño–Southern Oscillation (ENSO)
    - » The tropical Pacific underwent a transition from moderate La Niña to weak El Niño conditions during 2018.
- Pacific Decadal Oscillation (PDO)
    - » The PDO ranged from near-zero to weakly positive values during 2018.
- North Pacific Gyre Oscillation (NPGO)
    - » The NPGO was very negative throughout 2018, suggesting weakened primary production along Washington's coastline and within the California Current Ecosystem.
- Upwelling index
    - » Upwelling along the Washington coast began in February, two months earlier than normal, and lasted through October.

Local climate and weather

- The annual average air temperature in the Puget Sound region was warmer than normal, and precipitation was near-normal for 2018.
- February and March were the only months in 2018 with substantial cold-air temperature anomalies; most other months were near-normal or above-normal.
- Precipitation was highly variable, with a swing from wet conditions (the second-wettest April on record) to record dry conditions (the driest May–August on record), similar to 2017.
- Sunlight levels were generally higher than normal in 2018.

Coastal ocean and Puget Sound boundary conditions

- Conditions on the Washington shelf followed a typical seasonal cycle in 2018, with temperature, salinity, and DO at depth gradually becoming slightly cooler, saltier, and less-oxygenated as summer progressed.
- Distinct episodic intervals of hypoxic waters were observed that were unusually low (oxygen concentrations below 0.25 mg/L) and prolonged.
- Deep waters showed a warming trend of roughly 1°C from 2014 to 2018.
- Atmospheric measurements of the mole fraction of carbon dioxide (xCO_2) at the Ćháʔba· and Cape Elizabeth moorings on the Washington shelf continued their year-to-year increases in 2018, and were similar to the global averages. The summertime minimum was earlier at Cape Elizabeth in 2018 relative to other years.
- 2018 surface seawater xCO_2 values at Ćháʔba· and Cape Elizabeth were within the range of past years.

River inputs

- Cold and wet conditions early in 2018 produced an above-normal snowpack.
- Peaks in river discharge to the Salish Sea were early, unusually high, and relatively short-lived compared to normal.
- Summer flows were well below normal in most watersheds.
- Wet conditions early in November brought flows back above historical medians.

Water quality

- Temperature
  - » Puget Sound water temperatures were generally warmer than normal in 2018, except for a cool period in March.
  - » In the Central Basin, water temperatures were normal to slightly cooler in the first half of the year, becoming warmer than normal in the summer and fall.
  - » In the eastern Strait of Juan de Fuca and San Juan Channel, fall water temperatures approached values observed during the 2014–16 Blob years.
- Salinity and density
  - » Puget Sound waters were generally fresher than normal for the first half of 2018, becoming saltier at the end of the year.
  - » Fresher-than-normal waters in March coincided with cooler temperature anomalies.
  - » Saltier-than-normal waters from fall to the end of the year were in excess of two standard deviations above average in Hood Canal and Carr Inlet, and deep waters in the Main Basin and South Sound were the saltiest ever observed by profiling buoys (records from nine to 13 years).
  - » In the Central Basin, fresher-than normal surface waters in the first half of the year generated strong density gradients near the surface. Water-column stratification was observed less frequently in the second half of the year than in recent years.
  - » In Bellingham Bay, the wet spring (high Nooksack River discharge) and warm, dry summer (low discharge) conditions were reflected in the buoy observations, with cooler temperatures and fresher salinities observed in the spring followed by warmer temperatures and increasing salinities through the summer.
  - » In the eastern Strait of Juan de Fuca and San Juan Channel, fall salinity anomalies were similar to 2017 and generally positive, unlike the generally negative values observed during the 2014–16 Blob years.
- Nutrients and chlorophyll
  - » On average, nitrate concentrations in Puget Sound were higher in 2018 than the last five years.
  - » In the Central Basin, the spring phytoplankton bloom was larger than normal, but was delayed from the typical April timeframe until May 7. Even with the large spring bloom, chlorophyll levels overall were lower than normal in 2018.
  - » Surface nutrient levels in the Central Basin were higher than normal in April due to the delayed spring bloom, lower than normal in May during the large spring bloom, higher than normal in the summer months from lack of biological uptake, and notably lower than normal in October and November, likely from the dry fall resulting in less freshwater input.
  - » In Bellingham Bay, surface chlorophyll levels increased in early April, and there were two spring peaks instead of the three observed in the past two years. Chlorophyll levels rose again in August, which was not observed in 2016; there were no data during 2017.
- Dissolved oxygen
  - » Puget Sound waters had lower-than-normal DO levels in 2018, continuing a six-year trend that began in 2013.
  - » There were more favorable periods for hypoxic intrusions of upwelled oceanic water to spill over Admiralty Sill in Puget Sound than in any year since 2013.
  - » Hypoxia at southern Hood Canal was more extensive than observed during 2017, but not as severe as 2015–16. No fish kills were observed.
  - » Outer Quartermaster Harbor had more-frequent short hypoxic periods than normal.
- Ocean and atmospheric CO_2
  - » Atmospheric measurements of the mole fraction of carbon dioxide (xCO_2) in Hood Canal had values 15–17 ppm higher than globally averaged marine surface air xCO_2 in 2018, as typically seen in this record. Surface seawater CO_2 was within the bounds of past variability.
  - » As seen in prior years, partial pressures of CO_2 (pCO_2) potentially conducive to hypercapnia (harmfully high pCO_2) were present in the deep waters of Whidbey Basin and Hood Canal during 2018. Such high pCO_2 values were observed even shallower in September.

Plankton

- Phytoplankton
  - » The total annual biovolume of phytoplankton in the Central Basin was only 47% of previous years.
  - » In the Central Basin, the diatoms *Thalassiosira* and *Chaetoceros* spp. dominated the phytoplankton community by biovolume in early spring. The spring peak ended with a large bloom of the diatom *Rhizosolenia.* The harmful raphidophyte *Heterosigma* was abundant in late summer, and small dinoflagellates and the ciliate *Mesodinium* dominated during fall and winter.
- Zooplankton
  - » Zooplankton abundance and biomass in 2018 were generally similar to 2017. This was especially true for biomass in northern regions of Puget Sound, whereas biomass decreased in central and southern regions to levels close to 2014, potentially indicating a return to "normal" conditions after the warm period of 2015–16.
  - » In Padilla Bay, 2018 summer zooplankton community composition fell within the overlap of pre-Blob (2008–13) and Blob/post-Blob (2014–17) years, indicating a shift toward normal summer compositions—but not a full return.
- Harmful algae and biotoxins
  - » Paralytic shellfish poisoning, amnesiac shellfish poisoning, and diarrhetic shellfish poisoning toxins resulted in 18 commercial and 30 recreational harvest area closures, but caused no illnesses in 2018.
  - » *Alexandrium* cysts were found again in Bellingham Bay sediments in April/May 2018, a persistent seedbed since 2013.
  - » The SoundToxins program issued a total of 70 alerts in 2018 when action thresholds were exceeded for harmful algae that can cause shellfish toxicity (and fish kills). Harmful algae that can cause shellfish die-offs were observed in 2018 at more than a dozen stations.

Bacteria and pathogens

- In 2018, 96% percent of all marine beaches monitored had less than two swimming advisories or closures, a 5% increase from 2017.
- In the Central Basin, seven of the 20 beach monitoring stations failed one or both of the fecal coliform standards. Bacteria concentrations were generally highest in November, when samples were collected after a period of heavy rainfall.
- There were a total of 163 confirmed *Vibrio parahaemolyticus* illnesses in 2018 due to the consumption of raw oysters; 137 from commercially harvested oysters and 26 from noncommercial oyster harvests.

Fish

- Overall, Pacific herring biomass rebounded in 2018 relative to the ten-year average (2008–17); Central, Whidbey, and Hood Canal basin stocks were up, northern stocks were down sharply, and South Sound and Strait of Juan de Fuca stocks were mixed. Large schools of anchovies continue to be seen throughout the Salish Sea.

Marine birds

- Overwintering marine bird populations continued to fluctuate in 2018, potentially in response to the anomalously warm Blob years.
- Abundances of forage-fish specialist seabirds were lower during the 2017–18 season than the previous three seasons, particularly toward the end of the season, in March and April 2018.
- Scoter species abundances fluctuated across the season, but were generally within the range observed during the previous three seasons.
- Rhinoceros auklet breeding effort was slightly low but improved in 2018, suggesting that the population is recovering from the high breeding failure and unprecedented adult mortality event in 2016 and the low breeding effort in 2017.

Marine Mammals

- Fall 2018 abundances of marine mammals and seabirds in the eastern Strait of Juan de Fuca were low relative to the 15-year record. Since 2013, seabird abundance has been low and marine mammal densities have steadily declined, with 2018 the lowest of the record.
- The population size of Southern Resident killer whales was 75 individuals in 2018, down from 77 in 2017. There were no successful births observed during the 2016–18 census years. Multiple lines of evidence suggest that the SRKW population is not finding enough to eat.

Technical Summaries

1. Large-scale climate variability and wind patterns

Large-scale patterns of climate variability, such as the El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO), 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 and 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, PDO, and NPGO are large-scale climate variations that have similarities and differences in the ways that they influence the Pacific Northwest. ENSO and PDO are 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 winters of warm phases of ENSO and PDO, and can typically linger for two or three seasons. For PDO, these anomalously warm waters can reemerge four or five seasons later (Moore et al. 2008a). In contrast, the NPGO, which is related to processes controlling sea surface height, has a stronger effect on salinity and nutrients than on temperature. Variations in seasonal winds are an important factor in the NPGO. On the outer Washington coast, seasonal winds shift from dominantly southerlies during winter to northerlies during summer, and drive some of the largest variation in offshore coastal conditions: upwelling versus downwelling. Upwelling brings deep, cold, salty, nutrient-rich, oxygen-poor waters to the surface and into the Strait of Juan de Fuca as source water for Puget Sound, fueling phytoplankton growth. As such, the NPGO indicates fluctuations in the mechanisms driving planktonic ecosystem dynamics (Di Lorenzo et al. 2008).

A. El Niño–Southern Oscillation (ENSO)

Source: Nick Bond (nicholas.bond@noaa.gov) and Karin Bumbaco (OWSC); www.climate.washington.edu

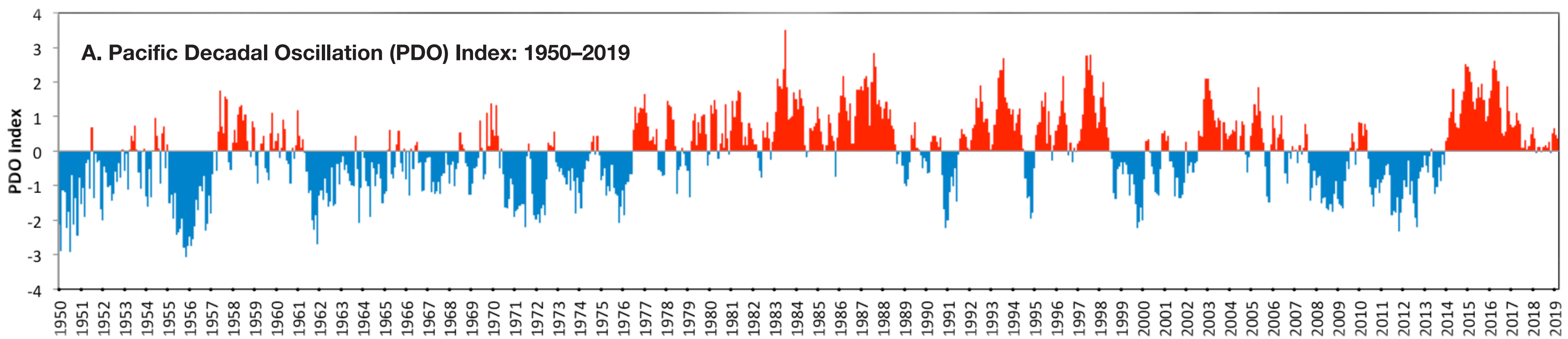
The 2018 calendar year featured a transition from moderate La Niña (winter 2017–18) to weak El Niño (winter 2018–19) conditions in the tropical Pacific. The associated warming was manifested both in warmer-than-normal sea surface temperatures and in enhanced upper-ocean heat content in the equatorial central and eastern Pacific Ocean. The atmospheric response in terms of the low-level winds and deep tropical convection was muted, which probably relates to the atypical atmospheric circulation over the North Pacific during the past winter (2018–19) compared to that during previous El Niño events.

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

B. Pacific Decadal Oscillation (PDO)

Source: Nick Bond (nicholas.bond@noaa.gov) and Karin Bumbaco (OWSC); www.climate.washington.edu

The PDO was in the positive phase (monthly values of 0.5–0.7) near the start and end of the 2018 calendar year, with values generally slightly above zero from spring through fall (Figure 1). The recent variations in the PDO reflect fluctuations in sea surface temperature (SST) anomalies in the Gulf of Alaska and off the coast of California; the SST offshore of the Pacific Northwest ranged from near-neutral in early 2018 to warmer than normal late in the year. From a multiyear perspective, the PDO has tended to be positive since early 2014.



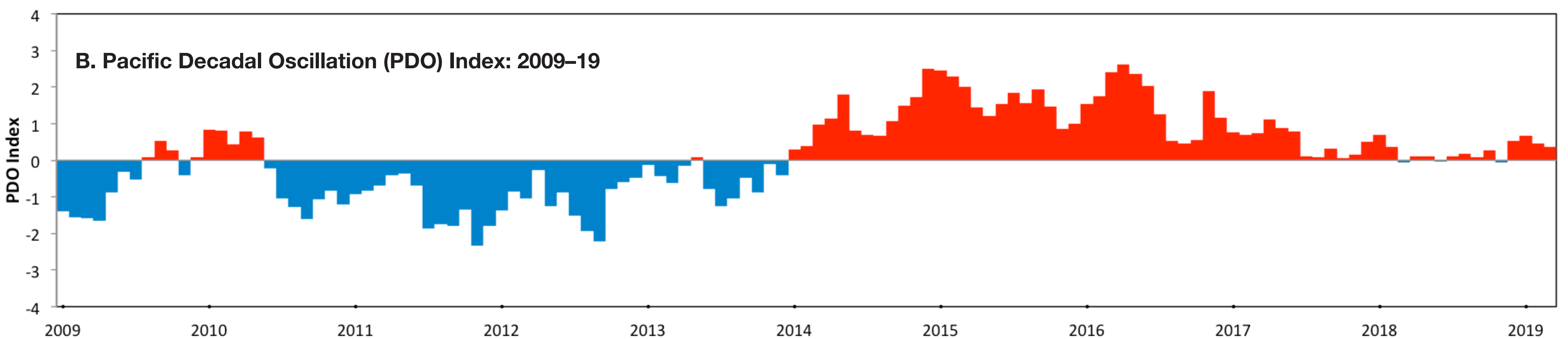


Figure 1. Monthly values of the Pacific Decadal Oscillation (PDO) Index from (A) 1950–2019 and (B) 2009–19.

C. North Pacific Gyre Oscillation (NPGO)

Source: Christopher Krembs (christopher.krembs@ecy.wa.gov, Ecology); http://www.ecy.wa.gov/programs/eap/marwat/index.html

The NPGO index was negative for the entire 2018 calendar year. The NPGO was mostly in the positive phase from 1998 through 2013, with the exception of 2005–07 when monthly values were negative (Figure 2). In October 2013, NPGO values turned negative and have remained so, with the exception of a few positive monthly values in 2014 and 2016. At the end of 2017, NPGO values became strongly negative and remained that way throughout 2018, suggesting that oceanic patterns supporting primary production along Washington's coastline and within the California Current System have weakened.

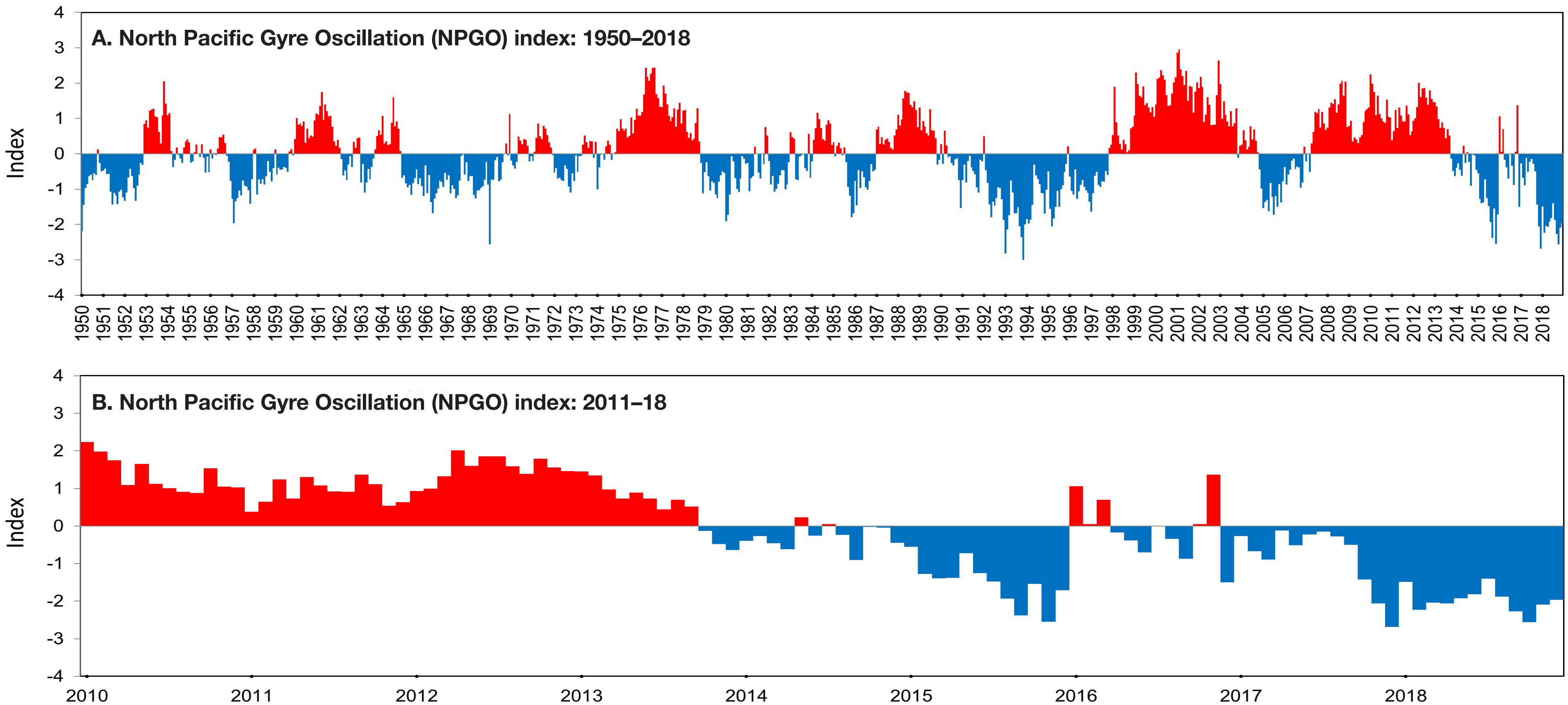


Figure 2. Monthly values of the North Pacific Gyre Oscillation (NPGO) index from (A) 1950–2018 and (B) 2011–18.

D. Upwelling index

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

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

Monthly mean values of the NOAA Pacific Fisheries Environmental Laboratory (PFEL) upwelling index at 48°N latitude and 125°W longitude were within historic (1967–present baseline period) interquartile ranges during 2018, with the exception of January and February. Strong downwelling in January led to lower-than-normal values, and sustained upwelling winds in February led to higher-than-normal values. The February onset of upwelling was two months earlier than normal. Upwelling conditions persisted until downwelling winds resumed again in November (Figure 3).

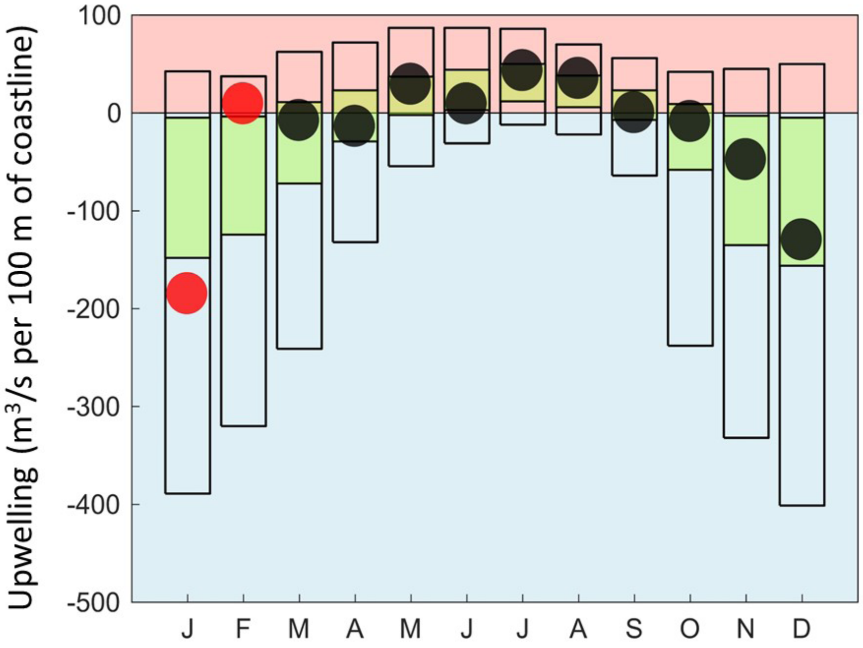


Figure 3. Monthly mean values of PFEL coastal upwelling index for 2018 (red and black dots) are presented in historical statistical context based on the index values at 48°N and 125°W from 1967 to 2017 (i.e., not including the current year). The box plot extent represents the 5th and 95th percentiles, with the interquartile range between the 25th and 75th percentiles shaded green. Values falling outside the interquartile range are colored red. Pink- and blue-shaded areas indicate upwelling and downwelling conditions, respectively. Data source: www.pfeg.noaa.gov/products/las/docs/upwell.nc.html.

2. Local climate and weather

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

A. Regional air temperature and precipitation

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

Washington State is divided into ten separate climate divisions based on similar average weather conditions within a region (http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php). The following summary uses data from the Puget Sound Lowlands division that encompasses most of Puget Sound.

The 2018 calendar year was warmer than normal, with near-normal precipitation for the Puget Sound area and the state as a whole. Annual average air temperatures (11.1°C/52.0°F), at 0.6°C above the 1981–2010 normal, were comparable to the warm anomalies measured in 2014 and 2016, but cooler than the hottest year on record (2015) and warmer than 2017. Total annual precipitation was 111.63 cm (43.95 in), which represents 98% of normal, and was drier than seven of the last eight years.

Monthly values give a better view of the variability throughout the year. Figure 4 shows monthly temperature and precipitation anomalies for the Puget Sound region relative to the 1981–2010 normals. February and March were the only months with substantial cold anomalies, and February featured a six-day period of much colder-than-normal temperatures that included one day of lowland snow. In contrast, the warm air temperature anomalies beginning in May ranked as the third-warmest May–August on record for the Puget Sound region (since 1895) and both the third-warmest May and July, individually. May–August also ranked as the driest on record for Puget Sound. In a similar fashion to 2017's large swings in precipitation anomalies from spring to summer, the second-wettest April on record preceded the driest May–August. There was a lack of major winter flooding during both early and late 2018 in the region. Finally, poor air quality from wildfire smoke in August was frequent in the Puget Sound region, with generally worse air quality in 2018 compared to summer 2017.

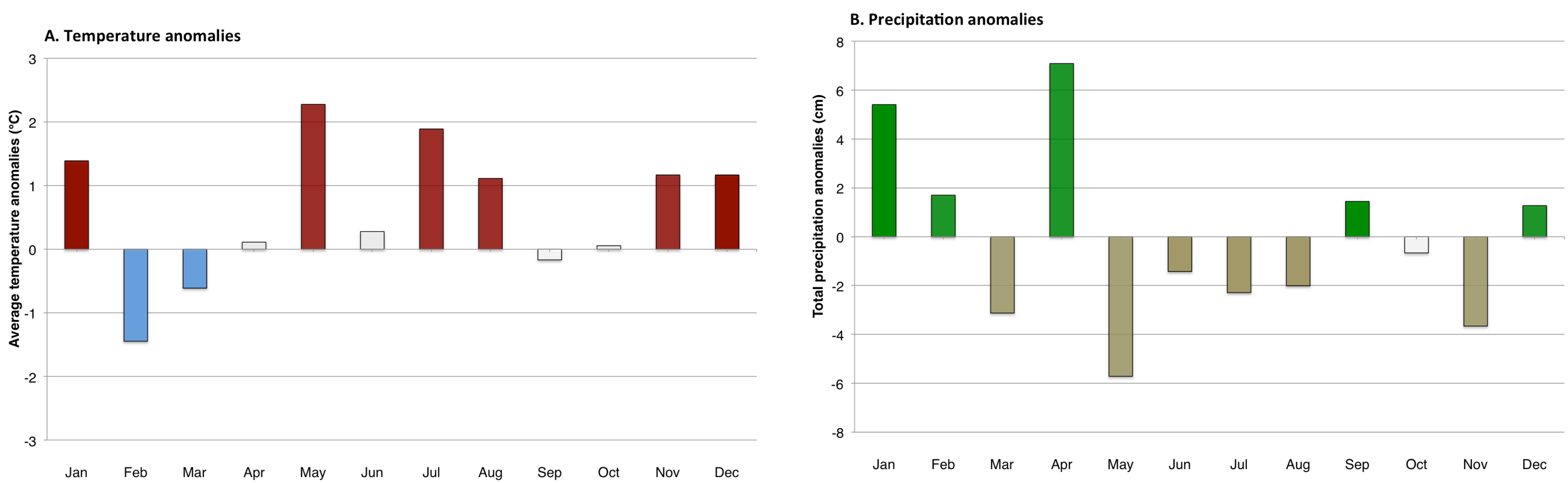


Figure 4. Monthly anomalies for (A) temperature (Celsius) and (B) precipitation (centimeters) for the Puget Sound Lowlands climate division in Washington State for the 2018 calendar year. Anomalies are relative to 1981–2010 climate normals and are colored red (green) for above-normal temperature (precipitation) anomalies, blue (brown) for below-normal temperature (precipitation) anomalies, and gray for near-normal anomalies.

2. Local climate and weather

B. Local air temperature and solar radiation

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

Air temperatures at SeaTac were mostly warmer than normal in 2018 (relative to a 1971–2000 historical baseline period), except during February, March, and September (Figure 5A) when they were cooler than normal. A new record dry period stretched from May to August. The year ended with warmer conditions ushered in by a weak El Niño.

Sunlight, as measured by daily solar energy flux, was generally above normal in 2018, except during January, February, and April when it was below average (Figure 5B, blue-filled area). Sunlight was also diminished at times during August and September, partially due to wildfire smoke in August.

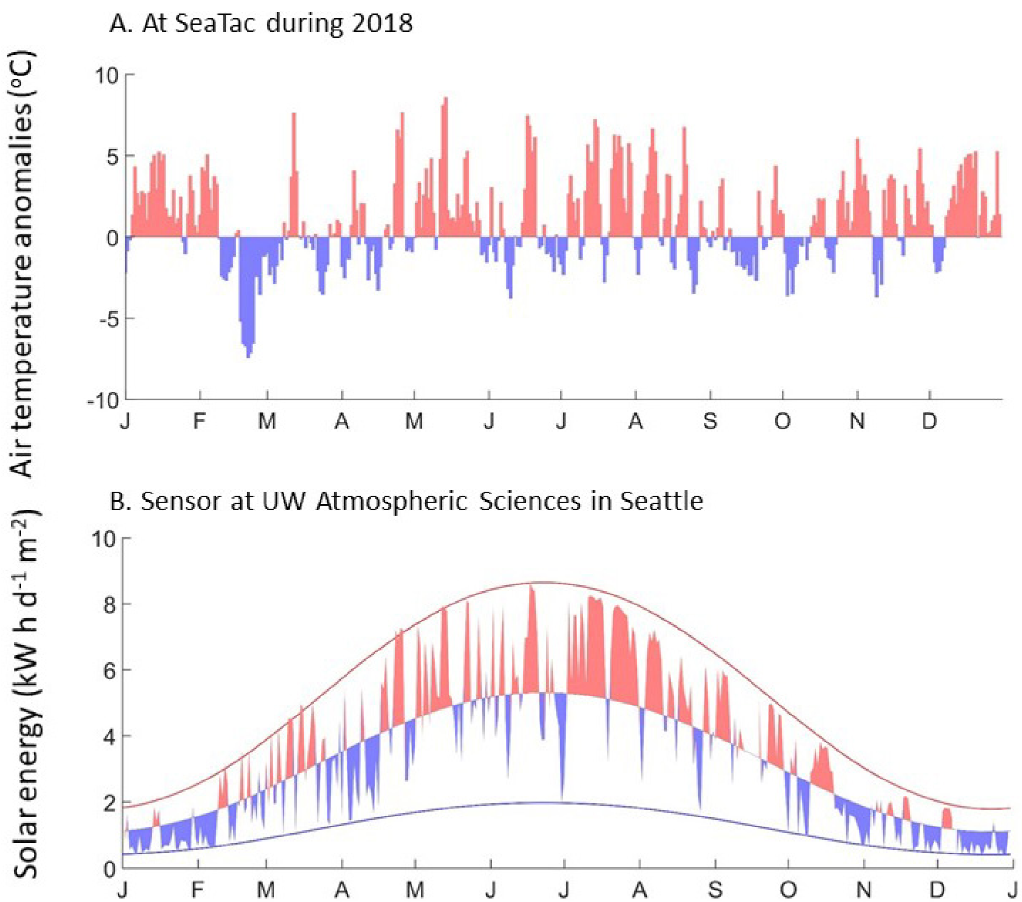


Figure 5. (A) Daily air temperature anomalies at SeaTac during 2018. Red (blue) shading indicates warmer- (cooler-)than-average values. (B) Daily solar energy values from the rooftop sensor at the UW Atmospheric Sciences Building (ATG) in Seattle. The solid red line indicates the highest theoretical solar energy for the latitude, and the solid blue line indicates when the sky is fully overcast. Red-filled area indicates when the sky is more than 50% clear (sunnier), and blue-filled area indicates when it is less than 50% clear (cloudier).

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

A large surface mooring called Ćháʔba· and an adjacent profiling mooring called NEMO-subsurface, maintained by the Northwest Association of Networked Ocean Observing Systems (NANOOS) and the University of Washington (UW), collect oceanographic and meteorological observations on the Northwest Washington shelf. The moorings are located off La Push in 100-m water.

Source: Zoltan Szuts (zszuts@apl.uw.edu), Jan Newton, and John Mickett (UW, APL); http://www.nanoos.org; http://nwem.ocean.washington.edu/

Conditions on the Washington shelf during 2018 followed a typical seasonal cycle (Figure 6), but deep waters show a long-term warming trend (Figure 7). Multiyear sampling of temperature throughout the water column shows that this deep warming trend continued in 2018, with a warming of roughly 1°C from 2014–18 (Figure 7). While water colder than 8°C was seen near 80-m depth in summer 2018, in 2016 the 8°C isotherm reached up to 60 m and in 2014 it reached up to 40 m.

Similar to 2017, in 2018 the temperature at 85 m (Figure 6) was significantly warmer (by 0.5–1°C) in late spring than during the same time period in prior years. The difference disappeared by mid-August. Although it is unclear whether warmer conditions in 2017 were a remnant of the Blob, the similar temperature pattern in 2018 suggests a longer-term response, or that other factors may be contributing.

As the 2018 summer progressed, temperature, salinity, and dissolved oxygen (DO) at depth gradually became slightly cooler, saltier, and less-oxygenated (Figure 6). At the end of the summer, episodic intervals of hypoxic waters occurred at depth. These hypoxic waters were unusually low, with DO concentrations reaching below 0.25 mg/L, and prolonged. The average value from 15 August to 15 October 2018 was 1.7 mg/L, the lowest value since observations began in 2013. The next-lowest year was 2014 (1.8 mg/L), compared to the average and standard deviation for 2013–18 of 2.3±0.5 mg/L.

During the 2018 hypoxic intervals, temperature and salinity were not anomalous; however, their variability is substantially less during hypoxic intervals. This suggests a homogeneous mass of bottom water passed the mooring site, displacing water that was more heterogeneous. The mechanism and source of these hypoxic waters are discussed in more detail in the callout box *Washington Coast hypoxic events*. After these late-summer intervals, which are related to the relaxation of downwelling winds, the deep waters rapidly become warmer, fresher, and more oxygenated.

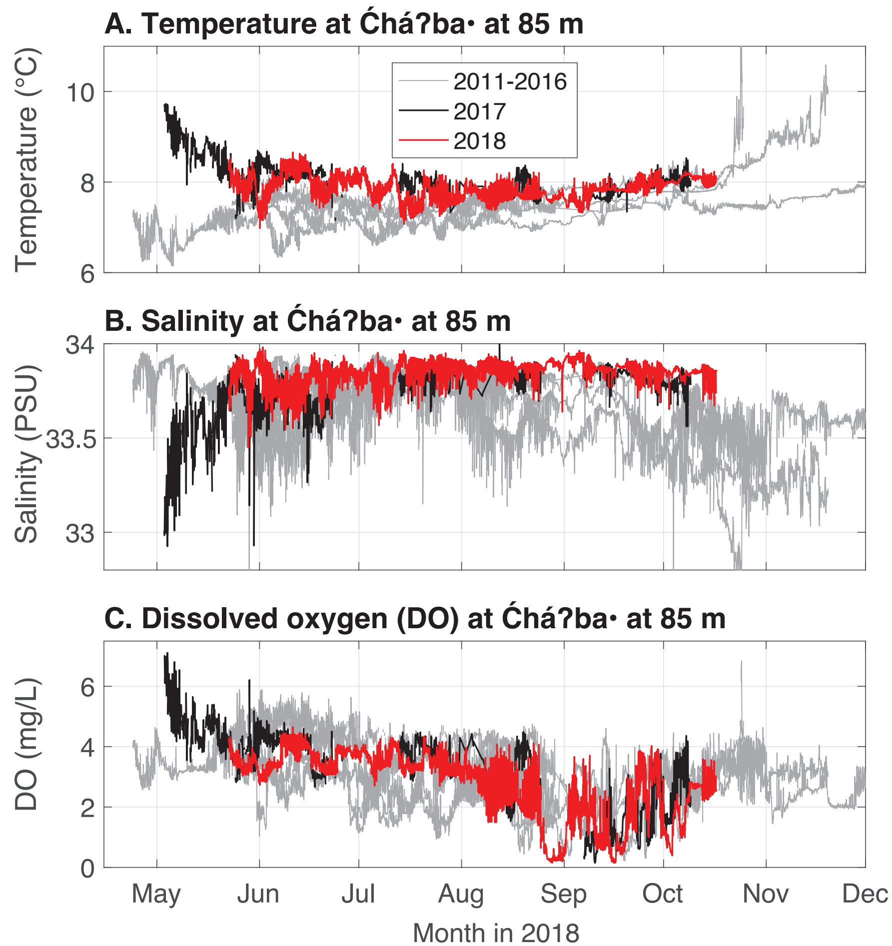


Figure 6. Interannual comparison of deep-water (85 m) properties at Ćháʔba·: (A) temperature, (B) salinity, and (C) dissolved oxygen.

B. Ocean and atmospheric CO_2

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

Source: Simone Alin (simone.r.alin@noaa.gov), Adrienne Sutton, Richard Feely (NOAA, PMEL), Sylvia Musielewicz (UW, JISAO), Jan Newton, John Mickett (UW, APL), and Christopher Sabine (Univ. Hawaii); http://pmel.noaa.gov/co2/story/La+Push; http://pmel.noaa.gov/co2/story/Cape+Elizabeth; PMEL contribution number 4978.

CO_2 sensors have measured atmospheric and surface seawater xCO_2 (mole fraction of CO_2) at three-hour intervals on the surface Ćháʔba· mooring off La Push since 2010, mostly from spring through fall, and year-round on the National Data Buoy Center mooring 46041 at Cape Elizabeth since 2006. Both time series had gaps during 2018, with Ćháʔba· measurements spanning late May through December and Cape Elizabeth late January through December, but missing seawater xCO_2 from 5 April to 15 August; Figure 8).

The full 2018 atmospheric xCO_2 range was 394–465 ppm (parts per million) at Ćháʔba· (Figure 8A) and 383–468 ppm at Cape Elizabeth (Figure 8B). Using all available observations at each mooring, average values for atmospheric xCO_2 were similar to the globally averaged marine surface air of 407 ppm for 2018 (NOAA/ESRL[1]). Gaps in observations at Ćháʔba· occurred from January to late May, during months when atmospheric xCO_2 values are higher. Without this

[1] NOAA/ESRL website: https://www.esrl.noaa.gov/gmd/ccgg/trends/gl_data.html; accessed April 17, 2019.

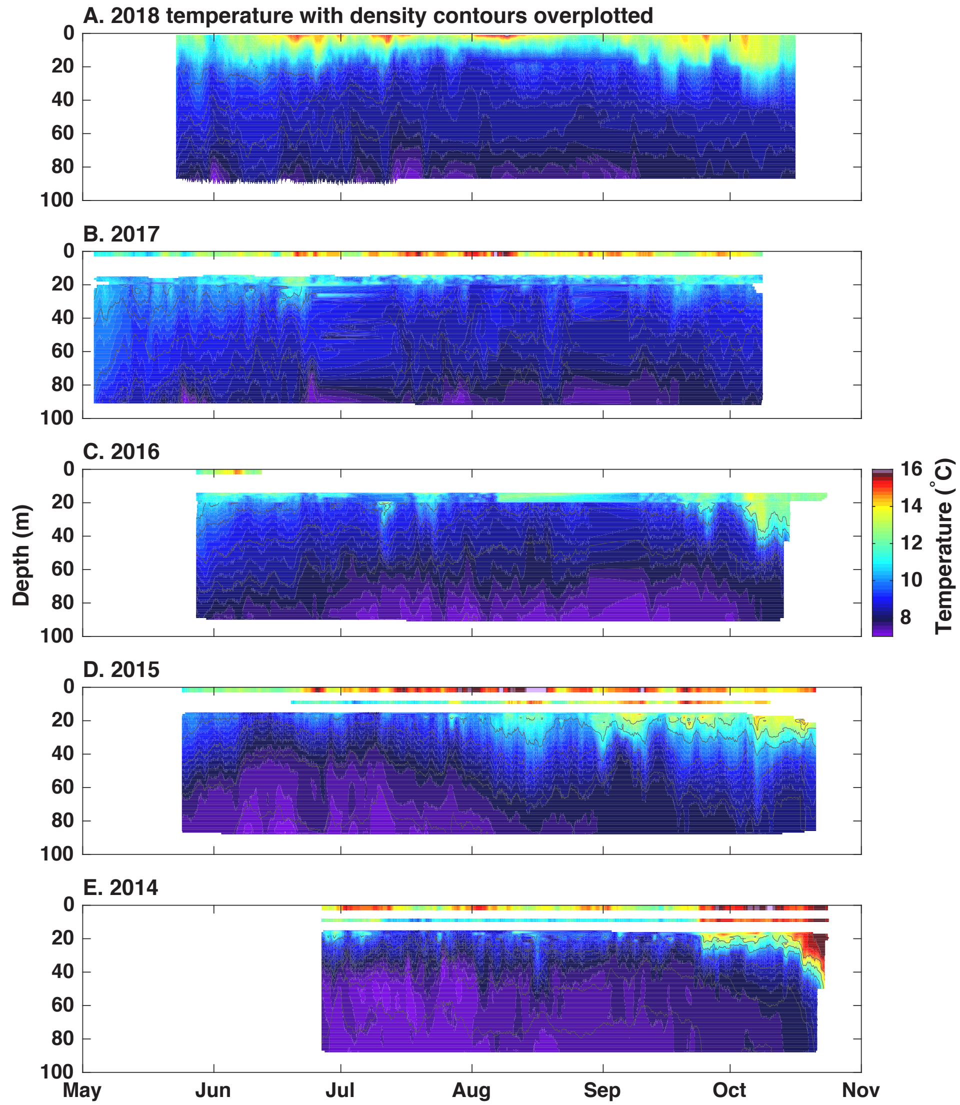


Figure 7. Water-column temperature with density contours overplotted for (A) 2018, (B) 2017, (C) 2016, (D) 2015, and (E) 2014.

gap, the Ćháʔba· average would likely be larger than the global mean due to the timing of missed observations when values are high. The summertime minimum was earlier at Cape Elizabeth in the relatively complete 2018 time-series. These data are preliminary, so it is possible that these patterns will change after real-time data are postprocessed and finalized.

Surface seawater xCO_2 ranges were 93–481 ppm at Ćháʔba· (Figure 8C) and 179–613 ppm at Cape Elizabeth (Figure 8D) during 2018. Average surface seawater xCO_2 values have been below the average atmospheric values for all years at both sites (Tables 1 and 2), and seawater xCO_2 variability is roughly an order of magnitude higher than atmospheric xCO_2 variability (as reflected by standard deviations). During 2018, average seawater xCO_2 was higher than during 2017 at Cape Elizabeth (we note a tendency for higher average xCO_2 values during years with lower data return, as 2018 was). In contrast, mid-July to mid-October average seawater xCO_2 values at Ćháʔba· were similar to those of 2012–14 and 2016.

Cape Elizabeth	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Atmosphere	386±8	390±7	390±6	389±7	393±6	394±8	397±8	402±7	403±8	402±8	406±6	407±8	405±7
Seawater	362±66	323±70	321±68	314±64	356±52	306±80	346±55	280±61	305±74	327±59	344±65	304±70	338±69
Data return	50%	89%	96%	82%	94%	107%	42%	90%	100%	69%	59%	73%	94%(atm), 58% (sw)

Table 1. Average (± standard deviation, SD) surface seawater (sw) and atmospheric (atm) xCO_2 values at Cape Elizabeth (year-round) moorings for all available years in parts per million (ppm). Percent data return is based on the assumption of measurements every three hours throughout the year and provides a simple metric for how much of each year is represented (during part of 2011, measurement frequency increased to hourly, resulting in a return over 100%).

Ćháʔba·	2010	2011	2012	2013	2014	2015	2016	2017	2018
Atmosphere	388±6	387±7	392±8	394±7	395±7	396±7	n.a.	404±8	406±7
Seawater	353±87	332±76	297±51	281±67	276±72	321±51	n.a.	271±91	287±66
Data return	100%	101%	108%	128%	100%	100%	0%	100%	100%

Table 2: Average (±SD) surface seawater and atmospheric xCO_2 values at Ćháʔba· (mid-July to mid-October) for all available years in parts per million (ppm). Percent data return is offered as a metric for how much of the mid-July to mid-October period was represented by measurements each year. Percent data return is based on the assumption of measurements every three hours throughout the year and provides a simple metric for how much of each year is represented (during part of 2011, measurement frequency increased to hourly, resulting in a return over 100%).

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

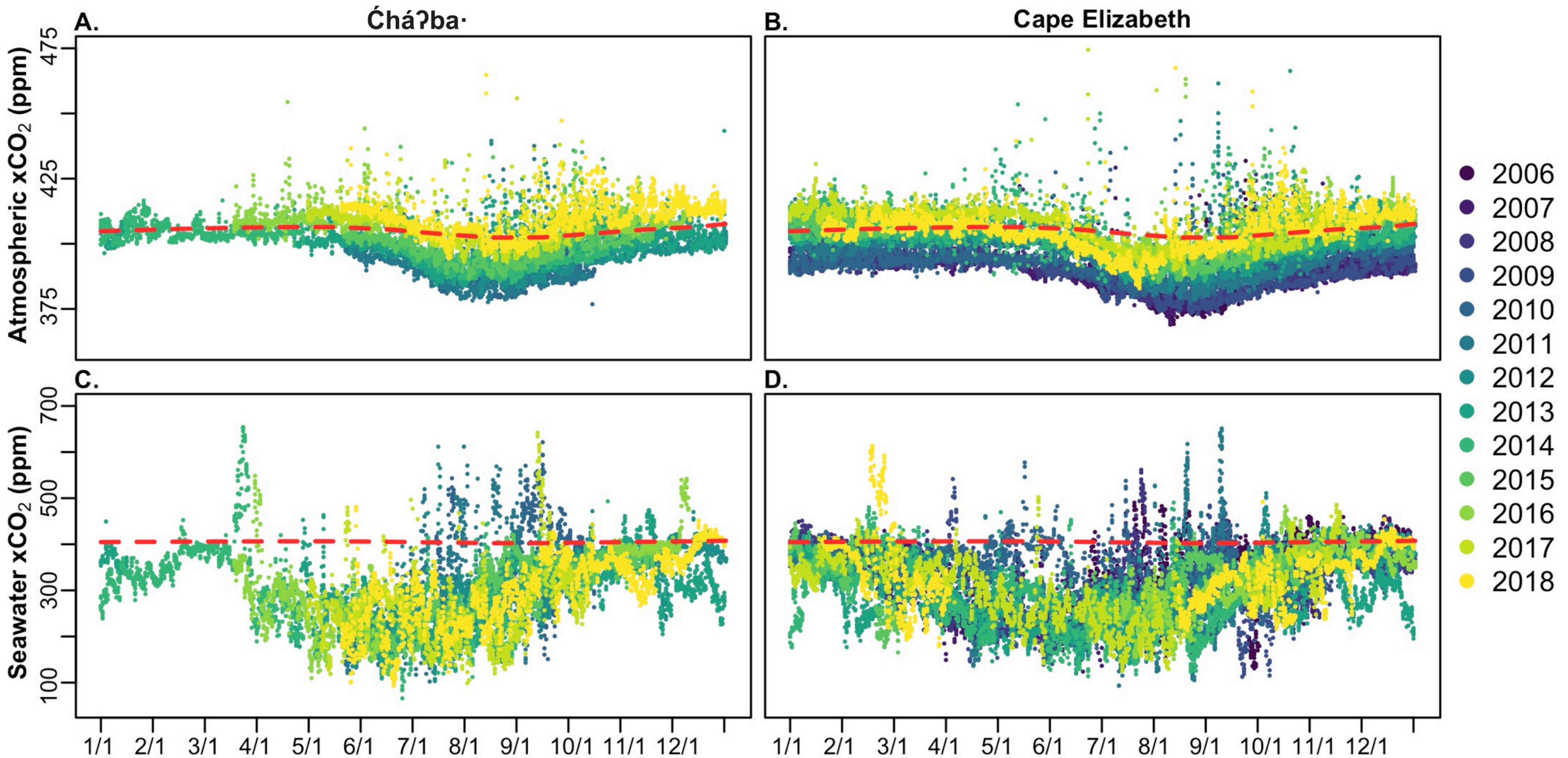


Figure 8. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater (A, B) and in surface seawater at 0.5 m depth (C, D) on the surface Ćháʔba· mooring off La Push, WA (A, C), and on the NDBC mooring 46041 off Cape Elizabeth, WA (B, D). Monthly mean atmospheric xCO_2 values for globally averaged marine surface air are shown by the dashed line in each panel (NOAA/ESRL[1]). Typical uncertainty associated with quality-controlled measurements from these systems is <2 ppm for the range 100–600 ppm and increases for values between 600 and 1,000 ppm.

CALL-OUT BOX: Washington Coast hypoxic events

The Ćháʔba· buoy off La Push has frequently recorded low levels of DO in waters 20 m off of the seafloor in the late summer and early fall (PSEMP Marine Waters Workgroup 2016, 2017, 2018). These concentrations usually reach hypoxic levels (<2.0 mg/L). These events were clearly evident from 2018 observations, with three pulses of extremely low-DO (<0.5 mg/L) water. Although discussed in previous reports, here we present more evidence of the location and cause of these events (Figure 9).

The hypoxic intervals (Figure 9A) are associated with northward-flowing bottom water (Figure 9C, B), which in turn is related to increased winds to the north (Figure 9C). Three intervals of low DO occurred after bottom water started flowing to the north. By integrating the water velocity backwards from the onset of northerly flow, we find that the bottom water originated from the south. The first interval experienced a relaxation of the upwelling winds from the north (Figure 9C), and was associated with weak directionless winds. Levels of DO dropped to near-anoxic levels coincident with the change in wind direction. The second event experienced upwelling-favorable winds and stronger currents to the north, but DO levels were not quite as low as the first event. The last event is suggestive of a weakening source pool: despite strong currents to the north, the minimum DO values are higher with values <1 mg/L only observed for two days.

These observations are consistent with results from Siedlecki et al. (2015) that describe a region off Cape Elizabeth that repeatedly experiences hypoxia year after year—and this remains true through 2018 (Siedlecki, pers. comm.). The net advection implied by deep currents (not shown) suggests that some of the hypoxic water off La Push may have originated at the location identified in Siedlecki et al. (2015). In September 2005, the pool was centered on 47.5°N with a minimum value of 1 mg/L, while in late September 2006 the 1-mg/L isoline spanned 47–47.7°N.

These intermittent periods of hypoxia generated by advection along the shelf are important locally for benthic organisms. This low-DO shelf water can be transported north into the Strait of Juan de Fuca, which is a source for Puget Sound via Admiralty Inlet.

Authors: Zoltan Szuts (zszuts@apl.uw.edu), John Mickett, Jan Newton (UW, APL), and Samantha Siedlecki (UCONN); http://www.nanoos.org; https://nwem.apl.washington.edu/

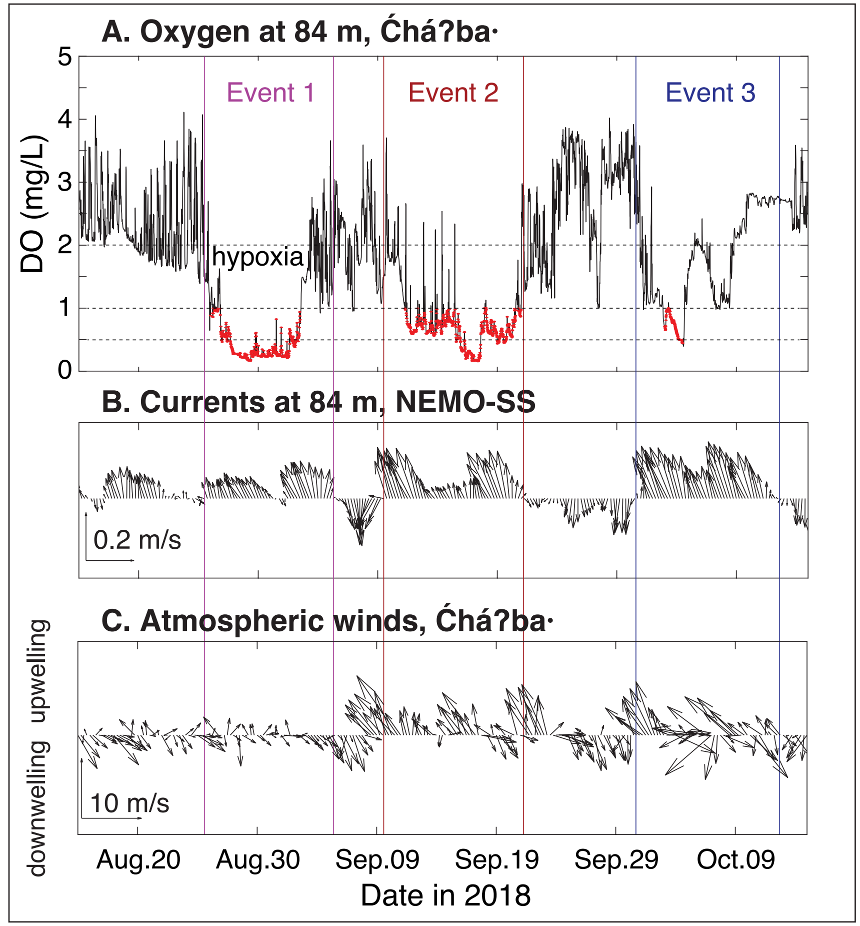


Figure 9. Relationship between dissolved oxygen, currents, and winds at the mooring site from 15 August – 15 October 2018. (A) Dissolved oxygen at 84 m at Ćháʔba·, with samples below 1 mg/L marked in red, and dashed reference lines for hypoxic levels (<2 mg/L), 1 mg/L, and 0.5 mg/L. (B) Currents at 84 m from the NEMO subsurface mooring, where the vector points in the direction that the water is moving. The currents are 24-hour low-pass filtered to remove tidal fluctuations. (C) Atmospheric winds at Ćháʔba·, where the vector points in the direction that the wind is moving (up is north) and is shown every six hours.

4. River inputs

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

A. Fraser River

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/index_e.html

Snowpack in the Fraser River watershed reached slightly above-normal levels (108%) in April 2018, due in part to La Niña conditions in the equatorial Pacific Ocean which generally lead to cooler- and wetter-than-normal weather in the Pacific Northwest. During the end of April and the first half of May, however, air temperatures shifted dramatically, with observations up to 5–10°C above normal across most of British Columbia, resulting in rapid snowmelt in lower and middle elevations (BCRFC 2018). These warm conditions resulted in the peak of spring runoff occurring nearly one month earlier than normal and 3,920 m^3/s above the historical median, and produced some flooding of low-lying areas (Figure 10). This pulse of snowmelt runoff was short-lived, and flows were briefly below normal (<25%) by mid-June, though rebounded temporarily by the end of the month due to further melting of higher-elevation snow. Beginning in July, flows dropped below normal (<25%) and remained there due to prolonged hot and dry conditions, and did not rebound until early November. A return to more typical precipitation, punctuated by a series of “atmospheric river” events in November, brought Fraser River flows within and often above the historic median through the remainder of the year.

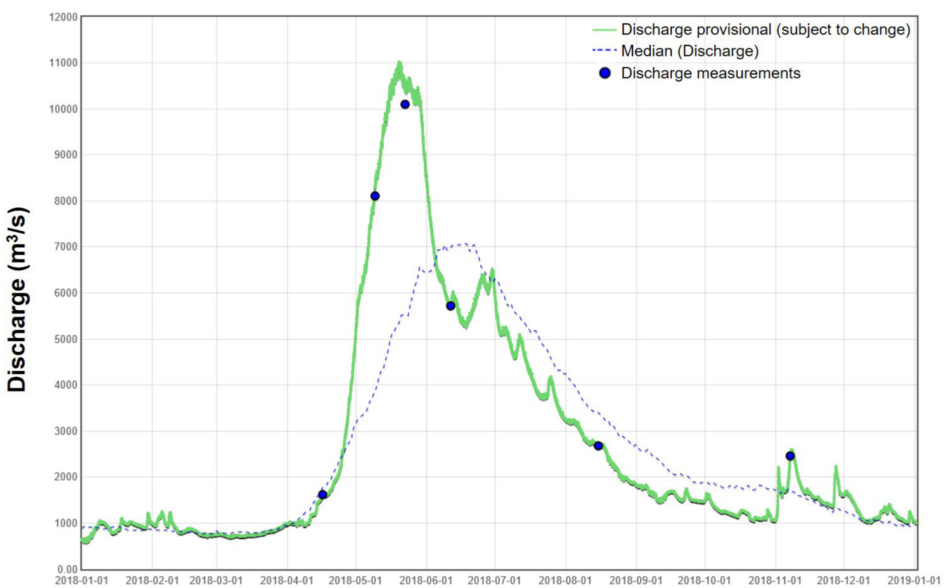


Figure 10. Fraser River daily discharge at Hope, B.C. (08MF005), for 2018, compared to the median value for the period of record (1912-2016). (Note: 1 m^3/s = 35.3 ft^3/s). Blue dots show site visits for discharge measurements.

4. River inputs (cont.)

B. Puget Sound rivers

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

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

Conditions in Puget Sound watersheds during 2018 developed similarly to those of the Fraser watershed in British Columbia. Above-normal precipitation interspersed with notable storms in early February and April kept streamflow conditions at or well above normal, depending on the intensity of the storm. La Niña conditions were present through much of the 2017–18 winter and 2018 early spring, leading to the accumulation of an above-average snowpack (111%) by the beginning of April. A shift to warm yet dry conditions occurred in late April and early May, causing rapid snowmelt and the onset of spring runoff (OWSC 2018). Many Puget Sound river flows reached levels much above normal, were generally early compared to historical means (Figure 11), and were contemporaneous with the Fraser River (Figure 10). A combination of thunderstorms and high-elevation snowmelt produced additional runoff peaks during periods of hot weather in June, though in most cases river flows did not reach levels observed the previous month. In most Puget Sound watersheds, these spring runoff events were smaller than those from fall and winter storms, but coupled with flows from the Fraser River they still contribute significantly to the total freshwater input to Puget Sound. In July, watersheds draining to Puget Sound started exhibiting the effects of early snowmelt and reached levels below normal, particularly watersheds draining the Olympics and to the south Puget Sound. As hot and dry conditions persisted throughout the remainder of the summer, flows from nearly all rivers draining to Puget Sound were much-to-severely below normal by early September or, in some cases, the latter half of October. All rivers recovered dramatically when precipitation from a series of strong-to-moderate "atmospheric river" events arrived at the end of October and November. Despite summer deficits, all rivers draining to Puget Sound exceeded their median annual cumulative discharges.

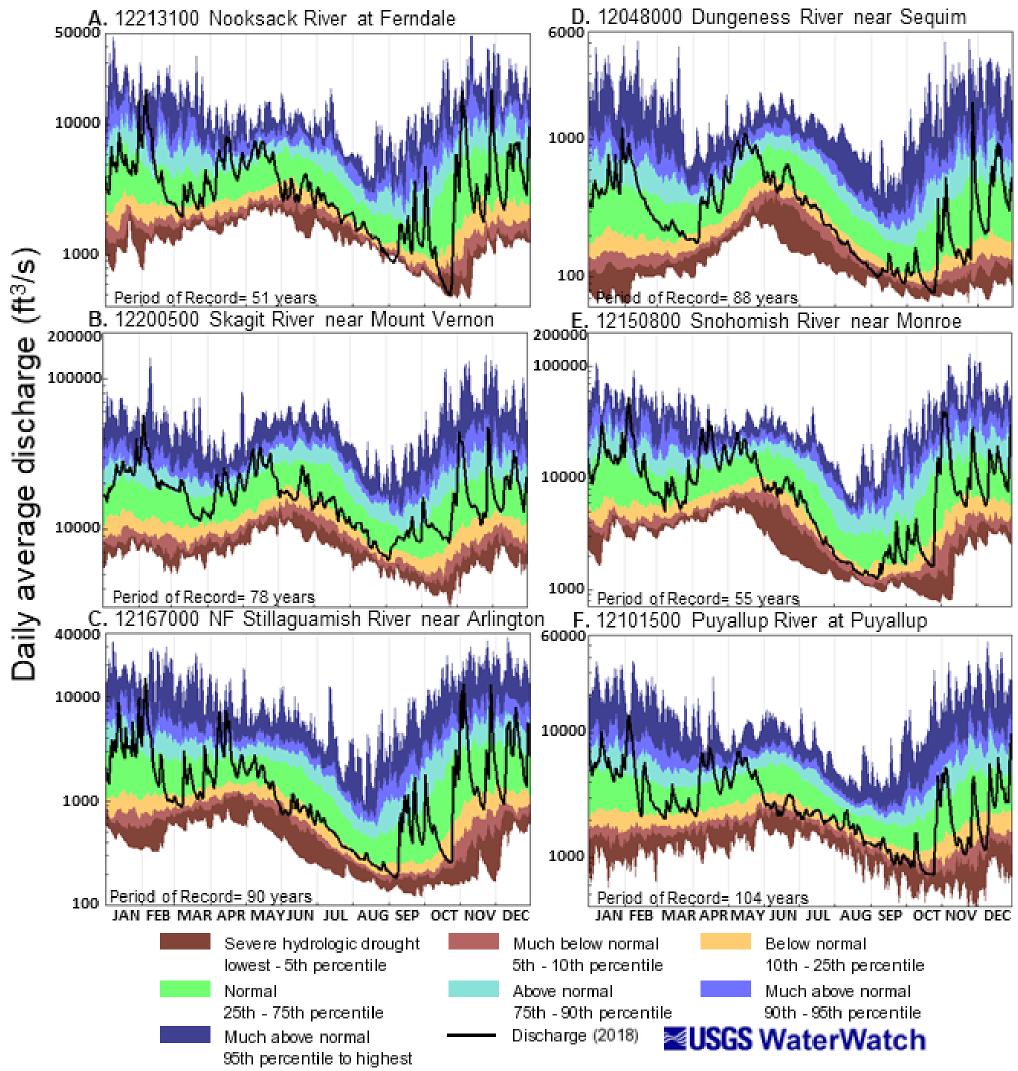


Figure 11. Daily average river discharge (ft³/s) at stations on the Nooksack (A), Skagit (B), North Fork (NF) Stillaguamish (C), Snohomish (D), Dungeness (E), and Puyallup (F) Rivers in 2018, compared to period of record percentile classes. (Note: The period of record varies for each station and is listed 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 that support Puget Sound's marine life. Many marine organisms have developed tolerances and life-cycle strategies for specific thermal and saline conditions. Nutrients and chlorophyll give insight into the production of organisms at the base of the food web. Phytoplankton are assessed by monitoring chlorophyll-*a*, their photosynthetic pigment. In Puget Sound, like most marine systems, nitrogen nutrients sometimes limit phytoplankton growth. On a mass balance, the major source of nutrients is from the ocean; however, rivers and human sources also contribute to nutrient loads. Dissolved oxygen in Puget Sound is quite variable spatially and temporally, and can quickly shift in response to wind, weather patterns, local biological processes, and upwelling influence via mixing at sills. In some parts of Puget Sound, dissolved oxygen is measured intensively to understand the connectivity between hypoxia and large fish kills. Dissolved oxygen is also an indicator of biological production, respiration, and consumption of organic matter, and a component for understanding the health of the food web.

A. Puget Sound long-term stations

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

A.i. Temperature and salinity

Source: Julia Bos (jbos461@ecy.wa.gov), Christopher Krembs, Skip Albertson, Mya Keyzers, and Allison Brownlee (Ecology)

Temperature in the upper 50-m water layer of Puget Sound was warmer than normal in 2018 (Figure 12A). An extended cold period from late February through March yielded cooler-than-normal water temperatures at most sites (with the exception of northern areas), yet the Sound-wide temperature anomaly remained slightly warmer than normal. Record warm air temperatures from May through August meant that Puget Sound summer water temperatures were higher than normal during this time, and they remained higher than normal in November and December in conjunction with milder winter weather and El Niño conditions. Water temperatures during the warmer-than-normal period in 2018 were similar to 2017, but not as anomalously warm as in 2015 and 2016.

Puget Sound (the upper 50-m water layer) was fresher than normal during the first half of 2018 and saltier than normal during most of the second half of the year (Figure 12B). Warm air temperatures

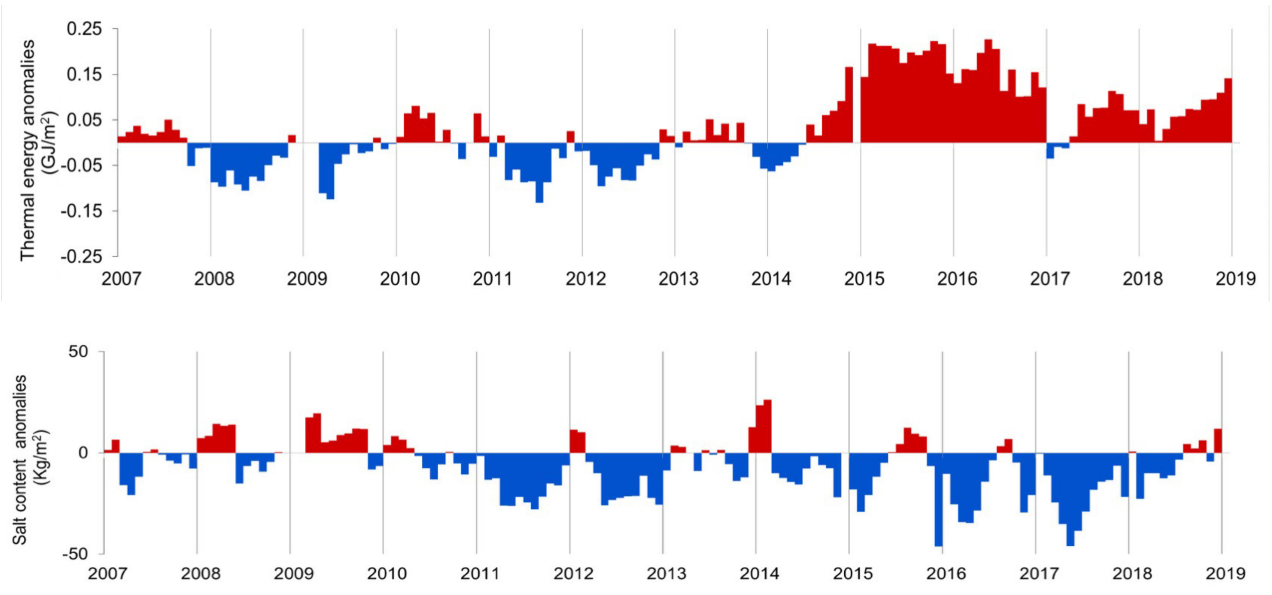


Figure 12. Puget Sound monthly temperature and salinity variation displayed as Sound-wide anomalies (columns) for (A) thermal energy and (B) salt content in the 0–50-m water layer from 2007–18. For monthly anomalies, blue = lower, red = higher. Monthly anomalies are calculated from site-specific monthly averages using a reference baseline from 1999–2008.

in early spring prematurely melted mountain snowpack, leading to higher-than-normal river flows that were also fed by record rain in late March and April (the second-wettest on record). These conditions lowered salinity at many sites to fresher-than normal conditions. This spring pattern is similar to that seen in every year from 2015 to 2017. Following the wet spring, a dry period from May through August set a new record for the driest summer on record. Puget Sound salinity responded to the lack of freshwater inputs, showing generally saltier-than-normal conditions through December.

A.ii. Dissolved oxygen

Source: Julia Bos (jbos461@ecy.wa.gov), Christopher Krembs, Skip Albertson, Mya Keyzers, and Allison Brownlee (Ecology)

Ecology puts DO measurements into a Puget Sound-wide context by reporting these as a DO “deficit.” The DO deficit is the difference between the measured DO saturation value and the theoretical fully saturated value integrated over water column depths from 20 m to near bottom, not including supersaturated results. When the DO deficit is high, measured DO in the water column is low (i.e., there is a large deficit between the amount of oxygen in the water and the amount that it could hold if it was fully saturated), and when the DO deficit is low, measured DO is closer to full saturation. Puget Sound-wide annual and monthly anomalies in the DO deficit are calculated from the monthly site-specific anomalies for all core monitoring stations deeper than 20 meters in Puget Sound (n = 14) relative to 1999–2008 baseline conditions.

Figure 13 shows the monthly Sound-wide anomalies in the DO deficit relative to baseline conditions. Overall, the DO deficit for 2018 was high and similar to the previous few years, continuing the pattern of lower-than-normal DO conditions which started in 2013. Prior to 2013, 2007 and 2008 also showed higher deficits, though not nearly as large as the current period. Deficits in 2009–11 varied between higher and lower patterns, while 2012, a La Niña year, showed a significantly lower deficit. Regionally, lower DO (higher deficit) was most persistent in Central Sound.

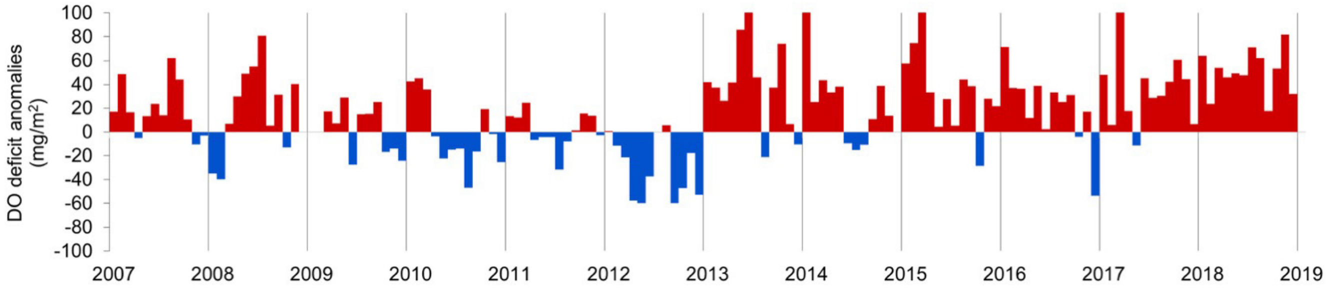


Figure 13. Puget Sound monthly dissolved oxygen variation displayed as Sound-wide anomalies (columns) of the DO deficit in the 20-m-to-bottom water layer from 2007–18. For monthly anomalies, blue = lower, red = higher. Monthly anomalies are calculated from site-specific monthly averages using a reference baseline from 1999–2008.

5. Water quality (cont.)

A.iii. Nutrients and chlorophyll

Source: Christopher Krembs (christopher.krembs@ecy.wa.gov), Skip Albertson, Julia Bos, Mya Keyzers, Allison Brownlee, and Carol Maloy (Ecology); https://ecology.wa.gov/Research-Data/Monitoring-assessment/Puget-Sound-and-marine-monitoring/Eyes-over-Puget-Sound

Ecology monitors nutrient and chlorophyll-*a* concentrations monthly to reveal long-term patterns and trends in Puget Sound water quality. Regional and seasonal patterns are removed by comparing site-specific monthly baselines to the 50th percentile of observations from 1999–2008. The anomalies (departures from baseline) are averaged over 12 months and 27 stations to evaluate large-scale and lower-frequency patterns.

Figure 14A shows the interannual variation in median nitrate concentrations for Puget Sound surface waters (the upper 50-m water layer). Nitrate concentrations had been mostly declining since 2008, but 2018 concentrations were higher than the previous five years. Nitrate concentrations in surface waters are influenced by many factors, including the amount of upwelled oceanic water (which is high in nitrate), biological uptake, biogeochemical processes, inputs from land, and other human inputs. The DIN:P (dissolved inorganic nitrogen to phosphate) nutrient ratio in 2018 was not as high as in 2017, but still higher than previous years going back to 2009 (Figure 14B).

Figure 14C shows a declining trend in median chlorophyll (Chl-*a*) over the upper 50 m, a proxy for phytoplankton biomass. The silicate-to-dissolved-inorganic-nitrogen (Si:DIN) ratio is recognized as a eutrophication indicator (Turner et al. 2003) and has generally declined in Puget Sound over the last 19 years.

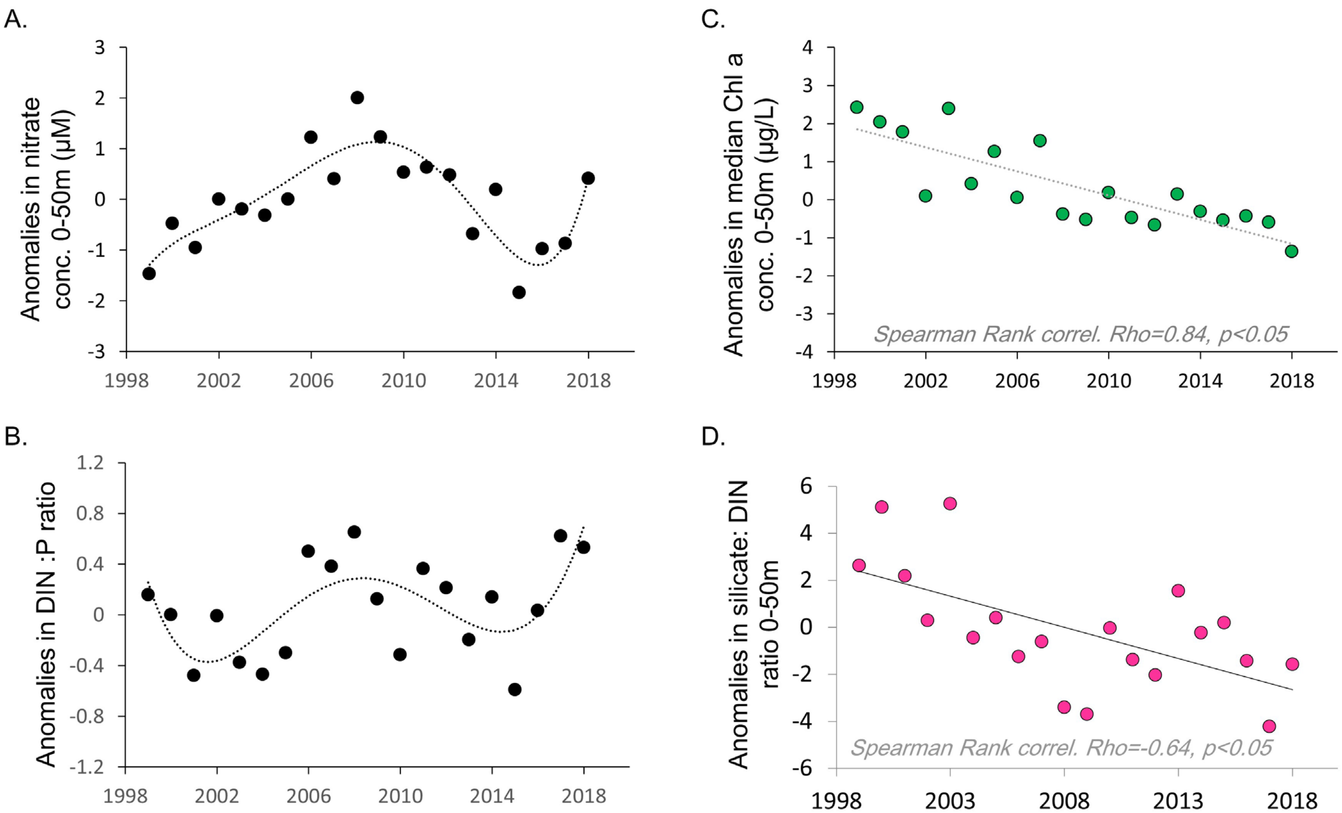


Figure 14. Interannual trends in (A) median nitrate concentration in the upper 50-m water layer, (B) DIN:P ratio, (C) depth-integrated chlorophyll (Chl-a) in the upper 30-m water layer, and (D) the ratio of silicate to dissolved inorganic nitrogen from 1999–2018.

5. Water quality (cont.)

A.iv. Water mass retention

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

Three governing factors need to occur for increased water exchange between the Pacific Ocean and Puget Sound: upwelling at the coast, sufficient riverine input, and weak tidal mixing. When these three factors align, intrusions of oceanic water spill over the sill at Admiralty Inlet and flow into Puget Sound at depth. Because the source of the incoming oceanic waters is upwelled waters from the coast, they are low in oxygen. In 2018, the three governing factors for hypoxic intrusions aligned more often than in either 2016 or 2017, as shown in Figure 15A. The figure is based upon the index created by Deppe (2017). Early onset upwelling (which started in February), record rain in April and early snowmelt in May (enabling sufficient riverine input to drive estuarine flow until June), combined with periods of weak tidal mixing over the Admiralty Inlet sill, contributed to the more-frequent favorable conditions for hypoxic intrusions in 2018.

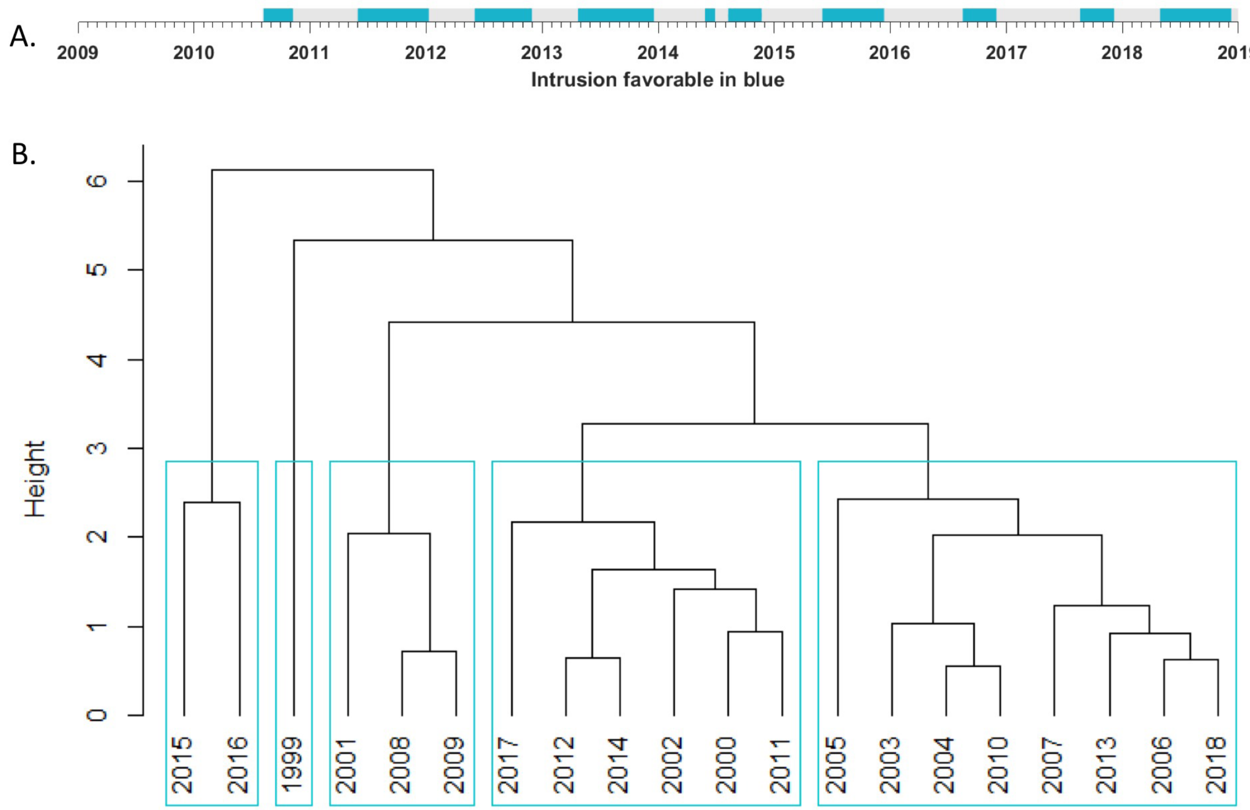


Figure 15. Annual variations in physical forcing show (A) hypoxic intrusion-favorable periods (blue coloration), and (B) cluster analysis of annual spring conditions that suggest prior years that may have been similar.

5. Water quality (cont.)

B. Puget Sound profiling buoys

Profiling buoys take frequent (1–4 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 OA Center: South Hood Canal (Twanoh), central Hood Canal (Hoodsport), Dabob Bay, Admiralty Inlet (Hansville), Main Basin (Point Wells), and Southern Puget Sound (Carr Inlet).

B.i. Temperature

Source: Zoltan Szuts (zszuts@apl.uw.edu), Jan Newton, and John Mickett (UW, APL); http://nwem.ocean.washington.edu; http://www.nanoos.org

Observations from the UW ORCA mooring program show that 2018 temperatures were warmer in Puget Sound than the climatological averages, but with substantial differences depending on location (Figure 16). Hood Canal (Hoodsport and Twanoh) had positive temperature anomalies more consistently throughout the year than South Sound (Carr Inlet), but both show the effects of a cool period in March, likely driven by cool air temperatures in late February. All locations showed positive temperature anomalies over the full water column by the end of the year.

Hood Canal started 2018 with warm anomalies throughout the water column. The early-March cold spell resulted in full-depth cold anomalies at the well mixed Admiralty Inlet mooring (Hansville, not shown), but only reaching the upper 20 m at Hoodsport and Twanoh. Warm anomalies returned in spring, then decreased over summer. Twanoh showed moderate surface cold anomalies toward the end of the summer. The seasonal deep-water renewal (warm and salty) was apparent at Hoodsport starting at the bottom in early September, reaching the surface by the end of the month. This renewal signal, warmer than average, took a few weeks longer to be seen at Twanoh. Depth-uniform warm anomalies of 0.5°C persisted through the end of 2018.

In contrast, both Carr Inlet and the Main Basin (Point Wells, not shown) showed a longer-lasting effect of the cooler-than-average March conditions that persisted into May, though the cool anomalies were weaker than those observed in Hood Canal. Conditions changed to slightly warmer-than-normal conditions by later summer, increasing in intensity by December.

These temperature variations reflect the diverse oceanographic characteristics of Puget Sound's sub-basins, but may be of a magnitude to consider for biological organisms. Hood Canal, with strongly stratified waters and slow circulation flushed annually by the seasonal renewal, responds to atmospheric forcing differently than the Main Basin, with stronger mixing that intensifies as this water feeds South Sound.

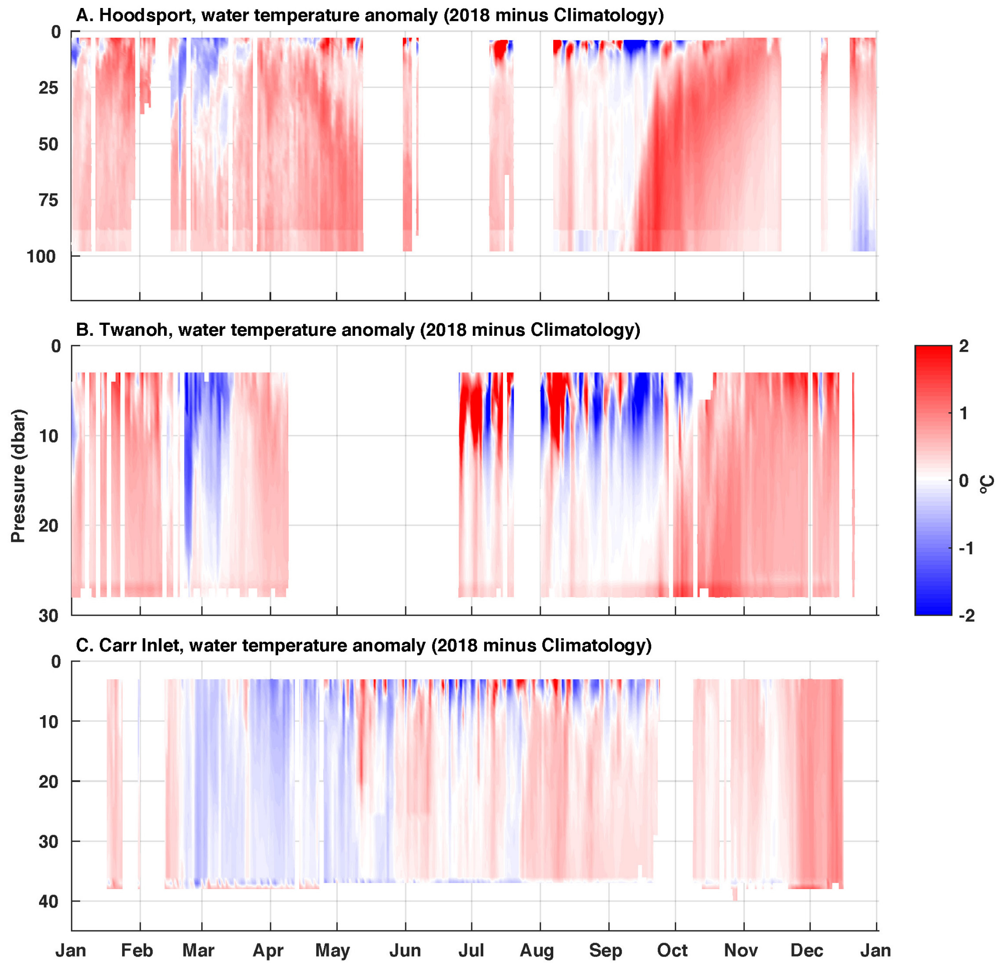


Figure 16. Water temperature anomalies in 2018 relative to the climatological average over 2005–17 for three locations in Puget Sound. (A) Hoodsport mooring, in mid-Hood Canal. (B) Twanoh mooring, in south Hood Canal. (C) Carr Inlet mooring, in south Puget Sound.

B.ii. Salinity

Source: Zoltan Szuts (zszuts@apl.uw.edu), Jan Newton, and John Mickett (UW, APL); http://nwem.ocean.washington.edu; http://www.nanoos.org

During 2018, observations at most UW ORCA moorings showed higher-than-average salinity, but with locational differences (Figure 17). Compared to the climatologies, the beginning of the year had average salinities, with lower values (fresher) during March when surface waters were cooler than average (Figure 16). Saltier-than-average conditions developed by April and were particularly pronounced from fall to the end of year. Hood Canal salinities returned to normal from June to September, whereas saltier-than-average conditions persisted in Carr Inlet from April through the end of the year.

Salinities at all three Hood Canal moorings were from average to one standard deviation above average throughout the water column for most of the year, with the last few months of 2018 consistently >1 SD above normal. At Hoodsport (Figure 17), the late-September renewal event increased salinities from normal to nearly 2 SD above normal, before decreasing to ~1 SD above normal for the rest of the year.

The Carr Inlet site in South Puget Sound started the year with average salinity before increasing to 1 SD above normal. The saltier-than-average conditions persisted through spring and summer, increased to 2 SD in October, and then well beyond that for the rest of the year. Deep salinity continued to increase until mid-November, a month later than normal. Carr Inlet salinity is driven strongly by river flow; salinity continued to be well explained by a single-layer mixing model (PSEMP Marine Waters Workgroup 2017, Figure 19) that estimates depth-averaged salinity from Nisqually and Puyallup river flows. The combination of salty conditions early in the year and delayed fall precipitation resulted in the saltiest water (30.5 PSU) recorded at this site. The extremely saline conditions at the end of 2018 precondition 2019 to be exceptionally salty in South Sound. The Point Wells site in the Main Basin had a remarkably similar pattern to Carr Inlet, with deep salinity the saltiest from our records there.

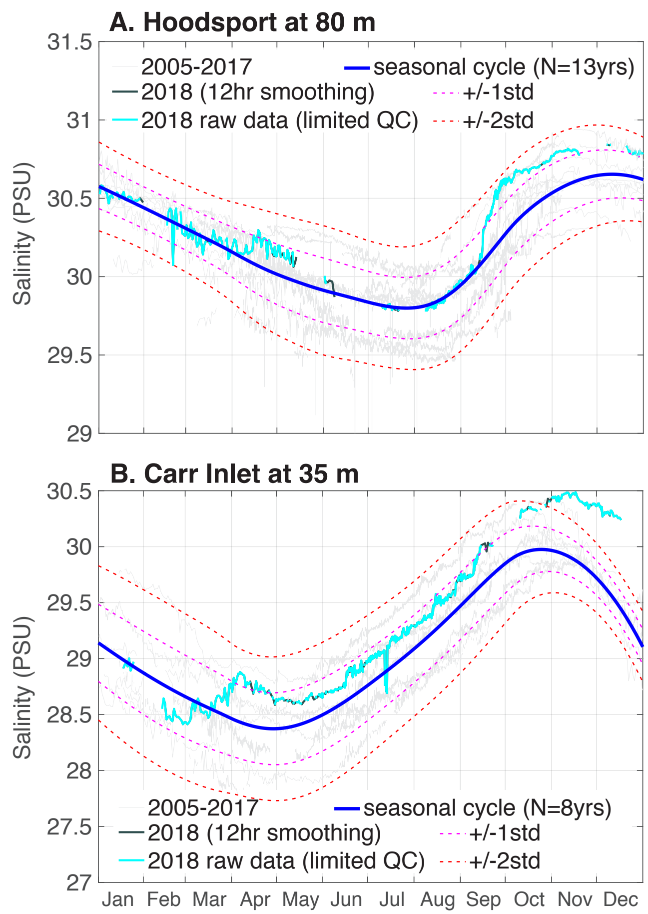


Figure 17. Near-bottom salinity records over 2018, comparing the current year (light blue), previous years (light gray), and seasonal cycle (average in dark blue, ±1 SD in dotted magenta, ±2 SD in dotted red). (A) Hoodsport mooring at 80 m, in central Hood Canal. (B) Carr Inlet mooring at 35 m, in south Puget Sound.

B.iii. Dissolved oxygen

Source: Zoltan Szuts (zszuts@apl.uw.edu), Jan Newton, and John Mickett (UW, APL); http://nwem.ocean.washington.edu; http://www.nanoos.org

DO anomalies during 2018 were quite variable over the year (Figure 18). Although hypoxia at southern Hood Canal was more extensive than observed during 2017, it was not as severe as 2015–16 (Figure 19). No fish kill events were observed in 2018.

Most sites began 2018 with lower-than-average DO; in March, this shifted to positive anomalies (higher DO) coinciding with observations of cooler and fresher anomalies (Figures 16–19). The March event was associated with particularly cool, windy, and rainy weather in late February that mixed oxygenated waters down. This was followed by in situ oxygen production, as indicated by high chlorophyll levels (not shown), aided by warm and sunny weather in mid-March. Lower-than-average DO developed during summer, possibly related to respiration. DO anomalies were most negative subsurface, from 5–10 m, where the chlorophyll maximum is typically observed, possibly due to stronger respiration or weaker production than average in 2018. This subsurface signal is more muted in Carr Inlet than either Hood Canal location, consistent with the well mixed waters of Carr Inlet. The seasonal renewal in September is very evident at both Hood Canal sites, occurring first at Hoodsport and then at Twanoh, consistent with the warm, salty, and relatively more-oxygenated waters that intrude from the Pacific Ocean into Puget Sound. The intrusion signal is more diffuse in the more weakly stratified South Puget Sound.

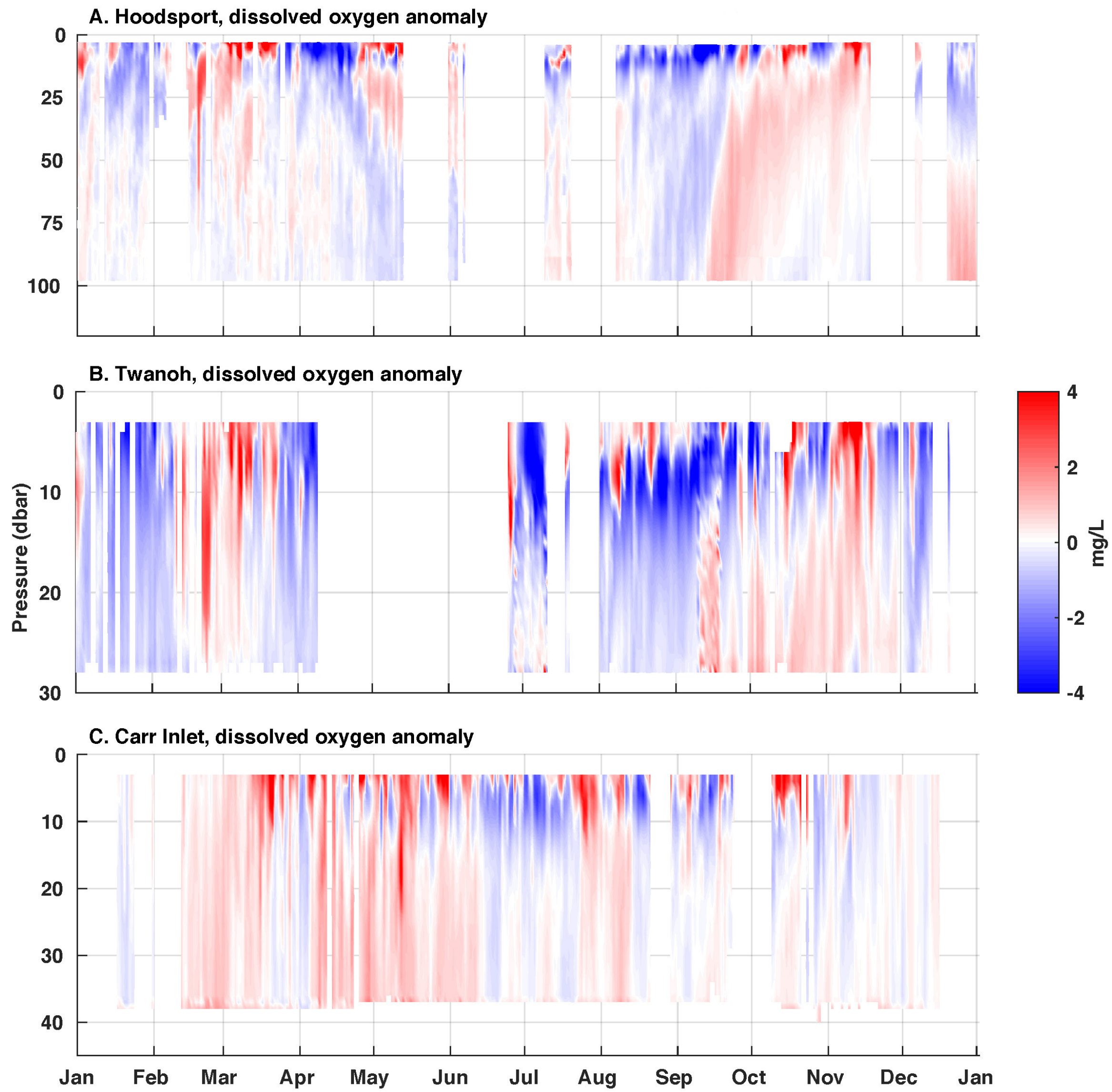


Figure 18. Dissolved oxygen anomalies in 2018 relative to the climatological average over 2005–17 for three locations in Puget Sound. (A) Hoodsport mooring, in mid-Hood Canal. (B) Twanoh mooring, in south Hood Canal. (C) Carr Inlet mooring, in south Puget Sound.

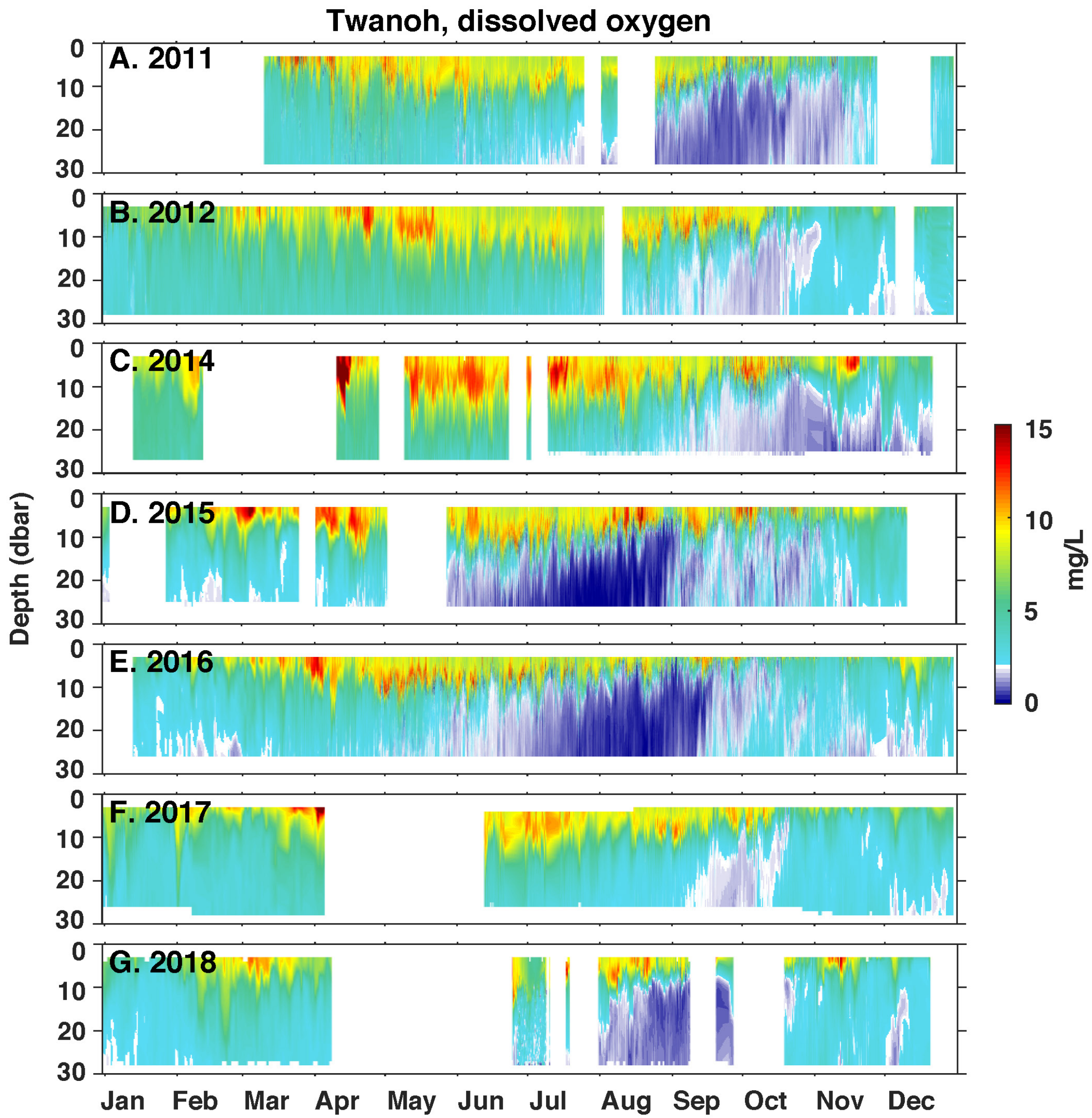


Figure 19. Time series of water column dissolved oxygen concentrations at the Twanoh ORCA mooring from 2011–18.

B.iv. Ocean and atmospheric CO_2 in Hood Canal

Source: Simone Alin (simone.r.alin@noaa.gov), Adrienne Sutton, Richard Feely (NOAA, PMEL), Sylvia Musielewicz (UW, JISAO), Jan Newton, John Mickett, Zoltan Szuts (UW, APL), and Christopher Sabine (Univ. Hawaii); http://www.pmel.noaa.gov/co2/story/Dabob; http://www.pmel.noaa.gov/co2/story/Twanoh; PMEL contribution number 4978.

CO_2 sensors have measured atmospheric and surface seawater xCO_2 (mole fraction of CO_2) at three-hour intervals on surface ORCA moorings in Dabob Bay since June 2011 and at Twanoh since July 2009. Both sites had data gaps from late January/early February to early May and 72–74% data return in 2018 (Figure 20).

During 2018, atmospheric xCO_2 at Dabob averaged 424±13 ppm with a range of 351–487 ppm. At Twanoh, xCO_2 averaged 422±15 ppm with a range of 389–517 ppm. Thus, average atmospheric values at both moorings were higher by 15–17 ppm than the 2018 global average for marine surface air of 407 ppm (NOAA/ESRL), despite three-month data gaps at both sites during winter/spring when atmospheric xCO_2 values are higher. Curiously, as with the coastal moorings, the more southerly of the pair of Hood Canal moorings also experienced a relatively lower rate of atmospheric xCO_2 increase during 2018.

Surface seawater xCO_2 at Twanoh had a range of 116–1,994 ppm in 2018, with an average of 445±233 ppm. At Dabob, 2018 surface seawater xCO_2 had a range of 137–1,479 ppm and averaged 419±250 ppm. While 2018 average surface seawater xCO_2 was higher at both Dabob and Twanoh than at Cape Elizabeth by the same margin as in 2017 (81–106 ppm), relative variability was even higher in Hood Canal in 2018 than on the coast, with 3.4–3.6 times higher standard deviations (cf. Table 1). The annual spring drawdown of xCO_2 after fall–winter highs occured during the period of missing observations, though it does not appear to have started as early in January as in 2016.

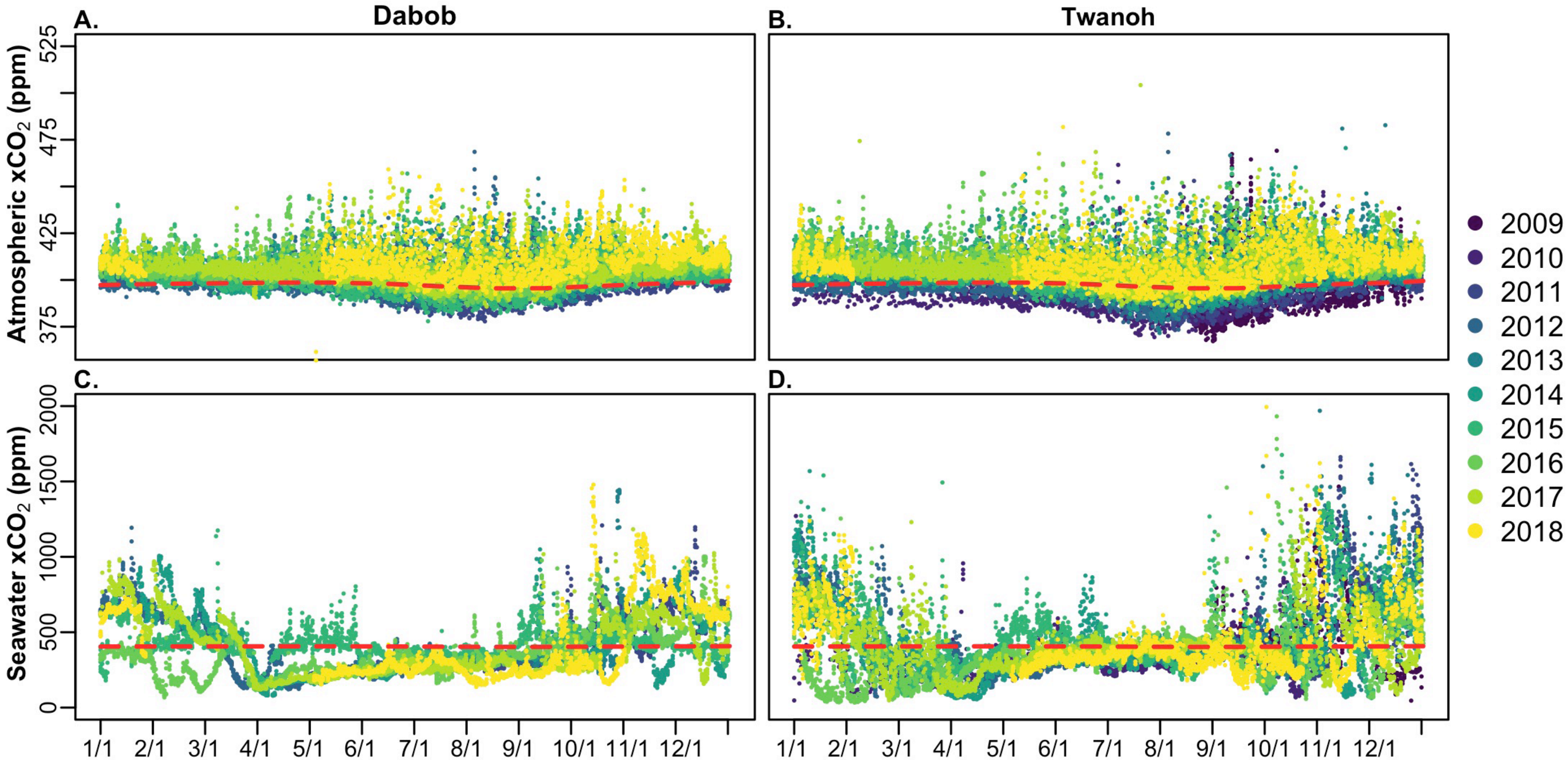


Figure 20. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater (A, B) and in surface seawater at 0.5-m depth (C, D) on the ORCA mooring in Dabob Bay (A, C) and on the ORCA mooring at Twanoh (B, D). Monthly mean atmospheric xCO_2 values for globally averaged marine surface air are shown by the dashed line in each panel (NOAA/ESRL[1]). Typical uncertainty associated with quality-controlled measurements from these systems is <2 ppm for the range 100–600 ppm, increases for values between 600 and 1,000 ppm, and is not well constrained above 1,000 ppm.

5. Water quality (cont.)

C. Central Basin long-term stations

Focusing on the Central Basin of Puget Sound, King County collects physical, chemical, and biological data twice a month at 12 open-water sites and two sites in Quartermaster Harbor. King County also collects monthly temperature, salinity, and nutrient data at 20 marine beach sites. Data may be accessed at http://green2.kingcounty.gov/marine/Download *and mooring data at* http://green2.kingcounty.gov/marine-buoy/Data.aspx *or by request.*

C.i. Temperature, salinity, and density

Source: Stephanie Jaeger (stephanie.jaeger@kingcounty.gov) and Benjamin Larson (KCDNRP); https://green2.kingcounty.gov/marine/Monitoring

Water temperatures in the upper water column (integrated 0–35 m) and deep depths (>75 m) were slightly cooler than normal in the first half of 2018 in the Central Basin (Figure 21A), with some variation between sites (not shown). However, from August through December 2018, warmer-than-normal temperatures were observed consistently across all sites, ranging from 0.4–1°C warmer in the upper water column and 0.3–0.7°C warmer at deep depths compared to the baseline mean (1997–2011). Although warmer than normal, these temperatures were not as warm as those observed during the marine heat wave of 2014–16. The pattern of cooler-than-normal conditions early in the year followed by warmer-than-normal conditions was similarly observed in 2017. Beach water temperatures were somewhat elevated from May to December 2018, coinciding with warmer-than-normal air temperatures.

Water-column salinity observations showed a different pattern in 2018 than in most recent years, with somewhat typical salinities at depth followed by saltier-than-normal conditions in the fall and winter (Figure 21B). Upper integrated water-column conditions were 0.2–0.8 PSU saltier than the baseline mean from October to December 2018, while deep waters were 0.1–0.4 PSU saltier than normal. This follows the period of dry conditions and low stream flows in the summer. Nearshore salinities were generally within observed ranges and somewhat elevated at some sites during low precipitation periods.

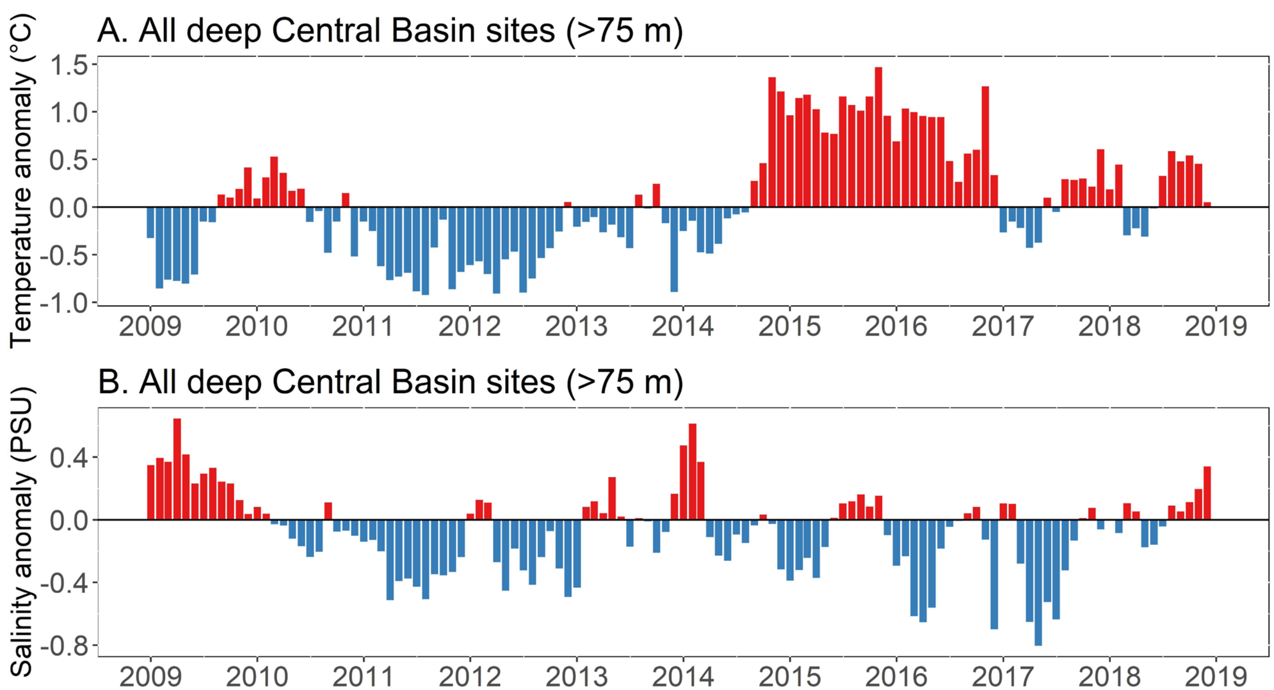


Figure 21. (A) Mean water-temperature anomalies from the last decade for the six deepest sites in the Central Basin, compared to a fixed baseline mean by month (1997–2011). Positive values (in red) indicate warmer-than-average conditions. (B) Mean salinity anomalies for the same sites and baseline dates. Positive values (in red) indicate saltier-than-average conditions at the end of 2018.

5. Water quality (cont.)

Wet conditions in early 2018 and again in the late spring resulted in lower surface salinities, producing strong density gradients near the surface exceeding 0.1 kg/m³ from 3–10 m (shown by stars in Figure 22). However, in the second half of 2018, along with drier conditions, water column stratification was less frequently observed than in recent years in the Central Basin. These more well mixed conditions could have influenced plankton dynamics in the summer and fall.

C.ii. Dissolved oxygen

Source: Stephanie Jaeger (stephanie.jaeger@kingcounty.gov) and Kimberle Stark (KCDNRP); https://green2.kingcounty.gov/marine/Monitoring

Observations from twice-monthly sampling in the Central Basin showed somewhat lower-than-normal DO levels throughout much of 2018. Deep-water (>75-m) DO levels across sites were 0.1–0.7 mg/L lower than the baseline mean (1997–2011), with the exception of August and December (Figure 23A). The lowest DO levels typically occur at depth in the fall in the Central Basin. In October 2018, deep DO levels were 4.7–5.5 mg/L across the Central Basin, about 0.3 mg/L below the baseline mean. At East Passage, where the lowest DO is typically observed in the mainstem, DO levels were slightly below 5 mg/L from 100 m and deeper in October (Figure 23B).

In the spring, deep-water DO levels remained above 7 mg/L across all sites and were, on average, 0.5 mg/L below the baseline mean. Spring conditions were generally less-oxygenated than the last two years, corresponding with higher salinities at depth. Near the surface, highly supersaturated DO conditions (>125% saturation or 12 mg/L at 10°C and 28 PSU) occurred from May to early June (shown in Figure 23B), and correspond to higher levels of chlorophyll and lower levels of nutrients (see section 5.C.iii, *Chlorophyll and nutrients*). Supersaturated periods were less frequent than typically observed, and followed the observations of generally lower chlorophyll values in 2018 in the mainstem of the Central Basin.

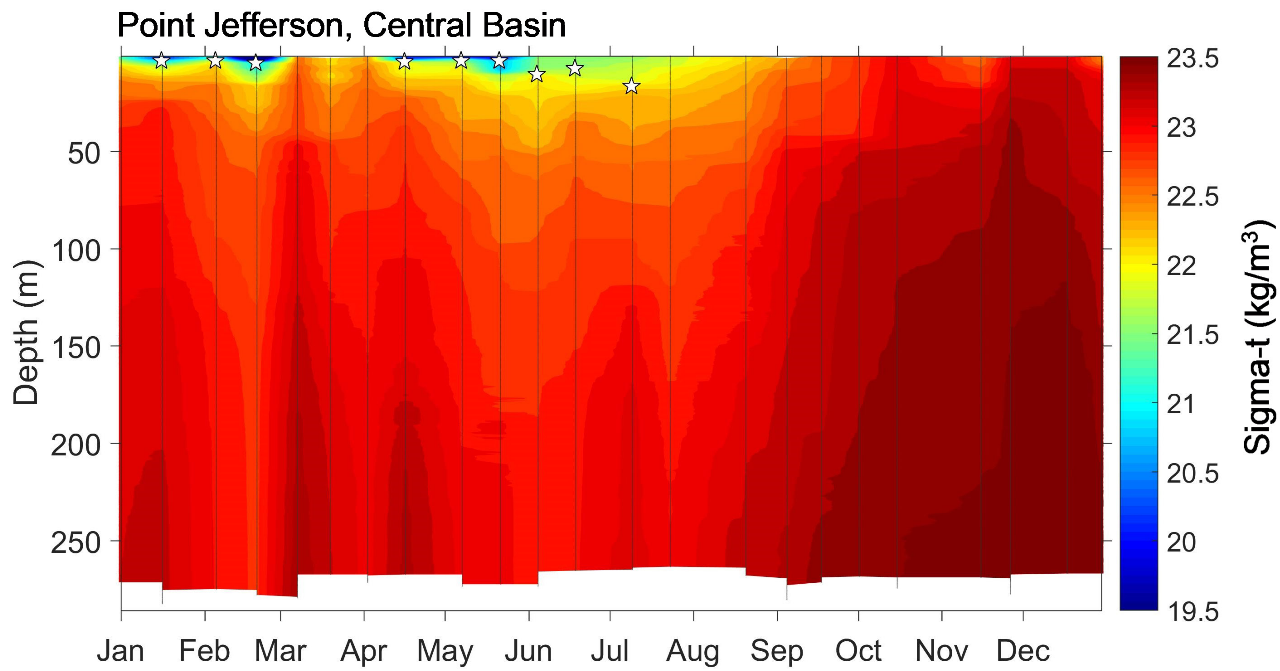


Figure 22. Density profiles near Point Jefferson, the deepest location in Puget Sound. Black vertical lines show when data were collected, and white stars indicate the depth of the sharpest density change that exceeds a threshold of 0.1 kg/m³ (as calculated in Moore et. al 2008).

5. Water quality (cont.)

In Quartermaster Harbor, which is very shallow and has longer flushing times, DO observations come from continuous mooring data sampled every 15 minutes. The inner harbor site showed typical conditions, changing as much as 10–15 mg/L in a single day. However, the outer harbor site at Dockton Park showed more frequent short periods of hypoxia from late July through early September than prior years (Figure 23C). These hypoxic periods lasted from two to six hours and typically occurred on an outgoing tide. Warmer-than-normal temperatures combined with decay of large phytoplankton blooms may have contributed to these conditions.

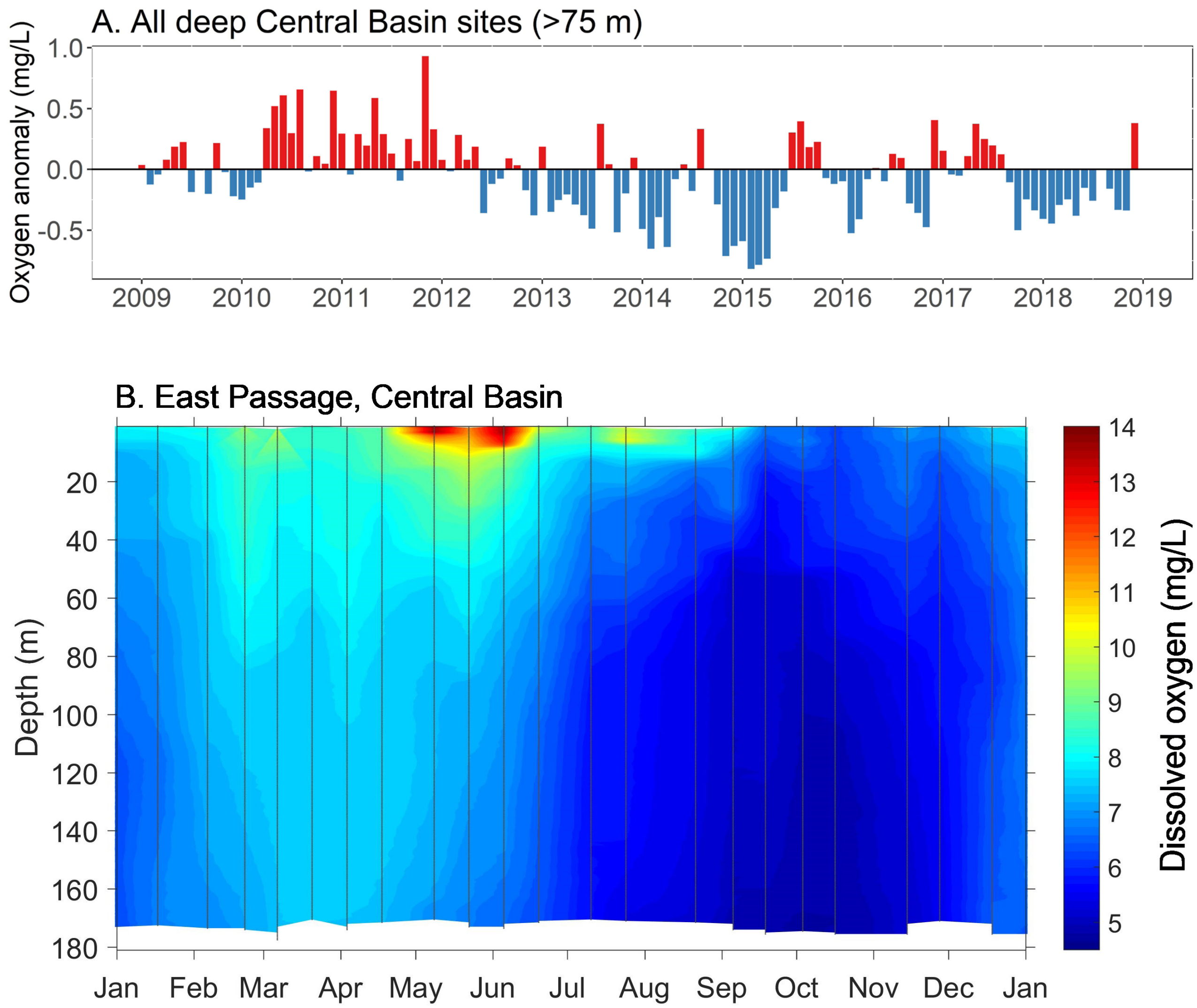


Figure 23. (A) Mean dissolved oxygen (DO) anomalies from the last decade for the six deepest sites in the Central Basin, compared to a fixed baseline mean by month (1997–2011). (B) Water column DO concentrations in East Passage. Black vertical lines show when profiles were collected.

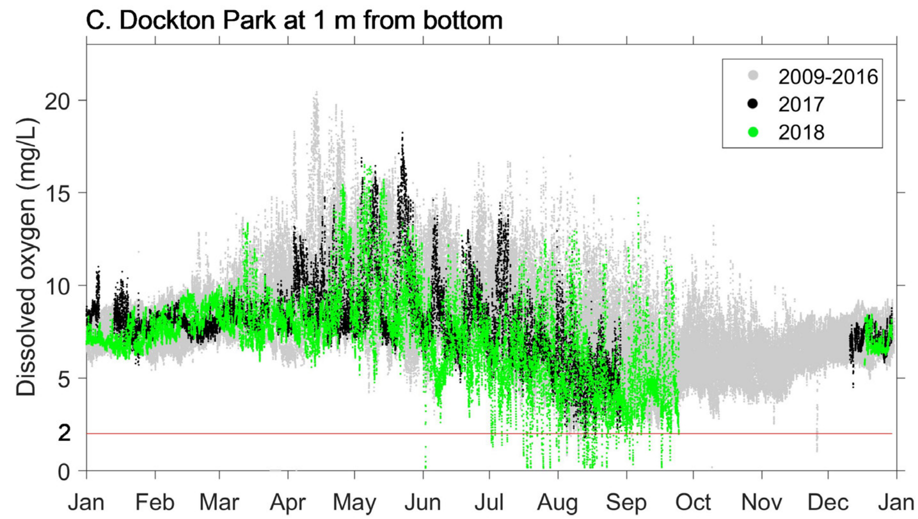


Figure 23C. Near-bottom mooring DO time series from Dockton Park (total water depth of 4–8 m), with all historical data for comparison.

C.iii. Chlorophyll and nutrients

Source: Kimberle Stark (kimberle.stark@kingcounty.gov) and Stephanie Jaeger (KCDNRP); http://green2.kingcounty.gov/marine/

The 2018 spring phytoplankton bloom was delayed in the Central Basin in 2018. Based on chlorophyll-*a* observations from both twice-monthly sampling and in situ moorings, the spring bloom did not occur until 7 May; however, it was larger than normal at all mainstem stations once initiated. One exception is that a small phytoplankton bloom occurred in March (evident during both sampling events) near Point Wells. The spring bloom typically occurs in April, and a delay in the timing of the spring bloom has not been observed since 2011.

Except for the spring bloom, 2018 chlorophyll-*a* levels were generally lower than baseline values from June through September throughout the Central Basin, excluding Quartermaster Harbor (Figure 24A). In addition, 2018 annual averages were the lowest since 2008 at most stations (Figure 24B). Quartermaster Harbor chlorophyll-*a* levels were lower than normal from March through June, which may have been related to nutrient limitation. Extremely low nitrate/nitrite levels (below detectable levels) were observed throughout the growing season, in addition to very low orthophosphate in May through August. Although Quartermaster Harbor nutrient levels were low in September, chlorophyll-*a* values were over two and three times as high as baseline values in both the inner and outer harbors, respectively.

Nutrients varied seasonally and surface values were correlated with chlorophyll-*a* levels. Nitrate/nitrite levels were higher than normal in April due to the delayed spring bloom, and lower than normal in May (Figure 24C). This same pattern was seen with other nutrients. Surface-water nutrients were higher than normal in the summer months, likely from lack of biological uptake, and notably lower than normal in October and November, likely related to the dry fall conditions with less freshwater input. Figure 24D shows a representative 2018 seasonal nitrate/nitrite pattern throughout the entire water column.

Nitrate/nitrite and orthophosphate levels in deep waters (>75 m) were fairly typical, but were higher than normal in May and slightly lower than normal during the summer and fall months. Ammonia levels in 2018 followed the same seasonal pattern as surface values, with overall lower values than normal through most of the year, particularly in October. Lower fall nutrient levels in deep waters corresponded with higher-than-normal salinities, and may be reflective of less freshwater influence at depth.

5. Water quality (cont.)

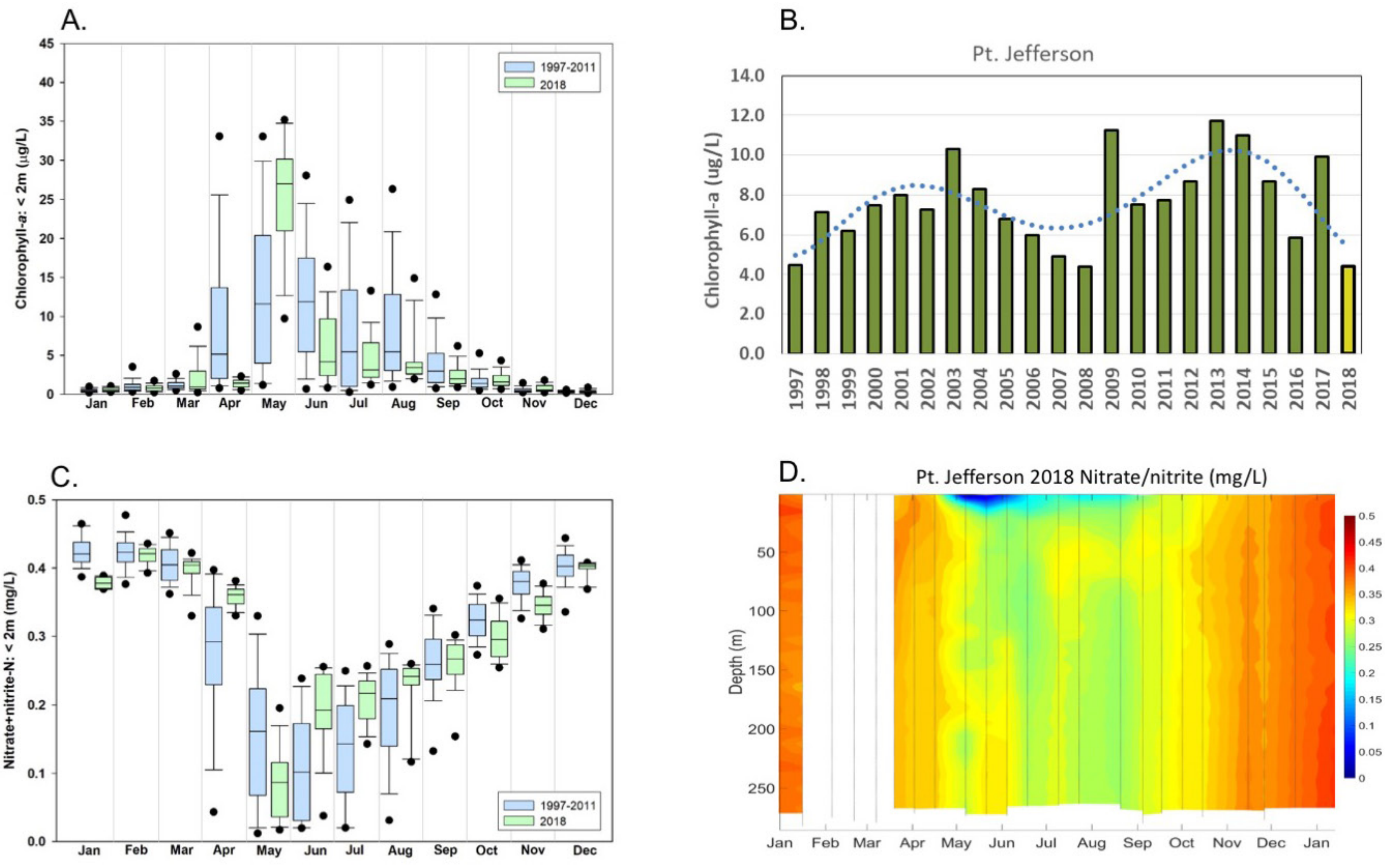


Figure 24. (A) Chlorophyll-a and (C) nitrate/nitrite levels for 12 Central Basin sites combined compared to long-term baseline. The line within the box denotes the median, box boundaries are 25th and 75th percentiles, whiskers are 10th and 90th percentiles. (B) Annual chlorophyll-a average for representative station, blue line denotes trend. (D) 2018 representative seasonal nitrate/nitrite pattern throughout the water column.

D. North Sound and Whidbey Basin

D.i. Padilla Bay 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), Nicole Burnett, Heath Bohlmann, Erin Matthews, and Suzanne Shull (Padilla Bay NERR/Ecology); www.padillabay.gov

Continuous monitoring of nearshore surface waters in Padilla Bay reveals temperatures ranging from 2.5–23.3°C throughout the year, with daily fluctuations in excess of 10°C during summer months. These large variations tend to occur from 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. The mean annual water temperature in 2018 (11.2±2.1°C) was warmer than in 2017, but not as high as in 2015–16 when anomalously warm water temperatures were recorded throughout the region. Despite 2018 being a generally warm year, average daily water temperatures measured February through April were cooler than in 2015, with a period in early February falling below the 20-year mean (Figure 25A). The dramatic transition in 2018 from below-normal temperatures in late winter/early spring to abnormally high temperatures in spring and summer may be representative of a broader regional phenomenon. Although mean annual temperature anomalies suggested a return to more “normal” water temperatures in 2017 (Figure 25B), the 2018 temperature anomaly indicates this may not be a long-term trajectory. Warmer and cooler periods shown in this figure correlate well with large-scale climatic cycles, specifically the PDO.

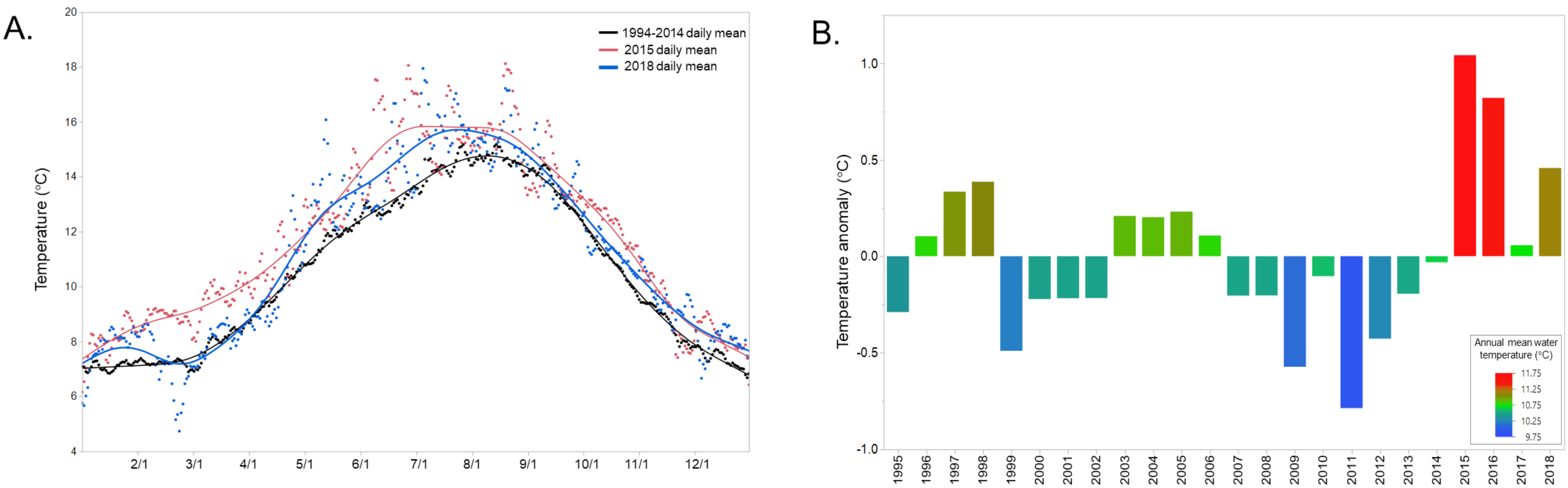


Figure 25. Long-term patterns in temperature in Padilla Bay, including (A) comparison of daily mean temperatures in 2015, 2018, and long-term (1994–2014) daily mean, and (B) long-term annual temperature anomalies, with bar colors representing annual mean temperatures for each year.

5. Water quality (cont.)

D.ii. Padilla Bay water column characteristics

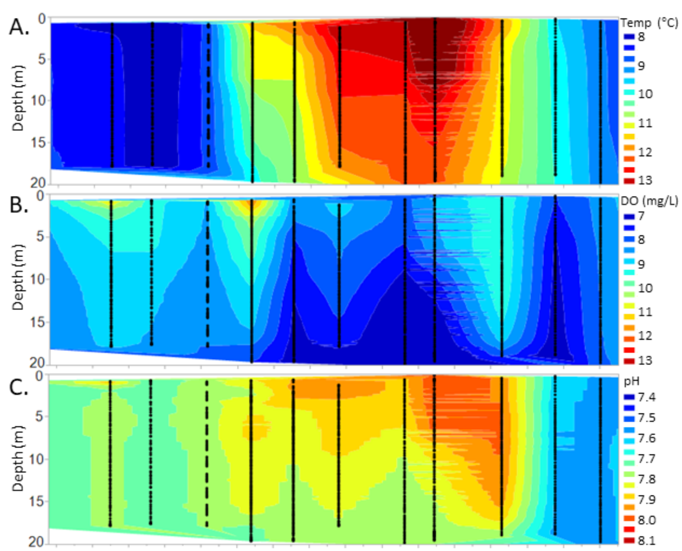
Source: Erin Matthews (ematthews@padillabay.gov), Nicole Burnett, Heath Bohlmann, and Jude Apple (Padilla Bay NERR/Ecology); www.padillabay.gov

Monthly water-column profiles have been collected at Guemes Channel and Gong Buoy to identify changes in water-column structure throughout the year in Padilla Bay. The water column in Padilla Bay reveals a strong seasonal influence in 2018. The year began with a cool, well mixed water column (Figure 26A, D) with a period of elevated surface DO (Figure 26B, E) and pH (Figure 26C, F) at both sites in early February. In spring, the water column became warmer and more stratified at both sites, which persisted until early fall when cool, well mixed conditions returned. Periodic increases in surface DO and pH in spring, summer, and late fall suggest additional periods of high phytoplankton productivity. These increases correspond with elevated chlorophyll in surface waters that may indicate elevated primary productivity and are corroborated by long-term monitoring data for Gong Buoy (data not shown).

Typically, water-column structure at these two sites is similar throughout the year. Exceptions to this include deep-water conditions at Guemes and evidence of small-scale differences in phytoplankton activity. In summer, conditions in the upper 20 m at Guemes Channel and Gong Buoy are similar (Figure 26). However, the presence of cooler, lower-pH, lower-DO water in the lower 40 m of Guemes Channel suggests that intrusions of water of marine origin move in and remain constrained to lower depths (i.e., they do not reach the surface waters of Padilla Bay).

Phytoplankton activity may also differ between these two sites. In July, we observed high pH and DO at Guemes Channel but not at Gong Buoy (Figure 26), showing effects of small-scale variability in phytoplankton activity and distribution, typical characteristics of Salish Sea surface waters.

Despite differences on smaller spatial and temporal scales associated with marine water intrusion and phytoplankton activity, water-column structure in Padilla Bay generally reveals a predictable seasonal pattern.



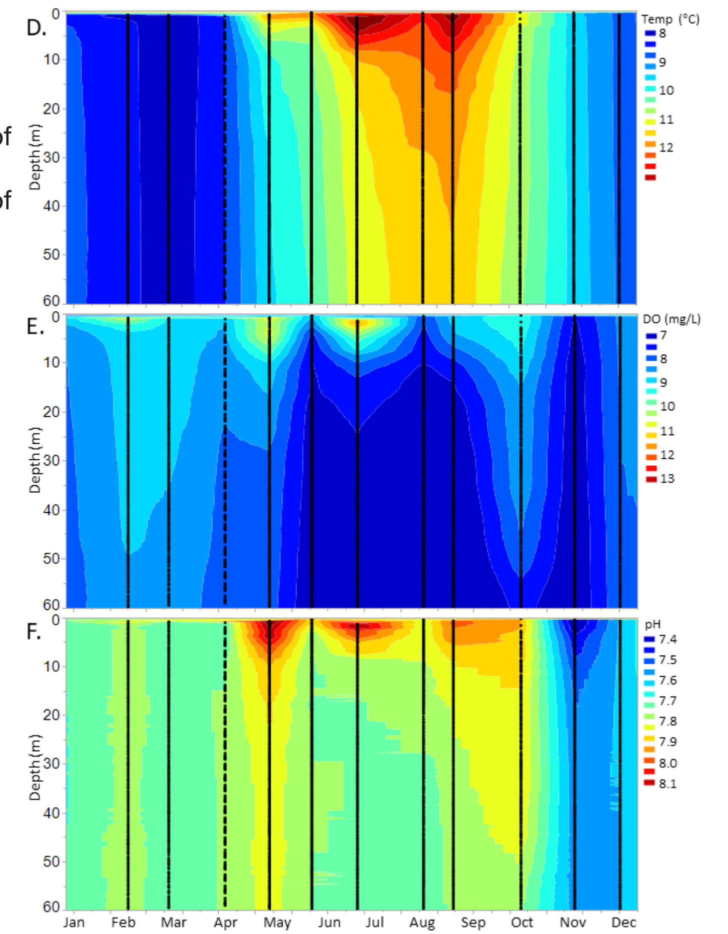


Figure 26. Marine water temperature, dissolved oxygen concentration, and pH levels throughout the water column at two sites within Padilla Bay in 2018.

5. Water quality (cont.)

D.iii. Bellingham Bay buoy

The oceanographic mooring in Bellingham Bay, called Se'lhaem, was installed in 2016 and is maintained through a partnership between UW, Northwest Indian College, Lummi Indian Nation, and Western Washington University, with data provided by NANOOS.

Source: Beth Curry (beth4cu@uw.edu), Jan Newton, John Mickett (APL, UW), Misty Peacock (NWIC), and Erika McPhee-Shaw (WWU); http://nwem.ocean.washington.edu; http://www.nanoos.org

During 2018, the Se'lhaem buoy was equipped with meteorological sensors at 2 m above sea level and oceanographic sensors at 0.5 m and 18 m (~7 m above the sea-bed). Data collected by these sensors from April to December are shown in Figure 27.

Buoy monitoring data provide evidence of atmosphere and watershed interactions with the surface waters of Bellingham Bay. During spring, surface-water salinity freshening correlates with high Nooksack River discharge (Figure 11), followed by increasing seawater temperatures and salinity throughout the summer consistent with higher air temperatures and reduced rainfall. After August, surface seawater cooling and episodic freshening for the remainder of the year are likely influenced by reduced solar radiation and fall storms.

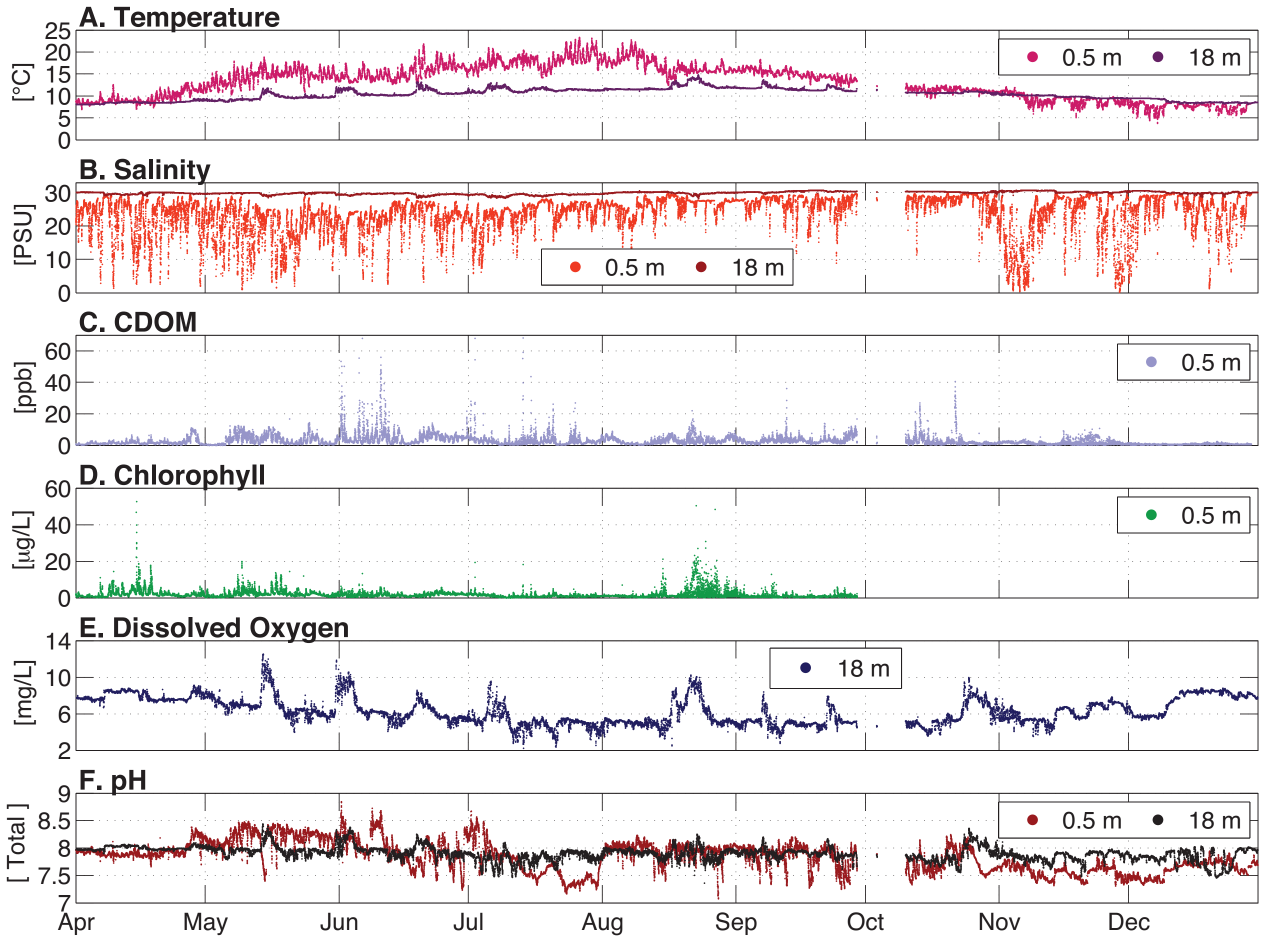


Figure 27. Water properties in Bellingham Bay during 2018. Shown are (A) temperature, (B) salinity, (C) colored dissolved organic matter, (D) chlorophyll, (E) dissolved oxygen, and (F) pH at either 0.5 m or 18 m below the water surface.

Surface chlorophyll in 2018 was similar to that observed in the two previous years, with the exception that chlorophyll increased earlier in April and there were two spring peaks instead of three. The highest chlorophyll concentrations during 2018 occurred in August, whereas no increase in chlorophyll was observed after June in 2016. Due to the absence of chlorophyll data after July 2017, similar comparisons could not be made for that year. There was no consistent relationship between chlorophyll and colored dissolved organic matter (CDOM) or pH in 2018, despite pH having tracked chlorophyll in previous years. Variability in CDOM did not match salinity during 2018 as it had previously. Similar patterns in peaks were observed between pH and oxygen measured at depth.

The variability in temperature and salinity data differs between the surface and near the bottom (Figure 27). Between May and October, water masses with increased temperature, increased DO, and decreased salinity were detected (Figure 28), suggestive of surface-water origin, but do not match the surface-water properties at the site. Near-fortnightly frequency may indicate that tidal modulation is involved. These events were also observed in 2016, but were not as obvious since the data record ended in July. In 2019, the buoy data will be combined with NWIC's weekly CTD profiles at the buoy to further investigate and understand the drivers of these events.

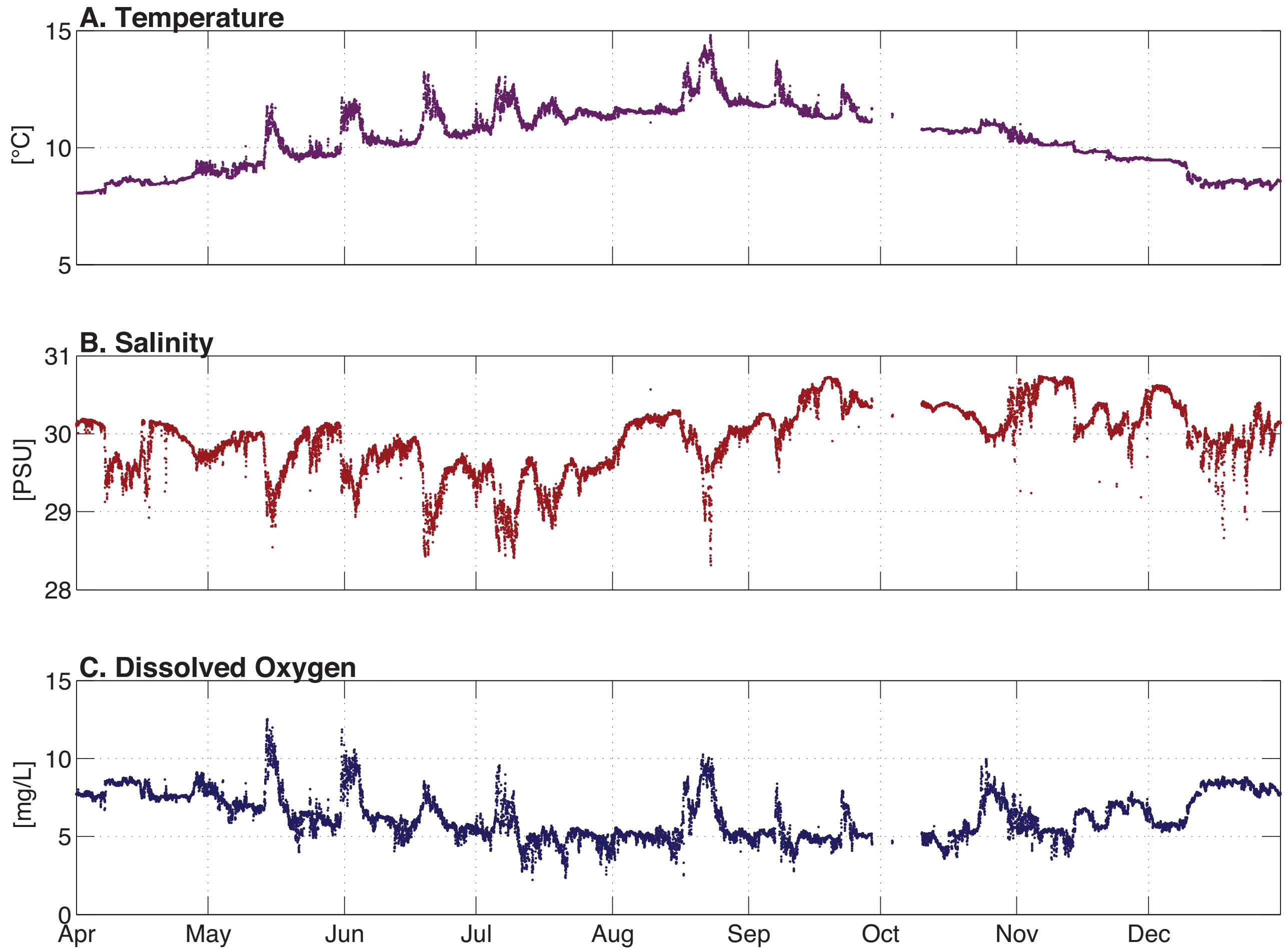


Figure 28. Water properties in Bellingham Bay at 18 m, ~7 m above the sea-bed, during 2018. Shown are (A) temperature, (B) salinity, and (C) dissolved oxygen.

5. Water quality (cont.)

D.iv. Port Susan buoy

The Stillaguamish Tribe installed a research mooring buoy into northern Port Susan Bay in 2011 to help better understand the drivers of out-migrating juvenile salmon survival. Port Susan is located at the north end of Possession Sound, to the east of Camano Island, and receives freshwater inputs from the Stillaguamish River. The buoy is stationed in the center of the bay in 11 m of water (MHW), 4 km west of the river mouth and less than 1 km north of the drop of the basin shelf to over 300 m. The buoy houses a multi-sensor water-quality sonde that collects data every 30 minutes at a depth of 0.8 m.

Source: Franchesca Perez (fperez@stillaguamish.com), Margaret Taylor (STOI); www.stillaguamish.com

Water-quality measurements were collected in northern Port Susan from February to October 2018. Near-surface water temperatures during this period ranged from 3.3–22.1°C (Figure 29). Diurnal swings of temperature and DO occurred throughout the year, attributed to shallow-water ebbing across 4 km of exposed mudflats back into deeper water. Average weekly water temperatures reveal the effect of local air temperatures that warm or cool the mudflats: from abnormally cool in late March/early April to unusually high regional air temperatures from late April to mid-May and from late July to late August (see section 2).

In summer, water temperatures fluctuate by as much as 7.6°C daily at nearly a meter below the surface. Though DO inversely tracks these extremes, DO levels tend to stay above 7.5 mg/L until late summer, when plankton (data not shown) and chlorophyll levels peak, then rapidly decline (Figure 29). Oxygen concentrations were often positively correlated with chlorophyll, with the exception of an event in late September when elevated chlorophyll and low DO were observed. These data have been linked to plankton and estuary prey observations by Tribal staff and may indicate that Port Susan is a productive bay capable of supporting juvenile salmon and forage fish.

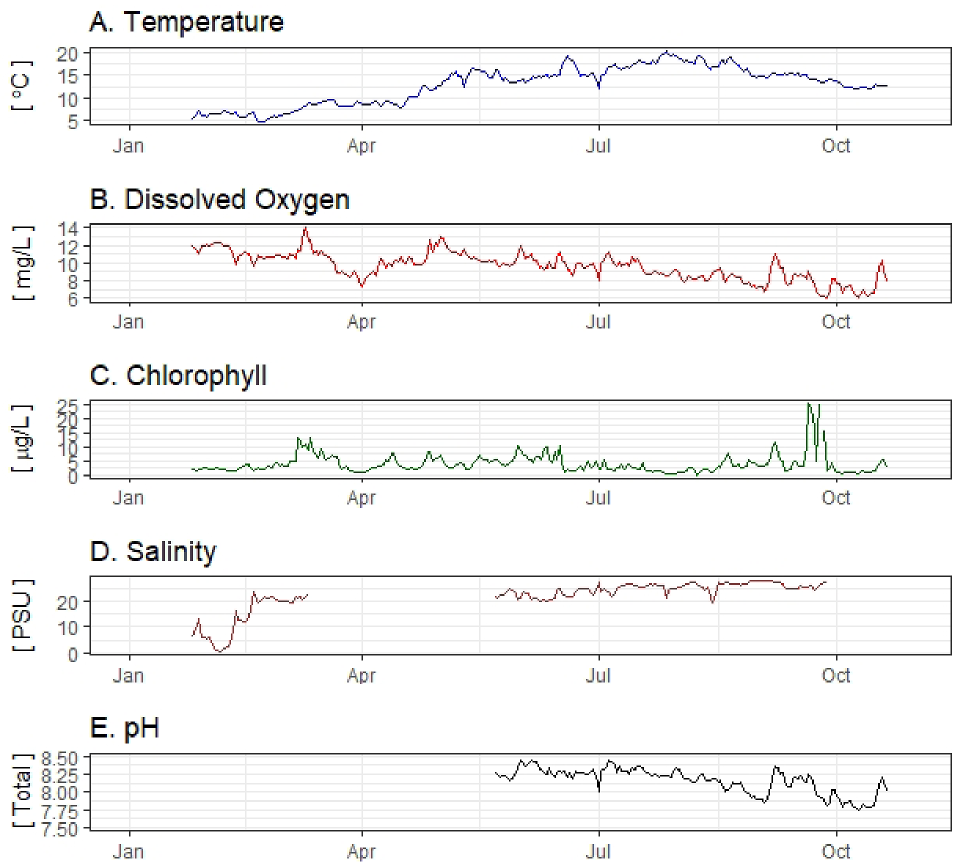


Figure 29. Water properties in Port Susan Bay in 2018. Shown are (A) temperature, (B) dissolved oxygen, (C) chlorophyll, (D) salinity, and (E) pH. No data were collected from November through January due to buoy mooring repairs.

5. Water quality (cont.)

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

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. Research apprentices sample along a transect from station "North" in the well mixed San Juan Channel, to station "South" 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) (APL, UW), Rebecca Guenther, John Dorsett, and Emily Hamacher (UW); http://courses.washington.edu/pelecofn/; www.nanoos.org

During fall 2018, water temperatures from 0–85 m depth at the South station were the fourth-warmest on record in our 15-year dataset (Figure 30). Surface waters are in the upper left of the graph, with denser deep waters in the lower-right. Surface salinity was higher than most observations on record, while deep salinities were well within the range of previous years.

Positive temperature anomalies (not shown) of 0.5–1.0°C were observed throughout fall 2018 in surface (0–20 m) and deep waters at both the North (~100–110 m water depth) and South (~70–80 m water depth) stations, as they had been during fall 2014–16 but not in fall 2017. However, similar to 2017, salinity anomalies (not shown) were generally positive, unlike the generally negative values observed during 2014–16.

In 2018, marine mammal (harbor porpoise, Steller sea lion, and harbor seal) and seabird (all species combined) abundances were low relative to the 13-year record shown (Figure 31). Since 2013, seabird abundance has been similar to the years prior to the cool conditions of 2010–12, but the 2018 density was the lowest except for 2007. Also, since 2013, observed marine mammal densities have steadily declined, with 2018 the lowest of the record. Whether these low numbers reflect a lingering response to warmer-than-average seawater conditions cannot be ascertained; we hope continuance of the time series will inform this question.

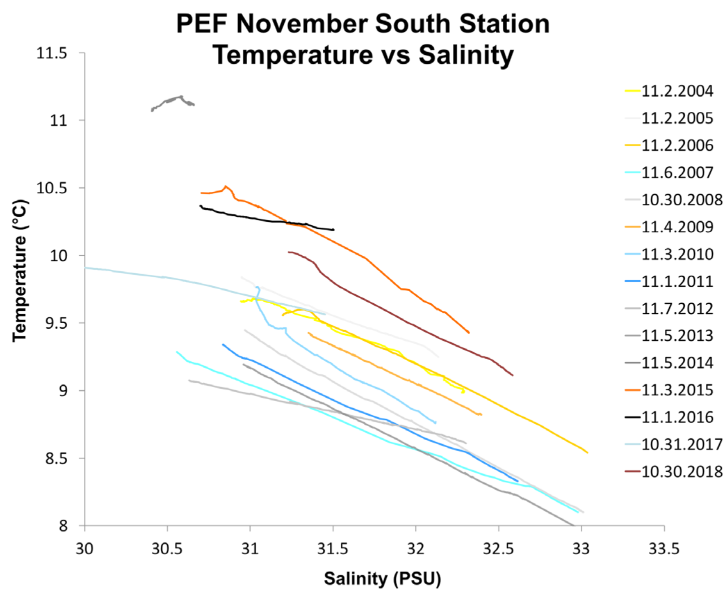


Figure 30. Temperature versus salinity from 80 m to the surface at the South station in the eastern Strait of Juan de Fuca during the first week of November. Deep waters (coldest and saltiest) are found on the right. Color coding: yellow = El Niño years; blue = La Niña years; gray = neutral years.

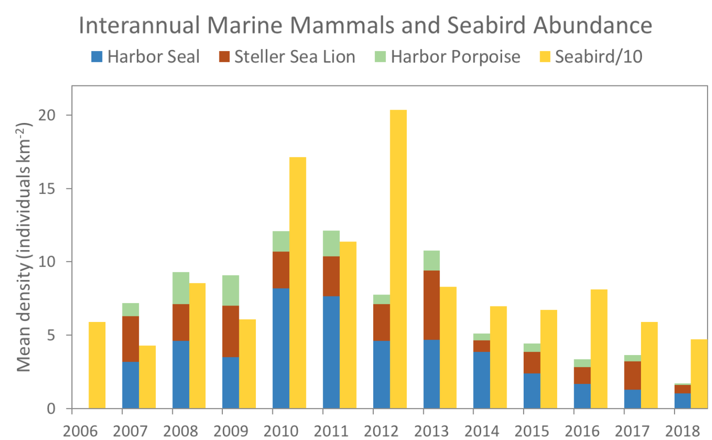


Figure 31. Interannual marine mammal and seabird densities, 2006–18. Note that seabird densities are divided by ten.

E.ii. Puget Sound pCO_2 surveys

Source: Simone Alin (simone.r.alin@noaa.gov) (NOAA, PMEL), Jan Newton, Beth Curry (APL, UW), Dana Greeley, Richard Feely (NOAA,PMEL); http://www.nanoos.org; PMEL contribution number 4978.

During 2018, three Washington Ocean Acidification Center Puget Sound cruises were conducted (in April, July, and September) to measure variables used to define ocean acidification effects. Carbonate chemistry was fully constrained by measuring CTD temperature and salinity along with bottle sample analyses for phosphate, silicate, nitrate, oxygen, dissolved inorganic carbon concentrations, and total alkalinity. Here we focus on water-column distributions of the partial pressures of carbon dioxide (pCO_2, which is close in value to xCO_2 presented in sections 3.B and 5.B.iv), in order to facilitate comparison of surface and deeper conditions observed by moorings versus cruises.

Water column pCO_2 values for all cruise transects in Admiralty Reach, Main Basin, and South Sound were in the range of ~500–1,100 µatm (Figure 32) and did not show steep near-surface stratification features during any cruise. In contrast, cruises to Whidbey Basin and Hood Canal showed strong near-surface stratification during early and late summer cruises, with enriched pCO_2 values in deeper waters on all three cruises. In Whidbey Basin, pCO_2 values in deep water progressively worsened from April to September. In Hood Canal, pCO_2 values near the entrance sill (10 km) were the highest in September. At the same time, sites in southern Hood Canal had the highest pCO_2 values at intermediate depths, reflecting the deep-water renewal process wherein deep, high-CO_2 waters are displaced toward the surface by marine intrusions entering over the Hood Canal entrance sill. In comparison to previous years, 2018 had similar pCO_2 distributions and dynamics to years prior to the 2014–16 marine heatwave; heatwave years were lower in September due to earlier flushing.

In Figure 32, the pCO_2 contour for 1,000 µatm is shown in bold, as this is a threshold for hypercapnia—a separate respiratory challenge from hypoxia characterized by too much CO_2 rather than too little O_2, that has been used in the ocean acidification literature. All Puget Sound transects had some water exceeding the hypercapnia threshold, but only Whidbey Basin and Hood Canal had large volumes of deep water with conditions conducive to hypercapnia during all three cruises.

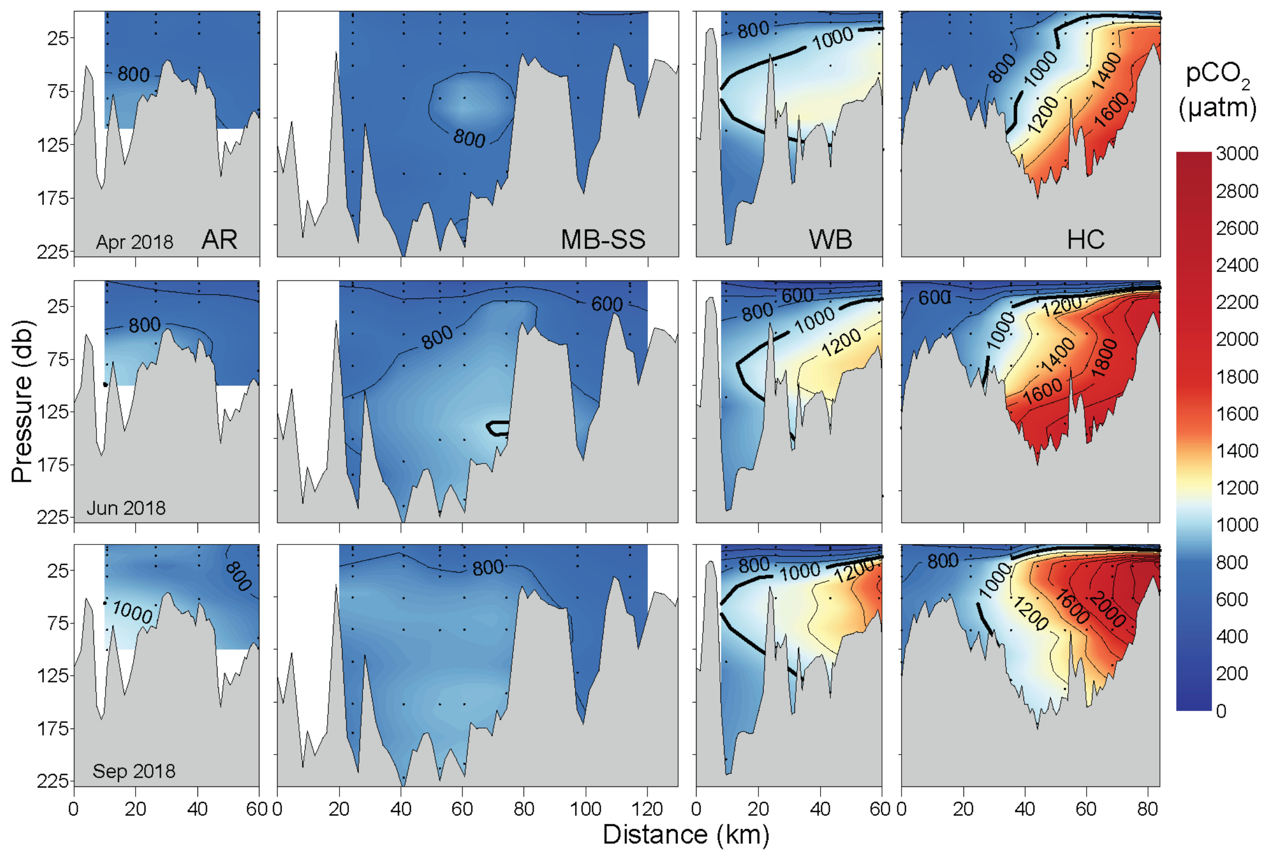


Figure 32. Plots of pCO_2 by depth and distance along transect (from the Strait of Juan de Fuca to the terminus of each sub-basin). Rows represent April, July, and September 2018 cruises, and columns represent Admiralty Reach (AR), Main Basin to South Sound (MB-SS), Whidbey Basin (WB), and Hood Canal (HC) transects. All pCO_2 contours are spaced 200 µatm apart, with the 1,000 µatm hypercapnia threshold in bold for emphasis. Sampling locations and depths are indicated by small black dots.

CALL-OUT BOX: San Juan pelagic ecosystem function: A 15-year retrospective

The University of Washington Pelagic Ecosystem Function Research Apprenticeship has been held at Friday Harbor Laboratories (September–December) since 2004, with data reported annually in the Puget Sound marine waters overview since 2012. The course aims to document variation and patterns in oceanography, plankton, fish, seabird, and marine mammals to discern underlying mechanisms that influence the pelagic ecosystem. We have identified three distinct time periods within the 15-year record, based upon results summarized in Table 3.

During 2005–09, we observed that water properties correlated with certain physical drivers. For instance, seawater temperature correlated with ENSO status, with generally warmer-than-average waters during El Niño and cooler during La Niña, and fresher-than-average salinities during high Fraser River discharge, and vice versa. We also found a correlation between DO and the timing of the Fall Transition (switch from upwelling to downwelling). Coastal upwelling brings deeper low-DO waters to the surface, where they are entrained in the Strait of Juan de Fuca and San Juan archipelago; thus, a prolonged upwelling season means fall-season DO values will be lower than average, and vice versa. While these attributes and their drivers make intuitive sense, no correlations in the food web were observed, implying a lack of coupling between physical drivers and the ecosystem, which had been expected. We note, however, that the physical state varied year to year, with neutral, warm, cool, neutral, and warm conditions.

During 2010–13, the PDO was in a cool phase for four consecutive years, with La Niña conditions in the first two years. During this period, we observed the highest abundances of seabirds, cetaceans, and pinnipeds in the record. Pacific sand lance abundance, assessed starting in 2010, reached the highest abundance in 2012 followed by the lowest in 2013. While phytoplankton abundance was higher than average throughout the period, zooplankton were lower than average; this may indicate that predation on zooplankton was high.

During 2014–16, the marine heatwave (the Blob) was evident. Seawater was at its warmest on record in 2014 for this time series. Salinity and dissolved oxygen varied, but all biological populations were lower than average, in some cases the lowest abundances on record. Reduced fish abundance in 2013 may reflect the onset of the Blob, compounded by density-dependent compensation related to high abundances the previous year. Fish abundance remained low in 2014, recovering in 2015–16, then declining in 2017–18. While seawater temperature returned to average in 2017, biological abundances stayed low. In 2018, seawater temperatures again were warmer than average, leading some to hypothesize another marine heat wave was developing. Biological abundances remained low, notably with zooplankton at their lowest in this record.

These observations may imply that the food web responds to strong physical signals that persist for multiple years, as evidenced by both the cool (2010–13) and the warm (2014–18) periods, in contrast to the variable period (2005–09). Yet we found no lag in the food-web abundance when physical conditions shifted (i.e., in 2010 and 2014). Continuation of this time series will reveal if the low biological abundances observed since 2014 will rebound with cooler seawater temperatures, or if a “new normal” has been found.

Authors: Jan Newton (janewton@uw.edu), Breck Tyler, and Matt Baker (UW, FHL); http://courses.washington.edu/pelecofn/class_information.html; http://www.nanoos.org

CALL-OUT BOX: San Juan pelagic ecosystem function: A 15-year retrospective (cont.)

	2005	2006	2007	2008	2009	2010	2011	2012	2013	**<u>2014</u>**	**<u>2015</u>**	**<u>2016</u>**	2017	2018
PDO	*Neutral*	*Neutral*	*Neutral*	*Cool*	*Neutral*	*Cool*	*Cool*	*Cool*	*Cool*	*Warm*	*Warm*	*Warm*	*Neutral*	*Neutral*
ENSO	*Neutral*	*El Niño*	*La Niña*	*Neutral*	*El Niño*	*La Niña*	*La Niña*	*Neutral - wk EN*	*Neutral*	*Neutral*	*El Niño*	*EN to wk LN*	*La Niña*	*Neutral - wk EN*
Sea Temperature	*Avg*	*Warmer*	*Cooler*	*Avg*	*Warmer*	*Cooler*	*Cooler*	*Avg - Cooler*	*Avg - Warmer*	*Warmest*	*Warmer*	*Warmer*	*Avg*	*Warmer*
Fraser River flow	*High*	*Low*	*High*	*Avg*	*Low*	*Avg*	*High*	*Low*	*Low - Avg*	*High*	*Low*	*High*	*High & Low*	*Low*
Salinity	*Fresher*	*Saltier*	*Fresher*	*Saltier*	*Saltier*	*Fresher*	*Fresher*	*Avg*	*Avg*	*Fresher*	*Saltier*	*Fresher*	*Avg*	*Saltier*
Fall Transition	*Early*	*Late*	*Early*	*Late*	*Early*	*Late*	*Early*	*Early*	*Mixed*	*Middle*	*Middle*	*Early*	*Late*	*Middle*
DO	*Lower*	*Lower*	*Higher*	*Lower*	*Higher*	*Higher*	*Higher*	*Mixed*	*Medium*	*Medium*	*Medium*	*Higher*	*Lower*	*Medium*
Phytoplankton		*Medium*	*Low - Med*	*Low - Med*	*High*	*High*	*High*	*Med - High*	*Med - High*	*Med - High*	*Low*	*Low*	*Low*	*Low*
Zooplankton	*Low*		*High*	*Low*	*High*	*Low*	*Low*	*Medium*	*Medium*	*Low*	*Low*	*Low*	*Low*	*Low*
Fish						*Medium*	*Medium*	*High*	*Low*	*Low*	*Medium*	*Medium*	*Low*	*Low*
Seabirds	*Medium*	*Medium*	*Low*	*Low*	*Low*	*High*	*Low*	*High*	*Low*	*Low*	*Low*	*Low*	*Low*	*Low*
Cetacean	*Low*	*Low*	*Low*	*Low*	*Low*	*High*	*High*	*High*	*High*	*Low*	*Low*	*Low*	*Low*	*Low*
Pinniped	*Low*	*Low*	*Low*	*Low*	*Low*	*High*	*High*	*Medium*	*High*	*Low*	*Low*	*Low*	*Low*	*Low*

Table 3. Time-series results of FHL Pelagic Ecosystem Function Research Apprenticeship measurements. Year is across the top, with marine heatwave years underscored. Rows are either climate drivers (in bold) or measured ecosystem variable. Color shading denotes when correlations were observed between ecosystem variables and climate drivers: Red/Blue/Gray show when sea temperature correlated with ENSO and/or PDO forcing; Green/Orange show when sea salinity correlated with the Fraser River flow intensity; Purple/Yellow indicate when dissolved oxygen correlated with the timing of the Fall Transition from upwelling to downwelling; and Light Blue/Pink show when biological abundances correlated with PDO and/or ENSO forcing, with low abundances in warmer waters and vice versa. 2004 is not presented graphically, as the food web components were not measured in the same way as they have been since 2005, but the physical relationships (T, S, DO) are consistent with those shown. Note that forage fish, primarily Pacific sand lance, abundance observations started in 2010. Cells with no text indicate that similarly quantifiable measurements are not available. The three time periods discussed in the text are shown by black outline.

6. Plankton

A. Phytoplankton

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. Starting in 2008 with traditional microscopy, the program progressed in 2014 to incorporate the use of a FlowCAM particle imaging analyzer in order to assess abundance, biovolume, and taxonomic composition of all microplankton particles in the 10–300 µm range.

Source: Gabriela Hannach (gabriela.hannach@kingcounty.gov) and Lyndsey Swanson (KCEL); http://green2.kingcounty.gov/marine/Monitoring/Phytoplankton

King County sampled ten long-term monitoring stations for phytoplankton in 2018, including two protected sites (Elliott Bay and Dockton in outer Quartermaster Harbor). Four years of biovolume data indicate that phytoplankton growth in 2018 was greatly reduced compared to previous years (Figure 33A). These observations are supported by long-term surface chlorophyll data from these sites (section 5.C.iii). The bloom season started at the beginning of May, which is unusually late for this basin. As in previous years, the spring bloom was initiated by *Thalassiosira* spp. and was later mixed with *Chaetoceros* spp., both chain-forming diatoms (Figure 33B). A large bloom of the needlelike diatom *Rhizosolenia* followed, continuing through the

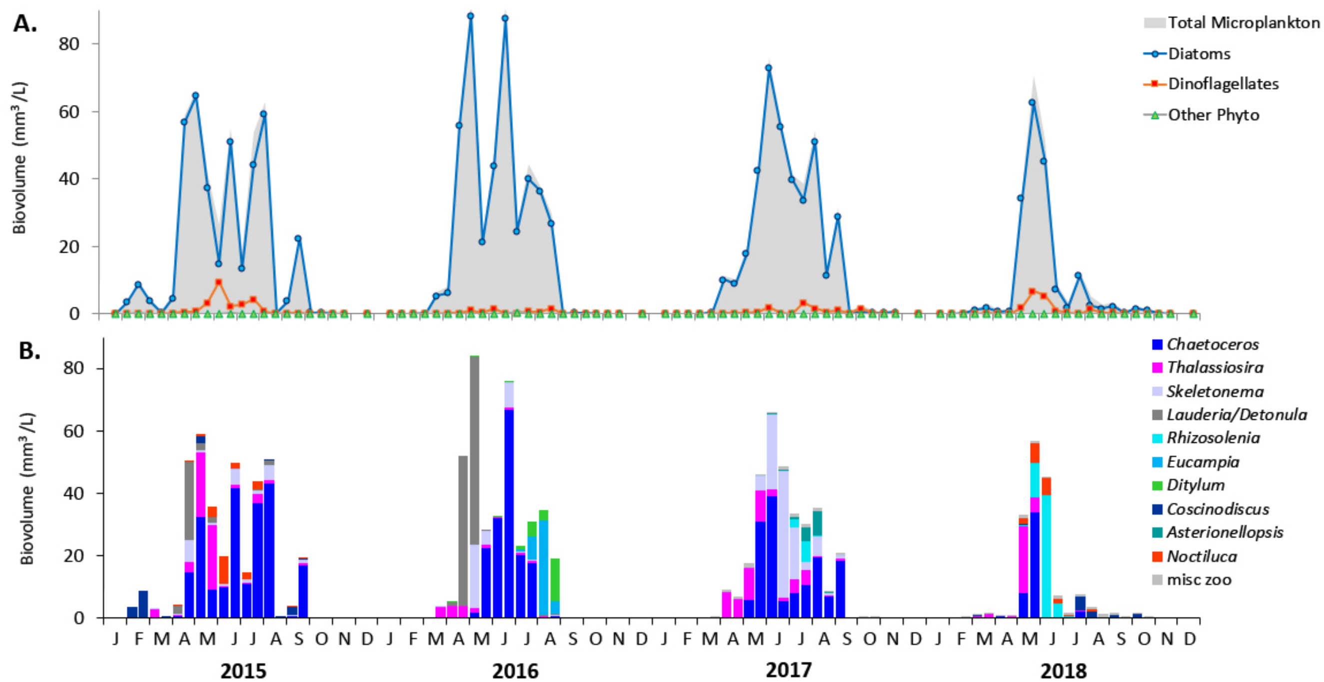


Figure 33. (A) Total biovolume (gray area), biovolume of main groups, and (B) biovolumes of top six taxa identified using FlowCAM between 2015 and 2018. Plotted values are means for Central Basin mainstem sites.

6. Plankton (cont.)

end of June, but very little growth was observed thereafter. Whereas multiple species of *Chaetoceros* typically persist throughout the summer and sometimes into the fall, they were minimally present during the summer of 2018 (Figure 34). These anomalies resulted in a large decrease in the total annual accumulated biovolume, which fell to 47% of the previous overall three-year average for offshore stations. The large heterotrophic dinoflagellate *Noctiluca scintillans,* which had conspicuous blooms in 2014 and 2015, made a comeback in 2018 (Figure 34B).

The delayed and shortened growth season observed in 2018 cannot be explained by nutrient limitation, but it closely mirrors the observed patterns in density stratification (section 5.C.i), suggesting that the dry summer conditions and increased mixing prevented the formation of a persistent stable layer where algal cells could thrive.

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. Few historical zooplankton data exist from Puget Sound; monitoring data are required to establish baselines and track the effects of change on Puget Sound ecosystems.

B.i. Puget Sound

Source: Julie Keister (jkeister@u.washington.edu), BethElLee Herrmann, and Amanda Winans (School of Oceanography, UW); http://faculty.washington.edu/jkeister/

Sampling[2] across Puget Sound shows that total mesozooplankton abundances and biomass in 2018 were similar to or lower than in 2017 in most regions, and lower than the anomalously warm years of 2015–16 (Figure 35A, B)[3]. Differences among regions, taxa, and phenology were observed. Zooplankton biomass and phenology at northern sites (San Juan Islands and Admiralty Inlet) showed similar patterns in 2017 and 2018, with slightly higher accumulated biomass in 2018. In more southern regions (Central Basin and South Sound), where biomass remained elevated in 2017 after the warm anomalies, biomass dropped in 2018 to near-2014 levels. In Central Basin (Figure 35C), copepod abundance saw its highest peak of all sample years in August 2018, with no significant earlier peak in June or July as seen in past years. Larvacean and gastropod abundances were similar to 2017, but with earlier timing. Bryozoan larva abundance was slightly lower than 2017, with similar timing. Barnacle larvae had the highest peak abundance of all sampling years and peaked about a month earlier.

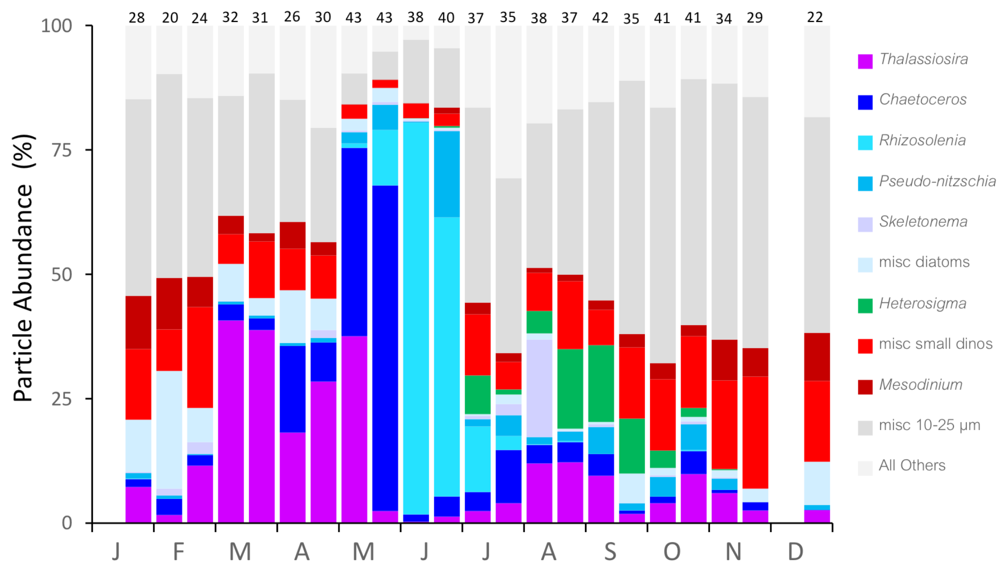
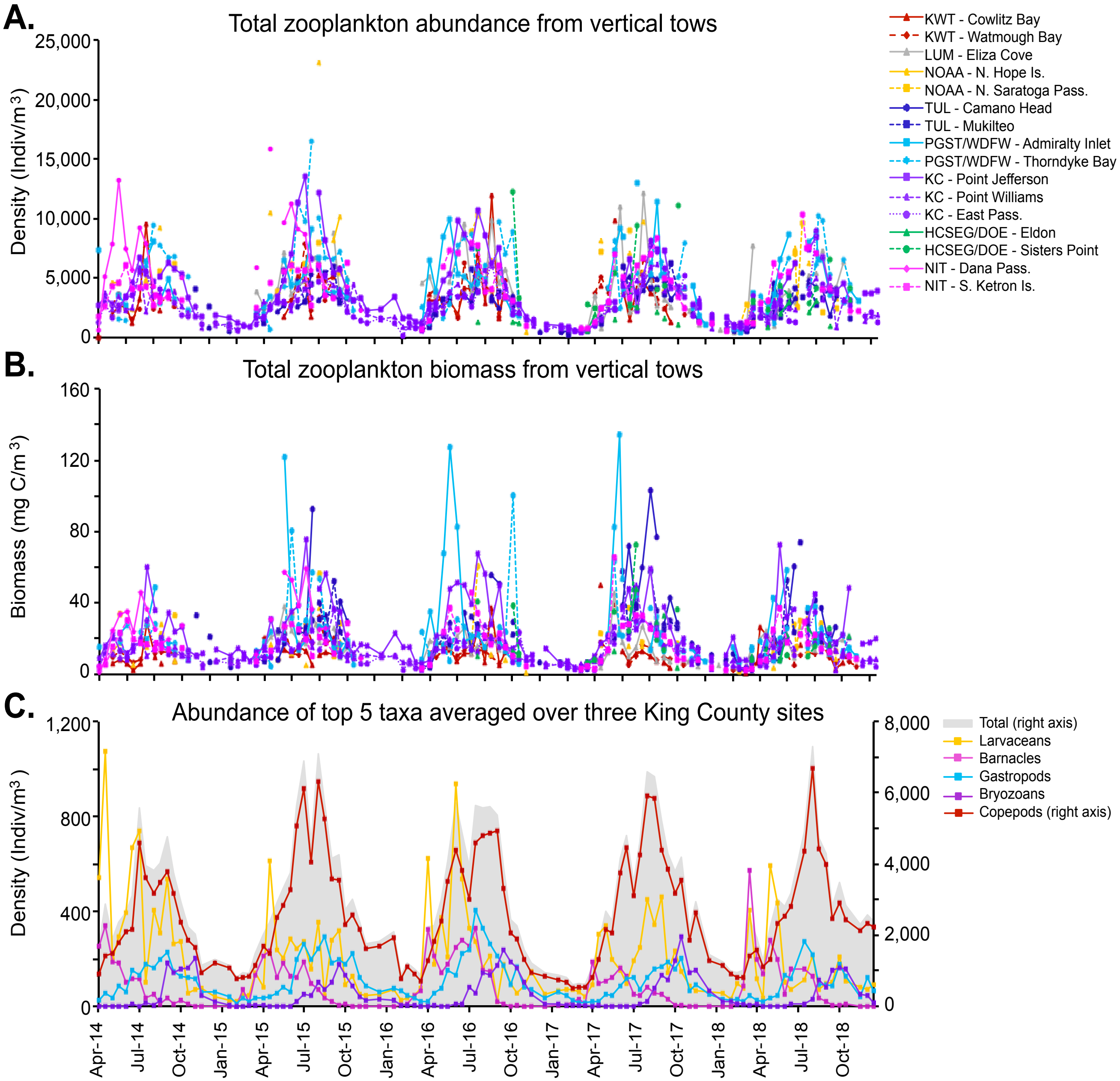


Figure 34. Relative abundance of taxonomic categories that contributed at least 10% in each sampling event (means for all stations) during 2018. Numerals above bars indicate the total number of taxonomic categories present, from a total of 58 categories identified by FlowCAM in the year. Note that "Particle abundance" may refer to whole chains, fragments, or individual cells, and is not indicative of biovolume.

[2]Zooplankton sampling was conducted by King County (KC), the Nisqually Indian Tribe (NIT), Tulalip Tribe (TUL), Kwiáht (KWT), Lummi Nation (LUM, since 2015), Port Gamble S'Klallam Tribe (PGST), WDFW, NOAA, the Hood Canal Salmon Enhancement Group (HCSEG), and Ecology (since late 2016). Funding for 2018 sampling was provided by WDNR, EPA, and King County.

[3]Data shown here were collected with 60-cm diameter, 200-µm mesh plankton nets towed vertically from 5 m off the bottom (or a maximum of 200 m in deep water) to the surface. Most locations were sampled bi-weekly from mid-March through October. Taxonomy by species and life stage was conducted at UW.



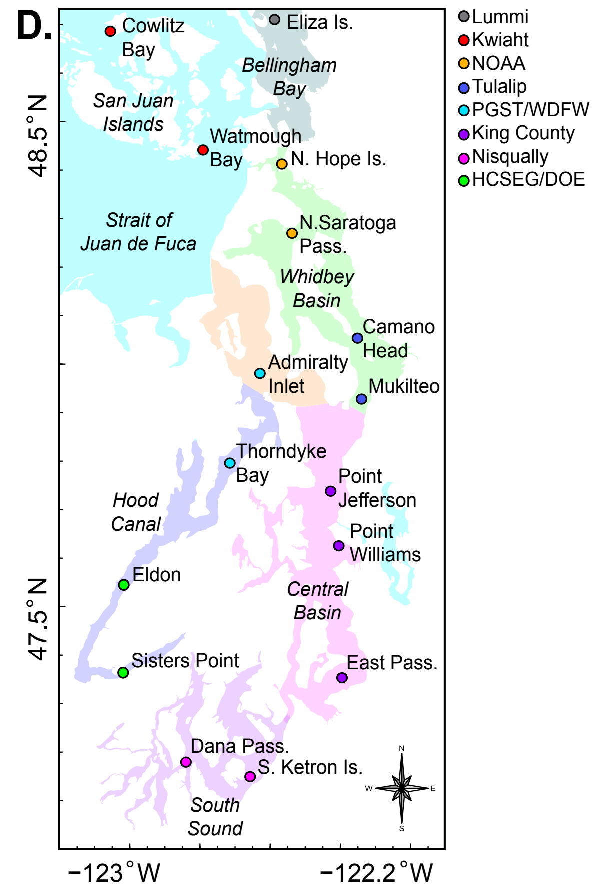


Figure 35. (A) Time series of total mesozooplankton abundance (indiv/m³) at each station in 2014–18. Note that not all stations were sampled in all years. (B) Time series of total mesozooplankton biomass (mg C/m³) at each station in 2014–18. (C) Time series of total abundance (filled gray area) and abundance of the five most-dominant taxa (indiv/m³) averaged over the three King County sites in Central Basin. Note that total and copepod abundances are on the right axis. (D) Map of the sampling locations.

6. Plankton (cont.)

B.ii. Padilla Bay

Source: Nicole Burnett (nburnett@padillabay.gov) and Jude Apple (Padilla Bay NERR); https://ecology.wa.gov/Water-Shorelines/Shoreline-coastal-management/Padilla-Bay-reserve

Padilla Bay National Estuarine Research Reserve has been monitoring mesozooplankton communities since 2008 in conjunction with long-term water-quality, nutrient, and meteorological data. Vertical tows to 18 m depth were performed monthly at an open-water site (Gong) using a 153-µm mesh net with a 1-ft diameter opening. Phytoplankton (chlorophyll-*a)* and zooplankton abundances are consistently low during the winter and high in both the spring and late summer to early fall, though the timing and magnitude of these peaks vary annually (PSEMP Marine Waters Workgroup 2018). In addition, zooplankton communities have distinct seasonal compositions that persist annually. For example, multidimensional scaling ordination shows that samples group together by season across all years, despite annual differences in water quality (Figure 36). There are also within-season differences, most notably in summer. For instance, 2008–13 summer samples (87.5%) and 2014–17 summer samples (88.9%) form distinct clusters. This shift in community composition is likely associated with the Blob and a switch to positive PDO as reflected in positive temperature anomalies in 2014–18 (Figure 37). Although temperatures in 2018 were not as warm as in previous years, they were still anomalously high. Similarly, 2018 summer zooplankton community composition falls within the overlap of the two clusters, indicating a shift toward normal summer compositions, but not a full return. The change in community composition during warmer years can be attributed to changes within many zooplankton groups. For example, copepods, larvaceans, and barnacle nauplii all had higher-than-normal abundances during this period, whereas crab larvae were fewer-than-normal. While 2018 *annual* anomalies of most zooplankton groups were less extreme and were closer to the climatology than the 2014–17 annual anomalies, *seasonal* anomalies of several groups remained as high or low as observed in 2014–17. Furthermore, some zooplankton groups had record or near-record abundances in late spring or early summer (data not shown), indicating that annual patterns of zooplankton communities may be returning to normal, but seasonal patterns still reflect patterns seen during warmer, anomalous years.

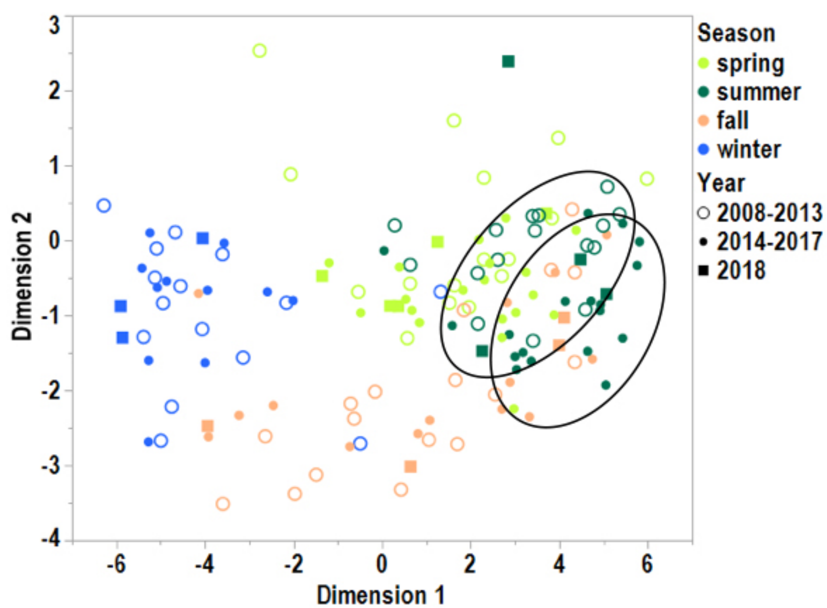


Figure 36. Multidimensional scaling ordination of zooplankton community with months (colors) and year (symbols).

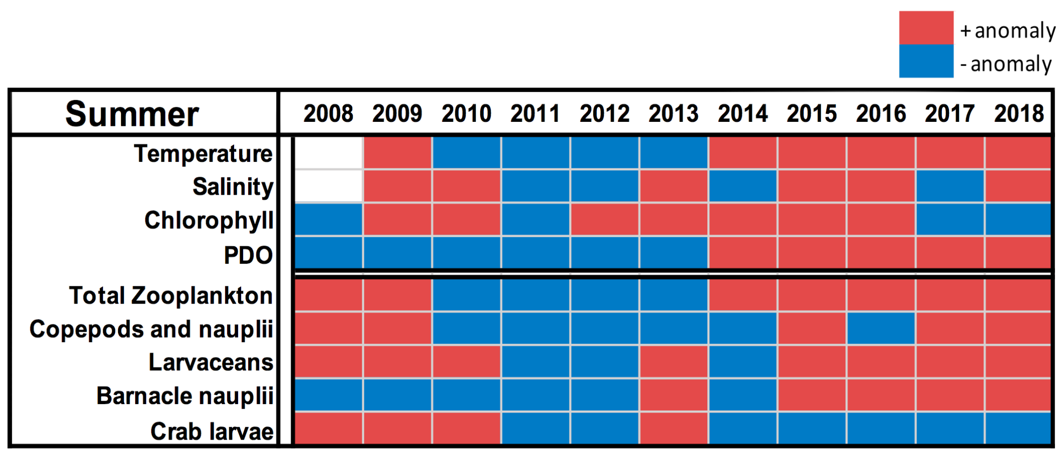


Figure 37. Heat map of summer anomalies for water-quality data and zooplankton groups (baseline is 2008–18).

6. Plankton (cont.)

C. Harmful algae

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

C.i. Biotoxins

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: Jerry Borchert (jerry.borchert@doh.wa.gov) and Audrey Coyne (WDOH); http://www.doh.wa.gov/CommunityandEnvironment/Shellfish/RecreationalShellfish/Illnesses

In 2018, the Washington State Department of Health (WDOH) Public Health Laboratory analyzed 2,880 shellfish samples for PSP toxin. PSP toxin events occurred in Whatcom, San Juan, Skagit, eastern Clallam, Kilisut Harbor, and Mystery Bay in Jefferson, Kitsap, King, and northern Pierce Counties. The highest PSP toxin level measured was 5,761 µg/100 g in blue mussels from Mystery Bay on 4 September. The FDA standard for PSP toxin is 80 µg/100 g of shellfish tissue. In 2018, unsafe levels of PSP toxins caused 18 commercial (11 geoduck clam tract, one pink scallop, and six general growing area) and 22 recreational harvest area closures.

A total of 2,315 shellfish samples were analyzed for ASP toxin in 2018. The highest ASP toxin level measured was 21 ppm in razor clams from Kalaloch Beach on March 20. The FDA standard for ASP toxin is 20 ppm. ASP caused no commercial and no recreational closures in 2018.

In 2018, 2,222 shellfish samples were analyzed for DSP toxins. DSP toxin events occurred in Bellingham Bay in Whatcom County, Sequim Bay in Clallam County, Quartermaster Harbor in King County, Budd Inlet in Thurston County, and various sites in Kitsap County. The highest DSP toxin level measured was 69 µg/100 g in blue mussels from Sequim Bay on 4 September. The FDA standard for DSP toxin is 16 µg/100 g of shellfish tissue. DSP toxins caused no commercial and eight recreational harvest area closures in 2018.

C.ii. SoundToxins

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

Source: Nancy Nguyen (soundtox@uw.edu), Teri King (WSG), and Vera Trainer (NOAA/NWFSC); www.soundtoxins.org

SoundToxins is a phytoplankton network using weekly monitoring of algal species at key sites throughout Puget Sound. Harmful algal blooms can appear very suddenly and rapidly accumulate toxins in shellfish. SoundToxins alerts WDOH through a “traffic-light” mapping system that pinpoints locations where harmful algae abundances are at concerning levels (Figure 38).

WDOH and partners were provided the following alerts in 2018:

Alexandrium **–** 22 alerts for cell counts >100 cells/L. The highest concentration was 287,079 cells/L at Mystery Bay on 8 October 2018. County Dock in East Sound reported three blooms, with two occurring in October.

Dinophysis **–** 32 alerts for cell counts >1,000 cells/L. The highest concentration was 905,848 cells/L at Glen Ayr on 28 September 2018.

Heterosigma **–** three alerts for cell counts above the action level of 500,000 cells/L, all in Sequim Bay. The highest concentration was 7,300,000 cells/L on 3 September 2018.

Pseudo-nitzschia **–** 13 alerts for large cell counts >50,000 cells/L. The highest concentration of *Pseudo-nitzschia* (small cell type) was 4,417,000 cells/L at Port Susan on 19 June 2018.

6. Plankton (cont.)

SoundToxins has observed three additional algal species associated with shellfish mortalities in Puget Sound—*Akashiwo sanguinea, Protoceratium reticulatum,* and *Phaeocystis globose*—and is seeking funding to add these species to the alert system.

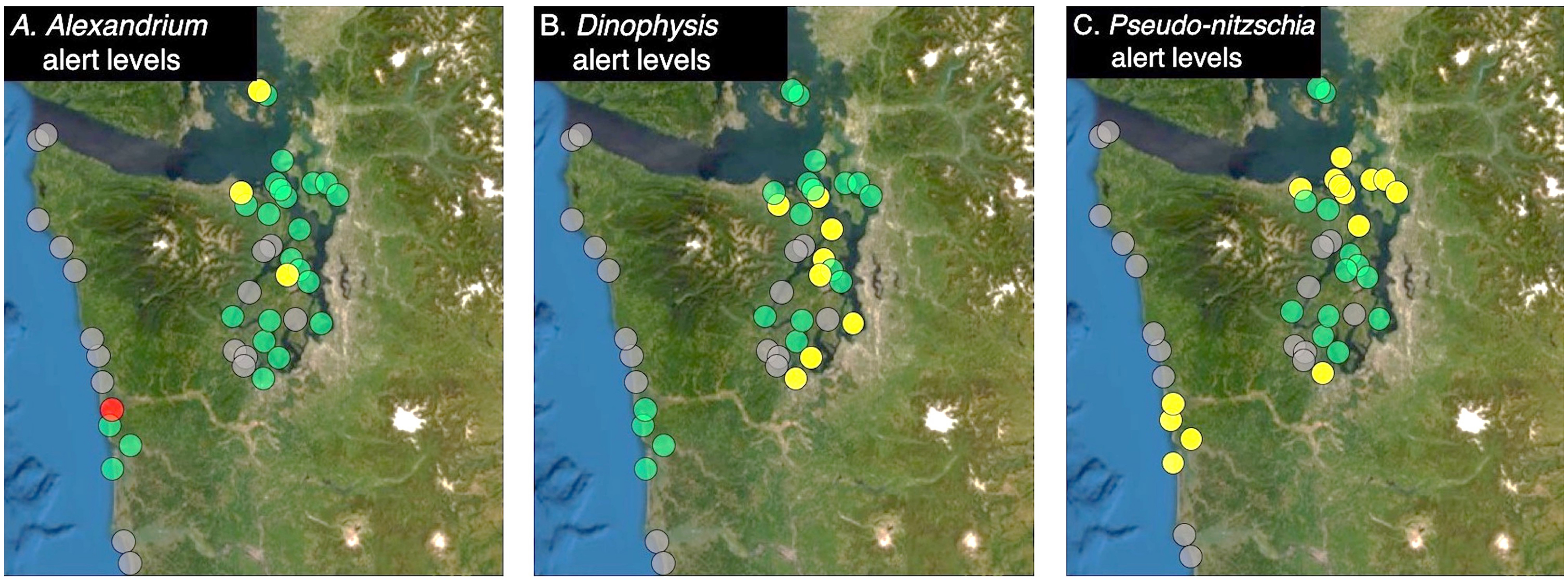
Shellfish-killing species observed in 2018:

Akashiwo sanguinea – 12 stations reported presence. Four stations reported blooms: Budd Inlet – Port Plaza, Oakland SS Flupsy, Spencer Cove – Harstine Island, and Totten Inlet. Blooms primarily occurred in July.

Protoceratium reticulatum – 11 stations reported presence. North Bay – Allyn had a month-long bloom in July.

Phaeocystis globosa – Five stations reported presence: Discovery Bay, Fort Worden, Mystery Bay, Port Townsend, and Sequim Bay.

Additionally, volunteers completed the final year of sampling for the *Azadinium* research program, reported blooms of phytoplankton, such as *Noctiluca,* in 2018, and collaborated with Eyes on Puget Sound to confirm species of interest.



Red: Present with cell count above 100 cells/L
Yellow: Present with cell count between 1-99 cells/L
Green: Absent
Grey: April-October: not sampled for more than 15 days. November-March: not sampled for more than 30 days.

Red: Present with cell count above 1,000 cells/L
Yellow: Present with cell count between 1-999 cells/L
Green: Absent
Grey: April-October: not sampled for more than 15 days. November-March: not sampled for more than 30 days.

Red: Present with small cell count greater than or equal to 1,000,000 cells/L or large cell count greater than or equal to 50,000 cells/L
Yellow: Present with small cell count below 1,000,000 cells/L and large cell count below 50,000 cells/L
Green: Absent
Grey: April-October: not sampled for more than 15 days. November-March: not sampled for more than 30 days.

Figure 38. "Traffic-light" map showing SoundToxins alert levels, corresponding to high (red), medium (yellow), and low (green) risk of shellfish toxicity, during a summer week for the three harmful algal bloom genera Alexandrium, Dinophysis, *and* Pseudo-nitzschia *(see definition of alert levels for each genus under each panel). These maps are used by state shellfish managers to determine locations where additional shellfish samples may be collected to ensure safe harvest for human consumers.*

C.iii. *Alexandrium* species cyst mapping

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 cells. "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: Cheryl Greengrove (cgreen@uw.edu), Julie Masura, Sebastian Dantes, Alex Natkha (UWT), Margaret Dutch, Sandy Weakland, Valerie Partridge, Dany Burgess, and Angela Eagleston (Ecology); https://depts.washington.edu/uwtocean/

Alexandrium spp., a dinoflagellate that produces a powerful neurotoxin, overwinters in the sediment as a cyst. In the spring and summer, when environmental conditions are right, cysts germinate and become vegetative cells in the water column. Identification and enumeration of cysts can be used to determine regions where there is a greater potential for HABs. Since 2013, Ecology's Puget Sound Sediment Monitoring Program has collected surface sediment samples via a van Veen grab sampler in April and May at ten standard stations in Puget Sound. In 2016, Ecology added 12 additional sampling sites co-located at their marine monitoring stations and, since 2017, has added an additional 28 randomly selected stations for a total of 50 sediment stations sampled annually throughout Puget Sound. In June 2018, an additional 30 stations were sampled in Budd Inlet

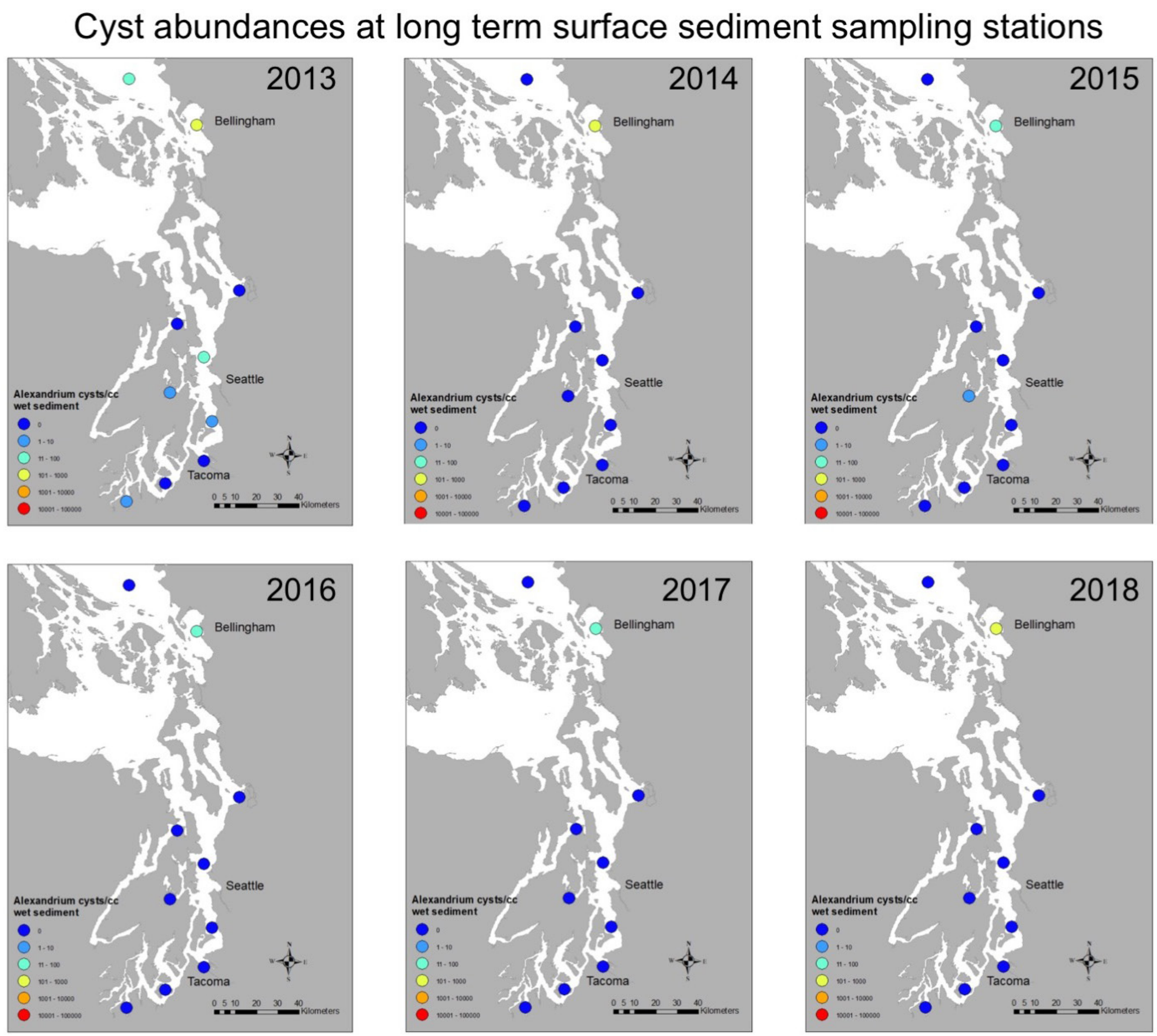


Figure 39. Distribution and concentration of Alexandrium *cysts from Ecology's ten long-term sediment monitoring stations in Puget Sound for 2013–18.*

6. Plankton (cont.)

as a part of Ecology's urban bay monitoring program. Though blooms typically occur in early spring and late summer, making it hard to determine cyst abundance in sediment, sampling in the spring still provides valuable information about the presence of this organism. Researchers at UW–Tacoma analyzed these sediments for the presence of cysts throughout the Puget Sound Basin and Budd Inlet.

Results from the ten Ecology standard long-term monitoring stations from 2013–18 show that *Alexandrium* is consistently present in Bellingham Bay, and often appears in Sinclair Inlet (Figure 39). A more detailed map of all 50 stations in 2017 shows the presence of cysts as far north as Birch Bay and as far south as Case Inlet (PSEMP Marine Waters Workgroup 2018). Cyst occurrences and abundances were greatest in 2013, and the seed bed in Bellingham Bay is a relatively constant source of cysts with a high potential for HABs of *Alexandrium* in the future. There were no cysts found in Budd Inlet (Figure 40).

2018 Budd Inlet cyst abundance

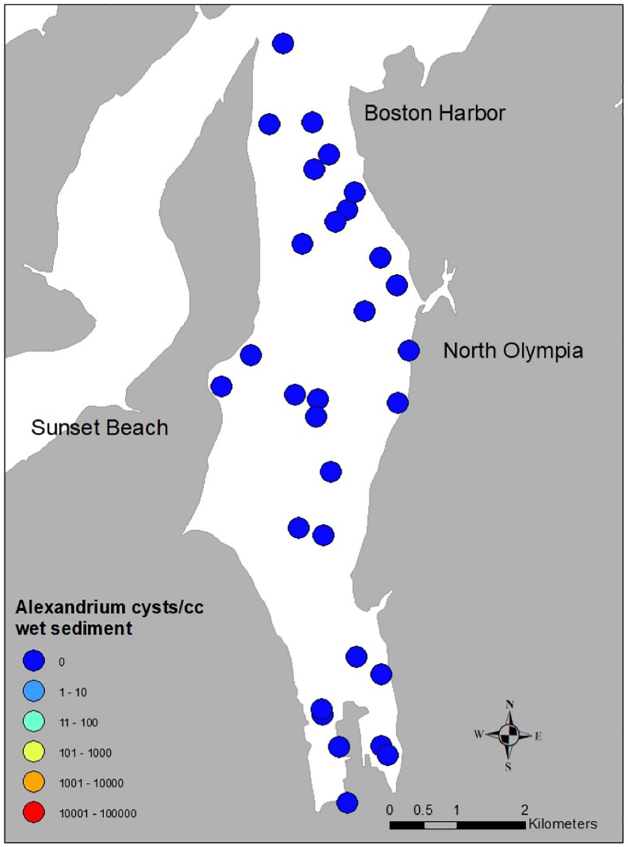


Figure 40. Distribution and concentration of Alexandrium *cysts from Ecology's surface sediment survey in Budd Inlet in 2018.*

CALL-OUT BOX: Organic matter deposition may adversely affect sediment-dwelling invertebrates in terminal inlets

In order to understand what drives observed patterns in the Puget Sound benthos (sediment-dwelling invertebrate communities), Ecology's Marine Sediment Monitoring Program annually characterizes surface sediments and benthic invertebrates. Three decades of monitoring have documented declines in Puget Sound benthic communities and found no significant correlation between the priority pollutant chemicals, toxicity, and benthos parameters (Weakland et al. 2018). Therefore, Ecology has begun to evaluate additional parameters which might explain declining benthic community health, including nutrients in sediments and monthly water-column measurements, to look for correspondences between water and sediment.

Initial results indicate spatial concordance between locations with high levels of organic matter (OM) in sediments and adversely affected benthic communities. In general, sediments rich in decomposing OM provide sediment-dwelling invertebrates with nutrient-rich food. Too much decomposing organic matter, however, can create stressful conditions and adversely affect benthic invertebrates (Hyland et al. 2005). Adversely affected communities tend to have fewer, but highly abundant, species, usually those known to be tolerant of oxygen depletion and buildup of toxic byproducts associated with the breakdown of OM, such as sulfide and ammonia. The benthos in Puget Sound's weakly flushed depositional terminal (or dead-end) inlets had lower taxa richness, and individual animals weighed more on average than in other areas of the Sound (Figure 41).

Spatial patterns observed in 2018 for sediment biogenic silica, total organic carbon, total nitrogen, and particle size indicate that OM accumulated preferentially in terminal inlets. Carbon and nitrogen content increased with fraction of fines (silt and clay), which also tends to be high in low-energy environments such as terminal inlets. Total carbon and nitrogen in surface sediments were strongly positively correlated (Figure 42), indicating that sediment nitrogen is primarily organic in origin and that the carbon and nitrogen supplies are controlled by similar processes (Goňi et al. 2013). From this relationship, it is evident that sediments with higher amounts of OM are most often found in the terminal inlets of the Sound (Figure 42).

Sediment carbon-to-nitrogen ratios and measurements of stable carbon and nitrogen isotopes suggest that the OM accumulating in these areas is primarily from marine algal production (Brandenberger et al. 2008, Krishna et al. 2013). Spatial patterns in sediment and water-column OM also correspond with visual observations of large algal blooms made by the Eyes Over Puget Sound program. In addition, estuarine circulation may transport and preferentially deposit OM to areas with higher residence times, often terminal inlets.

Both monitoring and modeled results document depletion of DO in terminal inlets and predict worsening depletion into the future (Roberts et al. 2014). Spatial concordance between adversely affected benthic communities and areas of low DO has been observed in Puget Sound.

Projected effects of climate change include longer water residence time, increased temperature, increased phytoplankton growth, lower DO, and consequently more potential to concentrate OM and byproducts of decomposition. Continued monitoring of sediments and water will provide insights into effects of climate change and anthropogenic nutrient input on benthos at the ecosystem scale.

Authors: Sandra Weakland (Sgei461@ecy.wa.gov), Danny Burgess, Angela Eagleston, Margaret Dutch, and Valarie Partridge (Ecology); https://ecology.wa.gov/Water-Shorelines/Puget-Sound/Sound-science/Marine-sediments

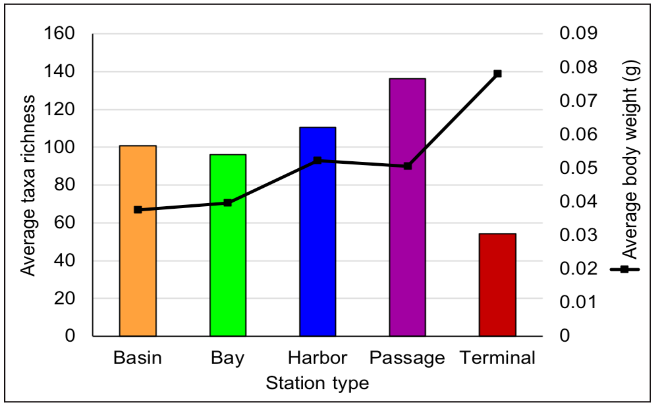


Figure 41. Average taxa richness (number of species) and average body weight per animal (excluding megafauna) for stations sampled in 2017, grouped by geomorphologic and water-body characteristic type or use (2018 data not available at time of publication).

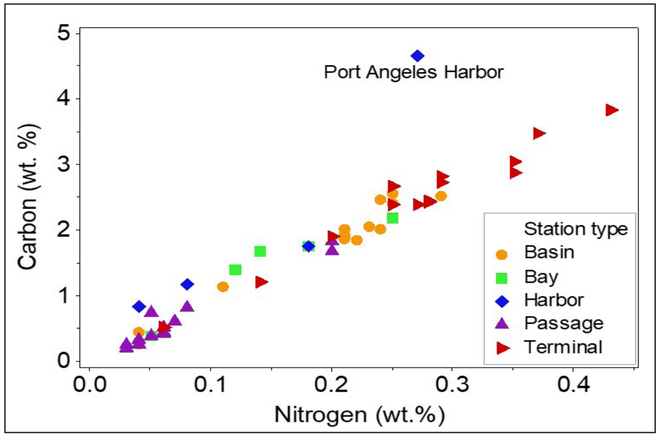


Figure 42. Relationship between weight percent content of detected carbon and nitrogen in surface sediments (top 2–3 cm) at 50 Puget Sound locations in 2018 (Spearman's rho = 0.97, p < 0.0001), also indicating geomorphologic and water-body type or use.

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

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

Source: Julianne Ruffner (julianne.ruffner@ecy.wa.gov) and Laura Hermanson (Ecology; WDOH); https://ecology.wa.gov/Water-Shorelines/Water-quality/Saltwater/BEACH-program; https://ecology.wa.gov/Research-Data/Monitoring-assessment/BEACH-annual-report

The BEACH Program coordinates weekly or bi-weekly monitoring from Memorial Day (May) to Labor Day (September) with local and county agencies, tribal nations, and volunteers. In 2018, 67 Washington beaches were sampled, including 42 core beaches (beaches that are consistently sampled from year to year). Figure 43 represents the percentage of all monitored beaches and core beaches that had less than two swimming advisories or closures during the swimming season from 2004–18. During the 2018 monitoring season, Bay View State Park (Padilla Bay), Kayak Point County Park (Port Susan), and Sooes Beach (Makah Bay, WA coast) had more than one advisory or closure. For that reason, these three beaches were not considered passing beaches. The Puget Sound Partnership uses BEACH data for their Vital Signs indicator and has set a target that all monitored beaches meet human health standards by 2020.

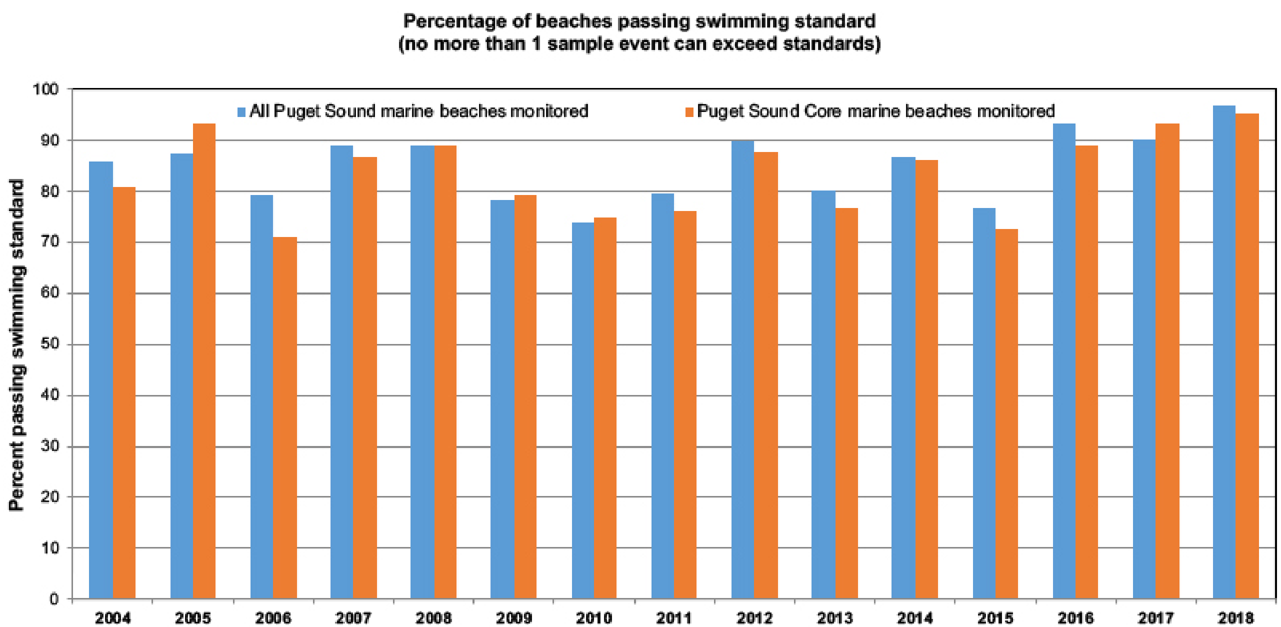


Figure 43. Percent of all marine beaches monitored and all core marine beaches (consistently sampled) that had no more than one swimming closure or advisory during the 2004–18 beach seasons.

7. Bacteria and pathogens (cont.)

A.ii. Central Basin stations

Source: Wendy Eash-Loucks (wendy.eash-loucks@kingcounty.gov) (KCDNRP); http://green2.kingcounty.gov/marine/

King County monitors fecal coliform bacteria monthly at 20 beach stations along Puget Sound Central Basin shorelines. Data collected during the discrete 12-month time period were compared to Washington State marine water-quality standards as a way to identify beaches with potential bacteria issues. State standards include a geometric mean standard of 14 colony forming units (CFU) per 100 mL, with no more than 10% of samples used to calculate the geometric mean exceeding 43 CFU/100 mL (peak standard). In 2018, 19 of the 20 beach monitoring stations met the geometric mean standard for the 12-month period, and 13 of these stations met the peak standard (Figure 44). The majority of fecal coliform samples with concentrations above 43 CFU/100 mL occurred in the months of August, October, November, and December (Figure 45). Mean concentrations were highest in November, likely due to the 3.27 inches of rain that fell in the three days prior to sampling. As in previous years, sites near freshwater sources such as creeks, rivers, and stormwater outfalls (e.g., Carkeek Park's Piper's Creek [Site C], Golden Gardens Park [Site D], Elliott Bay Sculpture Park Beach [Site H], Des Moines Creek Park [Site Q], Redondo Beach [Site S], and Dumas Bay [Site T]) are locations that typically have the highest bacteria concentrations.

King County also monitors bacteria at 14 offshore locations. Samples from 1-m depth were collected twice-monthly most of the year and monthly in January, August, and December at six ambient and eight outfall (both wastewater treatment plant and combined sewer overflows) stations. Fecal coliform data collected in 2018 show that all 14 offshore stations passed the geometric mean and peak standards for the 12-month period, continuing a trend seen over many monitoring years.

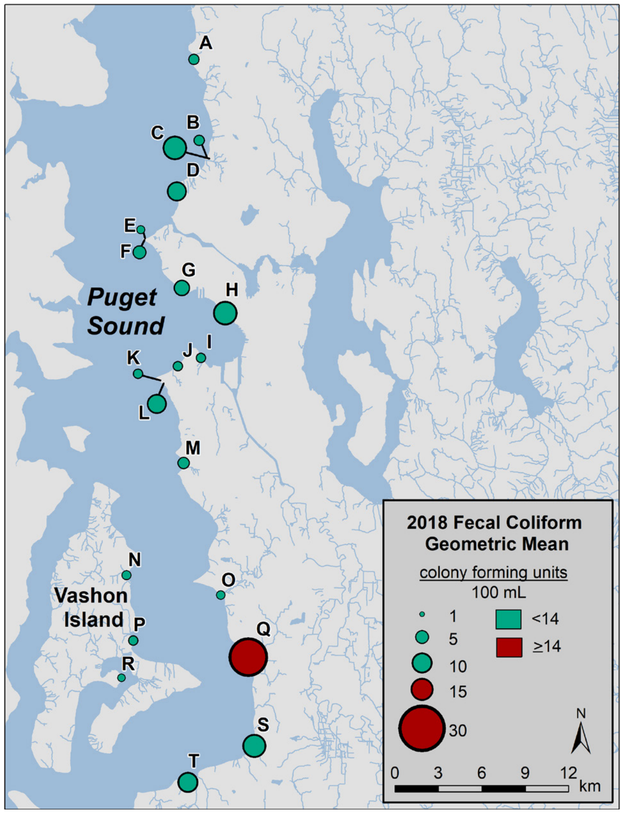


Figure 44. Map of King County's 2018 beach sampling sites and geometric mean values of those sites for the 12-month period. Concentrations are compared to the state geometric mean standard of <14 CFU/100 mL.

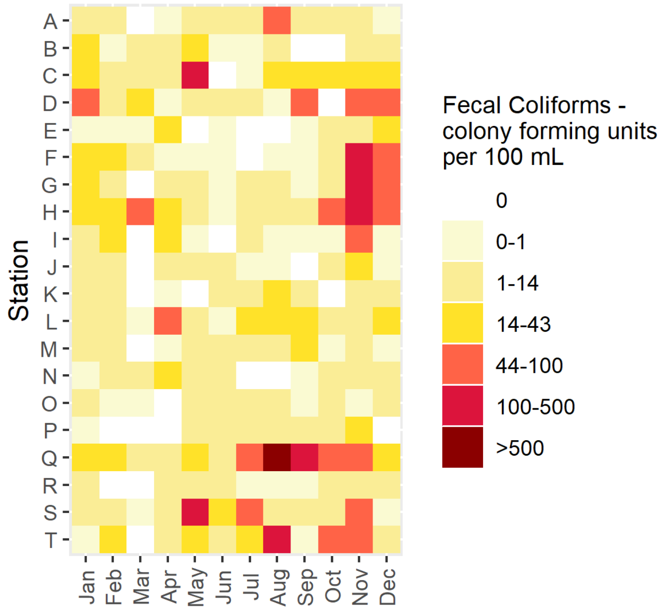


Figure 45. 2018 fecal coliform concentrations (CFU/100 mL) at King County's marine beach sites by month. Letters correspond to sampling stations in Figure 44.

B. *Vibrio parahaemolyticus*

Vibrio parahaemolyticus (Vp) *occurs naturally in the marine environment and is responsible for the majority of seafood-borne illnesses (mainly gastroenteritis) caused by the ingestion of raw or undercooked seafood, such as oysters, in the United States.* Vp *populations grow faster at higher temperatures and can cause illnesses, especially in the summer months. Genetic markers for virulent strains of* Vp *work well in other areas of the country, but are not effective in Puget Sound, significantly challenging health authorities. The Washington State Department of Health employs three strategies to control* Vp*-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: Erika Atherly (erika.atherly@doh.wa.gov) (WDOH); https://www.doh.wa.gov/CommunityandEnvironment/Shellfish

From June to September 2018, WDOH collected 139 samples from 13 sites and analyzed them for the presence of *Vp* (total and potentially pathogenic). One site in Puget Sound (Hood Canal 5) had the highest total *Vp* level, with greater than 110,000 MPN/g tissue. Four sites in Puget Sound (Dabob Bay, Hood Canal 5, Hood Canal 8, and Pickering Passage) had elevated total *Vp* levels (greater than 10,000 MPN/g tissue). While collecting oyster samples for *Vp* testing, samplers also record current weather conditions, salinity, and air, water, and tissue temperatures.

In 2018, the first laboratory-confirmed and epidemiologically linked illness associated with commercial oyster harvests contaminated with *Vp* occurred approximately one month earlier than normal in May, and there was an increase in illnesses associated with harvests from the coastal bays. There were 44 confirmed single-source illnesses from consumption of commercially harvested oysters (Figure 46). There were 93 multisource illnesses, 49 that were traced back to multiple possible Washington growing areas and 44 that were traced back to multiple possible Washington growing areas, other states, and/or Canada. Two portions of growing areas in Puget Sound (Dabob Bay and Henderson Bay) were closed due to *Vp* illnesses in 2018. Additionally, there were 26 laboratory-confirmed illnesses associated with noncommercial oyster harvests from public and private beaches in Washington.

The 2018 *Vp* illness counts exceeded prior years, including those reported during the last major outbreak in 2006. The majority of cases resulted from consuming oysters harvested from mid-June through late August, with most oysters coming from growing areas in South Puget Sound.

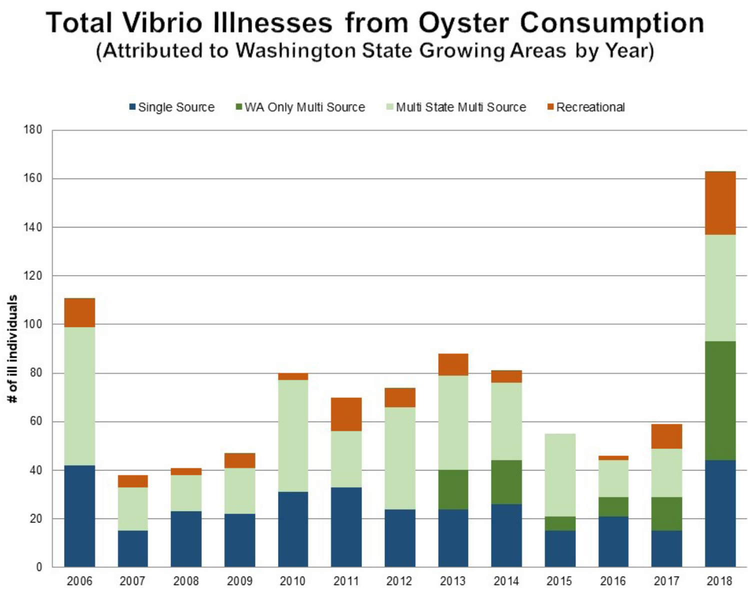


Figure 46. Vp*-related illnesses for both commercially and noncommercially harvested oysters. Description of illness types: single-source = illnesses that can be traced back to a single growing area, multisource = illnesses that cannot be traced back a single growing area (i.e., case consumed or could have consumed oysters from two or more growing areas).*

8. Forage Fish

Forage fish are a vital component of the marine food web, as they are prey throughout their life history for many invertebrates, fish, birds, and mammals. Pacific herring (*Clupea pallasii*) are the best-studied forage fish and are 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. Twenty-one stocks are monitored annually by the Washington Department of Fish and Wildlife (WDFW).

A. Pacific herring

Source: Todd Sandell (todd.sandell@dfw.wa.gov), Adam Lindquist, Patrick Biondo, Katie Olson, and Phillip Dionne (WDFW); https://wdfw.wa.gov/

In 2018, herring spawning biomass in Puget Sound totaled 10,279 metric ton (MT), slightly above the ten-year average for 2008–17. Hood Canal stocks, particularly Quilcene Bay, continue to bolster the overall Puget Sound biomass (Figure 47). The Quilcene Bay stock increased from 1,880 MT (2013) to 5,816 MT (2018) and made up over half of the total herring biomass for the region. The Port Gamble stock (451 MT) also increased 64% over 2017, slightly exceeding the ten-year average. The Central/South Sound basin stocks are considered to be depressed (only 29% of the 25-year mean; Sandell et al. 2018), but Squaxin and Elliott Bay had significant increases in 2018, and spawning was detected at Quartermaster Harbor and Port Orchard–Port Madison after a two-year hiatus. Most Whidbey Basin stocks increased in 2018 and the basin biomass was up 51% over 2017, but was just 45% of the ten-year average. In the North Puget Sound complex, the Cherry Point stock was again at an all-time low (249 MT in 2018, a 97% decline since 1973) and remains critical (Figure 47). Other northern stocks also declined in 2018. Large schools of northern anchovy (*Engraulis mordax*) in South Sound and throughout the Salish Sea (Duguid et al. 2018) suggest this species may provide an alternate source of prey for upper trophic levels; no biomass estimates are available for this or any other forage fish species.

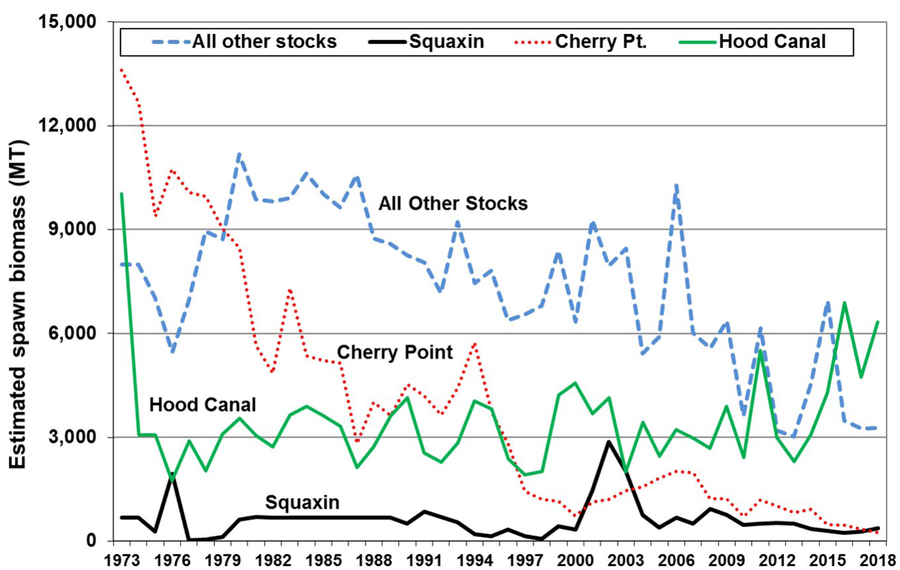


Figure 47. Estimated Puget Sound herring spawning biomass in Puget Sound basins, 1973–2018. Only the Cherry Point and Squaxin stocks are genetically distinct; Hood Canal is isolated from "All Other Stocks" to highlight the recent increases in spawning biomass.

9. Marine birds and mammals

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

A. Rhinoceros auklet: Long-term reproductive success

Source: Peter Hodum (phodum@pugetsound.edu) (University of Puget Sound), Scott Pearson (WDFW), and Thomas Good (NOAA/NWFSC).

The effectiveness of using seabirds as indicators of marine conditions is a function of their sensitivity to changing environmental conditions, with behaviorally plastic species typically showing little interannual variability in reproductive parameters. In 2016, we documented a highly anomalous breeding season for rhinoceros auklets (*Cerorhinca monocerata*) on Protection Island, WA, in the Salish Sea but not on Destruction Island, on the outer Washington coast. We continued our long-term breeding season monitoring at both breeding colonies in 2017 and 2018, providing us with the opportunity to evaluate the population-level response to the 2016 season. On Protection Island in 2017, burrow occupancy (the proportion of burrows that were reproductively active) was the lowest recorded in 12 years of monitoring (58% compared to the long-term mean of 72%; Figure 48), suggesting that the breeding population had been depressed due to breeding failure and a large adult mortality event the previous year. In 2018, occupancy was low but not anomalously so (65%). In contrast, hatching and fledging success were both comparable to the 11-year mean values (hatching = 85% and 80% in 2017 and 2018, respectively; fledging = 71% in 2017 and 77% in 2018). On Destruction Island, none of the three reproductive parameters differed from long-term mean values for the breeding populations in 2016–18. In stark contrast to 2016, nestling provisioning on Protection Island in both 2017 and 2018, as measured by fish per bill load and bill load weight, was comparable to long-term values. The nestling provisioning patterns on Destruction Island on the outer coast were comparable to long-term means. The increasing burrow occupancy on 2018 on Protection Island and average nestling provisioning suggest that the population is recovering from the 2016 breeding failure and an adult mortality event concurrent with that breeding season.

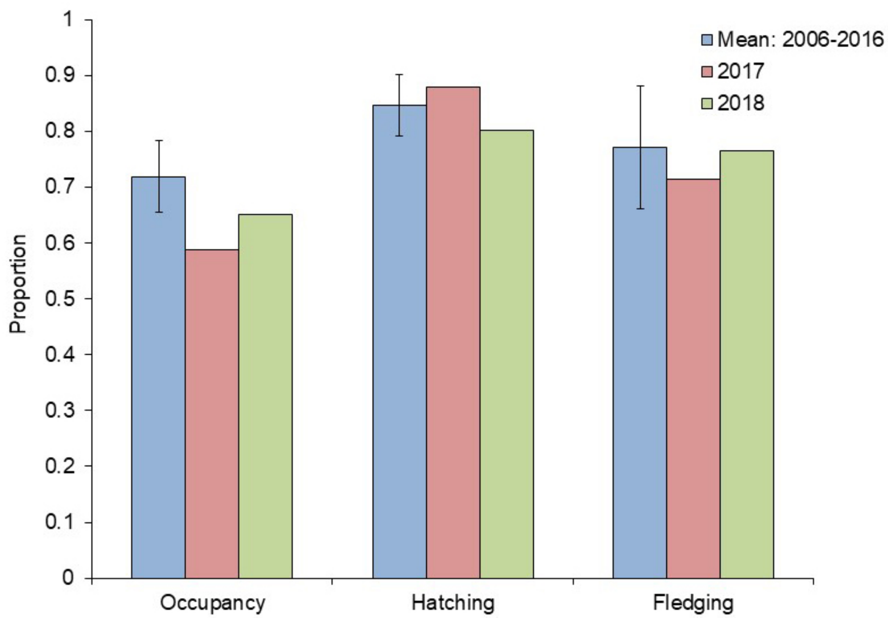


Figure 48. The proportion of rhinoceros auklet breeding burrows that were reproductively active and, for those that were active, the proportion of burrows that successfully hatched their egg (Hatching) or fledged their chick (Fledging) on Protection Island, WA.

9. Marine birds and mammals (cont.)

B. Wintering marine birds

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

Source: Toby Ross (tobyr@seattleaudubon.org), Jennifer Lang (Seattle Audubon Society), Peter Hodum (University of Puget Sound), and Scott Pearson (WDFW); https://seattleaudubon.org/sas/

During the 2017–18 season, a total of 208 volunteers conducted 842 surveys at 122 sites. The number of birds counted per survey ranged from 0–150 (median = 39 birds per survey). Monthly totals ranged similarly over the past three seasons (Figure 49A). A total of 54 species were detected, including diverse foraging guilds and both resident and migratory species.

Diving forage-fish specialists, which include alcids and grebes, have been identified by Vilchis et al. (2014) as a foraging guild that is vulnerable and declining in the Salish Sea. As is typical for birds in this system, we expect bird numbers to increase over the year and stabilize in the mid-winter months, reflecting migration and settlement into the system. But that was not observed in 2017–18. Compared to the previous three seasons, the number of forage-fish specialists was generally depressed throughout the 2017–18 season, particularly toward the end of the season (Figure 49B). Our results suggest that overwintering marine bird populations continue to fluctuate relative to the previous three seasons, which may relate to localized forage-fish availability. We may be experiencing the continuing influence of the Blob, which moved into Washington's inner marine waters in 2016.

Scoters (surf, white-winged, and black) as a group are a Puget Sound Vital Sign Indicator. Scoter counts fluctuated across the 2017–18 season, but were generally within the range of the previous three years (Figure 49C).

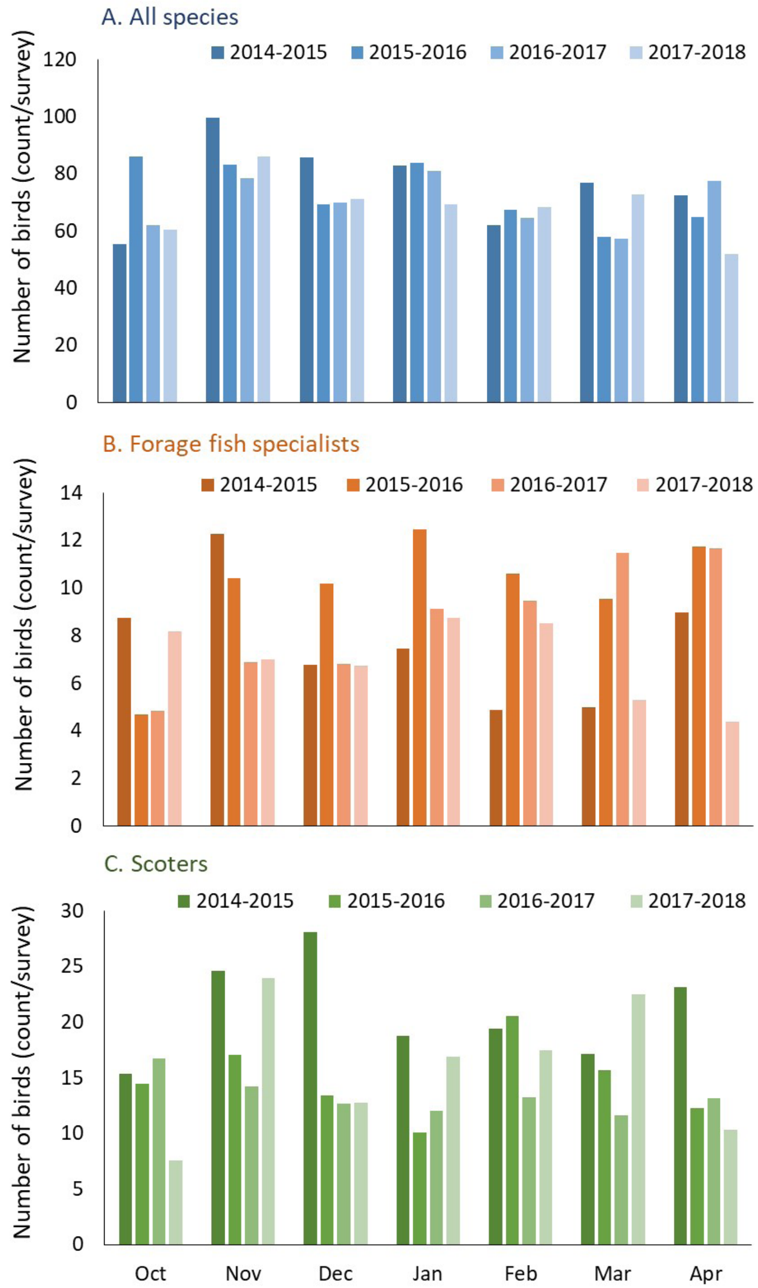


Figure 49. Numbers of birds counted per survey by month for (A) all species pooled, (B) diving forage-fish specialists (alcids and grebes), and (C) scoter species (surf, white-winged, and black).

C. Southern Resident killer whales

The Southern Resident killer whales (SRKWs) range seasonally from northern California to Haida Gwaii, B.C., in pursuit of their preferred prey, Chinook salmon. In typical years, all pods (J, K, and L) frequent Puget Sound between May and September to hunt salmon, primarily Fraser River Chinook salmon (Hanson et al. 2010). In the fall and winter, it is common for the SRKWs to seek other salmon, particularly chum, south of Admiralty Inlet. Thus, SRKWs are salmon specialists that serve as indicators of marine conditions over a wide area. Their population trends are driven primarily by survival (mortality and birth) rates which are strongly correlated with coastwide abundance indices for Chinook (Ford et al. 2010). The population is also affected by vessel interactions, which can reduce foraging efficiency, and by bioaccumulating pollutants, which can compound the health effects of starvation.

Source: Scott Veirs (sveirs@gmail.com) (Beam Reach, SPC), Monika Wieland (Orca Behavior Institute), Ken Balcomb (ken@whaleresearch.com) (Center for Whale Research), Cindy Elliser (Pacific Mammal Research), and Grace Ferrara (NOAA); PSEMP Marine Mammal Work Group; https://pspwa.box.com/v/psemp-mmwg-home

According to the annual census by the Center for Whale Research, the population size of SRKW (determined on 1 July) was 75 individuals in 2018, down from 77 in 2017. The recent downward trend (since 2016) in the total population was driven primarily by J pod (with a net loss of six), while L pod fell by one and K pod had no net loss (Figure 50). The most notable event of 2018 was the meteoric rise in public awareness about SRKWs catalyzed by J35, a 20-year-old female, who carried her dead newborn for 17 days (from 24 July to 8 August). Also notable was the loss of J50, a four-year-old female seen emaciated in June, and the transboundary efforts to diagnose and assist her. J53 (born 2015) is the only surviving female calf born into the population in the last seven years. While there were no successful births observed during the 2016–18 census years, the 2018 calendar year ended on a positive note with the birth of L124, most likely in December.

Multiple lines of evidence, such as the recent population decline, losses of relatively young whales, and drone-based observations of poor body condition in some individuals, suggest that the SRKW population is not finding enough to eat. Relatively low abundance of salmon within the Salish Sea is the most parsimonious explanation for trends in SKRW movement patterns that continued in 2018: later arrival in the spring and less residency. From April–June 2018, the SRKWs were observed in inland waters for only 17 days—fewer than any year from 1994–2016 (Shields et al. 2018). For the first time on record, SRKWs were not seen during all of May, whereas in some past years they were present in inland waters every day in May.

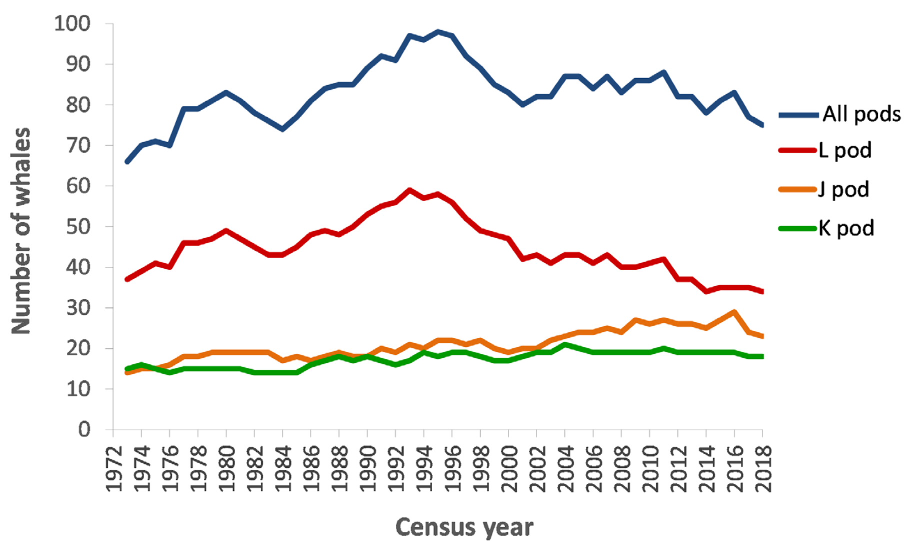


Figure 50. Number of Southern Resident killer whales (1973–2018), including the total population and the number of individuals in each pod (J, K, and L), recorded during the July 2018 census. Data source: Annual census as reported to NOAA by the Center for Whale Research (https://www.whaleresearch.com/orca-population).

CALL-OUT BOX: Microplastic mapping in Puget Sound sediments

In 2017, 348 million tons of plastics were produced worldwide, of which 87% were common polymers (i.e., polyethylene, polypropylene, polyvinyl chloride), 11% were synthetic fibers, and 2% were synthetic rubber (PlasticsEurope 2019). The rate of input of plastics into the oceans has been estimated to be approximately 9.5 million tons per year. The large amount of plastics found throughout the oceans and reported in the media have caught the attention of the public, thereby increasing awareness of this ocean pollution issue. Exploration of microplastics in Puget Sound began in 2008 with the development of field and laboratory methods by scientists at the University of Washington Tacoma's Center for Urban Waters.

Methods to monitor plastic pollution in the ocean were developed for three polymer types—polyethylene, polypropylene, and polyvinyl chloride—due to the sheer abundance of these materials manufactured and use throughout the world. Primary plastics are those found in the environment still in their manufactured size for use, and secondary plastics are those that have broken down from primary plastics. Of the primary plastics, 34% are synthetic textiles (fibers), followed by tires and city dust at 27% each, and the final 12% combined are road markings, marine coatings, personal care products, and plastic pellets (Boucher and Friot 2017). Plastics are also characterized by size; microplastics are smaller than 5 mm and macroplastics are larger than 5 mm. Plastics have been studied in the water column (surface focus), sea-floor sediments, and beach material.

This project explores microplastics in sediments collected throughout Puget Sound from 2014–18 to create baseline observations and determine whether concentrations have changed over time. Ecology's Puget Sound Sediment Monitoring Group provided sediment samples. Ten stations were sampled using a 0.1-m^2 stainless steel van Veen grab sampler to recover 2–3 cm of the top sediment from the sea bed. In the lab, samples were mixed in potassium metaphosphate to disaggregate sediment, filtered through stacked sieves to sort grain size, separated by density in lithium metatungstate to desired density, oxidized in hydrogen peroxide to remove biofilms, and separated by density in sodium chloride to desired density. The floating

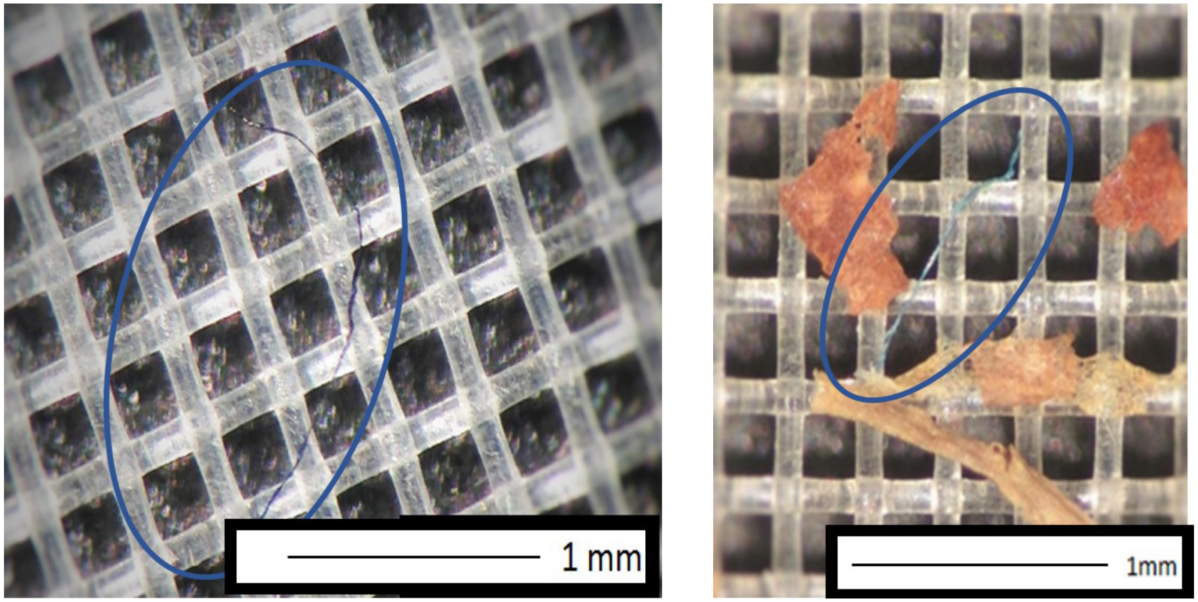


Figure 51. Microplastics fibers in a sieve, circled in blue for visual identification. Photo: Ren-Chieh Chang.

CALL-OUT BOX: Microplastic mapping in Puget Sound sediments (cont.)

material was sieved to 0.33 mm, washed with filtered water, and inspected for microplastics using a dissecting microscope at 40x magnification (Masura et al. 2015; Figure 51).

Results from the 2014–18 sampling show that microplastics were found every year at all but one station in 2017 (Figure 52). The highest density of microplastics was 27,171 microplastics/m^2 in 2017 at the Sinclair Inlet station, followed by 19,131 microplastics/m^2 in 2014 at the East Anderson Island station and 14,506 microplastics/m^2 in 2016 at the Thea Foss Waterway station. The average for all years was 4,574 microplastics/m^2, ranging from 704 microplastics/m^2 in 2018 to 7,357 microplastics/m^2 in 2014. Although numerically the number of microplastics has been decreasing with time, there has been no statistically significant change. Continued monitoring for microplastics in sediments throughout Puget Sound is needed to understand where this emerging pollutant accumulates (sinks), and its potential impacts on benthic organisms.

Authors: Julie Masura (jmasura@uw.edu), Cheryl Greengrove, Ren-Chieh Chang, Ashley Fowler, Margaret Baer, Brenda Solano Jimenez, Amy Self, and Abigail Deaton (UWT); www.tacoma.washington.edu

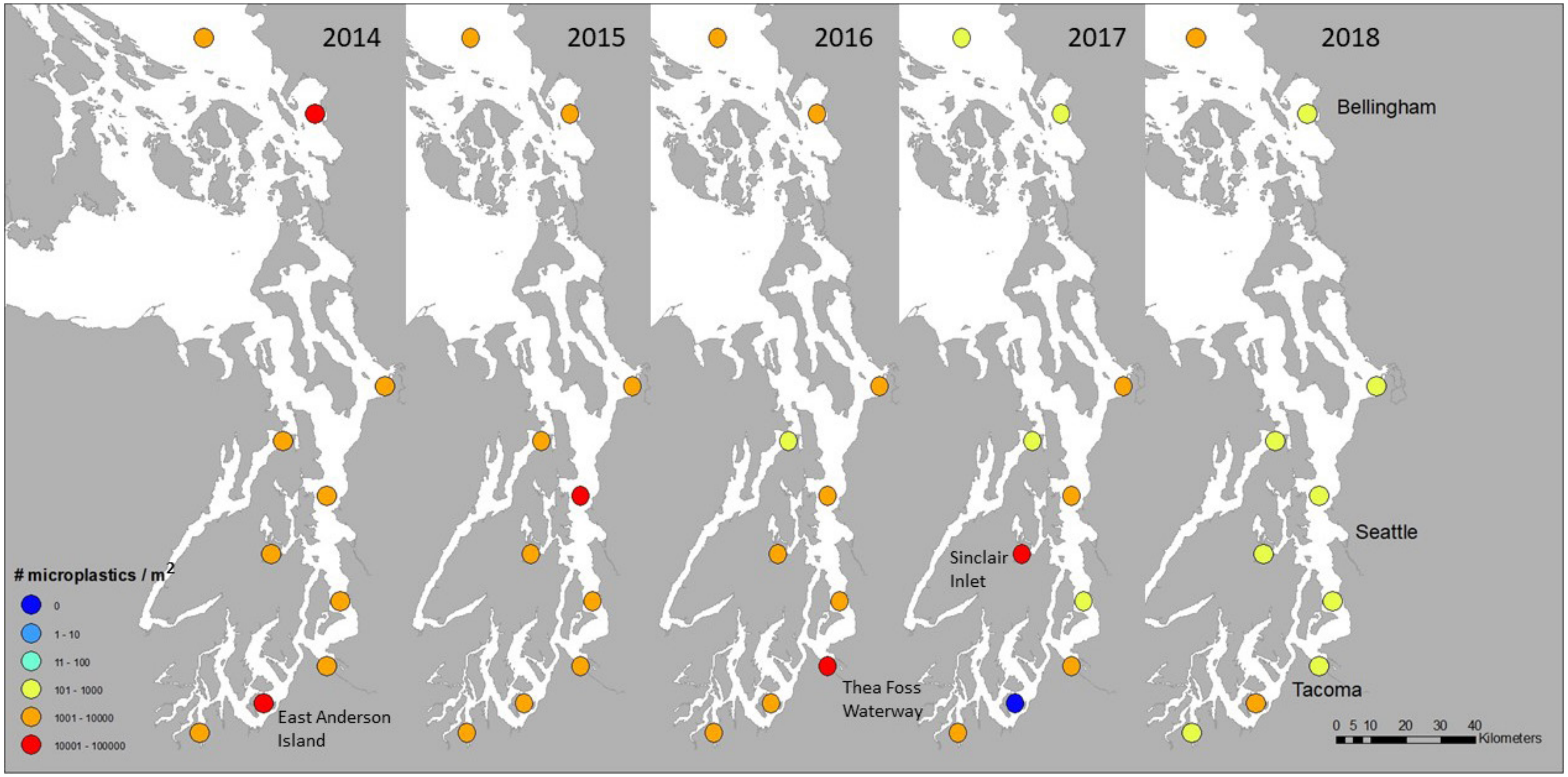


Figure 52. Microplastics concentration in sea-floor sediments at monitoring stations throughout Puget Sound from 2014–18. Each dot color represents an order of magnitude for the number of microplastics/m^2, from 0 (blue) to >10,000 (red).

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Acronyms

APL	Applied Physics Laboratory
AR	Admiralty Reach
ASP	amnesic shellfish poisoning
ATG	Atmospheric Sciences and Geophysics building
BCRFC	British Columbia River Forecast Center
BEACH	Beach Environmental Assessment, Communication, and Health
CDOM	colored dissolved organic matter
CFU	colony forming unit
Chl-*a*	chlorophyll-*a*
CO_2	carbon dioxide
CTD	conductivity, temperature,depth
DO	dissolved oxygen
DFO	Fisheries and Oceans Canada
DSP	diarrhetic shellfish poisoning
Ecology	Washington State Department of Ecology
ENSO	El Niño–Southern Oscillation
EPA	Environmental Protection Agency
ESRL	NOAA Earth System Research Laboratory
FDA	U.S. Food and Drug Administration
FHL	Friday Harbor Laboratories
ft^3/s	cubic feet per second
g	gram
HC	Hood Canal
HAB	harmful algal bloom
HCSEG	Hood Canal Salmon Enhancement Group
IOOS	Integrated Ocean Observing System
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
KC	King County
KCDNRP	King County Department of Natural Resources and Parks
KCEL	King County Environmental Laboratory
KWT	Kwiáht
L	liter
LUM	Lummi Nation
m	meter
m^2	meter squared
mL	milliliter
mm	millimeter
MB-SS	Main Basin to South Sound
MHW	mean high water
MPN	most probable number
MT	metric ton
m^3/s	cubic meters per second
mg C/m^3	milligrams carbon per meter cubed
mg/L	milligrams per liter
NANOOS	Northwest Association of Networked Ocean Observing Systems
NERRS	National Estuarine Research Reserve System
NEMO	Northwest Enhanced Moored Observatory
NIT	Nisqually Indian Tribe
NOAA	National Oceanic and Atmospheric Administration
NPGO	North Pacific Gyre Oscillation
NWFSC	Northwest Fisheries Science Center
NWIC	Northwest Indian College
OA	ocean acidification
ORCA	Oceanic Remote Chemical Analyzer
O_2	molecular oxygen
OM	organic matter
OWSC	Office of the Washington State Climatologist
PDO	Pacific Decadal Oscillation
PGST	Port Gamble S'Klallam Tribe
PFEL	Pacific Fisheries Environmental Laboratory
PMEL	Pacific Marine Environmental Laboratory
pCO_2	partial pressure of carbon dioxide
ppm	parts per million
PSEMP	Puget Sound Ecosystem Monitoring Program
PSP	paralytic shellfish poisoning
PSSS	Puget Sound Seabird Survey
PSU	practical salinity unit
S	salinity
Si:DIN	silicate to dissolved inorganic nitrogen
SRKWs	Southern Resident killer whales
SST	sea surface temperature
STOI	Stillaguamish Tribe of Indians
SoG	Strait of Georgia
T	temperature
T–S	temperature–salinity
TUL	Tulalip Tribe
µatm	microatmospheres
UCONN	University of Connecticut
µg	microgram
µm	micrometer
USGS	United States Geological Survey
UW	University of Washington
UWT	University of Washington–Tacoma
Vp	*Vibrio parahaemolyticus*
WB	Whidbey Basin
WDFW	Washington Department of Fish and Wildlife
WDOH	Washington State Department of Health
WDNR	Washington Department of Natural Resources
WSG	Washington Sea Grant
WWU	Western Washington University
xCO_2	mole fraction of CO_2
°C	degrees Celsius