2016
overview

puget sound MARINE WATERS

Puget Sound Ecosystem Monitoring Program

NOAA FISHERIES

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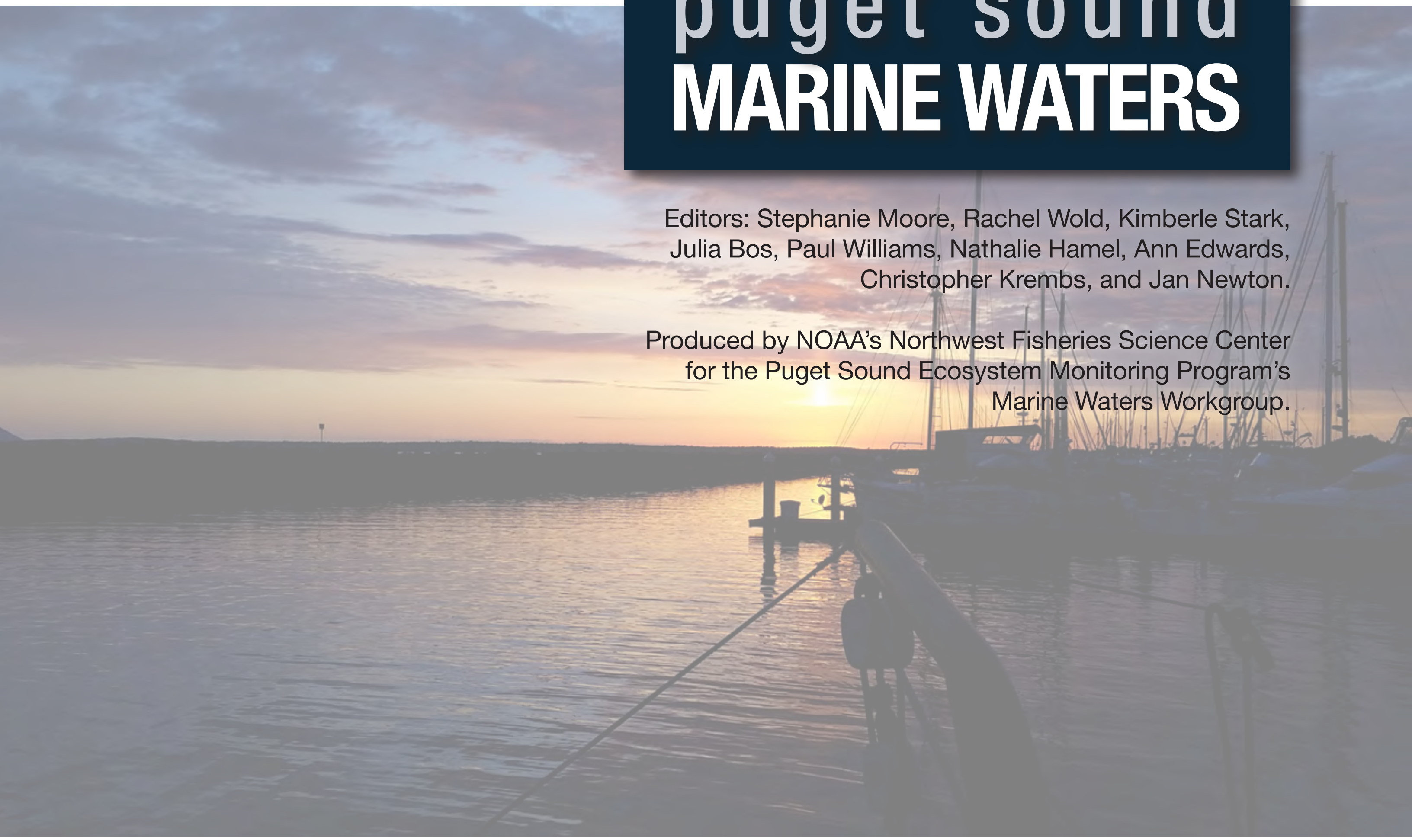


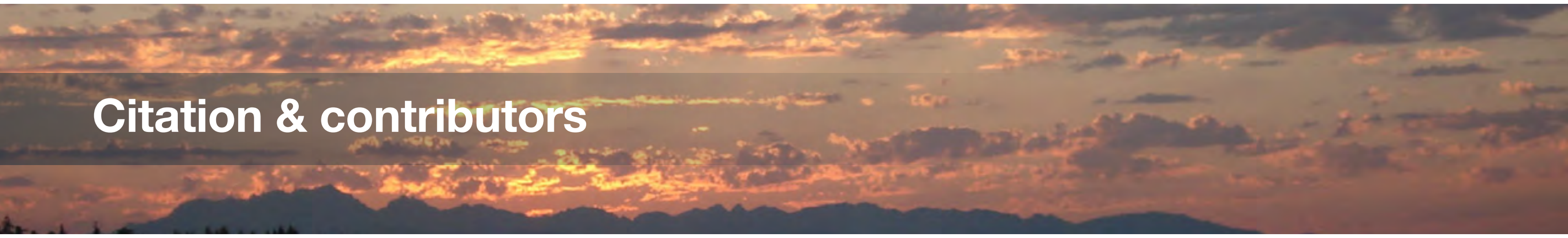
Editors: Stephanie Moore, Rachel Wold, Kimberle Stark, Julia Bos, Paul Williams, Nathalie Hamel, Ann Edwards, Christopher Krembs, and Jan Newton.

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

PSEMP
Puget Sound Ecosystem Monitoring Program

NOAA Fisheries

Front Cover & Title Page Photo Credit: Todd Sandell, DFW



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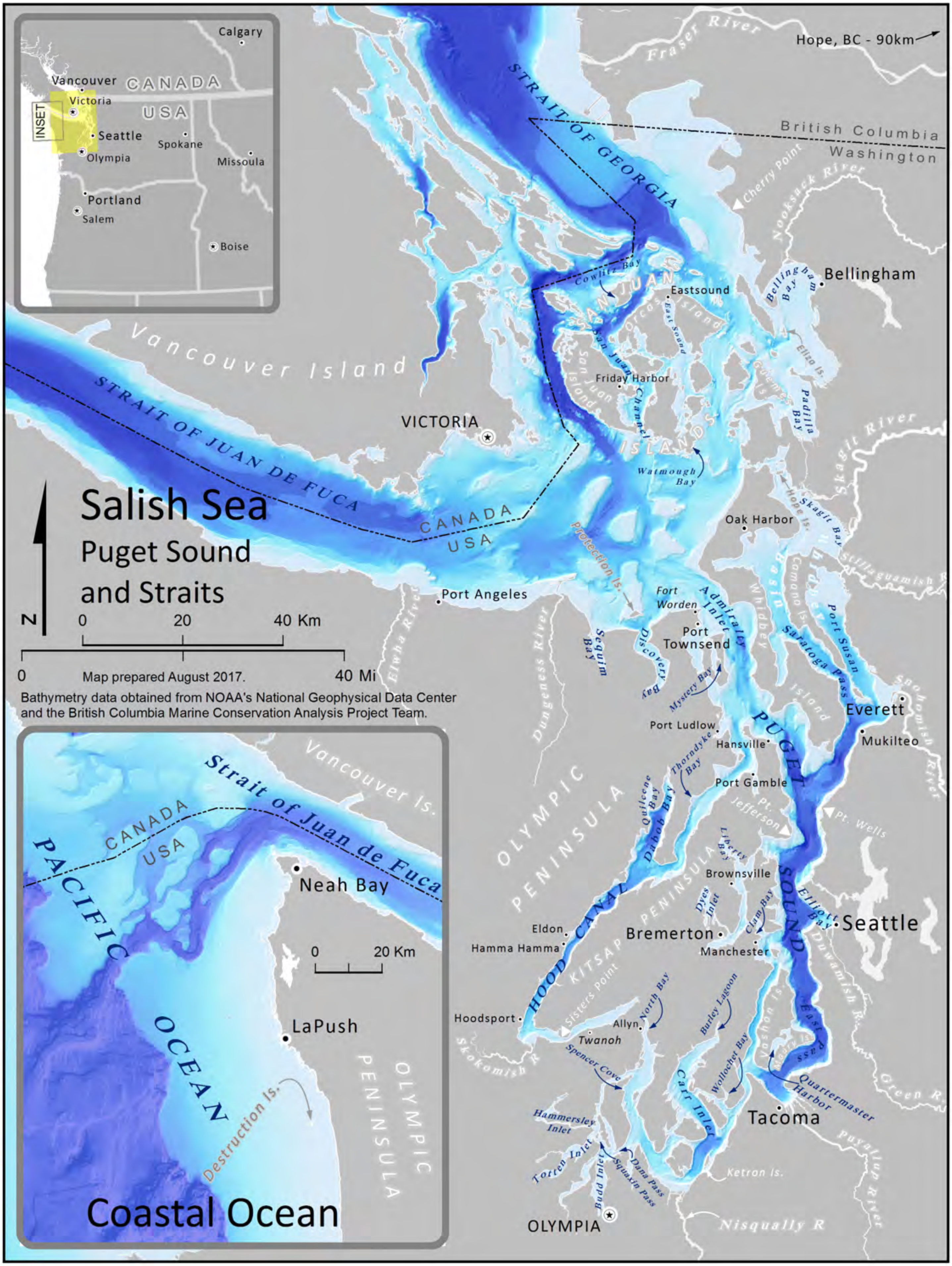


Map credit: Damon Holzer

Dedication

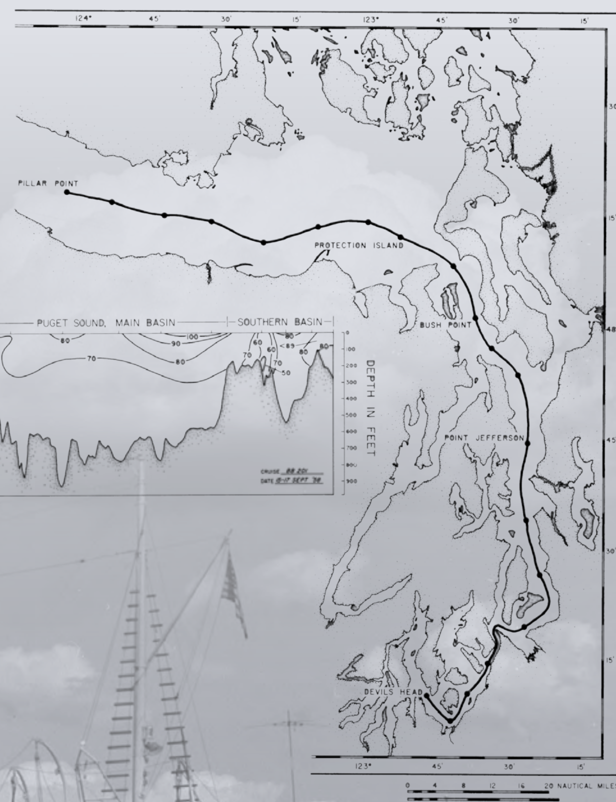
Eugene E. Collias (1925–2017)

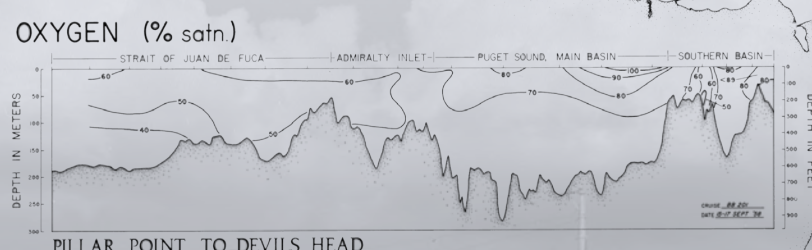
The editors and authors of the 2016 edition of the Puget Sound Marine Waters Overview Report dedicate this compilation to Eugene Collias. Eugene served as an inspiration to the Puget Sound Ecosystem Monitoring Program, not only for his scientific excellence but also for his foresight and care in assuring the preservation and use of Puget Sound oceanographic data.

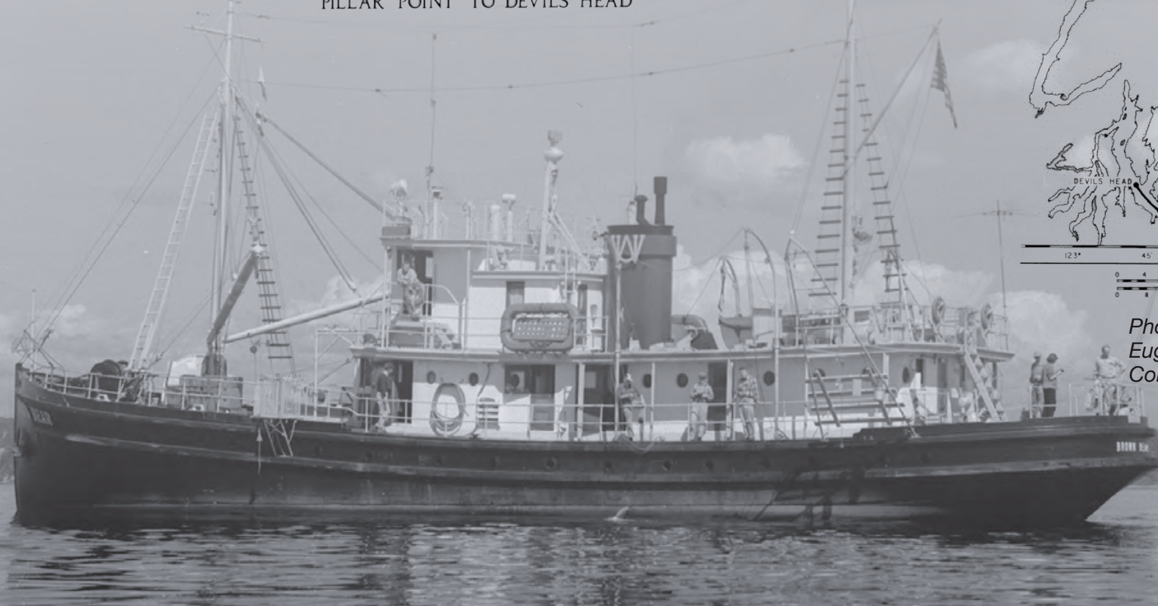
Eugene's oceanography career at the University of Washington spanned 34 years (1947–81). When Eugene retired, he estimated that he had been responsible for collecting about 70% of all the physical and chemical data available for Puget Sound up to that time. His publication, *Atlas of Physical and Chemical Properties of Puget Sound and Its Approaches*—which illustrated water properties throughout the Sound spanning from 1952 through 1966—lives on as a seminal contribution, aiding our interpretation of the region's variability and serving as a benchmark against which to evaluate change. He was an enthusiastic guardian and preserver of Puget Sound oceanographic data, and his passion to be sure that the data lived on in new hands never wavered, as well as his kind disposition toward the "new kids on the block."

The PSEMP Marine Waters Workgroup honors Eugene's significant contribution to the collection and preservation of the historical Puget Sound data, which serves as the baseline for us today.

Dedication by Lincoln Loehr and Jan Newton







Photos and figure: Eugene and Dorthy Collias Collection.

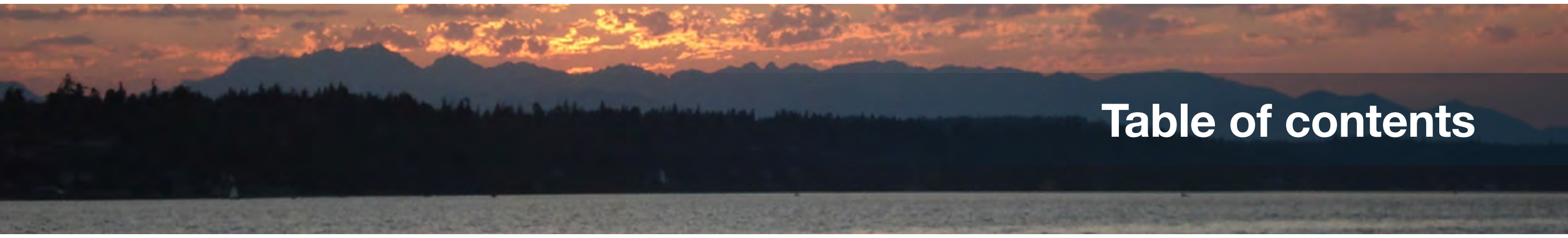


Table of contents

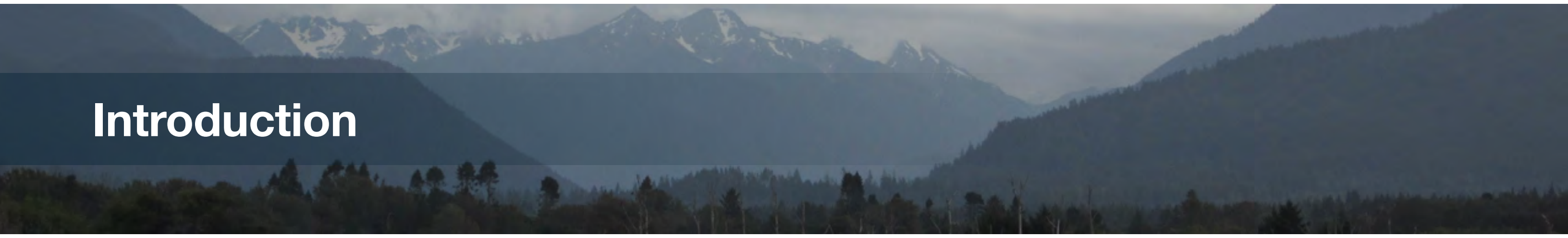
Table of contents (cont.)

About PSEMP

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

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

The Marine Waters Workgroup is one of several technical workgroups operating under the PSEMP umbrella, with a specific focus on the inland marine waters of Puget Sound and the greater Salish Sea, including the oceanic, atmospheric, and terrestrial influences and drivers affecting the Sound. For more information about PSEMP and the Marine Waters Workgroup, please visit sites.google.com/a/psemp.org/psemp/.



Introduction

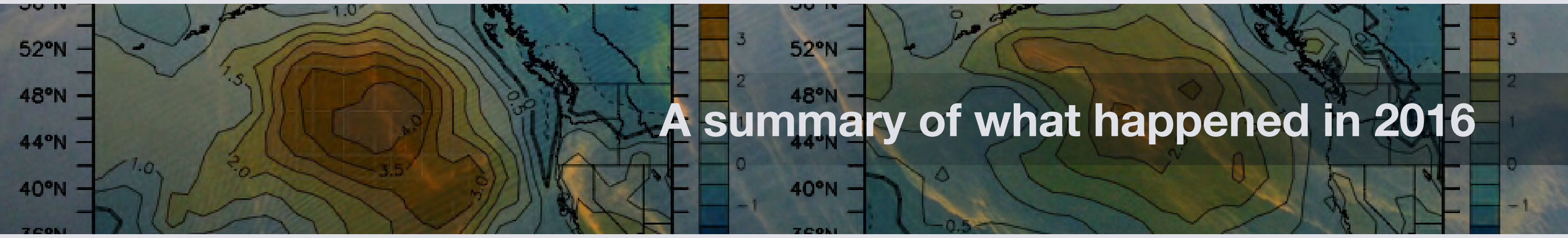
This report provides a collective view, from comprehensive monitoring and observing programs, of marine water quality and conditions and associated biota in Puget Sound in 2016. While the report focuses on the marine waters of greater Puget Sound, additional selected conditions are also included due to their influence on Puget Sound waters. These include large-scale climate indices and conditions along the Washington coast. It is important to document and understand regional drivers of variability and patterns on various timescales so that water quality data may be interpreted with these variations in mind, to better distinguish human effects from natural variations and change. This is the sixth annual report produced for the PSEMP Marine Waters Workgroup. What follows is our message to decisionmakers, policymakers, managers, scientists, and the public who are interested in the health of Puget Sound.

From the editors: Our objective is to collate and distribute the valuable physical, chemical, and biological information obtained from various marine monitoring and observing programs in Puget Sound. Based on mandate, need, opportunity, and expertise, these efforts employ different approaches and tools that cover various temporal and spatial scales. For example, surface surveys yield good horizontal spatial coverage, but lack depth information; regular station occupation over time identifies long-term trends, but can miss shorter-term variation associated with important environmental events; moorings with high temporal resolution describe shorter-term dynamics, but have limitations in their spatial coverage. 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 2016.

This report is the proceedings of an annual effort by the PSEMP Marine Waters Workgroup to compile and cross-check observations collected across the marine waters of greater Puget Sound during the previous year. Data quality assurance and documentation remains the primary responsibility of the individual contributors. All sections of this report were individually authored, and contact names and information are provided. The editors managed the internal cross-review process and focused on organizational structure and overall clarity. This included crafting a summary of what happened in 2016 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 2016.

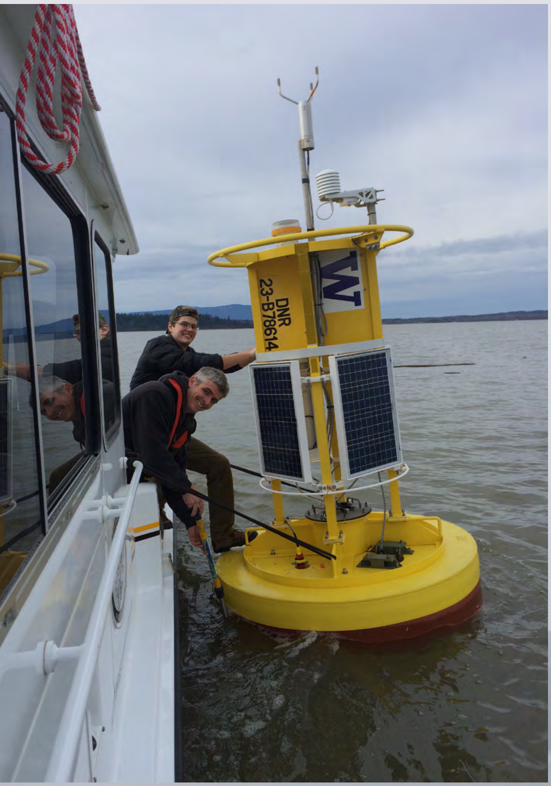
The larger picture that emerges from this report helps the PSEMP Marine Waters Workgroup to 1) maintain an inventory of the current monitoring programs in Puget Sound and determine how well these programs are meeting priority needs, 2) update and expand the monitoring results reported in the Puget Sound Vital Sign indicators (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. Most of the marine data presented here and an inventory of monitoring assets can be found through the NANOOS web portal (www.nanoos.org). Full content from each contributor can be found after the highlights from 2016 monitoring, including website links to more detailed information and data.

The Canadian ecosystem report, *The State of the Ocean for the Pacific North Coast Integrated Management Area* (www.dfo-mpo.gc.ca/oceans/publications/soto-rceo/2012/intro-eng.html), encompasses approximately 102,000 km^2, from the edge of the continental shelf east to the British Columbia mainland, and includes large portions of the Salish Sea. The annual report provides information that is also relevant for Puget Sound and is a recommended source of complementary information to this report.



A summary of what happened in 2016

This brief synopsis describes patterns in water quality and conditions and associated biota observed during 2016 and their association with large-scale ocean and climate variations and weather factors. The data compilation and analysis presented in the annual Puget Sound Marine Waters Overview, which began in 2011, offers the opportunity to evaluate the strength of these relationships over time, and is a goal of the PSEMP Marine Waters Workgroup.



Marco Hatch and his student, tying up the Northwest Indian College boat to the Bellingham Bay buoy for buoy maintenance and taking calibration samples.. Photos: Beth Curry

Puget Sound's marine waters during 2016 were a milder version of the exceptional years of 2014 and 2015, when warm-water temperature records were set and unprecedented harmful algal blooms occurred. The year 2016 may be regarded as a transitional year from the extreme conditions of the past two years to more typical conditions, but it was still warmer than normal and was marked by some unusual events and alarming trends in Puget Sound biota.

During 2016, forcing by large-scale climate patterns appeared relatively moderate, except for forcing from the tropical Pacific, which transitioned from strong El Niño to weak/moderate La Niña conditions. Atmospheric circulation patterns in Washington State responded unusually strongly to La Niña, producing wetter than normal conditions during the last three months of 2016. The other climate indices were more mild, with the Pacific Decadal Oscillation index starting positive, peaking during early spring, and nearing zero in fall, and the North Pacific Gyre Oscillation index near neutral or only slightly positive year-round.

Local weather within the Puget Sound region was, overall, warmer and wetter than average during 2016, and this appeared to affect many of the observed oceanographic patterns. The year 2016 was the third warmest year since records began in 1895, and the summer was sunnier than normal. Water temperatures throughout the Sound were well above normal, though not as extreme as during 2015. The especially warm spring caused rapid snowmelt at higher elevations that resulted in early and increased freshwater discharge to Puget Sound, followed by consequently lower than average late spring/summer streamflows. The fall wet season came early, and record rains fell in October. Puget Sound salinities responded to these weather patterns, with salinity anomalies that shifted from fresher (spring) to saltier (summer) to fresher again (fall/winter). Strong density stratification of the water column occurred during these fresher periods in spring and fall due to fresher surface waters overlying saltier deep waters. This inhibited mixing and may have contributed to the generally lower than normal dissolved oxygen concentrations observed throughout the Sound; however, no widespread fish kills were observed.

Warmer than normal water temperatures and strong spring density stratification may have influenced phytoplankton blooms in the Main Basin of Puget Sound, which in some locations happened early but did not persist as long as in previous years. Stratification in the presence of sunlight would favor blooms, but continued stratification can result in nutrient limitation. Indeed, nitrate concentrations in some areas were lower than normal during summer. A Main Basin fall bloom was not evident, as it usually is, despite available nutrients in September. While zooplankton were abundant in 2016, one species notable for coloring surface waters red, *Noctiluca*, was conspicuously absent. Increased

A summary of what happened in 2016 (cont.)

summer mixing due to less salinity stratification may have been a factor for this species that floats at the surface at the end of blooms as cells are senescing.

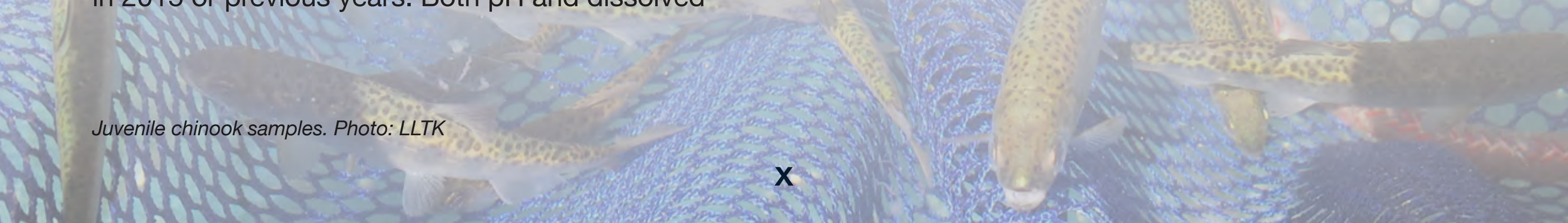
Various harmful algal blooms occurred throughout Puget Sound, with many associated commercial and recreational shellfish harvesting closures, but there were no reported illnesses. One of these blooms set a new state record for diarrhetic shellfish poisoning toxin levels—this occurred in mussels from Budd Inlet in South Sound. Despite high annual rainfall in 2016, overall, fecal coliform indicator bacteria concentrations were low. Conversely, there were almost 50 laboratory-confirmed and epidemiologically linked illnesses in 2016 due to the consumption of oysters in Washington contaminated with the bacteria *Vibrio parahaemolyticus*. Our weather may explain this pattern: a dry summer would not be conducive to human bacteria contamination, which is often via stormwater runoff; yet a warm summer is conducive to the growth of the *Vibrio* bacteria.

Ocean acidification conditions show differences between the coast and Puget Sound. While atmospheric levels of carbon dioxide (CO_2) at all mooring sites continued their year-to-year increase in 2016, the measurements from Hood Canal were higher than coastal sites and had values 14–15 ppm higher than the global average. Levels of CO_2 in the surface waters of Hood Canal were undersaturated (i.e., lower than atmospheric values) for a longer time and by a greater margin in early 2016 than we have observed before, likely due to persistent warmer than normal conditions. Ocean acidification conditions were relatively typical off the coast, though with continued warmer than normal ocean temperature conditions. The upwelling season was near normal, except for May, which had stronger than normal upwelling winds. However, winter downwelling was stronger than normal at both the start and end of the year. A notable observation from the coastal ocean was a very rapid transition from cooler, saltier, lower dissolved oxygen conditions to much warmer, fresher, higher dissolved oxygen conditions coincident with the fall shift to strong downwelling. Such a rapid transition was observed in 2016 and 2014, but not in 2015 or previous years. Both pH and dissolved oxygen at depth showed interannual variation in the seasonal pattern, as well as high-frequency variation over ranges relevant to the biological fitness of marine organisms.

Farther up the food web, some alarming trends and patterns were observed. Rhinoceros auklet chick survival and fledging success on Protection Island were the lowest during 2016 in 11 years of breeding season monitoring, apparently due to poor forage fish availability in the Salish Sea. For Pacific herring, critical to the Puget Sound ecosystem, 2016 was a bad year—in fact, it was the worst on record for the Cherry Point stock for the second consecutive year. For five stocks in South Sound and Main Basin, no spawn was recorded in 2016. A 13-year time series of top predators in the central Salish Sea during fall found low abundances of marine mammals and seabirds, similar to 2014 and 2015.

Evidence of disease was observed in Puget Sound. From May through September 2016, over 1,000 rhinoceros auklet carcasses were found by citizen science volunteers on beaches around the Salish Sea and on the Washington coast, which is highly unusual for this species. Necropsy analyses revealed bacterial septicemia to be the ultimate cause of death. Seagrass wasting disease, caused by a marine protist, significantly compromises eelgrass health and can lead to mass die-offs. The disease was more prevalent and severe in the shallower intertidal eelgrass beds of the San Juan Islands than in the deeper subtidal beds, perhaps indicating that eelgrass blades that are physiologically more stressed due to exposure at low tide are more susceptible to infection.

From these 2016 data and those from previous years, we know that climate and weather patterns yield strong influences on Puget Sound water properties and plankton at the base of the food web. Yet fully understanding all the factors driving effects higher up the food web is more complex and thus difficult. Our annual overview summaries are an effort to document what happened in a given year, so that further inquiry may see the patterns based on our long-term monitoring data with increased understanding.



Juvenile chinook samples. Photo: LLTK

Highlights from 2016 monitoring

Large-scale climate variability and wind patterns:

- El Niño–Southern Oscillation (ENSO):
  - The tropical Pacific transitioned from strong El Niño to weak/moderate La Niña conditions.
- Pacific Decadal Oscillation (PDO):
  - The PDO was positive, with peak values in early spring and nearing zero by fall.
- North Pacific Gyre Oscillation (NPGO):
  - The NPGO was near neutral or slightly positive.
- Upwelling index:
  - Upwelling winds were stronger than normal in May, and downwelling winds were stronger than normal from January through March and again from October through November.

Local climate and weather:

- The Puget Sound region experienced warmer and wetter than normal weather relative to 1981–2010 climate averages.
- An especially warm spring resulted in rapid melting of mountain snow pack and ultimately led to low stream flows in late spring and early summer.
- The wet season began early in fall, with record rain in October.
- Sunny weather dominated from April through September, while cloudier conditions meant darker skies from January through March and again from October through December.

Coastal ocean and Puget Sound boundary conditions:

- Subsurface waters on the shelf of the Washington coast showed a seasonal progression, with warmer, fresher, higher oxygen conditions in early summer, a slow transition to cooler, saltier, lower oxygen conditions in late summer, and a rapid transition to much warmer, fresher, higher oxygen conditions in late October.
- Deep pH and oxygen records at 50 m show a relatively steady decrease from early summer through fall, then a fall “renewal,” as well as high-frequency variation over ranges relevant to biological fitness.
- Atmospheric xCO_2 values (i.e., the mole fraction of CO_2) measured at Chá Bă (off La Push) and Cape Elizabeth continued their year-to-year increase.
- Surface seawater xCO_2 was consistent with the previous two years, which is in turn consistent with the persistent warmer-than-average conditions on the shelf.

River inputs:

- Despite near normal snowpack, warmer than normal spring temperatures caused early and reduced peaks in river discharge to the Salish Sea.
- Summer streamflows ranged from normal to much below normal.
- Flows rebounded during the cool, wet September for some rivers, and all rivers recovered dramatically in mid-October when an extratropical cyclone brought record rainfall.

Water quality:

- Temperature:
  - Puget Sound was warmer than normal, due in part to the marine heat wave in the Pacific, but not quite as warm as in 2015.
  - As in 2015, Puget Sound waters experienced significant, full-depth warm-water anomalies.
  - In the Central Basin, surface and bottom water temperatures were 0.5–1.0°C warmer than normal for most of the year.
  - In Quartermaster Harbor, daily spring temperatures were higher than normal.
  - In Padilla Bay, 2015 and 2016 annual mean water temperatures were the warmest on record (since 1995), with mean temperature anomalies in excess of 1°C.
  - In Bellingham Bay, atmospheric cooling of surface waters during fall 2016 resulted in a temperature inversion with deep waters being warmer than surface waters—this was especially evident in December when winds from the north were strong.
  - Fall temperatures in the eastern Strait of Juan de Fuca were well above average in the 14-year record, exceeded only by 2014, and a subsurface intrusion of warm waters came into the Strait during mid-November.

- Salinity and density:
  - » Salinity variations were remarkably similar to 2015 and covaried with weather conditions in three distinct periods: a warmer and wetter than normal spring; a summer drought; and an extremely wet fall. This produced extreme salinity reversals in South Sound and Hood Canal, from fresher anomalies to saltier to fresher again (with anomalies in either direction in excess of 2 standard deviations), though the 2016 annual averages were consistent with climatology.
  - » Density stratification followed seasonal patterns in salinity, with Puget Sound waters exhibiting strong stratification in spring and early summer, becoming more mixed in late summer, and becoming strongly stratified again in fall.
  - » South Sound and Hood Canal had record low salinities.
  - » The annual fall flushing in Hood Canal occurred more than 4 weeks earlier than in previous years, excluding 2015.
  - » In the Central Basin, fresher than normal waters were observed in the spring, but salinities were similar to average conditions during the low river flow and dry summer. Water column stratification was strongest from late March to June, showing a typical seasonal pattern.
  - » Residence time in Puget Sound's Central Basin was longer during the summer drought.
  - » The salinity record from a new buoy in Bellingham Bay revealed the strong influence of the Nooksack River plume, which lowers the surface salinity. When salinity dips low, increases in colored dissolved organic material and turbidity are evident, also indicating a riverine influence.
  - » The salinity range during fall in the eastern Strait of Juan de Fuca was uncharacteristically narrow, as it was in 2014.

- Nutrients and chlorophyll:
  - » The low nitrate levels observed throughout Puget Sound in 2016 were close to those observed in the late 1990s, and the downward trend in annual averages of chlorophyll-*a* anomalies and the silicate to nitrogen ratio (Si:DIN) continued.
  - » In the Central Basin, the timing of the spring phytoplankton bloom was typical, occurring in mid-to-late April, except in the northern Central Basin where the bloom occurred about 3 weeks earlier than normal, in mid-March.
  - » There was no fall bloom in September in the Central Basin (excluding Quartermaster Harbor); instead, chlorophyll-*a* levels were higher than normal in August.
  - » Surface nitrate/nitrite values in the Central Basin were lower than baseline levels from March through August, but September values were higher than normal from the lack of a fall bloom. This pattern was also seen for orthophosphate-P in surface waters, particularly in March, where levels were much lower than normal.
  - » Fifteen of 20 beach sites in the Central Basin had lower than normal nitrate/nitrite for most of 2016, except during September, when almost all sites had higher than normal values.
  - » Aerial observations did not capture *Noctiluca* blooms along the Victoria Clipper ferry route.

- Dissolved oxygen (DO):
  - » Puget Sound DO was lower than normal (relative to the past 10 years), continuing a 4-year period of higher than normal deficits, but not as low as in 2015.
  - » In South Sound, the Central Basin, and Hood Canal, DO anomalies were negative, ranging 1 to 2 standard deviations below the station long-term averages, with the most intense hypoxia and negative anomalies observed in southern Hood Canal.
  - » In the Central Basin, bottom water DO levels were normal or slightly above normal for much of 2016, except for slightly below-average periods in February, October and November. DO values were above 5.0 mg/L throughout the year, with the exception of brief lower periods in central Elliott Bay and Quartermaster Harbor.
  - » DO near Twanoh reached anoxia at depth (25 m) in September, but no widespread fall fish kills were reported.
  - » DO near Carr Inlet was much lower than average at depth (35 m)—the minimum value observed was ~4 mg/L.
  - » DO in Quartermaster Harbor was average and, at times, higher than normal.

   » In Padilla Bay, pelagic oxygen consumption varied seasonally and covaried with changes in chlorophyll and temperature. Incoming deeper waters of marine origin had relatively low and stable rates of oxygen consumption compared to surface waters.

- Ocean and atmospheric CO_2:
   » Atmospheric measurements at two Hood Canal moorings had xCO_2 values 14–15 ppm higher than globally averaged marine surface air xCO_2.
   » Hood Canal surface seawater xCO_2 values were undersaturated (i.e., lower than atmospheric values) for a longer time and by a greater margin in early 2016 than previously observed, likely due to persistent warm anomalies.

Plankton:

- Phytoplankton:
   » Lower than normal nitrate concentrations in the surface layer of the Central Basin did not seem to influence the magnitude of phytoplankton blooms.
   » As in previous years, chain-forming diatoms (*Thalassiosira, Lauderia/Detonula,* and *Chaetoceros* spp.) were typically the dominant taxa by biovolume from early spring to late summer.
   » Small dinoflagellates and the ciliate *Mesodinium* made up a significant portion of biological particles during fall and winter.

- Zooplankton:
   » Zooplankton abundances were high in 2016 compared to 2014, though generally not as high as in 2015.
   » Zooplankton community structure in 2015 and 2016 showed less variance overall compared to 2014.
   » *Noctiluca* abundances were very low.
   » In Padilla Bay, zooplankton community structures in summer were different from previous years with increased abundances of annelids, barnacles, and larvaceans and decreased abundances of crab larvae, but were similar to previous years in winter, spring, and fall.
   » In Skagit Bay, peak annual abundance of gelatinous zooplankton surpassed that observed even during the warm spring and summer of 2015.

- Harmful algae and biotoxins:
   » *Dinophysis* spp. cell counts were greater than 2,000 cells per liter at the peak of the Sequim Bay bloom in the fall.
   » *Pseudo-nitzschia* spp. were common throughout Puget Sound, with counts reaching over 80,000 cells per liter in Sequim Bay during the spring and in Discovery Bay during the fall.
   » Paralytic shellfish poisoning (PSP), domoic acid (DA), and diarrhetic shellfish poisoning (DSP) toxins resulted in 18 commercial growing area closures and 38 recreational harvest area closures, but caused no illnesses in 2016.
   » DSP was detected at 250 µg/100 g in blue mussels from Budd Inlet, which is a new record for the highest DSP level detected in shellfish in Washington.
   » Mapping of *Alexandrium* cysts in January 2017 found substantially lower concentrations of cysts in the surface sediments of Quilcene and Dabob Bays, and no cysts were detected throughout the rest of Hood Canal. There were no PSP-related shellfish bed closures in Hood Canal in 2016.

Bacteria and pathogens:

- 92% of the 62 Puget Sound beaches and 89% of the core beaches monitored for the Beach Environmental Assessment, Communication, and Health (BEACH) Program had less than two swimming closures or advisories during the swimming season.
- All King County offshore monitoring stations in the Central Basin passed the Washington State geometric mean and peak standards for fecal coliforms.
- None of the 20 marine beach monitoring stations in the Central Basin failed the geometric mean, though three failed the peak fecal coliform standard. Despite high rainfall in 2016, overall, indicator bacteria concentrations were low.

- There were 46 laboratory-confirmed and epidemiologically linked illnesses due to the consumption of commercially or recreationally harvested oysters in Washington contaminated with *Vibrio parahaemolyticus.*

Marine birds and mammals:

- Overall, the abundance and diversity of marine bird species were similar in 2015–16 to 2014–15. The abundance of diving forage-fish specialists (alcids and grebes) increased from 2014–15 to 2015–16, although the driver of this increase is unknown. The abundance of scoters, a Puget Sound Vital Sign Indicator, increased in four months of the 2014–15 season.
- From May through October, over 1,000 rhinoceros auklet carcasses were found by citizen science volunteers within the Salish Sea and on the Washington coast, which is highly unusual for this species. Necropsy analysis revealed bacterial septicemia to be the ultimate cause of death.
- Rhinoceros auklet chick survival and fledging success on Protection Island were the lowest in 11 years of breeding season monitoring, apparently due to poor forage fish availability in the Salish Sea.
- In the eastern Strait of Juan de Fuca, the pattern of low abundance of marine mammals and seabirds in fall was very similar to that observed in fall of 2014 and 2015.

Fish:

- 2016 was the worst year on record for the Cherry Point Pacific herring stock; stocks in South and Central Puget Sound have also been in decline in recent years, and five stocks had no spawn recorded in 2016.

Western Washington University faculty taught several courses in 2016 with students deploying instruments near the Bellingham Bay buoy and downloading and analyzing buoy-collected data to practice critical thinking and data analysis skills with environmental data. Photo: David Shull

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 is similar to human-sourced eutrophication (i.e., high nutrients, low oxygen). It is important to document and understand these regional processes and patterns so that water quality data may be interpreted with these variations in mind.

ENSO, 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 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 and PDO. ENSO events usually persist 6–18 months, whereas phases of the PDO typically persist for 20–30 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 2–3 seasons. For PDO, these anomalously warm waters can reemerge 4–5 seasons later (Moore et al. 2008). In contrast, the NPGO, which is related to processes controlling sea surface height, has a stronger effect on salinity and nutrients than temperature. Wind is an important factor in the NPGO, which can influence seasonal wind patterns in the eastern Pacific Ocean. 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, and oxygen-poor waters to the surface and into the Strait of Juan de Fuca as source water for Puget Sound.

A. El Niño–Southern Oscillation (ENSO):

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

The calendar year of 2016 featured a transition from a strong El Niño to a weak/moderate La Niña. Both the El Niño near the start of the year and the La Niña toward the end of the year were accompanied by substantial atmospheric circulation anomalies over the North Pacific. In both cases, these remote effects (also known as teleconnections) loosely resembled, rather than closely matched, expected patterns observed during past ENSO events. In particular, the anomalous atmospheric circulation over Washington State included stronger than normal flow from the west and wetter than normal weather during the first three (January through March) and last three (October through December) months of 2016. It is unclear why there was such a strong response to La Niña, since the negative SST anomalies were only of modest amplitude (0.5–1°C).

B. Pacific Decadal Oscillation (PDO):

Source: Nick Bond, OWSC (nicholas.bond@noaa.gov); www.climate.washington.edu; http://research.jisao.washington.edu/pdo/

The PDO was in a positive phase during the entire 2016 calendar year, with a maximum value of 2.62 in April and a minimum value of 0.45 in September (Figure 1). The recent positive PDO event began in early 2014.

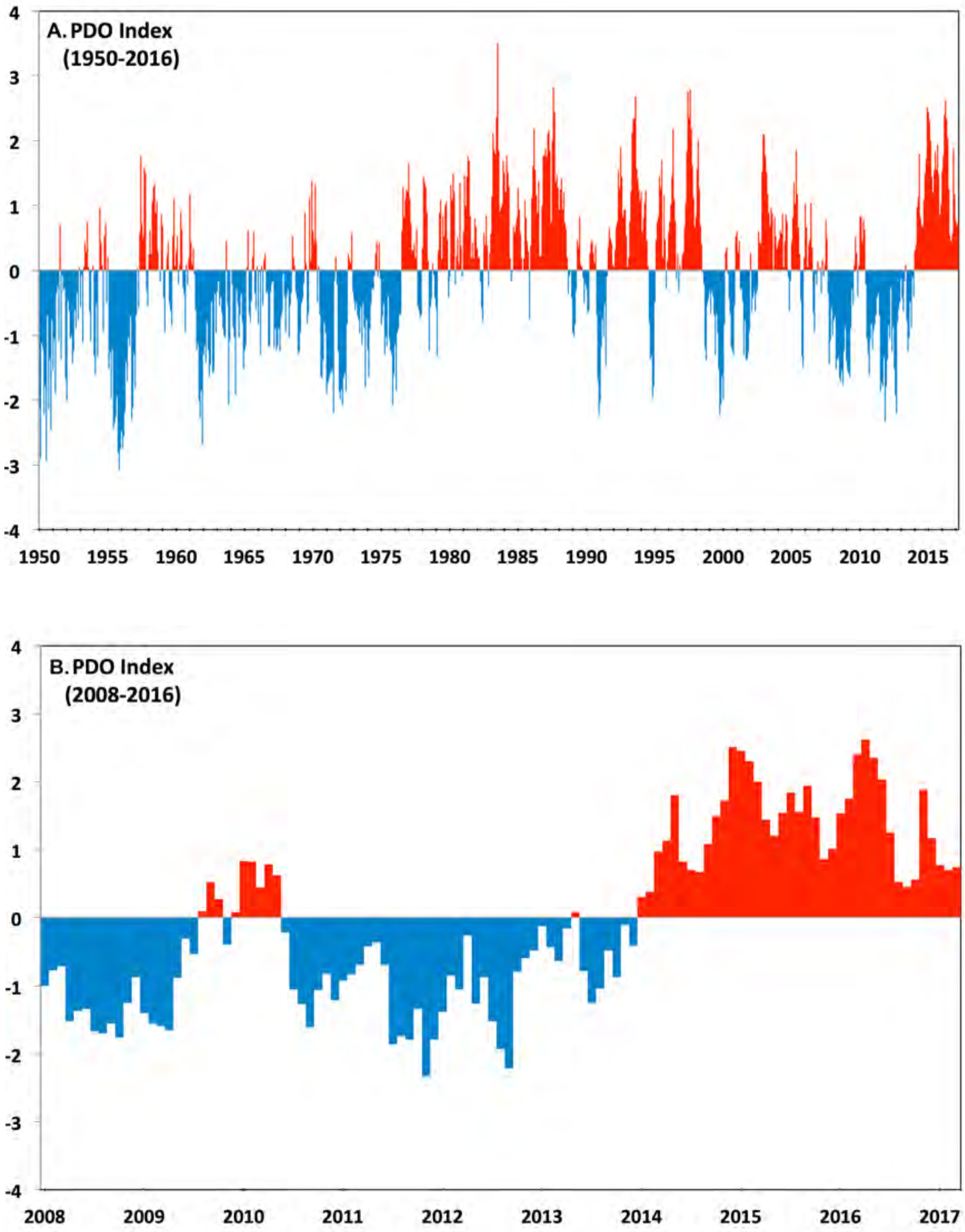


Figure 1. Monthly values of the Pacific Decadal Oscillation (PDO) Index from (A) 1950–2016 and (B) 2008–16.

C. North Pacific Gyre Oscillation (NPGO):

The North Pacific Gyre Oscillation (NPGO) is a climate pattern of sea surface height variability in the Northeast Pacific. Fluctuations in the NPGO are driven by regional and basin-scale variations in wind-driven upwelling and ocean currents—the fundamental processes controlling salinity and nutrient concentrations at the coast. The NPGO indicates fluctuations in the mechanisms driving planktonic ecosystem dynamics (Di Lorenzo et al. 2008).

Source: Christopher Krembs (christopher.krembs@ecy.wa.gov) and Skip Albertson (Ecology); www.ecy.wa.gov/programs/eap/mar_wat/index.html

The NPGO index during 2016 featured month-to-month variability as opposed to being systematically positive or negative. The NPGO was mostly in the positive phase from 1998–2013, with the exception of 2005–07 when monthly values were negative (Figure 2). In October 2013, NPGO values turned negative, with this trend continuing into 2014 and 2015. Beginning in January 2016, the NPGO became positive, switched to negative from spring through summer, and then returned to a positive state in fall. It is unknown whether this will mark 2016 as a transition year versus the onset of an extended period of high-frequency fluctuations in the NPGO. It does suggest that this mode of variability was not an important determinant of the overall primary production along the Washington coast during 2016.

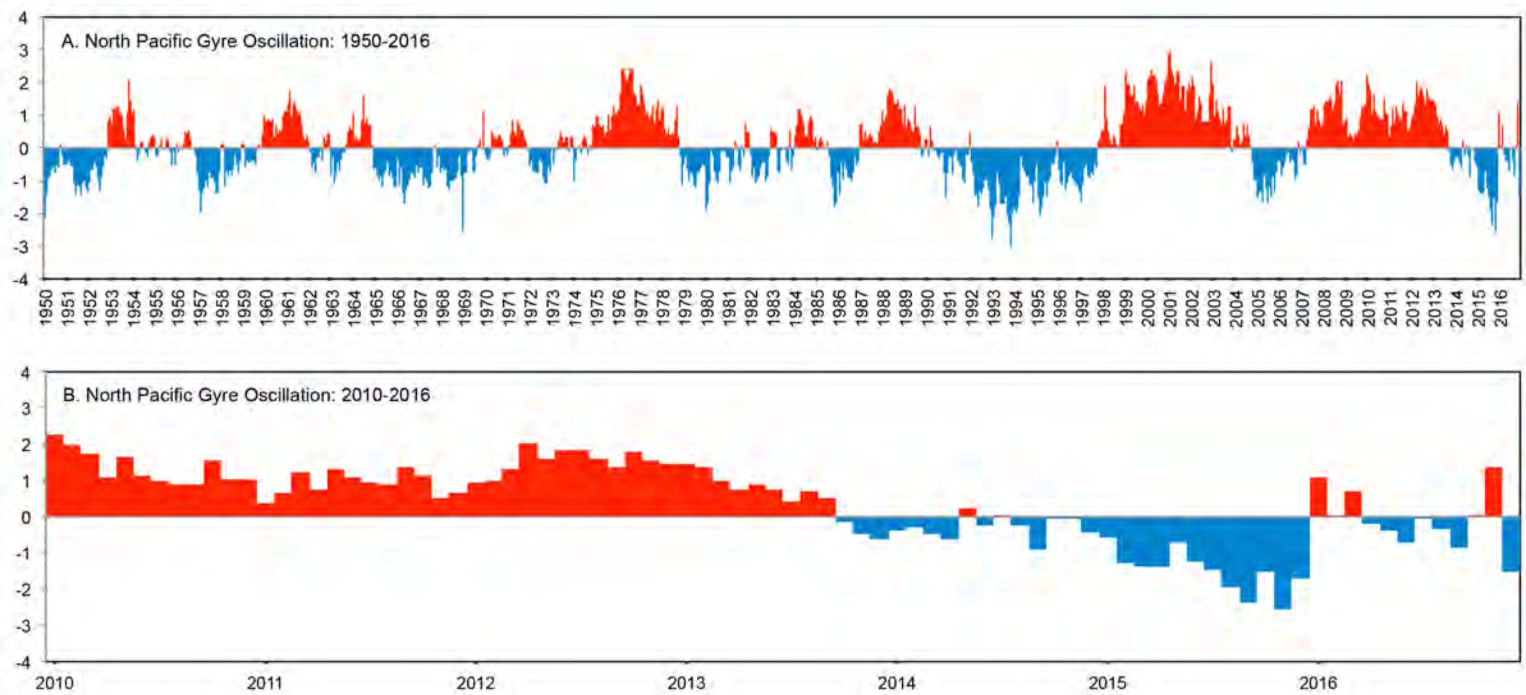


Figure 2. Monthly values of the North Pacific Gyre Oscillation index (NPGO) from (A) 1950–2016 and (B) 2010–16.

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, Carol Maloy, Mya Keyzers, and Laura Hermanson (Ecology); www.ecy.wa.gov/programs/eap/mar_wat/

Monthly mean values of the upwelling index at 48°N and 125°W in 2016 were mostly within historic (1967–present) interquartile ranges during the upwelling season, except in May when coastal upwelling was significantly stronger than normal (Figure 3). Stronger than normal downwelling conditions occurred during the period January–March, as well as during October and November.

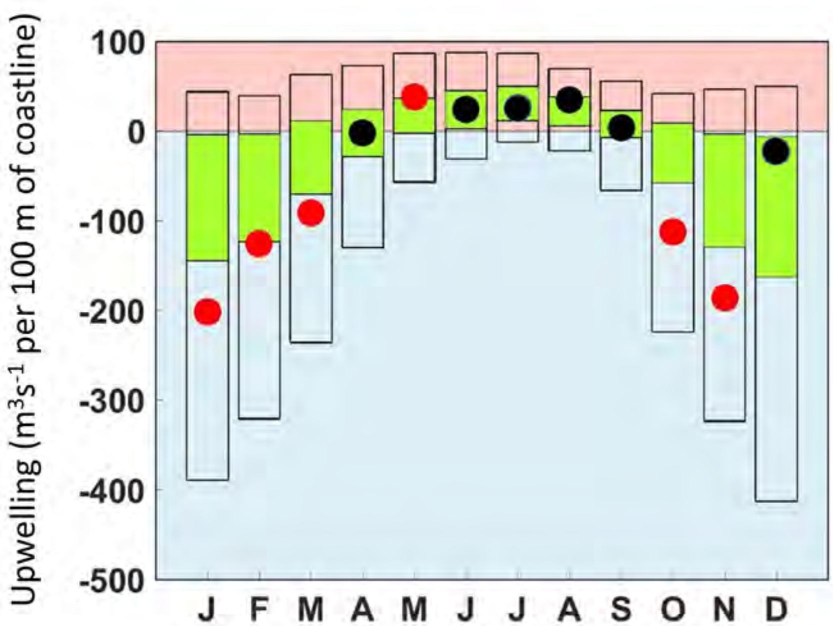
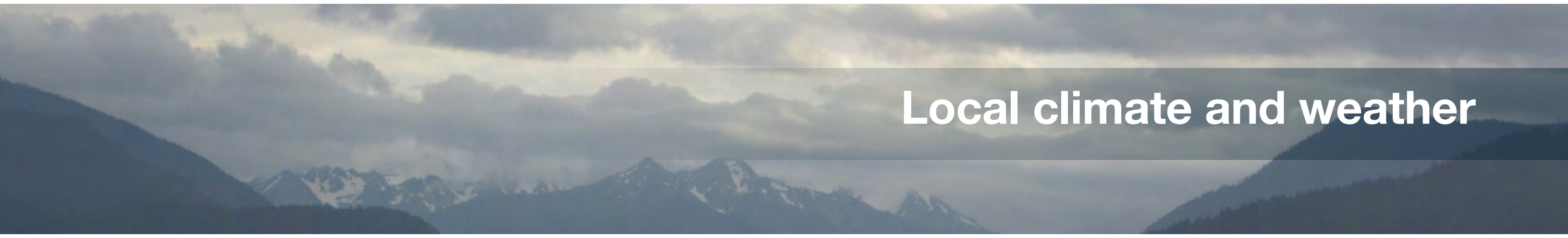


Figure 3. Monthly mean values of the PFEL coastal upwelling index for 2016 (red and black dots) are presented in historical statistical context based on the index values at 48°N and 125°W from 1967 to 2016. The box plot extent represents 5th and 95th percentiles, with the interquartile range between 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.



Local climate and weather

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

A. Regional air temperature and precipitation:

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

The calendar year of 2016 represented the third year in a row of highly above-average air temperatures for Washington State. Specifically, for the Puget Sound Lowlands climate division, 2016 was 1.0°C (1.7°F) warmer than the 1981–2010 normal, the third-warmest year since records began in 1895. The previous year of 2015 set the all-time record, with average temperatures of 1.4°C (2.5°F) above normal for the Puget Sound region.

The total annual precipitation during 2016 for the Puget Sound Lowlands climate division was 50.65 inches, which represents about 113% of normal. Similar precipitation anomalies as a percent of normal occurred during 2016 in the East Olympic Cascade Foothills and Cascade Mountains West climate divisions, whose regions include the upper elevations of the watersheds for the streams draining into Puget Sound.

Monthly values give a view of more variability throughout the year, however. Figures 4A and 4B show monthly temperature and precipitation anomalies for the Puget Sound climate division during 2016 relative to the 1981–2010 normals. The period of January through March was warm and wet across most of Washington State, resulting in an end of winter snowpack that was near normal in terms of overall water content. The very warm temperatures during spring, especially April, brought about more rapid melting than usual of the mountain snowpack. An important result was lower than normal streamflows in late spring and early summer 2016 that were exacerbated by the relatively dry period of April and May. The summer of 2016 was warmer than normal, but not nearly to the extent that had occurred in the years of 2013–15. Early fall featured the onset of very wet weather, with new record total precipitation for the Puget Sound climate division in October. The end of 2016 included notably cold weather in the Puget Sound region; these wintry conditions, especially relative to recent years, extended into calendar year 2017.

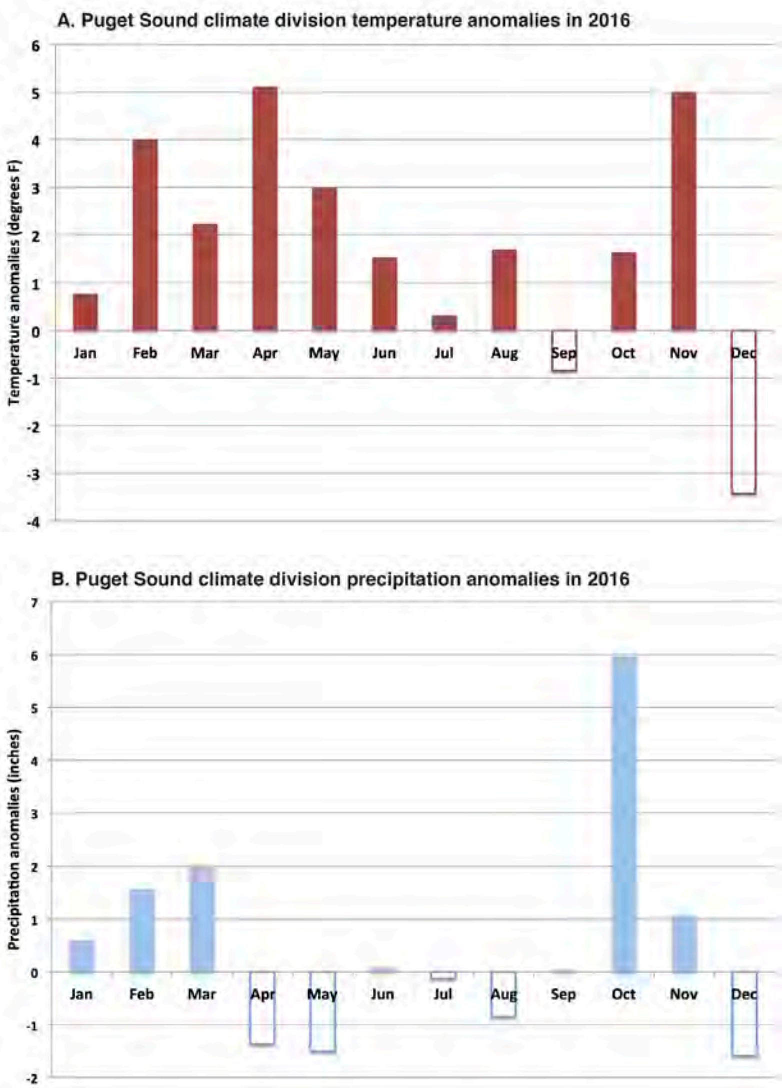


Figure 4. Monthly anomalies for (A) temperature (degrees F) and (B) precipitation (inches) for the Puget Sound Lowlands climate division in Washington State for the 2016 calendar year. Anomalies are relative to 1981–2010 climate normals.

B. Local air temperature and solar radiation:

Source: Skip Albertson (skip.albertson@ecy.wa.gov), Christopher Krembs, Julia Bos, Carol Maloy, Mya Keyzers, and Laura Hermanson (Ecology); www.ecy.wa.gov/programs/eap/pscoastalintro.htm

Air temperatures in 2016 were significantly warmer than normal, with the exception of September and December, which were below normal, and July, which was normal. Dramatic daily anomalies, both warm and cool, occurred throughout the summer, yet the warm anomalies (some greater than 10°C) dominated the monthly averages. Figure 5A shows anomalies in daily air temperatures at Sea-Tac Airport relative to the 1971–2000 historical baseline period.

Sunlight, as measured by daily solar energy flux, was generally above average from April through mid-May and again from July through September (Figure 5B, red-shaded area). Late July and August were especially sunnier than normal, with solar energy fluxes often approaching the theoretical maximum during this same period. January through March and October through December were particularly gloomy, with lower sunlight and very few sunny days (Figure 5B, solid blue-shaded area).

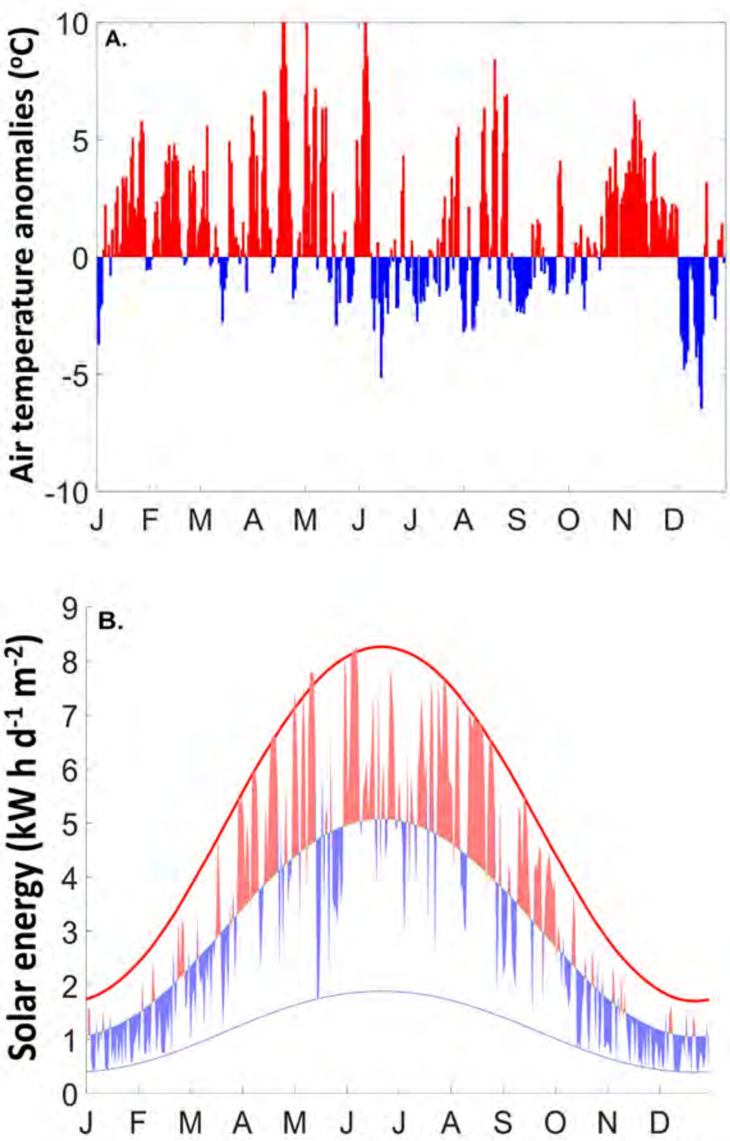


Figure 5. (A) Air temperature anomalies at Sea-Tac Airport, and (B) daily solar energy flux measured by a PAR sensor located at the University of Washington Atmospheric Sciences building (ATG), in 2016. In (A), red shading indicates higher than average air temperature, and blue indicates lower. The solid red line on the solar energy panel (B) shows the highest theoretical solar energy for this latitude, and the blue line is the solar energy if completely overcast. Red shading indicates when the sky is more than 50% clear (sunnier), and blue shading indicates when it is less than 50% clear (cloudier).

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:

Source: John Mickett (jmickett@apl.uw.edu) and Jan Newton, UW, APL; www.nanoos.org; http://orca.ocean.washington.edu/index.shtml

A large surface mooring called Chá Bă 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. Observations from these moorings and other coastal buoy data from the Northeast Pacific and coastal shelf show that surface waters in 2016 were warmer than average, with upwelling of cold water modulating temperature on the shelf (Figure 6). Subsurface waters on the shelf showed a seasonal progression, with warmer, fresher, higher-oxygen conditions in early summer, a slow transition to cooler, saltier, lower-oxygen conditions in late summer, and a rapid transition to much warmer, fresher, higher-oxygen conditions in late October (Figure 6). This rapid transition was not observed in 2015, but is consistent with that observed in 2014 (PSEMP Marine Waters Workgroup 2016), when winds and currents switched to a downwelling regime, fueling the onshore and northward advection of anomalously warm water.

As with other years, deep DO values in 2016 were highly variable on 1–2 week timescales, with especially high oscillations during September and October. Of interest is that the seasonal trend in deep (>50 m) DO and pH seen on the shelf in 2016 largely parallels the seasonal cycle observed within Puget Sound (see water quality section B; Puget Sound profiling buoys), with a relatively steady decrease from early summer through fall, and then a fall "renewal." This seasonal cycle was not apparent in shelf observations during 2015 and less so in 2014 for DO,

Volunteer John Parsons undertakes the arduous task of removing gooseneck barnacles that accumulate steadily during the annual six month deployment of the highly-equipped Chá Bă buoy off the Washington coast. Photo: Zoë Parsons

indicating that a more complex set of factors drives the dominant changes in pH and DO on the shelf compared to inshore waters.

The observed pH range at 50 m on the shelf is much larger than that observed at similar depths in the open ocean (Feely et al., 2009), and includes values below 7.6 that are observed at the same time as hypoxic DO concentrations. High-frequency variation implies that strong physical dynamics force the signal. Further, these variations occur over scales that are biologically relevant, indicating that biota at this depth encounter rapid oscillations between stressful versus non-stressful conditions.

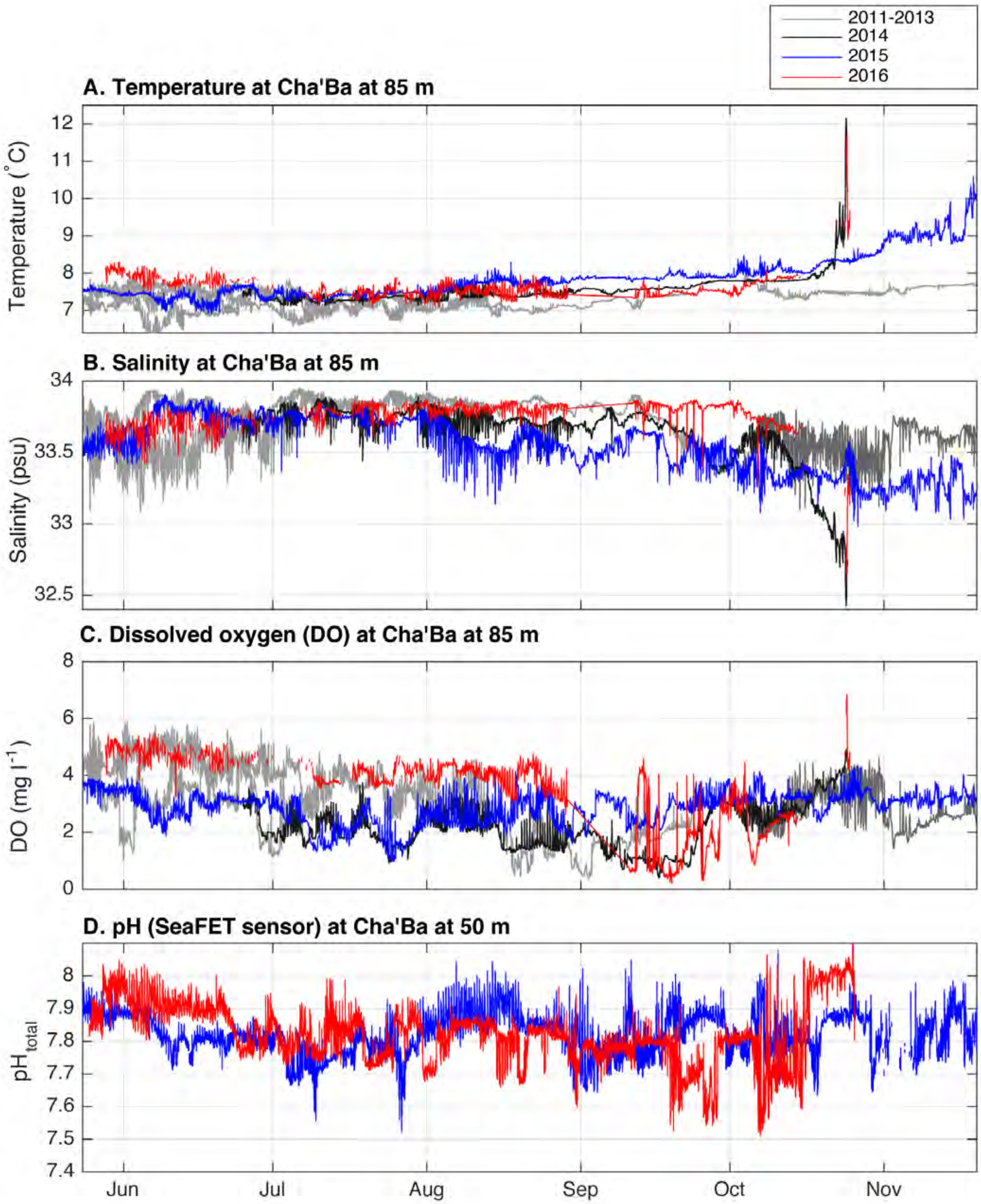


Figure 6. Interannual comparison of deep measurements at the Chá Bă mooring, with 2016 shown in red: (A) temperature at 85 m depth, (B) salinity at 85 m depth, (C) dissolved oxygen at 85 m depth, and (D) pH at 50 m depth.

B. Ocean and atmospheric CO_2:

Source: Simone Alin (simone.r.alin@noaa.gov), Christopher Sabine, Richard Feely, Adrienne Sutton (NOAA, PMEL), Sylvia Musielewicz (UW, JISAO), Jan Newton, and John Mickett (UW, APL); pmel.noaa.gov/co2/story/La+Push; pmel.noaa.gov/co2/story/Cape+Elizabeth; PMEL contribution number 4662

Carbon dioxide (CO_2) sensors have been measuring atmospheric and surface seawater xCO_2 (the mole fraction of CO_2) at three-hourly intervals on the Chá Bă surface mooring off La Push since 2010, mostly from spring through fall, and year-round on National Data Buoy Center (NDBC) mooring 46041 at Cape Elizabeth since 2006. Both time series had significant gaps during 2016 (Figure 7).

In 2016, the atmospheric xCO_2 range was 401–436 ppm at Chá Bă (Figure 7A) and 392–434 ppm at Cape Elizabeth (Figure 7B). The elevated minimum atmospheric xCO_2 value at Chá Bă during 2016 reflects the gap in the time series during the summer months, when atmospheric values manifest their annual minima. Including all available observations at both moorings, average values for atmospheric xCO_2 at Chá Bă and Cape Elizabeth are 5 and 3 ppm higher than globally averaged marine surface air for 2016, which was 403 ppm CO_2 (global data from NOAA/ESRL web site, ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_annmean_gl.txt). The observational gap would also inflate the offset at Chá Bă due to the timing of missed observations coinciding with the time of year when atmospheric xCO_2 values are lower.

Surface seawater xCO_2 ranged from 110–548 ppm at Chá Bă (Figure 7C) during the 2016 mooring deployment and from 151–482 ppm at Cape Elizabeth (Figure 7D) during 7.5 months of operation (no data from March to mid-July). The average Chá Bă 2016 seawater xCO_2 value was substantially higher than the previous several years, which reflects the gap in the time series during the growing season for phytoplankton (primary production uses CO_2). Average surface seawater xCO_2 values have been below average atmospheric values for all years at Cape Elizabeth (Table 1), and seawater xCO_2 variability is nearly an order of magnitude higher (as reflected by standard deviations).

Cape Elizabeth	2006*	2007	2008	2009	2010	2011	2012*	2013	2014	2015	2016*
Atmosphere	386±8	390±7	390±6	389±7	393±6	394±8	397±8	402±7	403±8	402±8	406±6
Seawater	362±66	323±70	321±68	314±64	356±52	306±80	346±55	280±61	305±74	327±59	344±65

Table 1. Average (±SD) surface seawater and atmospheric xCO_2 values at Cape Elizabeth (year-round) moorings for all available years in parts per million (ppm). Asterisks denote years with significantly less data.

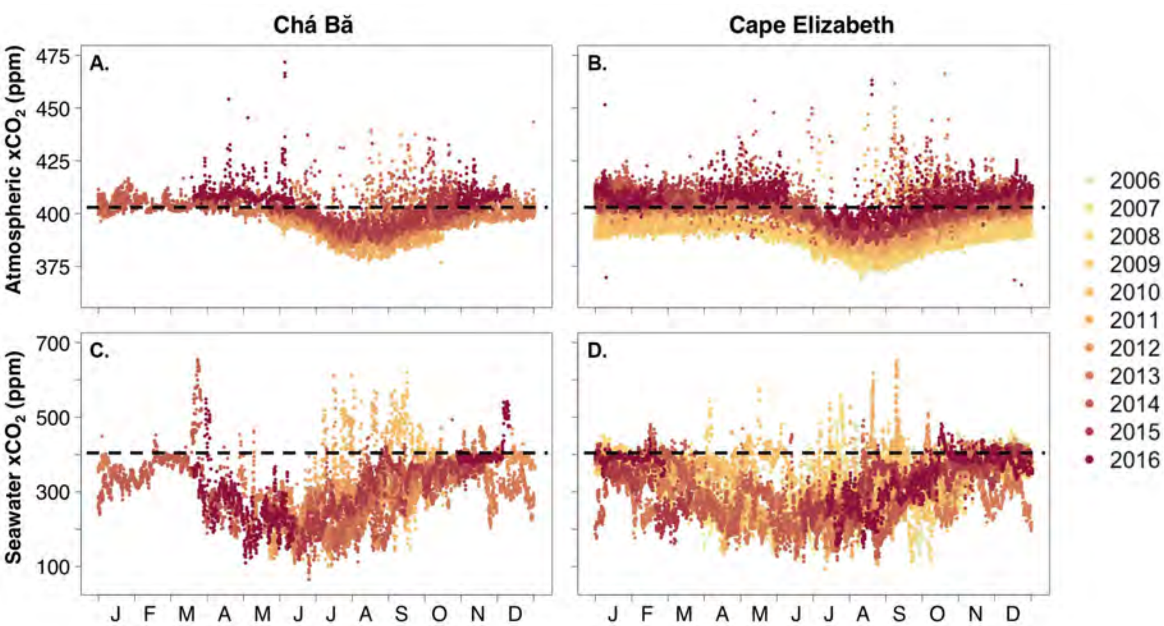


Figure 7. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater and in surface seawater at 0.5 m depth on (left) the Chá Bă surface mooring off La Push, WA, and (right) NDBC mooring 46041 off Cape Elizabeth, WA. Data from 2016 are in opaque symbols, and all prior years are in transparent colors as shown in the color scale. The 2016 globally averaged marine surface air annual mean xCO_2 value of 403 ppm is indicated with a dashed line in each panel. Typical uncertainty associated with quality-controlled measurements from these systems is <2 ppm for the range 100–600 ppm.

River inputs

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

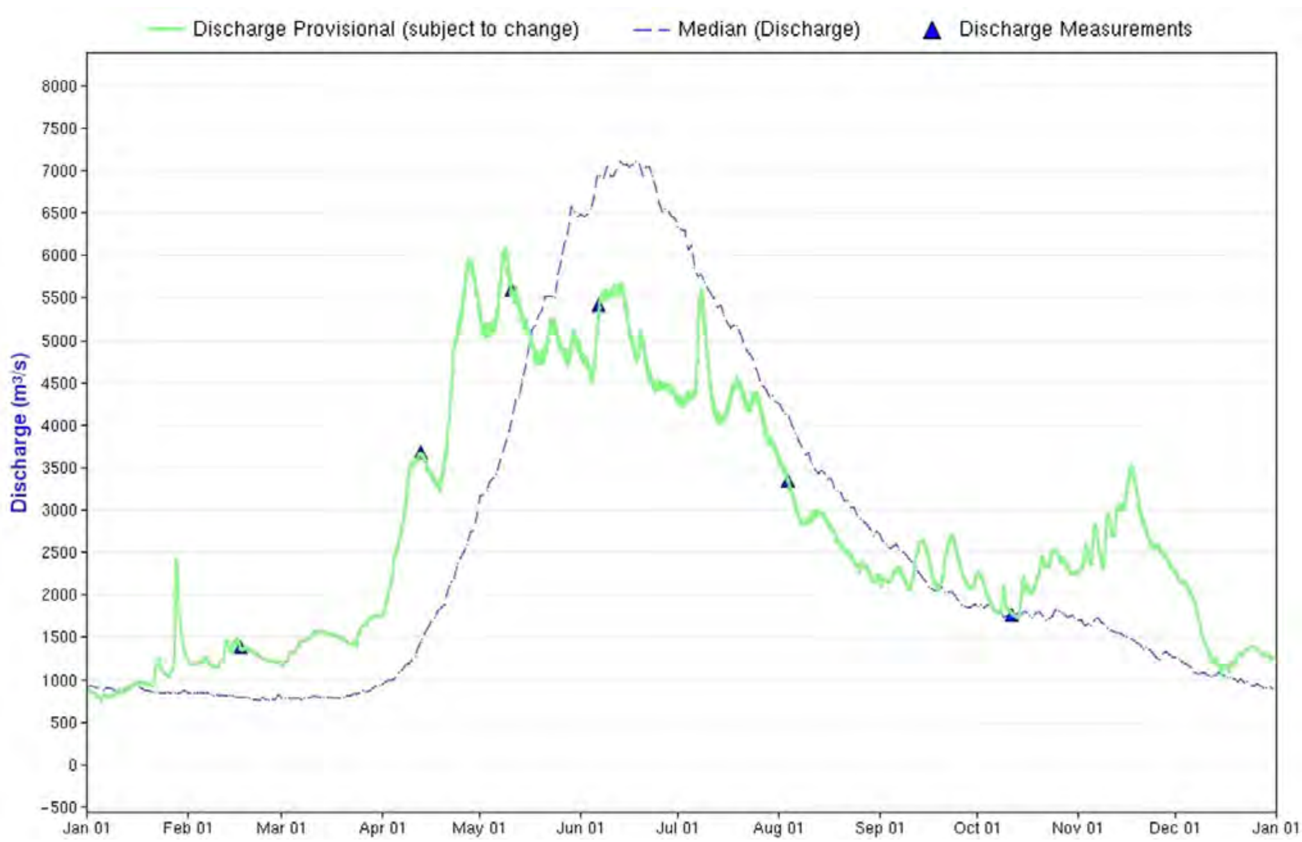
A. Fraser River:

Source: Tyler Burks, Ecology (tyler.burks@ecy.wa.gov), and Environment and Climate Change Canada; wateroffice.ec.gc.ca/index_e.html

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. A majority of this water is delivered during a single discharge peak in early summer, indicative of a snowmelt-dominated flow regime. This large pulse of freshwater affects salinity and drives estuarine circulation; therefore, its timing is critical and can have a significant impact on marine water quality conditions.

Near-normal snowpack conditions in 2016 at higher elevations were met with continued warm temperatures early in the spring. In April, 30% of the Fraser basin snowpack melted (BCRFC 2016). These April conditions resulted in the peak of spring snowmelt occurring approximately 4–6 weeks ahead of schedule and at a reduced level when compared to the historical median (Figure 8). This peak was likely muted by the lack of snow at lower elevations. During the months of June and July, flows were considerably below normal, not rebounding until mid-September and October when moisture from an extratropical cyclone brought the Fraser well above mean flows for the remainder of the year.

Figure 8. Fraser River daily discharge (m^3/s) at Hope, BC, Canada (08MF005) for 2016, compared to the median value for the period of record (1912–2016). (Note: 1 m^3/s = 35.3 ft^3/s).

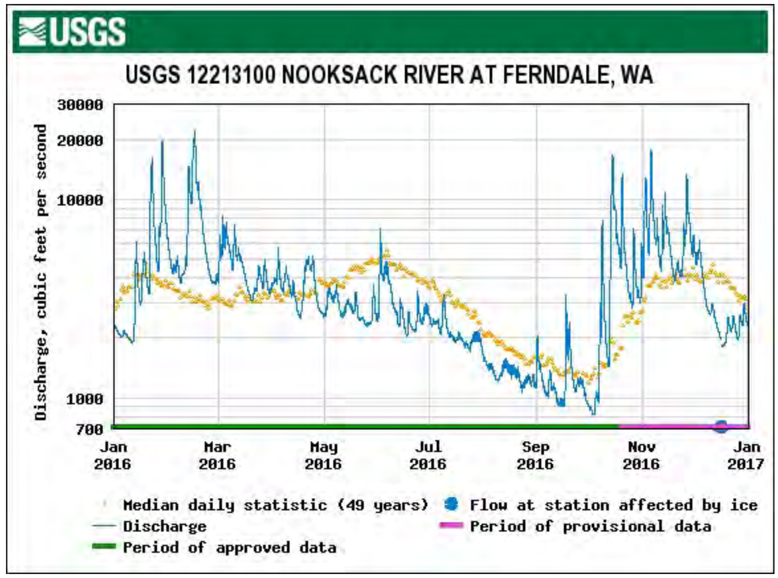


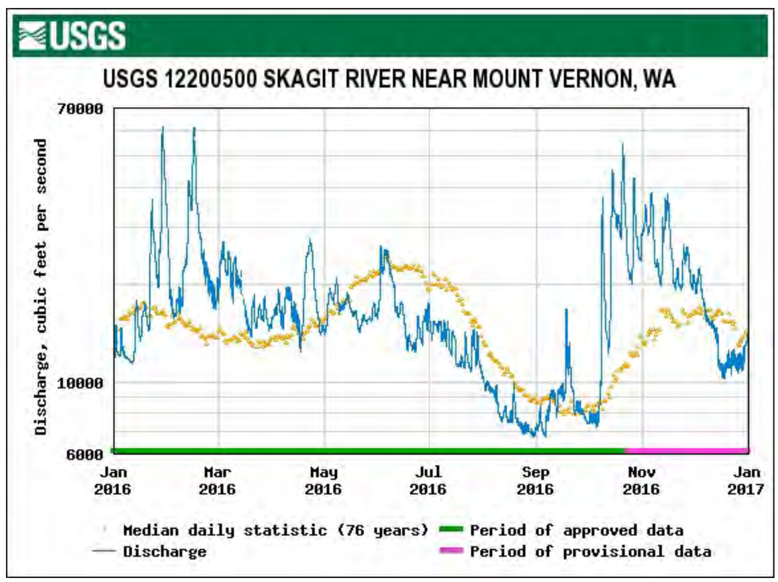
B. Puget Sound rivers:

Source: Tyler Burks, Ecology (tyler.burks@ecy.wa.gov), and U.S. Geological Survey; waterdata.usgs.gov/wa/nwis/rt

One-third of the freshwater supply to the Salish Sea is contributed by the rivers draining to Puget Sound. Quantities are led by the Skagit, Snohomish, Puyallup, Nooksack, and Stillaguamish Rivers. In contrast to the Fraser, the flow regime for the majority of Puget Sound rivers is characterized by dual peaks, the first when snowmelt peaks in spring and the second when rain returns in the fall. Though their contributions may be smaller, they are vital to the water-quality conditions of the complex marine basins of Puget Sound.

Conditions in Puget Sound watersheds during 2016 developed similarly to those of the Fraser watershed in British Columbia. Though there was some variability in timing, unusually warm early-spring temperatures produced a significant amount of snowmelt, leading to streamflow deficits as early as 1 May (Figure 9). Some basins experienced snowmelt peaks at the end of April, only to be equaled or exceeded by another peak in mid-June. During this event, some rivers, including the Skagit, exceeded average snowmelt discharge values with additional precipitation input from a notable June storm event, but these flows were short-lived. During midsummer, flows ranged from normal to much below normal, but rebounded in some areas by September due to a cool and wet end-of-summer period. Finally, all rivers recovered dramatically when moisture from an extratropical cyclone arrived midway through October. Despite summer deficits, all of these watersheds (except the Nooksack) met or exceeded their mean annual discharge.





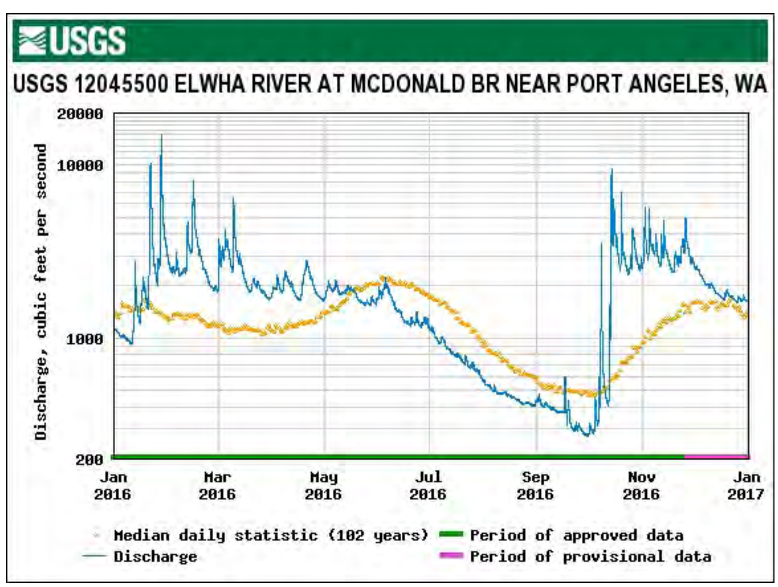
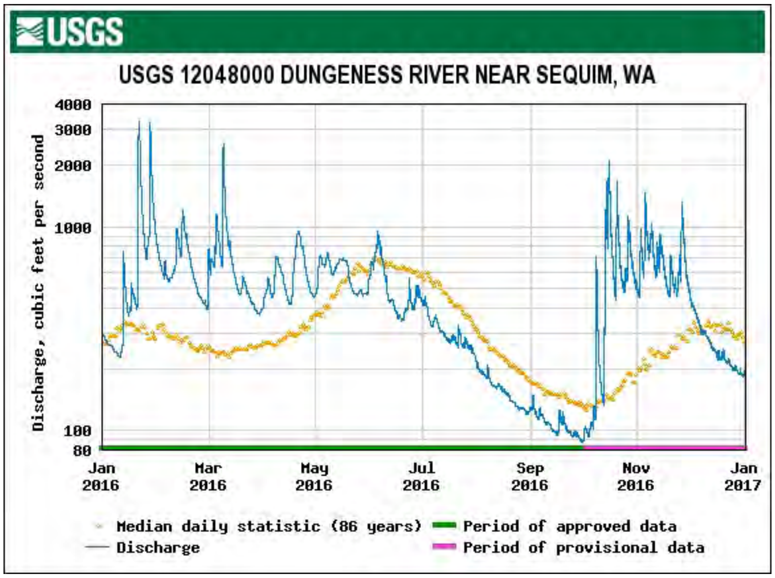
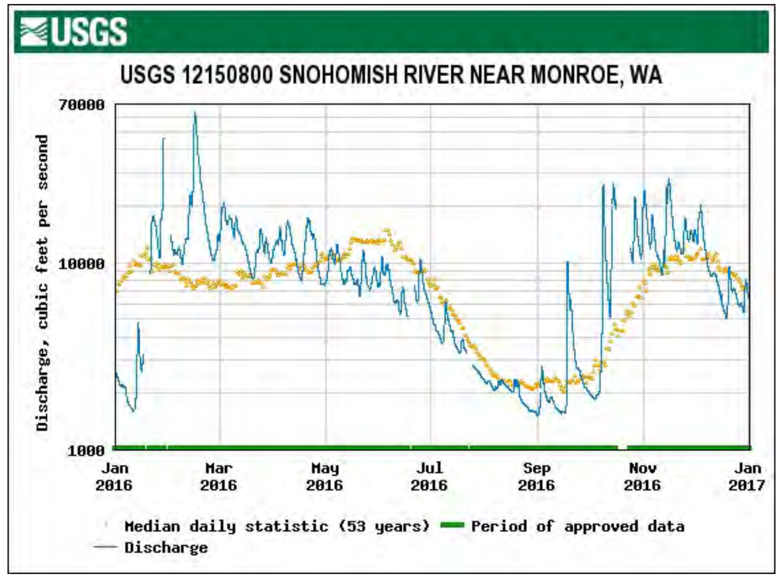
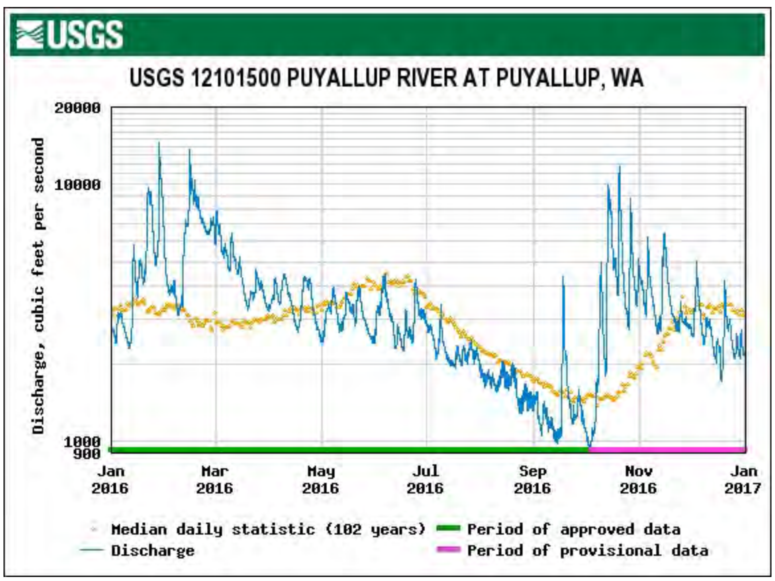
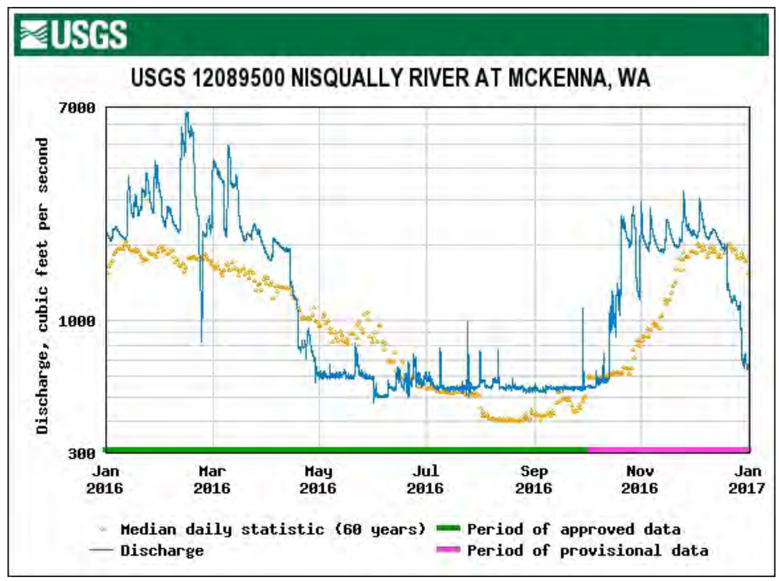


Figure 9. Daily discharge (ft³/s) at stations on the Nooksack, Skagit, and Elwha Rivers in 2016, compared to period-of-record median values. (Note: the period of record varies for each station and is listed in number of years in parentheses in the legend).









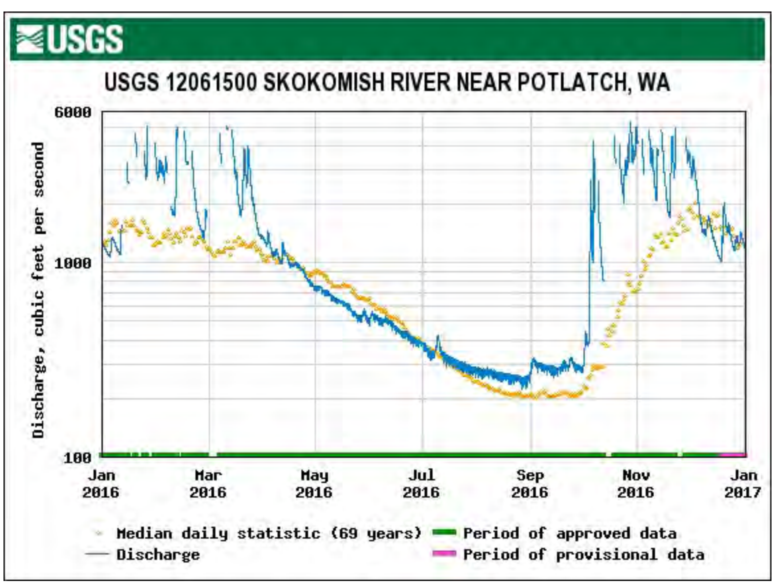


Figure 9. Daily discharge (ft³/s) at stations on the Dungeness, Snohomish, Puyallup, Nisqually, and Skokomish Rivers in 2016, compared to period-of-record median values. (Note: the period of record varies for each station and is listed in number of years in parentheses in the legend).

Temperature and salinity are fundamental water-quality measurements. They define seawater density and are important for understanding estuarine circulation and conditions favorable to Puget Sound's marine life. Many marine organisms have developed tolerances and life-cycle strategies for specific thermal and saline conditions. Nutrients and chlorophyll give insight into the production of organisms at the base of the food web. Phytoplankton are assessed by monitoring chlorophyll-a, their photosynthetic pigment. In Puget Sound, like most marine systems, nitrogen nutrients sometimes limit phytoplankton growth. On a mass balance, the major source of nutrients is from the ocean; however, rivers and human sources also contribute to nutrient loads. Dissolved oxygen in Puget Sound is quite variable spatially and temporally and can quickly shift in response to wind, weather patterns, and upwelling. 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 monitoring network of 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 trends; see www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html.

i. Temperature and salinity:

Source: Julia Bos (jbos461@ecy.wa.gov), Christopher Krembs, Skip Albertson, Mya Keyzers, Laura Hermanson, and Carol Maloy (Ecology)

In 2016, warmer than normal water temperatures persisted throughout all depths in all Puget Sound basins for the winter, spring, and into summer, normalizing late in the year. This anomaly continued the "marine heat wave" of the previous year. Departures from historical baselines (i.e., anomalies) showed temperature (calculated as thermal energy content) in the 0–50 m layer of the water column to be abnormally warm (Figure 10A). The 2016 annual averaged anomaly was high relative to the previous decade (Figure 10D).

Similar to 2015, warm air temperatures in early spring prematurely melted mountain snowpack, leading to higher than normal stream flows during that time. In response, salinity in Puget Sound was lower (i.e., fresher) than normal in spring. In late summer, salinities were higher than normal after months of low rainfall. Record rain fell in October and November, which produced abnormally high stream flows and low salinities again. The large seasonal swings in surface salinities relating to these events illustrate that the timing of freshwater supply to Puget Sound was very different in 2016 compared to previous years (Figure 10B). Monthly Sound-wide anomalies showed that Puget Sound was fresher in the 0–50 m layer for most months, leading to the freshest conditions seen in the last decade, even exceeding conditions during the record La Niña years of 2011 and 2012 (Figure 10E).

Temperature and salinity determine the vertical density structure of the water column and the energy required to thoroughly mix it (reported as delta potential energy). A more-stratified water column requires more energy to mix. Puget Sound is typically stratified because of freshwater inputs at the surface from rivers. A low anomaly value indicates that the water column is more stratified than normal and requires more tidal or wind energy to mix. Conversely, a high anomaly value means that it is more mixed than normal. With higher than normal river flows, the water column was more stratified than normal at many sites during spring and again in early fall 2016. Monthly stratification, expressed as potential energy, followed the pattern of surface salinity and was more stratified than normal (Figure 10F). This has implications for the food web and energy cycling, with less organic matter, surface oxygen, and nutrients reaching deeper waters. This also means that surface wastewater, pollutants from land, and other particles may mix less deeply and stay confined to the surface.

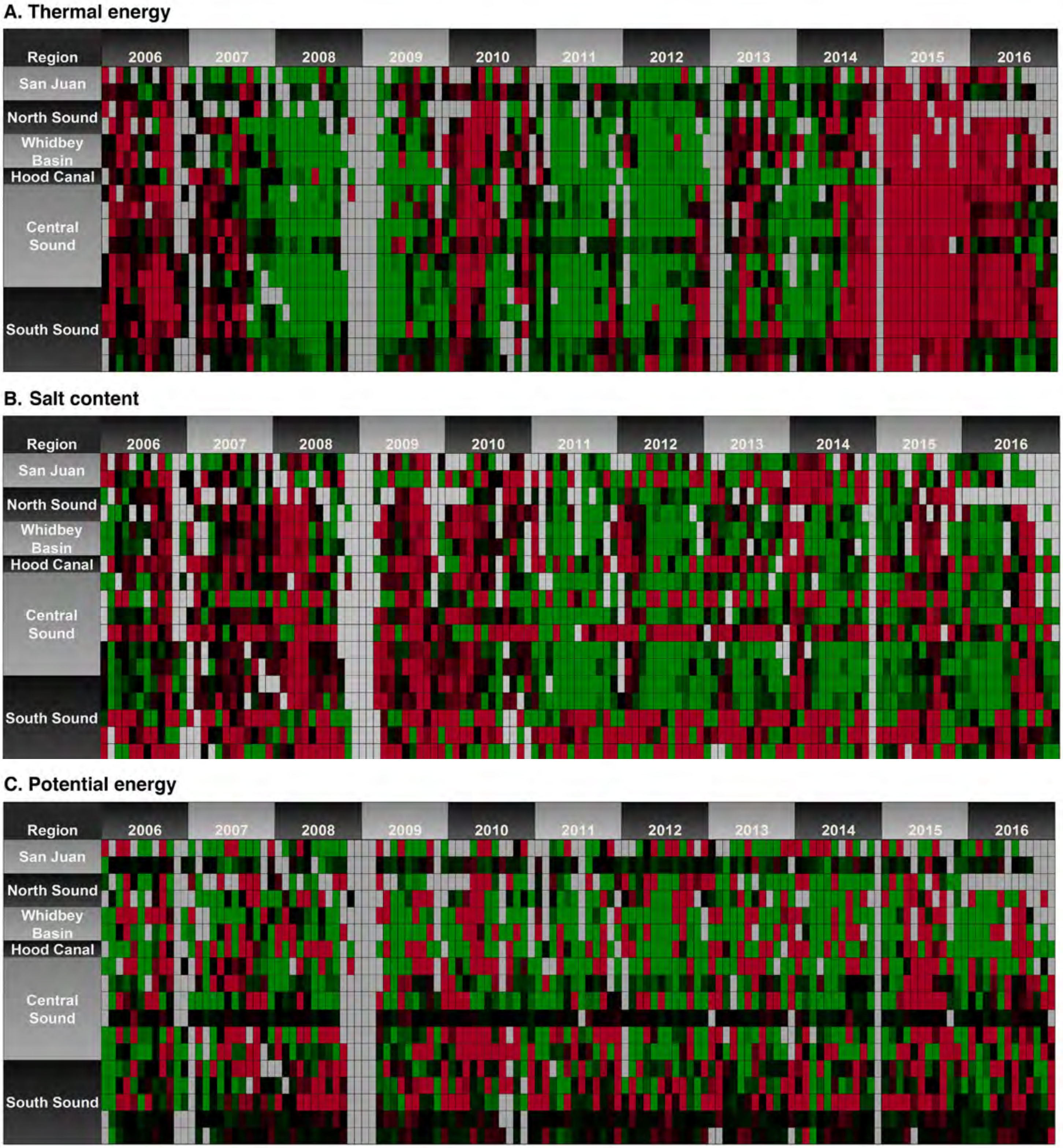


Figure 10. Heat map of (A) Puget Sound thermal energy, (B) salt content, and (C) potential energy anomalies for the 0–50 m water layer for 2006–16. Anomalies are calculated from site-specific monthly averages using a reference baseline for 1999–2008. Green = lower, red = higher, black = expected, and gray = no data.

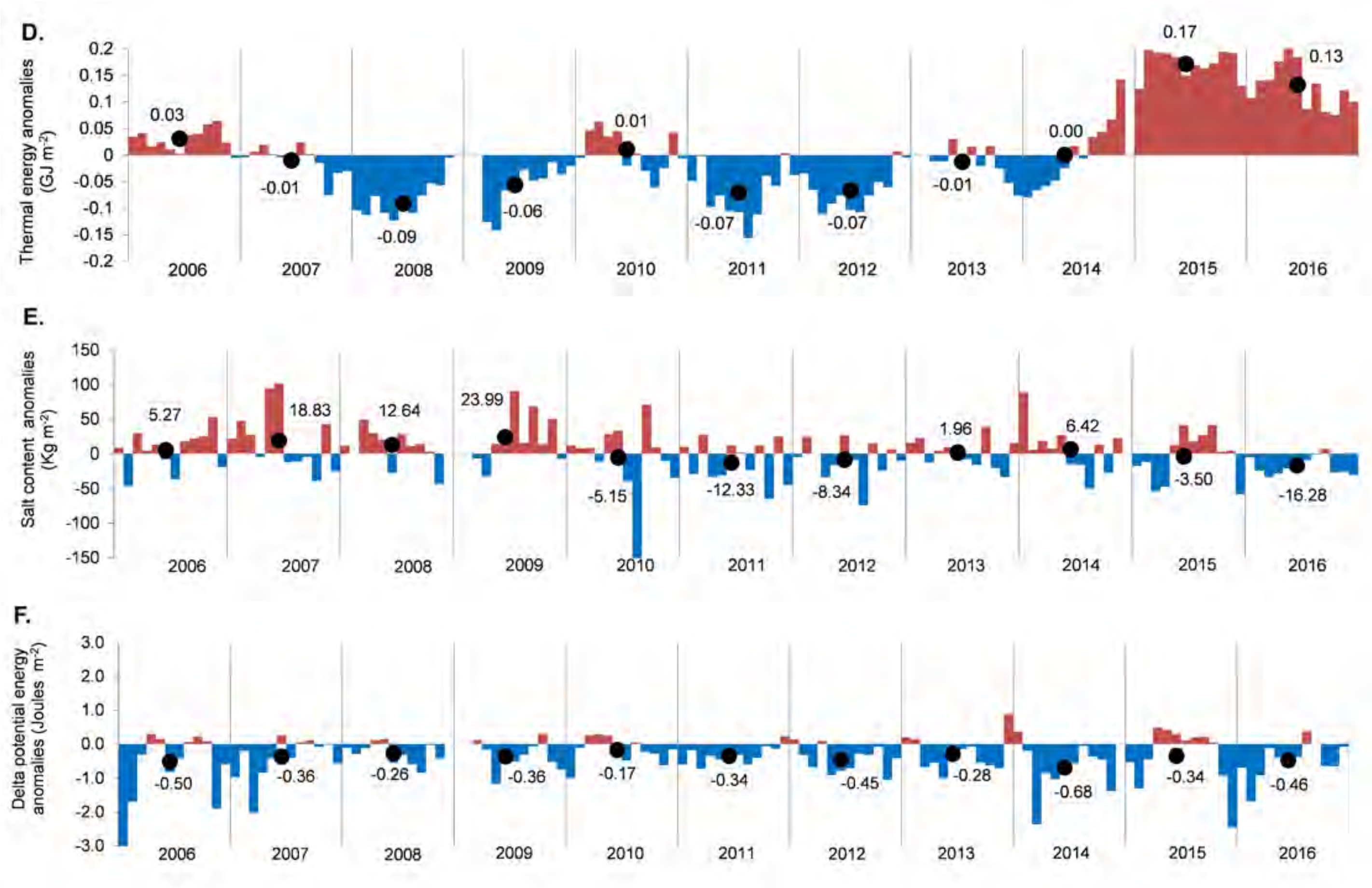


Figure 10. Monthly (columns) and annual (dots) variations are displayed as Puget Sound-wide anomalies averaged monthly and annually for (D) temperature, (E) salinity, and (F) potential energy in the 0–50 m water layer from 2006–16. For monthly anomalies, blue = lower and red = higher.

ii. Dissolved oxygen:

Source: Julia Bos (jbos461@ecy.wa.gov), Christopher Krembs, Skip Albertson, Mya Keyzers, Laura Hermanson, and Carol Maloy (Ecology)

In order to put DO measurements into a Puget Sound-wide context, Ecology reports a DO "deficit." The DO deficit is the difference between the measured value and the theoretical fully saturated value integrated over depths greater than 20 m, 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 DO anomalies for all core monitoring stations deeper than 20 meters in Puget Sound (n = 14).

At the beginning of 2016, the DO deficit was high and similar to early 2015 conditions. During both years, this was associated with anomalous ocean water entering Puget Sound. DO recovered briefly during the record wet and stormy spring. A long dry period during the summer led to less mixing and a higher deficit, which diminished with the onset of the rainy season at the end of the year. A heat map of monthly anomalies of the DO deficit for water deeper than 20 m for the period 2006–16 is shown in Figure 11A. The DO deficit was high from 2005–08 and decreased from 2009–12 (green), with improved oxygen conditions below 20 m. In 2013, the DO deficit shifted to higher than normal values (red), especially at northern sites, continuing through 2016. The anomaly in the DO deficit shows that the 2016 DO deficit was comparable to 2014 and slightly lower than 2015 (Figure 11B).

Figure 11. Puget Sound monthly DO deficit anomalies from 2006–16 compared to the 1999–2008 baseline. (A) Heat map of monthly anomalies calculated from site-specific monthly averages across Ecology's Sound-wide station network. Green = lower, red = higher, black = expected, and gray = no data. (B) Magnitude, seasonal, and interannual variation in DO conditions displayed as Puget Sound-wide DO deficit anomalies averaged monthly (columns) and annually (dots) from 2006–16. For monthly anomalies, blue = lower and red = higher.

iii. Nutrients and chlorophyll:

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

Long-term patterns and trends in Puget Sound nutrients and chlorophyll-*a* are determined by comparing Ecology's monthly data to baseline conditions (1999–2008) and generating site specific anomalies. The average of monthly anomalies at all of Ecology's Puget Sound monitoring stations is used to track largescale interannual changes.

Starting in 1999, monthly anomalies in nitrate increased until around 2008 and then decreased (Figure 12A). The low nitrate levels observed in 2016 were close to those observed in the late 1990s, and may be further influenced by the extreme events that characterized the previous two years. One such extreme event was a drought that was declared from March through December 2016. This drought affected the Fraser River, a major driver of estuarine circulation in the Salish Sea, potentially slowing estuarine circulation and water renewal and reducing nutrient input from the ocean during the summer.

The downward trend in annual averages of chlorophyll-*a* anomalies continued through 2016 (Figure 12B) and followed the decline in the silicate-to-nitrogen ratio (Si:DIN). The Si:DIN ratio is considered a putative eutrophication indicator and can reflect changing growth conditions at the base of the food web. A robust positive correlation of annual average values of Si:DIN and chlorophyll-*a* (Figure 12C) suggests that nutrients may play an integral role in phytoplankton interannual variability.

Year-to-year anomalies in chlorophyll detected near the bottom of Puget Sound were evaluated as a percentage of surface values, which range on average between 20% and 30%. Over time, these percentages have exhibited a decreasing trend (Figure 12D). This indicates that near-bottom chlorophyll concentrations have decreased at an even faster rate over time compared to surface concentrations (Figure 12B). This trend could indicate a change in the organic material reaching greater depths (>50 m) in Puget Sound, with potential implications for benthic communities. These observations require further research to understand the magnitude and mechanisms of the observed changes.

Large macroalgae mats washed ashore in 2016 (Figure 12E). Macroalgae are considered eutrophication indicators, and the presence of large mats in 2016 suggests that they were able to convert nutrient pools into large amounts of organic material, despite the low ambient nitrate concentrations. The contrasting findings of lower than normal values of nitrate and chlorophyll-*a* and the appearance of eutrophication indicators suggests that the base of the marine food web in Puget Sound could be changing, especially during the summer.

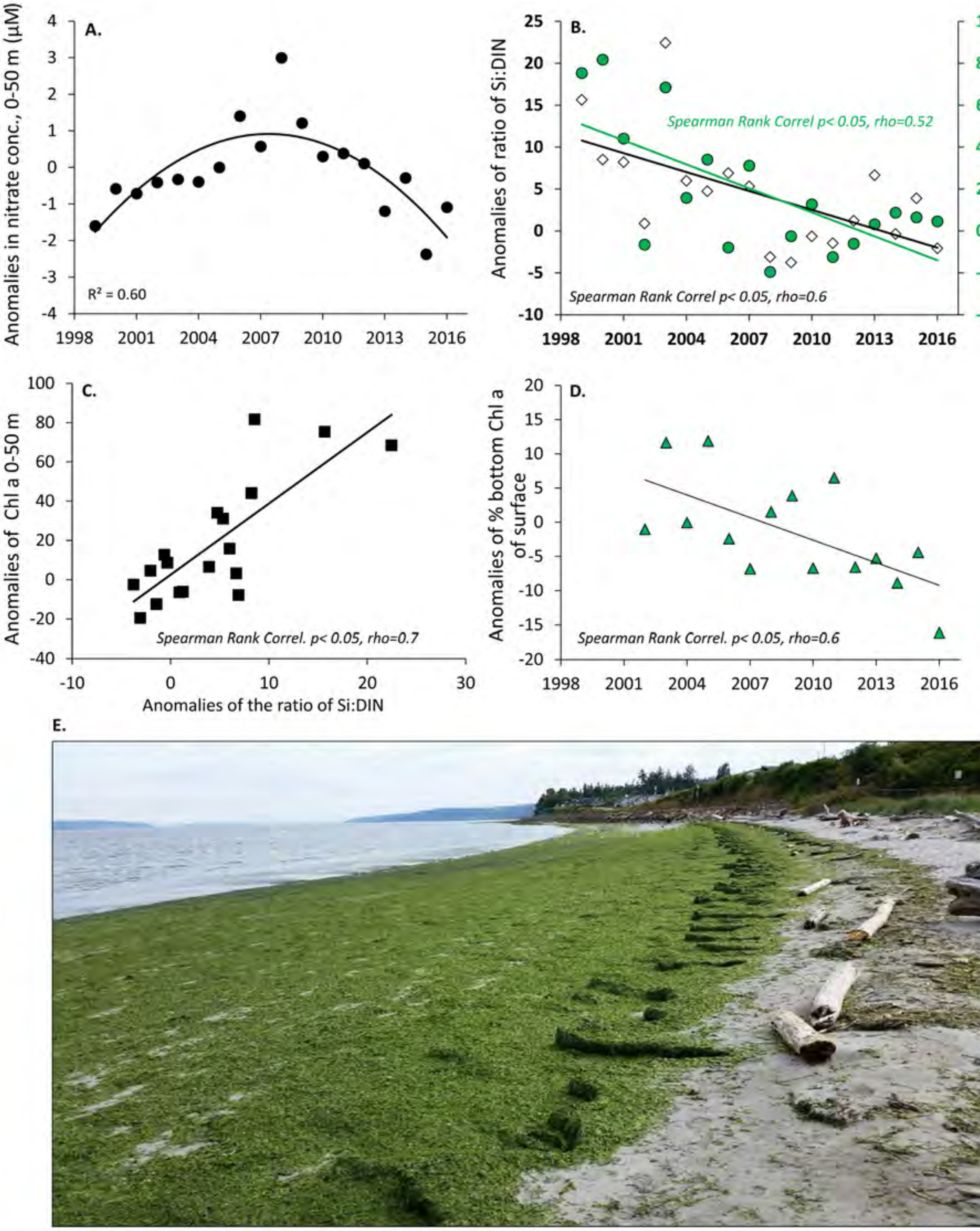


Figure 12. Puget Sound-wide annual anomalies of (A) nitrate, and (B) the ratio of silicate to dissolved inorganic nitrogen (DIN; open diamonds) and chlorophyll-a (green circles) from 1999–2016. (C) Sound-wide annual anomalies of Si:DIN plotted against chlorophyll-a for the period 1999–2016. (D) Sound-wide annual anomalies in chlorophyll-a detected near the bottom of Puget Sound as a percentage of surface chlorophyll-a values from 1999–2016. (E) Large macroalgae mats on the beach at Edmonds Underwater Park, Snohomish County, July 2016.

iv. Water mass characterization:

Source: Skip Albertson (skip.albertson@ecy.wa.gov), Christopher Krembs, Julia Bos, Carol Maloy, Mya Keyzers, and Laura Hermanson (Ecology); www.ecy.wa.gov/programs/eap/pscoastalintro.htm

Monthly data from Ecology's long-term marine monitoring program can be used to identify warm water masses (>15°C) in Puget Sound basins. Warm water temperatures are associated with lower densities (σT = 18–22), shallow depths (2–4 m, with the exception of South Basin where warm water was present as deep as 33 m in August at Dana Passage), and are observed mainly in the summer months (Figure 13A). There were fewer warm water masses in 2016 than in 2015; none in the Central Sound, and none during June in Whidbey Basin. The timing of the appearance of warm water masses was also different in 2016; they occurred a month earlier in Hood Canal and spanned fewer months in South Sound, losing a month on each end compared to 2015, but were present to greater depths.

To explore relationships between causal and resultant factors that control water masses, a Principal Component Analysis (PCA) of the average of July through September values (i.e., during upwelling conditions) from 1999–2016 was conducted (Figure 13B). Climatic forcing factors used in the analysis include Fraser and Puget Sound river flows, the PFEL upwelling index at lat 48°N, water temperature below 20 m, and Knudsen-derived residence time from deep salinity in the Central Basin. Rivers controlled about two-thirds (66%) of the total variability, and an additional 20% of variance was explained by a second factor related to upwelling winds.

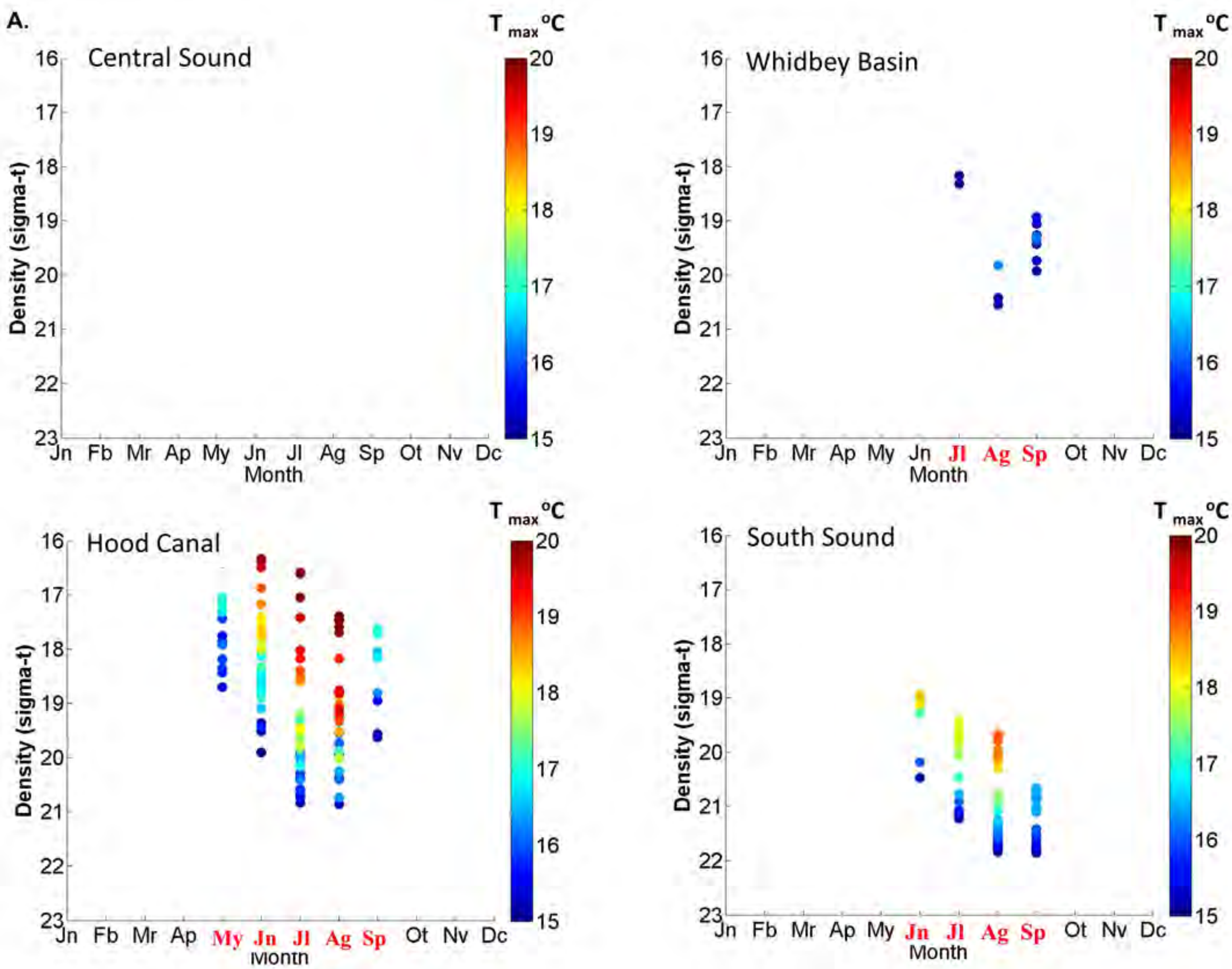


Figure 13A. Monthly plots of water temperatures exceeding 15ºC versus density, with color showing temperature. Results are shown for Central, Whidbey, Hood Canal, and South Basins.

Warm summers typically have associated upwelling with north wind coming off land; therefore, Puget Sound waters were expected to be colder. However, PCA showed the opposite, in that Puget Sound temperatures were instead warmer than expected. Warm summers typically have lower river flows, which causes an increase in the residence time, which in turn decreases the amount of cold ocean water entering Puget Sound. This is important as residence time can have a significant influence on the concentration of pollutants than can accumulate in the system.

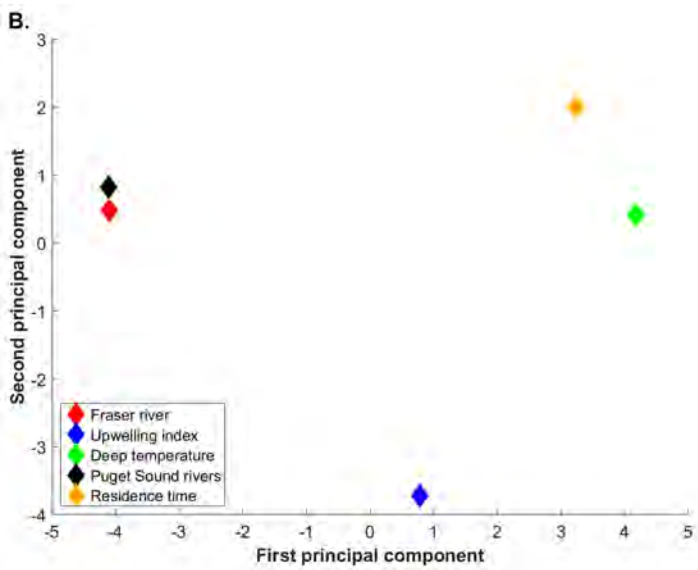


Figure 13B. Principal Component Analysis (PCA) of forcing factors (Fraser and Puget Sound river flow, upwelling index [PFEL]) and reactive factors (mean temperature in Central Basin below 20 m, Knudsen-based residence time from deep salinity).

B. Puget Sound profiling buoys:

Profiling buoys take frequent (more often than daily) full-depth measurements of water properties that allow characterization of both short- and long-term processes, including deep water renewal events and tracking water mass properties. There are currently six ORCA (Oceanic Remote Chemical Analyzer) moorings in Puget Sound, with data from four moorings presented here: southern Hood Canal (Twanoh and Hoodsport), Dabob Bay, and southern Puget Sound (Carr Inlet).

i. Temperature:

Source: Wendi Ruef (wruef@uw.edu), Al Devol (UW), Jan Newton, and John Mickett (UW, APL); nwem.ocean.washington.edu; www.nanoos.org

Observations from the UW ORCA mooring program, with high-frequency (more often than daily) full-depth profiles at six locations, show that Puget Sound waters again experienced significant, full-depth warm water anomalies throughout 2016 (Figure 14), though overall they were slightly less intense than those observed in 2015. At depth, temperature anomalies were at least 1 standard deviation above the 6- and 10-year observation means (2005–15) in South Sound and the Main Basin, with even more pronounced anomalies in southern Hood Canal, where temperatures at depth were consistently greater than +2 standard deviations for most of the year (Figure 15).

As observed in 2015, the entire water column at Twanoh in 2016 was generally anomalously warmer, with short-lived pulses of colder than average waters at the surface during summer and early fall (Figure 14C), likely due to wind-driven seiche-like motions in the basin lifting cooler deep waters toward the surface. Another pulse of colder than average surface water was observed in late December, corresponding to cooler than average atmospheric conditions.

Even though waters were warmer in 2016, the overall seasonal cycles were consistent with the historical averages throughout Puget Sound and Hood Canal, with cooling through the end of winter (January through March) followed by warming through late summer and cooling in early winter. However, as observed in 2015, the warmer than average waters coupled with anomalously low salinities (see Water quality section B.ii; Salinity) to result in some of the least-dense water observed in the southern Hood Canal record (since 2005). These waters were easily displaced by comparatively more-dense oceanic waters, and the Hood Canal experienced the annual fall flushing event more than four weeks earlier than in previous years (excluding 2015), with conditions similar to those observed during previous years with fish kill events. However, in contrast to 2015, no widespread fish mortality was observed during fall 2016 (see Water quality section B.iii, Dissolved oxygen).

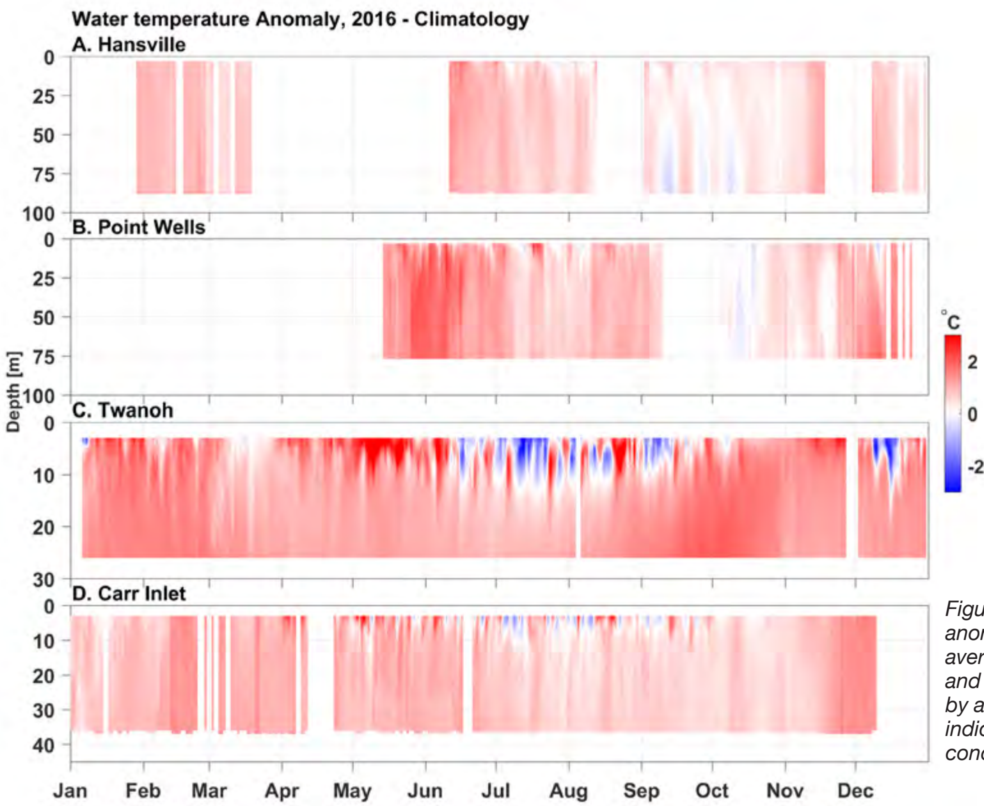


Figure 14. 2016 water temperature anomalies (compared to 2005–15 average) for North, Point Wells, Twanoh, and Carr Inlet moorings. Data are colored by a white threshold at 0, with red indicating warmer than historical average conditions, and blue colder.

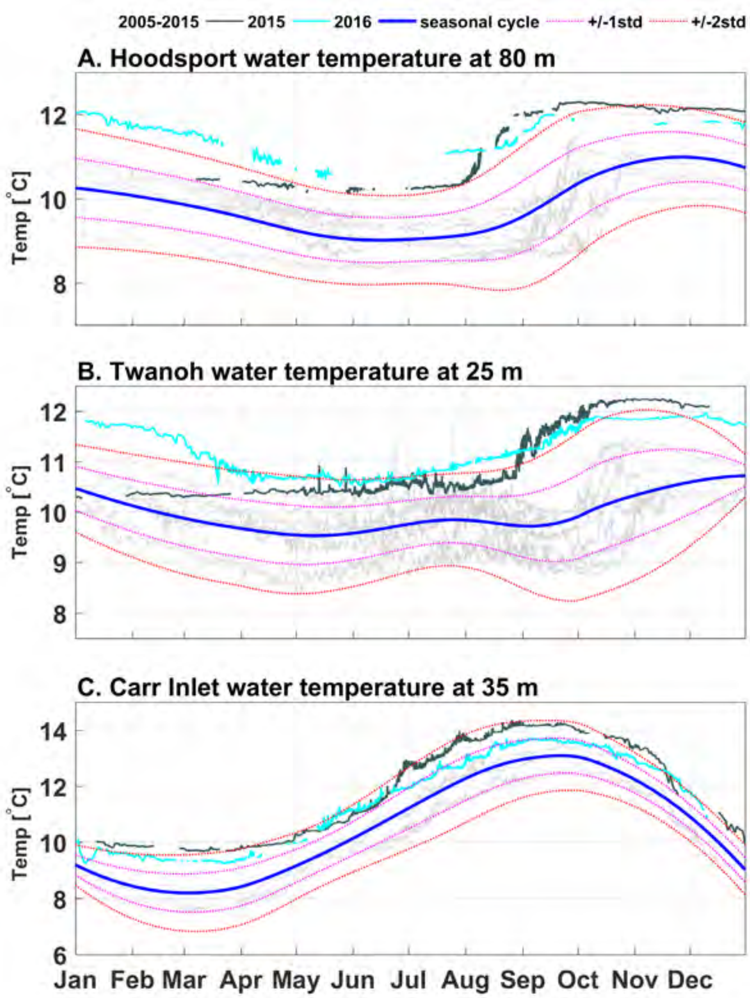


Figure 15. 2016 data (cyan line), 2015 data (dark grey line), climatology (dark blue line), and all historical data (gray lines) for near-bottom water temperatures at the Hoodsport (n = 10 years), Twanoh (n = 10 years), and Carr Inlet (n = 6 years) moorings; also shown are ±1 (pink dotted lines) and 2 (red dotted lines) standard deviations from the climatology.

ii. Salinity:

Source: Wendi Ruef (wruef@uw.edu), Al Devol (UW), Jan Newton, and John Mickett (UW, APL); nwem.ocean.washington.edu; www.nanoos.org

Observations from the UW ORCA mooring program, with high-frequency (more often than daily) full-depth profiles at six locations, showed that salinity varied in three distinct periods that covaried with rainfall and river flow conditions: 1) a wetter than normal spring with salinities fresher than long-term averages over the full water column; 2) a summer drought where salinities progressed from fresher (2 standard deviations below normal) to saltier (1 standard deviation above normal); and 3) an extremely wet winter that returned the water column to fresher than average (Figure 16). The pattern in the anomalies (Figure 17) was remarkably similar to that observed during 2015, but with a few distinct differences in 2016. The spring freshening, a result of rain influences rather than "blob"-originated waters as in 2015, resulted in salinities in both South Sound and southern Hood Canal that were more than 2 standard deviations below average and lower than any observed in the historical record (since 2010 and 2005, respectively). This was followed by a steep, summer drought-fueled increase in salinity, ending in early fall at more than 1 standard deviation above historical averages (though still less than the high salinities seen in early fall of 2015). Salinities quickly decreased as one of the wettest falls on record began, and continued to fall through early winter. As in 2015, these seasonal patterns diverged somewhat from the shape of the historical seasonal curve, yet were consistent with historical averages despite extreme high and low values. Observed local variations were consistent with differing river inputs and stratification similar to those seen in previous years.

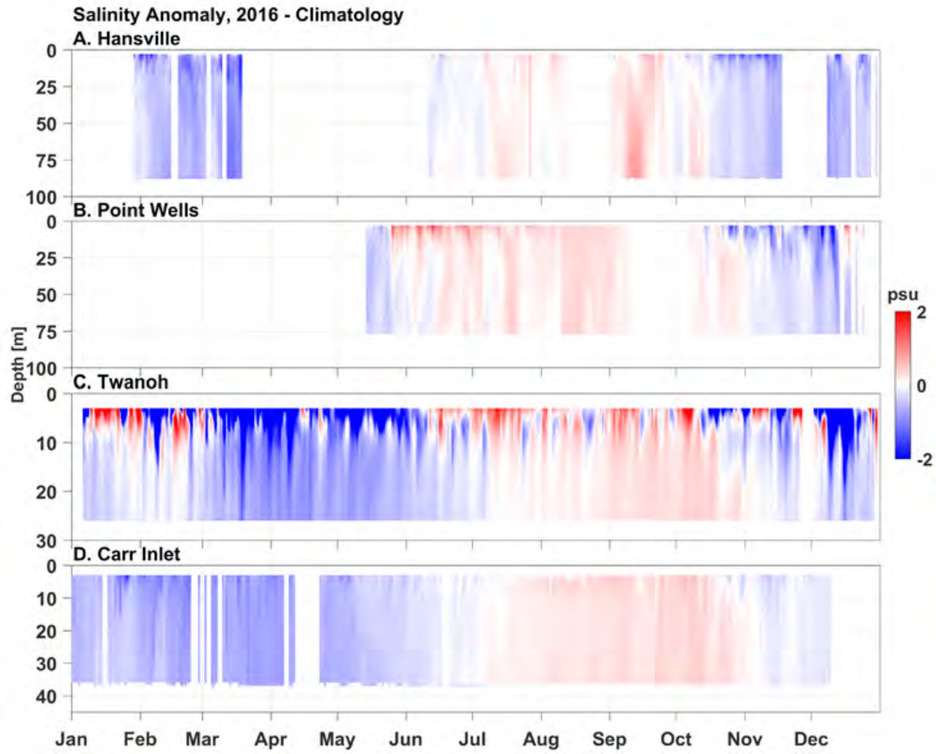


Figure 16. 2016 salinity anomalies (compared to 2005–15 average) for North, Point Wells, Twanoh, and Carr Inlet moorings. Data are colored by a white threshold at 0, with red indicating saltier than historical average conditions, and blue fresher.

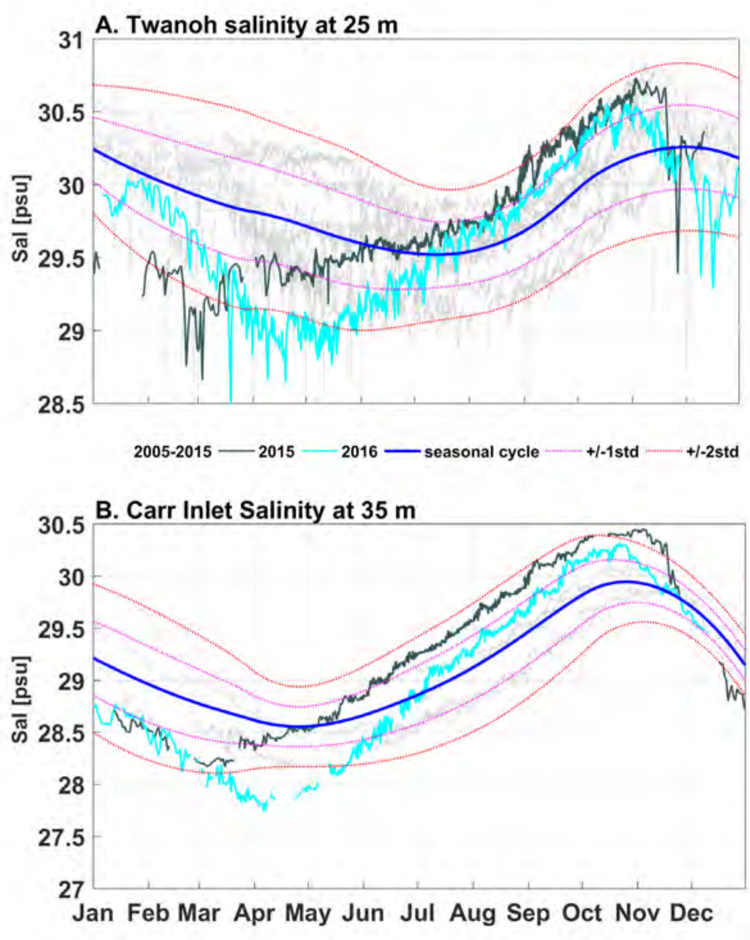


Figure 17. 2016 data (cyan line), 2015 data (dark grey line), climatology (dark blue line), and all historical data (gray lines) for near-bottom salinity at the Twanoh (n = 10 years) and Carr Inlet (n = 6 years) moorings; also shown are ±1 (pink dotted lines) and 2 (red dotted lines) standard deviations from the climatology.

iii. Dissolved oxygen:

Source: Wendi Ruef (wruef@uw.edu), Al Devol (UW), Jan Newton, and John Mickett (UW, APL); nwem.ocean.washington.edu; www.nanoos.org

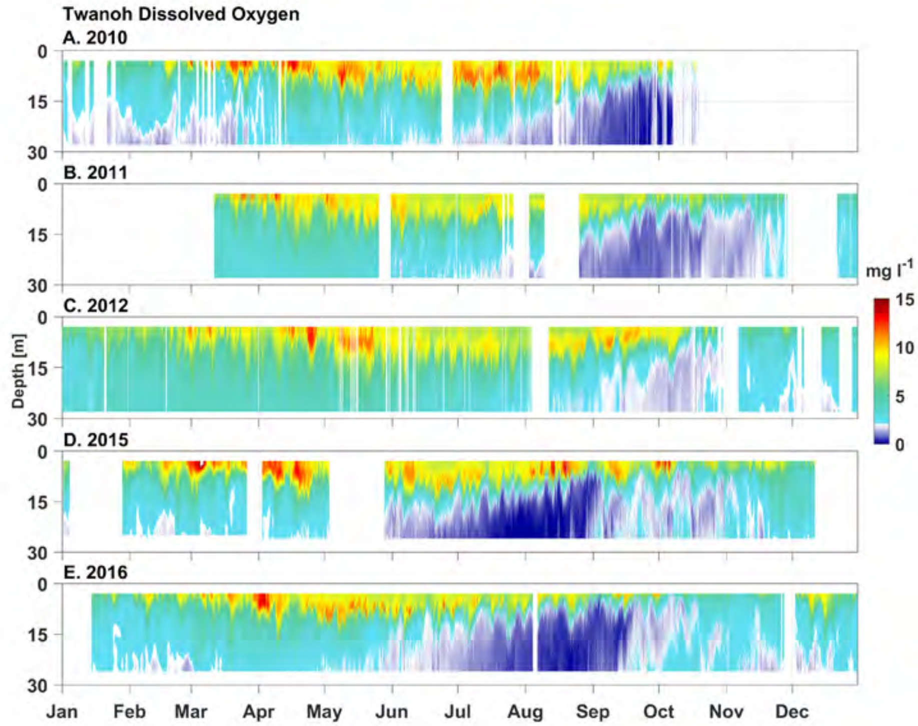


Figure 18. Time series of water column dissolved oxygen concentrations at the Twanoh ORCA mooring from multiple years (2010–16).

DO anomalies during 2016 were negative in South Sound, the Main Basin, and Hood Canal, ranging 1–2 standard deviations below site-specific long-term averages (Figure 19). The most intense hypoxia and negative oxygen anomalies were observed in southern Hood Canal. While oxygen concentrations were anomalously low in South Sound (Carr Inlet), the minimum values were high enough (~4 mg/L) that no biota mortality was evident. In contrast, in southern Hood Canal, minimum values reached anoxia (0 mg/L; Figure 19). Figure 18 illustrates how DO in southern Hood Canal during 2016 compared to four previous years, including 2015. Overall, seasonal DO cycles were similar to those observed in previous years, with seasonal hypoxia developing at depth through the summer and abating with the fall flushing. Compared to previous years, DO concentrations at depth during 2016 ranged from some of the lowest observed, followed by a steep increase during the fall flushing, to some of the highest observed (Figure 19A). The Skokomish Tribe and Washington Sea Grant reported unusually early, minor fish kills in July. No widespread fish mortality occurred during the fall, even though DO concentrations at Twanoh during 2016 were most similar to 2015 and 2010, both years with widespread fish kills. As in 2015, the seasonal flushing started early (~4 weeks), and the relative lack of southerly winds kept the very hypoxic waters (~1 mg/L) constrained at ~10–20 m depth. Even in the absence of major fish kills, hypoxia—coupled with persistent warm water temperatures (see Water quality section 5.B.i; Temperature)—is possibly a stressor that could affect the metabolic demands of biota, including fish, especially if it continues to be an annual occurrence.

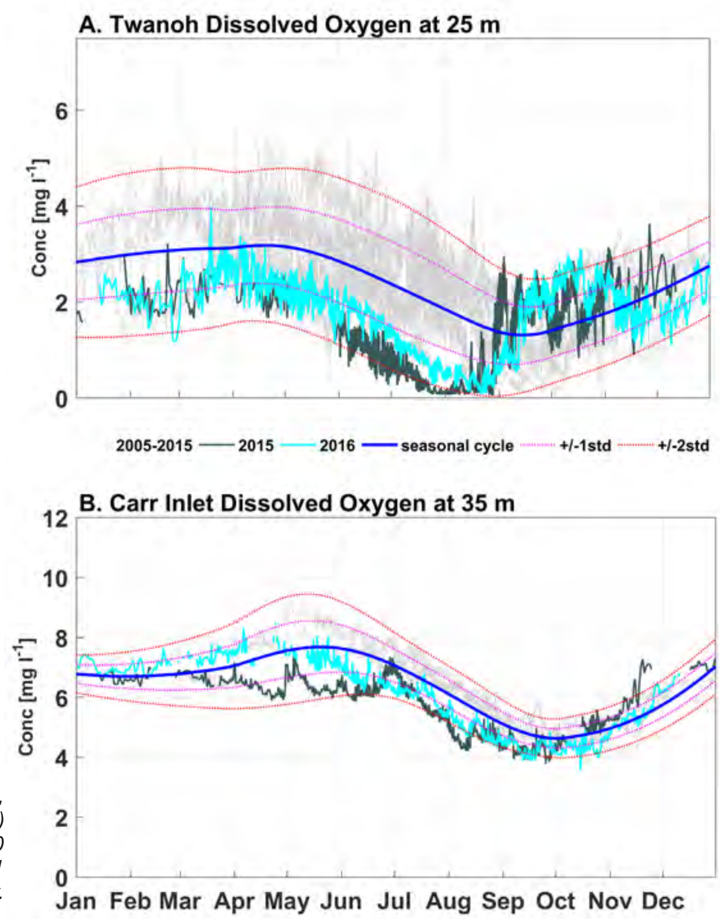


Figure 19. 2016 data (cyan line), 2015 data (dark gray line), climatology (dark blue line), and all historical data (gray lines) for near-bottom oxygen concentrations at the Twanoh (n = 10 years) and Carr Inlet (n = 6 years) moorings; also shown are ±1 and 2 standard deviations from the climatology.

iv. Ocean and atmospheric CO_2:

Source: Simone Alin (simone.r.alin@noaa.gov), Christopher Sabine, Richard Feely, Adrienne Sutton (NOAA, PMEL), Sylvia Musielewicz (UW, JISAO), Al Devol, Wendi Ruef (UW), Jan Newton, and John Mickett (UW, APL); www.pmel.noaa.gov/co2/story/Dabob; www.pmel.noaa.gov/co2/story/Twanoh; PMEL contribution number 4662

CO_2 sensors have been measuring atmospheric and surface seawater xCO_2 at three-hourly intervals on surface ORCA moorings in Dabob Bay since June 2011 and at Twanoh since July 2009. Atmospheric and seawater xCO_2 time-series for Dabob spanned the full year in 2016, and for Twanoh lacked only September through November observations (Figure 20).

During 2016, atmospheric xCO_2 at Dabob averaged 417±11 ppm and ranged from 390–473 ppm. At Twanoh, xCO_2 averaged 418±13 ppm and ranged from 388–488 ppm. Thus, average atmospheric values at both moorings were higher than the global average for marine surface air (which was 403 ppm for 2016, per NOAA/ESRL; ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_annmean_gl.txt) by 14–15 ppm in 2016.

Undersaturated surface seawater xCO_2 conditions (seawater values below atmospheric values) can happen in association with phytoplankton bloom events at any time of the year, although the spring bloom typically shows the most profound and often longest-lasting undersaturation. This usually occurs sometime in February to April in Hood Canal. However, at both Dabob and Twanoh, seawater xCO_2 values were more frequently undersaturated earlier in 2016. Surface seawater xCO_2 at Twanoh ranged from 34 to 1,233 ppm in 2016, with both the annual high and low occurring during January. Twanoh surface seawater xCO_2 was <200 ppm 49% of the time (and <100 ppm 20% of the time) from January through April 2016, compared to 13–27% <200 ppm (and 0.6–11% <100 ppm) during the other three years with sufficient data during the same period to compare (2012, 2014 and 2015). In contrast, xCO_2 values >600 ppm occurred at Twanoh just 3% of the time from January through April 2016, compared to 22–34% of the same period the other three years. Similar patterns were seen in the Dabob surface seawater xCO_2 record in 2016. The protracted period of undersaturated seawater xCO_2 values at both Hood Canal mooring sites early in 2016 would be consistent with stronger than average primary production and CO_2 drawdown during warmer and sunnier than average conditions throughout Puget Sound in early 2016.

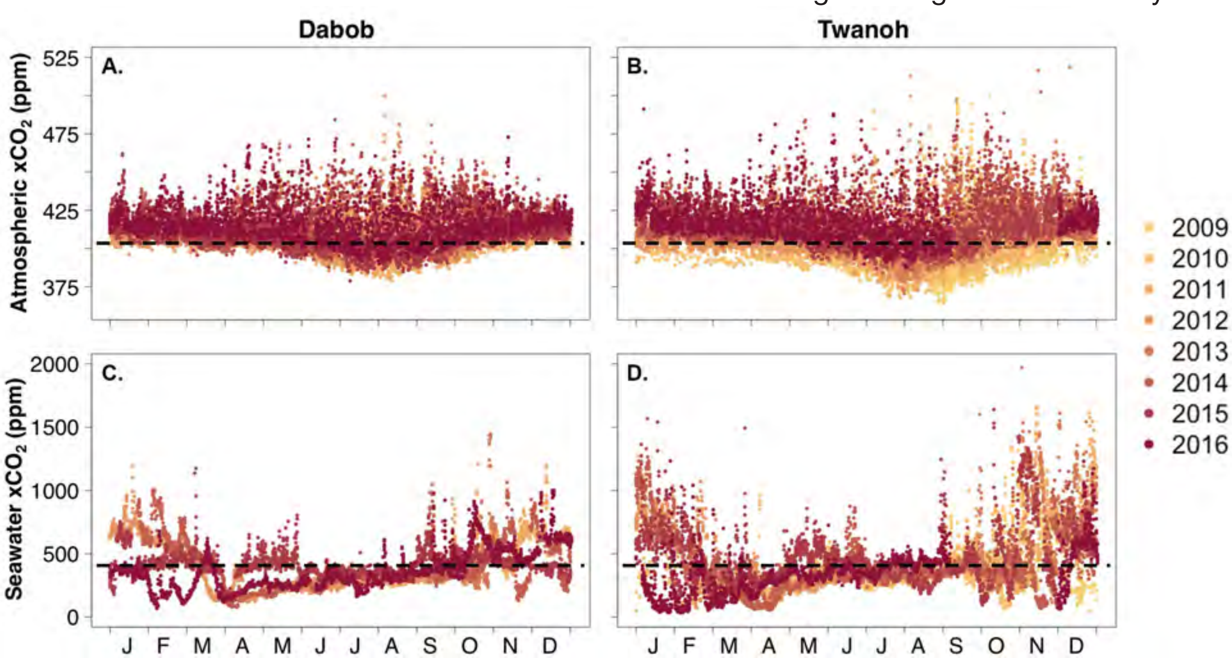


Figure 20. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater and surface seawater at 0.5 m depth in (left) Dabob Bay and (right) Twanoh in 2015. Data from 2016 are in opaque symbols, and all prior years are in transparent colors as shown in the color scale. The approximate 2016 global average atmospheric xCO_2 of 403 ppm is indicated with a dashed line in each panel. Typical uncertainty associated with quality-controlled xCO_2 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.

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 (excluding Quartermaster Harbor). King County also collects monthly temperature, salinity, and nutrient data at 20 marine beach sites. Data may be accessed at green2.kingcounty.gov/marine/Download and mooring data at green2.kingcounty.gov/marine-buoy/Data.aspx, or by request.

i. Temperature and salinity:

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

Surface (<2 m) and bottom (>75 m) water temperatures at Central Basin open-water sites were, on average, 0.5–1.0°C warmer than the baseline mean (1999–2010), with some sites reaching 1.5°C warmer (Figure 21A). This continued the trend in warm anomalies from 2015. In Quartermaster Harbor, where waters are typically warmer than open-water sites due to less water exchange and shallower depths, temperatures were similar to prior years. However, high daily averages were observed in the spring that exceeded spring values observed in 2015. Beach water temperatures show a similar pattern of warmer than normal values, with the exception of normal temperatures observed in September and December 2016. This corresponds to colder than normal regional air temperatures observed in these months.

Water column salinity in the Central Basin tracked wet and dry periods in 2016. Early in 2016, salinities were fresher than normal and fresher than 2015 observations, with bottom water salinities ~0.7 PSU lower than normal from February to April (Figure 21B). Increased vertical mixing during periods of high river flow and precipitation likely contributed to this freshening. During dry periods and lower than normal river flow in spring and summer, salinity observations were similar to prior years. Beach water salinities varied considerably due to proximity to freshwater sources, but overall followed a similar pattern.

Water column stratification showed a typical seasonal pattern for the Central Basin, with sharper density gradients in late March to June (Figure 21C). The water column became more mixed, and the highest deep-water densities (driven by higher salinities) were observed in September and October. The higher density values at depth were likely related to intrusions of oceanic waters.

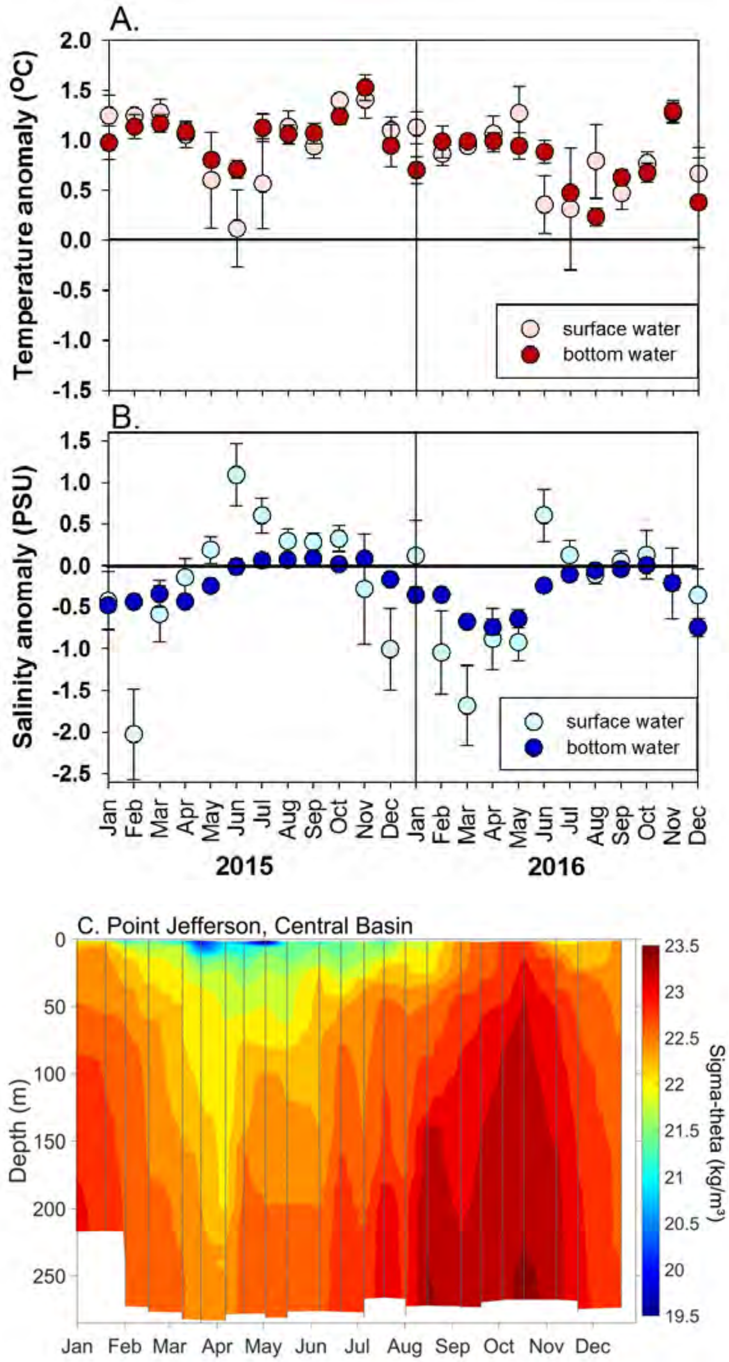


Figure 21. (A) Mean and standard deviation of 2015 and 2016 water temperature anomalies for the seven deepest sites in the Central Basin, compared to a fixed baseline average (1999–2010). Positive values indicate warmer than average temperatures. (B) Mean 2015 and 2016 salinity anomalies for the same sites. Negative values indicate fresher than average salinities. (C) Water column density near Point Jefferson, the deepest site in the Central Basin. Black vertical lines indicate when vertical profile data were collected.

ii. Dissolved oxygen:

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

Observations from biweekly discrete sampling at 12 sites and from 4 in-situ moorings (15-minute intervals) in the Central Basin indicate that DO levels in 2016 were above 5 mg/L throughout the year at all depths, with the exception of Quartermaster Harbor and Elliott Bay. DO in bottom waters (>75 m) in Elliott Bay reached 4.7 mg/L in October, about 0.5 mg/L below the baseline mean (1999–2010; Figure 22A). This corresponds with the highest salinity and density observations, a signature of oceanic water. For most sites, bottom water DO levels in 2016 were slightly above or at the baseline mean from May through August and in December, and slightly below normal (about 0.5–1.0 mg/L) in February and from October through November (Figure 22A). The lower than normal DO levels in 2016 coincide with above average temperature anomalies, particularly from February through March and in November (Figure 21A).

In Quartermaster Harbor, which is prone to low DO events, levels were lowest (<3 mg/L) for less than a week in August and September at the outer site (Figure 22B). DO was highest (>15 mg/L) in April due to a phytoplankton bloom. At the inner Quartermaster Harbor site, the lowest DO levels (<2 mg/L) occurred for less than a day in September only; generally, levels were higher than observed in prior years. Both Quartermaster Harbor mooring sites showed substantial diurnal variation, changing as much as 10 mg/L between day and night, particularly during spring and fall.

An increase in surface DO from primary production during phytoplankton blooms was evident at most sites from April through August (shown for Point Jefferson in Figure 22C), consistent with high levels of chlorophyll-*a* and periods of stratification.

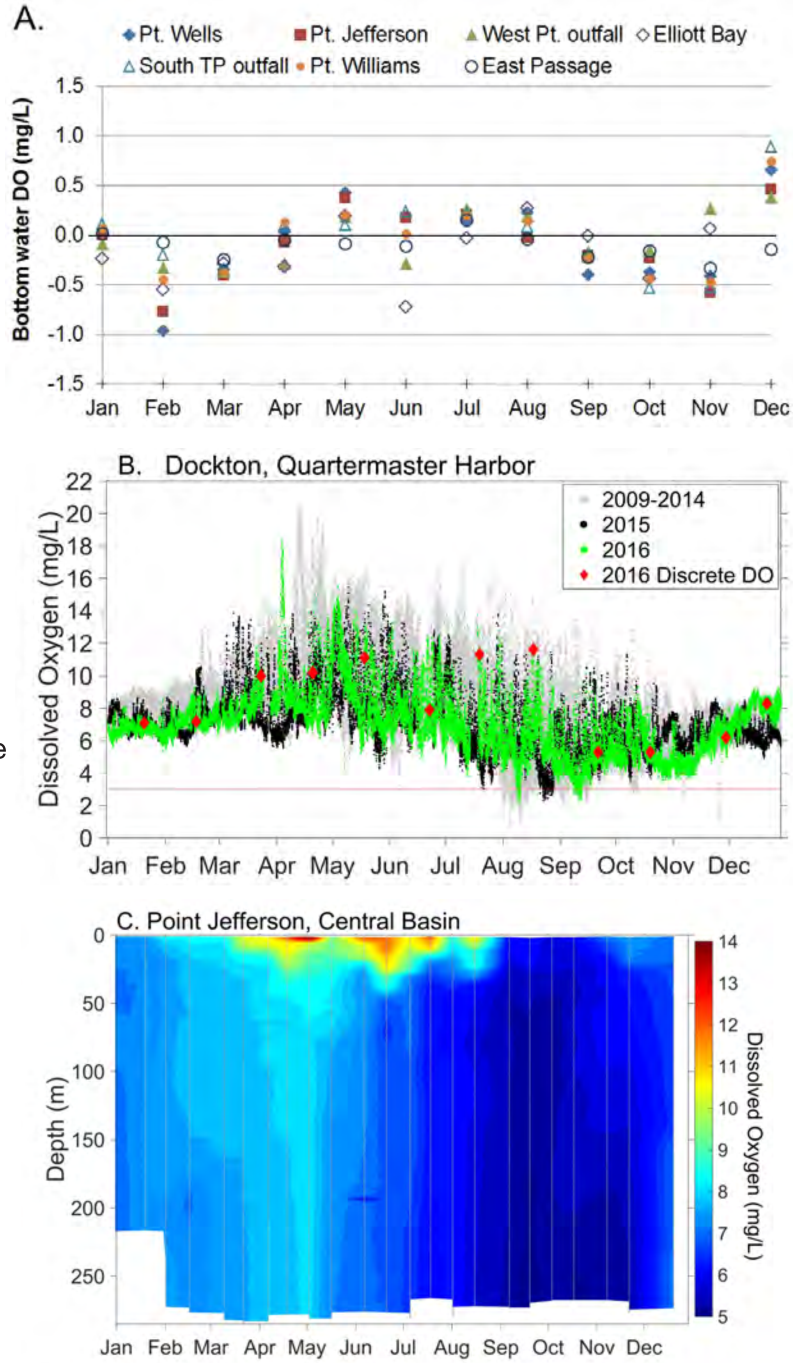


Figure 22. (A) DO anomalies in bottom waters at seven sites in the Central Basin in 2016 relative to a fixed baseline average at each site (1999–2010). (B) Time series of DO from a near-bottom mooring (4–10 m water depth) and from discrete water samples at the outer Quartermaster Harbor site in 2016. Historic DO data are shown for comparison. The red line shows the 3 mg/L level. (C) Water column DO concentrations near Point Jefferson. Gray vertical lines indicate when vertical profile data were collected.

King County's mooring buoy near Point Williams in the Central Basin. Photo: Stephanie Jaeger

iii. Nutrients and chlorophyll:

Source: Kimberle Stark, KCDNRP (kimberle.stark@kingcounty.gov); green2.kingcounty.gov/marine

Observations from biweekly discrete sampling at 14 sites and from 4 in-situ moorings (15-minute intervals) in the Central Basin show that from spring to midsummer, chlorophyll-*a* levels in 2016 were similar to the baseline mean (1999–2010; Figure 23A). The timing of the spring bloom in 2016, in mid-to-late April at most stations, was normal compared to baseline years, except in the northern Central Basin where the spring bloom occurred in mid-March, about three weeks earlier than normal. Except for Quartermaster Harbor, there was no fall bloom in September. Instead, chlorophyll-*a* levels were higher than normal in August.

Nutrient levels varied seasonally, and surface values (<2 m) generally correlated well with chlorophyll-*a* and the timing of phytoplankton blooms. The seasonal decrease in surface nitrate/nitrite levels began in March, consistent with phytoplankton uptake at the onset of the early spring bloom. From March through August, surface nitrate/nitrite values were lower than normal, but September values were higher than normal from the lack of a fall bloom. This pattern was also seen for orthophosphate-P in surface waters, particularly in March, where levels were much lower than normal. Ammonia levels in surface waters increased in May following the spring bloom, were variable during the summer months, and then sharply decreased in August. Ammonia levels in both surface and near-bottom waters in late summer and fall were lower than normal. Quartermaster Harbor nutrient and phytoplankton dynamics typically differ in magnitude and timing compared to open Central Basin waters. Although chlorophyll-*a* levels were only slightly lower than normal in 2016, nitrate/nitrite values in surface waters were lower than normal (below detectable levels) from late April through August.

Nutrient values at 20 beach sites in the Central Basin were variable dependent upon location (data not shown). However, all but five sites in 2016 had lower than normal nitrate/nitrite levels for most of the year. The exception was September, when almost all sites had higher values than normal. Ammonia levels were also lower than or close to normal at most sites and showed a different seasonal pattern than nitrate/nitrite throughout the year.

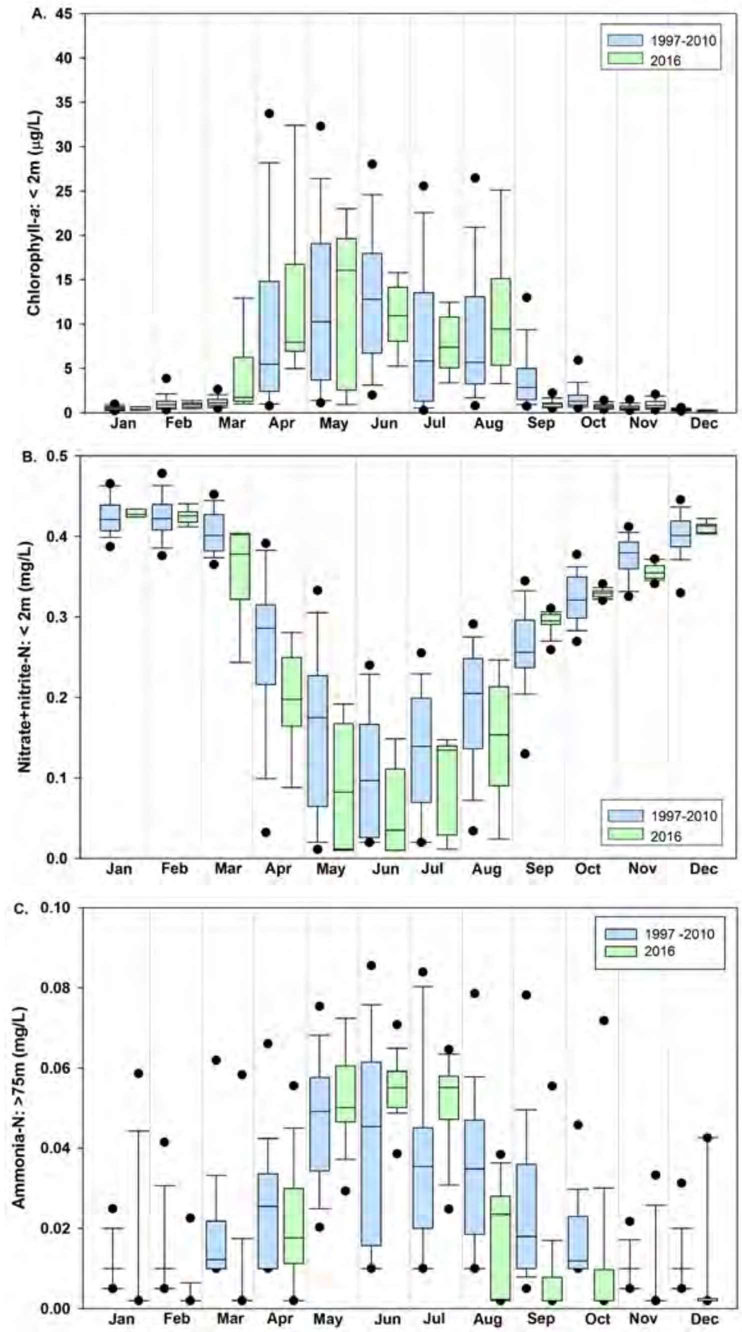
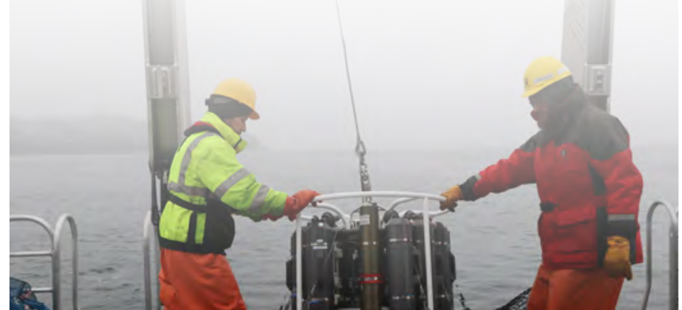


Figure 23. 2016 surface water (A) chlorophyll-a, (B) nitrate/nitrite levels, and (C) near-bottom water ammonia levels at 12 sites in the Central basin compared to the long-term baseline. The line within the box denotes the median, box boundaries are 25th and 75th percentiles, whiskers are 10th and 90th percentiles, and points are 5th and 95th percentiles.

King County Environmental Lab field staff lowering CTD and Niskins into the water. Photo: Kimberle Stark



D. Ferry observations:

i. Victoria Clipper water quality observations and *Noctiluca* blooms:

Source: Suzan Pool (suzan.pool@ecy.wa.gov), Christopher Krembs, Julia Bos (Ecology), and Brandon Sackmann (Integral Consulting, Inc.); www.ecy.wa.gov/programs/eap/mar_wat/index.html

Noctiluca scintillans *is a heterotrophic dinoflagellate that appears in high abundances in eutrophied coastal environments (Vasas et al. 2007). In Puget Sound, it may be an indicator for changes in water quality that impact lower trophic food webs. The seasonal patterns of ammonium and chlorophyll in relation to* Noctiluca *blooms suggest an important role of* Noctiluca *in material cycling within Central Sound in early summer.*

Ferry based monitoring from the *Victoria Clipper IV* began in 2010 as a time efficient and cost-effective means of measuring a large and representative area of Puget Sound surface waters. Data from regular ferry routes were analyzed with data from monthly water column stations and aerial photographs to document *Noctiluca* blooms. During ferry transits between Seattle and Victoria, BC, Canada, an optical fluorometer measures chlorophyll fluorescence at five-second intervals. Data are georeferenced and focus on the area between Admiralty Sill (~48°N) and Seattle (~47.6°N).

In previous years, reduction of surface chlorophyll concentrations in early summer coincided with aerial observations of *Noctiluca* blooming on the surface. The observations were supported by seasonal peaks of ammonium and suppressed chlorophyll in discrete samples. In addition, late summer algal blooms are typically observed in the ferry data (Figure 24).

In 2016, *Noctiluca* blooms were not observed in areas along the ferry route or during times of reduced surface chlorophyll. Decreased chlorophyll in mid-May may be explained by reduced river flows, particularly from the Fraser River (Figure 24). Another decrease in chlorophyll in early July coincided with a few days of winds that potentially mixed surface waters. From late July to early August, nutrient and chlorophyll concentrations were low. Though this period was followed by another increase in chlorophyll, it was not sufficient for a late summer algal bloom.

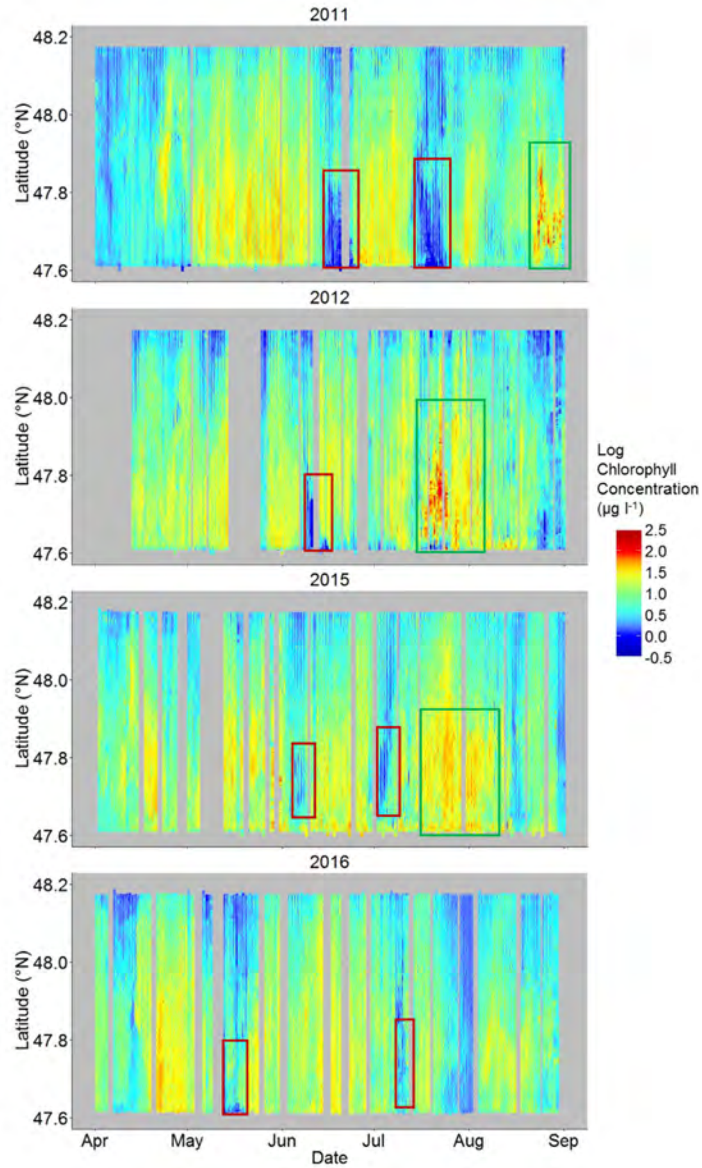


Figure 24. Spatial and temporal distribution of chlorophyll concentrations in Puget Sound during April–August in 2011, 2012, 2015 and 2016. Scatter plots show data collected at 5-second intervals during ferry transits on regular routes. Red boxes highlight decreases in chlorophyll concentrations. Green boxes indicate late summer peaks of chlorophyll.

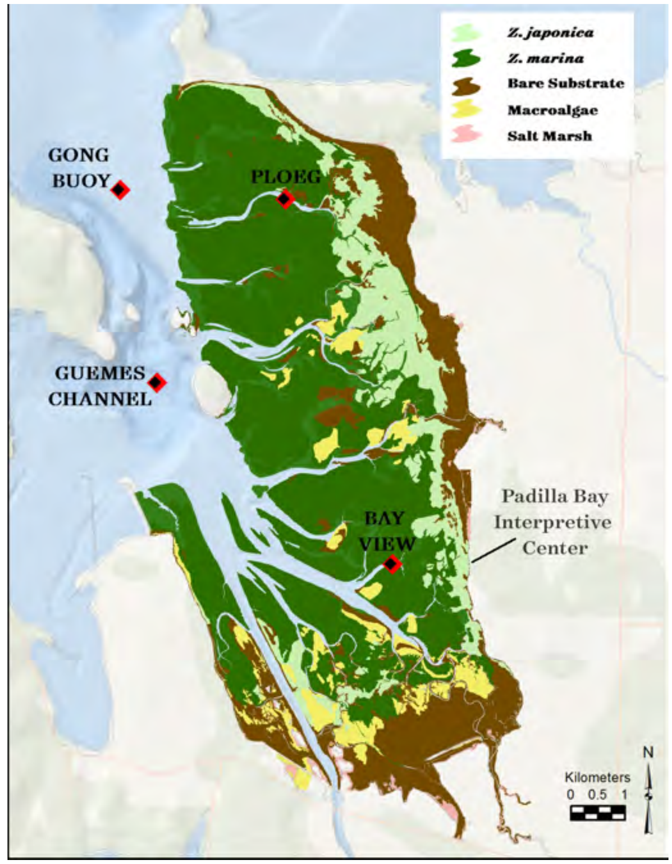
Victoria Clipper IV *private passenger ferry in Elliott Bay. Ferry vessel is carrying Ecology's sensors to measure surface marine water quality every five seconds between Seattle, WA and Victoria, BC. Photo: Suzan Pool*

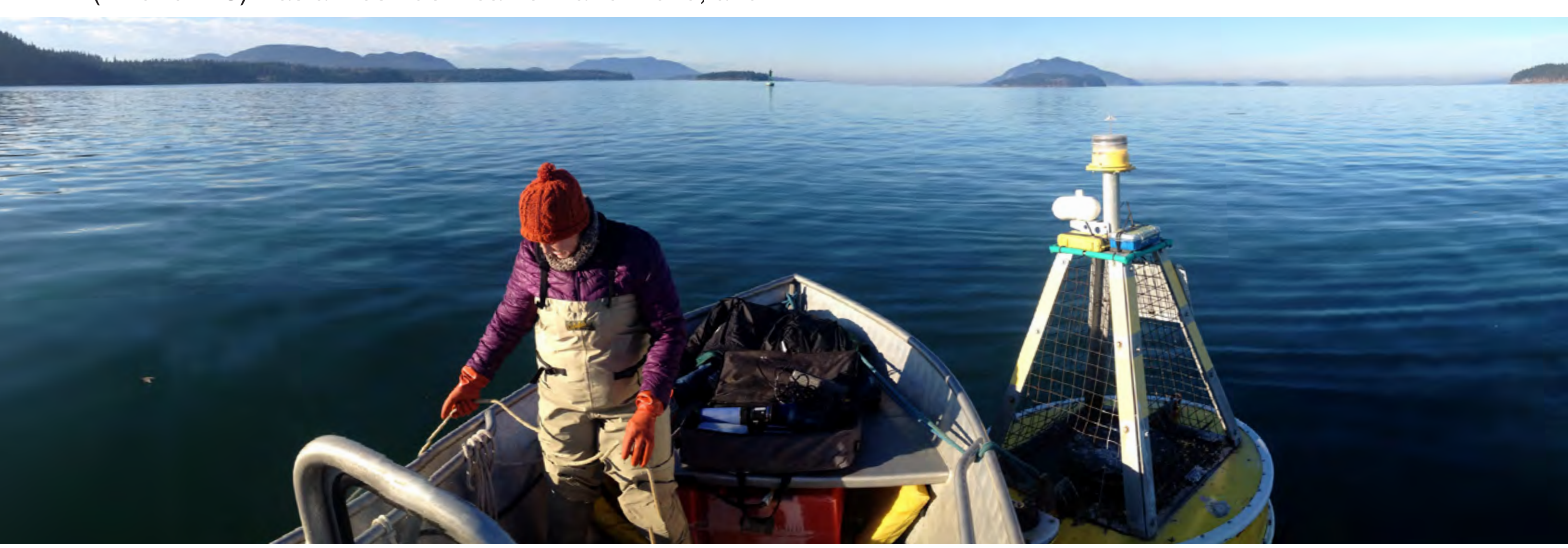
E. North Sound surveys:

i. Padilla Bay temperature:

Source: Jude Apple (japple@padillabay.gov), Nicole Burnett, Heath Bohlmann, and Claire Cook (Padilla Bay NERR/Ecology); www.padillabay.gov

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 (i.e., >20 yrs) 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 (Figure 25). High-frequency (15-minute interval) monitoring data reveal trends in water column structure, plankton community dynamics, and water quality parameters such as DO, pH, salinity and temperature. With recent trends in ocean warming, temperature is the focus of the following section. Data collected in nearshore eelgrass meadows reveal that water temperature is highly variable in Padilla Bay, ranging from 1.3–22.9°C, with daily fluctuations approaching 10°C in summer months. Water temperatures in 2016 were generally similar to 2015, with the exception of cooler daily mean temperatures in January and substantially warmer periods during spring and summer of 2016 (Figure 25A). Indeed, water temperatures in mid-April to May and again in August were the highest on record for these time periods. Mean annual water temperature in 2016 (11.5±3.4°C) was almost identical to that of 2015, and both years were significantly higher ($P < 0.001$) than all other years since continuous monitoring began in 1995. The elevated warm conditions observed in Padilla Bay and throughout Puget Sound in 2015 and 2016 are unprecedented in our long-term dataset, as evidenced by annual temperature anomalies (Figure 25B). These warmer and cooler periods shown by annual anomalies in Padilla Bay are associated with large-scale climatic cycles, as evidenced by a strong correlation with the PDO index.





Winter sampling and water column profiles at Gong Buoy in Padilla Bay with Washington Conservation Corps member Ashleigh Pilkerton (panoramic picture of boat and buoy). Photo: Heath Bohlmann

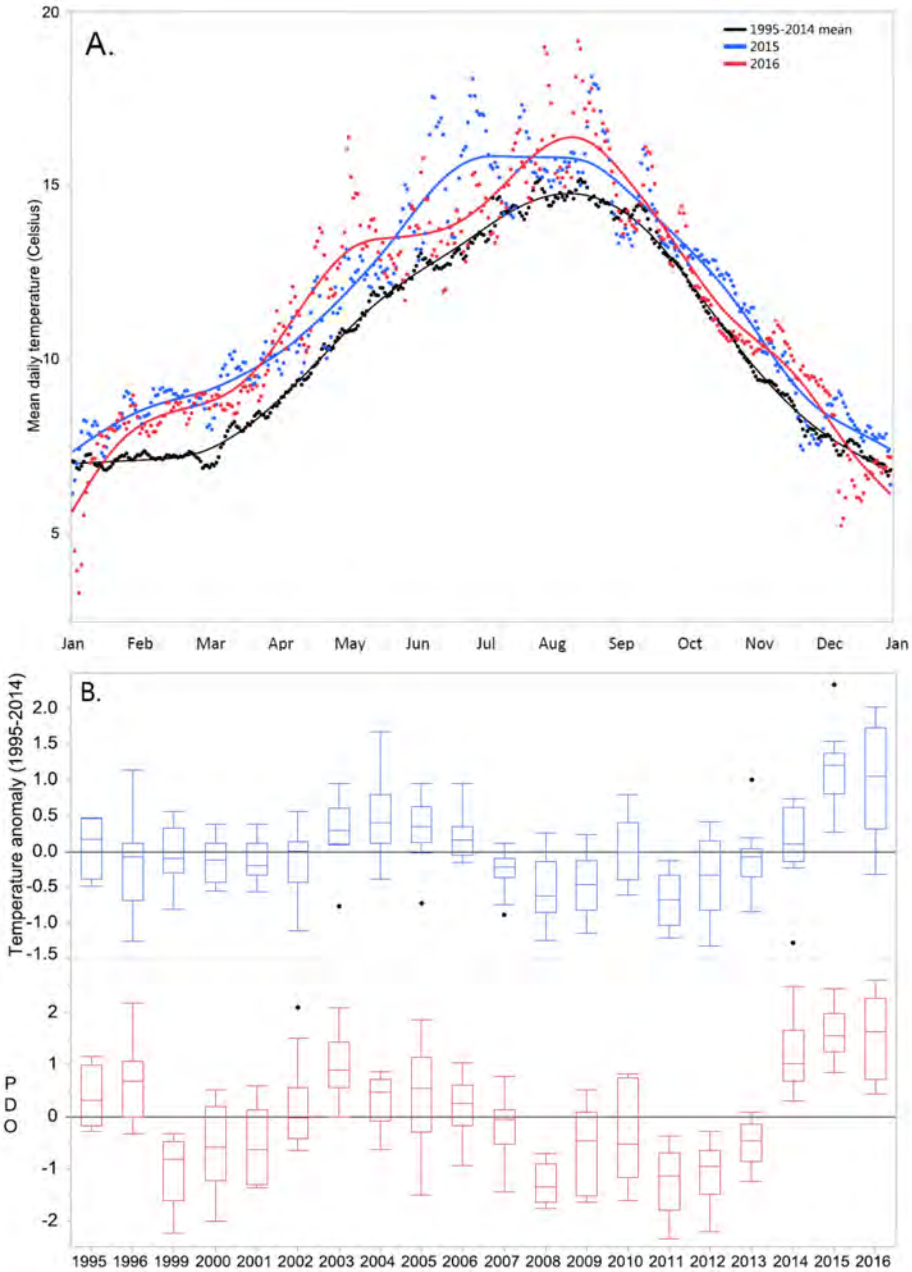


Figure 25. Map of Padilla Bay (previous page). Long-term patterns in temperature in Padilla Bay, including (A) comparison of daily mean temperatures in 2015, 2016, and long-term (1995–2014) daily means, and (B) long-term annual temperature and PDO anomalies.

ii. Padilla Bay density, chlorophyll, oxygen and pH:

Source: Claire Cook (ccook@padillabay.gov), Jude Apple, Heath Bohlmann, and Nicole Burnett (Padilla Bay NERR); www.padillabay.gov

Researchers at Padilla Bay NERR began conducting water column profiles in Guemes Channel (Figure 26) in late 2015, to identify changes in water column structure throughout the year and evaluate the contribution of deeper, marine waters to water quality and chemistry in Padilla Bay. A total of 13 water column profiles were collected in 2016. The year began with a well mixed water column that transitioned to a warmer, more stratified water column in spring and summer (Figure 26A). In late spring, there was evidence of intrusion of low-density surface water, likely a result of freshwater inputs to Padilla Bay. Stratification occurred again in late summer, driven by warmer, lower-density surface waters. Fall was characterized by colder, higher-salinity waters of marine origin, and the water column remained well mixed through the end of the year.

Density characteristics of the water column influence the depth at which primary production occurs. Chlorophyll profiles (Figure 26B) show elevated concentrations throughout the water column in late April, and at the surface in July to September, when surface-water stratification occurred. Water column DO concentrations (Figure 26C) and pH (Figure 26D) reflected patterns in water column structure and phytoplankton abundance, with higher values of DO and pH in surface waters during spring and late summer, and lower values in deeper waters during summer and early fall. Seasonal variation revealed a strong relationship between density, phytoplankton abundance, and water chemistry in Padilla Bay.

Optode bottles used in incubations to estimate rates of pelagic planktonic respiration. Photo: Jude Apple

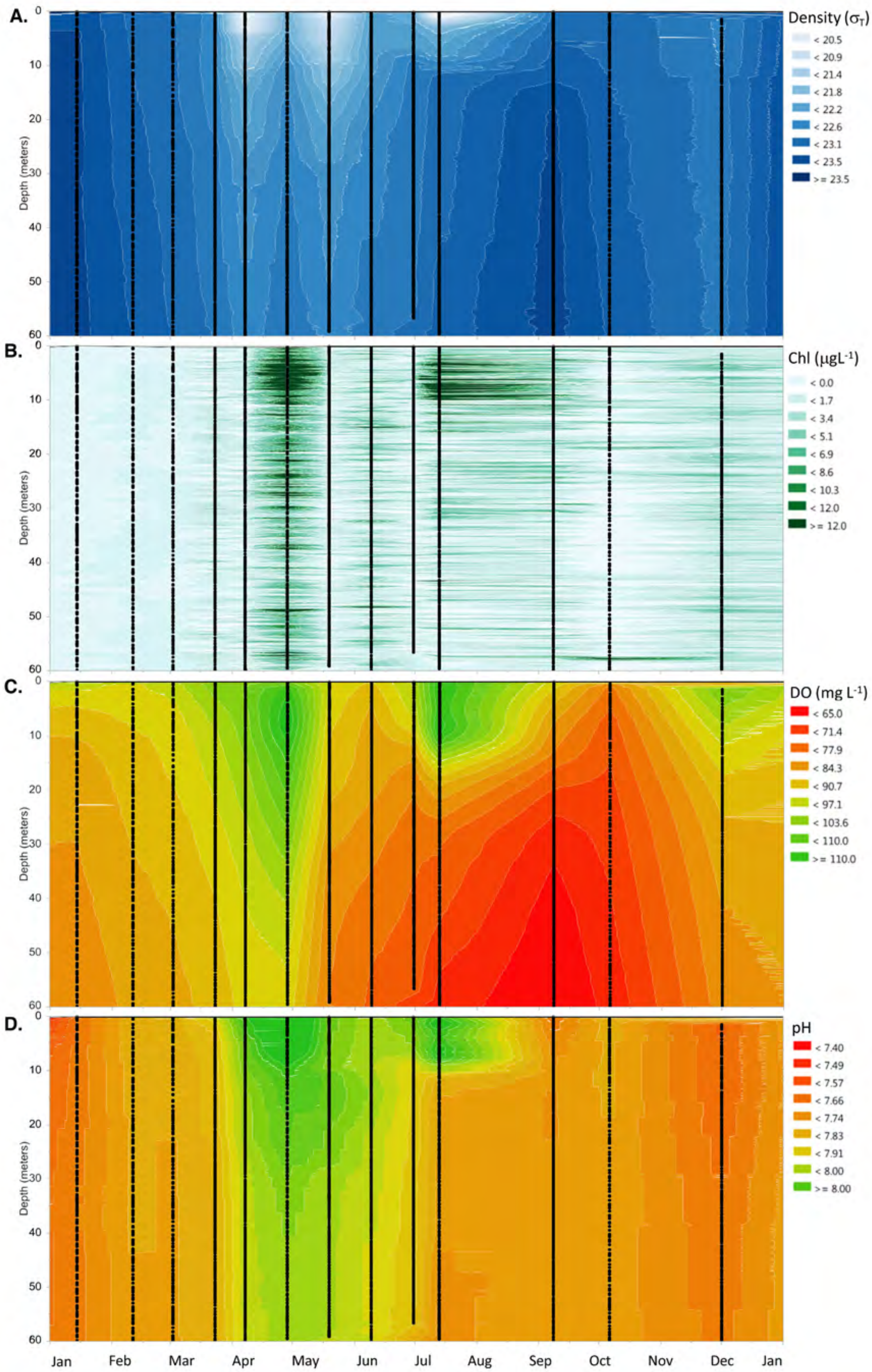


Figure 26. Water column profiles of (A) density, (B) chlorophyll, (C) dissolved oxygen, and (D) pH collected in Guemes Channel (Padilla Bay).

iii. Padilla Bay respiration:

Source: Jude Apple (japple@padillabay.gov), Claire Cook, Heath Bohlmann, and Nicole Burnett (Padilla Bay NERR/Ecology); www.padillabay.gov

Consumption of oxygen by pelagic microbes (i.e., water column respiration) is an important contributor to oxygen dynamics, carbon cycling, and ocean acidification in marine waters. However, empirical estimates of the range and variability of oxygen consumption in Puget Sound waters remain limited. In 2015, we began routine monitoring of water column respiration at four locations in Padilla Bay NERR (map on page 28). Samples were collected in surface and bottom (~20 m) waters at Gong Buoy and two sites where tidal waters inundate extensive eelgrass meadows: Bayview and Ploeg Channels. To estimate rates of respiration, water collected from each site was sub-sampled and incubated in the dark at in-situ temperatures to derive rates of oxygen consumption. Rates of pelagic respiration varied seasonally, with higher rates in late spring/early summer and lowest rates during winter months (Figure 27A). A dramatic peak in oxygen consumption in late April at Gong Buoy was also observed, coinciding with elevated concentrations of chlorophyll in the water column (see Water quality section E.ii; Padilla Bay density, chlorophyll, oxygen and pH), suggesting a strong linkage between oxygen consumption and phytoplankton-derived organic matter. Annual mean values (Figure 27B) reveal that oxygen consumption is consistently higher in eelgrass meadows than the open waters near Gong Buoy. The mean annual rate of oxygen consumption for waters inundating eelgrass habitat was 44% higher than that of deep waters at Gong Buoy. Incoming deeper waters of marine origin (i.e., Gong Buoy) were characterized by relatively low average rates of respiration (i.e., 4.2 μg O_2/L/h), which is representative of other deep-water measurements of respiration collected elsewhere in Puget Sound.

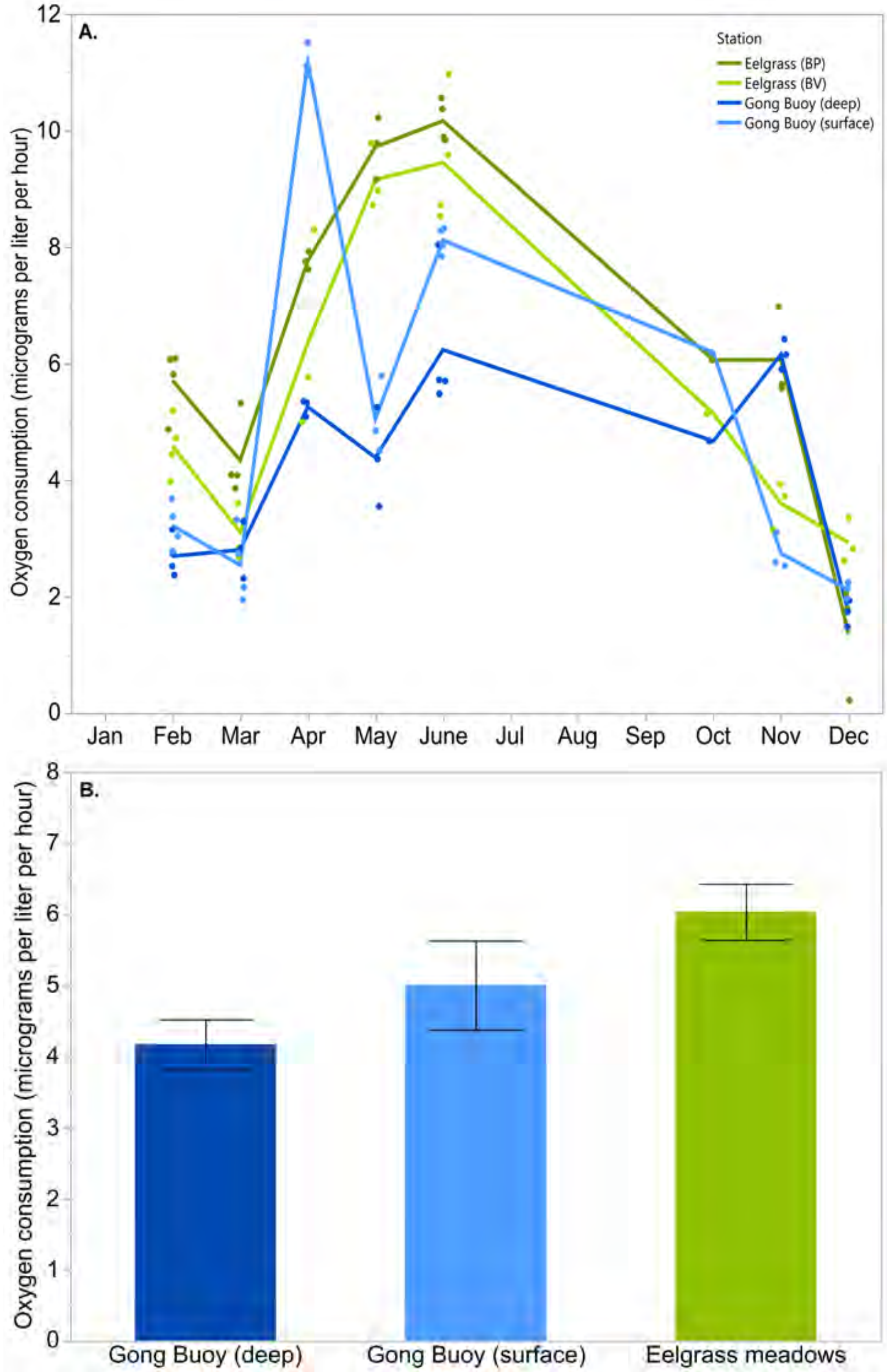


Figure 27. (A) Variability of pelagic oxygen consumption throughout the year, and (B) annual averages recorded at different sites in Padilla Bay.

iv. Bellingham Bay buoy:

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

The new oceanographic mooring in Bellingham Bay, the first north of Admiralty Inlet, was sited and is maintained through a partnership between the University of Washington, Northwest Indian College, Lummi Indian Nation, and Western Washington University, with data served over NANOOS. The buoy is equipped with atmospheric meteorological sensors and oceanographic sensors at 0.5 and 18 m depth. The first seasonal cycle of data (February through December 2016) is shown in Figure 28. Water temperature shows a predictable pattern, with surface temperatures warming in summer and deep temperatures remaining much more consistent over the year. During fall, atmospheric cooling of surface waters resulted in a temperature inversion, with deep waters being warmer than surface waters. This is especially evident in December, when increased winds from the north (direction not shown) were strong. The salinity record shows the strong influence of the Nooksack River plume, which lowers the surface salinity. When salinity dips low, increases in colored dissolved organic material (CDOM) and turbidity (not shown) are evident, also indicating a riverine influence. Deep salinity was near-constant at 30 PSU. A noticeable increase in surface oxygen in April was seen in surface waters, with a commensurate rise in chlorophyll and consistent with photosynthetic production of oxygen. However, when another rise in chlorophyll occured in June, the oxygen increase was minimal. The dynamics leading to the different oxygen responses to these blooms are not evident, but may be explained by advected or less actively growing cells in June versus in situ or rapid growth in spring. The magnitude of the June chlorophyll event, nearing 60 µg/L concentration, was quite large compared to the rest of the year. Oxygen at depth was much lower than at the surface, with late summer near-hypoxic spikes evident.

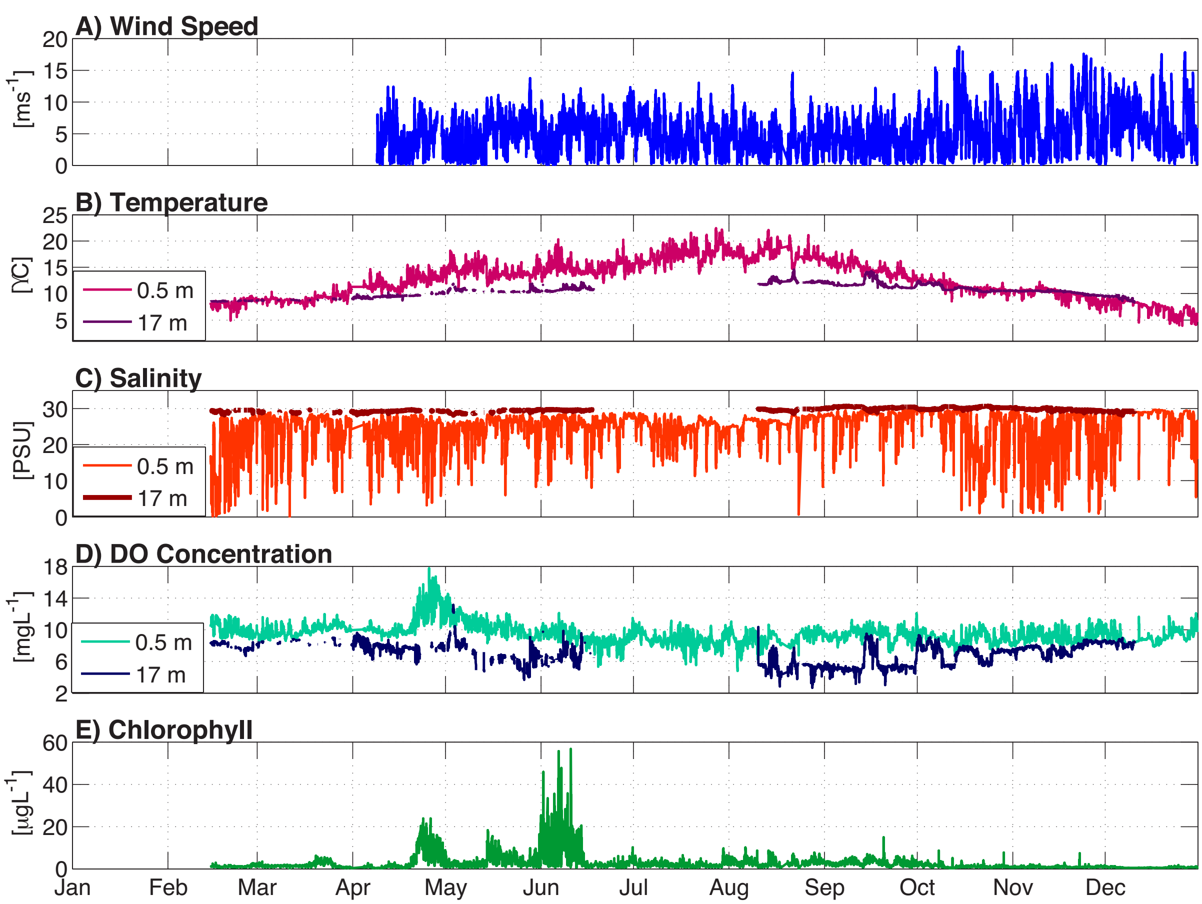


Figure 28. The annual cycle of atmospheric and water properties in Bellingham Bay during 2016. Shown are (A) wind speed, (B) temperature, (C) salinity, (D) dissolved oxygen, and (E) chlorophyll. Temperature, salinity, and dissolved oxygen are shown at two depths, 0.5 m and 17 m.

F. 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.

i. San Juan Channel/Juan de Fuca fall surveys: Source: Jan Newton (janewton@uw.edu) (APL, UW), Breck Tyler (UCSC), Natasha Christman, Ian Smith, and Erin Haphey (UW); courses.washington.edu/pelecofn/class_information.html

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

The 13-year record shows fall 2016 temperatures to be well above average, though not as warm as in 2014, based on the observations of temperature versus salinity from the sea surface to ~80 m at the South station measured during the first week of November (Figure 29A). Fall 2014 temperatures were about a degree Celsius above the next warmest waters in 2015, presumably affected by the North Pacific warm anomaly (the blob); the 2016 temperatures were more similar to 2015 surface waters. The salinity patterns of the last three years stood in stark contrast to the rest of the time series,

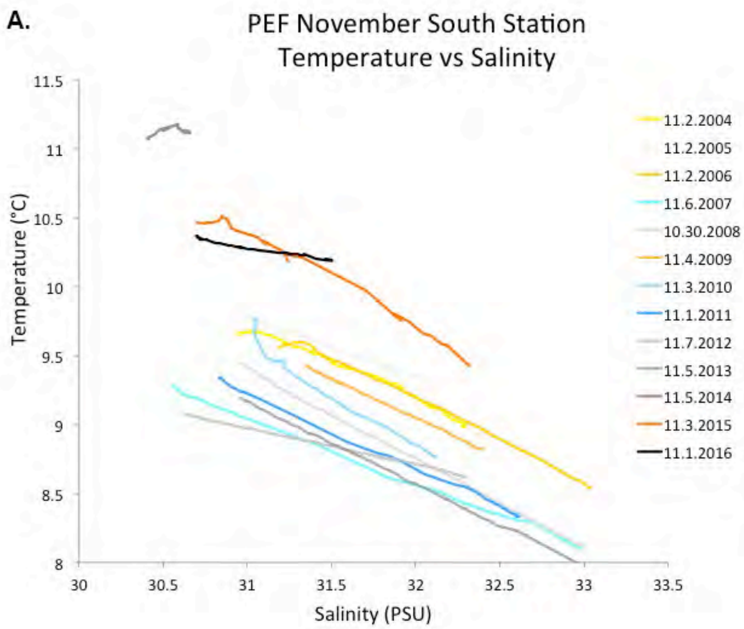


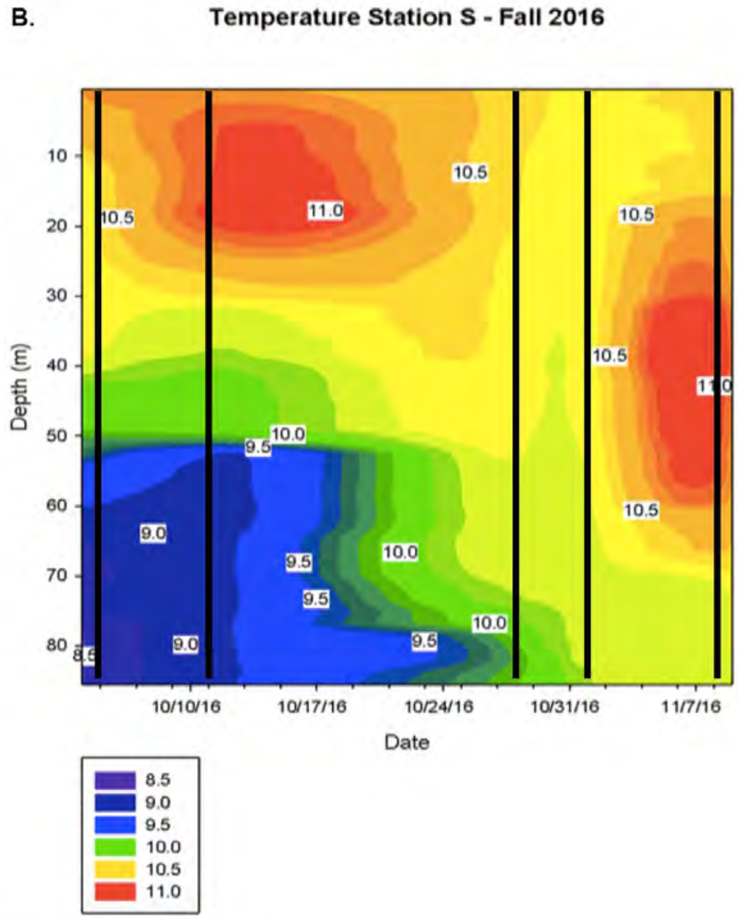
Figure 29A. Temperature versus salinity from 80 m to the surface at the South station in the eastern Strait of Juan de Fuca during the first week of November. Deep waters (coldest and saltiest) are found on the right. Color coding: yellow = El Niño years; blue = La Niña years; gray = neutral years.

Deploying the CTD. Photo: Breck Tyler

Seals on their favorite rock, Semiahmoo Bay. Photo: Todd Sandell though the driving mechanism is not entirely clear. The 2016 salinity range was narrower than in 2015, though not as narrow nor as fresh as in 2014. The narrower salinity range found during both fall 2014 and 2016 may reflect the influence of downwelled surface waters over the full water column at this station. A time series contour of water column temperatures over fall (Figure 29B) illustrates the typical seasonal shift from upwelling conditions with a cold, deep oceanic layer (10/4 and 10/11), to downwelling, with warmer temperatures distributed over the full water column (10/28 and 11/1). However, unique in 2016 was the observation in mid-November (11/9) of the warmest waters at mid-depth, which may reflect warm-anomaly waters being downwelled and advected into the Strait.

The effect of the widespread warm waters on regional biota is still under investigation, but for the top predators, the fall 2016 pattern was generally similar to the preceding years (Figure 29C). The predominant marine mammal species (harbor porpoise, Steller sea lion, and harbor seal) exhibited very low abundance during 2014–16, and the higher than normal mammal diversity observed in recent years was not evident in 2016. Seabird abundance was relatively low during 2013–16, but community composition did not differ from longer-term trends.

B.



C.

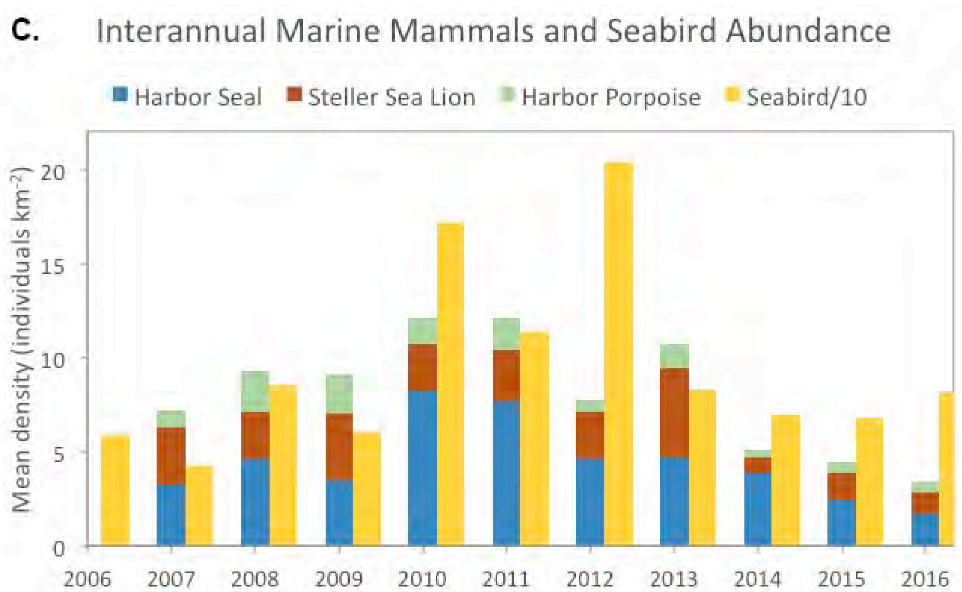
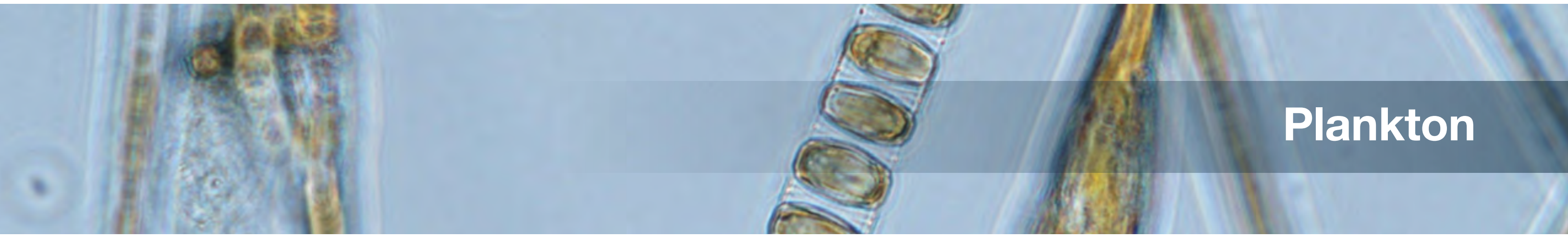


Figure 29. (B) Water column temperatures (degrees Celsius) contoured over fall 2016 at the South station. Cruise data are shown by black lines for the five dates occupied. (C) Interannual marine mammal and seabird densities, 2006–16. Note that seabird densities are divided by 10.



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

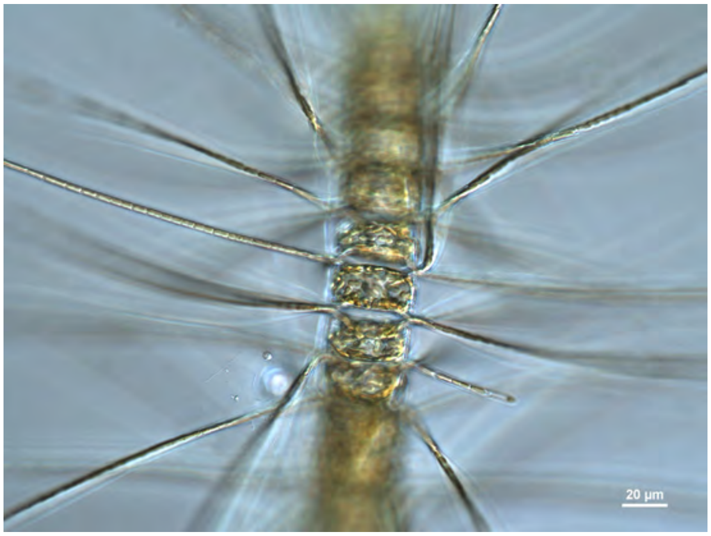
A. Phytoplankton:

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

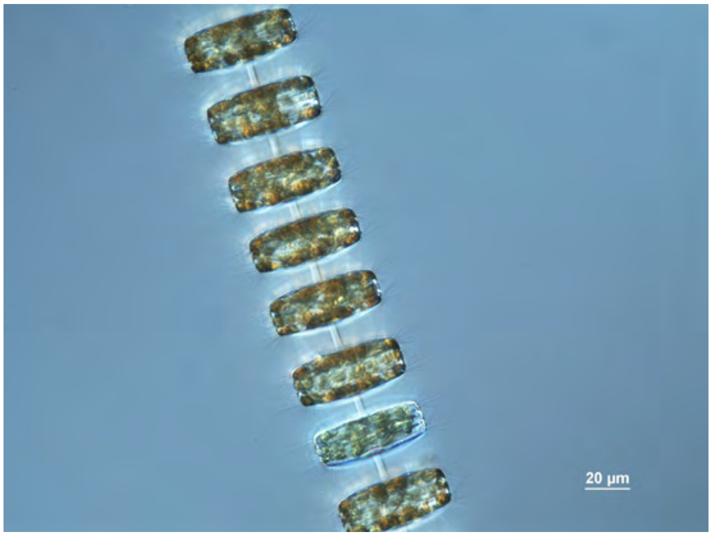
King County has analyzed phytoplankton samples semi-monthly in the Puget Sound Central Basin since 2008 using non-quantitative microscopy. Since May of 2014, phytoplankton has also been analyzed via FlowCAM—an imaging particle analyzer—to assess the abundance and biovolume (a proxy for biomass) of particles that are between 5 and 300 µm in size at eight long-term monitoring stations. Two more stations were added in 2016.

Puget Sound continued to experience above-normal water temperatures, with a dry summer and lower than normal nitrate concentrations in the surface layer; however, this did not result in a noticeable effect on seasonal phytoplankton growth in the Central Basin. Compared to the previous two years, 2016 spring and summer blooms were well marked but did not persist as long; and unlike 2015, no winter or fall blooms were detected (Figure 30A) with the exception of Dockton, a protected site. The atypically low plankton abundance in most of the Central Basin fall samples is consistent with the low levels of chlorophyll recorded at King County's stationary buoys. This anomaly could have been related to southerly winds occurring earlier than normal, as no evidence of early nutrient depletion or mixing of the water column was found.

As seen in previous years, chain-forming diatoms were dominant from early spring to late summer (Figure 30B). Similar to 2015, the chain-forming diatoms *Thalassiosira* and *Lauderia/Detonula* initiated the spring bloom, which started in late March and was followed by more diverse mixed diatom assemblages that generally remained dominated by *Chaetoceros* (multiple species) throughout the summer. Late summer saw an unusual increase in the larger-celled diatoms *Eucampia* and *Ditylum* up to the end of August. Small dinoflagellates (<25 µm) and the ciliate *Mesodinium* made up a significant portion of the identifiable biological particles during the late fall and winter months, when total biovolume was at its lowest (Figure 30C).



Chaetoceros eibenii. *Photo: Gabriela Hannach*



Thalassiosira rotula. *Photo: Gabriela Hannach*

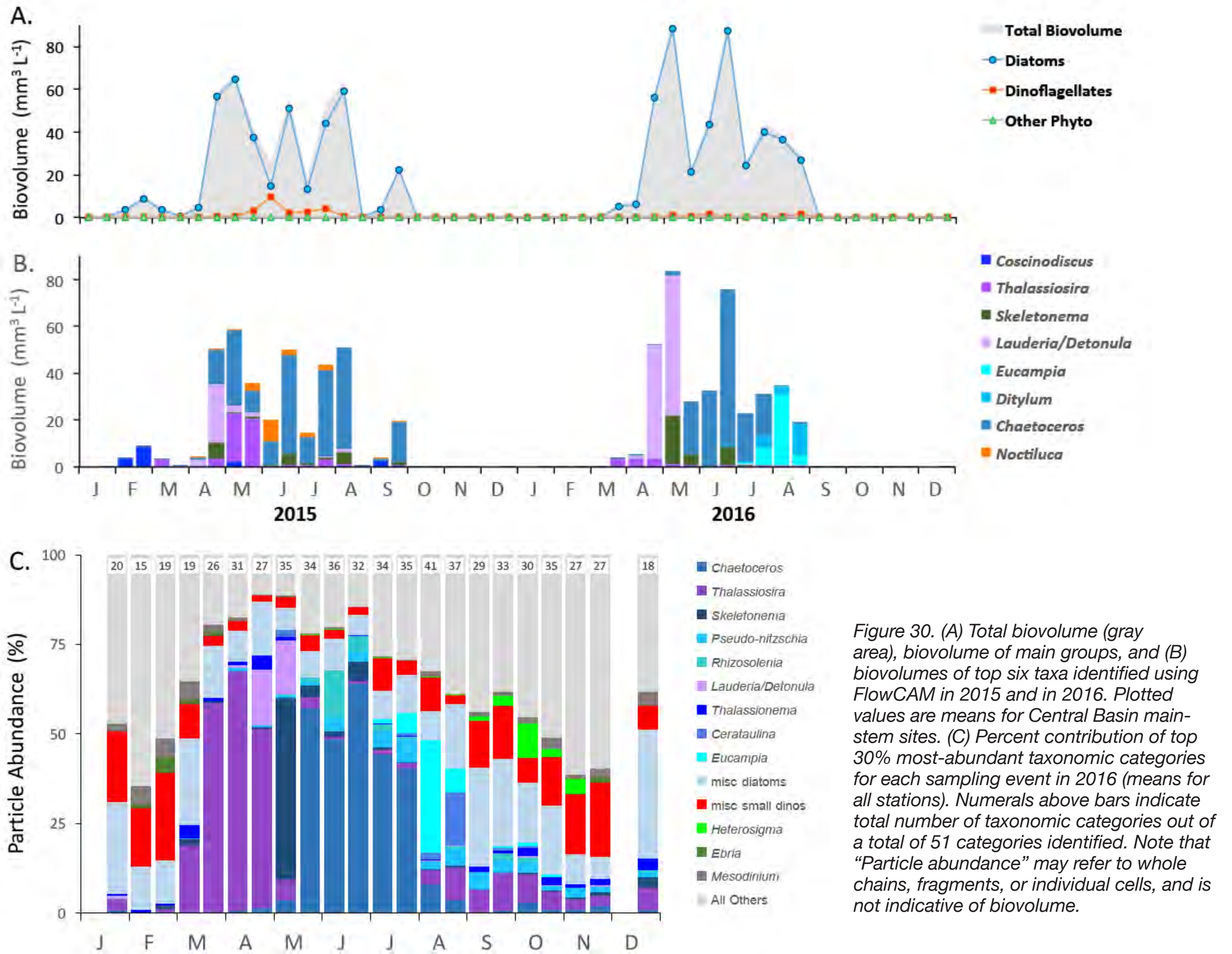


Figure 30. (A) Total biovolume (gray area), biovolume of main groups, and (B) biovolumes of top six taxa identified using FlowCAM in 2015 and in 2016. Plotted values are means for Central Basin main-stem sites. (C) Percent contribution of top 30% most-abundant taxonomic categories for each sampling event in 2016 (means for all stations). Numerals above bars indicate total number of taxonomic categories out of a total of 51 categories identified. Note that "Particle abundance" may refer to whole chains, fragments, or individual cells, and is not indicative of biovolume.

B. Zooplankton:

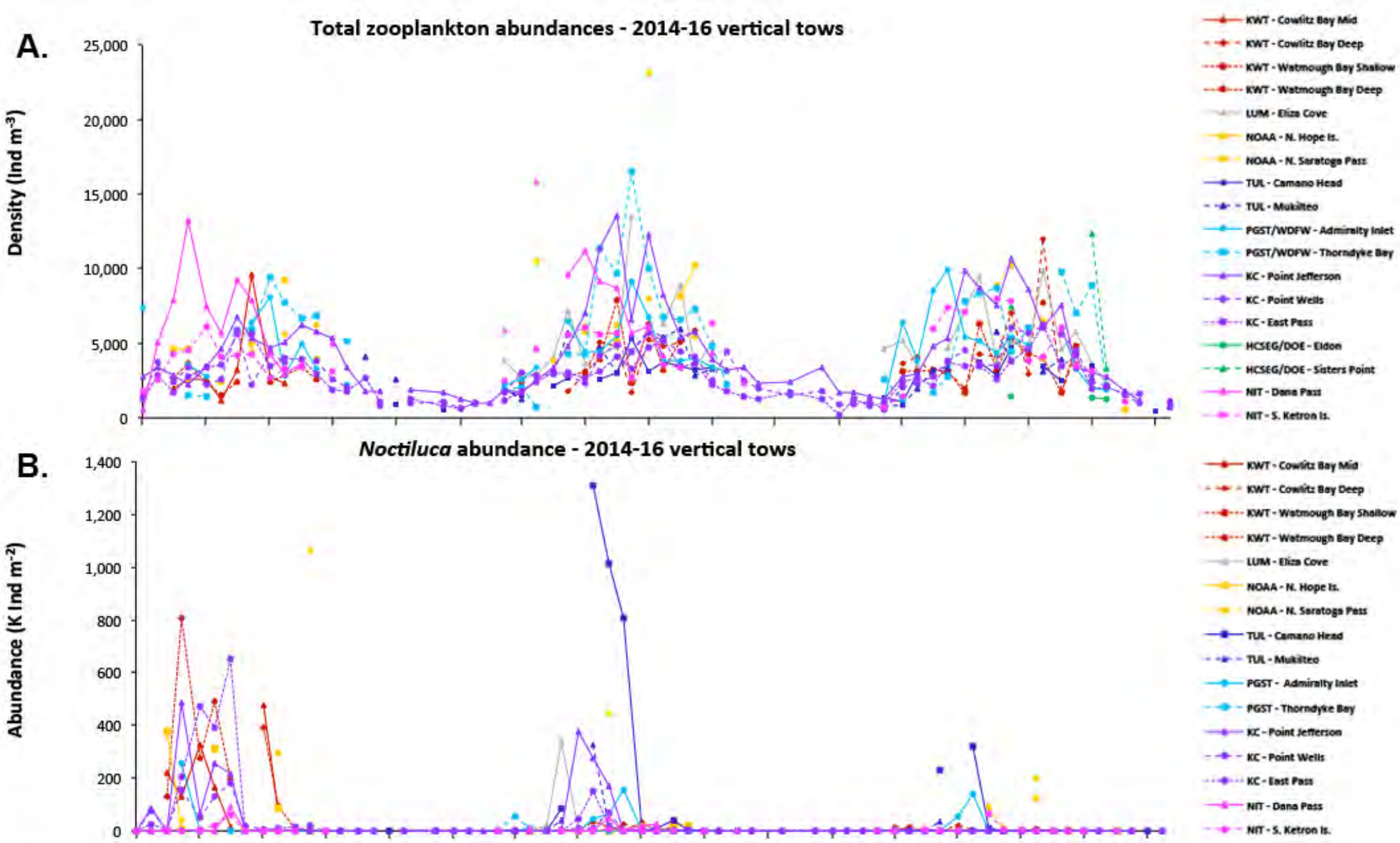
i. Puget Sound:

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

2016 was the third year of the Puget Sound Zooplankton Monitoring Program. Sampling was conducted by King County (KC), the Nisqually Indian Tribe (NIT), Tulalip Tribe, Kwiáht, Lummi Nation, Port Gamble S'Klallam Tribe (PGST), WDFW, and NOAA; the Hood Canal Salmon Enhancement Group (HCSEG) and Ecology (DOE) added stations in southern Hood Canal near the end of this year.

Most locations were sampled biweekly from mid-March through September, with the exception of KC, who continued sampling through the winter. Data shown here were collected with 60-cm diameter, 200-µm mesh plankton nets towed vertically from 5 m off the bottom (or from a maximum depth of 200 m in deep water) to the surface. Samples were taxonomically analyzed to species and life stage for most organisms at the University of Washington.

Overall, total mesozooplankton abundances remained high in most regions in 2016 compared to 2014, but were slightly lower than in 2015 (Figure 31A). Abundances of the heterotrophic dinoflagellate *Noctiluca* (Figure 31B) were very low at all stations in 2016. In Central Basin (Figure 31C), copepods remained abundant, bivalve larvae were particularly abundant, and larvaceans were abundant in spring, but dropped off early in summer compared to other years. Nonmetric multidimensional scaling (NMS) ordination of 2014–16 species abundances (excluding *Noctiluca*) showed that community differences among basins remained clear, but interannual differences were also large; in particular, community variance was considerably lower in 2015–16 than in 2014, particularly within Central Basin (Figure 31D). Taxa that were most strongly correlated with the dominant axis (Axis 3) were the copepods *Epilabidocera*, *Acartia hudsonica, Centropages, Pseudocalanus moultoni* and *newmani,* cladocerans, *Fabia* crab larvae, and barnacle larvae (all positively correlated with the axis). The copepods *Microcalanus* and *Triconia borealis* and larvaceans (all positively), and bryozoan larvae (negatively), correlated with Axis 1.



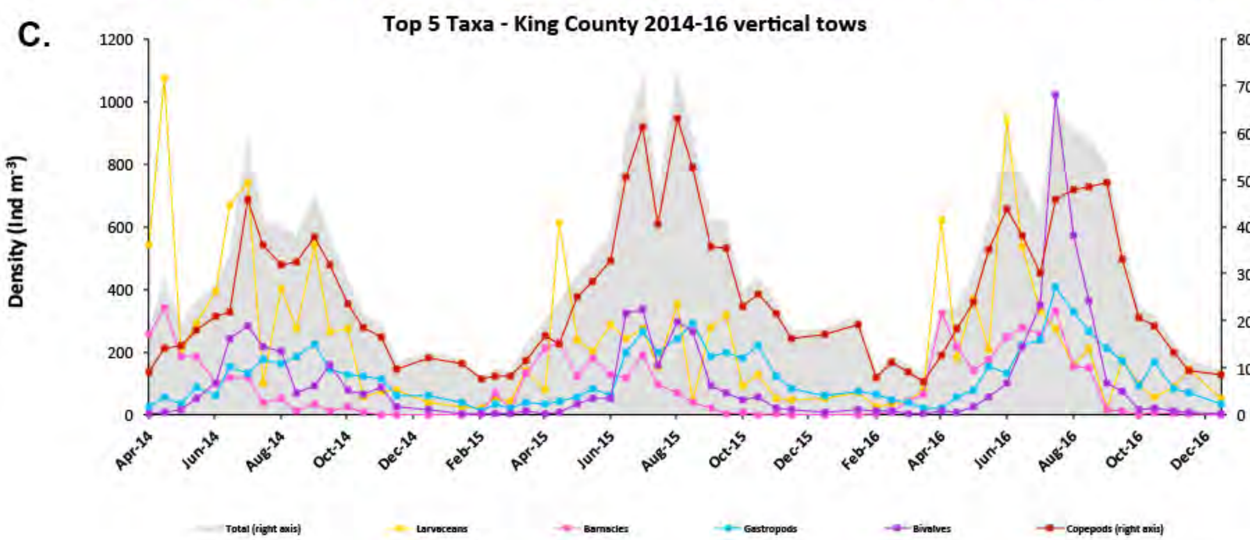


Figure 31. (A) Time series of total mesozooplankton (Ind m³) at each station in 2014–16. (Note that Dana Passage was not sampled in 2016.) (B) Time series of whole water column abundance of the dinoflagellate Noctiluca *(Ind m³). (C) Total abundance (gray area) and abundance of the five most common taxa averaged over the three KC sites in Central Basin; note that total and copepod abundances are on the right axis.*

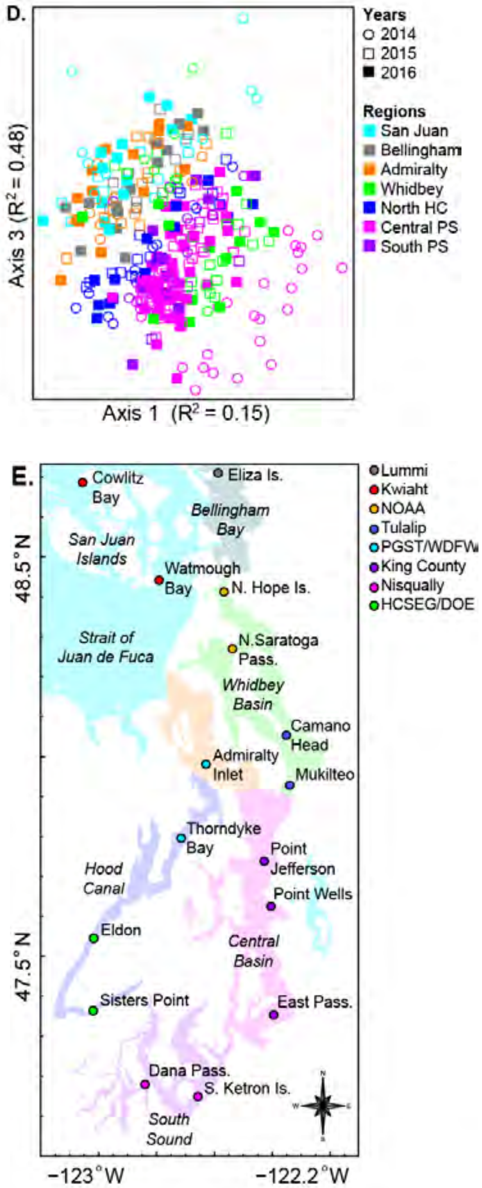


Figure 31. (D) Nonmetric multidimensional scaling ordination of the zooplankton community showing the two axes that carried the greatest portion of variance in community structure, with samples symbol-coded by basin. (E) Map of the sampling locations.

ii. Padilla Bay:

Source: Nicole Burnett (nburnett@padillabay.gov) and Jude Apple (Padilla Bay NERR); www.padillabay.gov; cdmo.baruch.sc.edu

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 plankton tows (60-ft depth) were performed at least monthly at an open-water site (Figure 25) with a 153-µm mesh net and a 1-ft diameter opening. Multidimensional scaling (MDS) ordination shows that winter, spring, and fall zooplankton communities were similar to previous years, but that there was a substantial shift in composition of the zooplankton community in summer of 2016 (Figure 32A). A similar shift was also observed in summer 2015 and is likely due to the warm waters off the coast of Washington and within Puget Sound. Indeed, water temperatures in shallow nearshore areas like Padilla Bay also reached their highest seasonal averages in 2015 and 2016. Average spring temperatures in 2016 (10.67°C) were more than 2°C higher than the coolest spring temperatures recorded in 2011. A heat map (Figure 32B) shows the difference between monthly averages and the long-term monthly average, providing insight to the community shift observed in the MDS. For example, compared to long-term averages, annelids, barnacles, and larvaceans were more abundant during the summer and early fall of 2015 and 2016. However, hydrozoans and echinoderms were more abundant in the spring. Other zooplankton responded with lower than average abundances, including copepods in the spring and crab larvae in the summer and late fall. Some of the changes observed in 2016 are of meroplankton, and may be linked to natural cycles and/or known collapses of their respective adult populations. Additionally, rising water temperature affects many biological processes of zooplankton (e.g., phenology, feeding, and fecundity), providing a mechanism by which temperature is a likely contributor to observed changes of community composition.

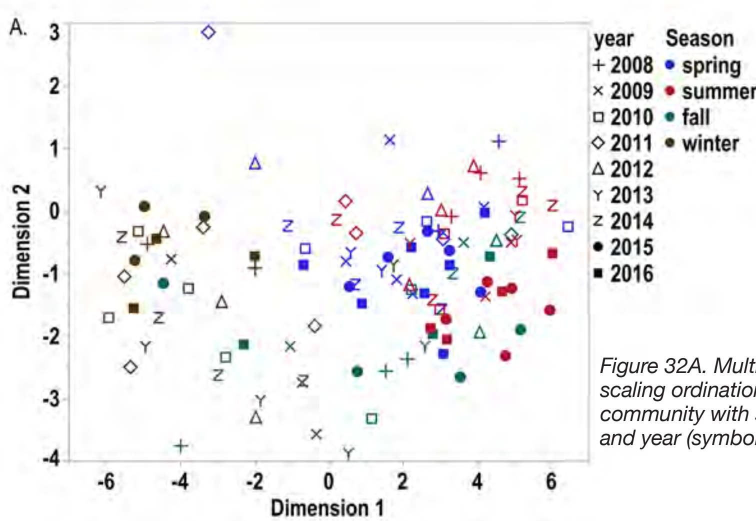


Figure 32A. Multidimensional scaling ordination of zooplankton community with season (colors) and year (symbols).

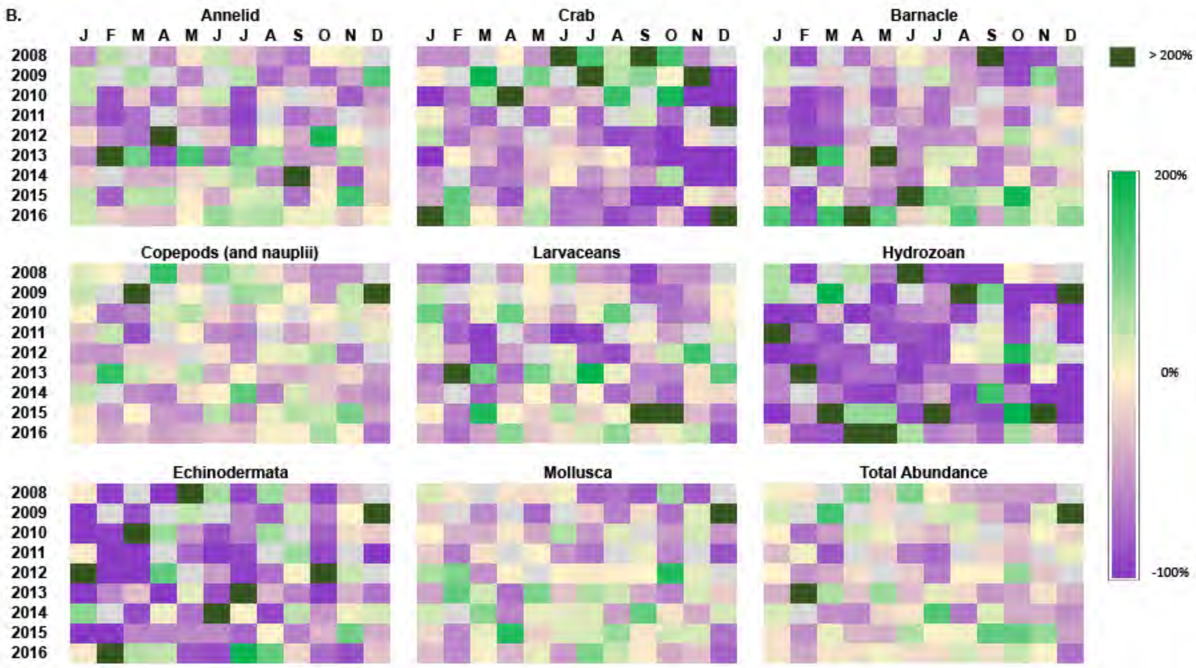


Figure 32B. Heat map of the relative change of zooplankton abundance between a given year's monthly average and the monthly long-term average (2008–16).

iii. Skagit Bay:

Source: Correigh Greene, NOAA/NWFSC (correigh.greene@noaa.gov)

Around the world, scientists have observed increases in the abundance of gelatinous zooplankton or "jellies" over the last 50 years, and these patterns have been associated with eutrophication, intensive fishing, and changing climate. Positive trends have been observed in some basins of Puget Sound (Greene et al. 2015), although the data were inconsistently collected. The Northwest Fisheries Science Center has been surface trawling in Skagit Bay since 2001, providing data on species in pelagic surface waters. The primary focus of this effort has been on juvenile pelagic fish (particularly Pacific salmon), but the Kodiak trawl effectively catches jellies as well. Two Puget Sound-wide efforts (in 2003 and 2011) revealed strong differences in the abundance of jellies among Puget Sound's basins (Rice et al. 2012), and total wet weight of jellies (phyla Cnidaria and Ctenophora) in each tow is now routinely measured.

Figure 33 summarizes the only time series of jellies in Puget Sound. Skagit Bay is an area dominated by the freshwater input of the Skagit River, yet jellies were commonly caught each year. Clear seasonal patterns have emerged, with high catch per tow peaking in late spring or summer months (Figure 33). In 2016, sampling started relatively late in the season, but nevertheless surpassed the previous peak observed in the very warm year of 2015. Peak abundances have been trending upward since 2010. Species-specific biomass data collected since 2007 reveal that fried egg jellyfish (*Phacellophora camtschatica*) have also been trending upward, and they were highly abundant in 2016.

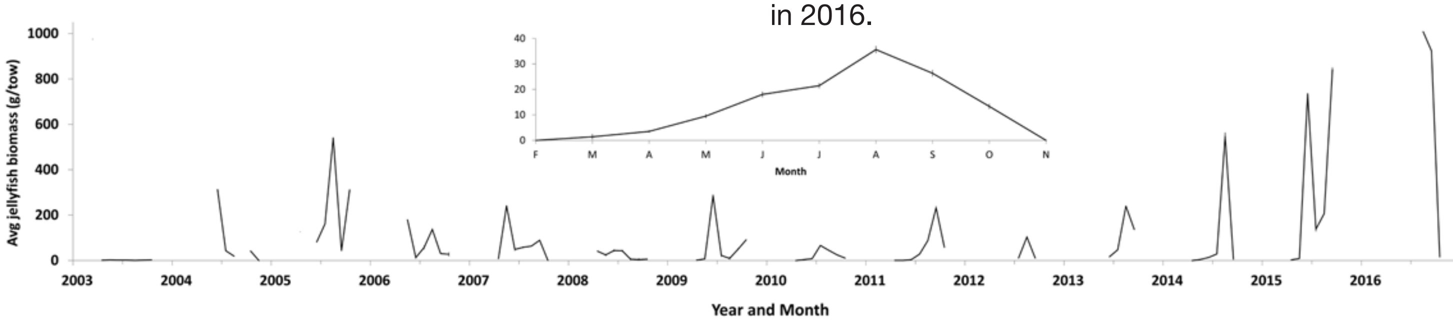


Figure 33. Trends in the geometric mean of wet biomass per tow (± standard error) of gelatinous zooplankton captured in Kodiak surface trawls in Skagit Bay. Time is graphed by year and month of sampling (alternate tick marks between years separate data from June and July sampling events). Kodiak trawls sweep surface waters, with a cross section of 18.9 m^2 and a linear distance of approximately 0.5 km through the water. However, both amount of water sampled and net spread can vary due to various causes (e.g., currents, shoreline complexity, and local boating activity). The inset graph shows monthly geometric means averaged across years to illustrate the strong seasonal pattern of abundance.

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

C. Harmful algae:

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. There were no marine biotoxin-caused illnesses reported in 2016 in Washington.

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

In 2016, The Washington State Public Health Laboratory analyzed 3,123 shellfish samples for PSP toxin. PSP toxin events were concentrated in the Strait of Juan de Fuca, Kilisut Harbor, and Mystery Bay in Jefferson County, East Sound in San Juan County, Quartermaster Harbor in King County, and Whatcom and Kitsap Counties. The highest PSP toxin level measured was 2,535 µg/100 g in blue mussels from Quartermaster Harbor on 19 September. The FDA standard for PSP toxin is 80 µg/100 g of shellfish tissue. In 2016, unsafe levels of PSP toxins caused 16 commercial (9 geoduck clam tract, 3 pink scallop, and 4 general growing area) and 22 recreational harvest area closures.

A total of 2,298 shellfish samples were analyzed for ASP toxin in 2016. The highest level of ASP toxin measured was 53 ppm in razor clams from Twin Harbors on 26 January. The FDA standard for ASP toxin is 20 ppm. ASP caused no commercial closures and three recreational closures on coastal beaches in 2016.

In 2016, 2,553 shellfish samples were analyzed for DSP toxins. DSP was detected at high levels throughout Puget Sound: Bellingham Bay in Whatcom County, Sequim Bay in Clallam County, Discovery Bay in Jefferson County, Liberty Bay in Kitsap County, Quartermaster Harbor in King County, and Budd Inlet in Thurston County. The highest DSP toxin level measured was 250 µg/100 g in blue mussels from Budd Inlet. This level of DSP toxin is a new high record for DSP measured in shellfish in Washington. The FDA standard for DSP toxin is 16 µg/100 g of shellfish tissue. DSP toxins caused 2 commercial (1 geoduck, 1 Pacific oyster) and 13 recreational harvest area closures.

WDOH collaborates with the phytoplankton monitoring groups SoundToxins and ORHAB to detect potential marine biotoxin-producing algae in Washington. This early-warning system helps WDOH identify and prioritize areas for additional biotoxin testing.

Aerial view of bloom patterns via Eyes over Puget Sound. Photo: Christopher Krembs

ii. SoundToxins:

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

The SoundToxins program inspects phytoplankton at key sampling stations throughout Puget Sound, providing an early-warning system for HABs. This information allows WDOH to prioritize shellfish toxin analyses, and alerts shellfish and finfish producers as well as researchers of potential blooms. Stations are monitored weekly from March through October, and biweekly from November through February. HAB species monitored include *Alexandrium, Dinophysis, Pseudo-nitzschia,* and *Heterosigma.* Cell concentrations of these four harmful species are reported through an online database. Monitoring was conducted at 25 stations in 2016. Figure 34 shows the dominant HAB species reported at each location by month for 2016.

Alexandrium were reported in low levels at 6 sampling stations throughout 2016. A bloom was observed in Quartermaster Harbor during August and September. During other years, *Alexandrium* can be seen as early as January (East Sound) and persist through November, depending on location. *Dinophysis* were present throughout the entire year at some stations. The highest reported cell concentrations occurred in August, with levels reaching 2,229 cells per liter at Sequim Bay. Reports of *Heterosigma* were extremely sparse, although it was found from January through September at various locations. *Pseudo-nitzschia* were present throughout most sampling areas in 2016, with both large and small cell types observed in January and persisting at various stations through December. Large blooms occurred between the months of May through September, with the majority occurring in May and June.

Chain of Alexandrium catenella *cells from a sample obtained September 2016 in Quartermaster Harbor. Photo: Karlista Rickerson*

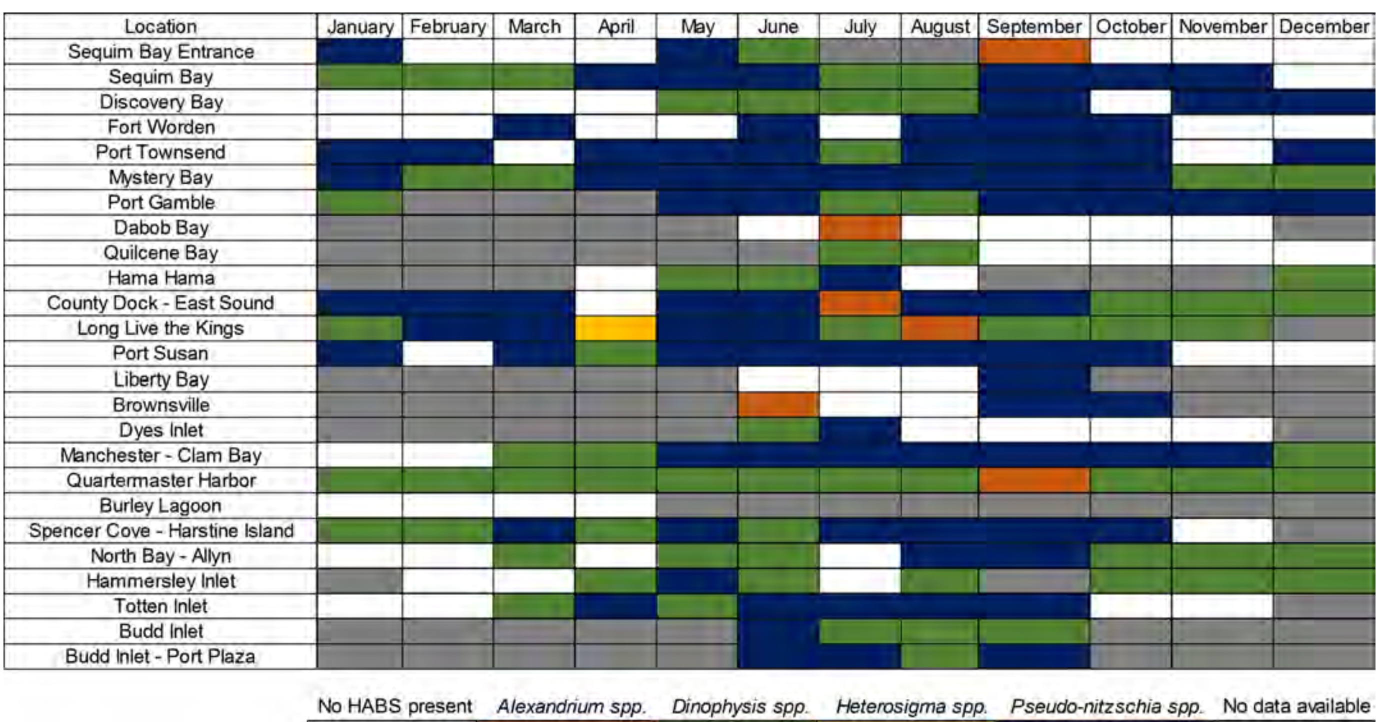
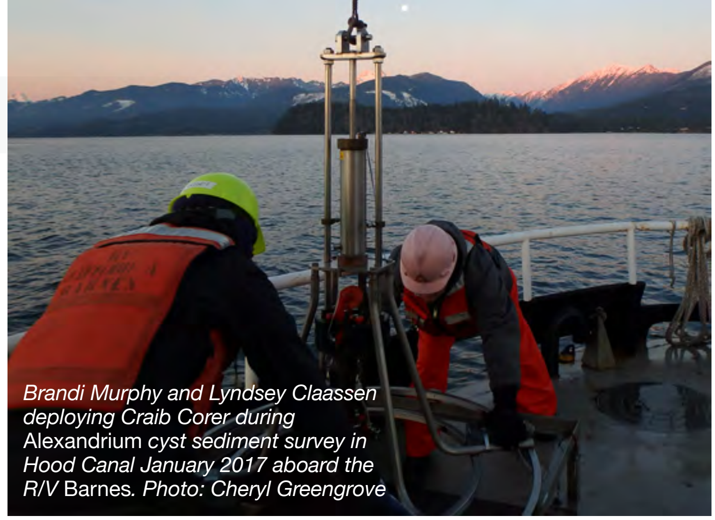


Figure 34. Site-specific dominance map of Puget Sound harmful algal bloom species reported during 2016. White = no HABs present, orange = Alexandrium, *green =* Dinophysis, *yellow =* Heterosigma akashiwo, *blue =* Pseudo-nitzschia, *and gray = no data.*



Brandi Murphy and Lyndsey Claassen deploying Craib Corer during Alexandrium *cyst sediment survey in Hood Canal January 2017 aboard the* R/V Barnes. *Photo: Cheryl Greengrove*

iii. *Alexandrium* species cyst mapping:

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

Source: Cheryl Greengrove (cgreen@uw.edu), Julie Masura (UWT), and Stephanie Moore (NOAA, NWFSC; UCAR); www.tiny.cc/psahab

An *Alexandrium* cyst mapping survey of Hood Canal was conducted 13–16 January 2017 as a follow-up to the emergency response cyst mapping done in January 2015 and 2016. In 2015, high concentrations of cysts were found in the surface sediments of Quilcene and Dabob Bays following an unprecedented 2014 fall bloom in this area. In April 2015, *Alexandrium* was detected in the water column, initially in Quilcene and Dabob Bays, and then, for the first time, southward throughout Hood Canal. This resulted in shellfish bed closures for the first time in this area. In 2016, cysts were again detected in Quilcene and Dabob Bays, but their abundance had decreased by 86% compared to 2015, and cysts were found in the surface sediments of southern Hood Canal for the first time. Compared to the prior two years, 2017 had substantially lower concentrations of cysts in the surface sediments of Quilcene and Dabob Bays, and no cysts were detected throughout the rest of Hood Canal. A few cysts were found in the surface sediments north in Port Gamble. Cyst abundances in the 1–3 cm sediment layer had slightly higher concentrations than the upper layer in Quilcene and Dabob Bays, and a few subsurface cysts were found in northern Hood Canal, Port Gamble, and Oak Harbor. There were no PSP-related shellfish bed closures in Hood Canal in 2016. The only nearby shellfish bed closures due to high PSP toxin levels were north in Port Ludlow and Kilisut Harbor. Maximum PSP toxin levels occurred in late July 2016 within days of a large, unusual coccolithophore bloom in Hood Canal.

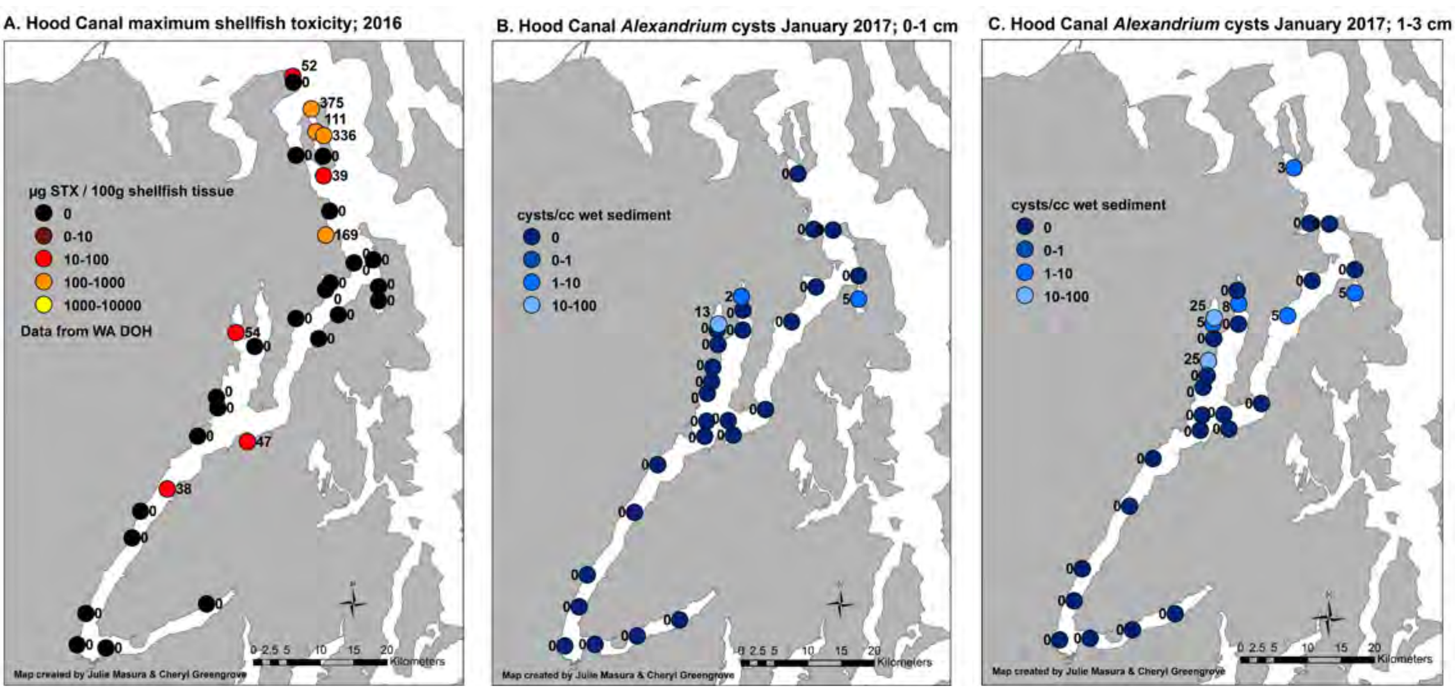


Figure 35. (A) Maximum shellfish toxicity (µg STX/100 g shellfish tissue) in Hood Canal for 2016 (WDOH); regulatory limit is 80 µg STX/100 g shellfish tissue, (B) Alexandrium *cysts/cc wet surface sediment (0–1 cm) in Hood Canal from January 2017, and (C)* Alexandrium *cysts/cc wet sediment (1–3 cm) in Hood Canal from January 2017.*

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 by 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.*

i. Puget Sound recreational beaches:

Source: Julianne Ruffner (julianne.ruffner@ecy.wa.gov) and Laura Hermanson (Ecology; WDOH); www.ecy.wa.gov/programs/eap/beach

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

BEACH coordinates weekly or biweekly monitoring from Memorial Day (May) to Labor Day (September) with local and county agencies, tribal nations, and volunteers. In 2016, 61 Puget Sound beaches were sampled, including 48 "core" beaches (beaches that are consistently sampled from year to year). There was a 16% increase in beaches passing the swimming standard from 2015 to 2016 (Figure 36). The Puget Sound Partnership uses BEACH data for their Vital Sign Indicators and has set a target that all monitored beaches meet human health standards by 2020. Details on 2016 beach sampling results can be found at *www.ecy.wa.gov/programs/eap/beach/AnnualReport.html.*

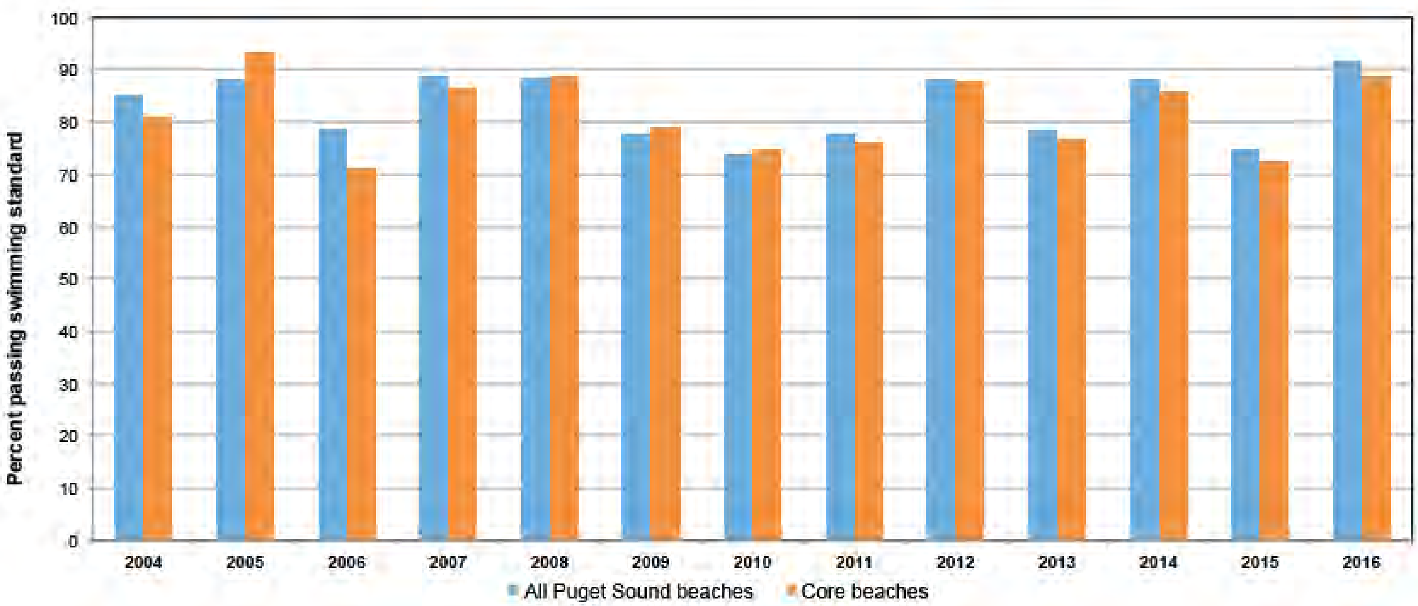


Figure 36. Percent of all monitored Puget Sound beaches and all core beaches (consistently sampled) that had less than two swimming closures or advisories during the 2004–16 beach seasons.

ii. Central Basin stations:
Source: Wendy Eash-Loucks, KCDNRP (wendy.eash-loucks@kingcounty.gov); green2.kingcounty.gov/marine

King County conducts water-quality monitoring at 14 offshore locations in the Central Puget Sound Basin. Samples were collected twice-monthly from February through November and monthly in January and December, from 1 m depth at six ambient and eight outfall stations. Ambient station locations were chosen to reflect ambient environmental conditions, while outfall stations are located near King County wastewater outfalls (both treatment plants and combined sewer overflows). Data were compared to Washington State marine water-quality standards. A geometric mean standard of 14 colony forming units (CFU) per 100 mL with no more than 10% of samples is used to calculate the geometric mean exceeding 43 CFU/100 mL (peak standard). Fecal coliform data collected in 2016 show that all 14 offshore stations passed both the geometric mean and peak standards for the year 2016, continuing a trend seen over many monitoring years.

King County also monitors fecal coliforms monthly at 20 beach stations along the western shoreline of the county and on Vashon and Maury Islands. In 2016, all of the beach monitoring stations met the geometric mean standard (Figure 37A). In addition, 17 of these stations met the peak standard, a much higher proportion than typical. Mean concentrations of fecal coliforms by month were lower than in previous years despite higher than normal total rainfall (Figure 37B). Fecal coliform concentrations are typically positively correlated with rainfall due to increased runoff and point-source discharges, but that pattern was not observed in 2016. It is possible that the increased rainfall caused higher than usual flushing and dilution before sampling occurred, leading to lower bacteria concentrations in samples.

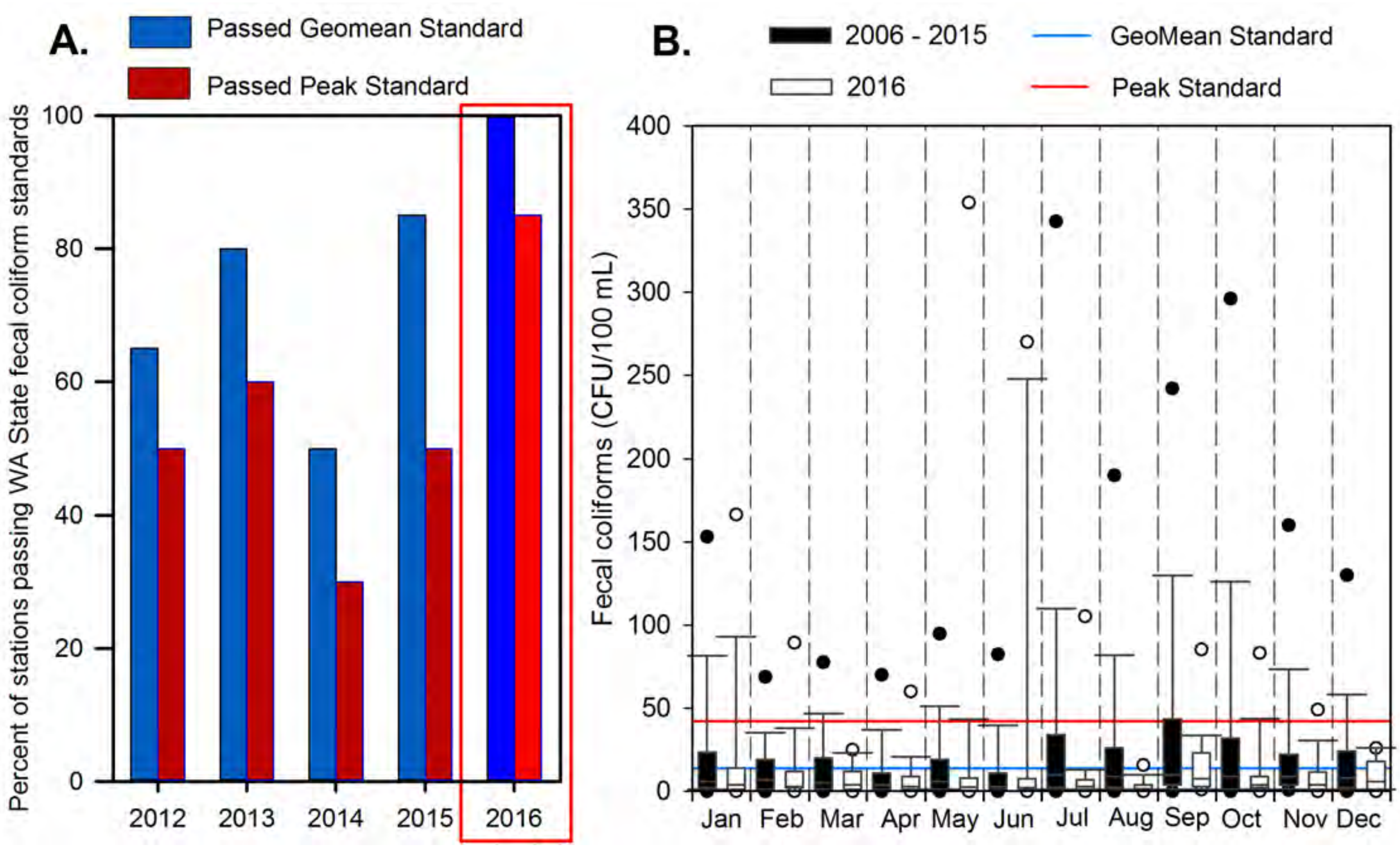


Figure 37. King County marine beach fecal coliform data: (A) Percent of beach stations passing fecal coliform standards annually, 2012–16; (B) Monthly fecal coliform concentrations at all beach stations in 2016 compared to the previous 10 years.

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 uncooked seafood, such as oysters, in the United States. A large outbreak of* Vp*-related illnesses occurred in 2006, and in spite of the implementation of stringent post-harvest controls, the number of confirmed cases remain elevated but significantly reduced after a 2015 revision to the regulations requiring proactive harvest and temperature controls. Genetic markers for virulent strains of* Vp *work well in other areas of the U.S., but are not effective in Puget Sound, significantly challenging health authorities.*

Source: Clara Hard, WDOH (clara.hard@doh.wa.gov); www.doh.wa.gov/CommunityandEnvironment/Shellfish

Vibrio parahaemolyticus (*Vp*) is a naturally occurring marine bacterium found in oysters that can cause gastrointestinal illness in humans when shellfish are eaten raw or undercooked. *Vp* populations grow faster at higher air and water temperatures and can cause illnesses, especially in the summer months. The Washington State Department of Health employs four strategies to control *Vp*-related illnesses: it 1) monitors *Vp* levels in oysters, 2) requires the commercial industry to cool oysters to 50°F after harvest, 3) sets temperature thresholds to limit harvests on the hottest days, and 4) closes growing areas to oyster harvest when high *Vp* levels or illnesses occur.

From June to September 2016, the Department collected 248 samples from 19 sites and analyzed them for the presence of *Vp* (total and potentially pathogenic). While collecting oyster samples for *Vp* testing, samplers also record current weather conditions, air, water and tissue temperatures, and salinity.

A site in Hood Canal had the highest *Vp* level in 2016, with >110,000 MPN/g tissue detected in June. Five shellfish-growing areas in Puget Sound were closed during 2016 due to high *Vp* levels in the environment. In 2016, there were 46 laboratory-confirmed and epidemiologically linked illnesses from consumption of oysters contaminated with *Vp* (Figure 38). Most confirmed cases came from commercially harvested oysters. There were two confirmed illnesses from recreationally harvested oysters. The majority of illnesses occurred among individuals who consumed raw oysters in August, which is consistent with historic illness occurrences. One growing area in Puget Sound (Totten Inlet) was closed due to *Vp* illnesses in August 2016.

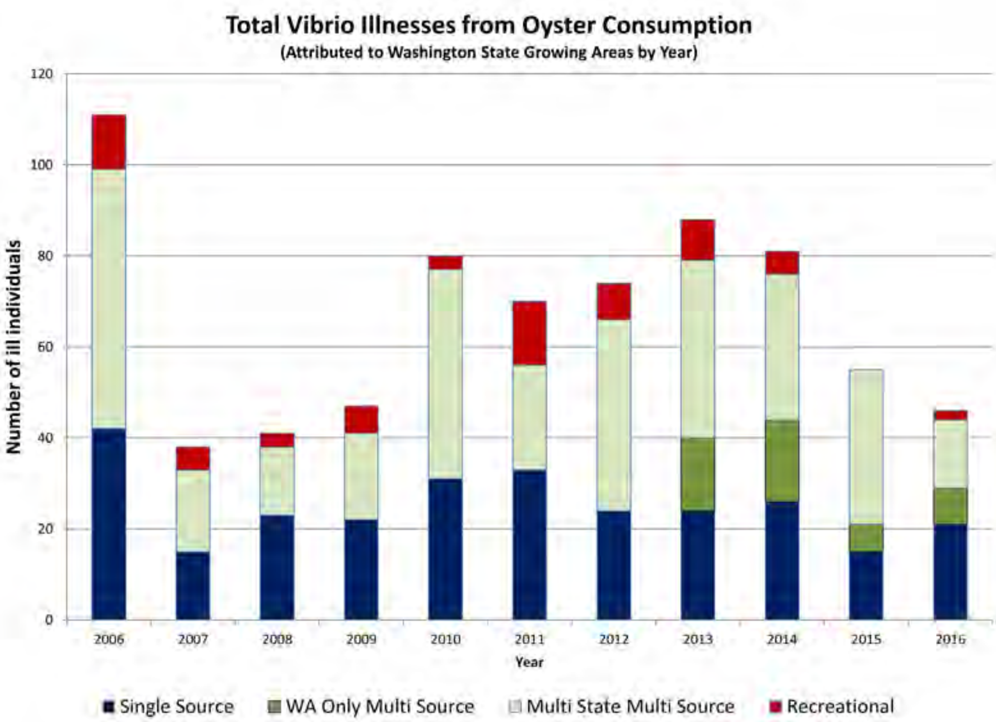


Figure 38. Vp*-related illnesses for both commercially and recreationally harvested oysters.*

CALL-OUT BOX: Intertidal and subtidal seagrass wasting disease in the San Juan Islands

Eelgrass (*Zostera marina L.*) structurally transforms coastal waters into safe feeding, spawning, and rearing grounds for economically valuable fish and invertebrates. Widely considered an indicator of ecosystem health, eelgrass is one of the Puget Sound Partnerships' Vital Sign Indicators, and its conservation is a top priority for local and federal agencies. Seagrass wasting disease (SWD) severely compromises eelgrass ecosystem services and can cause mass eelgrass mortality. Caused by the marine protist *Labyrinthula zosterae,* SWD threatens the health of eelgrass beds and the organisms that rely on them. In the San Juan Islands, long-term field surveys indicate variable levels of SWD throughout the archipelago (Groner et al. 2014, Groner et al. 2016, Eisenlord unpublished data).

A pilot study was conducted in July 2016 to determine if the prevalence and severity of SWD varies with tidal regime (i.e., intertidal versus subtidal). Eelgrass blades (n = 540) collected from two intertidal and four subtidal eelgrass beds were identified, and necrotic lesions were identified and measured to calculate disease prevalence (% blades infected) and severity (% blade area affected).

Longer, older blades had higher disease prevalence than shorter, younger blades, as seen by Groner et al. (2016). Tidal regime had little effect on the prevalence of the disease, but had a significant effect on disease severity, which was higher in intertidal eelgrass (Figure 39). This pattern was clearly seen in Kanaka Bay. Intertidal eelgrass beds are exposed at low tide, causing heat stress and desiccation. Eelgrass blades in the intertidal may therefore be physiologically more stressed, compromised, and susceptible to infection, potentially leading to higher levels of disease than in subtidal eelgrass. However, in Indian Cove, subtidal eelgrass were more likely to be affected by disease than intertidal eelgrass. This reversal could be due to the minimal tidal flushing at Indian Cove compared to other surveyed sites, which creates warmer water temperatures that would stress subtidal eelgrass and increase its susceptibility to infection. Preliminary data from controlled laboratory experiments show that *Labyrinthula zosterae* grows faster in warmer conditions (Dawkins et al. in preparation), suggesting temperature may be an important driver of SWD.

It is important to understand the dynamics and environmental drivers of SWD as it has important implications for the conservation and management of eelgrass beds, both within and beyond the San Juan Islands.

Author: Olivia Graham (ojg5@cornell.edu), Morgan Eisenlord, and Drew Harvell (Cornell University; UW, FHL)

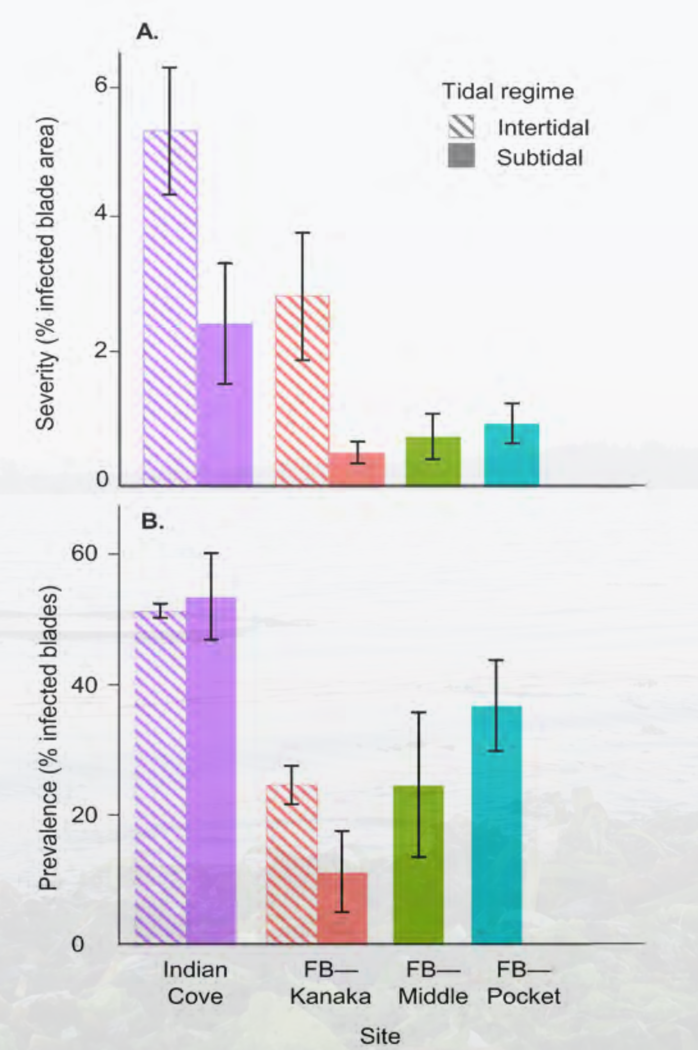


Figure 39. The (A) severity and (B) prevalence of seagrass wasting disease in four subtidal and two intertidal eelgrass (Zostera marina) beds, San Juan Islands; bars represent ±SE. Eelgrass blades from the following sites were collected and analyzed for lesions in July 2016: Indian Cove, False Bay (FB)—Kanaka, FB—Middle, FB—Pocket.

Eelgrass (Zostera marina) amidst beach wrack. Photo: Olivia Graham

Marine birds and mammals

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

A. Rhinoceros auklet:

Source: Peter Hodum (peter@oikonos.org) (University of Puget Sound), Scott Pearson (WDFW), and Thomas Good (NOAA, NWFSC)

Rhinoceros auklets (*Cerorhinca monocerata*) are one of the marine bird indicators for the Puget Sound Vital Signs. They are forage-fish eaters and, as a higher trophic-level species breeding in Puget Sound, are good indicators of marine trophic dynamics. Population trends, reproductive success, and diet at two colonies, Protection Island in the Salish Sea and Destruction Island on the Outer Coast of Washington, have been monitored since 2006 and 2008, respectively.

Of the reproductive success measures from Protection Island in 2016, burrow occupancy, or the percentage of burrows that are reproductively active, was higher (83%) than the mean occupancy in 2006–15 (71±5%). Hatching success was similar to the 2006–15 mean (82% versus 85±6%). Notably, fledging success (49%) was dramatically lower than the long-term average (81±5%) and was the lowest in 11 years of monitoring. In contrast, all three reproductive parameters on Destruction Island were comparable to long-term averages. In addition to the extremely poor chick survival on Protection Island, chick growth rates were lower. Diet monitoring at Protection Island revealed that the mass and caloric values of bill loads brought to chicks in 2016 were low, and that one of the principal prey species, Pacific herring, had shorter than average body lengths relative to previous years.

Dead adult rhinoceros auklet on Protection Island during the 2016 adult mass mortality event. Photo: Peter Hodum

These results suggest that there was insufficient and relatively low-quality food available to rhinoceros auklets during the 2016 breeding season. The poor nestling survival and fledging success were concurrent with a unique species-specific adult mass mortality event attributed to a bacterial infection (see Call-out Box: Beached birds 2016). Both the poor chick survival and the adult mass mortality event were localized to the Salish Sea. The year 2016 was unusual for breeding rhinoceros auklets and, as indicators, suggests that conditions in the Salish Sea were anomalous.

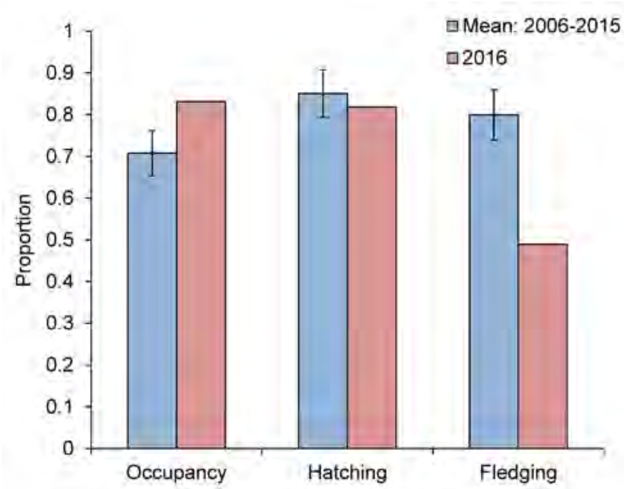


Figure 40. Comparison of burrow occupancy, hatching success, and fledging success of breeding rhinoceros auklets on Protection Island during the 2016 breeding season relative to long-term average values. Error bars represent standard deviation.

B. Wintering marine birds:

Source: Toby Ross (tobyr@seattleaudubon.org) (Seattle Audubon Society), Nathalie Hamel (Puget Sound Partnership), Peter Hodum (University of Puget Sound), and Kimberle Stark (Puget Sound Seabird Survey Volunteer); www.seabirdsurvey.org

Seattle Audubon's Puget Sound Seabird Survey (PSSS) is a citizen-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 overwintering populations, when abundance and diversity are highest in Puget Sound. The program, which began in 2007, has since expanded to include all Puget Sound basins except Hood Canal.

A total of 156 volunteers conducted 790 surveys at 120 survey sites during the 2015–16 season. A total of 57 confirmed species were detected in 2015–16, which is comparable to the 56 total species recorded during the 2014–15 season. Approximately 57,300 and 57,600 birds were recorded during 2014–15 and 2015–16, respectively, with similar levels of survey effort between years. The number of birds per survey ranged between 0 and 1,737 (median = 37 birds per survey during the 2015–16 season). Counts for a given month were generally comparable between the two seasons (Figure 41A).

Diving forage-fish specialists, including alcids and grebes, have been identified by Vilchis et al. (2014) as a foraging guild that is both vulnerable and declining in the Salish Sea. In both years, forage-fish specialist numbers increased in Puget Sound after the initial October surveys, indicating the arrival of migrants into the system. There was an apparent increase in the number of forage-fish specialists from 2014–15 to 2015–16 (Figure 41B). The driver of this increase is unknown, but may have been related to improved food availability in 2015–16.

Scoters (surf, white-winged, and black) are a Puget Sound Vital Sign Indicator. No clear patterns emerged in scoter numbers, but higher counts were recorded in four months of the 2014–15 season.

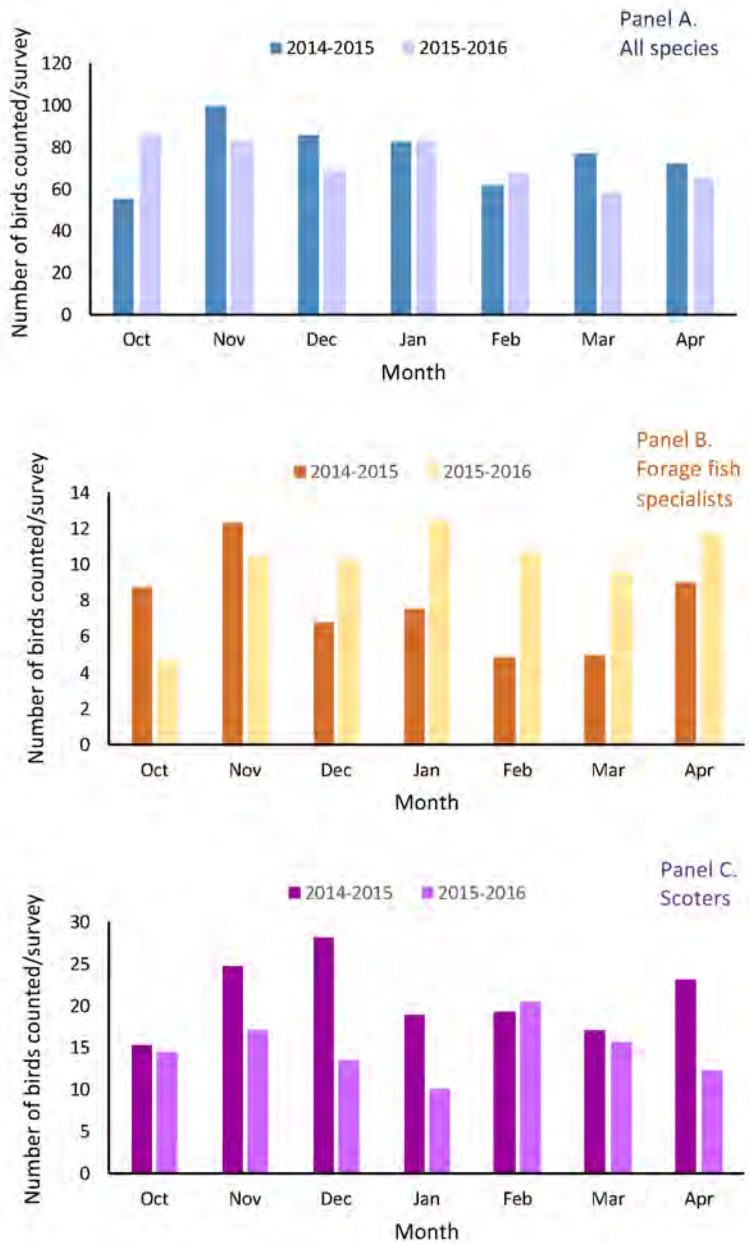


Figure 41. Numbers of birds counted per survey by month for (A) all species pooled, (B) diving forage-fish specialists (alcids and grebes), and (C) three scoter species.

CALL-OUT BOX: Beached birds 2016: An unusual mortality event of rhinoceros auklets in the Salish Sea

Five Rhinoceros Auklet carcasses found by COASST volunteers on Dungeness Spit in August 2016. Photo: Mary-Sue Brancato

The Coastal Observation and Seabird Survey Team (COASST) is a citizen-science program that collects information on the abundance and identity of beachcast seabirds from Northern California to Alaska, including the protected waters of Puget Sound. In May 2016, COASST received reports of an unusual number of rhinoceros auklet (*Cerorhinca monocerata*) carcasses on Dungeness Spit. Similar reports of rhinoceros auklet carcasses on beaches in the southeast corner of Vancouver Island were received by Bird Studies Canada (BSC) and the British Columbia Interagency Wildbird Mortality Hotline.

Rhinoceros auklets are a medium-sized seabird in the Alcidae family that feed by diving for forage fish. They breed on islands in British Columbia, Washington, and Alaska. Outside of the breeding season, they can be found throughout the temperate waters of the North Pacific, from California to southeast Alaska.

The 2016 Salish Sea die-off peaked in late July/early August at a rate 70 times higher than the long-term baseline (based on COASST data from 2001–15) and continued through September. The majority of carcasses found within the Salish Sea were within 50 km of Protection Island, the largest rhinoceros auklet colony in the Salish Sea that supports ~72,000 breeding birds, potentially indicating a colony-specific die-off.

There were also anomalously high carcass encounter rates (peaking at 20 times higher than baseline) around Grays Harbor on the outer Washington coast. This outer coast signal occurred later than the Salish Sea event, and may be indicative of birds migrating from Protection Island to the outer coast following the end of the breeding season. From May through October, over 540 carcasses were found during COASST and BSC beach surveys. Additional reports from members of the public increased the recorded death toll to over 1,000; however, the actual death toll is likely much higher.

Necropsy analysis performed by U.S. and Canadian agencies on collected carcasses revealed that mortality in the majority of cases was due to bacterial septicemia. Reports from members of the public described beachcast moribund birds as very weak and unable to support themselves, with several birds observed vomiting brown/yellow fluid prior to death. The specific bacteria responsible belongs within the Pasteurellaceae family, which also contains the causative agent of avian cholera. Little else is known about its usual prevalence in rhinoceros auklet, or other seabird, breeding populations.

During 2016, seabird biologists on Protection Island observed a normal start to the breeding season, with average burrow occupancy and hatching success rates. However, fledging success later in the season was exceptionally low (49% compared to 71% in 2015), and adults were observed returning to feed chicks with fewer and smaller fish than usual. This may be indicative of an additional shortage of forage fish within the Salish Sea at this time, which may have exacerbated the die-off. This die-off, affecting a minimum of 1% of the Salish Sea's breeding population of rhinoceros auklets (~75,000 breeding birds), is alarming due to both the unprecedented death toll and the previously undocumented causal agent.

Author: Timothy Jones (timothy.t.jones@gmail.com), Hillary Burgess, Julia Parish (UW), Scott Pearson (WDFW), Barbara Bodenstein (USGS – National Wildlife Health Center), Victoria Bowes (British Columbia Ministry of Agriculture), and Karen Devitt (Bird Studies Canada); depts.washington.edu/coasst

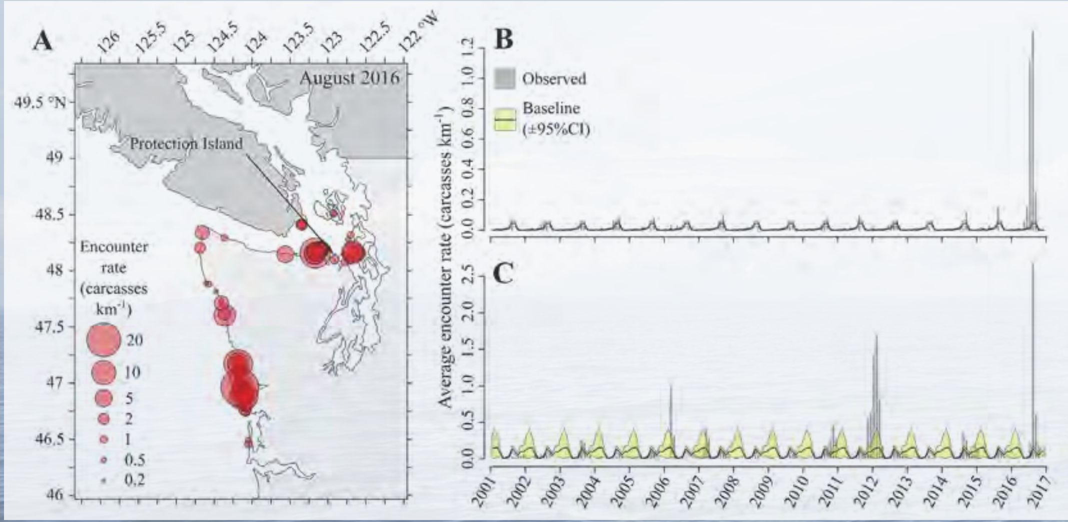


Figure 42. (A) Survey locations where rhinoceros auklet carcasses were found in August 2016 at the peak of the die-off, with bubble size scaled according to encounter rate (ER; the number of carcasses per km of beach surveyed). (B) Time series of month-averaged rhinoceros auklet ER from 2001–16 for the Salish Sea within 50 km of Protection Island. (C) Same as (B) but for the outer coast of Washington state from Neah Bay to the Columbia River mouth. The long-term mean seasonal signal (monthly ER averaged across 2001–16) for these regions is overlaid as a measure of baseline carcass deposition.

Forage fish

A. Pacific herring:

Source: Todd Sandell (todd.sandell@dfw.wa.gov), Dayv Lowry, Adam Lindquist, and Patrick Biondo (WDFW); wdfw.wa.gov/conservation/research/projects/marine_fish_monitoring/herring_population_assessment

Pacific herring (*Clupea pallasii*) are a vital component of the marine food web and an indicator species of overall Puget Sound health. These small forage fish are prey for most of the upper trophic levels throughout their life cycle. Herring stocks are defined by spatiotemporal isolation of spawning activity; 21 stocks typically spawn annually. Stock assessment is based on annual estimates of tonnage of spawning adults. Genetic studies have concluded that the Cherry Point and Squaxin Pass herring stocks are demographically distinct, but that all other stocks in Puget Sound are genetically homogenous (Beacham et al. 2001, Small et al. 2005, Mitchell 2006).

Despite significant interannual variation (common among forage fish), the abundance of herring in Puget Sound overall has not changed markedly since the 1980s, although the dramatic decline in the Cherry Point stock had already occurred by that time. In 2016, the spawning biomass was 13% above the 10-year average with all stocks combined (Figure 43). This relative stability was driven mainly by increases in the Quilcene Bay stock (Hood Canal), estimated at 7,409 tons in 2016, the highest spawning biomass on record (a 59% increase from 2015) and now accounting for half of all spawn in Puget Sound.

Stocks in the South and Central Sound have been in decline in recent years, and five stocks had no spawn recorded in 2016. Two of these stocks, Purdy and Wollochet Bay, have now recorded zero spawn for two years in a row, and are being closely monitored in 2017.

Both the Cherry Point and Squaxin Pass stocks declined slightly from 2015, and Cherry Point was again at an all-time low (516 tons, a decline of over 95% since 1973). Concerns continue regarding declines in herring biomass on a Sound-wide basis and the resultant ecosystem-wide impacts of this reduction in prey abundance.

Pacific herring are critical to the Puget Sound ecosystem and both long-term and short-term declines in their abundance have been documented. 2016 was the worst year on record for the Cherry Point stock; stocks in South and Central Puget Sound have also been in decline in recent years and five stocks had no spawn recorded in 2016.

Young herring on the measuring board. Photo: Chris Fanshier, DFW

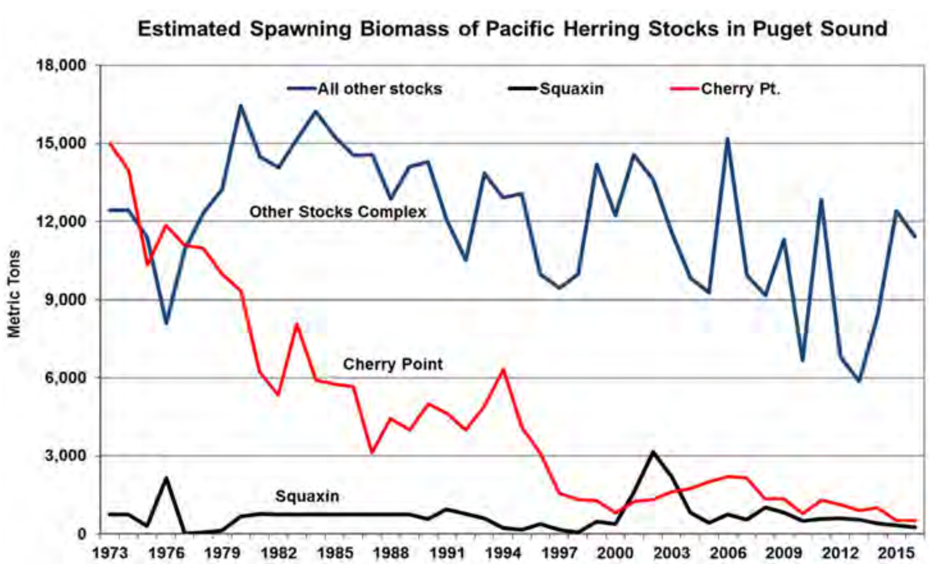


Figure 43. Annual estimated herring spawning biomass, in tons, by genetic lineage.

CALL-OUT BOX: Puget Sound pelagic fish monitoring mid-water trawl study

Splitting the catch aboard F/V Chasina. Photo: Chris Fanshier, DFW

Recognizing the vital role forage fish play in sustaining the Puget Sound food web, in 2015 the Washington state legislature funded a study of pelagic fish abundance and distribution using a mid-water trawl/hydroacoustic survey design. Sampling occurred every other month from February 2016 to February 2017 across 18 reaches from Olympia to the Canadian border. Hydroacoustic data were paired with 225 pelagic trawls, and 127 vertical plankton tows and 73 profiles of salinity and temperature were obtained.

Trawl catch data demonstrated that Pacific herring, a common prey of salmon, groundfish, seabirds, and marine mammals, was the most abundant forage fish in the surveyed area, making up 61% of the total catch. In Hood Canal (Quilcene Bay), where herring abundance has increased markedly over the last few years, herring made up 89% of the total catch. Herring were the most abundant catch in all four sub-basins (Figure 44A), although they exhibited large seasonal fluctuations and were a minor component of the catch in June, August, and December (Figure 44B). Low herring catches in December were likely the result of fish moving into pre-spawn holding areas near shore that were too shallow to trawl.

As expected, species abundance varied by both basin and season. For example, Pacific hake comprised 15% of the overall catch, but were the dominant species caught during several months in Saratoga Passage (Whidbey Basin). Northern anchovy were infrequently captured, but sometimes represented a large percentage of an individual trawl catch, particularly in the southern basin (Figure 44A) in the late summer and early fall (Figure 44B). Despite numerous reports of high anchovy abundance in the nearshore of Puget Sound, these fish made up only 11% of the total catch in South Sound, 3% in Central Sound, and ~1% in the North Basin and Hood Canal. It is likely the mid-water trawl missed many anchovy schools occurring in shallow waters.

During the summer (June–August), invertebrates accounted for ~60% of overall catch as fish numbers declined (Figure 44B), due in part to emigration of Pacific herring to the ocean. In the North and South basins, gelatinous zooplankton (jellies) made up 25% and 29%, respectively, of the total catch for the year. Overall, water jellies comprised 9% and cross jellies 4% of the catch.

Although 96 different species of fish and invertebrates were captured in the trawls, nine species made up 96% of the overall catch. Four species of salmon were collected, including 187 juvenile and subadult Chinook, 71 chum, 16 coho, and 51 pink salmon. Many of these salmon, and the zooplankton samples, were retained for collaborators at NWFSC and UW, and a variety of other samples were shared with collaborators at USGS, the Burke Museum, Portland State University, NOAA Fisheries, and others. Overall, the study captured a “snapshot” of the pelagic fish community in Puget Sound after an extended period of anomalously warm surface waters in the northeastern Pacific Ocean, and will serve as a reference point for future studies. Analyses of hydroacoustic data are ongoing.

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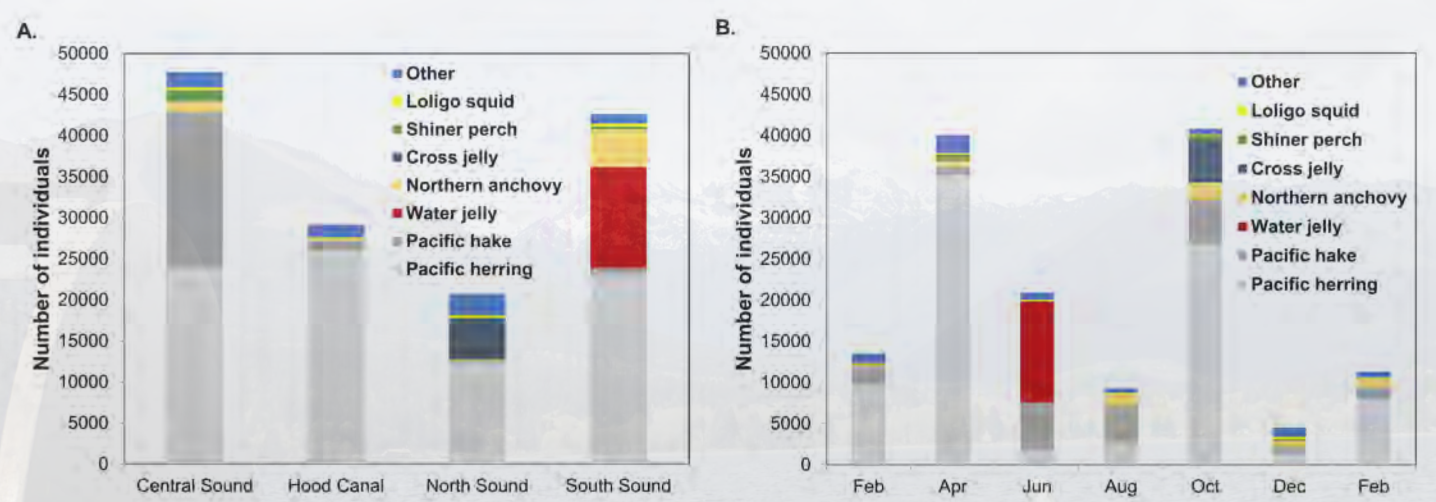
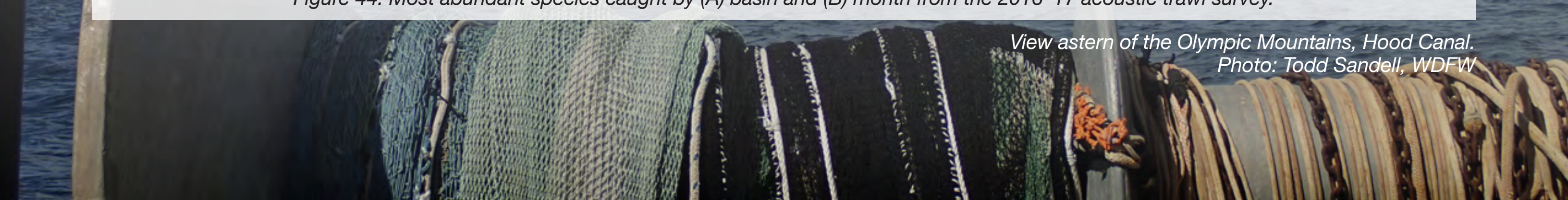


Figure 44. Most abundant species caught by (A) basin and (B) month from the 2016–17 acoustic trawl survey.



View astern of the Olympic Mountains, Hood Canal. Photo: Todd Sandell, WDFW

CALL-OUT BOX: Salish Sea Marine Survival Project

Salish Sea Chinook, coho, and steelhead salmon populations have experienced more pronounced declines since the 1980s and limited recovery compared to coastal populations. Studies suggest the juvenile stage within the Salish Sea is critical to overall survival. The Salish Sea Marine Survival Project (SSMSP) seeks to determine the most significant factors affecting juvenile Chinook, coho, and steelhead survival in Puget Sound and the Strait of Georgia. Now in its fourth year (2014–18), 32 Puget Sound and 43 Strait of Georgia studies are currently underway. The project is coordinated by Long Live the Kings and the Pacific Salmon Foundation of Canada, with over 60 federal, state, and local agencies, tribes, and First Nations, as well as academic, private, and nonprofit organizations, participating. It is critical to the recovery of salmon and Puget Sound that these efforts be sustained.

Jenny Gardner working in Dave Beauchamp's UW lab, processing a chinook salmon gut. Photo: LLTK

SSMSP researchers have developed novel approaches to improve research and management, such as microtrolling (a nonlethal, low-cost sampling technique to capture juvenile Chinook), molecular tests to identify broader suites of diseases in their early stages, and treatments developed to kill the parasite *Nanophyetus salmincola.* In addition, a Salish Sea-wide, collaborative zooplankton monitoring program was established in 2014 involving 13 entities in Puget Sound and citizen scientists in the Strait of Georgia (see Plankton section B.i; Puget Sound). End-to-end Salish Sea ecosystem models and suites of indicators are being developed to comprehensively assess the factors affecting marine survival and act as decision support tools for salmon and ecosystem recovery.

A few initial results show:

- Steelhead early marine mortality is driven more by processes in the lower river or marine waters than by intrinsic effects of population or freshwater rearing (Moore and Berejikian 2017).
- There are strong correlations between Puget Sound zooplankton community composition and coho and yearling Chinook marine survival (Keister et al. unpublished).
- Fish as prey provide a substantial growth advantage for juvenile Chinook in the San Juan Islands (Chamberlin et al. unpublished).
- Harmful algal blooms may impact salmon gill health and zooplankton availability (Esenkulova et al. 2017).
- *Nanophyetus salmincola* was highly prevalent in steelhead from central and southern Puget Sound watersheds. High parasite loads are associated with gill and heart lesions, and may cause reduced swimming speed, poor health, and mortality (Chen et al. in review).
- Harbor seal predation contributes to steelhead mortality within Puget Sound (Berejikian et al. 2016, Thomas and Jeffries unpublished). Other potential predators of steelhead include harbor porpoises and cormorants (Pearson et al. 2015). A recent study found a ninefold increase in Chinook consumption by Puget Sound harbor seals (Chasco et al. 2017).
- Contaminants in several urban river systems and throughout the Puget Sound marine environment exceed adverse-effects thresholds for juvenile Chinook and are also a concern for steelhead in some rivers (O'Neill et al. 2015 and unpublished).
- In 2016, steelhead early marine survival through Puget Sound was almost 40%; previous years' survival ranged from 10–20%. Coho also appeared to survive well within Puget Sound in 2016 (Moore et al. unpublished).

Crab zoea from a zooplankton sample. Photo: LLTK

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Beach seine on the Snohomish River. Photo: LLTK

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R/V Edna Brezeale *approaching the Bayview long-term monitoring station in Padilla Bay during a 24 hour study. Photo: Jude Apple*

APL	Applied Physics Laboratory
ASP	Amnesic Shellfish Poisoning
ATG	Atmospheric Sciences and Geophysics building
BCRFC	British Columbia River Forecast Center
BEACH	Beach Environmental Assessment, Communication, and Health
CFU	Colony Forming Unit
COASST	Coastal Observation and Seabird Survey Team
CSO	Combined Sewer Overflow
CTD	Conductivity Temperature Depth
DA	Domoic Acid
DO	Dissolved Oxygen
DSP	Diarrheic Shellfish Poisoning
Ecology	Washington State Department of Ecology
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
ESRL	NOAA Earth System Research Laboratory
FDA	US Food and Drug Administration
FHL	Friday Harbor Laboratories
HAB	Harmful Algal Bloom
Ind m^{-3}	Individuals per cubic meter
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
MDS	Multi-dimensional Scaling
MPN	Most Probable Number
m^3/s	Cubic Meters per Second
NANOOS	Northwest Association of Networked Ocean Observing System
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
ONI	Oceanic Nino Index
ORCA	Oceanic Remote Chemical Analyzer
ORHAB	Olympic Region Harmful Algal Blooms
OWSC	Office of the Washington State Climatologist
PAR	Photosynthetically Active Radiation
PCA	Principal Component Analysis
PDO	Pacific Decadal Oscillation
PGST	Port Gamble S'Klallam Tribe
PFEL	Pacific Fisheries Environmental Laboratory
PMEL	Pacific Marine Environmental Laboratory
PS Partnership	Puget Sound Partnership
PSEMP	Puget Sound Ecosystem Monitoring Program
PSP	Paralytic Shellfish Poisoning
PSSS	Puget Sound Seabird Survey
SJC	San Juan Channel

Acronyms (cont.)

SSMSP	Salish Sea Marine Survival Project
STX	saxitoxin
SWD	seagrass wasting disease
UCAR	University Corporation for Atmospheric Research
USGS	United States Geological Survey
UW	University of Washington
UWT	University of Washington-Tacoma
Vp	*Vibrio parahaemolyticus*
WDFW	Washington Department of Fish and Wildlife
WDOH	Washington State Department of Health
WSG	Washington Sea Grant
WWU	Western Washington University

Puget Sound Ecosystem Monitoring Program

NOAA FISHERIES