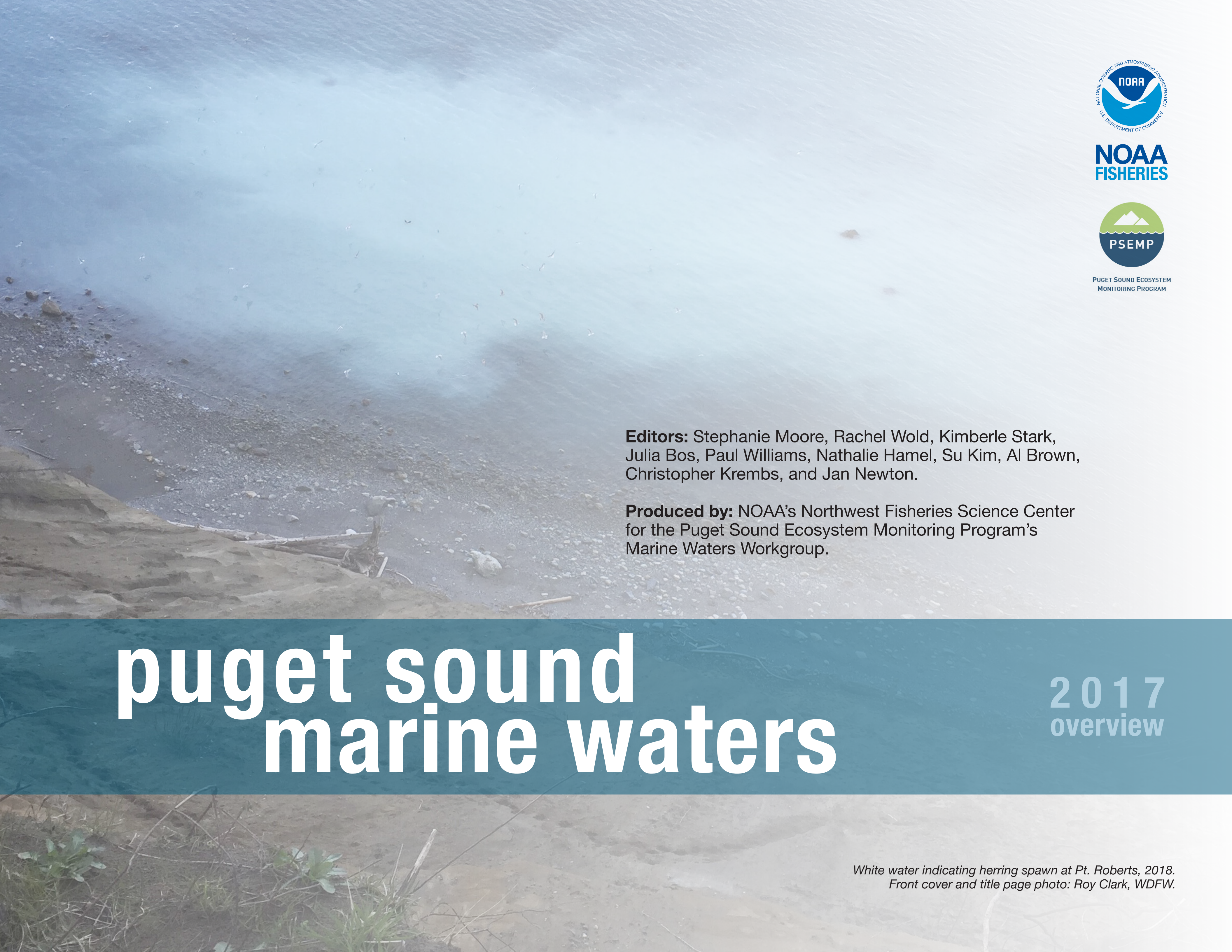
puget sound marine waters

2017 overview



Editors: Stephanie Moore, Rachel Wold, Kimberle Stark, Julia Bos, Paul Williams, Nathalie Hamel, Su Kim, Al Brown, Christopher Krembs, and Jan Newton.

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puget sound marine waters

2017 overview

White water indicating herring spawn at Pt. Roberts, 2018.
Front cover and title page photo: Roy Clark, WDFW.

Citation and contributors

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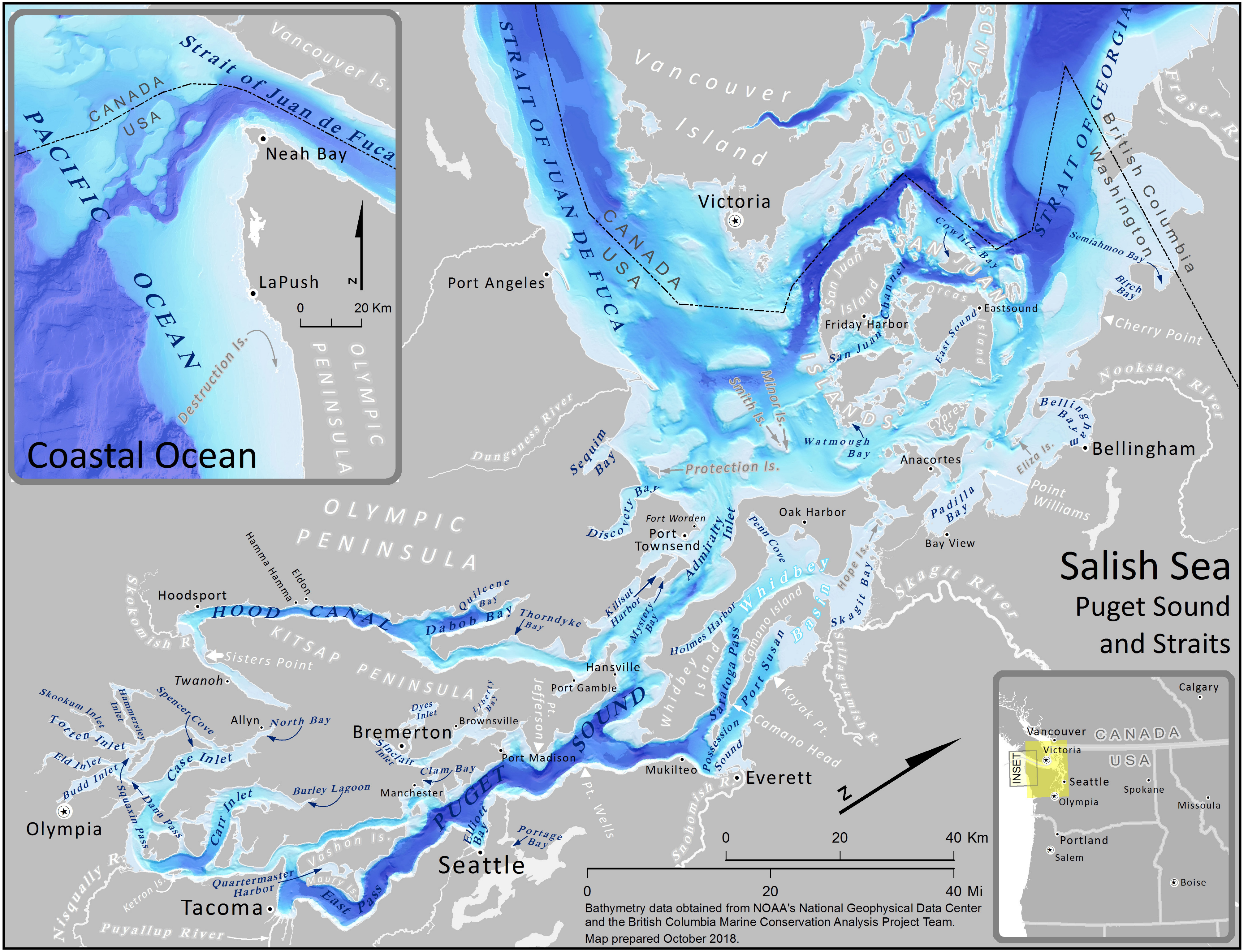
Contributors

Adam Lindquist
Adrienne Sutton
Al Devol
Allison Brownlee
Amanda Winans
Angela Eagleston
Audrey Coyne
Benjamin Larson
Beth Curry
BethElLee Herrmann
Breck Tyler
Carol Maloy
Cheryl Greengrove
Christopher Krembs
Christopher Sabine
Clara Hard
Correigh Greene
Dany Burgess
Erika McPhee-Shaw
Gabriela Hannach
Gary A. Winans
Heath Bohlmann
Helen Berry
Jacqueline Busby
Jan Newton
Jennifer Lang
Jerry Borchert
John Mickett
Jude Apple
Julia Bos
Julianne Ruffner
Julie Keister
Julie Masura
Karin Bumbaco
Kathy Welch
Kimberle Stark
Laura Hermanson
Lyndsey Claassen
Lyndsey Swanson
Maggie Dutch
Michelle McCartha
Misty Peacock
Mitch Schatz
Mya Keyzers
Nicole Burnett
Nicole Marks
Nick Bond
Patrick Biondo
Peter Hodum
Phillip Dionne
Rachel Wilborn
Rebecca Guenther
Richard Feely
Sandy Weakland
Scott Pearson
Shauna Bjornson
Simone Alin
Skip Albertson
Stephanie Moore
Stephanie Jaeger
Stuart Munsch
Suzanne Shull
Sylvia Musielewicz
Tara Wilson
Teri King
Thanh-Thuy Nguyen
Thomas Good
Toby Ross
Todd Sandell
Tyler Burks
Valerie Partridge
Vera Trainer
Wendi Ruef
Wendy Eash-Loucks



Map: Damon Holzer.

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About PSEMP

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

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

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

This report provides a collective view of 2017 Puget Sound marine water quality and conditions and associated biota from comprehensive monitoring and observing programs. While the report focuses on the marine waters of greater Puget Sound, additional selected conditions are also included due to their influence on Puget Sound waters. These include large-scale climate indices and conditions along the Washington coast. It is important to document and understand regional drivers of variability and patterns on various timescales so that water quality data may be interpreted with these variations in mind, to better attribute human effects versus natural variations and change. This is the seventh annual report produced for the PSEMP Marine Waters Workgroup. Our message to decision makers, policy makers, managers, scientists, and the public who are interested in the health of Puget Sound follows.

From the editors: Our objective is to collate and distribute the valuable physical, chemical, and biological information obtained from various marine monitoring and observing programs in Puget Sound. Based on mandate, need, opportunity, and expertise, these efforts employ different approaches and tools that cover various temporal and spatial scales. For example, surface surveys yield good horizontal spatial coverage, but lack depth information; regular station occupation over time identifies long-term trends, but can miss shorter-term variation associated with important environmental events; moorings with high temporal resolution describe shorter-term dynamics, but have limitations in their spatial coverage. However, collectively, the information representing various temporal and spatial scales can be used to connect the status, trends, and drivers of ecological variability in Puget Sound marine waters. By identifying and connecting trends, anomalies, and processes from each monitoring program, this report adds significant and timely value to the individual datasets and enhances our understanding of this complex ecosystem. We present here that collective view for the year 2017.

This report is the proceedings of an annual effort by the PSEMP Marine Waters Workgroup to compile and cross-check observations collected across the marine waters of greater Puget Sound during the previous year. Data quality assurance and documentation remains the primary responsibility of the individual contributors. All sections of this report were individually authored and contact names and information are provided. The editors managed the internal cross-review process and focused on organizational structure and overall clarity. This included crafting a synopsis in the “Summary of what happened” section that is based on all of the individual contributions and describes the overall trends and drivers of variability and change in Puget Sound’s marine waters during 2017.

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

The Canadian ecosystem report, *State of Physical, Biological, and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2017* (http://waves-vagues.dfo-mpo.gc.ca/Library/40717914.pdf), describes an area encompassing approximately 102,000 km² from the edge of the continental shelf east to the British Columbia mainland and includes large portions of the Salish Sea. The annual report provides information that is also relevant for Puget Sound and is a recommended source of complementary information to this report.

A summary of what happened in 2017

This brief synopsis describes patterns in water quality and conditions and associated biota observed during 2017 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.

Anacortes ferry terminal. Photo: Rachel Wold.

The year 2017 signaled an end to the widespread and persistent warm seawater temperature anomalies associated with the NE Pacific marine heatwave (a.k.a. “the Blob”) that were evident in Puget Sound since 2014. For the most part, seawater temperatures in Puget Sound returned to normal or cooler than normal conditions early in 2017 and then became warmer than normal again during the summer. Some differences in seawater temperature anomalies were observed between basins and over seasons, but none of the observed responses were as large as those documented during recent years. The region experienced both the wettest spring and the driest summer on record, strongly affecting freshwater inputs to Puget Sound and salinity patterns. In general, many biological observations within Puget Sound revealed lower than normal abundances, including chlorophyll, zooplankton, forage fish, seabirds, and marine mammals. How much of this observed biological pattern during 2017 was an aftermath of the warmer years versus a response to the immediate conditions should be further evaluated.

During 2017, the El Niño-Southern Oscillation shifted to a moderate La Niña and the Pacific Decadal Oscillation shifted to near-neutral by the end of the year. The cooler than normal air temperatures observed in the Puget Sound region towards the end of the year are consistent with this shift in these large-scale climate patterns. The North Pacific Gyre Oscillation became strongly negative over the course of the year, indicating less primary production in the California Current System.

Over the year, seasonal differences in marine water temperature and salinity anomalies were evident that were mirrored to a large extent by regional weather anomalies. Air temperatures in the Puget Sound region were cooler than normal in winter-spring, warmer than normal in summer, and cooler than normal in fall. In general, Puget Sound seawater temperatures returned to normal or cooler than normal in early 2017 and then became warmer than normal in summer through the end of the year – but not as warm as conditions documented during the marine heatwave. Some differences in seawater temperature anomalies were observed between basins and over seasons, such as in southern Hood Canal where waters at depth were warmer than normal at the start of the year. This different pattern may reflect its longer residence time. The regional precipitation pattern in 2017 had both the wettest spring on record and the driest summer on record. River flows were particularly high in spring, then well below normal through summer. At the start of 2017, salinities were saltier or close to normal, then became much fresher than normal by April commensurate with a very wet spring. Even though river flows were well below normal during the dry summer, salinities stayed fresher than normal through late summer, but became progressively saltier such that by late fall conditions were near normal or saltier than normal. A similarity to the unique salinity pattern (fresher, saltier, then fresher than normal again) observed in the previous two years is a strongly fresher than normal spring that transitioned to saltier than normal conditions by fall. A difference is that 2015 and 2016 began the year fresher than normal with conditions became saltier than normal more quickly, by mid-summer. The overall influence of the salinity pattern in 2017 is that the fresher than normal waters lasted for a longer part of the year, and thus density stratification was greater than normal for much of the year, essentially from spring to fall.

Chlorophyll concentrations, indicating phytoplankton biomass, were similar to those of recent years, though this varied across the region. Sunlight was less than normal (cloudier) through May, but then it was sunnier than normal for the rest of the year, which includes the phytoplankton growing season.

Concentrations of nitrate, an essential nutrient for phytoplankton growth, were largely similar to those observed during 2016, having decreased to levels that were typical of two decades ago. While both light and nutrients are required for phytoplankton to grow, other complex factors, such as water column stability and grazing pressure, also govern phytoplankton dynamics resulting in highly variable and site-specific blooms. In the mixed waters of the Central Basin, phytoplankton blooms were sustained from April through August, perhaps due to sufficient stratification (keeping cells from mixing downward out of the photic zone) and sunlight and an apparent lack of nutrient limitation. In the more persistently stratified Quartermaster Harbor, lower than normal chlorophyll levels may have indicated nutrient limitation there. Similarly, dissolved oxygen tended to be highly variable over time and space. Observations at the Washington coast off La Push and within Hood Canal revealed that atmospheric carbon dioxide continued its steady increase. Surface seawater carbon dioxide showed a stronger seasonal drawdown to lower values, indicative of photosynthetic uptake by phytoplankton, a pattern that was not as evident during the anomalously warm seawater years associated with the Blob.

Public health outcomes related to marine water conditions varied in 2017. While harmful algae and the toxins they produce were evident in Puget Sound waters and shellfish, causing closures in 37 commercial growing areas and 41 recreational harvest areas, none of the blooms were exceptional nor caused illnesses. However, there were 59 confirmed illnesses due to the consumption of oysters contaminated with *Vibrio* bacteria. This is higher than what was reported in 2015 and 2016, but still lower than the annual number of illnesses reported during the five years prior to the 2015 revision to regulations requiring proactive harvest and temperature controls. While over 90% of beaches had less than two closures or advisories during the swimming season, in King County, 11 of the 20 beach stations failed standards for fecal coliform, mostly linked with high runoff conditions.

In general, abundances of fish, seabirds and marine mammals were lower than normal in 2017. The relative annual zooplankton abundance since the Blob years has varied spatially; levels during 2017 either continued the lower abundances observed during 2014 or were higher. Most herring stocks also continued to decline, especially at Cherry Point. Several species of marine birds and mammals had abundances that were generally low, either comparable to or lower than that observed during the Blob years. There were some limited positive stories, such as the relatively large increase in the biomass of Hood Canal herring stocks and an increase over the last year to more normal levels of reproductive success for rhinoceros auklets, despite their low breeding effort.

In summary, the observations of 2017 mostly show a rebound of the physical and chemical marine water conditions that were typical prior to the anomalous Blob years that lingered from 2014-2016 in Puget Sound. However, the biological observations continued to show lower than normal abundances and did not reflect a similar rebound. This may be expected for some organisms with longer generation times, as lags in populations can occur, or it may signal a shift toward sustained lower abundances. This underscores the importance of continued monitoring and observation. The data compiled in these annual reports can help to document the status of and any changes to Puget Sound's marine waters.

Collecting a beach water sample from eastern Vashon Island. Photo: Stephanie Jaeger.

Highlights from 2017 monitoring

Large-scale climate variability and wind patterns

- El Niño–Southern Oscillation (ENSO)
  - » The ENSO index was positive during spring (warming in the tropical Pacific) and then negative (cooling) during the summer and fall of 2017, to the extent that a moderate La Niña formed by the end of the year.
- Pacific Decadal Oscillation (PDO)
  - » The PDO declined from moderately positive to near-neutral values over the course of 2017, marking the demise of the NE Pacific marine heat wave of 2014–16 (a.k.a. "the Blob").
- North Pacific Gyre Oscillation (NPGO)
  - » The NPGO was negative throughout 2017, becoming strongly negative in the summer.
- Upwelling index
  - » The upwelling index was mostly normal in 2017, except that the spring transition from downwelling to upwelling conditions began a little later than normal and winter downwelling was particularly strong in November.

Local climate and weather

- Puget Sound annual average air temperature was near normal, with above normal precipitation for 2017.
- On seasonal timescales, air temperature and precipitation were more variable. The start of 2017 was colder than normal, most of the summer was much warmer than normal, and several cold spells occurred in the fall with one in early November bringing snow to the Puget Sound lowlands. The 2017 spring (February–April) was the wettest on record, and the summer (July–September) was the driest summer on record for the Puget Sound region.
- Sunlight was lower than normal from February to May, and generally higher than normal from June through the end of 2017, with the exception of November.

Coastal ocean and Puget Sound boundary conditions

- Deep waters on the Washington shelf had substantially lower salinities, warmer temperatures, and higher dissolved oxygen (DO) concentrations in spring 2017 compared to previous years. Salinity increased and temperature and DO decreased throughout the upwelling favorable period. DO dropped rapidly upon the fall transition to southerly winds, likely a consequence of wind shifts bringing low DO water from the south to this location, as seen in 2016. The warmer-than-normal (by about 0.8°C) deep water could potentially be the delayed signal of the Blob waters mixing downward in the water column.
- Atmospheric xCO_2 (i.e., the mole fraction of carbon dioxide) values at the Chá Bă mooring off La Push and at Cape Elizabeth continued their year-to-year increase in 2017, despite observational gaps in winter. Surface seawater xCO_2 was lower in 2017 than in 2015–16, years when the Washington coast was strongly influenced by the Blob, and more similar to conditions observed during years prior to 2015.

River inputs

- Following a wet start to 2017 and an above normal snowpack, warmer than normal weather in May and June caused early, unusually high, prolonged river discharge to the Salish Sea. Summer flows dropped quickly to levels well below normal in most watersheds following persistent hot and dry conditions through mid-September. All rivers recovered dramatically in mid-October, when precipitation from a series of atmospheric river events brought flows back to historical medians.

Water quality

- Temperature
  - » Puget Sound water temperatures returned to normal or slightly cooler than normal conditions in early 2017, ending the period of warmer-than-normal conditions in 2015–16 associated with the Blob. Temperatures became warmer than normal from May to December, though not as warm as in 2015–16.
  - » At Carr Inlet in South Sound, variations in water temperature were similar to the Sound-wide pattern, with temperature anomalies at depth beginning 2017 cooler than normal and then shifting during summer to average for the remainder of the year. At Twanoh in Hood Canal, however, the temperature anomaly pattern was opposite; temperature anomalies at depth began the year warmer, then shifted to average during summer, then warmer again during fall.
  - » In the Central Basin, surface and bottom water temperature variations were also similar to the Sound-wide pattern, returning to normal during the first half of 2017 and then becoming warmer than normal for the second half of the year.
  - » In Padilla Bay, 2017 water temperatures returned to normal conditions and were almost 1°C cooler than those recorded in 2015–16.

- » In Bellingham Bay, water temperature and other water quality variables were characterized by high frequency variations except for brief (several days) “flat” periods in January and February that were associated with large drops in barometric pressure, likely stormy conditions that mixed the water properties.
  - » In the eastern Strait of Juan de Fuca, water temperatures during fall 2017 were near normal for the 14-year record, though relatively cooler at the surface.

- Salinity and density
  - » Overall, Puget Sound waters were fresher than normal for most of 2017, but especially in spring and early summer following a record wet spring and the melting of an above normal snowpack. Density stratification followed seasonal patterns in salinity, with Puget Sound waters exhibiting stronger than normal stratification during 2017.
  - » At Carr Inlet and Twanoh, salinity fluctuated in three distinct periods in 2017 that co-varied with rainfall and river flow, similar to the patterns observed during 2015–16. The record wet spring produced fresh anomalies, followed by summer drought where salinities progressed from fresher to saltier, and then an extremely wet fall that reduced salinities back to near the climatological average. The low salinity anomaly during spring at depth for both Twanoh and Carr Inlet was the most extreme on record. River flow from the Nisqually and Puyallup Rivers captured >90% of the variance of salinity changes at Carr Inlet in south Puget Sound.
  - » Central Basin waters followed the Sound-wide trend and were fresher than normal at all depths for most of 2017. The water column was stratified more frequently from March through August than observed in prior years.
  - » In Bellingham Bay, salinity frequently varied over a large range (0 to 30 PSU) in 2017 and appeared to be highly correlated with colored dissolved organic matter and turbidity, likely related to strong influence from the Nooksack River plume.
  - » In the eastern Strait of Juan de Fuca, the salinity range during fall was wider in 2017 compared to 2014–16 when the Blob occurred, with the first reappearance of salinity >32.5 PSU since 2013. These high salinity waters were warmer than five of the six years in which such waters have ever been observed.

- Nutrients and chlorophyll
  - » On average, nitrate in Puget Sound in 2017 returned to levels observed two decades ago; however, non-oceanic sources of nitrate (determined using salt as a conservative tracer) continue to hover above levels observed 10 years ago. Sound-wide anomalies of chlorophyll-*a* and silicate:nitrate levels have declined over the past two decades, but in recent years have remained at comparable levels that are close to zero.
  - » In the Central Basin, surface nitrate/nitrite levels were lower than normal from June through the end of 2017, and orthophosphate, total nitrogen, and silica were lower from June through August, corresponding to higher chlorophyll levels. Nutrient levels in July were lower than normal, and below detectable levels near the surface at some locations in deep areas of Central Basin. The spring phytoplankton bloom was evident on April 3 in the northern area, but occurred later in the southern area. Sustained chlorophyll-*a* levels occurred throughout much of the growing season.
  - » In inner Quartermaster Harbor, chlorophyll-*a* levels were generally lower than normal, and phytoplankton may have been nutrient-limited.
  - » In Bellingham Bay, surface chlorophyll-*a* levels rose in mid-April, consistent with the timing in 2016. This rise was accompanied by an increase in surface oxygen and pH, consistent with photosynthetic production. A much larger increase in chlorophyll in June was not accompanied by a similarly large response in oxygen or pH.

- Dissolved oxygen
  - » On average, DO in Puget Sound in 2017 was lower than baseline (1999–2008) conditions, continuing a five-year trend. However, observations at different locations revealed varying trends.
    - In Hood Canal and some other locations in Puget Sound, DO anomalies during 2017 were small and positive, with minimal hypoxia and no fish-kill events observed in southern Hood Canal. DO levels near Twanoh were the least hypoxic on record since 2011. The dynamics of the fall intrusion of oceanic water into southern Hood Canal were unusual, beginning with warmer, higher DO waters observed at depth in late summer, followed by cooler

hypoxic waters in mid-September. The hypoxia was short lived, as fall flushing brought in warmer and higher DO waters.
- In the Central Basin, deep DO levels in 2017 showed a strong seasonal signal, with higher than normal values in spring, and lower than normal values in fall. Near-surface DO levels were high and reflected the seasonal pattern of stratification and phytoplankton growth from spring through summer.
- In Quartermaster Harbor, DO levels were generally within typical seasonal ranges, though levels were not as high in the spring as in prior years.

- Ocean and atmospheric CO_2
  - » Atmospheric measurements of the mole fraction of carbon dioxide (xCO_2) at two moorings in Hood Canal had values 13–17 ppm higher than globally averaged marine surface air xCO_2 in 2017, with a substantial atmospheric xCO_2 enrichment seen at both sites during the pronounced stagnant-air event in December.
  - » Surface seawater seasonality in xCO_2 in 2017 resembled years before the Blob in terms of timing of the spring bloom and drawdown of CO_2.

Plankton
- Phytoplankton
  - » In the Central Basin, persistent stratification of the water column likely stimulated sustained phytoplankton growth from early April to late August. As in previous years, chain-forming diatoms, notably *Thalassiosira*, *Skeletonema*, and *Chaetoceros* spp., were the dominant taxa by biovolume from early spring to late summer.
  - » There was an unusual midsummer bloom of *Asterionellopsis* and an increase in *Prorocentrum* late in the season. Small dinoflagellates and the ciliate *Mesodinium* made up a significant portion of biological particles during fall and winter.
  - » Taxonomic composition changes were noted in 2017, with an absence or much lower abundance of certain taxa and a new appearance or much higher abundance of others. In addition, abundance of the large heterotrophic dinoflagellate *Noctiluca*, which had conspicuous blooms in 2014 and 2015, dropped considerably in 2017.
  - » As was seen in 2016, a coccolithophore bloom occurred throughout Hood Canal in mid to late July 2017.

- Zooplankton
  - » Zooplankton biomass and abundances declined in 2017 compared to 2015–16 in many regions of Puget Sound, but remained high compared to 2014 in central and southern regions.
  - » In Padilla Bay, zooplankton abundances in the spring were lower than normal in 2017, continuing a period of low abundances observed since 2014. Zooplankton community composition during the summers of 2014–17 were different from previous years, but similar to previous years in the winter, spring, and fall.
  - » In Skagit Bay, gelatinous zooplankton have been highly variable over the last 13 years, and average annual biomass in 2017 declined from the record highs of the Blob years to very low levels. These changes were also associated with continued decline of the main forage fish species of Puget Sound.

- 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 of 2017.
  - » *Pseudo-nitzschia* spp. were common throughout Puget Sound in 2017, with counts reaching over 80,000 cells per liter in blooms observed within Sequim Bay in the spring and Discovery Bay in the fall.
    - Paralytic shellfish poisoning (*Alexandrium*), amnesiac shellfish poisoning (*Pseudo-nitzschia* spp.), and diarrhetic shellfish poisoning (*Dinophysis* spp.) toxins resulted in 37 commercial growing area closures and 41 recreational harvest area closures, but caused no illnesses in 2017.
    - *Alexandrium* cysts were present far north to Birch Bay and south to Case Inlet in April 2017, with the highest number of cysts in the Central Basin, Liberty Bay, and Sinclair Inlet.
    - In Bellingham Bay, higher concentrations of *Alexandrium* cysts were found in the center of the bay, with fewer near shore in June 2017.
    - In Quartermaster Harbor, a persistent seed bed of *Alexandrium* cysts exists with a fairly consistent spatial

distribution pattern. In 2017, cyst concentrations were, on average, a factor of two less than in 2007 in the surface sediments.

Bacteria and pathogens

- In 2017, 91% of the 62 Puget Sound beaches and 93% of the core beaches monitored for the BEACH Program had less than two swimming closures or advisories during the swimming season.
- In the Central Basin, all offshore monitoring stations passed the Washington State geometric mean and peak standards for fecal coliforms during 2017. Eleven of the 20 beach monitoring stations failed one or both of the geometric mean or peak fecal coliform standards. Bacteria concentrations were typically highest from September through December during periods of heavy rain, but also in July after a month of no rainfall at several stations located near freshwater sources.
- There were 59 laboratory-confirmed and epidemiologically linked illnesses in 2017 due to the consumption of commercially or recreationally harvested oysters in Washington contaminated with *Vibrio parahaemolyticus*.

Kelp

- Floating kelp canopy area decreased by half at survey areas following the onset of anomalously warm water conditions in late 2013. The exact timing of declines varied with location, as did the subsequent recovery. Kelp beds along the Strait of Juan de Fuca and in San Juan Archipelago recovered most quickly, in 2014 and 2015. These areas are well mixed and close to oceanic influence. At Cherry Point, recovery was delayed until 2017. Sites in inner basins, namely Possession Sound and south Puget Sound, continued to decline in 2017, based on kayak surveys.

Marine birds and mammals

- Diving forage fish specialists (alcids and grebes) were observed in low abundances early in 2016–17, but increased and ultimately reached levels similar to 2015–16.
- Numbers of scoters, a Puget Sound Vital Sign Indicator, were generally lower than in the previous two years.
- Following a highly anomalous breeding season on Protection Island in 2016, characterized by historically low fledging success, rhinoceros auklets experienced low breeding effort, as defined by the proportion of breeding burrows that are reproductively active, but otherwise had representative reproductive success in 2017.
- Abundances of seabirds and marine mammals in the eastern Strait of Juan de Fuca during fall 2017 continued to be low relative to the 14-year record. Since 2013, seabird abundance has been low, similar to the years prior to the cool conditions of 2010–12. Since 2013, observed marine mammal densities have steadily declined, with 2017 having the lowest of the record.

Fish

- In 2017, another all time low for the Cherry Point stock of Pacific herring was observed; stocks in South and Central Puget Sound have also been in decline in recent years, but have been buoyed by large increases in the Hood Canal herring biomass.

Coccolithophore bloom in Hood Canal July 24 2017. Photo: Christopher Krembs, Eyes Over Puget Sound.

Technical summaries

Deception Pass, Whidbey Island.
Photo: Rachel Wold.

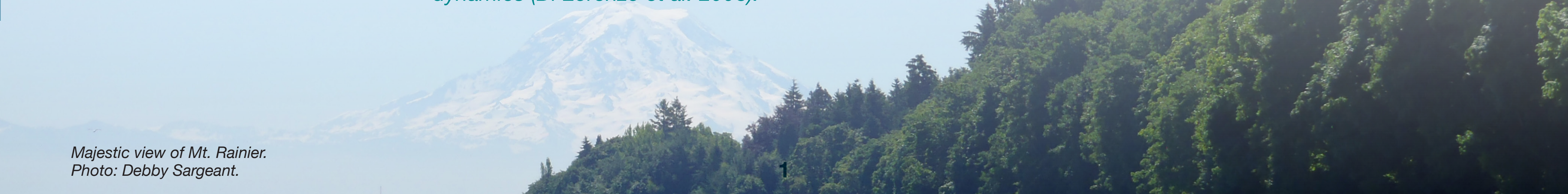
Large-scale patterns of climate variability, such as the El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO), can strongly influence Puget Sound's marine waters. Seasonal upwelling winds on the coast, with intrusions of upwelled waters into Puget Sound, also strongly influence Puget Sound water properties, generating a signal that is similar to human-sourced eutrophication (i.e., high nutrients, 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 tend to be associated with atmospheric conditions in the Pacific Northwest, particularly in winter. For example, warm phases of ENSO (El Niño) and PDO generally produce warmer-than-usual coastal ocean temperatures and drier-than-usual winters. The opposite is generally true for cool phases of ENSO (La Niña) and PDO. ENSO events usually persist from 6 to 18 months, whereas phases of the PDO typically persist for 20 to 30 years. In Puget Sound, warm water temperature anomalies are produced during the winter of warm phases of ENSO and PDO, and can typically linger for 2–3 seasons. For PDO, these anomalously warm waters can reemerge 4–5 seasons later (Moore et al. 2008a). In contrast, the NPGO, which is related to processes controlling sea surface height, has a stronger effect on salinity and nutrients than on temperature. Variations in seasonal winds are an important factor in the NPGO. On the outer Washington coast, seasonal winds shift from dominantly southerlies during winter to northerlies during summer, and drive some of the largest variation in offshore coastal conditions: upwelling versus downwelling. Upwelling brings deep, cold, salty, nutrient-rich, oxygen-poor waters to the surface and into the Strait of Juan de Fuca as source water for Puget Sound, fuelling phytoplankton growth. As such, the NPGO indicates fluctuations in the mechanisms driving planktonic ecosystem dynamics (Di Lorenzo et al. 2008).

1.A. El Niño–Southern Oscillation (ENSO)

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

The start of 2017 was characterized by cooler than normal conditions in the tropical Pacific in association with La Niña. There was warming in the tropical Pacific during spring 2017, with some indications that a weak El Niño would develop later in the year. Instead, there was cooling during the summer and fall of 2017 to the extent that a moderate La Niña formed by the end of the year. This period featured higher than normal sea level pressure over the North Pacific (i.e., a relatively weak Aleutian low). Past cool ENSO events have had similar manifestations of the atmospheric circulation over the North Pacific and the Pacific Northwest, with this most recent case representing a rather strong response to tropical Pacific conditions of moderate amplitude.



Majestic view of Mt. Rainier. Photo: Debby Sargeant.

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

1.B. Pacific Decadal Oscillation (PDO)

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

The PDO decreased from values near +1 at the beginning of 2017 to values closer to zero at the end of the year (Figure 1). This decline corresponds with the demise of the Northeast Pacific marine heat wave of 2014–16 (a.k.a, “the Blob”), which included a systematically positive state for the PDO, with a peak amplitude of about 2.5.

View of Seattle from the Bainbridge Ferry. Photo: Su Kim.

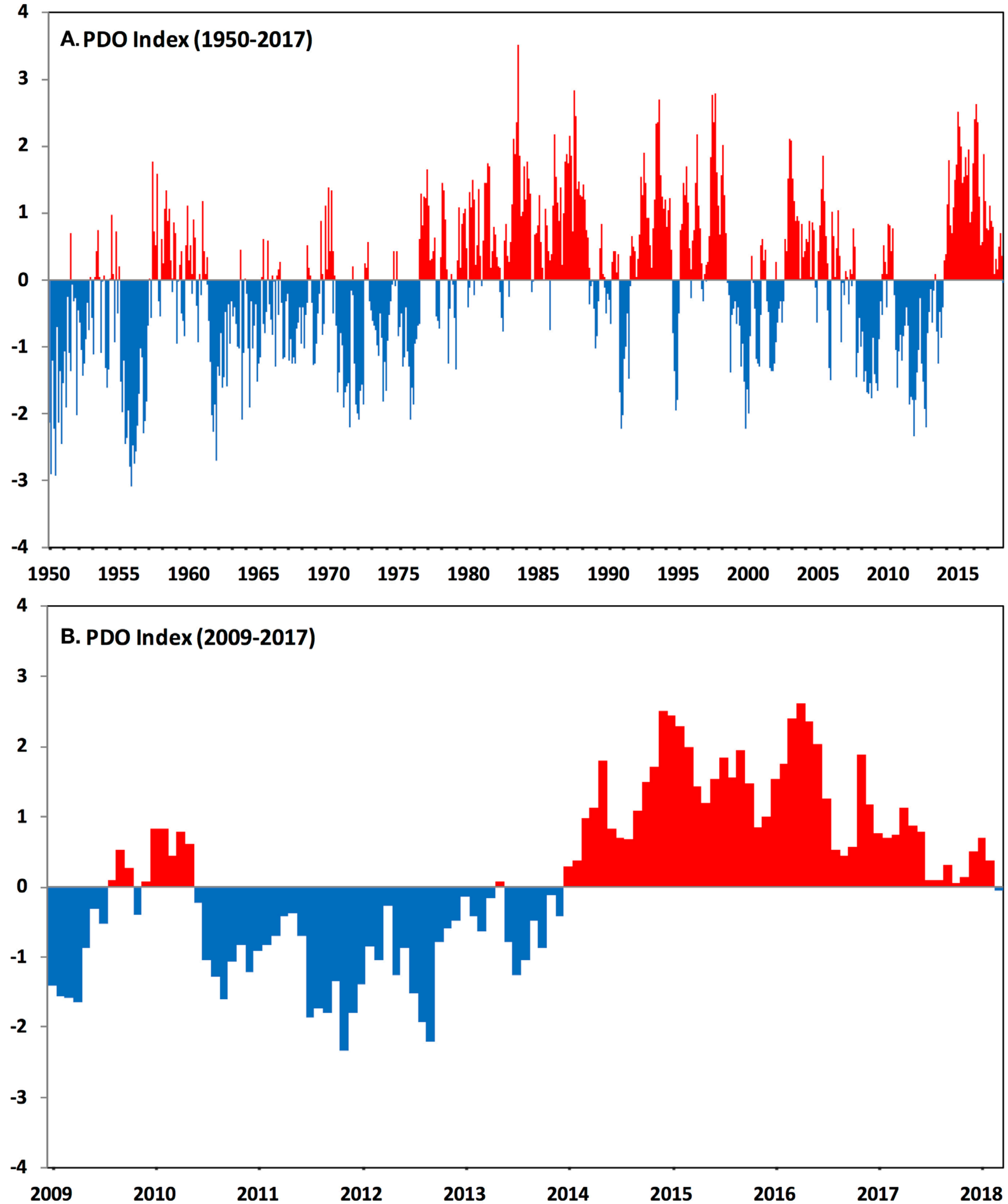


Figure 1. Monthly values of the Pacific Decadal Oscillation (PDO) index from (A) 1950–2017 and (B) 2009–2017.

1.C. North Pacific Gyre Oscillation (NPGO)

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

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

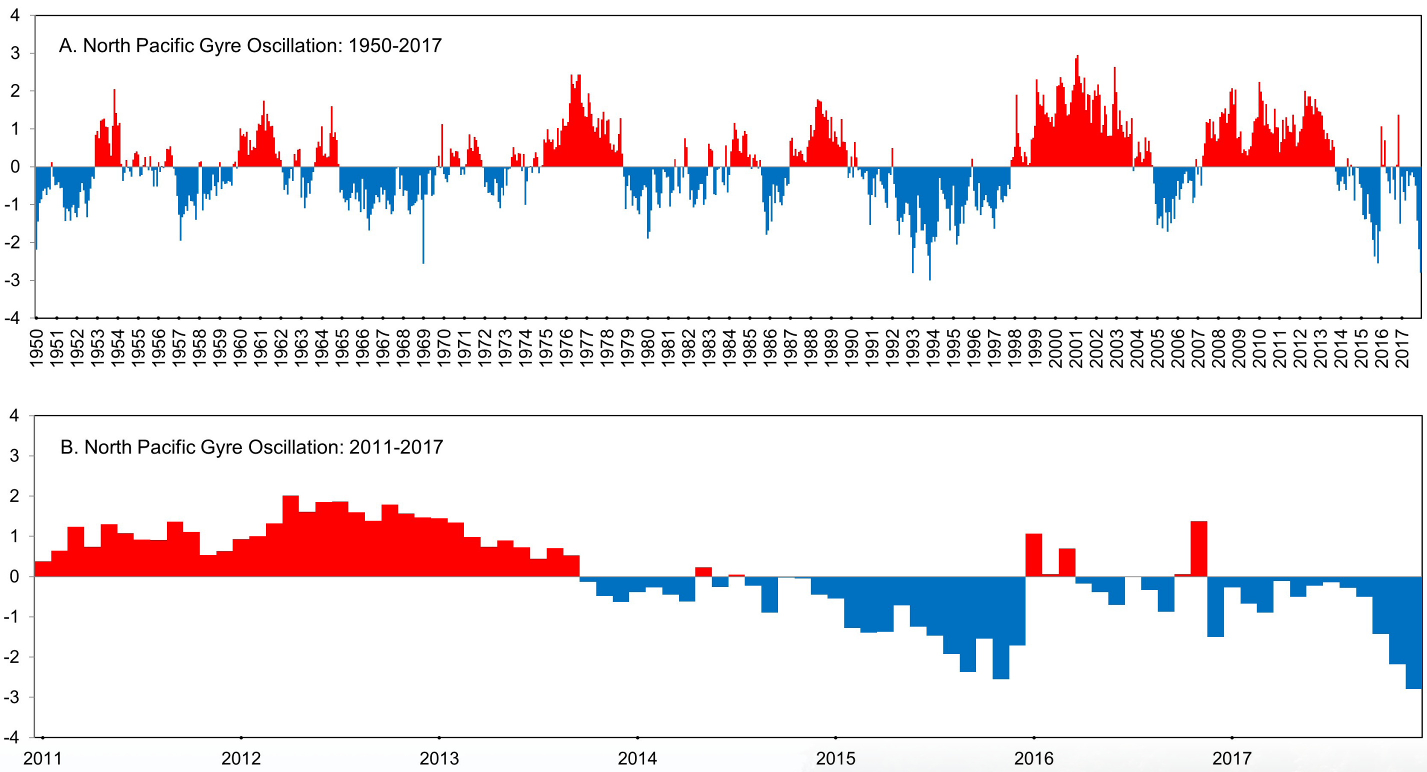


Figure 2. Monthly values of the North Pacific Gyre Oscillation (NPGO) index from (A) 1950–2017 and (B) 2011–17.

Beachgoers enjoying Owens Beach.
Photo: Debby Sargeant.

1.D. Upwelling index

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

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

Monthly mean values of the NOAA Pacific Fisheries Environmental Laboratory upwelling index at 48°N and 125°W in 2017 were mostly within historic (1967–present) interquartile ranges during the upwelling season. However, the spring transition from downwelling to upwelling conditions began later than normal, with downwelling winds dominating in April (Figure 3). Stronger than normal downwelling conditions also occurred in November.

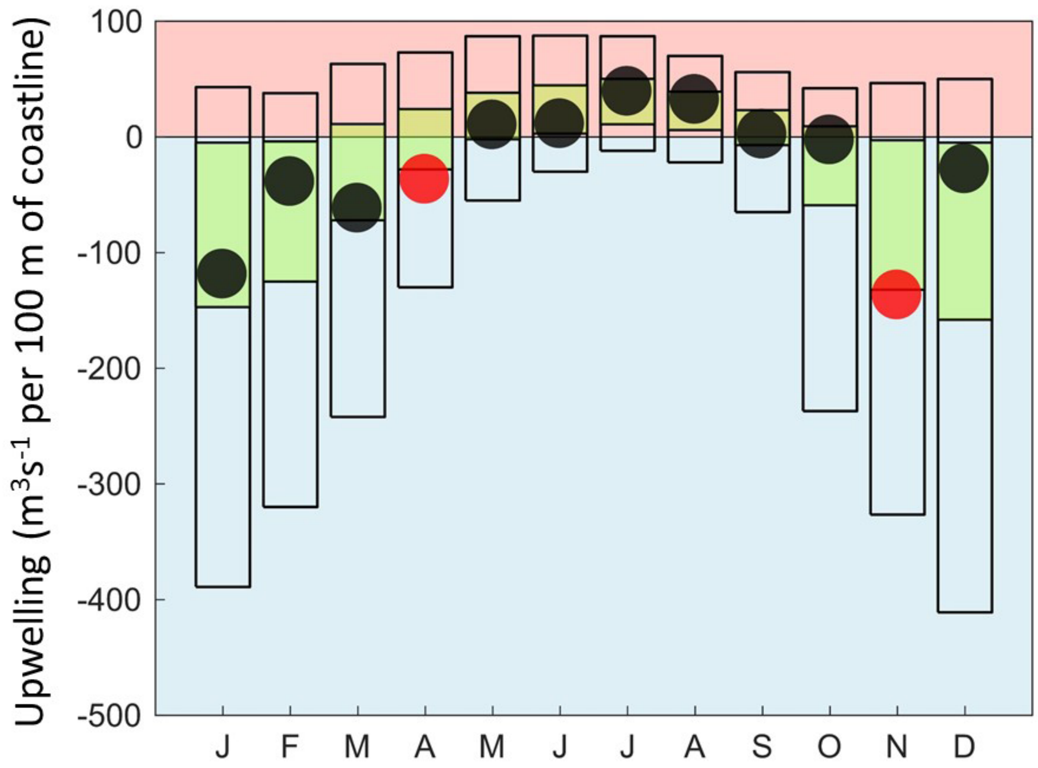


Figure 3. Monthly mean values of the NOAA/PFEL coastal upwelling index at 48°N and 125°W for 2017 (red and black dots). The box plots represent 5th and 95th percentiles, with the interquartile range between 25th and 75th percentiles shaded green based on the index values from 1967–2016. Values falling outside the interquartile range are colored red. Pink- and blue-shaded areas indicate upwelling and downwelling conditions, respectively. Data source: http://www.pfeg.noaa.gov/products/las/docs/upwell.nc.html.

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. 2008a).

2.A. Regional air temperature and precipitation

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

The year 2017 was wetter than normal, with near-normal air temperatures for the Puget Sound area and Washington State as a whole. Washington State is divided into ten separate climate divisions based on similar average weather conditions within a region (http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php). The following summary uses data from the Puget Sound Lowlands division that encompasses most of Puget Sound.

The Puget Sound region experienced three consecutive years of above normal air temperatures in 2014, 2015, and 2016, but annual average temperatures returned to normal in 2017. As in 2013, the annual average temperature was equal to the 1981–2010 normal (10.5°C/50.9°F). Total annual precipitation was 127.13 cm (50.05"), which represents 112% of normal, and is similar to the amount of precipitation received in 2016.

While the annual average values were unremarkable from a historical ranking standpoint, monthly values give a view of more variability throughout the year, with several record seasonal precipitation anomalies occurring. Figure 4 shows monthly air temperature and precipitation anomalies for the Puget Sound region relative to the 1981–2010 normals. In particular, February through April marked the wettest spring on record (since 1895) for the region and the state as a whole. Accompanied by relatively cool temperatures, the spring conditions helped build the state's snowpack well into April. That wet period was followed by the driest July–September on record for the Puget Sound region. Several stations in the region observed their longest stretch of dry days in the historical record. This period was also accompanied by the warmest August on record, with anomalies 1.8°C above normal for the region. Smoke from wildfires throughout the Pacific Northwest was a common occurrence, and there were several extended periods throughout the summer with poor air quality. The calendar year ended with another period of poor air quality; for nearly two weeks in December, a ridge of high pressure suppressed the usual parade of landfalling storms, resulting in mostly calm, clear weather and a low-level temperature inversion.

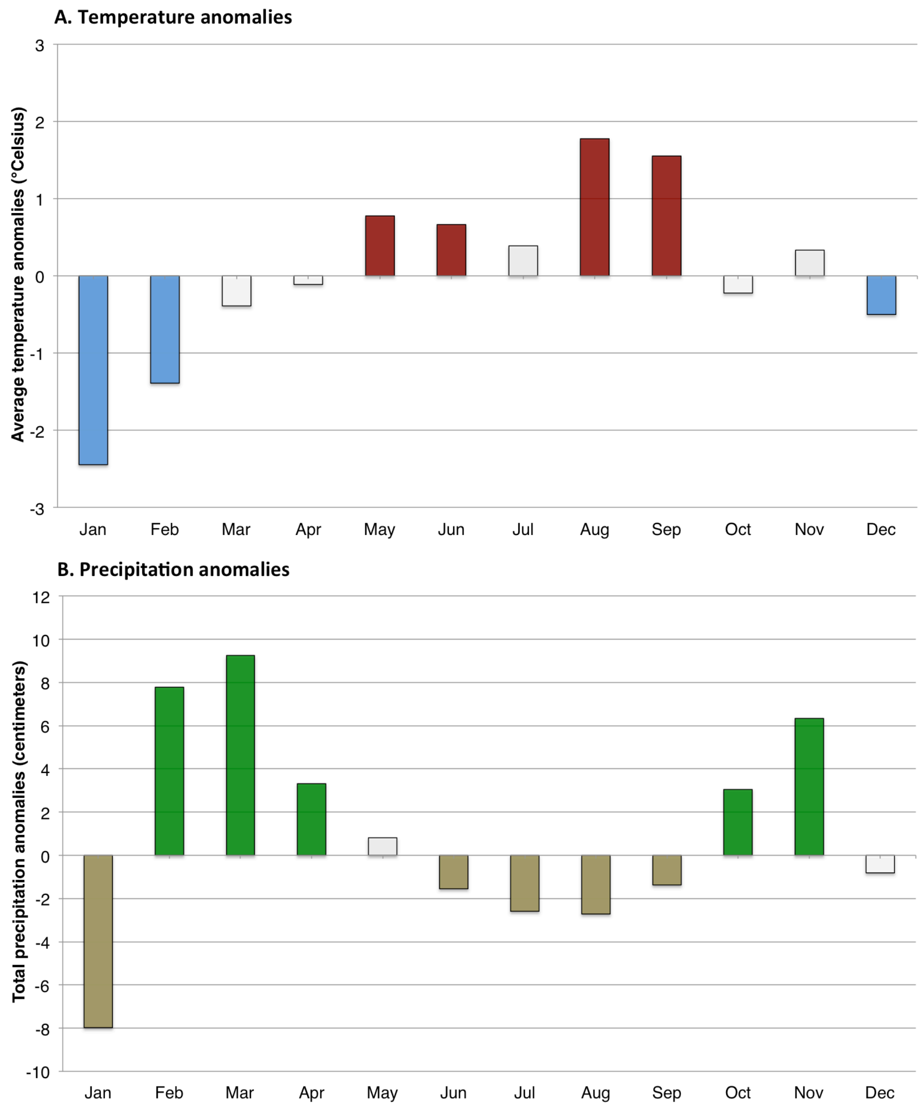


Figure 4. Monthly anomalies for (A) temperature (Celsius) and (B) precipitation (centimeters) for the Puget Sound Lowlands climate division in Washington State for the 2017 calendar year. Anomalies are relative to 1981-2010 climate normals and are colored red (green) for above normal temperature (precipitation) anomalies and blue (brown) for below normal temperature (precipitation) anomalies.

2.B. Local air temperature and solar radiation

Source: Skip Albertson (skip.albertson@ecy.wa.gov), Christopher Krembs, Julia Bos, Allison Brownlee, and Carol Maloy (Ecology); https://ecology.wa.gov/Water-Shorelines/Puget-Sound

Air temperatures at SeaTac were colder than normal (relative to a 1971–2000 historical baseline period) at the start of 2017, and then highly variable during spring, switching between warmer than normal and colder than normal periods (Figure 5A). By July, there was no measureable rain, and air temperatures were much warmer than normal from July through September. During this time, wildfires occasionally caused periods of hazy skies. There were several cold spells in the fall, beginning with one in early November that brought snow to the Puget Sound lowlands.

Sunlight, as measured by daily solar energy flux, was below average from February to May, and generally above average from June through until the end of 2017, with the exception of November (Figure 5B, red shaded area).

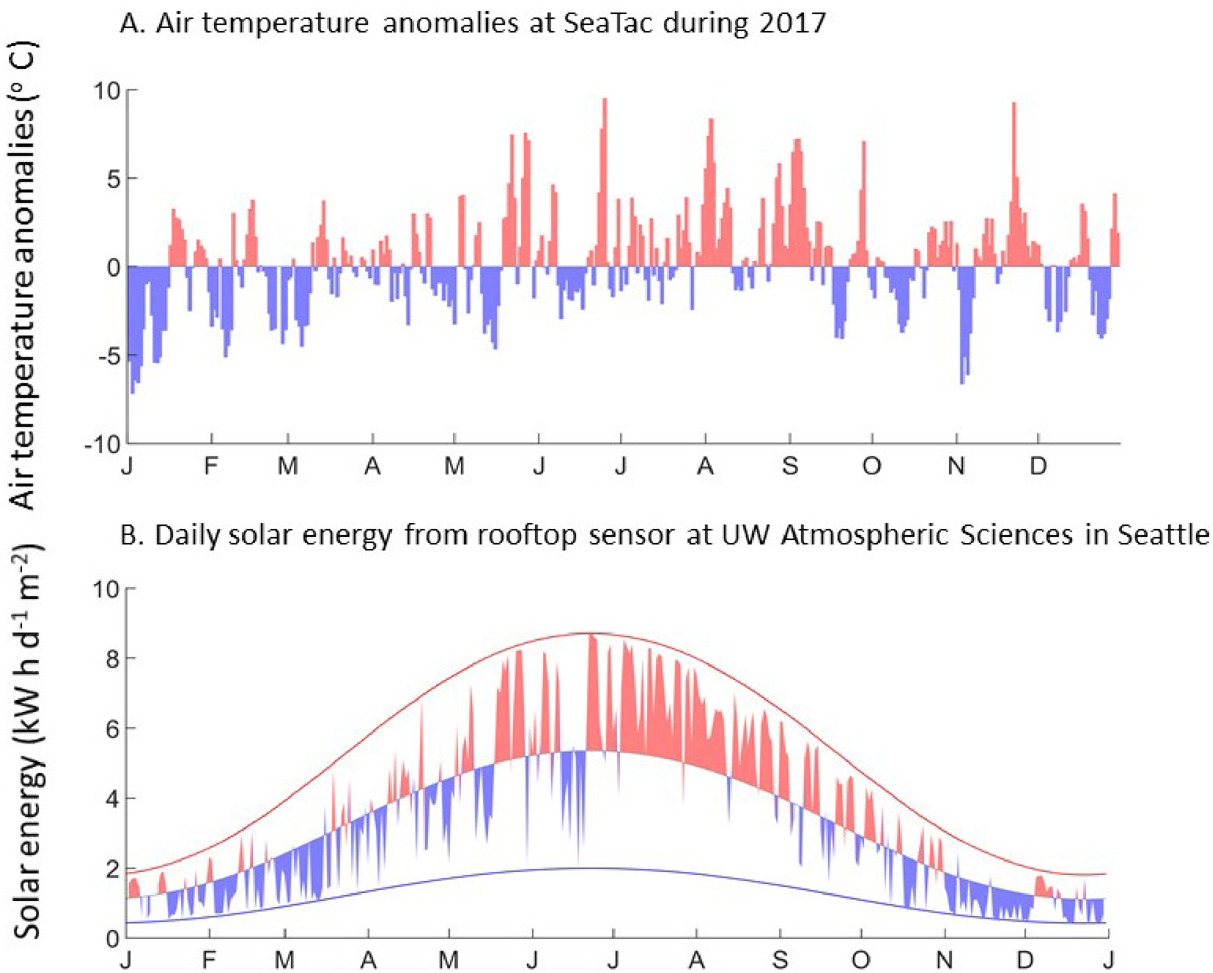


Figure 5. (A) Daily air temperature anomalies at SeaTac during 2017. Red (blue) shading indicates warmer (cooler)than average values. (B) Daily solar energy values from the rooftop sensor at the UW Atmospheric Sciences building (ATG) in Seattle. The solid red line indicates the highest theoretical solar energy for this latitude and the solid blue line indicates expected values if it were 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).

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.

3.A. NW Washington Coast water properties

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.

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

Notably, the deep waters on the Washington shelf had substantially lower salinities, warmer temperatures and higher DO concentrations in spring 2017 compared to previous years; though its cause is unknown if from increased of the Columbia River influence, a relict deep Blob signal, or some other mechanism.

Local winds measured by Chá Bă suggest that steady upwelling conditions did not set in until late June 2017, compared to April–May in previous years; however, a relatively steady decrease in deep (85 m) temperature and increase in deep salinity and nitrate was observed in early May from the start of the mooring deployment (Figures 6A, B). This trend continued until about mid-September, when downwelling conditions began to take over. Early-season deep salinity was lower than previous spring observations, potentially in response to record rainfall over the winter and spring of 2017, but rapidly increased in May with the onset of intermittent upwelling conditions (Figure 6B). Deep DO showed a relatively steady, slow decrease until late August, when it dropped rapidly to hypoxic levels (2 mg/L) with the onset of downwelling conditions (Figure 6C). This rapid drop is likely a consequence of wind shifts bringing low-DO water from the south to this location, as reported in previous reports (PSEMP Marine Waters Workgroup 2016, 2017). The seasonal trend of the relatively steady decrease in DO was similar to 2016 observations, but is not a consistent seasonal pattern. In 2014 and 2015, for example, upwelling season peaks in deep salinity and nitrate and minima in deep

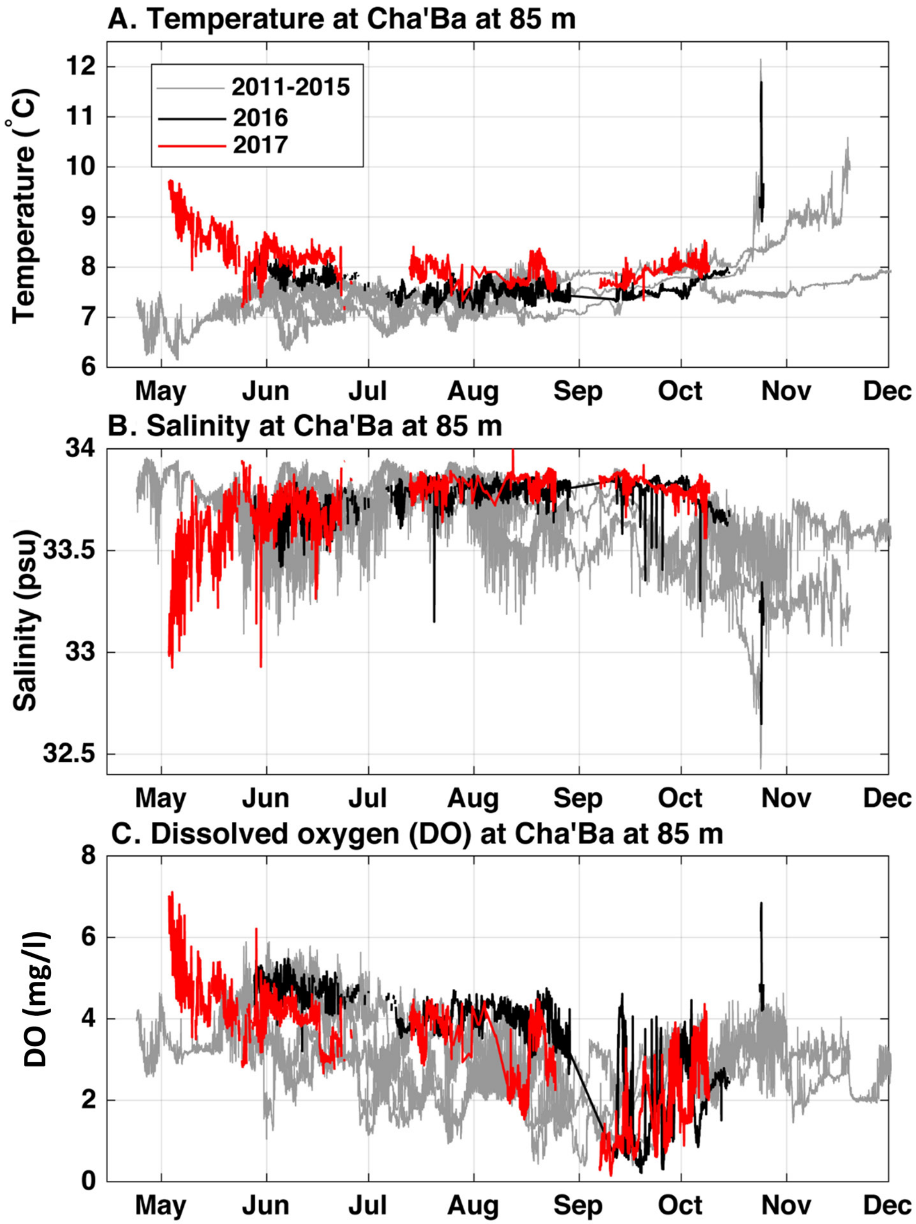
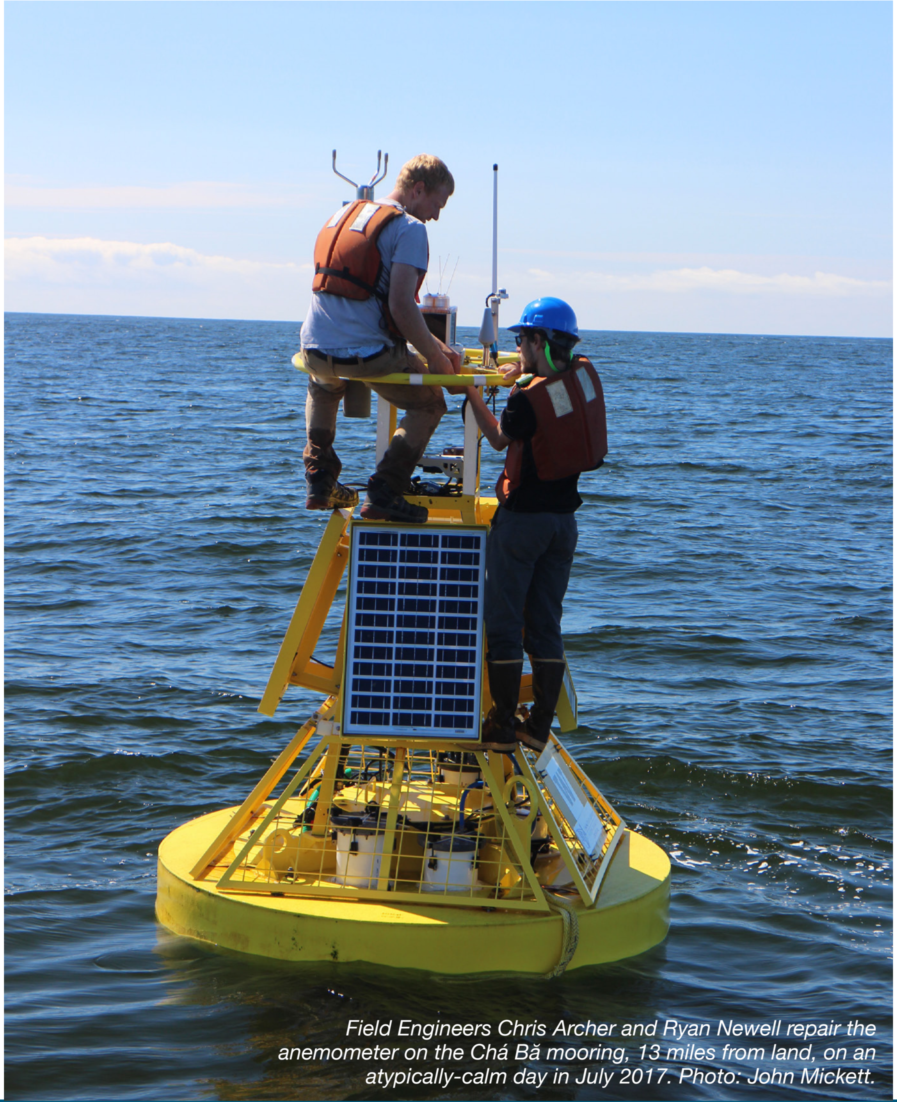


Figure 6. Interannual comparison of deep water (85 m) properties at Chá Bă: (A) temperature, (B) salinity, and (C) dissolved oxygen.

temperature occurred in June and July, and were linked to periods of the strongest upwelling winds.

For most of the 2017 record, deep waters (i.e., water below about 40–50 m depth in 100 m total water depth) were on-average warmer (~0.8°C) than previous years at this site (Figure 7). This could be the delayed signature of the Blob, characterized by a warmer mixed layer (Bond et al. 2015) slowly subducting or mixing downward to reach upwelling source water depths.



Field Engineers Chris Archer and Ryan Newell repair the anemometer on the Chá Bă mooring, 13 miles from land, on an atypically-calm day in July 2017. Photo: John Mickett.

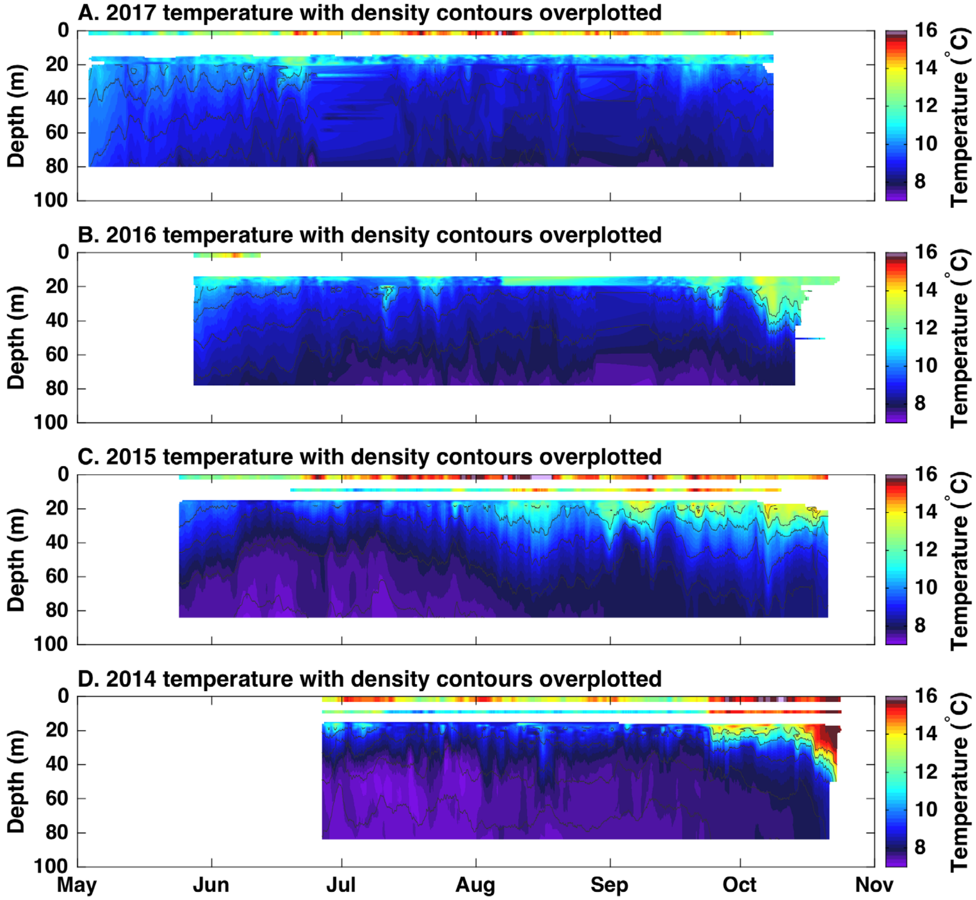


Figure 7. Water column temperature with density contours overplotted for (A) 2017, (B) 2016, (C) 2015, and (D) 2014. The warmer deep water in 2017 is readily apparent when compared to 2016, 2015, and 2014.

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

3.B. Ocean and atmospheric CO_2

Source: Simone Alin (simone.r.alin@noaa.gov), Adrienne Sutton, Richard Feely (NOAA, PMEL), Sylvia Musielewicz (UW, JISAO), Jan Newton, John Mickett (UW, APL), and Christopher Sabine (Univ. Hawaii); http://pmel.noaa.gov/co2/story/La+Push; http://pmel.noaa.gov/co2/story/Cape+Elizabeth; PMEL contribution number 4783

Carbon dioxide (CO_2) sensors have measured atmospheric and surface seawater xCO_2 (mole fraction of CO_2) at three-hour intervals on the surface Chá Bă mooring off La Push since 2010, mostly from spring through fall, and year-round on the National Data Buoy Center mooring 46041 at Cape Elizabeth since 2006. Measurements were mostly from spring through fall, and year-round on the National Data Buoy Center mooring 46041 at Cape Elizabeth since 2006. Both time series had gaps during 2017, with Chá Bă measurements available from May through mid-October and Cape Elizabeth measurements all year except from August 20 through September 24 and mid-November through December (Figure 8).

In 2017, the atmospheric xCO_2 range was 393–456 ppm at Chá Bă (Figure 8A) and 387–474 ppm at Cape Elizabeth (Figure 8B). Using all available observations at each mooring, average values for atmospheric xCO_2 at Chá Bă and Cape Elizabeth were 1 and 2 ppm higher than globally averaged marine surface air of 405 ppm for 2017[1]. The gaps in observations at Chá Bă (i.e., January through late April and mid-October through December) occured during months when atmospheric xCO_2 values are higher. Without this gap the difference between the Chá Bă average and the global mean would be larger due to the timing of missed observations.

Surface seawater xCO_2 ranged from 99 to 642 ppm at Chá Bă (Figure 8C) and from 126 to 502 ppm at Cape Elizabeth (Figure 8D) during 2017. Average surface seawater xCO_2 values have been below average atmospheric values for all years at both sites (Tables 1 and 2), and seawater xCO_2 variability is roughly an order of magnitude higher than atmospheric xCO_2 variability (as reflected by standard deviations). During 2017, average seawater xCO_2 was lower than in 2015 and 2016, years when the Washington coast was strongly influenced by the Blob, at both sites; it was more similar to values from 2011 and 2014 at Cape Elizabeth and 2013 and 2014 at Chá Bă.

[1] NOAA/ESRL website: *ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_annmean_gl.txt* accessed May 12, 2018.

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

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

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

Table 2. Average (± standard deviation) surface seawater and atmospheric xCO_2 values at Chá Bă (mid-July to mid-October) for all available years in parts per million (ppm). Percent data return is offered as a metric for how much of the mid-July to mid-October period was represented by measurements each year.

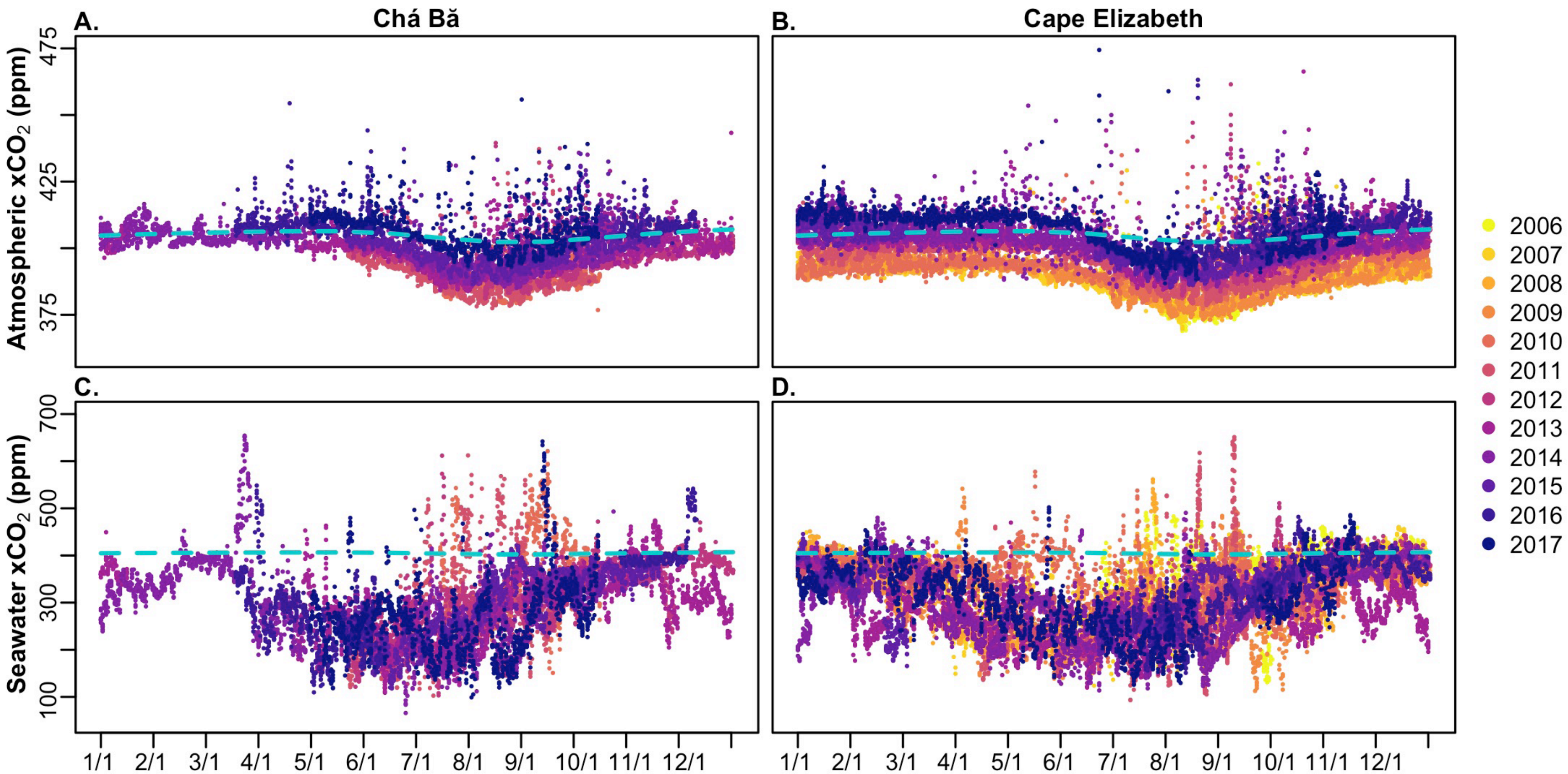


Figure 8. The mole fraction of carbon dioxide (xCO2) in air at 1.5 m above seawater (A, B) and in surface seawater at 0.5-m depth (C, D) on the surface Chá Bă mooring off La Push, WA (A, C), and on NDBC mooring 46041 off Cape Elizabeth, WA (B, D). Monthly mean atmospheric xCO2 values for globally averaged marine surface air are shown by the dashed line in each panel (NOAA/ESRL)[1]. Typical uncertainty associated with quality-controlled measurements from these systems is <2 ppm for the range 100–600 ppm and increases for values between 600 and 1,000 ppm.

CALL-OUT BOX
A decade of cruises in the Salish Sea to understand ocean acidification

Since 2008, researchers at UW and NOAA's Pacific Marine Environmental Laboratory (NOAA/PMEL) have established a time series of biogeochemical data in the Salish Sea to improve understanding of regional ocean acidification (see PSEMP Marine Waters Workgroup 2012, Coastal ocean section 3.B; text box for OA introduction) and its interaction with hypoxia. This Salish Cruise time series extends the PRISM cruise time series started in 1998. Funding from the Washington Ocean Acidification Center, UW School of Oceanography, UW Applied Physics Laboratory, and NOAA/PMEL has sustained this partnership since 2014.

The Salish Cruises occur mainly in April, July, and September and visit approximately 30 monitoring stations in five sub-basins of Puget Sound, the Strait of Juan de Fuca, and the northern Washington shelf. Full water-column surveys of dissolved inorganic carbon (DIC), alkalinity (TA), oxygen, temperature, salinity, nutrients, chlorophyll, phytoplankton, and zooplankton are conducted. Pteropod abundance and condition are also determined. Twenty-five Salish Sea cruises have been completed since 2008.

Aragonite saturation values reflect overall acidification in Salish Sea waters and can provide insights to biological impacts. They reflect a combination of natural and anthropogenic processes and give a sense of how easy or difficult it is for calcifying organisms, including pteropods and Pacific oysters, to synthesize their shells (Bednaršek et al. 2014, 2017; Waldbusser et al. 2015; Feely et al. 2010, 2016). The Salish Sea has some of the lowest values seen anywhere in the global ocean, but these values differ by basin and depth and can also vary seasonally. To better understand the range of conditions to which organisms are exposed, the mean aragonite saturation state (Ω_{arg}) in surface and bottom waters was calculated from DIC, TA, and other oceanographic data (Table 3).

Region	Feb	Apr	Jul	Sep	Nov
Eastern Strait surface	0.92	1.2	1.2	0.95	0.80
Eastern Strait deep	0.94	1.2	1.0	0.79	0.77
Admiralty Inlet surface	0.84	1.2	1.7	1.2	0.85
Admiralty Inlet deep	0.86	1.1	1.1	0.90	0.78
Whidbey Basin surface	0.77	1.7	2.0	1.6	
Whidbey Basin deep	0.63	0.65	0.62	0.83	
Main Basin surface	0.79	1.3	1.8	1.4	
Main Basin deep	0.80	0.81	0.97	0.90	
South Sound surface	0.78	1.3	1.6	1.3	
South Sound deep	0.72	0.83	1.4	1.0	
Hood Canal surface	0.79	2.2	2.1	1.3	0.49
Hood Canal deep	0.69	0.48	0.60	0.72	0.68

Table 3. Mean aragonite saturation state (Ω_{arg}) in surface and bottom waters within each subregion for each month when Salish Cruises with ocean acidification measurements have taken place (2008–17). Surface waters are defined here as the upper 5 meters and bottom waters as the bottom 10 meters of the water column at each station. Cells are colored by the value within each cell to facilitate visual interpretation by highlighting values falling within 0.5 Ω_{arg} units above saturation and 0.25 units below. The abbreviation "n.d." stands for "no data."

Water entering Puget Sound at depth and exiting at the surface via the Eastern Strait averages just above aragonite saturation (Ω_{arg} = 1) in spring and summer, falling below saturation during fall and winter. Mean Ω_{arg} values through Admiralty Inlet are very similar, except with higher summertime surface values. The similarity of surface and deep Ω_{arg} in the Eastern Strait and Admiralty Inlet is likely due to strong tidal mixing.

The four basins within Puget Sound show much stronger gradients between surface and deep; these areas share a pattern of elevated surface Ω_{arg} during

Holmes Harbor, Whidbey Island. Photo: Rachel Wold.

CALL-OUT BOX (cont.)
A decade of cruises in the Salish Sea to understand ocean acidification

April–September, and typically undersaturated deep waters year-round, likely related to enhanced production (surface) and respiration (deep). However, there is substantial variation among basins and through seasons and years. Hood Canal has the strongest gradient between surface and deep waters of all basins. Mean surface Ω_{arg} values there are higher in spring to midsummer and lower in fall, while bottom waters are the most strongly and consistently undersaturated year-round. Whidbey Basin has the second strongest gradient, with second-highest surface Ω_{arg} values in summer and second-lowest bottom Ω_{arg} values in all seasons. Average bottom-water Ω_{arg} conditions in South Sound are the most variable through the seasons, likely due to shallow depths. South Sound and Main Basin show similar surface Ω_{arg} values in all months sampled, with lower spring–midsummer values than Hood Canal or Whidbey Basin. Main Basin bottom-water Ω_{arg} values are always somewhat undersaturated, but not nearly to the extent seen in Hood Canal or Whidbey Basin. Late fall–winter conditions (Nov.–Feb.), though based on limited cruises, tend to be more homogenous; notable are the highly undersaturated conditions in November in Hood Canal, and the remarkably similar average surface Ω_{arg} values (0.77–0.79) across Puget Sound in February.

The strong gradients and major differences among basins have implications for organisms who migrate vertically or move throughout the Salish Sea. In general, hypoxia is strongest where deep Ω_{arg} values are lowest, indicating multiple stressors for organisms, but aragonite undersaturation is far more spatially and temporally extensive than hypoxia.

We have a growing understanding of surface and bottom Ω_{arg} values in the southern Salish Sea. Collectively, these data will enable assessment of how anomalous conditions related to future marine heatwaves, acidification, and hypoxia events affect the ecosystem. These results show that organisms sensitive to carbonate chemistry or hypoxia experience a range of conditions that vary on multiple scales, and that their exposure may be cumulative across space, time, and depth within Puget Sound waters. Experimental design and regional assessments of potential biological impacts require information on environmental variability to be most relevant to impacts, adaptation, and mitigation.

Authors: Simone Alin (simone.r.alin@noaa.gov) (NOAA, PMEL), Jan Newton (UW, APL), Beth Curry (UW, APL), and Richard Feely (NOAA, PMEL); http://nvs.nanoos.org/CruiseSalish; PMEL contribution number 4783

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

4.A. Fraser River

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

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

Snowpack in the Fraser River watershed reached normal levels in April 2017, though this was delayed due to cold and dry conditions early in the year. Air temperature conditions shifted dramatically in the latter half of May, with observations up to 10°C above normal in the British Columbia Interior, resulting in rapid snowmelt (BCRFC 2017). These May conditions resulted in the peak of spring runoff occurring approximately two weeks earlier than normal and 2,830 m^3/s above the historical median (Figure 9). This peak in snowmelt-dominated flows was augmented by above-average precipitation from March through May. Beginning in July, flows dropped below normal (<25%) due to prolonged hot and dry conditions, and did not rebound until mid-October. Precipitation from a series of atmospheric river events in mid-October and November brought Fraser River flows well above the historic median for the remainder of the year.

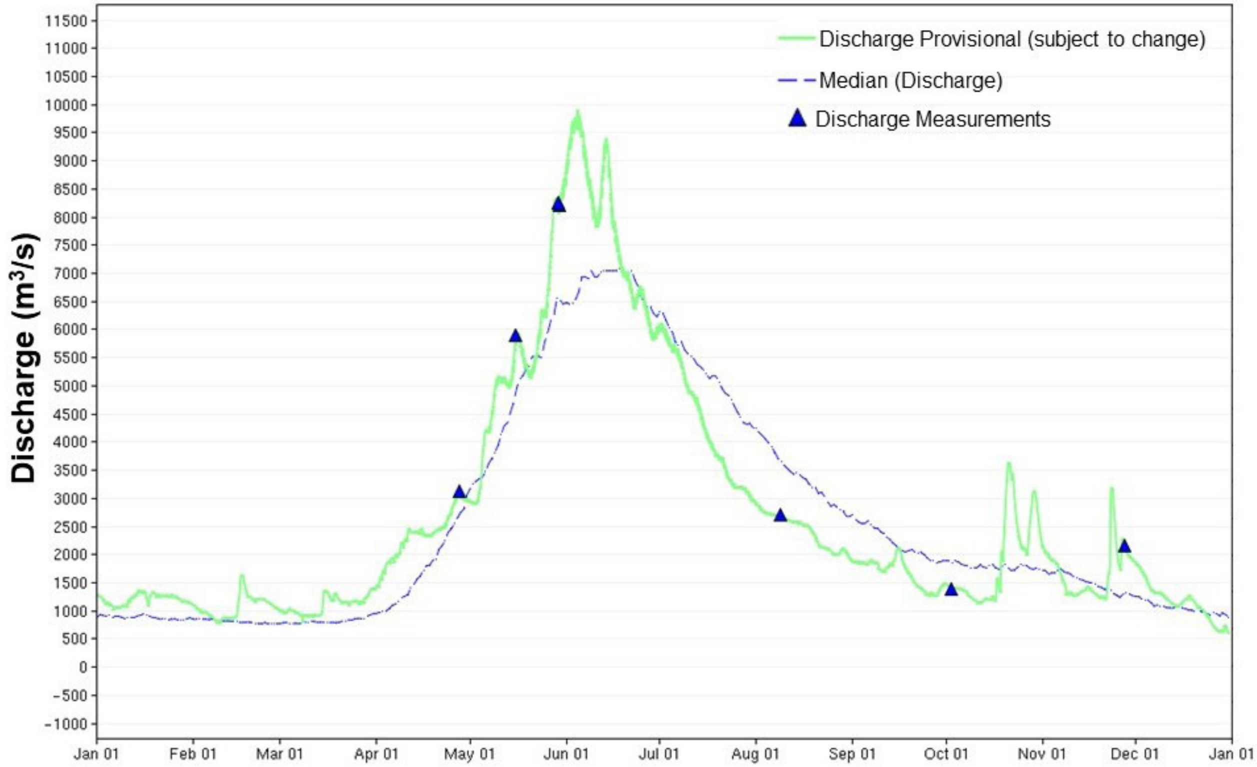


Figure 9. Fraser River daily discharge (m^3/s) at Hope, B.C. (08MF005) for 2017, compared to the median value for the period of record (1912–2017). (Note: 1 m^3/s = 35.3 ft^3/s).

4.B. Puget Sound rivers

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

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

Conditions in Puget Sound watersheds during 2017 developed similarly to those of the Fraser watershed in British Columbia. Due to unseasonably wet conditions through much of the winter and early spring, streamflow conditions remained at or well above normal, depending on the storm event. After building to an above-average snowpack through April, a shift to warm conditions in early May caused rapid snowmelt and the onset of spring runoff (OWSC 2017), raising river flows to levels much above normal (Figure 10). The snowpack persisted to sustain additional runoff peaks during periods of hot weather in June, though in most cases river flows did not reach levels observed the previous month. In most Puget Sound watersheds, these spring runoff events were smaller than those from fall and winter storms, but, coupled with flows from the Fraser River, they still contributed significantly to the total freshwater input to Puget Sound. In July, watersheds draining to north and central Puget Sound reached levels below normal, while watersheds draining the Olympics and to south Puget Sound remained near normal. As hot and dry conditions persisted throughout the remainder of the summer, flows from nearly all rivers draining to Puget Sound were much below normal by mid-September. All rivers recovered dramatically with precipitation from two rainfall events in mid-October and again in November. Despite summer deficits, all rivers draining to Puget Sound exceeded their average annual runoff.

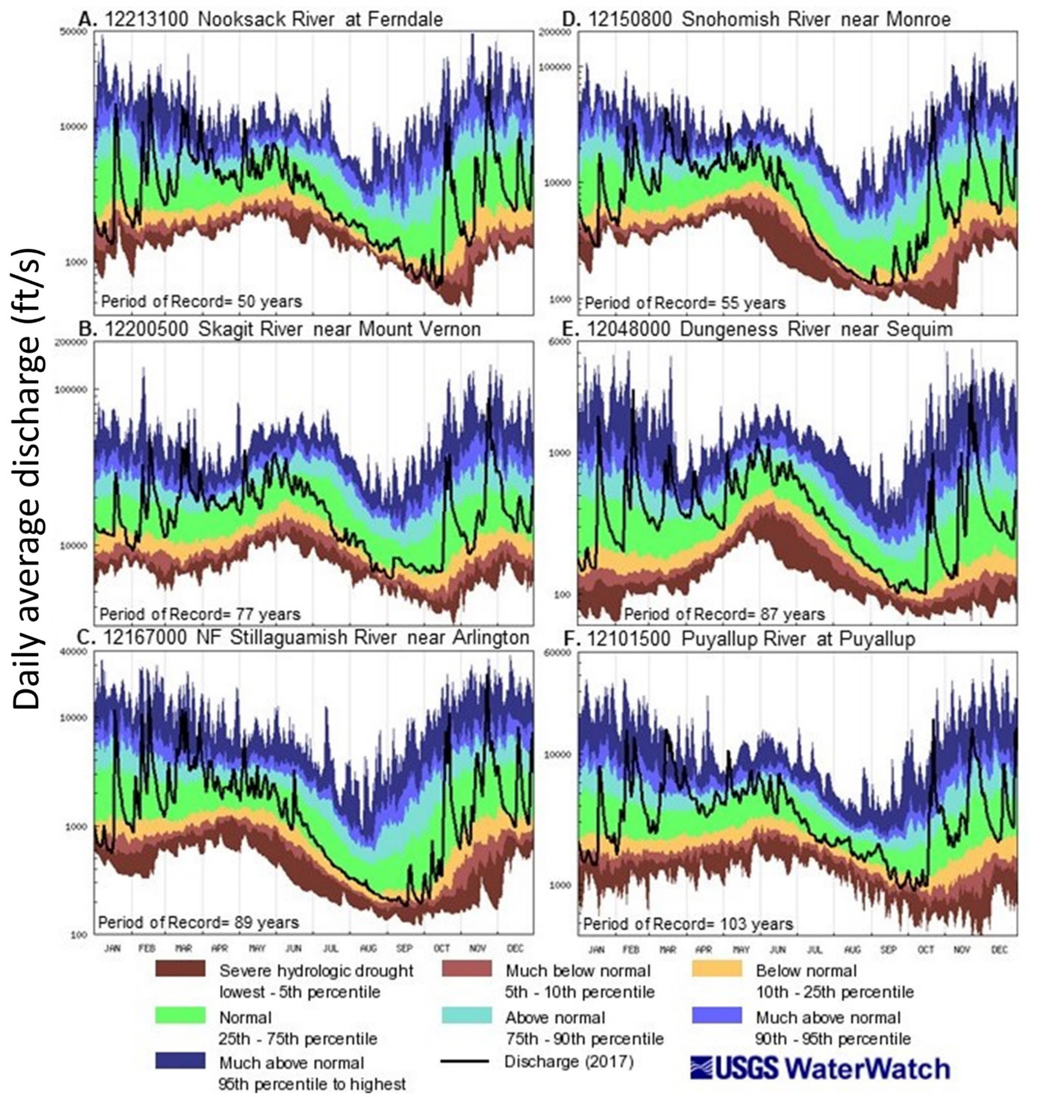


Figure 10. River discharge (ft^3/s) at stations on the Nooksack, Skagit, NF Stillaguamish, Dungeness, Snohomish, and Puyallup Rivers in 2017, compared to period-of-record median values. (Note: The period of record varies for each station and is listed in number of years in parentheses in the figure legend.)

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, local biological processes, and upwelling influence via mixing at sills. In some parts of Puget Sound, dissolved oxygen is measured intensively to understand the connectivity between hypoxia and large fish kills. Dissolved oxygen is also an indicator of biological production, respiration, and consumption of organic matter, and a component for understanding the health of the food web.

5.A. Puget Sound long-term stations

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

5.A.i. Temperature and salinity

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

From January through April 2017, water temperatures throughout Puget Sound were cooler than normal. In late spring, warmer-than-normal water temperatures developed and persisted through the end of the year. The early cold period marked the end of impacts from the Northeast Pacific marine heat wave on Puget Sound water temperatures that started in late 2014. The warmer than normal period in 2017 was not as anomalously warm as in 2015 and 2016. Departures from historical baselines (anomalies) from 1999–2008 show 2017 water temperatures (calculated as thermal energy content) in the 0–50 m layer of the water column (Figure 11A).

Puget Sound was fresher than normal for most of 2017, setting new record minima in salinity at many sites in May and June. Similar to 2015 and 2016, warm air temperatures in early spring prematurely melted mountain snowpack, leading to higher than normal river flows. This condition, together with record rain, increased river inputs to levels high enough to lower salinity at 18 sites to new historic minima. Monthly Sound-wide anomalies for the 0–50 m layer showed Puget Sound continued to have record fresh conditions similar to the past few years, exceeding conditions during the record wet La Niña years of 2011 and 2012 (Figure 11B).

Temperature and salinity determine water column vertical density structure 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 surface freshwater inputs. A low-delta potential energy anomaly value indicates a more stratified water column that requires more tidal or wind energy to mix than normal. A higher anomaly value means that it is more mixed than normal. With higher than normal river flows, the water column for the 0–50 m depth layer was more stratified in 2017 than the historical baseline, particularly in the spring months (Figure 11C). Monthly stratification, expressed as potential energy, followed the pattern of surface salinity.

Ferry view of the San Juan Islands. Photo: Su Kim.

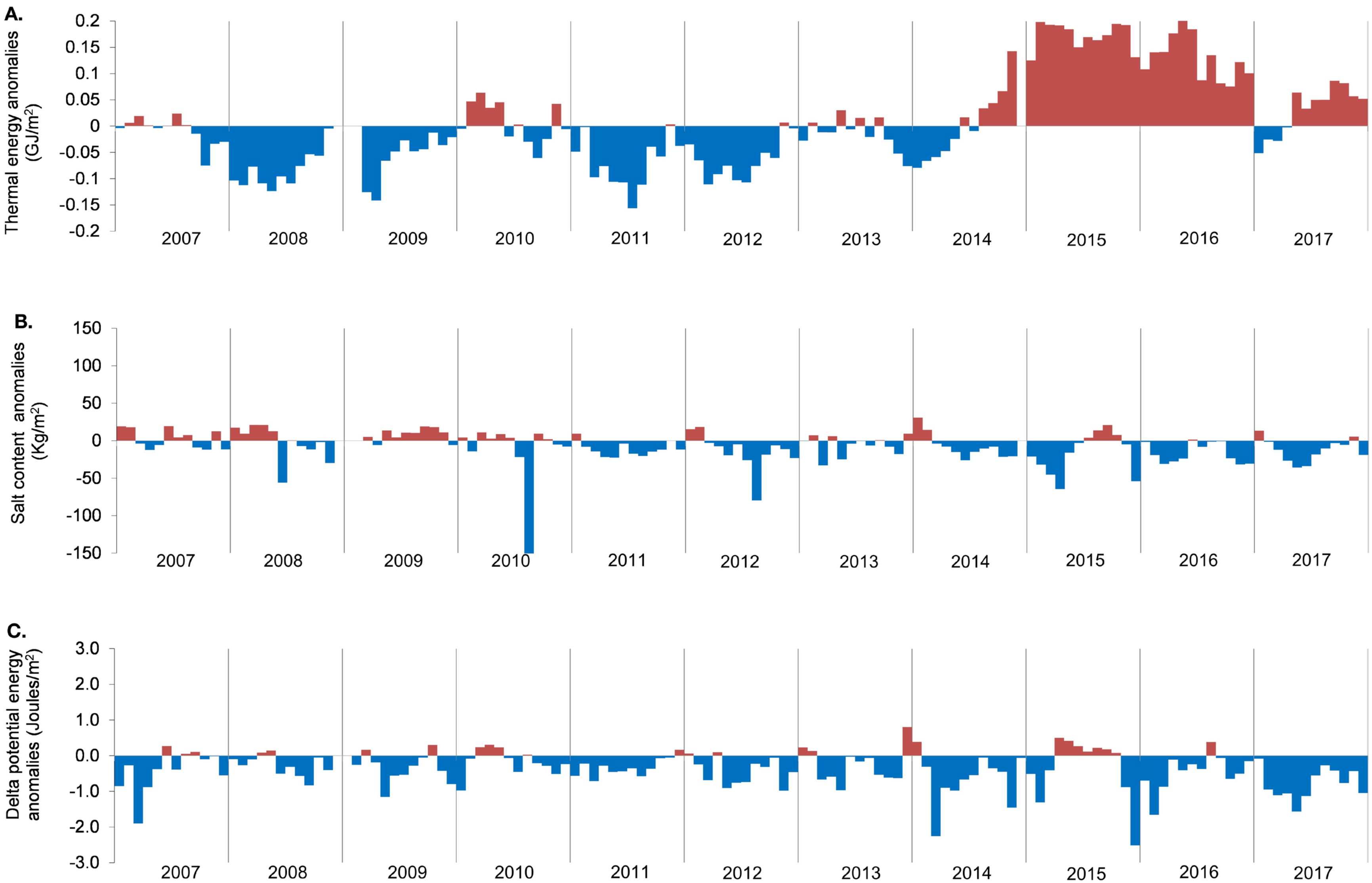


Figure 11. Average Puget Sound-wide monthly anomalies of (A) thermal energy, (B) salt content, and (C) potential energy in the 0–50 m water layer from 2007–17. Monthly anomalies are calculated from site-specific monthly averages using a reference baseline from 1999–2008. Blue = lower, red = higher.

5.A.ii. Dissolved oxygen

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

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

Figure 12 shows the monthly and annual Sound-wide anomalies in the DO deficit relative to the baseline conditions. Overall, the DO deficit for 2017 was high and similar to the previous few years, continuing the pattern of lower DO conditions which started in 2013.The exception to this was May, when DO recovered briefly in the spring after record rainfall and runoff. Prior to 2013, 2007 and 2008 also showed higher deficits, though not nearly as large as the current period. Deficits in 2009–11 varied between higher and lower patterns, while 2012, a La Niña year, showed a significantly lower deficit.

(Top) Algae bloom in Budd Inlet South Sound, July 24 2017. (Bottom) Puyallup River discharging fine sediments, July 24 2017. Photos: Christopher Krembs, Eyes Over Puget Sound.

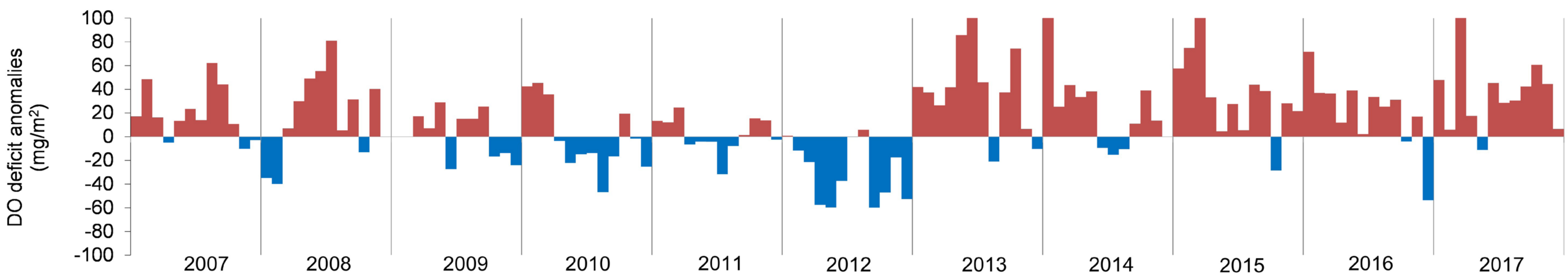


Figure 12. Average Puget Sound-wide monthly anomalies of the dissolved oxygen deficit in waters greater than 20 m from the bottom from 2007–17. Monthly anomalies are calculated from site-specific monthly averages using a reference baseline from 1999–2008. Blue = lower, red = higher.

5.A.iii. Nutrients and chlorophyll

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

Ecology's monthly sampled nutrient and chlorophyll-a concentrations reveal long-term patterns and trends in Puget Sound water quality. To understand trends within the large natural range of variability, regional and seasonal patterns are removed by comparing site-specific monthly baselines to the 50th percentile of observations from 1999–2008. The anomalies (departures from baselines) are averaged over 12 months and 27 stations to evaluate large-scale interannual changes.

Figure 13A illustrates the interannual variation in median nitrate concentrations for surface waters (0–5 m, 5–20 m, and 20–50 m depth bins). Nitrate concentrations peaked at most stations in 2008 and then returned to levels seen a decade before. 2017 nitrate concentrations were slightly higher than the previous two years. Variation in nitrate concentrations is driven by many factors, including the amount of upwelled oceanic water (which is high in nitrate) that enters Puget Sound. To separate ocean influences from other sources of nitrate, salt is used as a conservative tracer to construct a dilution line of mixing between ocean and freshwater (that enters Puget Sound from rivers, the Strait of Juan de Fuca, and other land-based sources). Deviations of nitrate along this dilution line reflect regional and seasonal processes of nutrient cycling (Krembs 2012). Subtracting baselines of the enrichment patterns, the anomalies of non-oceanic nitrate are revealed. Figure 13B shows a general increase in the yearly anomalies of nitrate enrichment relative to ocean-source waters since 1999, with conditions from 2008–17 remaining similar.

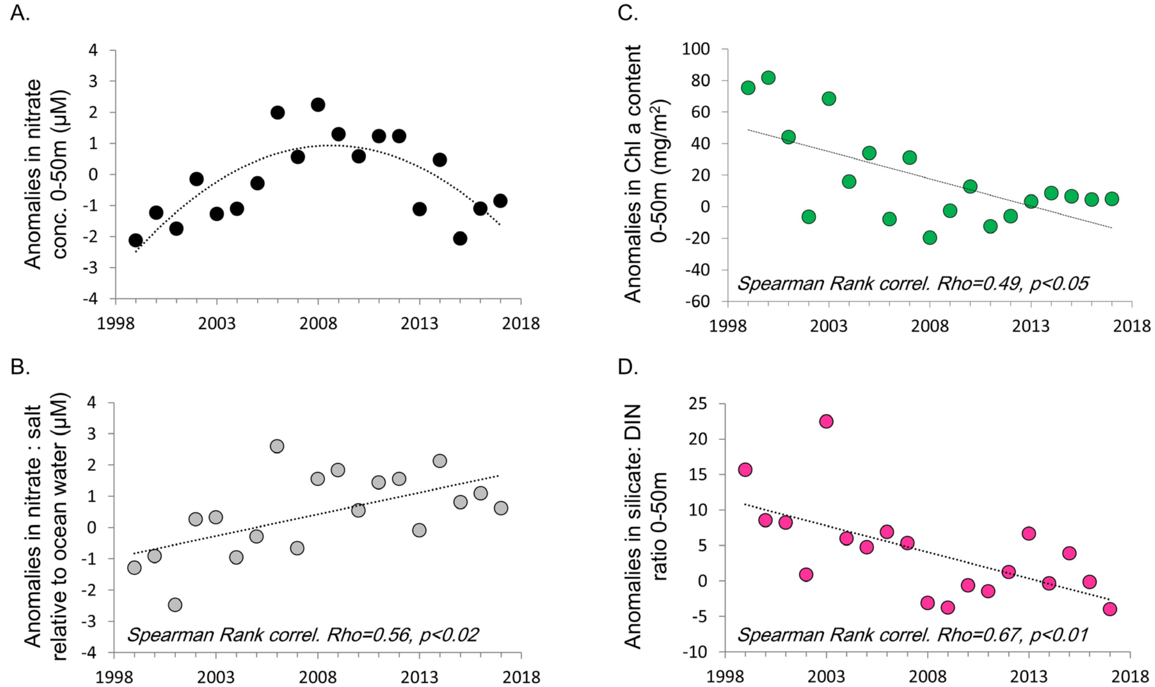


Figure 13. (A) The yearly variation in median nitrate concentration in surface waters (0–5 m, 5–20 m, and 20–50 m). (B) Non-oceanic nitrate trends over time. (C) Declines in depth-integrated chlorophyll (Chl-a). (D) The ratio of silicate to dissolved inorganic nitrogen trends.

Non-oceanic nitrate trends in surface waters are influenced by many remaining factors, including biological uptake, biogeochemical processes, and inputs from land. Figure 13C shows a declining trend in depth-integrated chlorophyll, a proxy for phytoplankton biomass, which is significantly correlated with non-oceanic nitrate (Spearman Rank correlation rho = -0.71, $p < 0.002$, $n = 19$). Similar to the trend observed for non-oceanic nitrate (Figure 13B), chlorophyll concentrations have remained at comparable levels in recent years (Figure 13C). This shows that changes in phytoplankton biomass should be considered alongside changes in nutrients. The silicate-to-dissolved inorganic nitrogen (DIN) ratio is recognized as an indicator of eutrophication (Turner 2002) and has consistently declined over the last 19 years (Figure 13D).

Ecology's EOPS program documents aerial observations of putative indicators of eutrophication, including blooms of Noctiluca and other dinoflagellates, jellyfish, and mats of macro-algae (Vasas et al. 2007). In August of 2017, we documented Noctiluca in Carr and Case Inlets and macro-algae next to Maury Island and Port Madison. Purple-brown dinoflagellates dominated Dyes, Sinclair, Eld, and Budd Inlets and Liberty Bay into October. Jellyfish abundance, on the other hand, was low in 2017 compared to previous years.

5.A.iv. Water mass retention

Source: Skip Albertson (skip.albertson@ecy.wa.gov), Christopher Krembs, Julia Bos, Allison Brownlee and Carol Maloy (Ecology); https://ecology.wa.gov/Water-Shorelines/Puget-Sound

Hydrographic data from Ecology and King County's long-term marine monitoring programs along a transect through Puget Sound (Figure 14) show that the low-salinity water which formed during the wet spring of 2017 persisted through the summer, when there was virtually no additional freshwater input (Figure 15). The observation of this fresh water mass, through a warm and especially dry summer, can only be the result of retention of the record-breaking winter/spring precipitation and associated river flows. Offshore salinity was reported as elevated (see Coastal ocean section 3.A; NW Washington Coast water properties) below 60 m after a delayed onset in coastal upwelling. Salinity in the Strait of Juan de Fuca and Bellingham Bay was as expected (see Water quality section 5.E.i; San Juan Channel/Juan de Fuca fall surveys), but throughout Puget Sound, salinity remained anomalously low. These anomalies are shown from a station midway along a transect through Puget Sound at East Passage (EAP001; circled in red in Figure 14) in Figure 16. Salinity throughout the water column gets progressively saltier from July through September, but remains outside of the interquartile range (fresher than normal) for the entire summer.

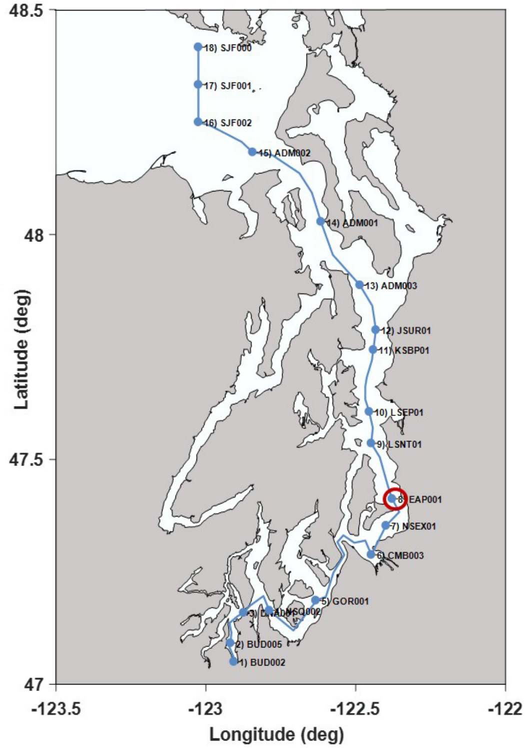


Figure 14. Map showing the locations of Ecology's and King County's long-term monitoring stations used to construct the salinity transect through Puget Sound from Olympia to Admiralty Inlet.

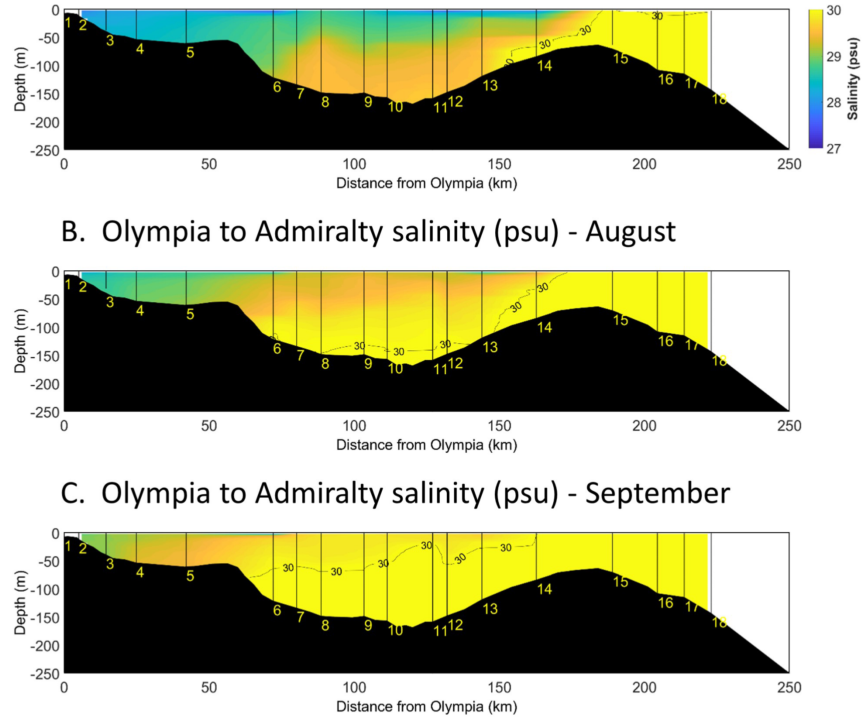


Figure 15. Salinity along a transect in Puget Sound from Olympia to Admiralty Inlet for (A) July, (B) August, and (C) September 2017.

Calculations of "residence" or "flushing" times often do not include the effect of refluxing shallow, low-salinity water exiting from a basin. Mixing over the entrance sill(s) in Admiralty Inlet, and to a lesser extent in Tacoma Narrows, causes some of the departing fresher surface water to mix downward and flow back into the basin. Cokelet and Stewart (1985) used the term "mean tracer age" to account for refluxing, although perhaps "retention time" is a simpler concept. A longer retention time could have implications for worsening water quality.

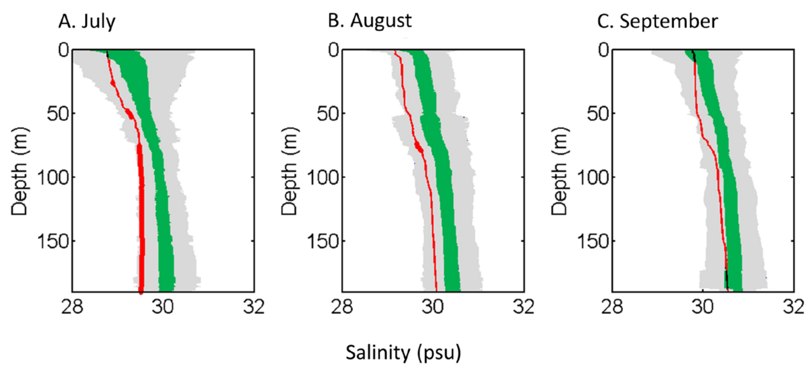


Figure 16. Vertical profiles of salinity at station EAP001 in East Passage for (A) July, (B) August, and (C) September 2017. The profile of salinity is the solid vertical line that is red when outside (black inside) the green interquartile range (climatology of 1999–2016).

5.B. Puget Sound profiling buoys

Profiling buoys take frequent (> 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: Hood Canal (Twanoh and Hoodsport), Dabob Bay, the Main Basin (Point Wells), Admiralty (Hansville), and southern Puget Sound (Carr Inlet).

5.B.i. Temperature

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

Observations from the UW ORCA mooring program show that temperature trends in 2017 at most locations were closer to the climatological averages than in the previous two years and were varied, both over time and between basins. Southern Hood Canal showed the most dramatic pattern, with temperatures at depth at Twanoh (Figure 17A) starting the year above the climatological average by two standard deviations, hovering around the climatological average during the summer, then increasing steeply to +1 standard deviation during the fall flushing in late September. This pattern is in stark contrast to temperature trends observed at Carr Inlet in South Sound (Figure 17B), where temperatures were slightly cooler than the climatological average throughout the water column from the start of the year until the late-summer warming of the surface waters; temperatures at depth hovered near average throughout the year. Temperature anomalies at Point Wells (Main Basin) and Hansville (near Admiralty Inlet) were smaller and exhibited similarly over the full water column, with a fortnightly signal associated with tidal fluctuations at Hansville.

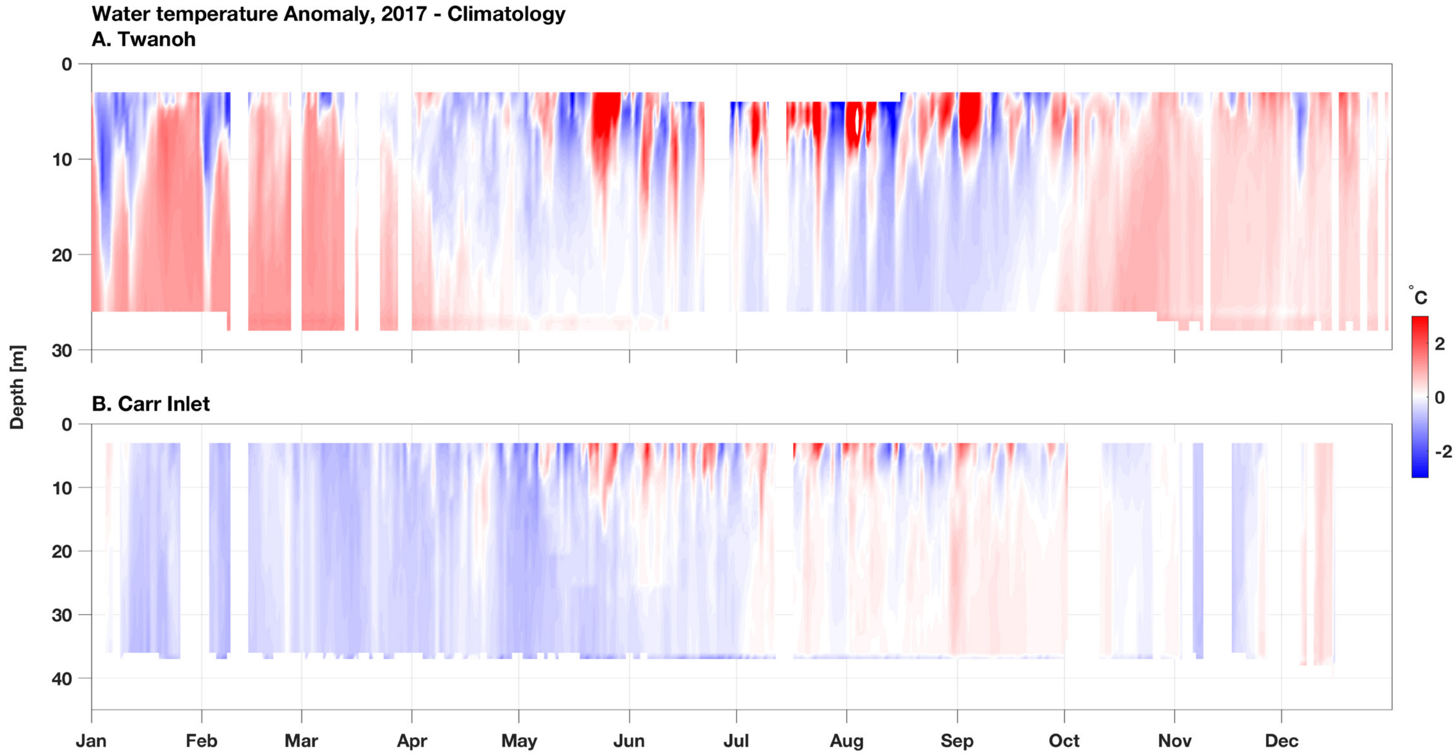


Figure 17. 2017 water temperature anomalies (compared to 2005–16 average) for Twanoh and Carr Inlet moorings. Data are colored by a white threshold at zero, with red indicating warmer than historical averages conditions, and blue colder.

5.B.ii. Salinity

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

The UW ORCA mooring observations showed that salinity fluctuated in three distinct periods in 2017 that co-varied with rainfall and river flow, similar to the patterns observed during 2015 and 2016. Though the magnitude of the anomalies was strongest at Twanoh and Carr Inlet (Figure 18), these changes were observed throughout Puget Sound and Hood Canal. As seen in both 2015 and 2016, a wetter than normal

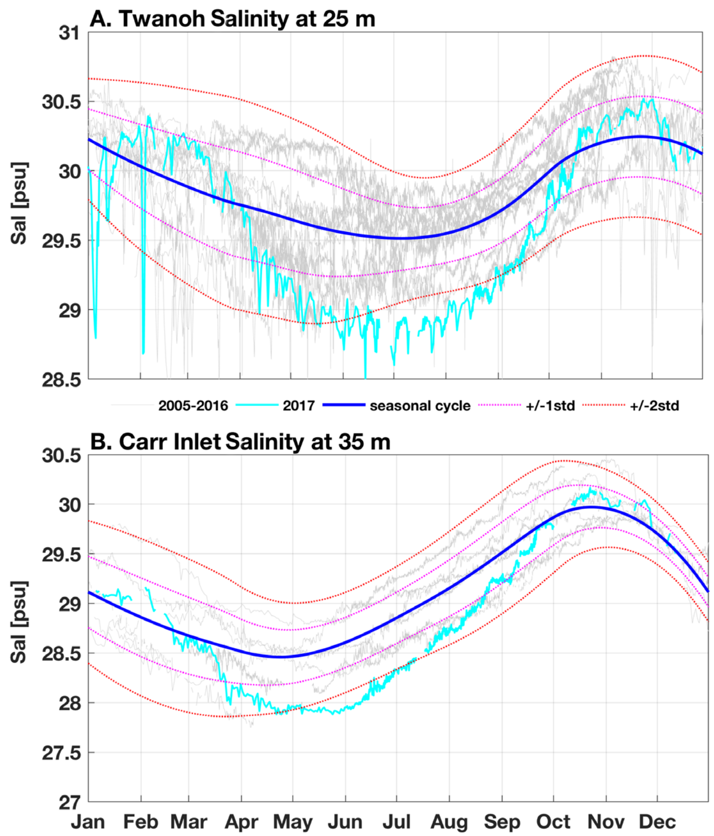


Figure 18. 2017 data (cyan line), climatology (dark blue line), and all historical data (gray lines) for near-bottom salinity at the Twanoh (n = 11 years) and Carr Inlet (n = 7 years) moorings; also shown are ±1 (pink dotted line) and 2 (red dotted lines) standard deviations from the climatology.

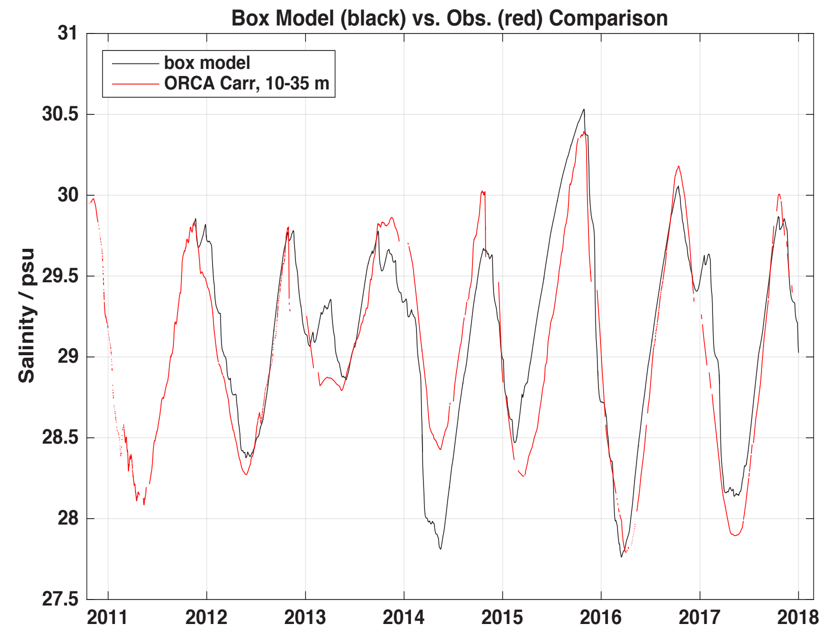


Figure 19. Observed (red) and predicted (black) salinity at the Carr Inlet mooring.

spring in 2017 produced fresh (lower salinity) anomalies over the full water column. This was followed by a summer drought where salinities progressed from fresher (two standard deviations below normal) to saltier (<1 standard deviation above normal). Finally, an extremely wet fall reduced salinities back to near the climatological average throughout the water column.

The spring low salinity anomaly at depth for both Twanoh and Carr Inlet was the most extreme observed there, though the magnitude of the late-summer high salinity anomaly in 2017 was not as large as in previous years. As noted above, these patterns were closely correlated with river flow. A simple one-layer box model for South Sound, which includes varying flows from the Nisqually and Puyallup Rivers as the only time-dependent input, produced >90% of the variance of salinity changes in South Sound over six years as measured from the Carr Inlet ORCA mooring (Figure 19). This result indicates that changes in South Sound salinity are dominated by changes in river flow, not changes in the salinity of deep water entering Tacoma Narrows from the Main Basin. This has implications for density driven circulation.

5.B.iii. Dissolved oxygen

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

The UW ORCA mooring observations showed that DO anomalies during 2017 were small and positive throughout Puget Sound and Hood Canal, with minimal hypoxia and no fish kill events observed in southern Hood Canal. Oxygen concentrations measured at Twanoh were the least hypoxic on record over the last several years (Figure 20).

Dynamics for the 2017 fall intrusion in southern Hood Canal, however, were unusual, with warmer and higher than average oxygen waters observed at depth in late summer, followed by hypoxic cooler waters in mid-September (Figure 21). The hypoxia was short-lived at Hoodsport (Figure 21C), as the fall flushing event brought in warmer, saltier, and higher oxygen waters, with deep water oxygen concentrations rapidly increasing to one standard deviation above the climatological average by October 1. This brief hypoxic event was also seen at Twanoh (Figure 20F), but, as expected, lagged behind the Hoodsport observations by roughly two weeks. The strong freshwater anomaly in Hood Canal deep

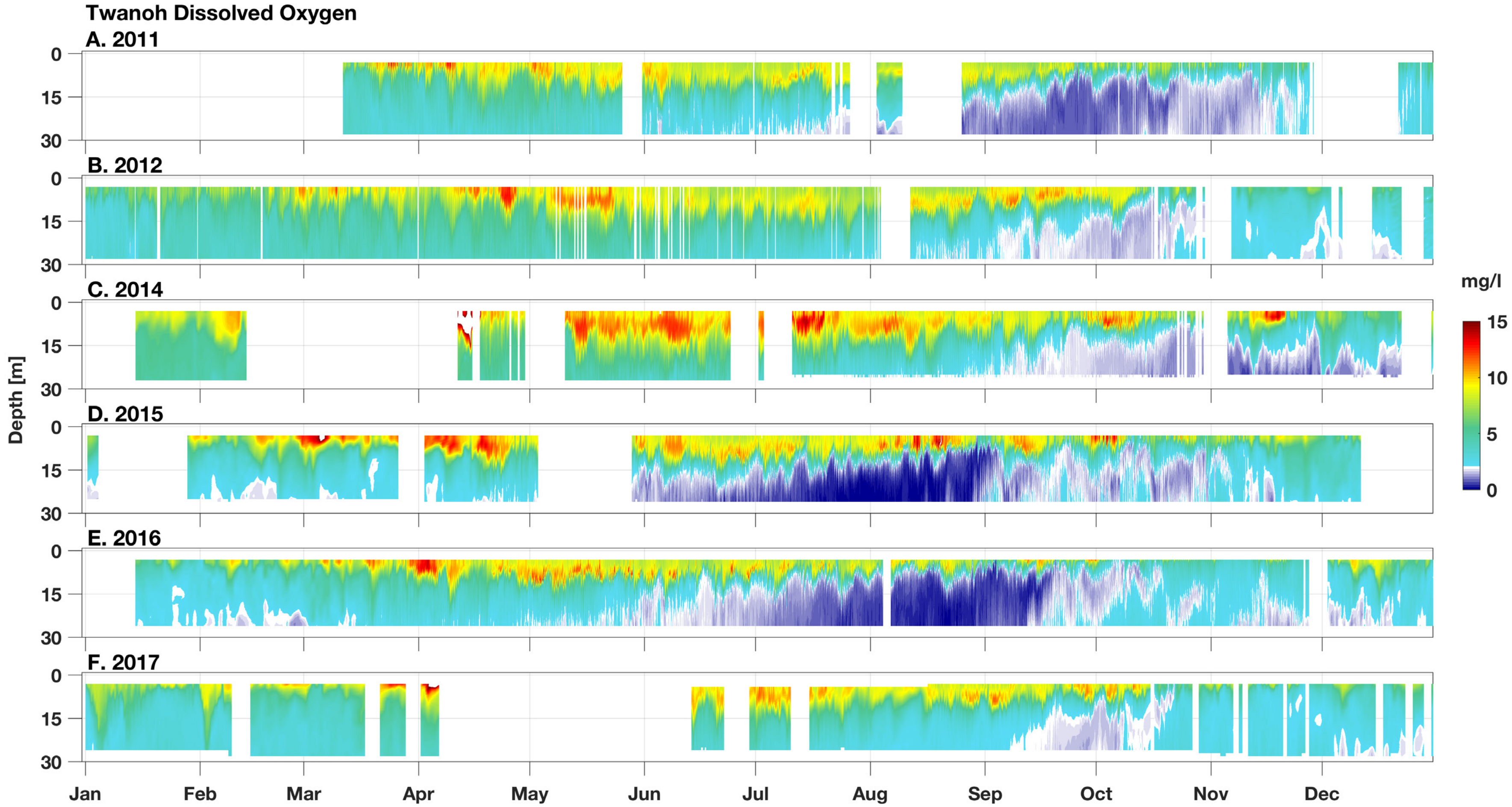
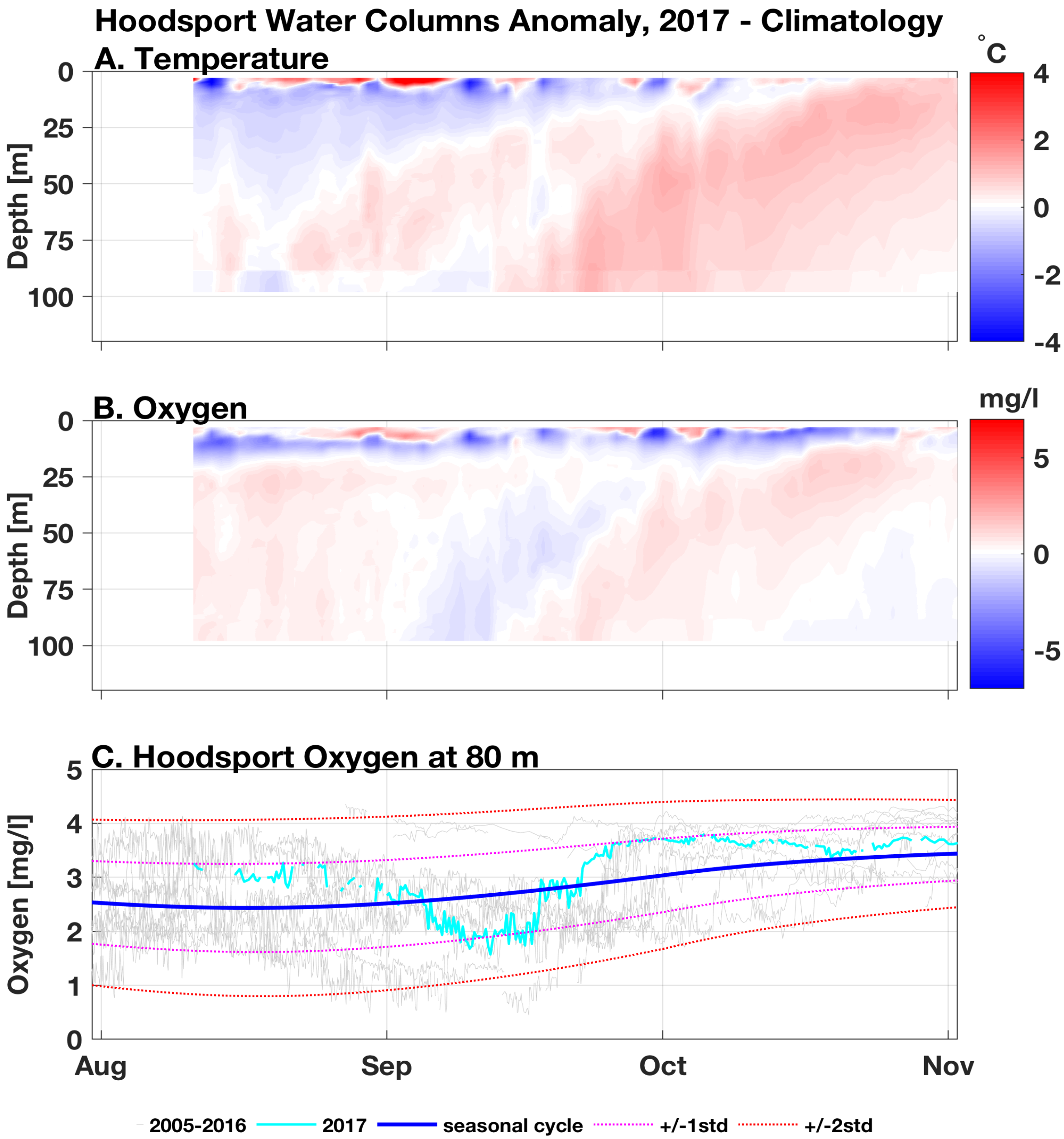


Figure 20. Time series of water column dissolved oxygen concentrations at the Twanoh ORCA mooring from multiple years (2011–17).



waters (see Water quality section 5.B.ii; Salinity) that was a consequence of the wet winter/spring of 2017 resulted in large negative density anomalies. This water was, in turn, more easily replaced by water from the Hood Canal and Admiralty sills. A steady increase of deep density and salinity throughout the summer, which indicates a steady inflow of new water, supports this conclusion and explains the anomalously high deep DO levels in 2017. If wetter winters/springs and drier summers become the norm under a changing climate, these 2017 observations suggest that stronger summer flushing and higher DO levels may occur in Hood Canal; however, unpredictability in coastal upwelling dynamics could offset this and lead to increased variability.

Figure 21. (A) 2017 water temperature anomalies (compared to 2005–16 average) for Hoodsport. Data are colored by a white threshold at 0, with red indicating warmer than historical average conditions, and blue colder. (B) 2017 dissolved oxygen anomalies for Hoodsport. (C) 2017 data (cyan line), climatology (dark blue line), and all historical data (gray lines) for near-bottom oxygen concentrations at the Hoodsport (n = 11 years) mooring; also shown are ±1 (pink dotted line) and 2 (red dotted lines) standard deviations from the climatology.

5.B.iv. Ocean and atmospheric CO_2

Source: Simone Alin (simone.r.alin@noaa.gov), Adrienne Sutton, Richard Feely (NOAA, PMEL), Sylvia Musielewicz (UW, JISAO), Al Devol, Wendi Ruef (UW, Oceanography), Jan Newton, John Mickett (UW, APL), and Christopher Sabine (Univ. Hawaii); http://www.pmel.noaa.gov/co2/story/Dabob; http://www.pmel.noaa.gov/co2/story/Twanoh; PMEL contribution number 4783.

Carbon dioxide sensors have measured atmospheric and surface seawater xCO_2 (mole fraction of CO_2) at three-hour intervals on surface ORCA moorings in Dabob Bay since June 2011 and at Twanoh since July 2009. Both sites had full-year data coverage and 97–98% data return in 2017 (Figure 22).

During 2017, atmospheric xCO_2 at Dabob averaged 418±11 ppm and ranged from 389 to 485 ppm. At Twanoh, xCO_2 averaged 420±14 ppm and ranged from 387 to 673 ppm. Thus, average atmospheric values at both moorings were higher than the global average for marine surface air of 405 ppm[2] by 13–17 ppm in 2017. During the pronounced stagnant air event over Puget Sound in December 2017, a noticeable enrichment in atmospheric xCO_2 developed. Between December 7 and 21, atmospheric xCO_2 climbed roughly 23–24 ppm at Twanoh and 16–19 ppm at Dabob above the mean baseline values during the days before and after that period.

The surface seawater xCO_2 record at both Dabob and Twanoh exhibited seasonal timing more typical of years prior to the extended marine heat wave of 2015 and 2016. The annual spring drawdown of xCO_2 after fall–winter highs occurred in March–April 2017 rather than January–February as in 2015–16.

Surface seawater xCO_2 at Twanoh ranged from 48 to 1,448 ppm in 2017, with an average of 412±183 ppm. At Dabob, 2017 surface seawater xCO2 ranged from 121 to 1,183 ppm and averaged 385±194 ppm. Average surface seawater xCO_2 was thus 81–108 ppm higher than at the Cape Elizabeth coastal ocean buoy during 2017, with 2.6–2.8 times higher variability as reflected by the standard deviation (see Coastal ocean section 3.B; Ocean and atmospheric CO_2; Table 1).

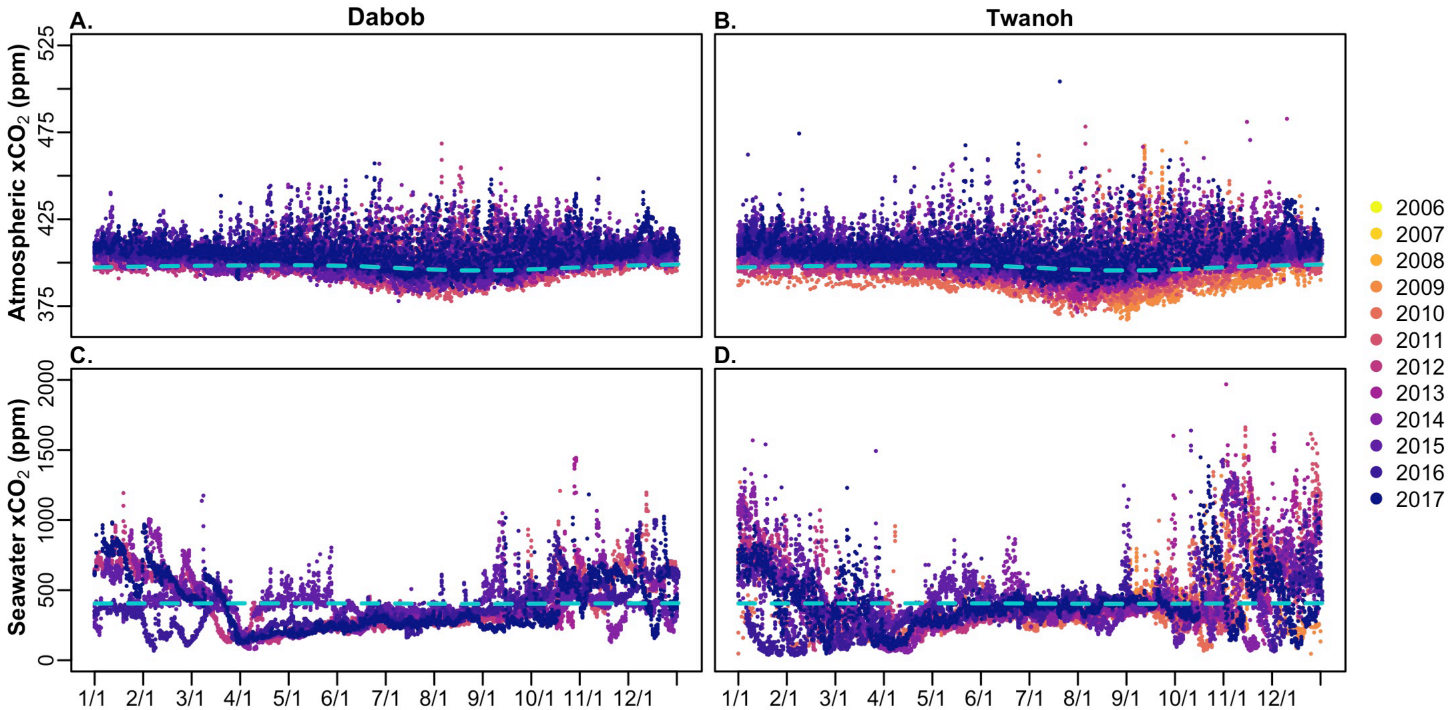


Figure 22. The mole fraction of carbon dioxide (xCO2) in air at 1.5 m above seawater (A, B) and in surface seawater at 0.5 m depth (C, D) on the ORCA mooring in Dabob Bay, WA (A, C), and on the ORCA mooring at Twanoh, WA (B, D). Monthly mean atmospheric xCO2 values for globally averaged marine surface air are shown by the dashed line in each panel (NOAA/ESRL)[2]. Typical uncertainty associated with quality controlled measurements from these systems is <2 ppm for the range 100–600 ppm, increases for values between 600 and 1,000 ppm, and is not well constrained above 1,000 ppm.

[2] NOAA/ESRL website: ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_annmean_gl.txt; accessed May 12, 2018.

5.C. Central Basin long-term stations

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

5.C.i. Temperature, salinity and density

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

In the first half of 2017, water temperatures both at the surface (<2 m) and deep depths (>75 m) returned to normal or slightly cooler than normal conditions in the Central Basin, ending the period of warmer than normal temperatures from 2015–16 (Figure 23A). Beginning in July 2017 and continuing through the rest of the year, warmer than normal conditions were observed, though not as warm as in 2015–16. Water temperatures in the second half of 2017 were on average 0.3–0.7°C warmer than the baseline mean (1999–2010). This timing coincided with warmer than normal air temperatures. Beach water temperatures were elevated in summer as well, but were otherwise generally within typical observed ranges.

Water column salinity observations were generally lower than normal for much of 2017, with deep salinities reaching 0.9 PSU fresher than the baseline mean in the spring (Figure 23B). This spring pattern is similar to 2016; however, the timing differs in that fresher than normal conditions continued late into summer. This may be related to high river flows in the spring through June, when increased mixing and exchange at sills in Puget Sound could contribute to freshening at deep depths. Nearshore salinities were generally within observed ranges, with the exception of lower than normal salinities in February, March, and November at several sites, corresponding to higher than normal precipitation during these months.

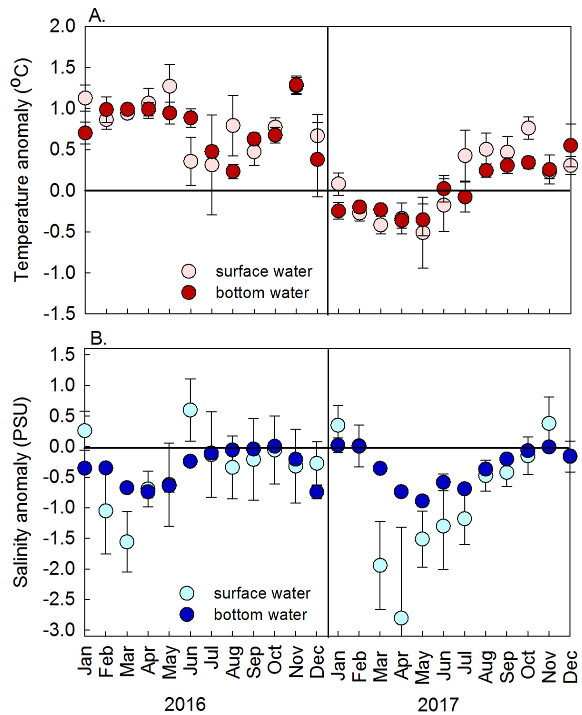


Figure 23. (A) Mean and standard deviation of 2016–17 water temperature anomalies for the seven deepest sites in the Central Basin, compared to a fixed baseline average (1999–2010). (B) Mean salinity anomalies for the same sites. Negative values indicate fresher-than-average conditions.

While density patterns showed typical seasonal differences throughout the water column, density gradients in upper layers exceeding 0.1 kg/m^3 were observed from 4–20 m in almost all weekly and biweekly profiles from late March through the first week of September, with some profiles showing much stronger gradients (shown by stars in Figure 24). This water column stratification was more frequently observed in 2017 than in prior years in the Central Basin during the growing season, and has important implications for plankton dynamics. Sharp near-surface density gradients were driven primarily by fresher surface waters for much of the year, with water temperature also playing a role from July through September. High densities in deep waters occurring in the fall were likely related to intrusions of higher-salinity oceanic water masses.

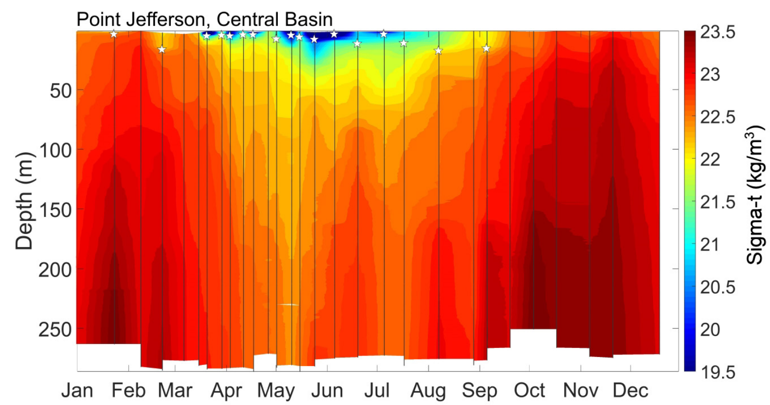


Figure 24. Density profiles near Point Jefferson, the deepest site in the Central Basin. Black vertical lines show when data were collected, and white stars indicate the depth of the sharpest density change that exceeds a threshold of 0.1 kg/m3 (as calculated in Moore et al. 2008b).

5.C.ii. Dissolved oxygen

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

Observations from twice-monthly sampling in the Central Basin showed a strong seasonal signal in DO levels in 2017. Deep-water DO (>75 m) was higher than normal in the spring and lower than normal in the fall (Figure 25A). October deep-water DO levels ranged from 4.5–5.5 mg/L across the Central Basin, about 0.5 mg/L below the baseline mean (1999–2010). At East Passage, which tends to show the lowest DO in the deep basin, DO levels were below 5 mg/L from 60 m and deeper (Figure 25B). This period overlaps with higher density observations (shown for Point Jefferson in Water quality section 5.C.i; Temperature, salinity and density; Figure 24) and is likely related to both oxygen consumption during decay of phytoplankton blooms and intrusions of lower-oxygen oceanic waters. In May, deep water DO levels reached 0.8 mg/L above the baseline in the northern central sites, coinciding with fresher-than-normal conditions (Figure 23B). This supports the concept of increased mixing and exchange at the Admiralty sill in the spring that could lead to freshening and more oxygenated conditions at depth.

From April through early September, higher surface DO (Figure 25B) levels corresponded to higher levels of chlorophyll-*a* and stratification.

In Quartermaster Harbor, which is very shallow and has long flushing times, DO levels were lowest in the fall (<35% DO saturation, or 3 mg/L at 15°C and a salinity of 28 PSU) at the inner harbor site (Figure 25C). During the spring and early summer, supersaturated conditions (>100%) persisted due to primary production, though levels were not as high as in prior years. Both mooring sites in the harbor showed high diurnal variability, changing as much as 10–15 mg/L between day and night during the fall.

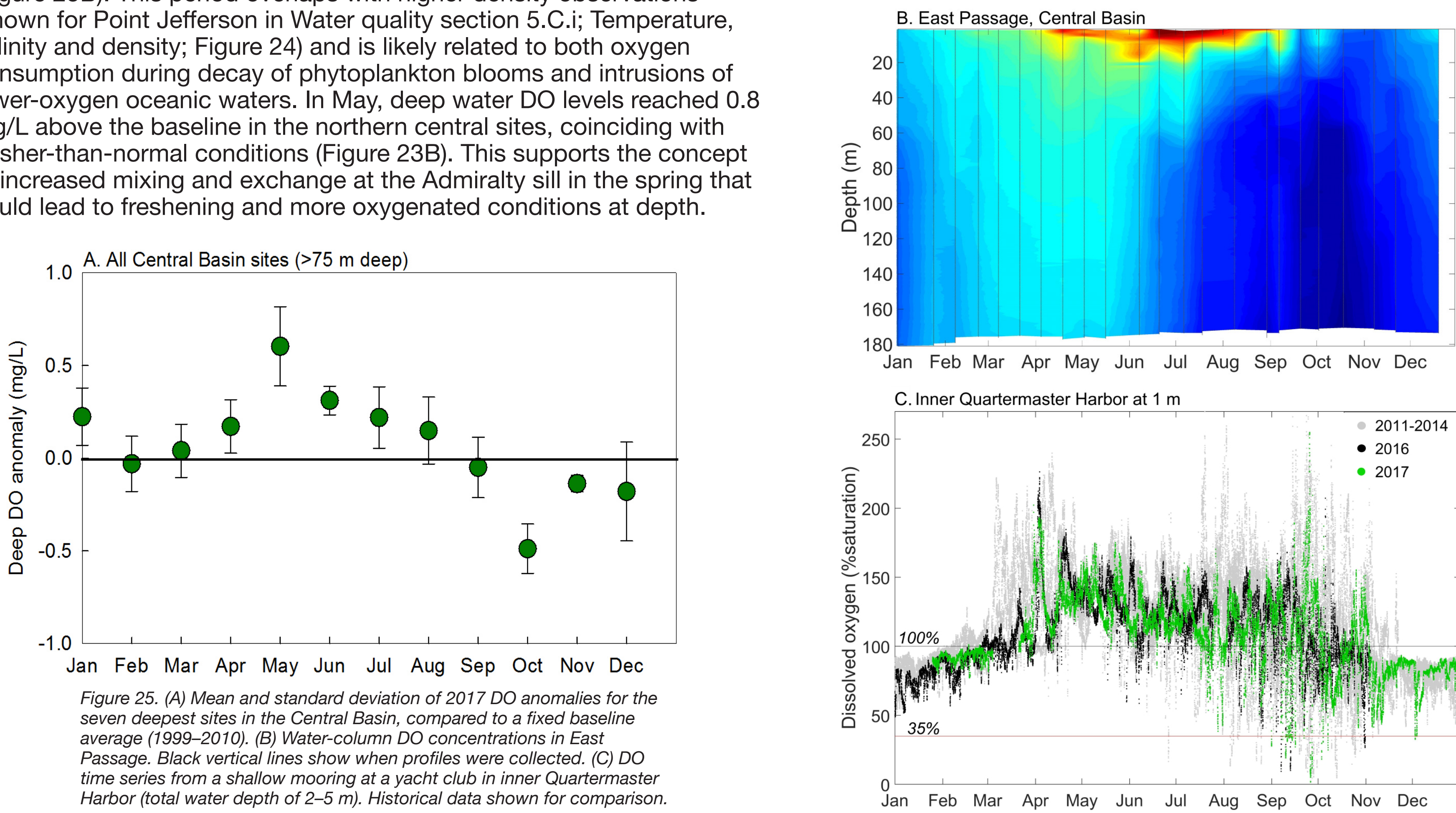


Figure 25. (A) Mean and standard deviation of 2017 DO anomalies for the seven deepest sites in the Central Basin, compared to a fixed baseline average (1999–2010). (B) Water-column DO concentrations in East Passage. Black vertical lines show when profiles were collected. (C) DO time series from a shallow mooring at a yacht club in inner Quartermaster Harbor (total water depth of 2–5 m). Historical data shown for comparison.

5.C.iii. Nutrients and chlorophyll

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

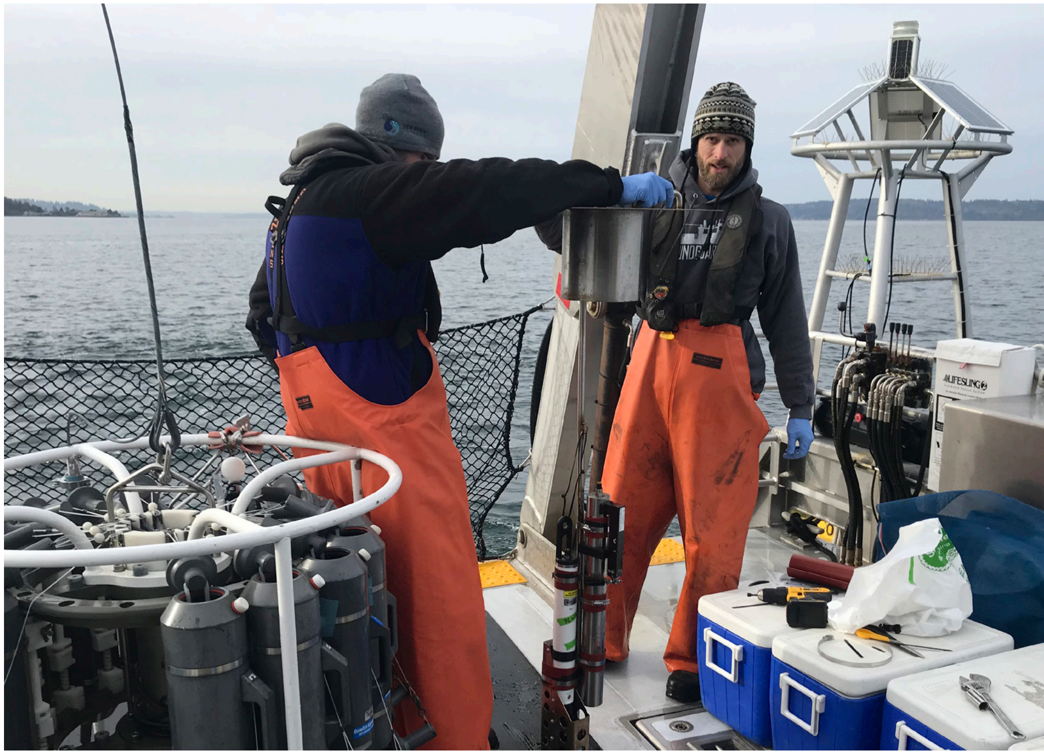
Observations from twice-monthly sampling and in situ moorings in the Central Basin show that the spring phytoplankton bloom in 2017 was evident on April 3 in the northern and central area of the basin, but began later in the month in the southern area. Moored sensor measurements from Point Williams are shown in Figure 26A. Chlorophyll-*a* and nitrate data (15-minute intervals) from April demonstrate the initiation of the spring bloom and subsequent nitrate uptake along with daily variability.

Overall, 2017 chlorophyll-*a* levels throughout the Central Basin were higher than baseline values from April through July, particularly in July (Figure 26B). Persistent spring and summer density stratification may have contributed to these sustained levels; weekly sampling at five sites in the spring showed a pattern of alternating higher and lower chlorophyll-a values that corresponded to the strength of observed water column stratification. Unlike in 2016, the typical fall bloom was observed in 2017.

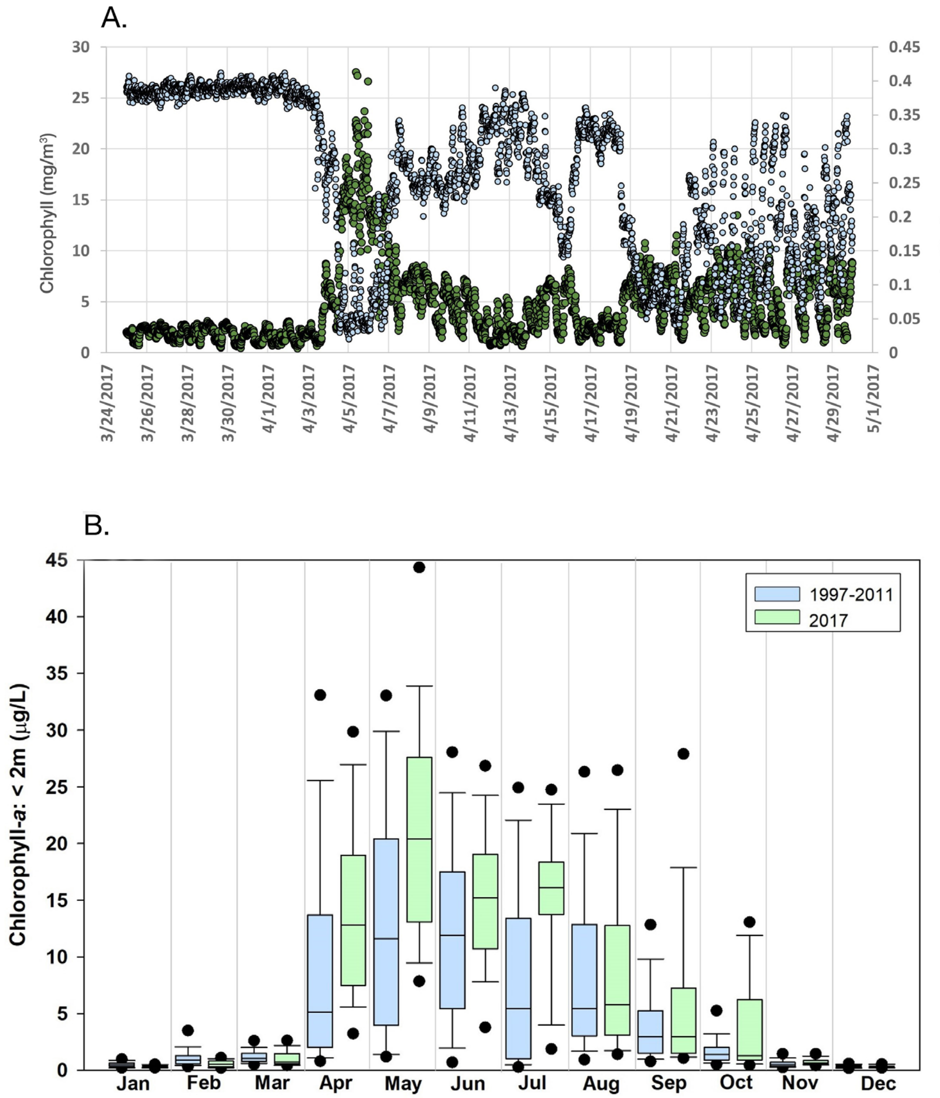
Nutrient levels varied seasonally, with lower surface values correlating well with higher chlorophyll-*a* levels. Nitrate/nitrite levels from June through the end of the year were lower than normal (Figure 26C), as were orthophosphate, total nitrogen, and silica from June through August due to the sustained summer bloom. Surface water nutrients observed in July, including orthophosphate, were lower than normal, with concentrations below detectable levels at some locations. It was atypical to have all surface nutrients depleted (Figure 26D). The West Point Treatment Plant failure in early February and subsequent three months of reduced treated effluent discharged to the Central Basin did not result in a measurable increase in nutrients compared to historical conditions. A detailed water quality monitoring report following the West Point flooding event can be accessed at https://your.kingcounty.gov/dnrp/library/2018/kcr2953/kcr2953.pdf.

Nitrate/nitrite levels in deep waters (>75 m) were lower than normal from August through December. Ammonia and orthophosphate levels were slightly lower than normal in the summer, but fairly typical the remainder of the year. Silica levels in both surface and deep waters were higher than normal during the first part of the year, corresponding to higher than normal freshwater inputs, and then were slightly lower than normal from June through September.

Chlorophyll-*a* levels in inner Quartermaster Harbor were generally lower than normal, which may have been related to nutrient limitation. Extremely low nitrate/nitrite levels were observed throughout the growing season, and very low orthophosphate and silica (below detectable levels) occurred from April through May. Although nutrient levels in the outer harbor were occasionally low, chlorophyll-*a* levels were fairly typical compared to prior years.



Getting new sensors ready for deployment at Point Williams buoy. Photo: Bob Kruger.



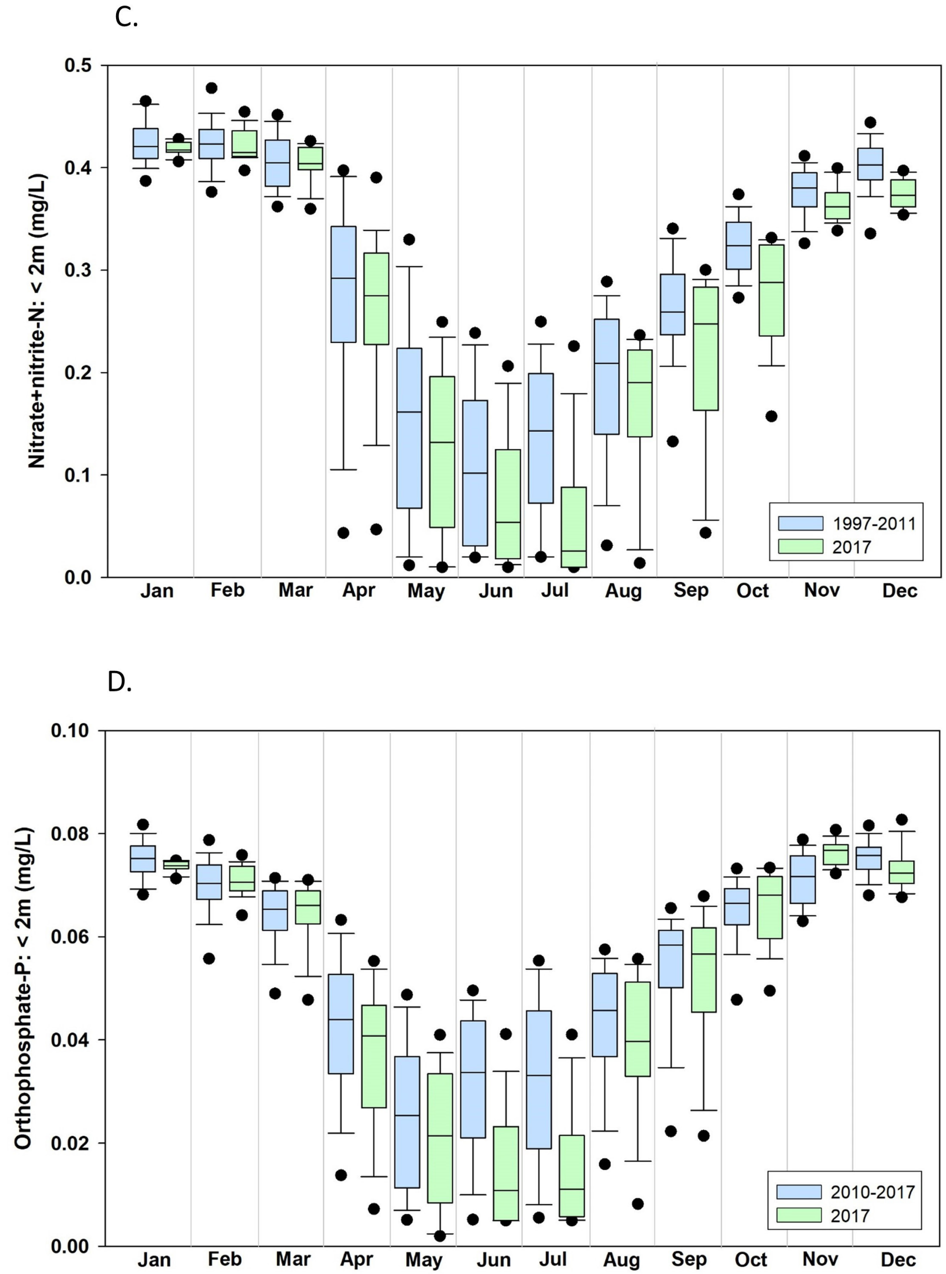


Figure 26. (A) 15-minute surface chlorophyll and nitrate data at Pt. Williams. Surface water (B) chlorophyll-a, (C) nitrate/nitrite levels, and (D) orthophosphate at 12 sites in the Central Basin compared to the long-term baseline. The line within the box denotes the median, box boundaries are 25th and 75th percentiles, whiskers are 10th and 90th percentiles, and points are 5th and 95th percentiles.

5.D. North Sound surveys

5.D.i. Padilla Bay temperature

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

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

Nearshore surface water temperature in Padilla Bay ranged from 2.1–23.2°C throughout the year, with daily fluctuations in excess of 10°C during summer months. These large variations tend to occur during periods of high tidal exchange, where colder water of marine origin is introduced to the otherwise warm water overlying the tidal flats.

Water temperatures in early 2017 (January–May) were substantially cooler than those recorded during the same period in 2016, but otherwise similar throughout the rest of the year (Figure 27). Mean annual water temperature in 2017 (10.7±2.1°C) was substantially cooler (~1°C) than those for the previous two years, indicating a shift away from the anomalously warm water temperatures recorded throughout the region during 2015–16. Mean annual temperature anomalies over the past two decades illustrate a return to more "normal" water temperatures in 2017 (Figure 28). Warmer and cooler periods shown in this figure correlate well with large-scale climatic cycles, specifically the PDO.

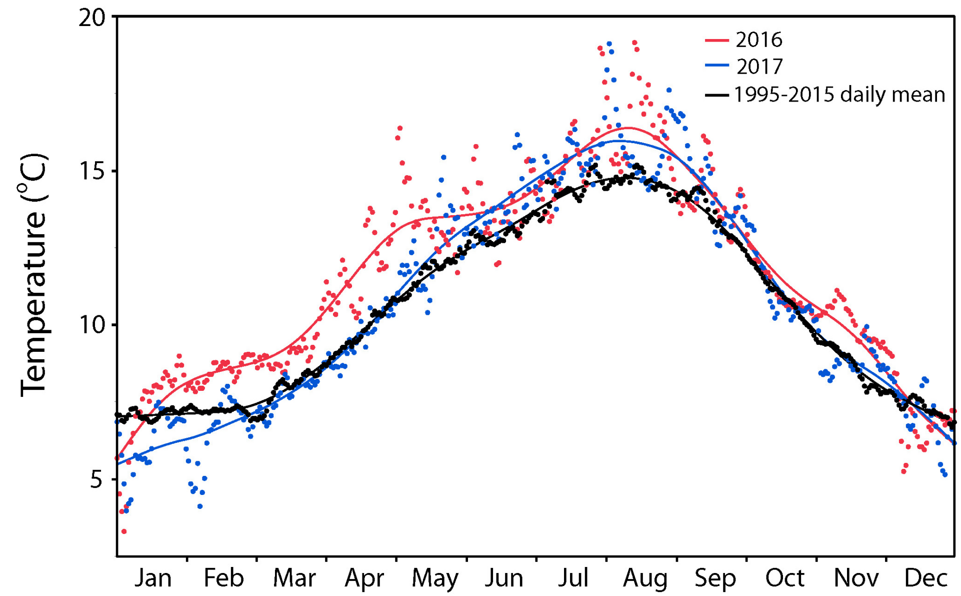


Figure 27. Daily mean water temperature in Padilla Bay during 2016 and 2017. Also shown is the long-term (1995–2014) daily mean.

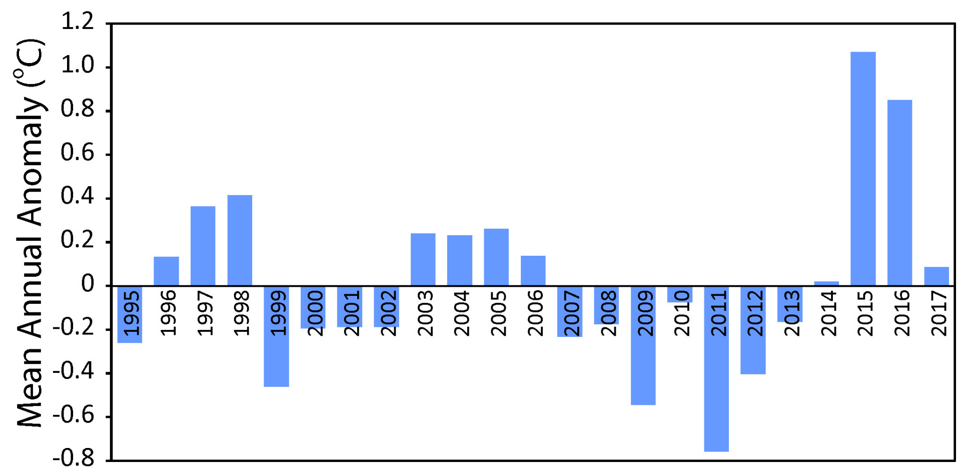


Figure 28. Mean annual water temperature anomalies in Padilla Bay from 1995–2017.

5.D.ii. Bellingham Bay buoy

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

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

During 2017, the Bellingham Bay buoy was equipped with meteorological sensors and oceanographic sensors at 0.5 m depth. The partial seasonal cycle of data is shown in Figure 29 for January to July 2017. Water temperature shows a seasonal temperature increase with high-frequency variation. Notable are periods in January and February when the high-frequency variation is lacking, shown in the other variables as well. These "flat" periods are associated with large drops in barometric pressure (not shown) and stormy conditions that likely resulted in strong mixing, obliterating vertical and possibly reducing horizontal variability. The salinity, CDOM, and turbidity (not shown) 2017 data show strong correlation, as was seen during 2016, suggesting riverine influence likely from the Nooksack River. The large variation in salinity, CDOM, and turbidity observed at the mooring site (~5.5 km from the river mouth) suggests highly dynamic surface conditions (e.g., salinity ranging from 0–30 PSU within a day) exist in the middle of Bellingham Bay.

Surface chlorophyll increased noticeably in mid-April, with a commensurate rise in oxygen consistent with photosynthetic production. This same pattern was observed in 2016. An increase in pH was noted during this same time period, again consistent with uptake of CO_2 from photosynthetic production. As seen in 2016, a large increase in chlorophyll during June was not accompanied by a similarly large change in DO or pH (pH was only measured in 2017). The cause of the different oxygen responses to the April versus June blooms during 2016 and 2017 is not known. One possible explanation for the lack of corresponding increase in DO may be due to advected or less actively growing phytoplankton cells in June versus in situ or rapid growth in April; the repeated pattern offers the potential for future investigation.

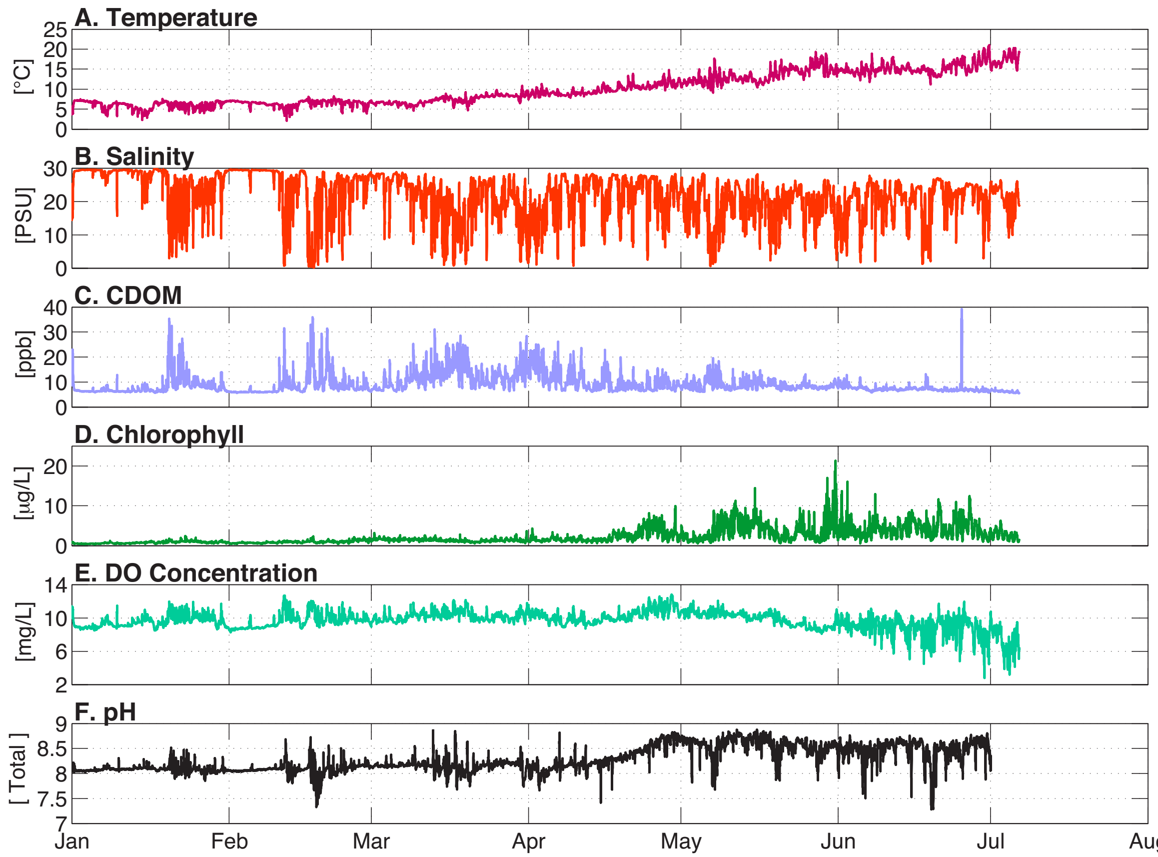


Figure 29. Water properties in Bellingham Bay during 2017. Shown are (A) temperature, (B) salinity, (C) colored dissolved organic matter, (D) chlorophyll, (E) dissolved oxygen, and (F) pH.

5.E. Snapshot surveys

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

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

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

Source: Jan Newton (janewton@uw.edu) (APL, UW), Breck Tyler (UCSC), Rebecca Guenther, and Tara Wilson (UW); http://courses.washington.edu/pelecofn/index.html; http://www.nanoos.org

Based upon the past 14 years of data from 0–80 m depths, fall 2017 water temperatures at the South station were generally near average, but with relatively cooler surface temperatures during the first week of November (Figure 30). Deep (80 m) salinity observations were the highest observed since 2013. Waters with salinity >32.5 PSU have only been observed during six of the 14 years; 2017 equaled 2006 for the highest recorded temperatures of the high-salinity waters. The narrow range of relatively lower salinity in 2014–16 was in stark contrast to the rest of the time series, likely influenced by the Blob. In 2017, the salinity range returned to a much wider and typical distribution, though the relative warmth of the highest-salinity waters may indicate a lingering influence of the Blob.

Warmer than normal (positive) temperature anomalies were clearly observed in deep waters at both the North (~100–110 m) and South (~70–80 m) stations during 2014–16 (Figure 31). However, excluding the 2014–16 marine heat wave years, water temperature anomalies at the North and South stations reveal different patterns; North steadily declined over fall, while at South, temperature generally increased over the same time period. This is consistent with the source of the Strait's deep waters from the coastal ocean that reflect the fall transition from upwelled cooler waters to downwelled warmer waters.

In 2017, marine mammal (harbor porpoise, Steller sea lion, and harbor seal) and seabird (all seabird species combined) abundance was low relative to the 12-year record shown (Figure 32). Since 2013, seabird abundance has been similar to the years prior to the cool conditions of 2010–12. Also since 2013, observed marine mammal densities have steadily declined, with 2017 the lowest of the record. Whether these low numbers reflect lingering response to marine heat wave conditions cannot be ascertained; we hope continuance of the time series will inform this question.

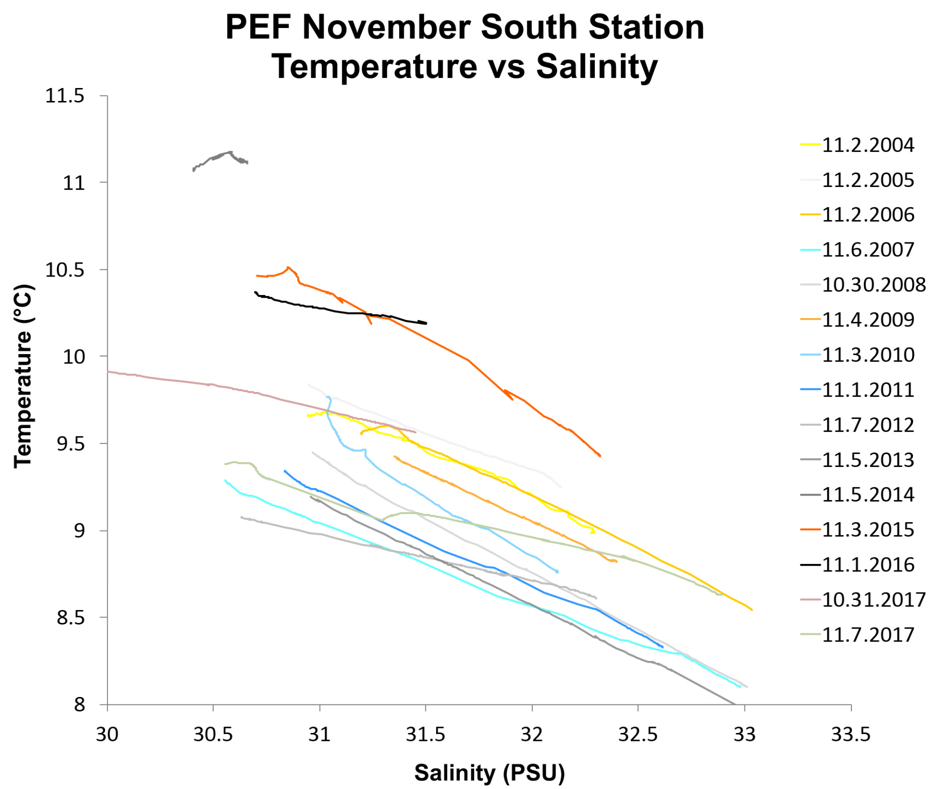


Figure 30. Temperature versus salinity from 80 m to the surface at the South station in the eastern Strait of Juan de Fuca during the first week of November. Deep waters (coldest and saltiest) are found on the right. Color coding: yellow = El Niño years; blue = La Niña years; gray = neutral years.

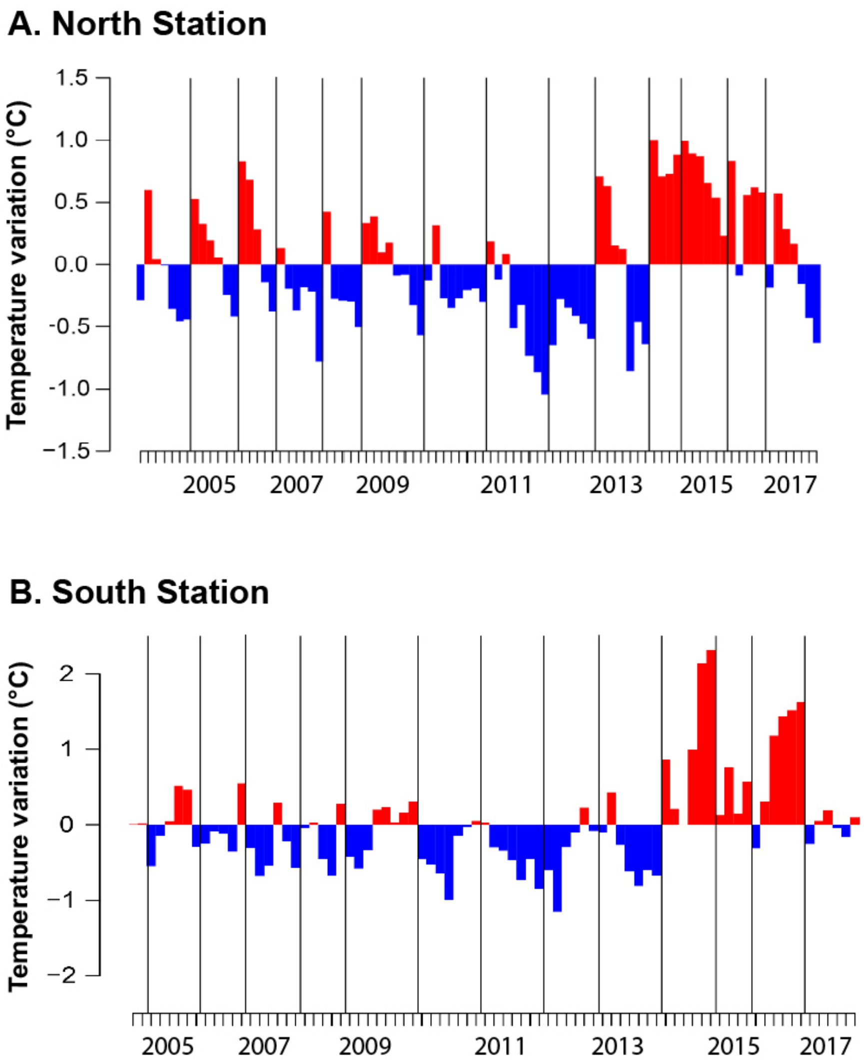


Figure 31. Temperature anomalies for deep waters of the (A) North (~100–110 m) and (B) South (~70–80 m) stations since 2004. Vertical lines denote the year and tick marks indicate sample dates.

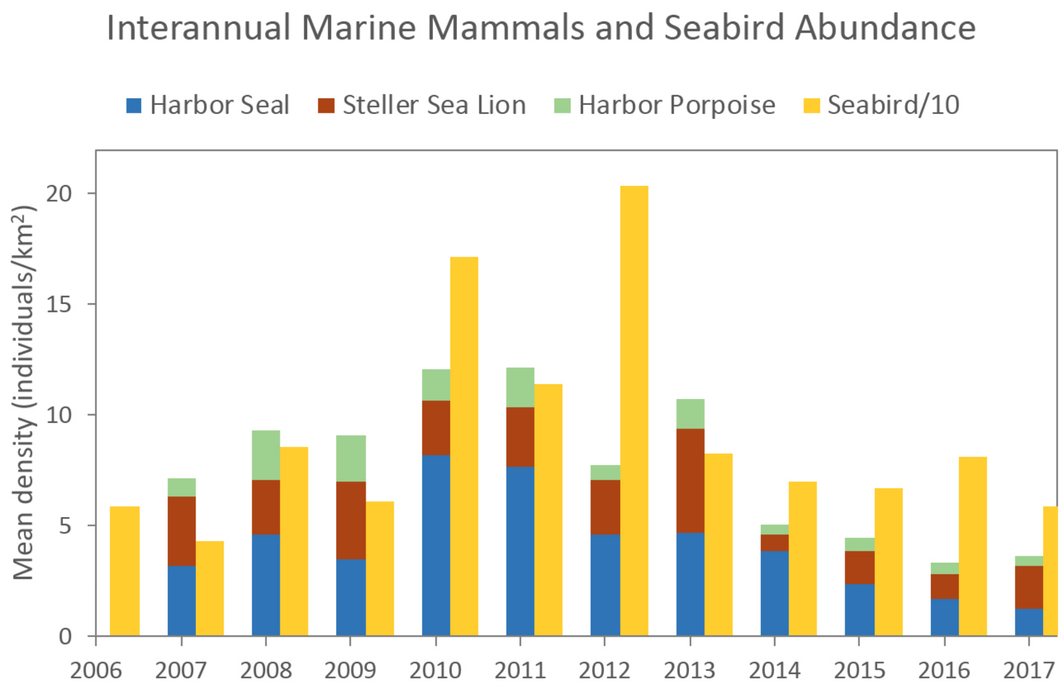


Figure 32. Interannual marine mammal and seabird densities, 2006–17. Note that seabird densities are divided by 10.

6.A. Phytoplankton

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

King County analyzes phytoplankton samples semi-monthly in the Puget Sound Central Basin. Starting in 2008 with traditional microscopy, the program progressed in 2014 to incorporate use of a FlowCAM® imaging particle analyzer in order to assess abundance, biovolume, and taxonomic composition of all microplankton particles in the 10–300 µm range.

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

King County sampled ten long-term monitoring stations for phytoplankton in 2017, including two protected sites (Elliott Bay and outer Quartermaster Harbor). Biovolume data for 2017 indicate a well marked bloom season that was characterized by sustained growth from early April through August, likely supported by an unusually persistent density stratification, and an early fall bloom in September (Figure 33A). While chlorophyll-*a* levels were generally higher than normal (see Water quality section 5.C.iii; Nutrients and chlorophyll), the total annual accumulated biovolume was similar to previous years (data not shown).

As in previous years, chain-forming diatoms were dominant from early spring to late summer (Figure 33B). Several species of *Thalassiosira* initiated the spring bloom in mid-March, followed by *Chaetoceros* and a large bloom of the narrow-chained diatom *Skeletonema*. As usual, multiple species of *Chaetoceros* remained dominant throughout the summer. These three taxa form a characteristic seasonal progression in the Central Sound, along with other diatoms that may vary from year to

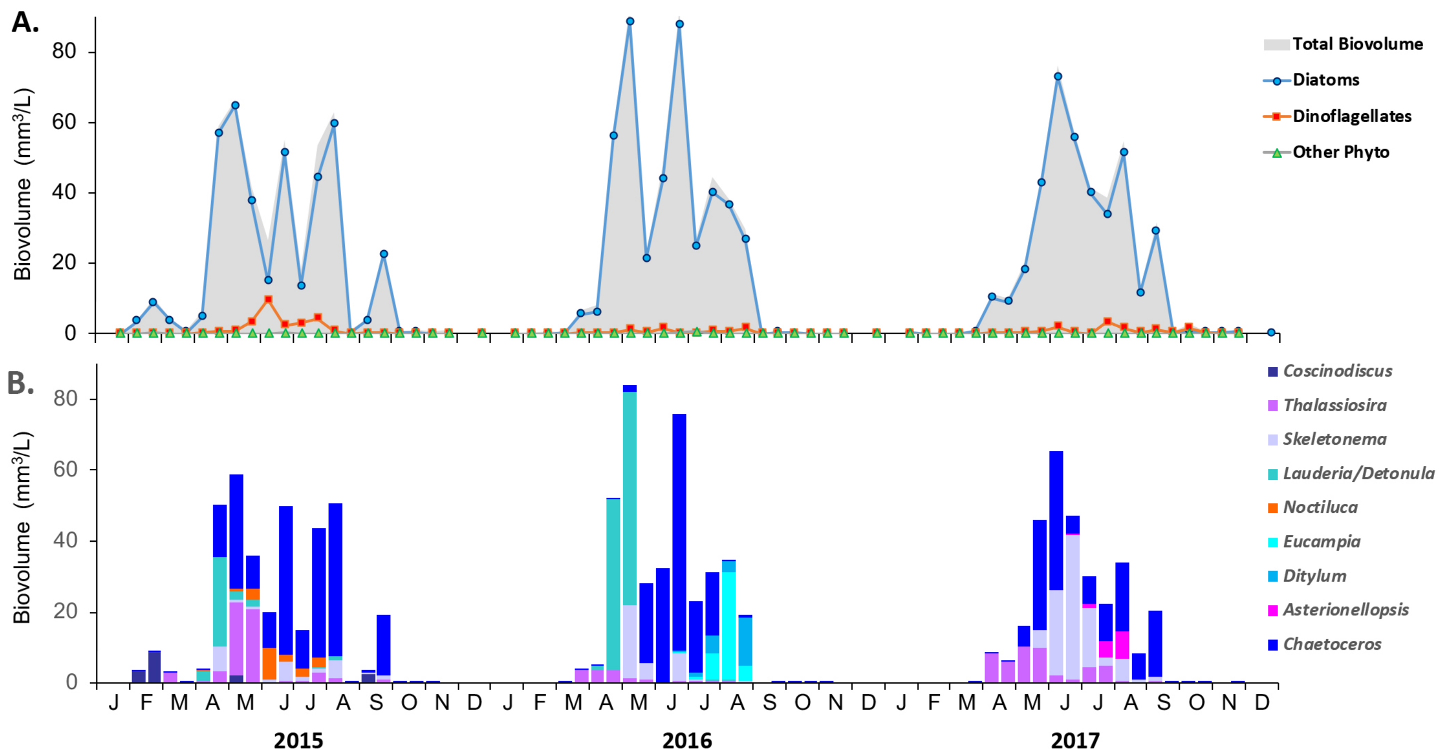


Figure 33. (A) Total biovolume (gray area), biovolume of main groups, and (B) biovolumes of top six taxa identified using FlowCAM between 2015 and 2017. Plotted values are means for Central Basin main-stem sites.

year. Notable in 2017 was a midsummer bloom of *Asterionellopsis* (Figure 33B) and an increased abundance of the small dinoflagellate *Prorocentrum* (two species) late in the season (Figure 34). Small dinoflagellates (<25 μm) and the ciliate *Mesodinium* typically make up a significant portion of the identifiable biological particles during the late fall and winter months (Figure 34).

Overall, the return to normal temperatures in 2017 was not evident in the phytoplankton biovolume data. However, we observed some changes in taxonomic composition that may have been related to this climate anomaly. There was an absence (*Tropidoneis*) or much lower abundance of certain taxa (e.g., *Odontella*, *Karlodinium*) and a new appearance (*Bacteriastrum, Asterionella formosa*) or much higher abundance of others (e.g., *Asterionellopsis, Skeletonema, Cochlodinium, Prorocentrum micans*). In addition, abundance of the large heterotrophic dinoflagellate *Noctiluca*, which had conspicuous blooms in 2014 and 2015 (Figure 33B), dropped considerably in 2016 and 2017.

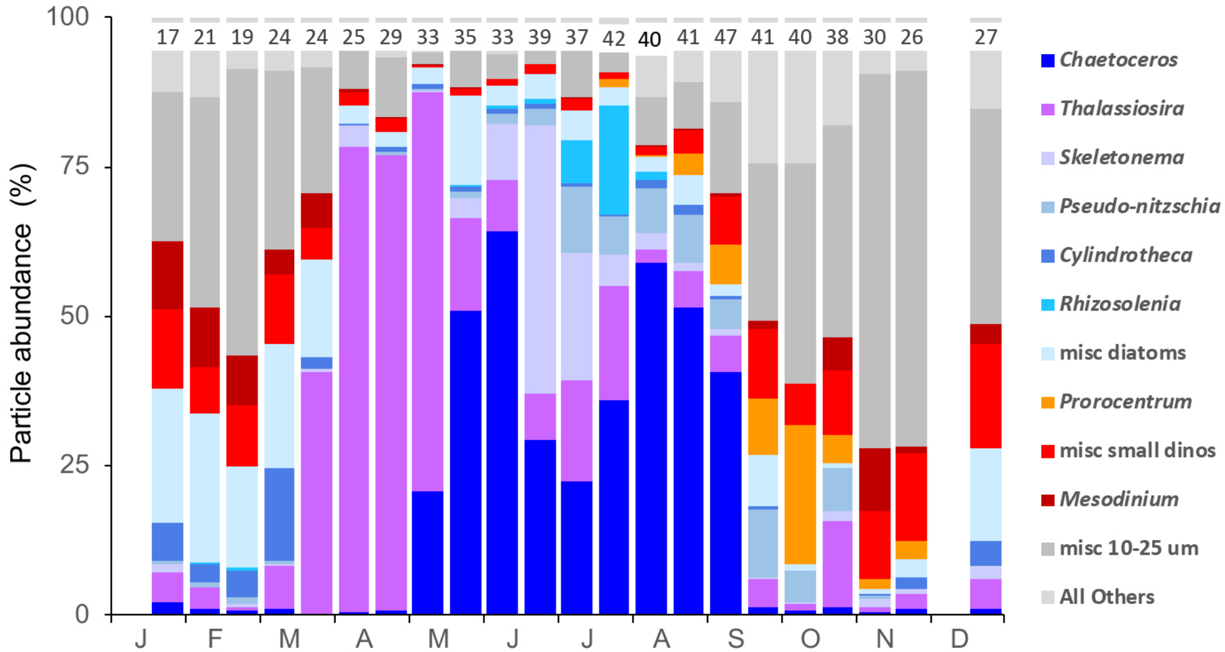


Figure 34. Relative abundance of taxonomic categories that contributed at least 10% in each sampling event (means for all stations) during 2017. Numerals above bars indicate the total number of taxonomic categories present, from a total of 57 categories identified by FlowCAM in the year. Note that Particle abundance may refer to whole chains, fragments, or individual cells, and is not indicative of biovolume.

The diatom Asterionellopsis glacialis was unusually abundant in mid-summer in the Central Puget Sound basin. Photo: Gabriela Hannach.

6.B. Zooplankton

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

6.B.i. Puget Sound

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

Sampling[3] across Puget Sound as part of the Salish Sea Marine Survival Program has been conducted since 2014,

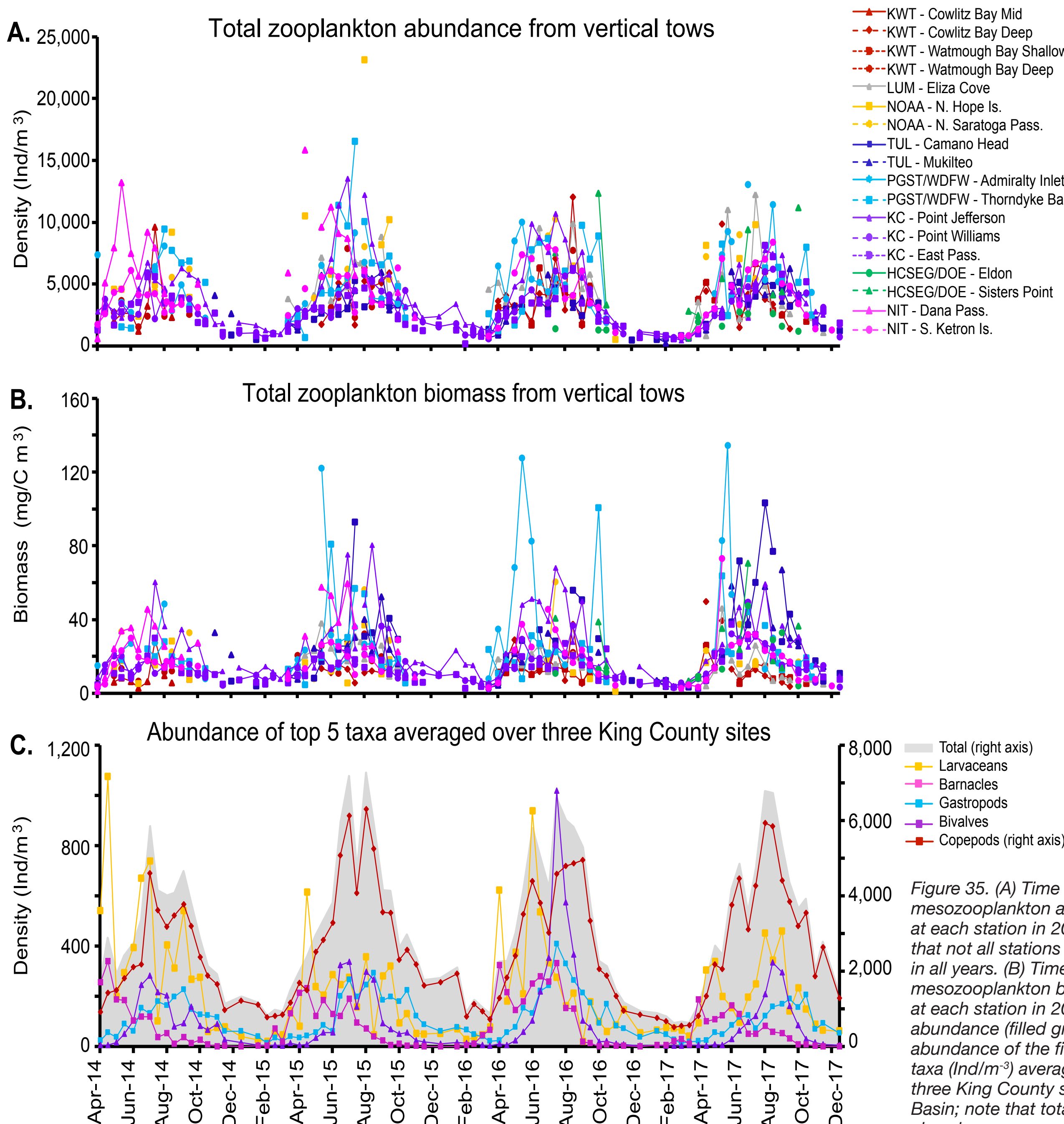


Figure 35. (A) Time series of total mesozooplankton abundance (Ind/m^{-3}) at each station in 2014–17. Note that not all stations were sampled in all years. (B) Time series of total mesozooplankton biomass (Ind/m^{-3}) at each station in 2014–17. (C) Total abundance (filled gray area) and abundance of the five most dominant taxa (Ind/m^{-3}) averaged over the three King County sites in Central Basin; note that total and copepod abundances are on the right axis.

[3] Zooplankton sampling was conducted by King County (KC), the Nisqually Indian Tribe (NIT), Tulalip Tribe, Kwiáht, Lummi Nation (since 2015), Port Gamble S'Klallam Tribe (PGST), WDFW, and NOAA; the Hood Canal Salmon Enhancement Group (HCSEG) and WA Department of Ecology (DOE) added stations in southern Hood Canal near the end of 2016. Funding for 2017 sampling was provided by DNR, EPA, and King County.

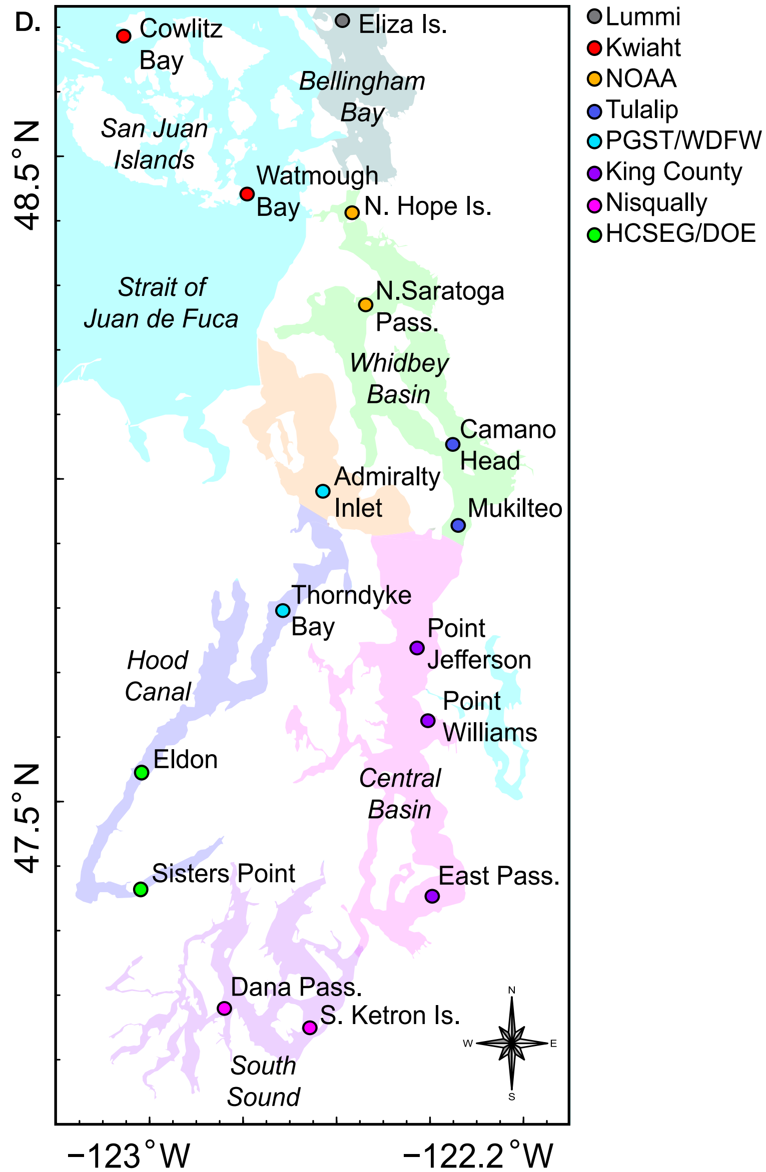
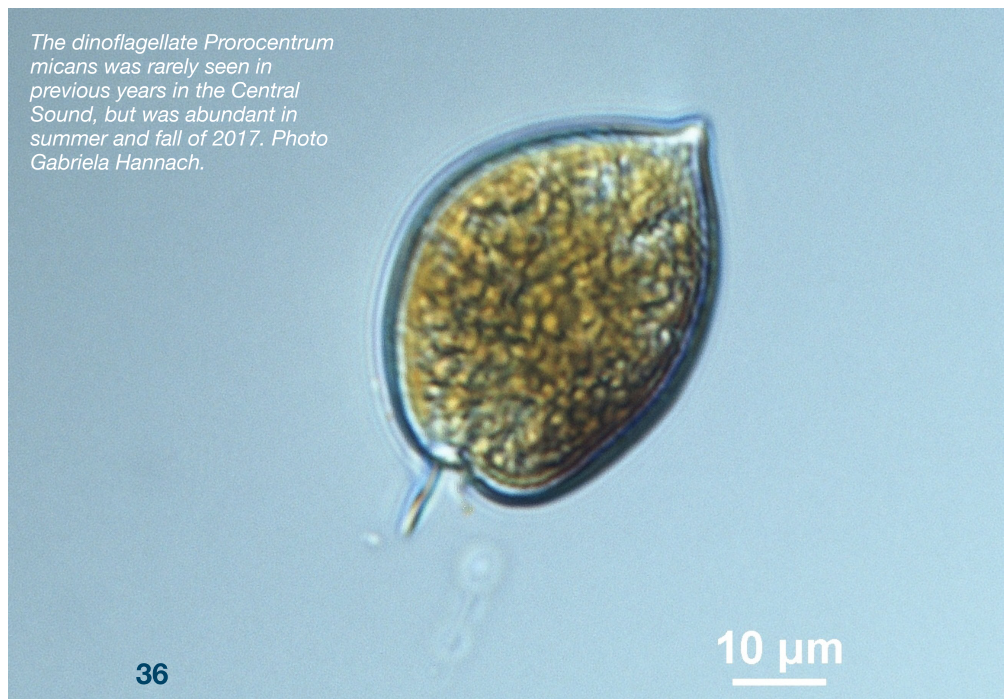


Figure 35.(D) Map of the sampling locations.

enabling comparison of zooplankton abundance, biomass, and species composition among regions in response to the warm anomalies of 2015–16 and the return to approximately normal temperatures in 2017[4]. Overall, total mesozooplankton abundances and biomass were lower in most regions in 2017 compared to the warm years of 2015 and 2016, but still somewhat elevated compared to 2014 (Figure 35A, B). However, substantial differences among regions and taxa were observed. In regions with higher ocean influence (San Juan and Admiralty Inlet sites), zooplankton biomass and phenology in 2017 was more like 2014 than at sites farther south in Puget Sound, which retained relatively high biomass in 2017 and earlier seasonal timing. The differences are likely related to regional differences in temperature anomalies, but predation and changes in advection cannot be accounted for at this point. Different species response patterns were apparent in the Central Basin (Figure 35C), where copepods (which almost always dominate the zooplankton) remained very abundant in 2017, whereas bivalve larvae, barnacles, gastropods, and larvaceans were lower in 2017 than in other years.

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



The dinoflagellate Prorocentrum micans was rarely seen in previous years in the Central Sound, but was abundant in summer and fall of 2017. Photo Gabriela Hannach.

6.B.ii. Padilla Bay

Source: Nicole Burnett (nburnett@padillabay.gov) and Jude Apple (Padilla Bay NERR); https://ecology.wa.gov/Water-Shorelines/Shoreline-coastal-management/Padilla-Bay-reserve; http://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 in Padilla Bay with a 153-µm mesh net and a one-foot diameter opening. Phytoplankton abundance (chlorophyll-*a*) and zooplankton abundances are consistently low during the winter and high in the spring and late summer/ early fall (Figure 36). Timing and magnitude of the peaks of both phytoplankton and zooplankton vary annually. In 2017, chlorophyll-*a* and zooplankton abundance were lower than average during the spring bloom. This decreased spring zooplankton abundance was similar to decreases that were observed in 2014–16.

Conversely, late-summer and early-fall zooplankton abundances during this period of time were higher than previous years. This was likely a reflection of the warm waters occurring in Padilla Bay and throughout the Puget Sound. Furthermore, multidimensional scaling ordination (Figure 37) 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 communities in summers of 2014–17. Water temperature affects many biological processes of zooplankton (e.g., phenology, feeding, fecundity) as well as the adult stages of meroplankton, providing mechanisms by which temperature is a likely contributor to observed changes of community composition. Although water temperatures in 2017 in Padilla Bay were not as warm as in 2014–16, the patterns of zooplankton abundance and community composition observed during warmer years persisted in 2017. This is an indication that some zooplankton may be slow to recover from environmental changes.

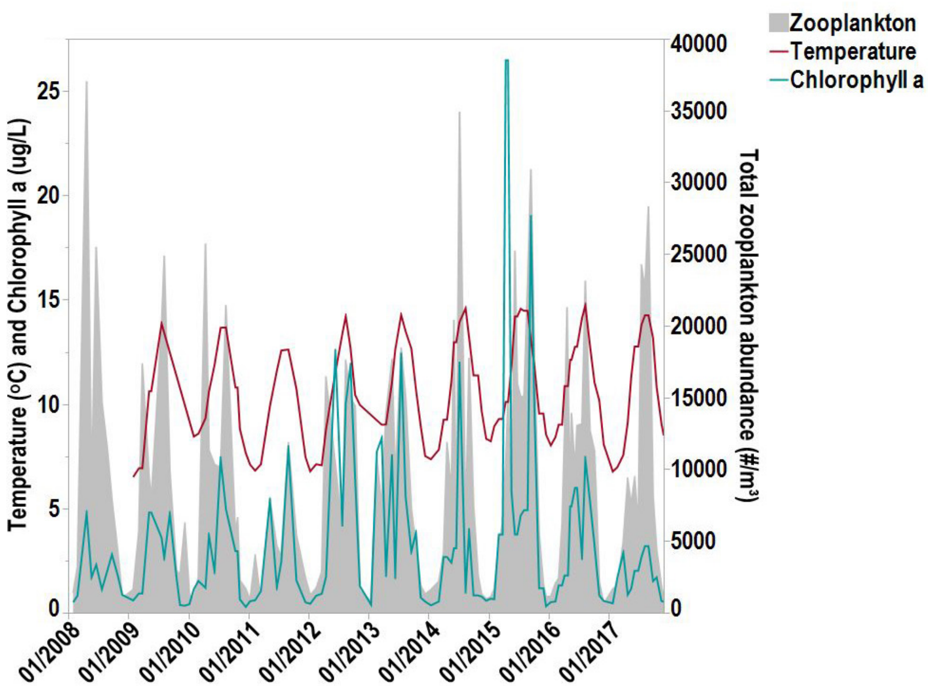


Figure 36. Monthly average zooplankton abundance, chlorophyll-a, and water temperature.

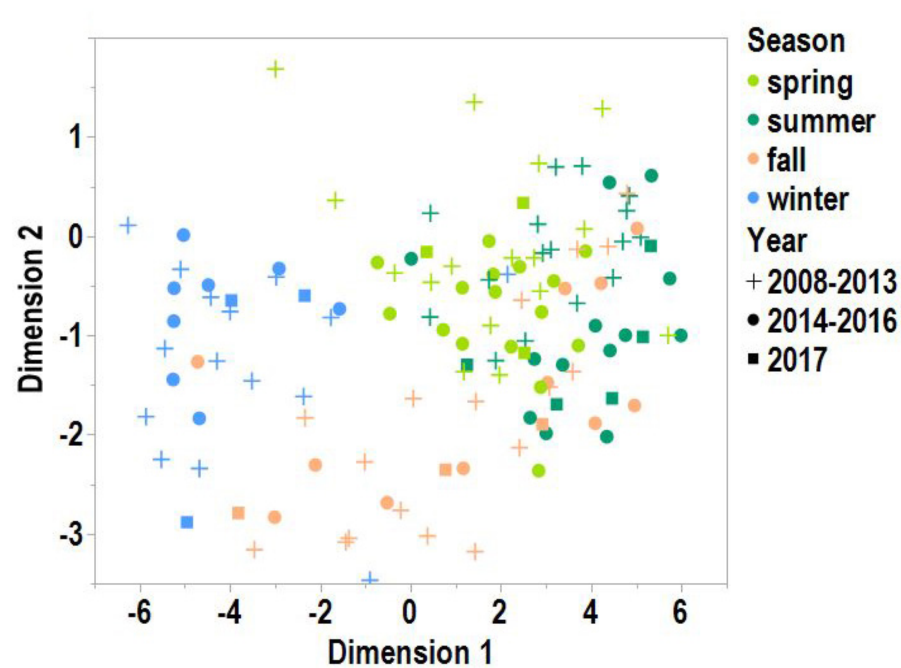


Figure 37. Mutidimensional scaling ordination of zooplankton community with months (colors) and year (symbols).

6.B.iii. Skagit Bay

Source: Correigh Greene (correigh.greene@noaa.gov) and Stuart Munsch (NOAA, NWFSC)

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 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. Total wet weight of jellies (phyla Cnidaria and Ctenophora) in each tow is now routinely measured.

Figure 38 summarizes the only time series of jellies in Puget Sound. We took advantage of the spatial and temporal richness of our sampling to build statistical models of annual jellyfish biomass across Skagit Bay. These models confirm previous observations of high biomass in the warm years of 2014–16. In 2017, however, biomass declined to the second lowest level observed since recording started in 2003. These lower levels of biomass are concomitant with cooler sea surface temperatures in Skagit Bay and Puget Sound in general.

These same models can be used to summarize annual abundance patterns of other pelagic species (Figure 39). Some species, such as larval fish, three-spined stickleback, and Chinook salmon, exhibited either positive or no obvious trends over time. However, forage fish such as Pacific herring, sandlance, and surf smelt all exhibited declines across the years, and 2017 was generally a poorer year for these species.

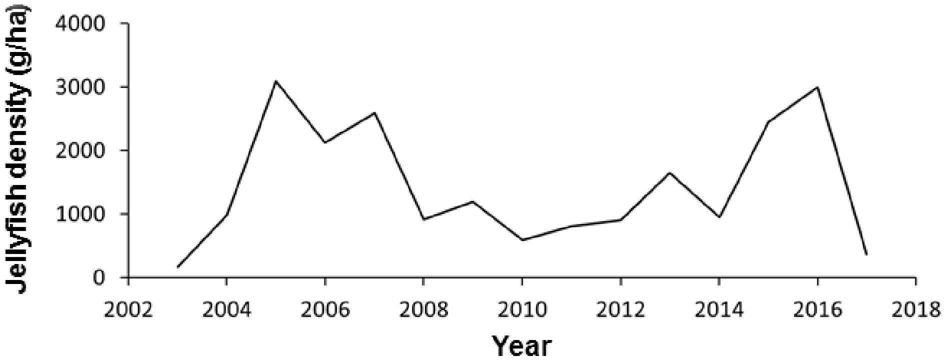


Figure 38. Trends in average annual density (wet biomass/ha) of gelatinous zooplankton captured in Kodiak surface trawls in Skagit Bay.

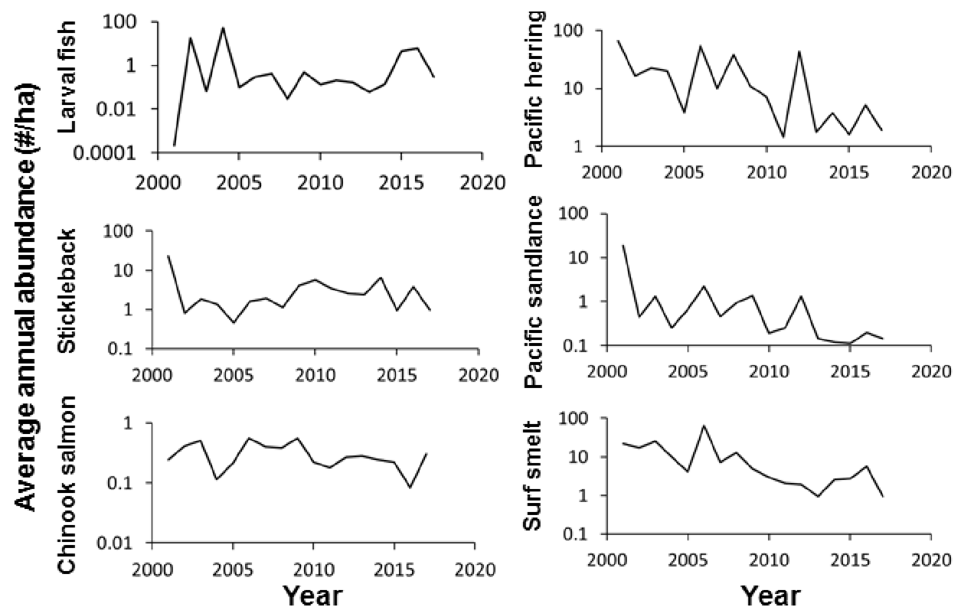


Figure 39. Trends in average annual density (fish/ha) for larval fish, three-spined stickleback, unmarked (presumed wild) Chinook salmon, juvenile Pacific herring, Pacific sandlance, and surf smelt.

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

6.C. Harmful algae

6.C.i. Biotoxins

Biotoxins are produced by certain HABs and can accumulate in shellfish. Health authorities monitor biotoxins in commercial and recreational shellfish to protect humans from illness associated with eating contaminated shellfish. Shellfish are tested for biotoxins that cause paralytic shellfish poisoning (PSP toxins including saxitoxin), amnesic shellfish poisoning (ASP; domoic acid), and diarrhetic shellfish poisoning (DSP toxins including okadaic acid). Harvest areas are closed when toxin levels exceed regulatory limits for human consumption. There were no marine biotoxin-caused illnesses reported in 2017 in Washington.

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

Coccolithophore bloom in Hood Canal July 24 2017. Christopher Krembs, Eyes Over Puget Sound.

In 2017, the Washington State Public Health Laboratory analyzed 3,309 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 1,690 µg/100 g in blue mussels from Kayak Point in Port Susan on October 17. The FDA standard for PSP toxin is 80 µg/100 g of shellfish tissue. In 2017, unsafe levels of PSP toxins caused 34 commercial (20 geoduck clam tract, 4 pink scallop, and 10 general growing area) and 35 recreational harvest area closures.

A total of 2,324 shellfish samples were analyzed for ASP toxin in 2017. The highest level of ASP toxin measured was 52 ppm in razor clams from the Willapa Spits on February 7. The FDA standard for ASP toxin is 20 ppm. ASP caused one commercial and two recreational closures on coastal beaches in 2017.

In 2017, 2,570 shellfish samples were analyzed for DSP toxins. DSP was detected at elevated levels throughout Puget Sound; at 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 108 µg/100 g in rock scallops from Sequim Bay. The FDA standard for DSP toxin is 16 µg/100 g of shellfish tissue. DSP Toxins caused two commercial and four recreational harvest area closures in 2017.

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

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

6.C.ii. SoundToxins

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

Cells of *Alexandrium catenella*, the dinoflagellate that produces PSP toxin, were reported at low levels at most stations over the course of the year, with a significant bloom occurring at Sequim Bay Entrance from August through October and peaking at greater than 10,000 cells/L in September. Blooms were also observed at Long Live the Kings Orcas Island from May to August, peaking at an average of 525 cells/L in June. Quartermaster Harbor experienced two blooms—from March to May and from August to December—and observed peak average values of 334 cells/L and 268 cells/L, respectively. *Alexandrium catenella* was first observed in February at Long Live the Kings Orcas Island and reported as late as December at Sequim Bay Entrance.

Dinophysis, the DSP-causing dinoflagellate, was present throughout the entire year at various stations, with the highest reported concentrations occurring in June at Long Live the Kings Orcas Island, where they reached an average of 1,198 cells/L. Figure 40 shows abundances of *Dinophysis* at selected sites in 2017.

Heterosigma was largely absent from Puget Sound throughout the year. It was found from January through September at various locations, but cell counts were extremely low.

Pseudo-nitzschia was common throughout Puget Sound, with counts reaching over 2,000,000 cells/L at the peak bloom at County Dock East Sound in October. Long Live the Kings – Orcas Island also reported blooms that averaged 72,000 cells/L from September through October.

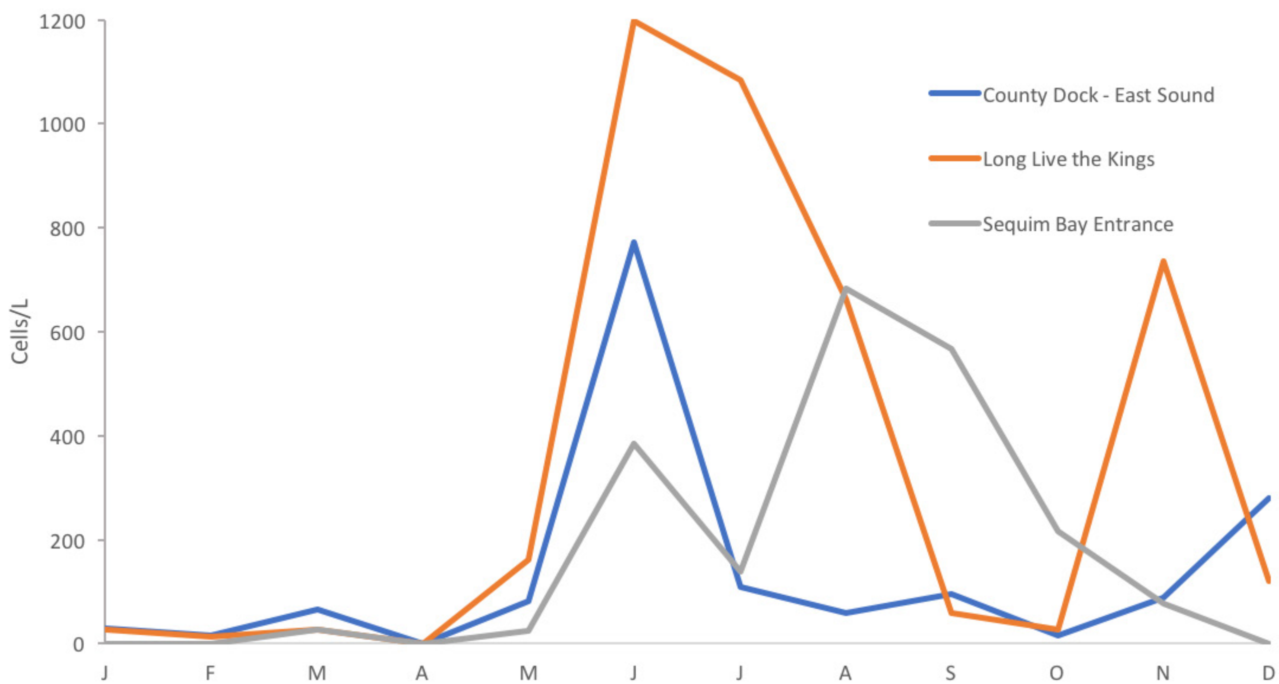


Figure 40. Monthly Dinophysis spp. cell counts reported from net tow samples at selected locations in 2017.

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

6.C.iii. *Alexandrium* species cyst mapping in Quartermaster Harbor

Source: Cheryl Greengrove (cgreen@uw.edu), Julie Masura, Thanh-Thuy Nguyen, and Mitch Schatz (UWT)

Alexandrium spp. have been present in Quartermaster Harbor for many years (Nishitani and Chew 1984, Horner et al. 2011) resulting in frequent shellfish bed closures in the bay (https://www.doh.wa.gov/CommunityandEnvironment/Shellfish). In order to see if there were any spatial changes in the distribution and relative abundance of *Alexandrium* cysts over time, the surface sediments in Quartermaster Harbor were sampled at 24 stations using a van Veen grab in winter 2007 (Figure 41A) and again in winter 2017 (Figure 41B). Cysts were found to be present in both the inner and outer harbor in both years, with concentrations, on average, a factor of two lower in 2017 than in 2007. The spatial distribution pattern was similar in both years, but 2017 had more cysts near the mouth of the harbor than 2007. The physical configuration of this shallow bay leads to warm, stratified conditions in the summer that are conducive to *Alexandrium* germination and growth (Moore et al. 2015, Bill et al. 2016) and the long residence time of water in the bay (Albertson 2013) may lead to the retention of phytoplankton and the resulting accumulation of cysts which form a persistent seed bed for future *Alexandrium* blooms.

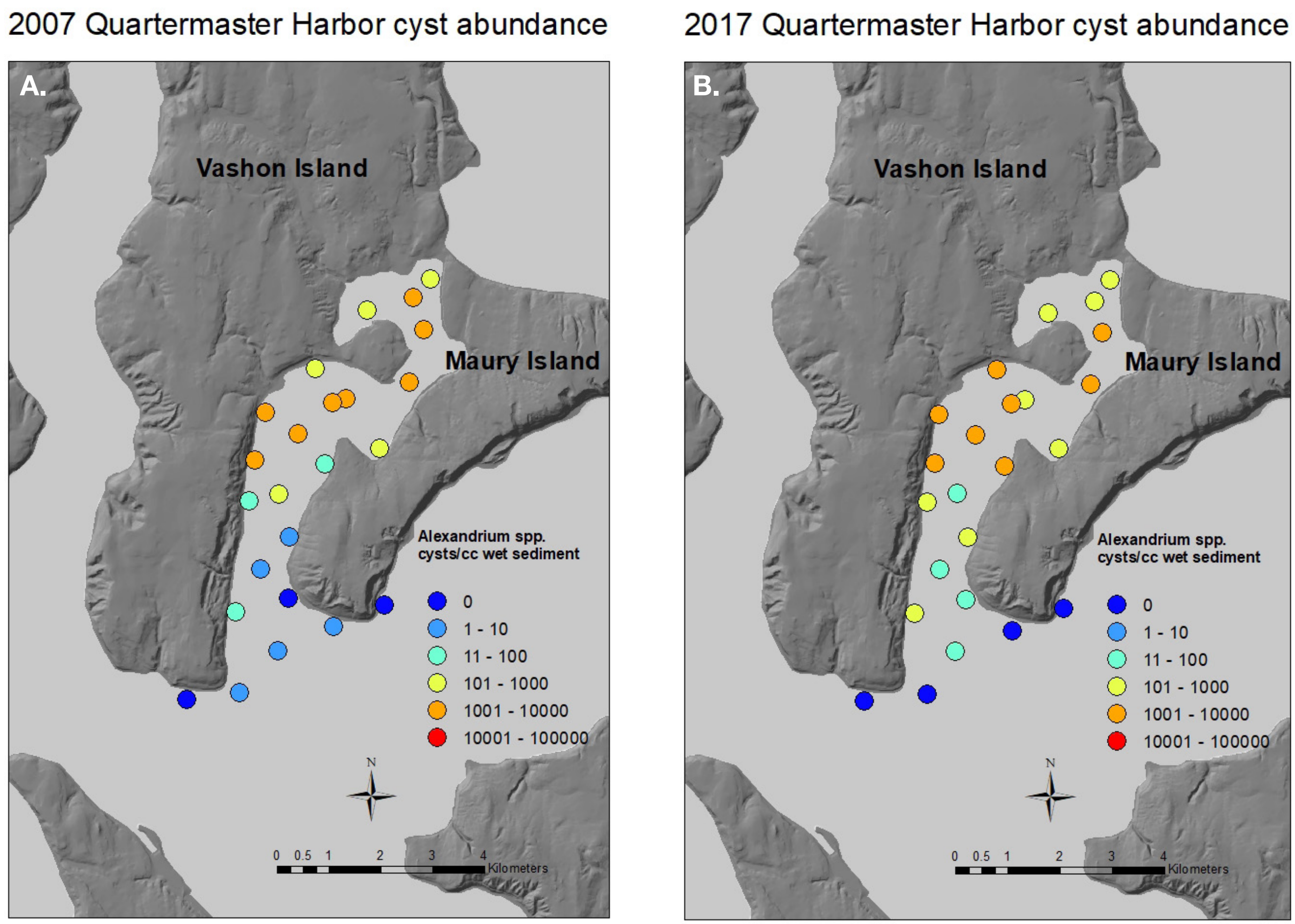


Figure 41. Distribution and concentration of Alexandrium cysts in the surface sediments of Quartermaster Harbor from (A) 2007 and (B) 2017.

6.C.iv. *Alexandrium* species cyst mapping throughout Puget Sound and Bellingham Bay

Source: Julie Masura (jmasura@uw.edu), Cheryl Greengrove, Jacqueline Busby (UWT), Maggie Dutch, Sandy Weakland, Valerie Partridge, Kathy Welch, Dany Burgess, and Angela Eagleston (Ecology)

Ecology's Puget Sound Sediment Monitoring Program collected 50 surface sediment samples via a van Veen sediment grab sampler in April 2017. In June, an additional 30 stations were sampled in Bellingham Bay as a part of Ecology's urban bay monitoring program. Though *Alexandrium* blooms typically occur in early spring and late summer, sediment sampling in the spring still provides valuable information denoting the presence of this organism. Researchers at the University of Washington Tacoma analyzed these sediments for the presence of cysts throughout the Puget Sound Basin and Bellingham Bay.

Results from Ecology's April 2017 long-term monitoring stations show that *Alexandrium* was present as far north as Birch Bay and as far south as Case Inlet (Figure 42A). The highest number of cysts were found in the Central Basin, Liberty Bay, and Sinclair Inlet. The Bellingham Bay analysis revealed higher concentrations in the center of the bay and further from shore, with fewer cysts near the mouth of the Whatcom Creek Waterway (Figure 42B). The presence of cysts throughout Bellingham Bay creates a seed bed with an increased potential for HABs of *Alexandrium* given favorable environmental excystment and growing conditions. Previous years of sediment work show similar cyst abundances in 2015 and 2016 and an order of magnitude greater abundance in 2013 and 2014, indicating that the seed bed in Bellingham Bay is a relatively consistent source of cysts with a high potential for harmful algal blooms of *Alexandrium* in the future.

2017 Long term sampling stations cyst abundance

2017 Bellingham Bay cyst abundance

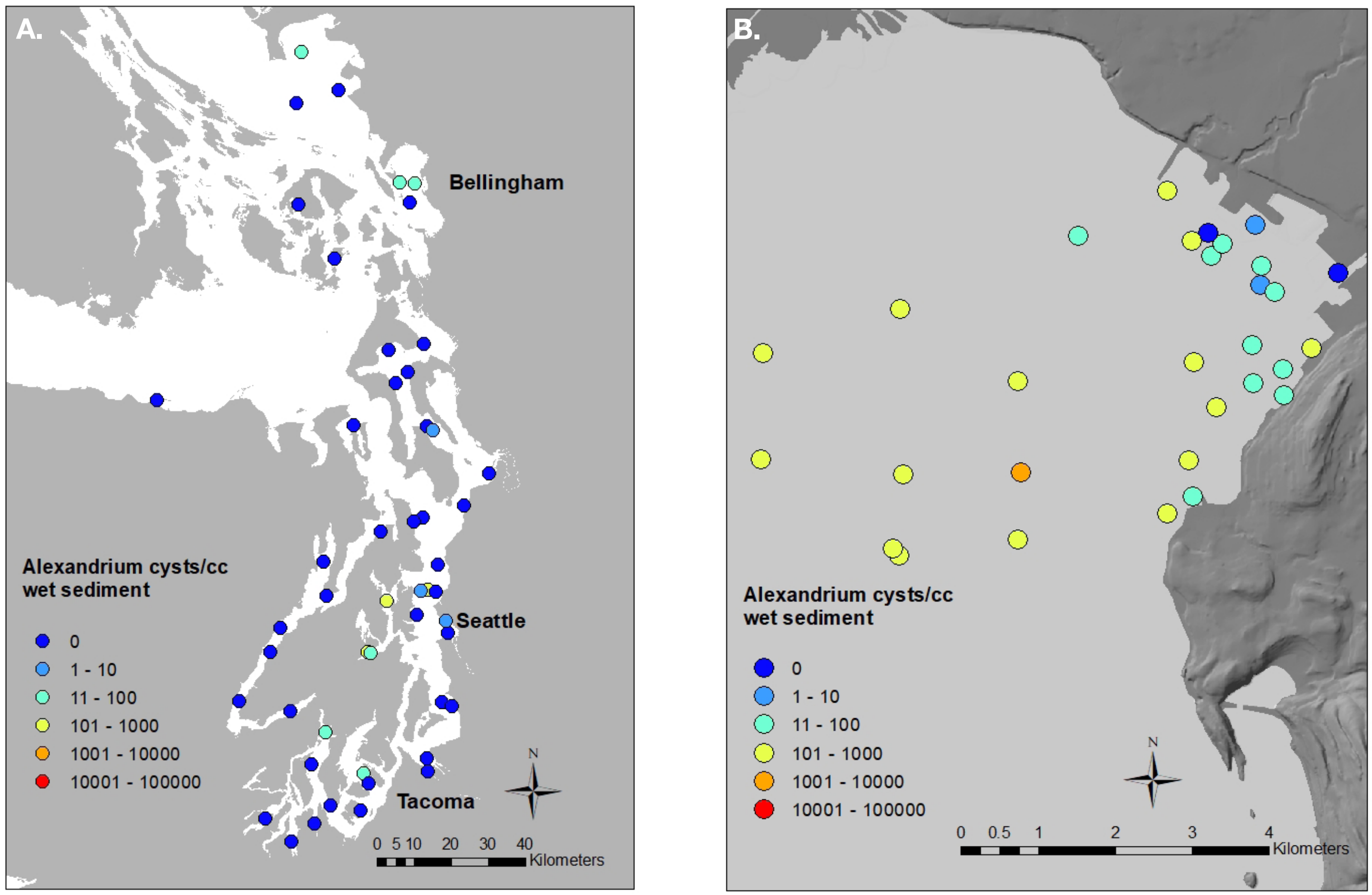


Figure 42. (A) Distribution and concentration of Alexandrium cysts from (A) Ecology's long-term sediment monitoring stations in Puget Sound, and (B) Ecology's urban bay sediment monitoring stations in Bellingham Bay.

CALL-OUT BOX
Understanding the formation of harmful algal blooms on the Washington shelf using advanced, near real-time mooring observations

The oceanography and biogeochemistry of waters on the Washington continental shelf are important drivers of HABs. In 2017, the deployment of an Environmental Sample Processor (ESP; PSEMP Marine Waters Workgroup 2014) on the NANOOS/UW shelf subsurface mooring provided new insights into the details of bloom formation by complementing the Washington Shelf mooring observations with near real-time HAB species identification, cell concentrations, and toxin concentrations. These comprehensive observations allowed a detailed look at mechanisms leading to the early detection of a potential HAB in May 2017.

Over most of May, nitrate levels at depths less than 40 or 50 m were low (<10 μmol/L). Toward the middle of the month, however, these conditions were interrupted by a short-lived (four-day) increase in nitrate at all measured depths, with values above 40 meters increasing to 10–20 mmol/L (Figure 43E). This increase in nitrate, which coincided with a switch from a week-long stretch of steady upwelling winds to several days of downwelling winds (Figure 43A), appears to have initiated a week-long diatom bloom as evidenced by high levels of fluorescence, changes in ocean chemistry (DO, pCO_2, and pH) as well as direct cell count measurements from the ESP of *Pseudo-nitzschia* spp. (Figure 43B,D). The ESP also detected significant levels of the toxin domoic acid (>100 ng/L) over this period, signaling the presence of a potential HAB. Deep currents, which were associated with water that was salty, low in DO, and high in nitrate, were from the south-southeast during the period of rapid bloom growth (Figure 43F), suggesting the source of nutrient-rich water feeding this bloom may have been from the Quinault Canyon region. Additionally, anomalously low near-surface salinities (Figure 43C), which were likely due to Columbia River plume water apparent from May 8–12 and then very heavy regional rainfall/river input starting on May 13 (Figure 43C), increased stratification within the euphotic zone, potentially further supporting bloom formation.

One potential mechanism to explain these observations is that salty, cold, high nutrient waters associated with enhanced upwelling in the vicinity of the head of Quinault Canyon, which flow southward during upwelling conditions, are transported north to the mooring site when winds shift to southerly. Dynamics such as wind-driven coastally trapped waves may account for the pulse-like switch to northward deep currents (red in Figure 43F) when winds shift from upwelling to downwelling favorable. In contrast to this May event, in late summer 2017 after upwelling conditions persisted for several months and deep nitrate levels were high, the blooms were larger and persisted longer as indicated by DO/pCO_2 levels, fluorescence measurements, and ESP cell counts.

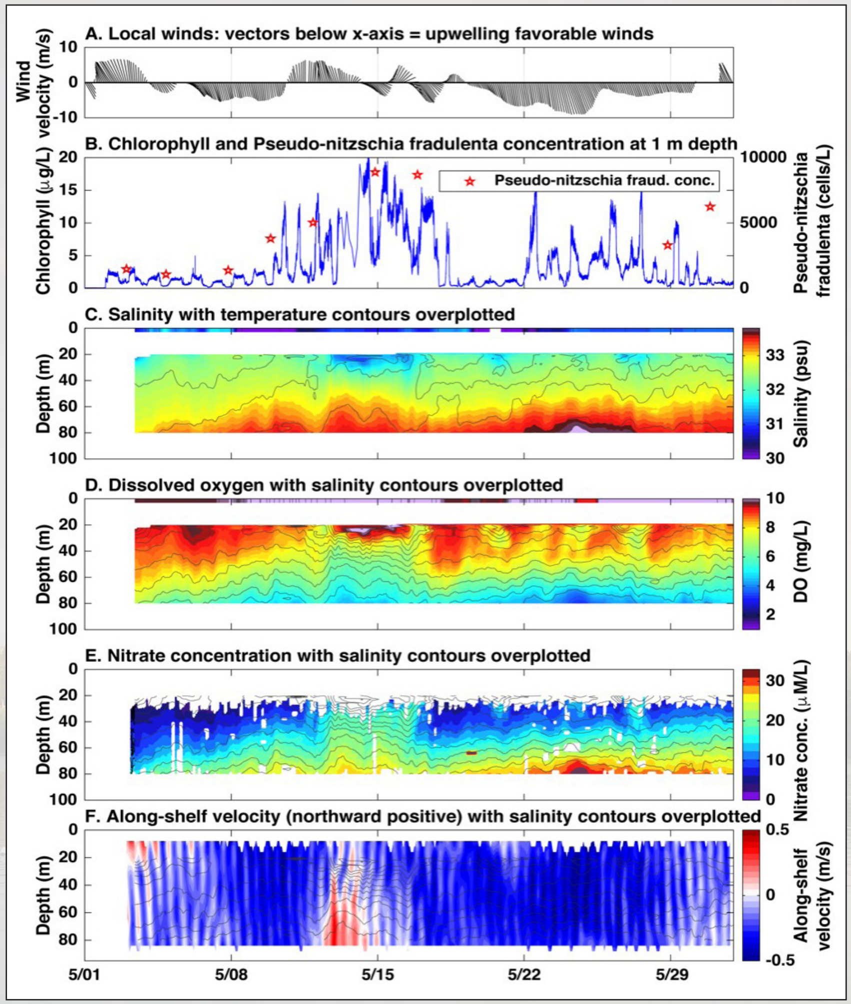


Figure 43. Details of environmental conditions associated with a potential HAB event in May 2017, as measured by the UW/NANOOS shelf moorings. (A) Local winds. (B) Near-surface chlorophyll concentration as measured by a fluorometer and Pseudo-nitzschia fradulenta concentration as measured by the ESP. (C) Salinity with temperature contours over-plotted. (D) Dissolved oxygen concentration with salinity contours over-plotted. (E) Nitrate concentration with salinity contours over-plotted. (F) Along-shelf currents with salinity over-plotted.

Author: John Mickett (jmickett@apl.uw.edu), Jan Newton (UW, APL), and Stephanie Moore (NOAA, NWFSC); http://www.nanoos.org/products/real-time_habs/; http://nwem.ocean.washington.edu/; https://www.nwfsc.noaa.gov/

CALL-OUT BOX
Cryptofauna: The hidden biodiversity at the bottom of Puget Sound

Biodiversity is the backbone of a functional and well balanced ecosystem. By cataloging species over time, we can more completely monitor the presence of species, and begin to understand how communities and ecosystems respond to environmental change. As part of a NOAA-led worldwide effort to establish critical biodiversity baselines, we report here preliminary results of the first systematic survey of the benthic community that focuses on the small, understudied cryptofauna in the Salish Sea.

We use a standardized approach developed primarily at the NOAA Pacific Islands Fisheries Science Center that uses plates called Autonomous Reef Monitoring Structures (ARMS). An ARMS unit is a stack of nine PVC plates (22.5 × 22.5 cm) separated by 1.27 mm gaps. The stack is attached to a base plate, which in turn is fixed to the bottom using rebar. The 3D nature of ARMS provides spaces and surfaces for invertebrates, fish, algae, and other organisms as shelter and/or substrate. ARMS have been referred to as invertebrate hotels (https://www.youtube.com/watch?v=Zt_VR1UpuHo).

After one or two years, the ARMS are brought to the surface for analysis. Organisms greater than 2 mm in size are removed from the ARMS, identified visually, and subsampled for individual DNA barcoding at a later time. The remaining biofilm—the unseen cryptofauna—is scraped off the plates, homogenized, preserved, and later analyzed via metabarcoding methodology (https://www.pifsc.noaa.gov/cred/survey_methods/arms/index.php).

In 2018, seven ARMS were retrieved after approximately two years in –40 to –60 ft MLLW from three sites in the southern Salish Sea: at Shannon Point near Western Washington University's Shannon Point Marine Center, Anacortes; at Manchester, WA, near the NOAA Manchester Field Station pier; and the Nisqually River delta, near Anderson Island.

Hundreds of animals were found on each ARMS (mean = 511 specimens from only one ARMS recovered at Shannon Point; 211 specimens from three ARMS at Manchester; 170 specimens from three ARMS at Nisqually). Generally, more species were found at Shannon Point.

There was a greater number of species of crab, shrimp, and mollusks at Shannon Point (Figure 44). Most notably, seven crab species, all about 40 mm or less in size, were identified at Shannon Point, but only one of these species, the black-clawed crab, was seen at Nisqually (Figure 45A). The most abundant species at Shannon Point (n = 142) was the porcelain crab (Figure 45B), about 20 mm in size, but this species was not seen elsewhere.

Between 80 to 120 individual pygmy eualid shrimp, about 10 mm in size, were seen on each ARMS at all sites (Figure 45C). Dock prawn were prominent in the two southern sites (Figure 45D).

In the summer of 2018, three ARMS at Neah Bay will be retrieved to complete our initial survey of the southern Salish Sea. Contingent upon funding, the metagenomics analyses will be accomplished at NOAA NWFSC. Long-term goals are to repeat ARMS surveys in the southern as well as the northern Salish Sea, and to contribute to the Smithsonian Institute's worldwide baseline at www.oceanarms.org.

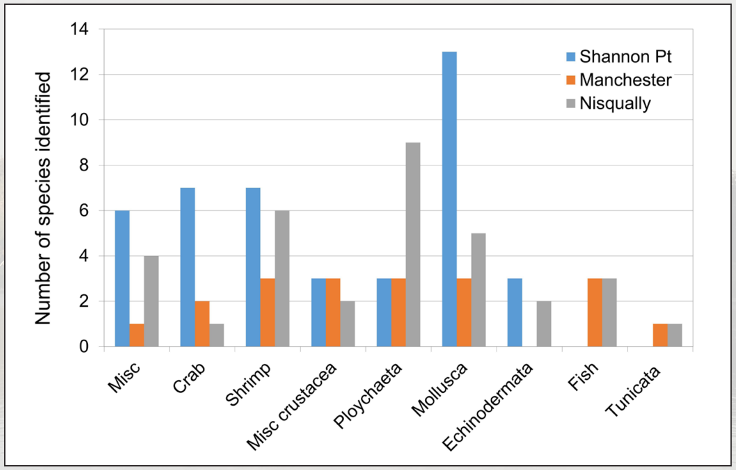


Figure 44 (left). Histogram of numbers of species identified from Autonomous Reef Monitoring Structures surveys recovered from sites in the south Salish Sea in 2018.

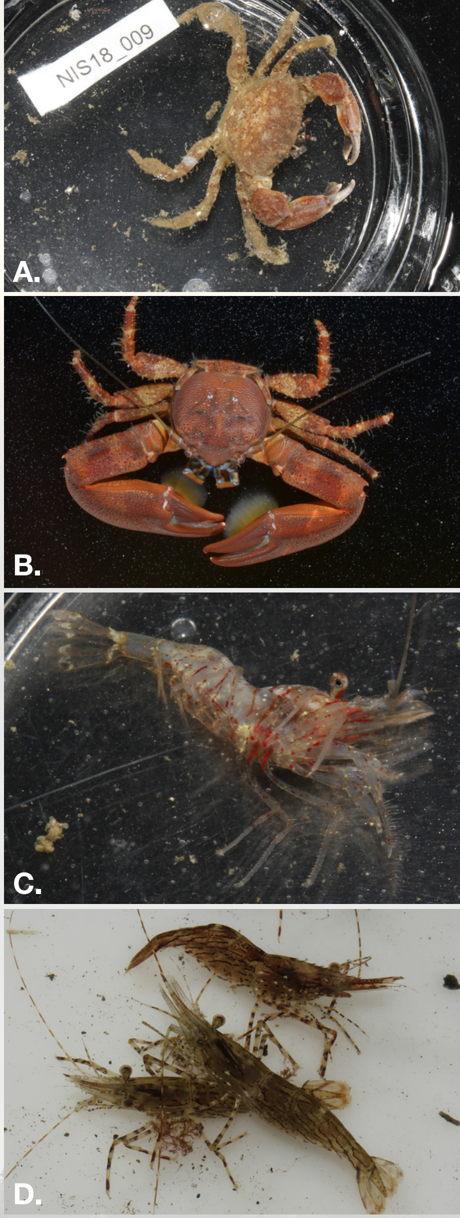
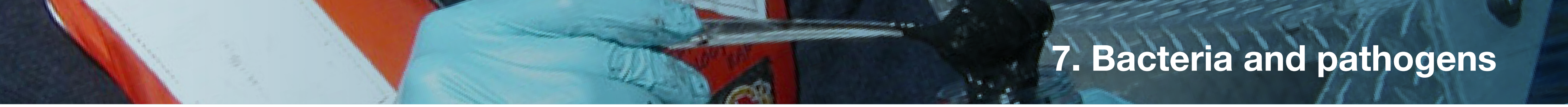


Figure 45 (above). (A) Black-claw crab (B) Porcelain crab (C) Pygmy shrimp (D) Dock prawn. (Photos A,B,D: Mike Bainter/C: Gustove Paulay)

Author: Gary A. Winans (gary.winans@noaa.gov) (NOAA, NWFSC; https://www.nwfsc.noaa.gov/



7.A. Fecal indicator bacteria

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

7.A.i. Puget Sound recreational beaches

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

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

The BEACH Program coordinates weekly or biweekly monitoring from Memorial Day (May) to Labor Day (September) with local and county agencies, tribal nations, and volunteers. In 2017, 67 Washington beaches were sampled, including 45 core beaches (beaches that are consistently sampled from year to year). There was a 1% decrease in all 67 beaches passing the swimming standard from 2016 to 2017, but a 4% increase in the core beaches (Figure 46).

There are three beaches that do not pass the swimming standard each year for various reasons. During summer at Freeland Park in Holmes Harbor, north winds cause decaying marine vegetation to accumulate along the southern shoreline, which may be a source of the summer bacteria increases. The vegetation can be up to two feet thick in areas. Little Squalicum Beach in Bellingham has consistent low-to-moderate bacteria levels, with occasional high-bacteria spikes. A permanent swimming advisory is in place for this beach.

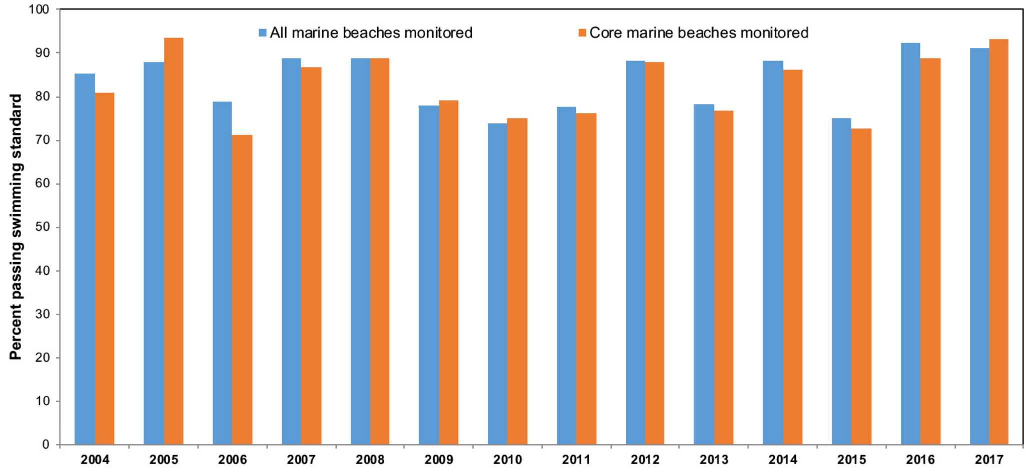


Figure 46. Percent of all marine beaches monitored and all core marine beaches (consistently sampled) that had no more than one swimming closure or advisory during the 2004–17 beach seasons.

Although standards were exceeded in 2017, bacteria levels at Bay View State Park have improved due to a collaboration with Skagit County. Between the 2015 and 2016 sampling season, the Skagit County Pollution Identification and Correction (PIC) Program found and fixed several sources of pollution.

The Puget Sound Partnership uses BEACH data for their Vital Sign indicator and has set a target that all monitored beaches meet human health standards by 2020. Details on 2017 beach sampling results can be found at: https://ecology.wa.gov/Research-Data/Monitoring-assessment/BEACH-annual-report.

Large amounts of macroalgae covering the entire beach north of the jetty. Photo: Hugh Matheson.

7.A.ii. Central Basin stations

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

King County monitors fecal coliform bacteria monthly at 20 beach stations along Central Puget Sound Basin shorelines. In 2017, weekly samples were collected at six stations from April to June in response to the West Point Treatment Plant flooding event. 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 used to calculate the geometric mean exceeding 43 CFU/100 mL (peak standard). In 2017, 15 of the 20 beach monitoring stations met the geometric mean standard during the discrete 12-month period, and nine of these stations met the peak standard (Figure 47). Mean concentrations of fecal coliforms were lower than normal in the first half of the year, and increased later in the year (Figure 48). Mean concentrations were highest in July, driven by high values at two stations near creeks and one near a stormwater outfall, possibly due to concentration from over a month without rain. Sites near freshwater sources such as creeks and stormwater outfalls typically have the highest bacteria concentrations.

King County also monitors bacteria at 14 offshore locations. Samples are typically collected twice-monthly from February through November and monthly in January and December from the 1-m depth at six ambient and eight outfall (both wastewater treatment plant and CSO) stations. For four stations, samples were collected weekly from March to early June. Fecal coliform data collected in 2017 show that all 14 offshore stations passed the geometric mean and peak standards for the 12-month period, continuing a trend seen over many monitoring years.

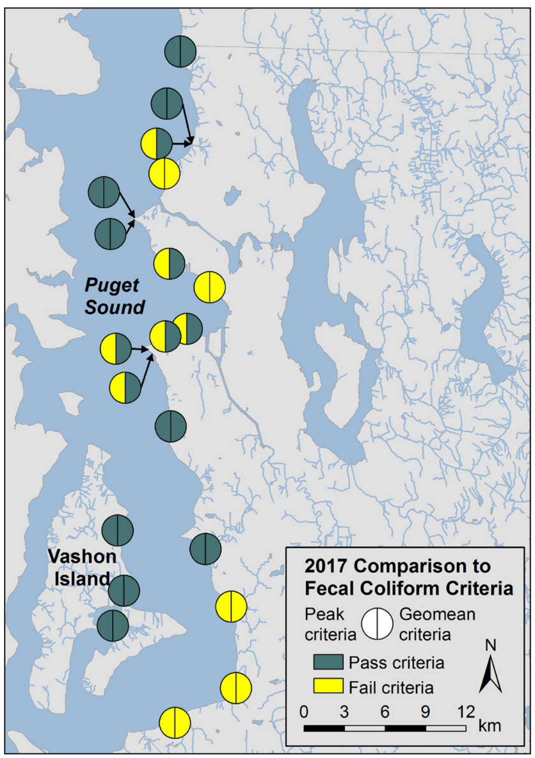


Figure 47. Map of King County's 2017 beach bacteria monitoring results. Fecal coliform concentrations sampled from the 12-month period are compared to the State of Washington's water-quality standards.

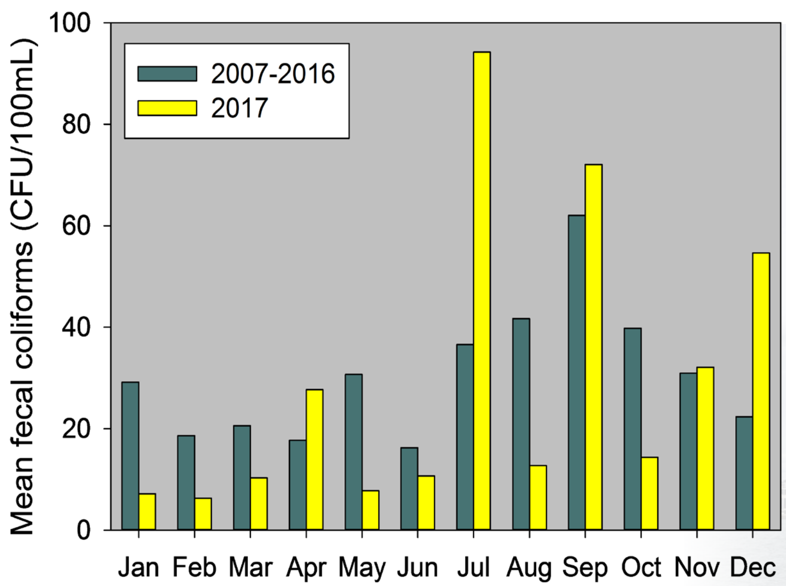


Figure 48. Monthly mean concentrations of fecal coliforms (colony forming units/100 mL) from King County's 20 beach monitoring stations in 2017 compared to the prior 10 years.

View of Elliott Bay from King County's SoundGuardian. Photo: Wendy Eash-Loucks.

7.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. *Vp* populations grow faster at higher temperatures and can cause illnesses especially in the summer months. Genetic markers for virulent strains of *Vp* work well in other areas of the country, but are not effective in Puget Sound, significantly challenging health authorities. The Washington State Department of Health employs three strategies to control *Vp*-related illnesses: require the commercial industry to cool oysters to 50°F after harvest; set temperature thresholds to limit harvest on the hottest days; and close growing areas to oyster harvest when illnesses occur.**

Shellfish harvesters enjoying the last day of the season at Penrose State Park. Photo: Laura Hernmanson.

Source: Audrey Coyne (audrey.coyne@doh.wa.gov) (WDOH); http://www.doh.wa.gov/CommunityandEnvironment/Shellfish/RecreationalShellfish/Illnesses/Vibriosis

From June to September 2017, WDOH collected 165 samples from 13 sites and analyzed them for the presence of *Vp* (total and potentially pathogenic). Two sites in south Puget Sound, Skookum and Totten Inlets, had the highest Vp levels with greater than 110,000 MPN/g tissue. While collecting oyster samples for *Vp* testing, samplers also record current weather conditions, air, water, and tissue temperatures, and salinity.

In 2017, there were 15 laboratory-confirmed and epidemiologically linked illnesses from consumption of oysters contaminated with *Vp* that were single source illnesses that traced back to specific Washington growing areas. There were 14 multi-source illnesses that were traced back to multiple possible Washington growing areas, and there were 20 multi-source illnesses that were traced back to multiple possible Washington growing areas or other states or Canada. Two growing areas in Puget Sound were closed due to *Vp* illnesses in 2017. Most confirmed cases came from commercially harvested oysters. There were ten 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 occurrence.

8. 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.

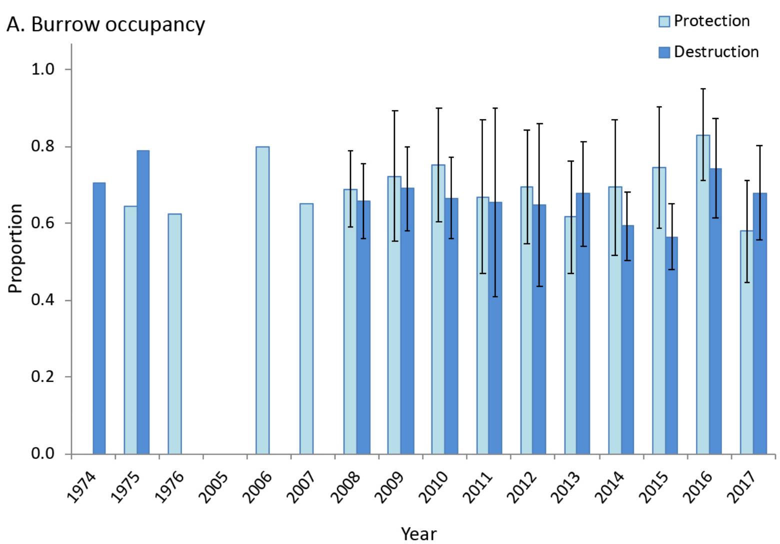
8.A. Rhinoceros auklet: Long-term reproductive success

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

The effectiveness of using seabirds as indicators of marine conditions is a function of their sensitivity to changing environmental conditions, with behaviorally plastic species typically showing little interannual variability in reproductive parameters. In 2016, we documented a highly anomalous breeding season for rhinoceros auklets on Protection Island (PI) in the Salish Sea, but not on Destruction Island (DI) on the outer Washington coast. The season on PI was most notable for historically low fledging success and a species-specific adult mass mortality event.

We continued our long-term breeding season monitoring at both breeding colonies in 2017, providing us with the opportunity to evaluate the population-level response to the 2016 season. On PI, burrow occupancy (the proportion of burrows that were reproductively active) was the lowest recorded in 12 years of monitoring (58% compared to the long-term mean of 72%; Figure 49A). In contrast, hatching and fledging success were both comparable to the 12-year mean values, 85% and 78% respectively (Figure 49B). In stark contrast to 2016, nestling provisioning on PI, as measured by fish per bill load and bill load weight, was comparable to long-term values. On DI, however, none of the three reproductive parameters differed from long-term mean values for the DI breeding population in 2017, as in 2016.

The lower burrow occupancy on PI suggests a population-level effect from the 2016 breeding failure and an adult mortality event concurrent with that breeding season, whereas the DI population was unaffected. This depressed breeding effort appears to have been restricted to the population breeding in the Salish Sea and may have been driven by elevated adult mortality the previous summer and/or birds deciding not to breed during the 2017 season.



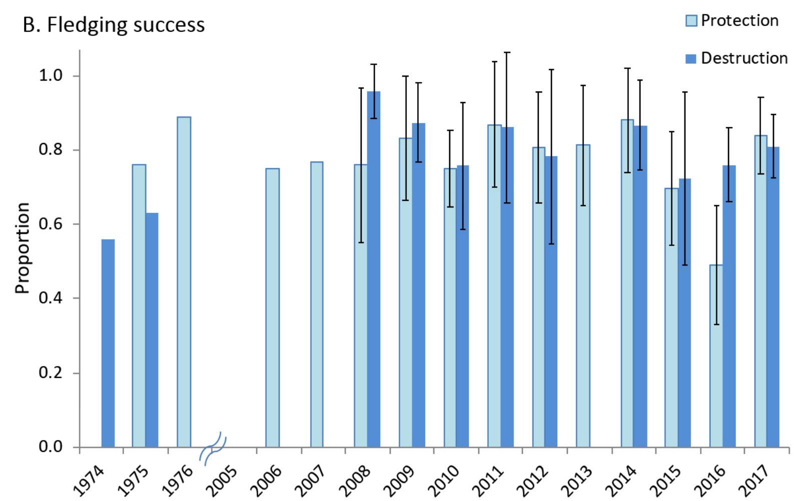


Figure 49. The proportion of breeding burrows (A) that were reproductively active, and (B) that successfully produced a fledgling on Protection and Destruction islands, WA.

8.B. Wintering marine birds

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

Source: Toby Ross (tobyr@seattleaudubon.org), Jennifer Lang (Seattle Audubon Society), and Peter Hodum (University of Puget Sound); http://www.seabirdsurvey.org

During the 2016–17 season, a total of 208 volunteers conducted 809 surveys at 121 survey sites. The number of birds counted per survey ranged from 0–1,610 (median = 36 birds per survey). Counts for a given month were generally comparable over the past three seasons (Figure 50A). A total of 57 species were detected in 2016–17, including diverse foraging guilds and both resident and migratory species.

Diving forage-fish specialists, which include alcids and grebes, have been identified by Vilchis et al. (2014) as a foraging guild that is vulnerable and declining in the Salish Sea. As is typical for birds in this system, we would expect bird numbers to increase over the year and stabilize in the midwinter months, to reflect migration and settlement into the system, but that is not what we observed in 2016–17. In comparison to the previous two seasons, the number of forage-fish specialists was depressed early in the 2016–17 season, but steadily increased throughout the season, ultimately reaching similar levels to 2015–16 (Figure 50B). Although unconfirmed, the driver of these fluctuations across the past three seasons may relate to forage-fish availability. In particular, the reduced number of forage-fish specialists in 2014–15 might be attributed to effects of the Blob.

Scoters (surf, white-winged, and black) as a group are a Puget Sound Vital Sign Indicator. Scoter counts in 2016–17 were generally lower than the previous two years, but are somewhat comparable to 2015–16 (Figure 50C).

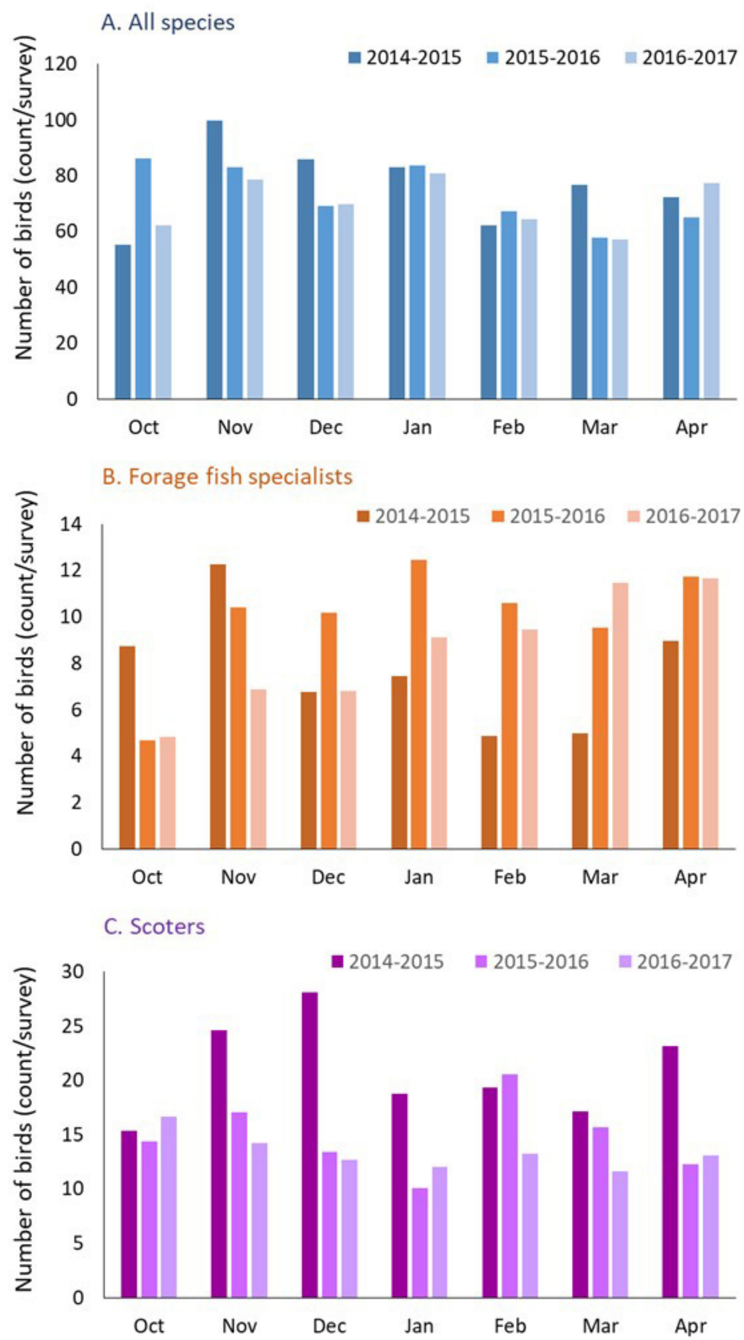


Figure 50. Numbers of birds counted per survey by month for (A) all species pooled, (B) diving forage-fish specialists (alcids and grebes), and (C) scoter species (surf, white-winged, black).

9. Forage fish

Forage fish are a vital component of the marine food web and an indicator species of overall Puget Sound health. These small fish are prey for most upper trophic levels throughout their lives. Pacific herring are the best studied forage fish; stocks are defined by spatiotemporal isolation of spawning activity, and 21 stocks are monitored annually. Genetic studies concluded that the Cherry Point and Squaxin Pass herring stocks are distinct, but that all other stocks in the southern Salish Sea are genetically homogenous (Beacham et al. 2001, Small et al. 2005, Mitchell 2006).

9.A. Pacific herring

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

In 2017, the total herring spawning biomass in Puget Sound stood at 9,466 tons, which was 15% below the ten-year average for 2007–16. Furthermore, herring abundances were 18% lower in 2017 than the three-year average for 2014–16. The effect of the Blob may have influenced recruitment.

Stock dynamics are spatially distinct. The abundance of South and Central Puget Sound herring stocks (which include Hood Canal) has remained “healthy” (as defined in Stick et al. 2014). However, this status is driven entirely by large increases in the Quilcene Bay stock, which increased >240% over the past five years and now contributes over half of all Puget Sound herring. If Hood Canal stocks are excluded, the Central and South Sound grouping has decreased dramatically (Figure 51) and is now considered to be depressed (only 29% of the 25-year mean). In the North Puget Sound complex, the Cherry Point stock was again at an all-time low (372 tons in 2017, a 96% decline since 1973) and remains critical. In contrast, Semiahmoo Bay and Portage Bay have had robust years.

Concerns persist regarding declines in herring biomass on a Sound-wide basis and the resultant ecosystem-wide impacts of this reduction in prey abundance.

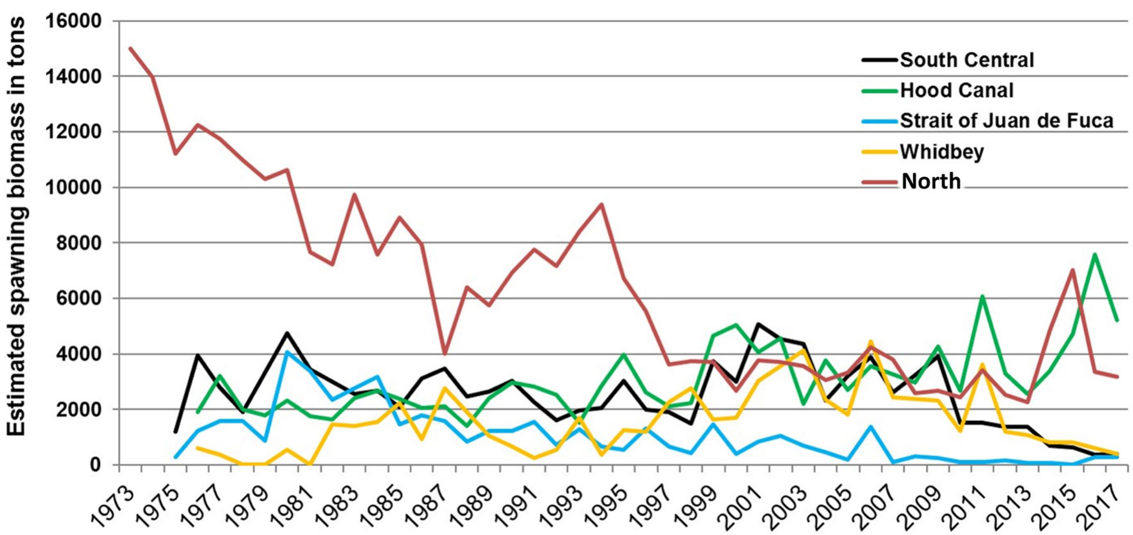


Figure 51. Estimated herring spawning biomass (tons) in Puget Sound basin. Note that biomass for the North region includes Cherry Point but not the San Juan Islands due to poor data quality. South/Central Puget Sound traditionally includes Hood Canal, but Hood Canal has been shown separately here to highlight the differing trends in these areas.

Herring spawn washed ashore at Right Smart Cove, Quilcene Bay, Hood Canal. Photo: David Wingate.

CALL-OUT BOX
Warm conditions associated with declines in floating kelp

There are more than 20 species of kelp in the Salish Sea. These algae are considered to be foundation species because they create biogenic habitat that supports diverse communities. Floating kelp is the most visible constituent of the Salish Sea's kelp community, as it forms extensive canopies on the water's surface. Floating canopies are composed of bull kelp and giant kelp.

DNR monitors floating kelp at long-term survey areas in Puget Sound and along the outer coast (Figure 52). In 2014, measures of floating kelp abundance decreased by 54% relative to 2013 throughout DNR's long-term monitoring areas (Figure 53). The timing of both loss and recovery has been spatially distinct. In 2015, floating kelp abundance along the outer coast and Strait of Juan de Fuca returned to previous levels. Recovery was delayed at Aquatic Reserves, located inside the Salish Sea, which are more distant from oceanic influence. Kelp canopies returned to previous abundance in 2016 at Cypress and Smith and Minor Islands and 2017 at Cherry Point.

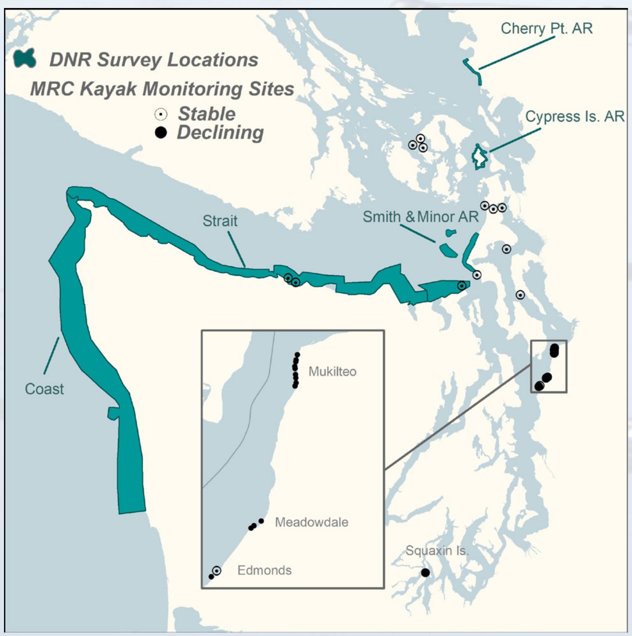


Figure 52. DNR aerial photography survey areas and MRC kayak-based monitoring sites for floating kelp. DNR surveys have been completed annually along the outer coast and Strait of Juan de Fuca since 1989 and at Aquatic Reserves since 2011. Kayak surveys were completed at each site for at least two years between 2015 and 2017.

Site-scale monitoring data collected by volunteer kayakers from Marine Resource Committees (MRCs) show results consistent with the pattern in DNR's monitoring. Where waters are well mixed, floating kelp abundance was relatively stable between 2015 and 2017 (Figure 53). In contrast, inner Salish Sea sites declined, including Possession Sound and Squaxin Island. Observers have also anecdotally reported losses in 2017 at other locations within inner basins, such as Bainbridge Island and the Canadian Gulf Islands.

The timing and spatial pattern of decline and recovery is likely to be related to exceptionally warm water conditions that began in 2013 on the outer coast and intensified in subsequent years within the Salish Sea, with related changes in freshwater input, circulation, and stratification. Kelp is a temperate species that thrives in cool climate conditions (Pfister et al. 2017). In addition to climate, other factors are known to affect kelp abundance, such as grazers, sedimentation, water quality, and non-native species.

Scientists and volunteers will be watching closely in 2018 to see if kelp recovery continues in the inner basins in response to less-extreme climate conditions.

Author: Helen Berry (helen.berry@dnr.wa.gov) (WDNR), Suzanne Schull (Padilla Bay NERR), and volunteer kayakers for the Marine Resources Committees of Clallam, Island, Jefferson, San Juan, Skagit, Snohomish, and Whatcom counties; www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science; www.nwstraits.org

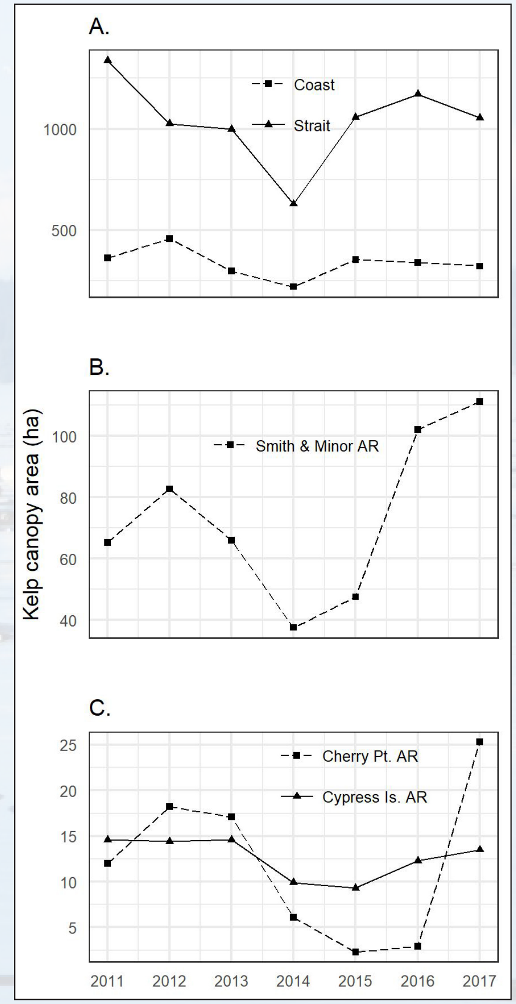


Figure 53. Time series of kelp canopy area at DNR aerial photography monitoring areas: (A) outer coast and Strait of Juan de Fuca, (B) DNR's Smith and Minor Island Aquatic Reserve (AR), and (C) DNR's Cypress Island and Cherry Point Aquatic Reserves.

Kayakers surveying a floating kelp bed. Photo: Snohomish County Marine Resources Committee.

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Acronyms

APL	Applied Physics Laboratory
ARMS	Autonomous Reef Monitoring Structures
ASP	Amnesic Shellfish Poisoning
ATG	Atmospheric Sciences and Geophysics building
BCRFC	British Columbia River Forecast Center
BEACH	Beach Environmental Assessment, Communication, and Health
CDOM	Colored Dissolved Organic Matter
CFU	Colony Forming Unit
CSO	Combined Sewer Overflow
CTD	Conductivity Temperature Depth
DA	Domoic Acid
DO	Dissolved Oxygen
DNA	Deoxyribonucleic Acid
DNR	Department of Natural Resources
DSP	Diarrheic Shellfish Poisoning
Ecology	Washington State Department of Ecology
ENSO	El Niño Southern Oscillation
EOPS	Eyes Over Puget Sound
EPA	Environmental Protection Agency
ESRL	NOAA Earth System Research Laboratory
FDA	US Food and Drug Administration
FHL	Friday Harbor Laboratories
HAB	Harmful Algal Bloom
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
MLLW	Mean Low Low Water
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
NWSI	Northwest Straits Initiative
ORCA	Oceanic Remote Chemical Analyzer
ORHAB	Olympic Region Harmful Algal Blooms
OWSC	Office of the Washington State Climatologist
PDO	Pacific Decadal Oscillation
PGST	Port Gamble S'Klallam Tribe
PFEL	Pacific Fisheries Environmental Laboratory
PMEL	Pacific Marine Environmental Laboratory
PRISM	Puget Sound Regional Synthesis Model
PS Partnership	Puget Sound Partnership
PSEMP	Puget Sound Ecosystem Monitoring Program
PSP	Paralytic Shellfish Poisoning
PSSS	Puget Sound Seabird Survey
PSU	Practical Salinity Unit
UCSC	University of California Santa Cruz
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
WDNR	Washington Department of Natural Resources
WSG	Washington Sea Grant
WWU	Western Washington University