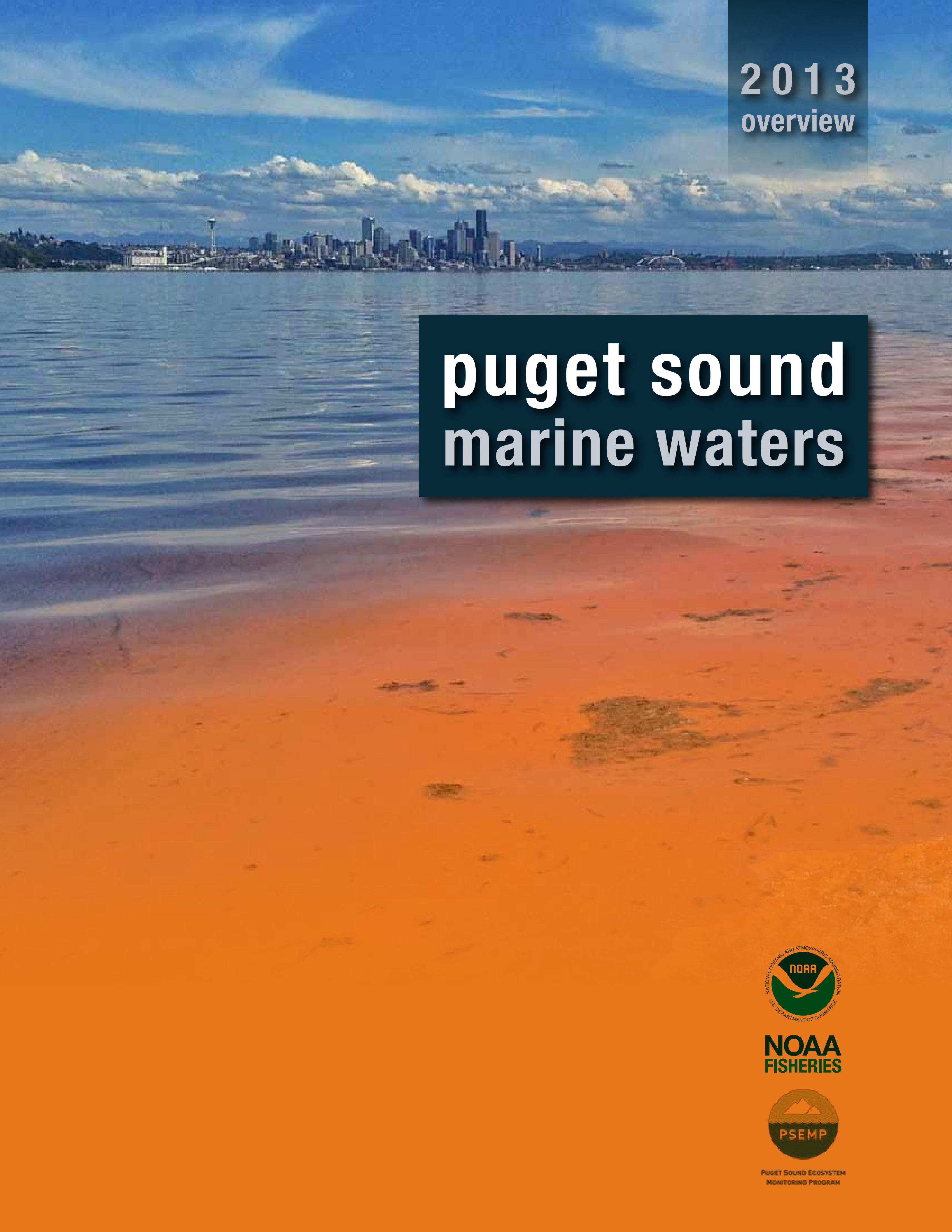

2013
overview

puget sound marine waters

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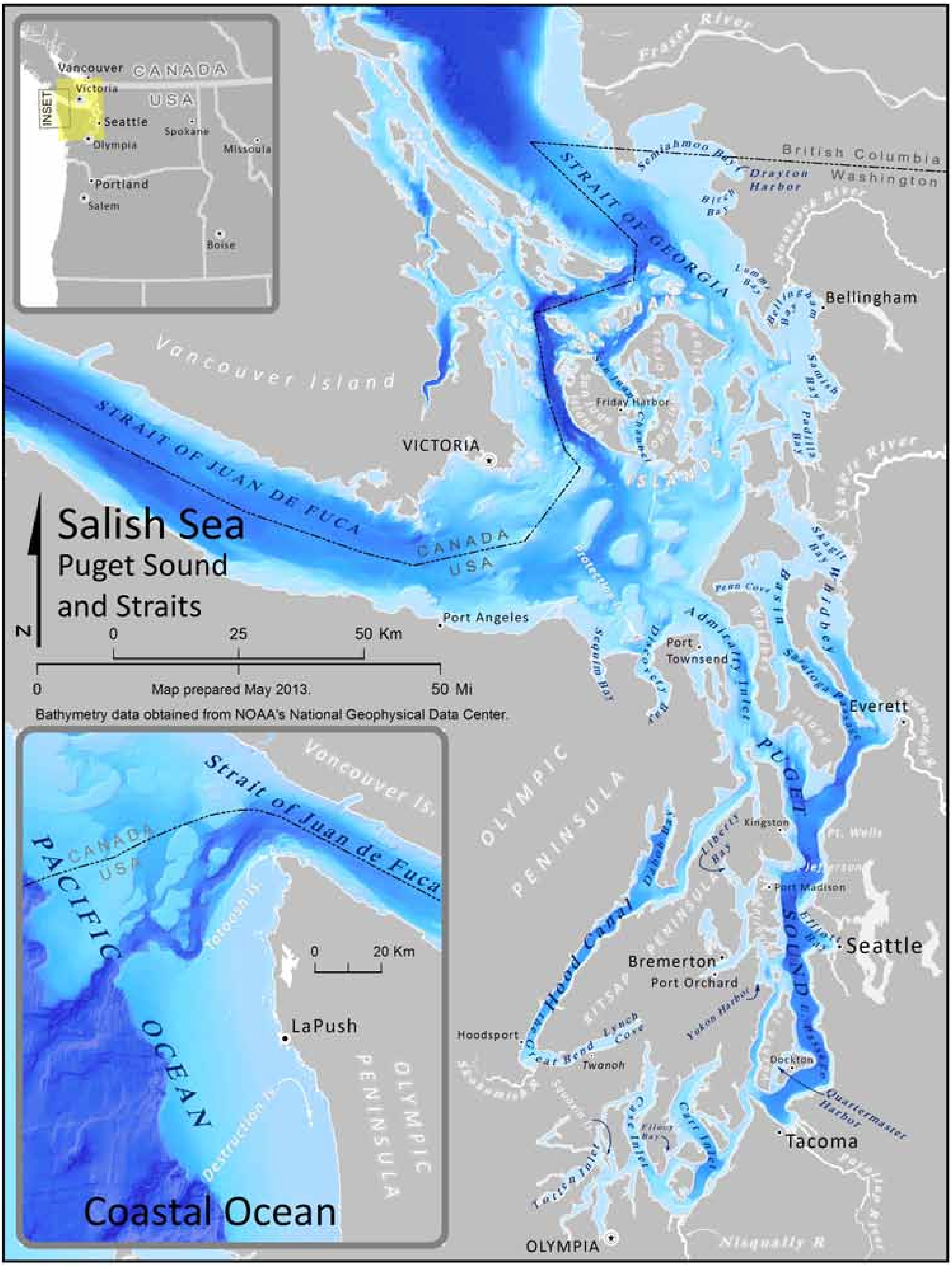
Puget Sound Ecosystem Monitoring Program



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Map prepared May 2013.
Bathymetry data obtained from NOAA's National Geophysical Data Center.
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Salem
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Fraser River
British Columbia
Washington
Semiahmoo Bay
Drayton Harbor
Birch Bay
STRAIT OF GEORGIA
Lummi Bay
Bellingham Bay
Bellingham
Samish Bay
Padilla Bay
Vancouver Island
STRAIT OF JUAN DE FUCA
VICTORIA
Friday Harbor
SAN JUAN ISLANDS
Skagit River
Skagit Bay
CANADA
USA
Port Angeles
Penn Cove
Whidbey Basin
Admiralty Inlet
Port Townsend
Sequim Bay
Discovery Bay
Saratoga Passage
Everett
PUGET SOUND
OLYMPIC PENINSULA
Kingston
Liberty Bay
Dabob Bay
Hood Canal
KITSAP PENINSULA
Port Madison
Elliott Bay
Seattle
Bremerton
Port Orchard
Yukon Harbor
Hoodsport
Lynch Cove
Great Bend
Twanoh
Dockton
Quartermaster Harbor
Tacoma
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Carr Inlet
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CANADA
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PACIFIC OCEAN
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LaPush
OLYMPIC PENINSULA
Coastal Ocean

2013 overview

puget sound marine waters

Editors: Stephanie Moore, Kimberle Stark, Julia Bos, Paul Williams, Jan Newton and Ken Dzinbal

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

Front Cover Photo Credit: Jim Devereaux

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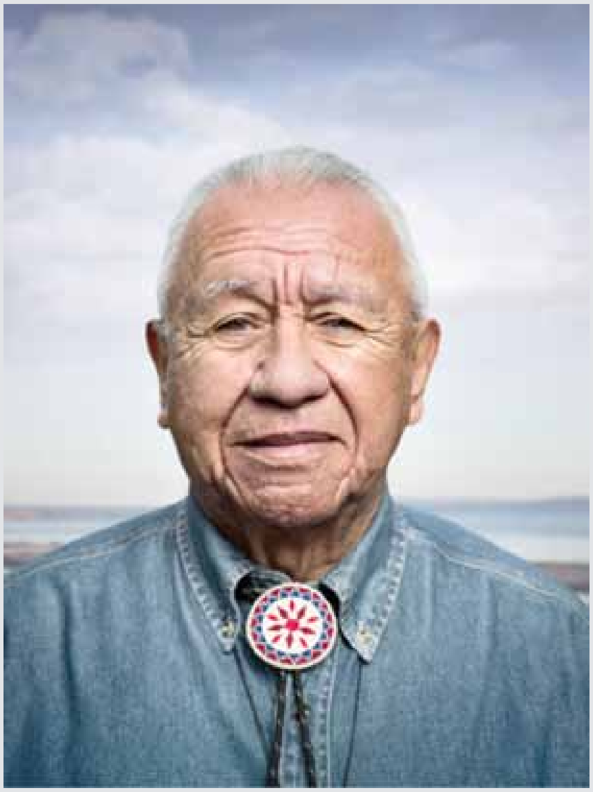
Dedication

The editors and authors of the 2013 edition of the Puget Sound Marine Waters Overview dedicate this compilation to Billy Frank, Jr. We have been inspired by Billy's lifetime of work to help preserve the health of the marine ecosystem upon which we and so much depends. We miss him greatly.

Billy Frank Jr.



(1931-2014)

"I don't believe in magic," Billy once said. "I believe in the sun and the stars, the water, the tides, the floods, the owls, the hawks flying, the river running, the wind talking. They're measurements. They tell us how healthy things are. How healthy we are. Because we and they are the same. That's what I believe in. Those who learn to listen to the world that sustains them can hear the message brought forth by the salmon."

We seek to live up to Billy's words. In these pages we bring forth to you measurements; measurements of the water, the atmosphere, and the organisms. We hope you find not only science in this presentation but also the very essence of what defines Puget Sound.

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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, non-governmental organizations, watershed groups, businesses, and private and volunteer groups.

The objective of PSEMP is to create and support a collaborative, inclusive, and transparent approach to regional monitoring and assessment that builds upon and facilitates communication among the many monitoring programs and efforts operating in Puget Sound. PSEMP's fundamental goal is to assess progress towards 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. For more information about PSEMP and the Marine Waters Workgroup, please visit: https://sites.google.com/a/psemp.org/psemp/.

Introduction

This report provides an overview of 2013 marine water quality and conditions and associated biota in Puget Sound from comprehensive monitoring and observing programs. 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, such as selected climate indices and conditions along the outer Washington coast. This is the third annual report produced for the PSEMP Marine Waters Workgroup.

The objective of this report 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 of the monitoring programs, 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 2013.

The data and interpretations presented here are 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 have been provided. The editors managed the internal cross-review process and focused on organizational structure and overall clarity. This included crafting a synopsis of what happened in 2013 that is based on all of the individual contributions.

The larger picture that emerges from this report helps the PSEMP Marine Waters Workgroup to (i) develop an inventory of the current monitoring programs in Puget Sound and conduct a gap analysis to determine how well these programs are meeting priority needs; (ii) update and expand the monitoring results reported in the Puget Sound Vital Sign indicators (http://www.psp.wa.gov/vitalsigns/index.php); and (iii) 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 and an inventory of monitoring assets can be found through the NANOOS web portal (http://www.nanoos.org). Full content from each contributor can be found after the executive summary, including website links to more detailed information and data.

The Canadian ecosystem report "The State of the Ocean for the Pacific North Coast Integrated Management Area" (http://www.dfo-mpo.gc.ca/science/coe-cde/soto/Pacific-North-eng.asp), encompasses 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 2013

From the editors: We have come together through PSEMP to share our understanding of monitoring data from Puget Sound in the context of natural variability, including ocean and climate factors that strongly influence local estuarine conditions. This understanding is critical to recognize and document regional drivers and patterns so that water quality and biological data may be assessed with these variations in mind. These data are necessary to attribute human effects versus natural alterations and shifts in marine and estuarine conditions. This synthesis highlights monitoring from various programs throughout Puget Sound, including both year-round, long-term monitoring as well as temporally and/or spatially focused studies. The PSEMP Marine Waters Workgroup is the impetus behind this document but we have reached out to colleagues monitoring other ecosystem aspects, such as the abundance of marine birds and mammals. In subsequent editions, we hope others will contribute so that it encompasses the full spectrum of monitoring efforts in Washington waters. The synthesis below provides a brief summary of Puget Sound conditions during 2013. An attempt was made, where appropriate, to discuss how these multiple monitoring components are inter-related.

Overall, with regard to physical water properties and climate and weather patterns, 2013 was close to average compared to recent years. However, the term "average" is both appropriate and inaccurate; while no persistent anomalous patterns were observed in these data on annual timescales, some variables, such as rainfall and air temperature, showed strong departures from typical values over periods of limited duration. These short-lived departures had a considerable effect on other parameters.

2013 was considered a neutral year for the El Niño/Southern Oscillation (ENSO), and continued the cool phase of the Pacific Decadal Oscillation (PDO). Based on the 2013 ENSO and PDO states, slightly cooler than normal coastal sea surface temperatures were expected. Instead, anomalously warm sea surface temperatures were observed during late summer, particularly in September, along the outer coast at La Push and also in the San Juan Channel and Strait of Juan de Fuca. Significantly lower upwelling along the Washington coast during August and September, consistent with unusual southerly winds at that time, likely contributed to the warmer than average sea surface temperatures.

The annual average air temperature for the Puget Sound region was near-normal and annual total precipitation was 86% of normal for 2013. However, substantial anomalies in regional climate conditions occurred during some months. January was much colder than normal. It was also drier than normal from January through March and then wet in April. The summer was warm and dry with warmer than usual nighttime temperatures and high humidity during August. We had the wettest September on record for the Puget Sound region, followed by the third driest October through December period. The unusual southerly winds during summer and early fall brought storms to the region, followed by an unusual high pressure ridge during October that persisted through December and brought dry but foggy conditions.

Puget Sound river flows corresponded with rainfall, and flows were below historic median levels in early 2013 and then increased in the spring. Flows sharply increased in September following the record rainfall. Although late September/early October is typically when rivers are at their driest, rivers reached close to annual peak flows during this time.

The 0-50 m water layer throughout Puget Sound was warmer than normal from January through June and cooler than normal late in 2013. However, surface water temperatures (<2 m) in the Central Basin were either typical or slightly cooler than normal from January through March and then much cooler than normal in April, likely due to the increased riverine input.

The anomalous weather conditions may have contributed to the unusual phytoplankton bloom dynamics in 2013. The timing of the spring phytoplankton bloom (early April) was typical, however, an unusually large August through early September bloom dominated by diatoms occurred throughout the Central Basin and much of Puget Sound. This large bloom corresponded with the stretch of warm, dry summer weather. Phytoplankton seasonality in 2013 was markedly different than the previous few years in that diatom genera were prevalent throughout the year, even into late summer when dinoflagellate abundances typically increase. Increased dissolved oxygen (DO) in surface waters was noted during the April and late summer blooms in addition to decreased nitrate concentrations from phytoplankton uptake. Episodes of new maximum DO values were observed in July and August in Admiralty Inlet during the large blooms.

There were several low DO events noted in deep waters on the outer coast. The most severe event occurred in mid-August and was the likely cause of a crab die-off near Ruby Beach. This DO decrease was associated with a wind reversal from upwelling favorable winds from the NW to downwelling favorable winds from the SE; deep currents paralleled this wind shift. DO concentrations in southern Hood Canal were typical in 2013 and no fish kills due to low DO were recorded.

2013 was a relatively quiet, average year for marine biotoxins in Washington. Domoic acid remained below regulatory limits in 2013, and paralytic shellfish poisoning and diarrhetic shellfish poisoning toxin levels resulted in 32 commercial growing area and 35 recreational harvest area closures. No illnesses were reported in 2013 due to biotoxins in shellfish. However, a relatively high number (88) of laboratory-confirmed and epidemiologically-linked illnesses occurred in 2013 due to the consumption of oysters contaminated with *Vibrio parahaemolyticus*. This increase in *Vibrio* contamination may be linked with warmer seawater temperatures, though analysis has not yet been conducted.

Focused studies of reproductive success of pigeon guillemots on Protection Island and rhinoceros auklets in the Salish Sea showed that breeding success in 2013 was similar to the past three years. Aerial surveys of wintering marine birds conducted in December 2013 and January 2014 showed that while scoter populations continue to increase, the western grebe population continues to decline. A 92% decline in 2013/2014 from the high recorded in 1995 was the lowest estimate recorded for this species since the aerial surveys began in 1994. Southern resident killer whales in 2013 continued a declining trend in the number of days they were observed in the Salish Sea, possibly corresponding to fewer (and later) Chinook salmon returns to the Fraser River and an 80-year record return of Chinook to the Columbia River system.

This brief summation provides an overview of measured observations throughout Puget Sound and how weather factors, physical, chemical, and biological variables were related in 2013. The highlights that follow provide a more detailed account for components of the ecosystem for which monitoring data were made available for this report. The effort to provide an annual overview of Puget Sound marine waters began in 2011 and offers the opportunity to evaluate these relationships over time, which is a goal of the PSEMP Marine Waters Workgroup. We hope to investigate relationships between other components of the pelagic marine food web, such as zooplankton and higher trophic levels, as monitoring data become available in order to assess the linkages between physical and water quality conditions and biological response.

Samish Bay Taylor Shellfish Farm (this page: Stephanie Moore), and Noctiluca cells (opposite page: Gabriela Hannach).

Highlights from 2013 Monitoring

Large-scale climate variability and wind patterns:

- El Niño-Southern Oscillation (ENSO):
  - » ENSO was in the neutral state for the entire 2013 calendar year.
- Pacific Decadal Oscillation (PDO):
  - » The negative phase of the PDO that has persisted for the vast majority of months since September 2007 continued for 2013, aside from a very small positive anomaly in May.
- North Pacific Gyre Oscillation (NPGO):
  - » NPGO values were positive for most of 2013, then began to trend negatively in Octoer.
- Upwelling index:
  - » Upwelling winds were near-normal in the spring and early summer, but were below normal in August and September relative to the 1967-2012 baseline period.

Local climate and weather:

- Puget Sound annual average temperature was near-normal and annual total precipitation was below normal for the 2013 calendar year. There were some extremes in monthly anomalies; most notable were a colder than normal January, a wet April, warmer than usual nighttime temperatures and humidity during August, a wet September, and an unusually dry October through December period.
- Air temperatures were cooler than normal in January 2013, but then warmer through September. Much of 2013 was cloudy, but marine clouds burned-off during summer and early fall to warm sunny afternoons.

Coastal ocean and Puget Sound boundary conditions:

- Coastal ocean:
  - » Observations from the NANOOS/UW Chá bă mooring on the northwest Washington outer shelf showed 2013 to be an anomalously warm summer in near-surface observations; primarily in September. 2013 was also characterized by a number of low-DO events in the deep waters, with the last and most severe event likely connected to a crab die-off in the vicinity of Ruby Beach observed on August 16th.
  - » The upwelling signal in the 2013 surface seawater xCO_2 record at Chá bă was relatively quiescent, reflecting a dominance of biological production over upwelling at the site between May and September.
- Admiralty Inlet:
  - » Bottom waters (60 m depth) at Admiralty Reach were generally warmer and saltier from February to May. Conditions typical of "summer" started in May, one month earlier compared to previous years. Minimum values of salinity were higher during the summer months compared to previous years. DO was lower from February through June compared to previous years; however, episodes of new maximum DO values were observed in July and August.

River inputs:

- River flows exceeded historic averages in the spring and early summer of 2013, dropping to below normal (northern rivers) or near normal (southern rivers) summer flows. In Puget Sound, heavy precipitation and storms in September and early October produced extremely large runoff events when rivers are typically at their driest. November through December flows dropped below historic medians except for several large pulses associated with individual storm events.

Water quality:

- Temperature and salinity:
  - » The 0-50 m water layer throughout Puget Sound was warmer than normal from January to June and cooler than normal late in 2013. Compared to the previous 3 years, the 0-50 m water layer was slightly saltier but did not approach values observed during the mid-2000s.
  - » Puget Sound basins have a unique temperature and salinity signature that characterizes the water masses and defines flow between basins.
  - » Carr Inlet is generally well-mixed while Twanoh, Hoodsport, Dabob Bay have strong stratification, with the strongest gradient above 20 m.
  - » Surface temperatures (<2 m) in the Central Basin were either typical or slightly cooler than the long-term average (1999-2010) from January through March and then ~0.5-0.8°C cooler than normal in April.
  - » Surface salinities in the Central Basin were fairly typical in 2013 compared to the long-term average, with the exception of May and July which was fresher than normal, likely due to increased freshwater input from snowmelt.

  - While the 2013 Tribal canoe journey data showed marine surface water properties that reflected typical weather and average river flow conditions, along-track variability in temperature, pH, and dissolved oxygen in south and south central Puget Sound was greater and patchier in 2013 than previous years, likely reflecting localized areas of more thorough mixing and/or upwelling of bottom waters associated with sills and/or isolated eddies. Localized effects of river plumes were notable.
  - Observations from fall cruises in the San Juan Channel and Strait of Juan de Fuca showed 2013 to be a transitional year; compared to the 10-year mean, warmer temperatures were found in late-September and cooler conditions by mid-November. In the context of the 10-year record, ENSO and PDO effects are evident, with 2013 being a neutral year.
- Nutrients and chlorophyll:
  - The long-term trend of increasing nitrate and phosphate concentrations and decreasing chlorophyll-*a* was interrupted in 2013 by large phytoplankton biomass and lower concentrations of macro-nutrients.
  - Late summer chlorophyll-*a* was highest in Carr Inlet, with much lower concentrations at Hoodsport and Dabob.
  - The timing of the 2013 spring phytoplankton bloom in the Central Basin was typical, occurring in early April, but an unusually large bloom occurred from August through early September. This bloom was comprised of a variety of diatoms and dinoflagellates, but dominated by diatoms, and resulted in a decrease in nitrate during bloom development and increase in ammonia following bloom degradation. It is suspected that the large *Noctiluca scintillans* bloom observed in the Central Basin during mid to late June reduced chlorophyll-*a* levels (by grazing) and also increased ammonia concentrations (by excretion).
- Dissolved oxygen:
  - The 2013 DO deficit for Puget Sound was higher than what was observed from 2009 through 2012, equivalent to the 2007 and 2008 deficits, but below values of 2006. In 2013, lower than normal DO was observed from February through June in the San Juan Basin, North Sound, Whidbey Basin, and Hood Canal.
  - Although the 2013 fall intrusion in southern Hood Canal was similar in timing to the 2010 event, oxygen concentrations were different between the two years.
  - Oxygen concentrations in southern Hood canal were average in 2013 compared to the previous 10 years.
  - Oxygen super-saturation was evident at all ORCA stations but most profound at Hoodsport. Hypoxia in southern Hood Canal was moderate in 2013 with no observed fish kills.
  - An increase in DO from primary production during the large April and August/September phytoplankton blooms was evident in the upper 30 m of the water column in the Central Basin. In October 2013, inner Quartermaster Harbor DO levels dropped below 1.0 mg/L at night.
- Ocean and atmospheric CO_2:
  - Surface ORCA moorings at Dabob Bay and Twanoh in Hood Canal yielded only partial records for 2013 but showed fairly typical seasonal patterns for xCO_2 compared to previous years, except that average atmospheric xCO_2 values jumped more from 2012 than they had across previous year-to-year comparisons. Surface seawater xCO_2 also increased later in the fall than in previous years.

Plankton:

- Phytoplankton:
  - The chain-forming diatoms *Chaetoceros, Pseudo-nitzschia* and *Thalassiosira* were the most abundant genera at all three Central Basin sites sampled in 2013, with the large genus *Chaetoceros* being the most abundant throughout the entire sampling period at each site.
  - In 2013, the spring April bloom in the Central Basin was dominated by diatoms and followed by a sharp drop in the diatom component during June.
  - 2013 seasonality was markedly different from previous years as diatom genera remained prevalent throughout the year, even during the early to late summer period when dinoflagellate populations typically increase and diversify.
- Harmful algae and biotoxins:
  - Concentrations of marine biotoxins in shellfish were average during 2013. PSP and DSP toxins were detected at levels above regulatory limits resulting in 32 commercial growing area closures and 35 recreational harvest area closures; however, no illnesses were reported.
  - *Alexandrium* spp. counts were low or absent from most SoundToxins monitoring stations throughout 2013 with the exceptions being East Sound and Long Live the Kings on Orcas Island, Discovery Bay, and Sequim Bay.

» *Dinophysis* spp. were identified at all SoundToxins monitoring stations except North Bay, with the highest cell abundances observed in Discovery Bay and Sequim Bay.
» *Pseudo-nitzschia* spp. were commonly observed at SoundToxins monitoring locations, with the highest cell abundances observed in Sequim Bay, Mystery Bay, and Penn Cove; however, no shellfish closures occurred due to domoic acid levels.
» *Heterosigma akashiwo* had variable presence among SoundToxins monitoring stations.
» Robotic detection of harmful algae at two facilities in Puget Sound provided near real-time information in support of proactive fisheries management efforts. The fish-killing alga *Heterosigma akashiwo* was intermittently detected at Lummi Bay, and none of the HAB target species were detected at Samish Bay during the deployment period.
» The highest surface sediment *Alexandrium* spp. cyst concentrations for 2013 continued to be in Quartermaster Harbor in central Puget Sound, Bellingham Bay to the north and Port Madison, Liberty Bay and Port Orchard on the west side of the Central Basin. Abundances remained the same as 2012 for Quartermaster Harbor, but were lower in Bellingham Bay and the bays on the west side of the Central Basin than the previous year.

Bacteria and pathogens:

- Fecal indicator bacteria:
  » In 2013, 78% of the 60 Puget Sound beaches monitored by the BEACH program met EPA's standards for safe swimming.
  » All King County offshore monitoring stations in the Central Basin passed the Washington State geometric mean and peak standards for fecal coliforms during 2013. Nine of 20 monitoring stations at marine beaches in the Central Basin within King County failed both the geometric mean and peak fecal coliform standards.
- *Vibrio parahaemolyticus:*
  » There were 88 laboratory-confirmed and epidemiologically-linked illnesses in 2013 due to the consumption of oysters contaminated with *Vibrio parahaemolyticus* (79 from commercially harvested oysters and 9 from recreationally harvested oysters).

Marine birds and mammals:

- Pigeon guillemot:
  » Breeding success of pigeon guillemots on Protection Island in 2013 was close to average based on the past three years in both natural cavities and artificial nest boxes.
- Rhinoceros auklet:
  » Rhinoceros auklet breeding populations in the Salish Sea had similar reproductive success rates and diet composition in 2013 as they had in recent previous years, 2005-2012, as well as in the 1970s.
- Wintering marine birds:
  » The 2014 (Dec 2013-Jan 2014) population index for scoters of 54,103 continues to increase from the low recorded in 2010 of 42,317, but is 57% below the high estimate in 1995 of 125,287.
  » The 2014 (Dec 2013-Jan 2014) western grebe population index of 9,099 represents a 92% decline from the high recorded in 1995 (120,850), and was the lowest estimate recorded for this species since the WDFW aerial surveys began in 1994.
- Harbor porpoise:
  » Acoustic and land-based observations of Harbor porpoises in Burrows Pass from 2011, 2012, and 2013 are consistent, and show strong seasonal and diurnal activity patterns.
- Southern resident killer whales:
  » Southern resident killer whales in 2013 continued a declining trend in the number of days they were observed in the Salish Sea, possibly corresponding to fewer (and later) Chinook salmon returns to the Fraser River and 80-year record returns of Chinook to the Columbia River.

Large-scale climate variability and wind patterns

Large-scale patterns of climate variability, such as the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO), can strongly influence Puget Sound marine waters. In addition, seasonal upwelling winds on the outer coast, with intrusion of upwelled waters into Puget Sound, are a strong signal that has similar indicators as 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 that can also strongly influence atmospheric conditions, particularly in winter. For example, warm phases of ENSO and PDO generally produce warmer and drier than usual winters in the Puget Sound Basin. The opposite is generally true for cool phases of ENSO and PDO. ENSO climate cycles usually persist for 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 to 3 seasons. For PDO, these anomalously warm waters can reemerge 4 to 5 seasons later (Moore et al. 2008). In contrast, the NPGO, which is related to processes controlling sea surface height, has a stronger effect on salinity and nutrients, as opposed to temperature. Wind is an important factor in the NPGO, which can influence the seasonal wind pattern in the eastern Pacific Ocean. On the outer Washington coast, seasonal winds shift from dominantly southerlies during winter to northerlies during summer and drive some of the largest variation in offshore coastal conditions: upwelling vs. 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.

A. El Niño-Southern Oscillation (ENSO):

Source: Karin Bumbaco (kbumbaco@uw.edu) (OWSC; UW, JISAO), and Skip Albertson (Ecology); http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

ENSO was in the neutral state for the entire 2013 calendar year. For both indicators mentioned here, positive values indicate the warm phase of ENSO and negative values indicate the cool phase. The Oceanic Niño Index (ONI), which is a 3-month running mean of sea-surface temperature (SST) anomalies in the Niño3.4 region of the equatorial Pacific, shows negative values throughout the year (Figure 1). The average SST anomalies were only slightly negative, however, with values no less than -0.6°C and a 2013 mean of -0.3°C. The other commonly used indicator, the Multivariate ENSO Index (MEI), also shows a preference for negative values, but can still be considered neutral. The MEI is a more comprehensive index than ONI, and uses sea-level pressure, surface winds, surface air temperature, and cloud fraction in addition to SSTs to form the index. While generally negative, the index was positive for several two-month periods, with the highest in April-May at 0.108. The lowest occurred in July-August with a value of -0.614.

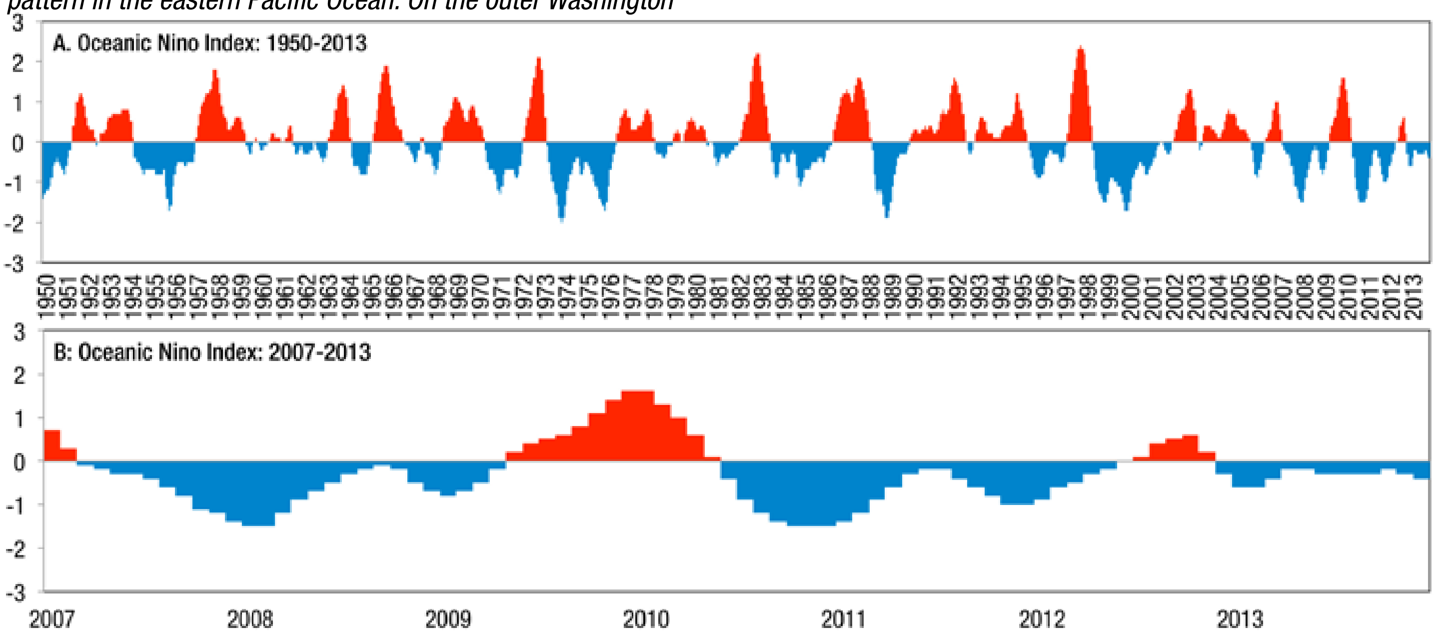


Figure 1. Monthly values of the Oceanic Niño Index (ONI) from A. 1950-2013 and B. 2007-2013.

B. Pacific Decadal Oscillation (PDO):

Source: Karin Bumbaco (kbumbaco@uw.edu) (OWSC; UW, JISAO), and Skip Albertson (Ecology); http://jisao.washington.edu/pdo.PDO.latest

The PDO has been in the negative phase for the vast majority of the months since September 2007 (Figure 2). The negative phase of the PDO is associated with northerly winds and colder water along the Pacific coast of Washington State. For 2013, the negative polarity persisted aside from a very small positive anomaly in May with a value of 0.08. The strongest negative index was in July with a value of -1.25. The negative phase of the PDO was weaker in 2013 compared to the previous two calendar years, as shown in the Figure 2.

C. North Pacific Gyre Oscillation (NPGO):

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

Source: Christopher Krembs (ckre461@ecy.wa.gov) (Ecology); http://www.o3d.org/npgo/data/NPGO.txt

The NPGO has been showing positive values since the late 90s with the exception of intermittent negative values occurring between 2005 and 2007 (Figure 3). Since October 2013, however, NPGO values have started to trend negatively. Decreasing NPGO values suggest a decreasing primary productivity pattern that can be expected for 2014 along Washington's coastline and the California Current. Such a change can eventually extend into reaches of the Salish Sea and Puget Sound.

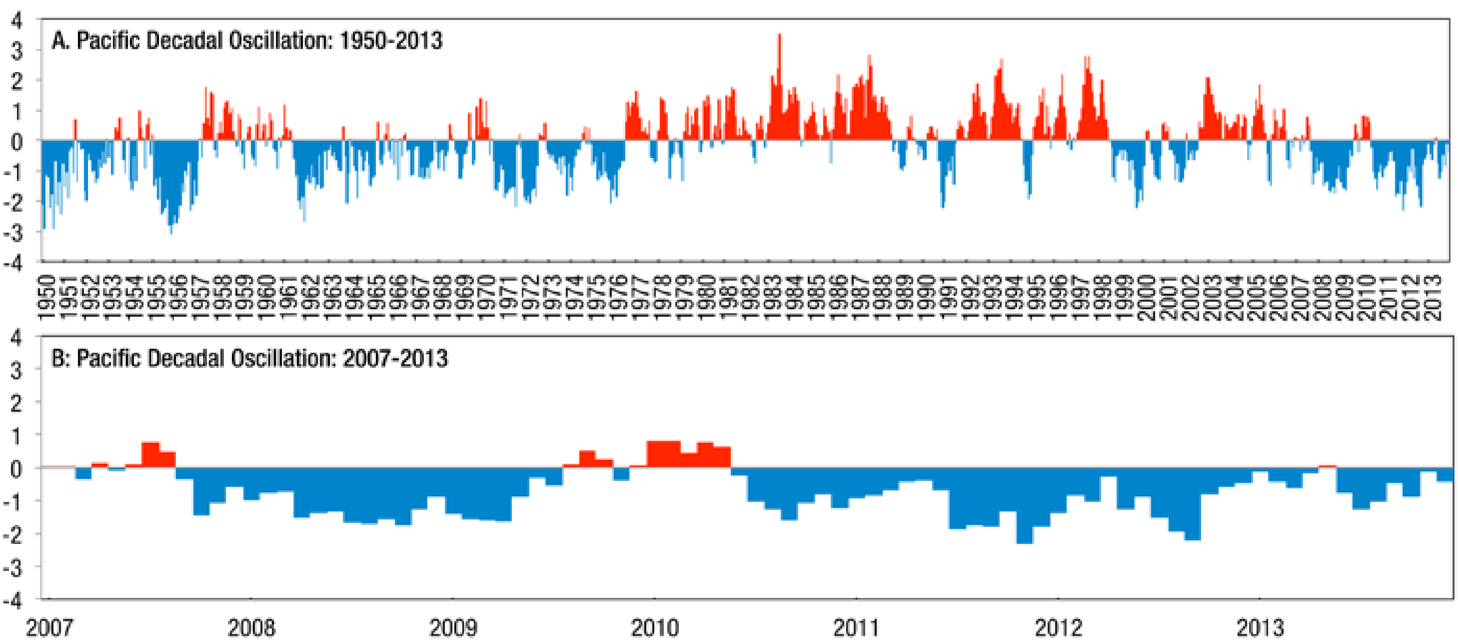


Figure 2. Monthly values of the Pacific Decadal Oscillation index (PDO) from A. 1950-2013 and B. 2007-2013.

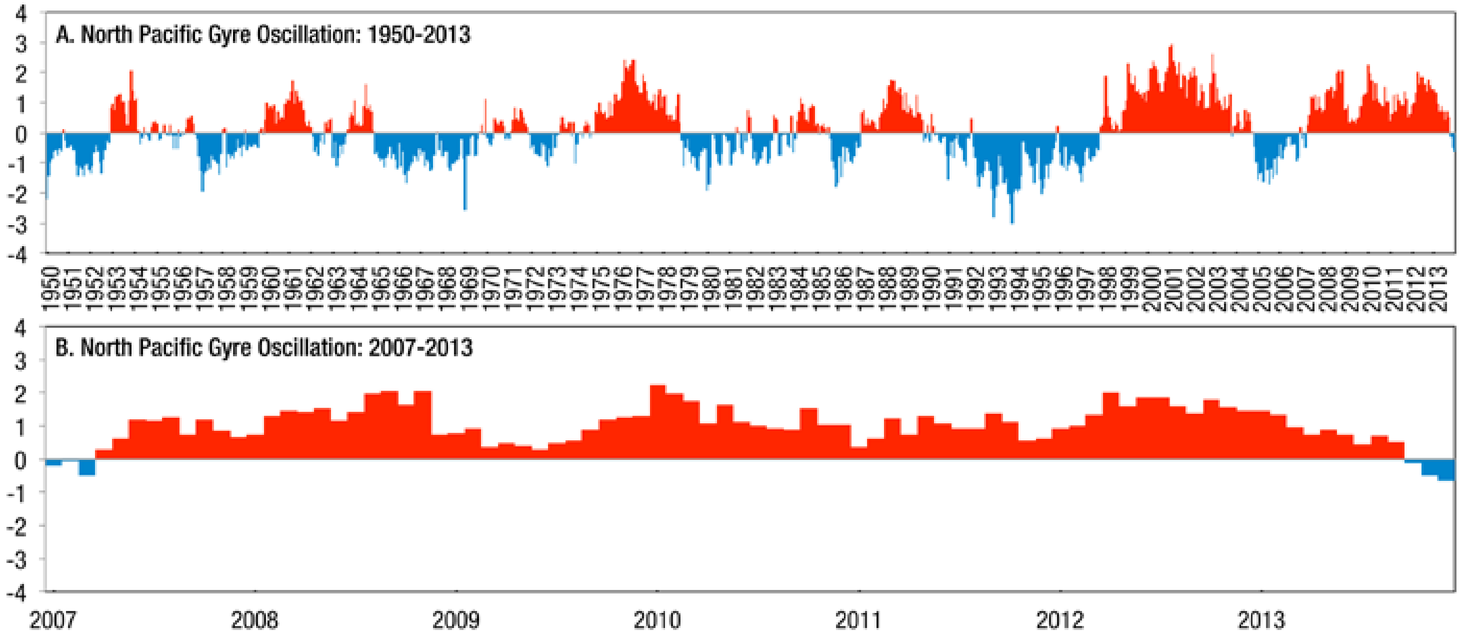


Figure 3. Monthly values of the North Pacific Gyre Oscillation index (NPGO) from A. 1950-2013 and B. 2007-2013.

D. Upwelling index:

Upwelling favorable winds (i.e., equatorward winds) on the outer Washington coast bring deep ocean water in through the Strait of Juan de Fuca and into Puget Sound. The upwelled water is relatively cold and salty, with low oxygen and high nutrient concentrations. The typical upwelling season for the Pacific Northwest is from April through September.

Source: Skip Albertson (salb461@ecy.wa.gov), Christopher Krembs, Mya Keyzers, Laura Hermanson, Julia Bos, and Carol Maloy (Ecology); www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html

Monthly mean values of the upwelling index at 48°N and 125°W were mostly within the historical interquartile range in 2013 with the exception of August and September when coastal upwelling underwent a significant reduction (Figure 4). This coincided with warming of NE Pacific Ocean surface water in late summer (not shown). Downwelling events were significantly absent in December, which is uncommon.

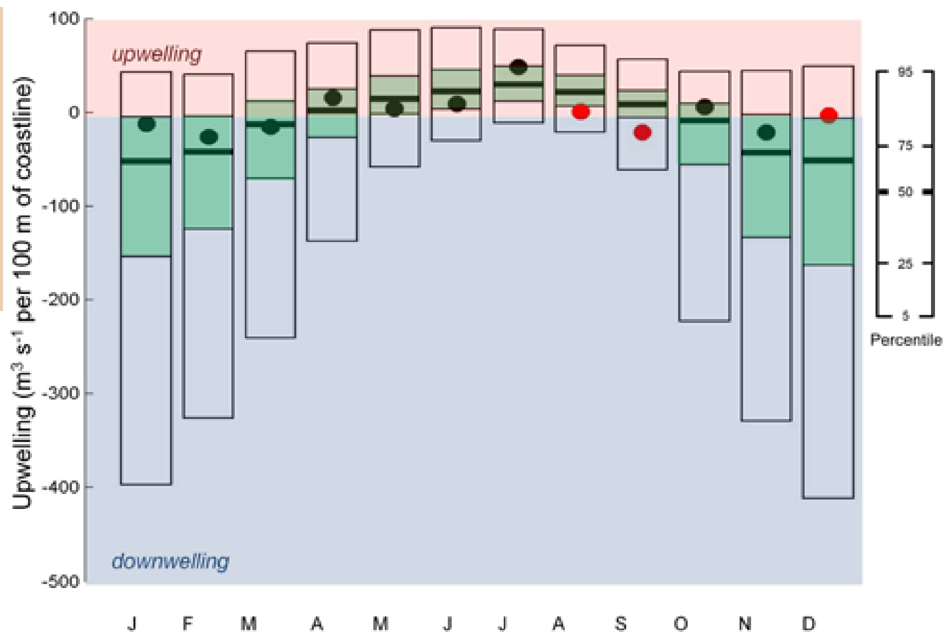
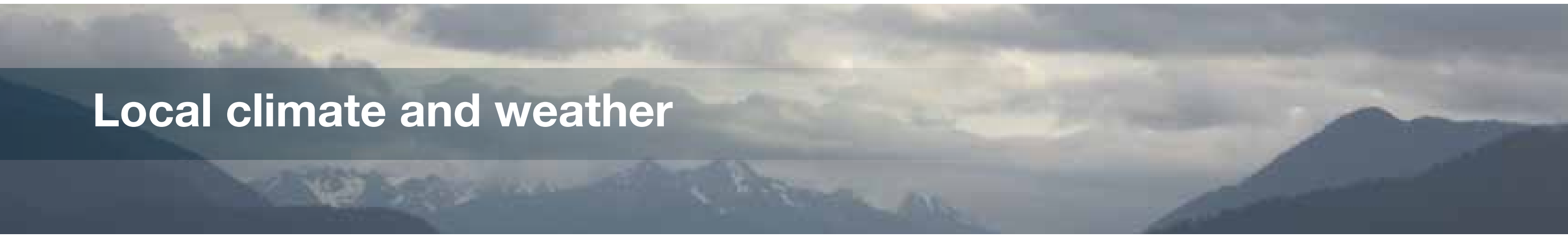


Figure 4. Monthly mean values of the coastal upwelling index (PFEL, NOAA) at 48°N and 125°W for 2013 (red and black dots) superimposed onto a statistical historical context of the index from 1967-2012. Percentiles of 5, 25, 50 (median shown with thick black line), 75 and 95 are presented. Values falling outside of the interquartile range (green) are considered significant and colored red. Pink and blue shaded areas indicate upwelling and downwelling conditions, respectively. Data source: www.pfeg.noaa.gov/products/las/docs/upwell.nc.html



Local climate and weather

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

A. Regional air temperature and precipitation:

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

For the 2013 calendar year, Puget Sound conditions were drier than normal with near-normal temperatures, compared to the 1981-2010 climate averages. Washington State is divided into 10 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 Puget Sound lowlands division that encompasses most of the Puget Sound is used for this summary. The 2013 average temperature for the division was within 0.1°C of normal (10.4°C) and total precipitation was 86% of normal (97.2 cm). Temperature anomalies are spatially consistent throughout the Puget Sound region for the calendar year. However, there are some spatial differences for precipitation; northern Puget Sound had precipitation much closer to normal (between 90 and 110% of normal) while precipitation anomalies were below normal elsewhere in the region (between 70 and 90% of normal).

While the average conditions provide one perspective on the calendar year, it is also worthwhile to consider temperature and precipitation anomalies on shorter time scales. Figure 5 shows the monthly temperature and precipitation anomalies for the Puget Sound relative to 1981-2010 normals. January was much cooler than usual, due to a dominant ridge of high pressure causing a temperature inversion that lasted for over 2 weeks. Despite a wet April (156% of normal precipitation), temperatures in spring and early summer were warmer than normal, marking a faster transition to spring than in the previous 3 years. Summer was marked by higher than usual minimum temperatures, especially in August when humidity was high. The precipitation for September was also quite anomalous – it was the wettest September on record for the Puget Sound region. However, the weather pattern shifted in October, ushering in another persistent ridge of high pressure that blocked typical fall storms from impacting the region. October through December was much drier than usual and ranked as the third driest on record for the Puget Sound lowlands.

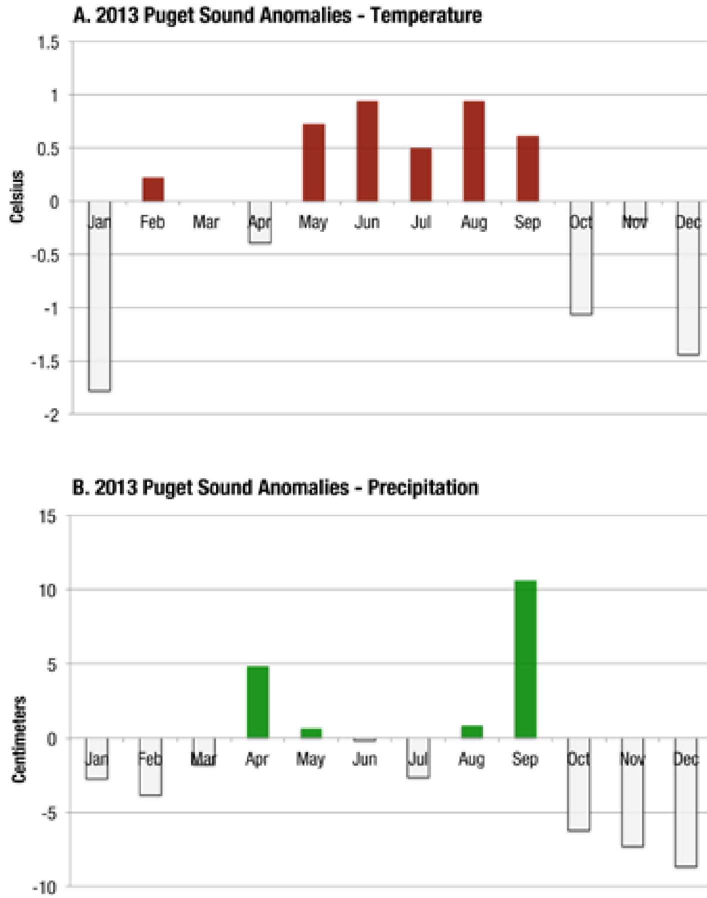


Figure 5. Monthly anomalies for (A) temperature (Celsius) and (B) precipitation (centimeters) for the Puget Sound lowlands climate division in Washington State for the 2013 calendar year. Anomalies are relative to 1981-2010 climate normals.

Seattle Waterfront. Photo: Stephanie Moore.

B. Local air temperature and solar radiation:

Source: Skip Albertson (salb461@ecy.wa.gov), Christopher Krembs, Mya Keyzers, Laura Hermanson, Julia Bos, and Carol Maloy (Ecology); www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html

Anomalies of daily air temperature at Sea-Tac Airport, relative to the 1971-2000 baseline period, show that 2013 began with a cold spell in January, followed by warmer-than-normal conditions through September (Figure 6A). October and December were generally cool, but November was noticeably warmer. Anomalies of daily solar energy flux (UW PAR sensor), relative to the 1971-2000 baseline period, show that January through April were cloudier than normal (Figure 6B). Starting in May and lasting through August, higher than normal sunlight prevailed, especially for an extensive period from late June through August. Summer and early fall were characterized by mornings of marine clouds that burned off to warm sunny afternoons.

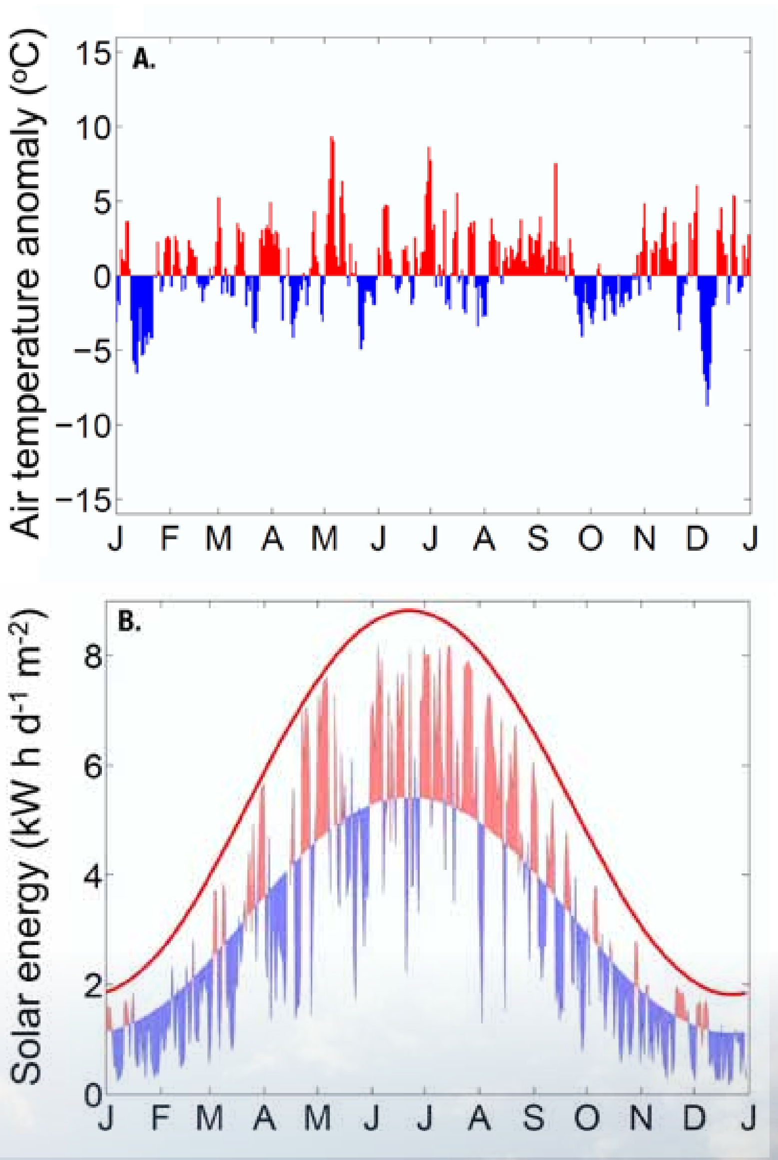


Figure 6. Air temperature anomalies (A) and daily solar energy (B) at SeaTac Airport and UW ATG building, respectively, in 2013. Red indicates higher than average and blue indicates lower than average air temperature. The solid red line on the solar panel shows the highest theoretical solar energy, and red indicates approximately when the sky is more than 50% clear and blue when it is less than 50% clear.

Strait of Juan de Fuca. Photo: Ruth Howell.

Coastal ocean and Puget Sound boundary conditions

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

A. Coastal ocean:

i. Interannual comparison of water properties:

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

Observations during 2013 from the NANOOS/UW Chá bă mooring on the northwest Washington outer shelf revealed near surface seawater temperatures fluctuating significantly for extended durations both above and below those of the previous two years, with anomalously warm summertime conditions (Figure 7). 2013 was characterized by a number of low-DO events in the deep waters, with the last and most severe event coincident with the August 16th crab die-off observed in the vicinity of Ruby Beach (Schumacker, pers comm). Long periods of anomalously warm near-surface (3 meters) temperature during the summer were primarily a consequence of local weather patterns with light SE winds (not upwelling favorable) and humid conditions. When compared to 2011 and 2012, 2013 near-surface temperatures were as much as 2°C higher in early July and 5°C higher in early September. However, during episodes of relatively consistent upwelling-favorable winds in the latter half of July and early August, near surface temperatures were roughly 1-2°C *less* than 2012.

Chá bă buoy observations from mid-April through mid-October 2013 revealed three low DO events of deep water (~85 m), which were characterized by sudden reductions in DO concentrations from roughly 4 mg/l to values of near 1.5 mg/l or less. These events lasted about a week for the first two events in late May/early June and late June/early July respectively, and for more than 3 weeks for the third event extending from mid-August to early September. The third event was the most severe, with values dropping to severely hypoxic conditions of less than 0.7 mg/l. A decrease in DO of the deep water at the mooring site was associated with reversal of upwelling-favorable NW winds to downwelling favorable SE winds. Deep currents paralleled this wind shift, changing from the predominant NW flow to flow from the SE, suggesting the lowest DO water likely originated inshore and southward of the mooring site, consistent with the crab die-off location and timing and consistent with data from the OCNMS nearshore buoy. ECOHAB surveys of near-bottom DO levels conducted in September of 2003-2006 revealed a similar pattern. The mean deepwater DO values were about 1.4 mg/l lower in 2013 than in 2011.

Large phytoplankton blooms, indicated by chlorophyll-*a*, occurred in May, June, and July and did not coincide with the deep DO minima, suggesting differences in when and where consumption occurs. Pulses of low salinity water, also observed and reported in previous years, show a repeating occurrence on ~1 June and 1 July. Current data indicate these pulses originate from the Columbia River.

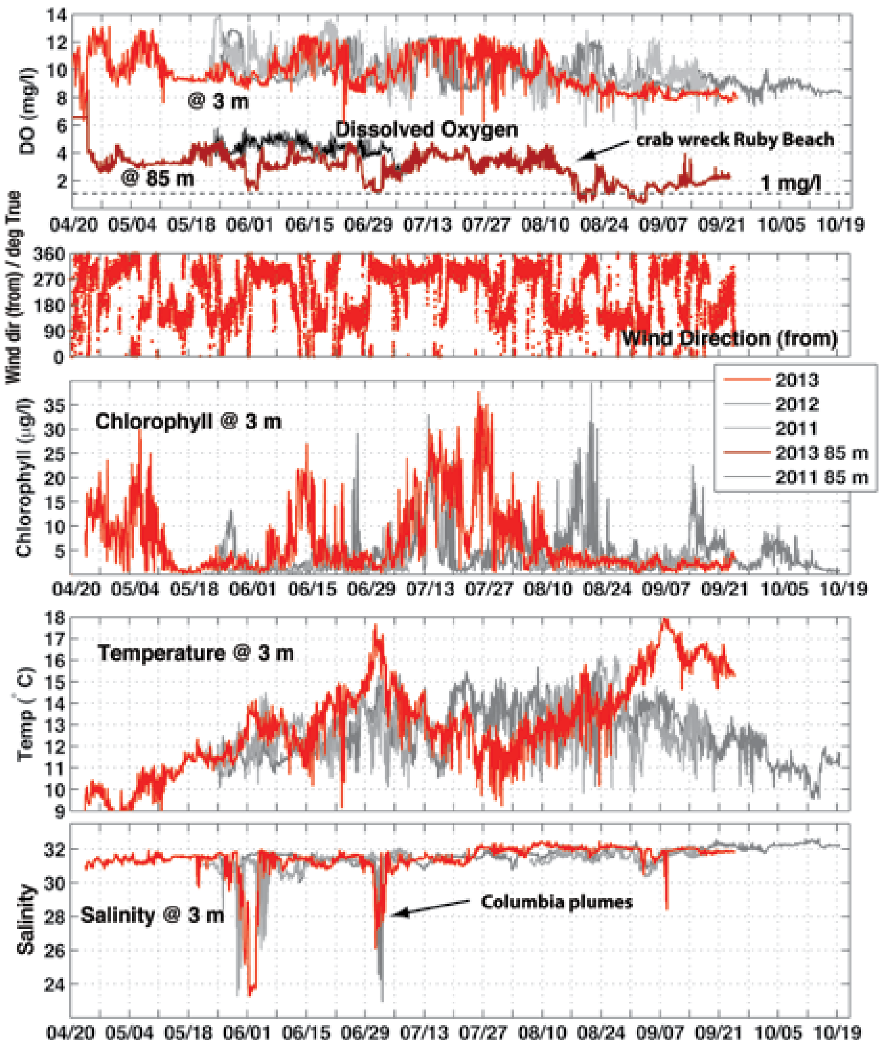


Figure 7. Interannual comparison of observations at the Chá bă mooring, 13 nautical miles WNW of La Push at 47° 58' N, 124° 57' W.

ii. Ocean and atmospheric CO_2:

Source: Simone Alin (simone.r.alin@noaa.gov), Jeremy Mathis, Christopher Sabine (NOAA, PMEL), Adrienne Sutton, Sylvia Musielewicz (UW, JISAO), Jan Newton, and John Mickett (UW, APL); http://www.pmel.noaa.gov/co2/story/La+Push

CO_2 sensors have been measuring atmospheric and surface seawater xCO_2 (mole fraction of CO_2) at three-hour intervals on the surface Chá bă mooring since 2010. During the May-December 2013 deployment of the Chá bă surface mooring, the atmospheric xCO_2 ranged from 370 to 443 ppm, with an average value of 398±7 ppm (±SD), which is quite close to the global atmospheric average for 2013 (Figure 8). During the same period, surface seawater xCO_2 varied between 109 and 465 ppm, with an average of 275±70 ppm at the site, indicating that surface seawater conditions were predominantly lower than atmospheric xCO_2 during the 2013 deployment. These undersaturated surface seawater values reflect the influence of primary production consuming CO_2, whereas supersaturated surface seawater values (above atmospheric xCO_2) reflect dominance of upwelling and/or respiration processes. The 2013 seawater xCO_2 record is thus dominated by a signal of biological production rather than upwelling.

Relative to previous deployments (2010-2012), the peak 2013 surface seawater xCO_2 value was markedly lower (474 ppm vs. 612-621 ppm in previous years). In previous years, peak seawater xCO_2 values occurred during the upwelling season (May-September), but during 2013, no seawater xCO_2 values rose above either global or local atmospheric xCO_2 levels for more than a few consecutive measurements before November.

Since the original deployment in July 2010, the most complete and continuous xCO_2 records were collected from June through September for 2011, 2012, and 2013. Average surface seawater values during this interval in 2011 were 289±95 ppm, 275±53 ppm in 2012, and substantially lower, at 243±63, ppm in 2013. The respective average atmospheric xCO_2 values increased by a few ppm per year and were 389±7 ppm (2011), 393±7 ppm (2012), and 395±7 ppm (2012). The 2010 and 2011 time-series show strong variability in seawater xCO_2 records, reflecting upwelling events, whereas the 2012 and 2013 time-series show far fewer and no peak xCO_2 values typical of upwelling events, respectively.

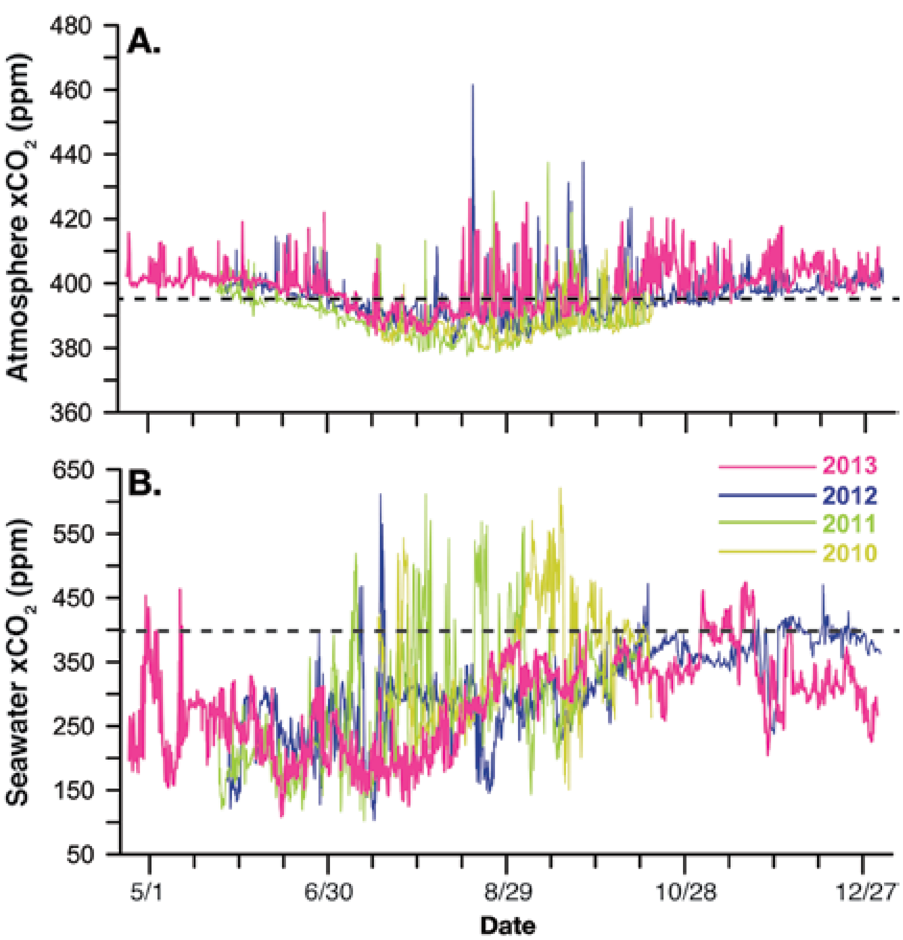


Figure 8. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater (A) and surface seawater at 0.5 m depth (B) from mid-May through December at the surface Chá bă mooring off La Push, WA. Data from all deployment years are included for comparison (color key in panel B applies to all panels, data available in: Mathis et al. 2011). Approximate 2013 global average atmospheric xCO_2 of 395 ppm is indicated with a dashed line in each panel. Typical uncertainty associated with quality controlled xCO_2 measurements from these systems is <2 ppm for the range 100-600 ppm. Note different scales of vertical axes.

B. Admiralty Inlet:

Admiralty Inlet connects the Strait of Juan de Fuca to Puget Sound. Conditions at depth at Admiralty Inlet are representative of the water masses coming into the Sound from the coastal ocean. These conditions are responsive to the tides and upwelling (i.e. northerly) winds on the outer Washington coast.

Source: Julia Bos (jbos461@ecy.wa.gov), Christopher Krembs, Suzan Pool, David Mora, Skip Albertson (Ecology), and Jim Thomson (UW, APL); www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html

In collaboration with the UW Applied Physics Laboratory, the Dept. of Ecology deployed a moored sensor package at the bottom of Admiralty Inlet (60 m depth) to monitor characteristics of water exchange across the sill between Puget Sound and the Strait of Juan de Fuca. Operating since 2009, these continuous data provide the temporal context for describing seasonal and event driven dynamics connecting Pacific Ocean and Puget Sound water. The largest variability in daily observations of temperature, salinity, and DO across Admiralty Reach occurs from late spring through early fall and indicates the development of strong horizontal gradients in water properties. The largest ranges are explained by tidal excursions of this gradient. Peaks in variables are associated with seasonal warming, upwelling, and phytoplankton productivity. The highest salinity and lowest DO conditions are observed during the summer and correspond to periods of upwelling along the Washington coast. During the winter, gradients are small. Nevertheless, distinct events of warmer, saltier, low-DO offshore water entering Puget Sound occur when the typical strong southerly wind pattern temporarily weakens in the winter. In 2013, warmer, saltier, low-DO waters were observed from February through June (Figure 9). Conditions typical of "summer" began one month earlier compared to previous years. Larger variability in daily observations of water properties compared to previous years suggests that horizontal gradients were less uniform across Admiralty Reach. From June to September, temperatures and salinities north of the sill were higher than in previous years. Several episodes of high DO occurred during July and August, when an unusually large summer phytoplankton bloom occurred (data not shown in this plot).

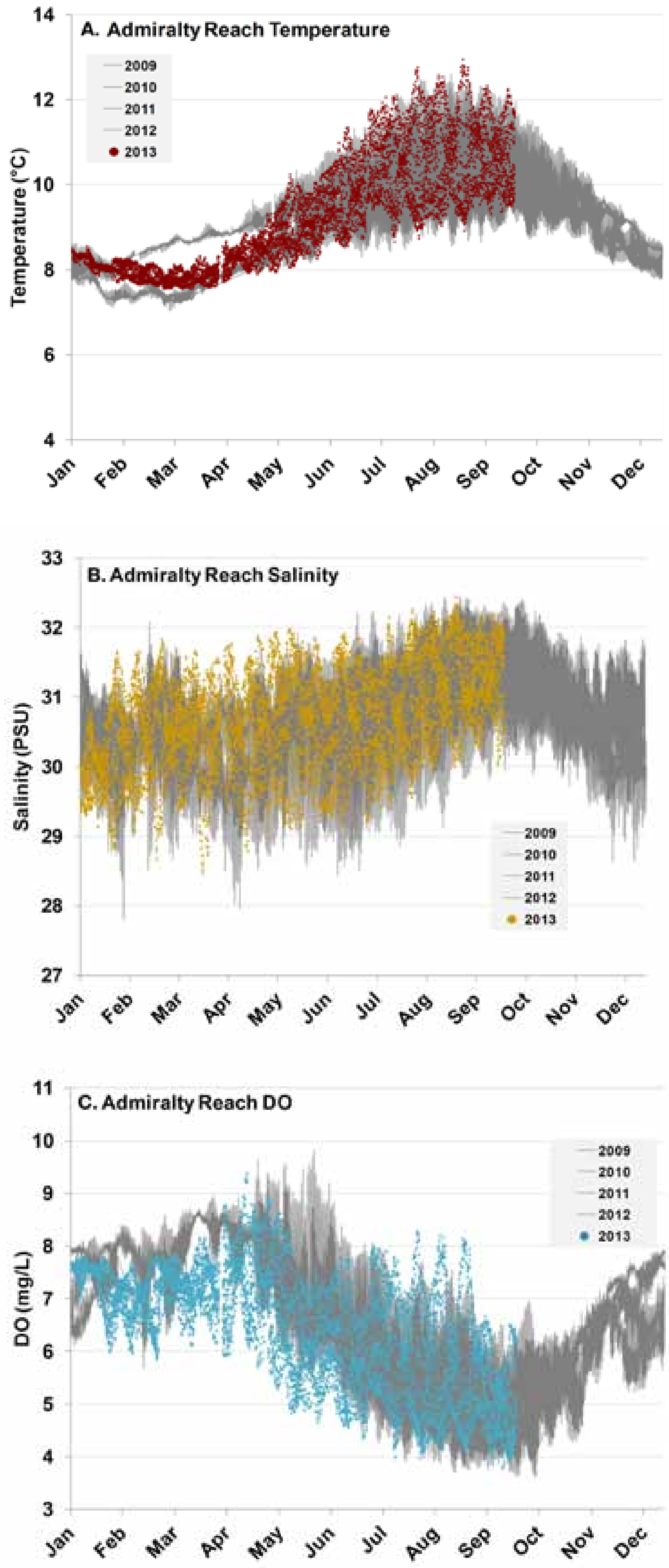


Figure 9. Admiralty Inlet mooring data at ~60 m depth. Shown are continuous measurements collected every 45 minutes of (A) temperature, (B) salinity, and (C) dissolved oxygen.

CALL-OUT: ATMOSPHERIC AND SURFACE SEAWATER CO_2 AT THE COAST AND HOOD CANAL

During 2013, atmospheric and surface seawater mole fractions of carbon dioxide (xCO_2) were measured May 12-December 31 at the Chá bă mooring off La Push, WA, September 10-November 1 at the Dabob Bay mooring, and July 26-December 31 at the Twanoh mooring (Figure 10). Comparison of conditions at the air-sea interface across these sites, with Chá bă representing coastal conditions and Dabob Bay and Twanoh representing Hood Canal, illustrates the different biogeochemical drivers different sites experience.

Atmospheric xCO_2 was higher than average global atmospheric xCO_2 during most of the 2013 record at all three sites. Both Chá bă and Twanoh atmospheric xCO_2 values fell below the global average during parts of the July-September period, likely reflecting regional drawdown of atmospheric CO_2 via biological production. During September-November, strong coherence in atmospheric xCO_2 variability at Dabob Bay and Twanoh was visually apparent. Substantially higher average and peak values for atmospheric xCO_2 within Hood Canal versus offshore at La Push suggest that anthropogenic activity (e.g. traffic or land-use factors) within the Puget Sound basin may elevate atmospheric xCO_2 values over Hood Canal by roughly 20 ppm relative to coastal atmospheric xCO_2 values. However, the coherent patterns of change in the atmospheric xCO_2 signals across all three sites suggest that weather also plays a role in modulating the variability seen across both regions.

As with atmospheric xCO_2, surface seawater xCO_2 observations typically reflect biological production during summer months with undersaturated xCO_2 values at all sites (Figure 10). Peak surface seawater xCO_2 values in Hood Canal are far higher during the fall and do not show the same consistency between sites as seen in atmospheric xCO_2 values, with the highest seawater peaks during the short Dabob Bay 2013 record falling between intervals with peak CO_2 values at Twanoh and substantially higher peak values at Twanoh. This suggests that the physical processes controlling CO_2 dynamics at the two Hood Canal sites diverge.

Authors: Simone Alin (simone.r.alin@noaa.gov), Richard Feely, Jeremy Mathis, Christopher Sabine (NOAA PMEL), Jan Newton (UW, APL), and Adrienne Sutton (UW, JISAO)

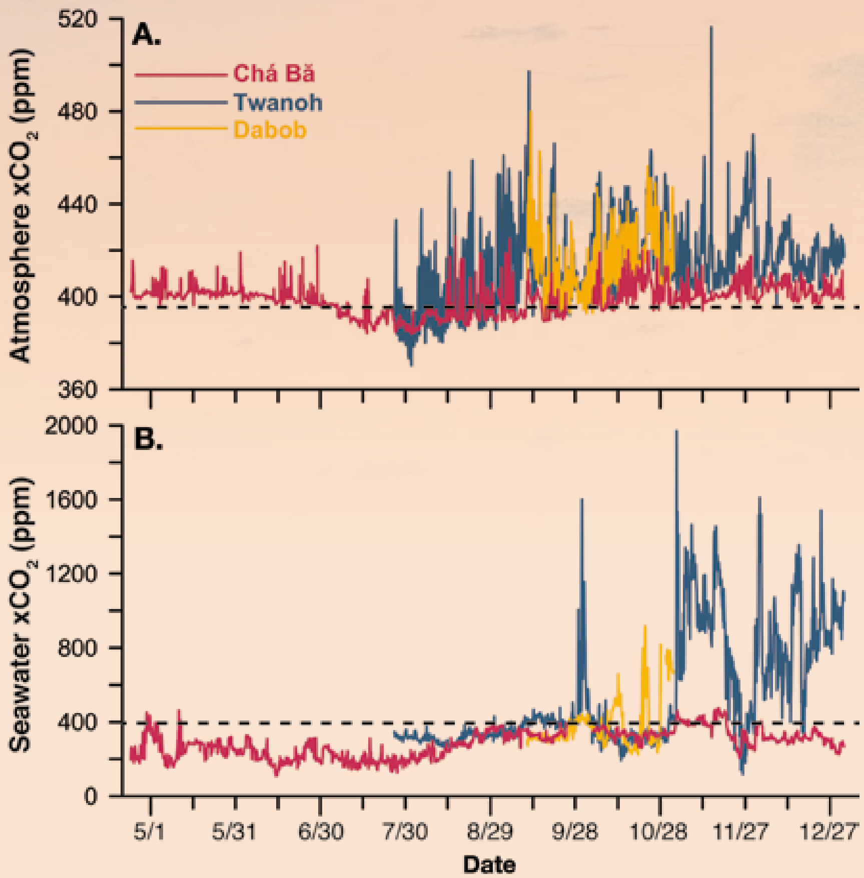


Figure 10. The atmospheric (A) and surface seawater (B) xCO_2 records collected between late April and December 2013 on the Chá bă, Dabob Bay, and Twanoh surface moorings. Information about the layout, axes, and uncertainty associated with this figure is presented in figures 8 and 20.

River inputs

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

A. Puget Sound rivers:

Source: Ken Dzinbal (ken.dzinbal@psp.wa.gov) (PS Partnership) and U.S. Geological Survey; http://waterdata.usgs.gov/wa/nwis/current/?type=flow

Puget Sound rivers contribute about one-third of freshwater inflow to the Salish Sea, with the largest volume coming from the Skagit River. Many Puget Sound rivers exhibit two discharge peaks per year – a peak in early summer produced by melting mountain snowpack, followed by a peak starting mid-fall with the onset of winter storms and rain, and extending through the winter. Compared to long-term records, flows in early 2013 were below historic median levels. Flows then increased above median levels from March into June coinciding with unusually heavy spring precipitation (Figure 11). Summertime river discharge dropped to below average (northern rivers) or near average (southern rivers) levels, and then increased rapidly in all regions as September precipitation reached record levels. Rivers reached nearly peak annual flow conditions in late September and early October during what is typically the period of lowest annual flow. Levels then dropped below historic medians in November and December, except for occasional high pulses associated with individual storm/precipitation events.

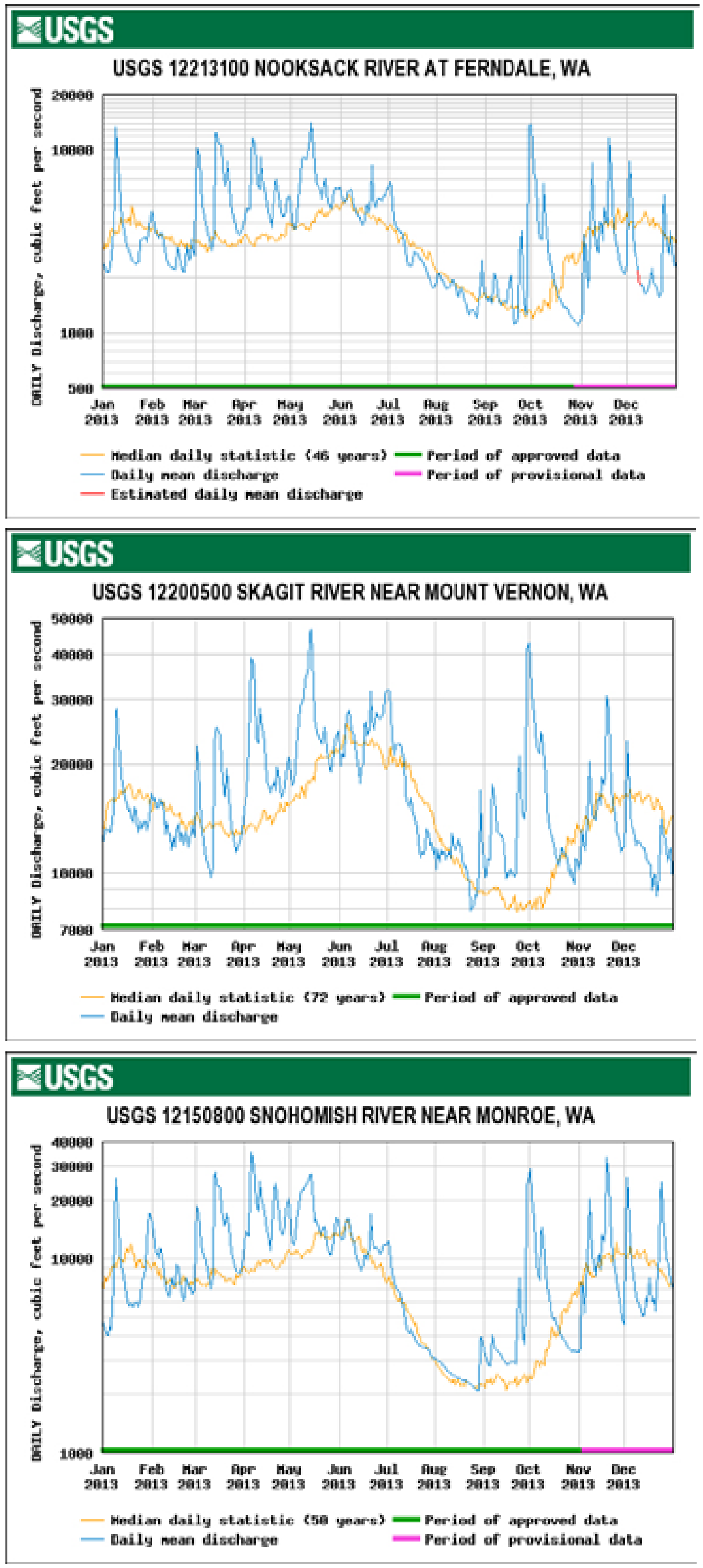
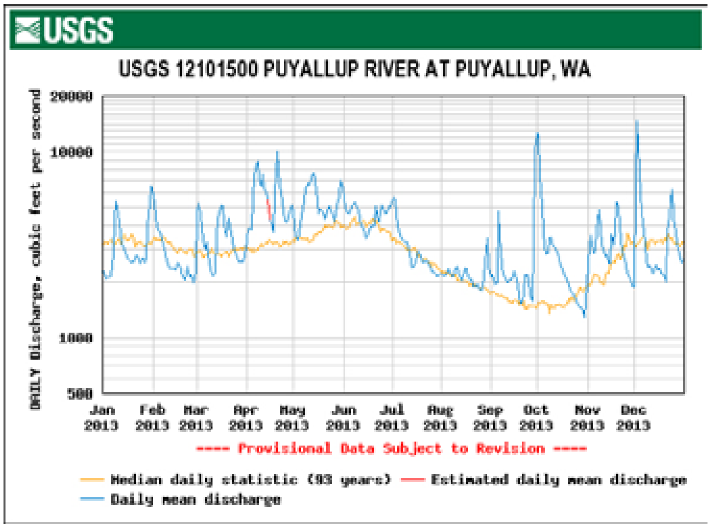
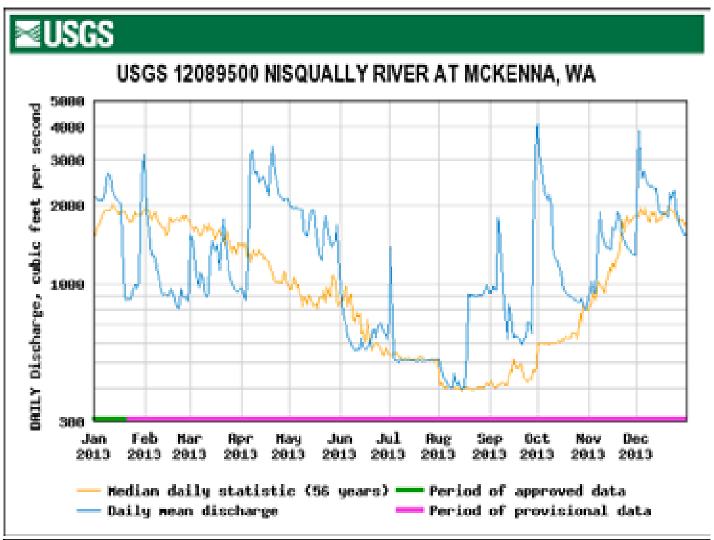
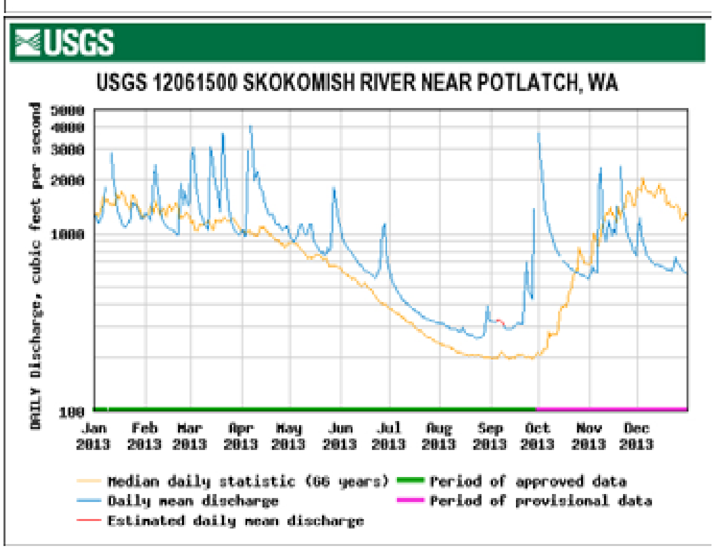


Figure 11. Daily discharge (cfs) at stations in Nooksack, Skagit, Snohomish, Puyallup, Nisqually, and Skokomish Rivers for 2013, compared to long-term median values. Note the period of record varies and is indicated separately for each station.







B. Fraser River:

Source: Ken Dzinbal (ken.dzinbal@psp.wa.gov) (PS Partnership) and Environment Canada; http://www.wateroffice.ec.gc.ca/text_search/search_e.html?search_by=p&region=BC

The Fraser River is by far the largest single source of freshwater to the Salish Sea, accounting for roughly two-thirds of all river inflow. The annual flow regime is characterized by a single, early summer discharge peak (Figure 12). Fraser River waters can strongly influence conditions in the Strait of Juan de Fuca including the water entering Puget Sound through Admiralty Inlet. In 2013, Fraser River discharge was normal from January to March but rose above the long term mean in April and May. An unusually large peak occurred mid-May, a month earlier than average. Flows then dropped below normal levels through summer and remained low for the rest of the calendar year with the exception of a single, moderate runoff pulse in early October.

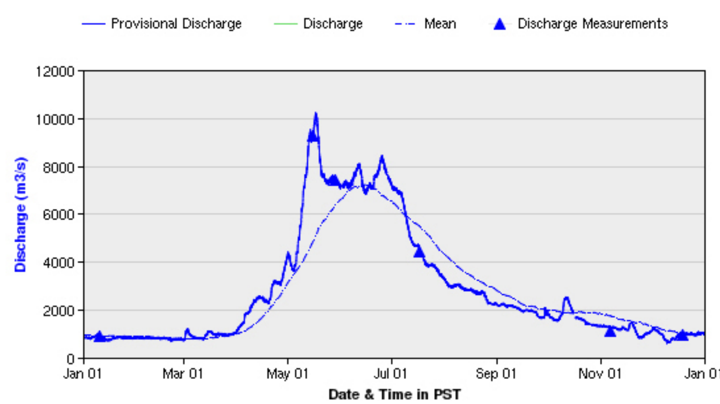


Figure 12. Fraser River daily discharge (m^3/s) at Hope, B.C. for 2013, compared to the mean value from long-term records (1912-2014). (Note: 1 m^3/s = 35.3 cfs).

CALL-OUT: PUGET SOUND BENTHIC MACROINVERTEBRATE ASSEMBLAGES

The Washington State Department of Ecology (Ecology) Marine Sediment Monitoring Program (MSMP) has documented declines in benthic macroinvertebrate community condition in several geographic regions and urban bays of Puget Sound, based on comparisons of data from baseline (1997-2003) and resample (2004-2012) surveys (Partridge et al., 2012, 2013; Weakland et al., 2013a,b). Community condition was characterized with a suite of abundance and diversity indices and an overarching Benthic Index which classifies the sediment-dwelling invertebrate communities (i.e. benthos) as either "adversely affected" or "unaffected" by natural or human-induced stressors. The sample design allows estimation of the spatial extent of benthos condition, as well as temporal comparisons for each sampling area.

Figure 13 displays the percent area of adversely affected and unaffected benthos condition for each Puget Sound region and urban bay sampled between 1997 and 2011. Most regions and bays resampled at roughly decadal intervals have shown increases (some statistically significant) in percent area of adversely affected condition. Concentrations of over 150 chemical contaminants collected from these sediments have generally been low, and do not correspond well with declines in benthic assemblage condition. Ecology's Chemistry Index calculated for these sediments has generally met or shown improvement in target values set by the Puget Sound Partnership. However, sediment toxicity, measured with laboratory bioassays and summarized with a Toxicity Index, has actually shown significant declines in some regions and bays. The decline in the Benthic and Toxicity indices, associated with not change or improvements in the Chemistry Index, suggest benthic assemblage condition is likely responding to variables other than individually measured chemicals. There are other environmental attributes and pressures that haven't yet been evaluated that may be affecting the benthos. These include changes in the Puget Sound food web, water quality condition, natural oceanic cycles, sediment movement, and unmeasured contaminants.

In response to a hypothesis that shifting nutrient ratios and planktonic assemblages in Puget Sound may be reducing nutrient loads reaching the seabed, Ecology's Marine Waters Monitoring Program and MSMP scientists are looking for evidence of changes in the benthic food web. Benthos data collected from 1997 to 2012 are being reexamined to characterize macroinvertebrate assemblages on a functional, rather than structural basis. Feeding guild and functional role classifications developed by Macdonald et al. (2012) have been assigned to all taxa, and changes in the spatial distribution of feeding guild types are being examined. Early results indicate declines in abundance and distribution of surface deposit feeders and facultative detritivores in some locations, and may support a hypothesis of changes in food availability for the macrobenthos. This and other hypotheses will be explored in our continued monitoring of Puget Sound sediment quality and macrobenthos.

Authors: Margaret Dutch (margaret.dutch@ecy.wa.gov), Valerie Partridge, Sandra Weakland, Kathy Welch (Ecology), and Clifton Herrmann (Ecology, WCC/AmeriCorps)

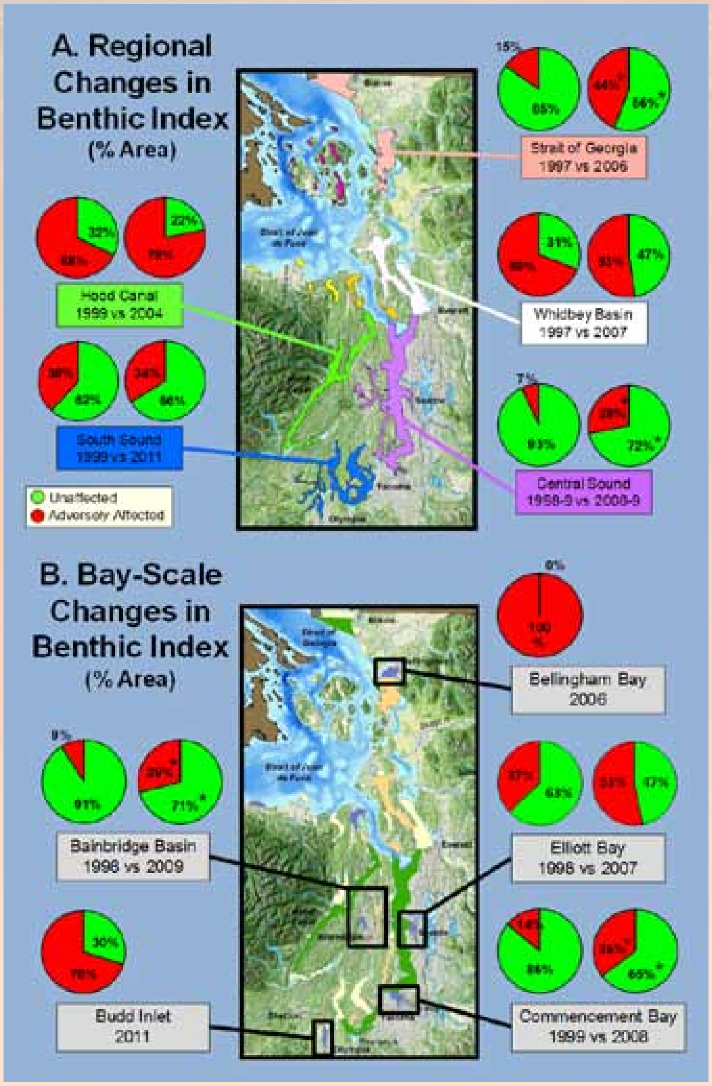


Figure 13. Regional (A) and bay-scale (B) spatial changes in Ecology's Sediment Benthic Index based on sediment quality monitoring in five regions and five urban bays conducted between 1997 and 2011. (Significant changes over time are denoted with an asterisk.)

Temperature and salinity are fundamental water quality measurements. They define seawater density and as such are important for understanding estuarine circulation. Various organisms also may have tolerances and preferences for thermal and saline conditions. Nutrients and chlorophyll give insight into the production 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 nutrients loads. Dissolved oxygen in Puget Sound is quite variable spatially and temporally and can quickly shift in response to wind, weather patterns and upwelling. In some parts of Puget Sound, dissolved oxygen is measured intensively to understand the connectivity between hypoxia and large fish kills.

A. Puget Sound long-term stations:

The Washington Dept. of Ecology maintains a long-term station monitoring network throughout the southern Salish Sea including the eastern Strait of Juan de Fuca, San Juan Islands, and Puget Sound basins. This network of stations provides the temporal coverage and precision needed to identify long-term trends; www.ecy.wa.gov/programs/eap/mar_wat/mwm_intr.html.

i. Temperature and salinity:

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

In 2013, temperature and salinity measurements at Ecology's long-term station network showed a distinct change from the colder, fresher, more oxygenated conditions of the 2011-2012 La Nina years. Heat maps of monthly anomalies calculated from historical site-specific averages are used to display results across Ecology's station network. Thermal energy (heat) content in the 0-50 m layer of the water column was higher (warmer) through the summer of 2013, but then decreased (turned colder) in the fall (Figure 14A). Salt content in the 0-50 m layer increased, especially at shallow stations and in the northern reaches, yet a fresher signal persisted for most of the year in several basins (Figure 14B). Overall Puget Sound-wide annual anomalies in 0-50 m temperature and salinity are calculated from averaged monthly site-specific anomalies and show that there was more thermal energy in the system in 2013 compared to 2011-2012, but Puget Sound was not as warm as in 2010 or 2003-2007 (Figure 14C). Comparatively, salt content was higher in 2013 compared to 2010-2012, but not as high as the period 2005-2009 (Figure 14D).

Ecology's long term monitoring station network is sampled by seaplane. Photo: Christopher Krembs.

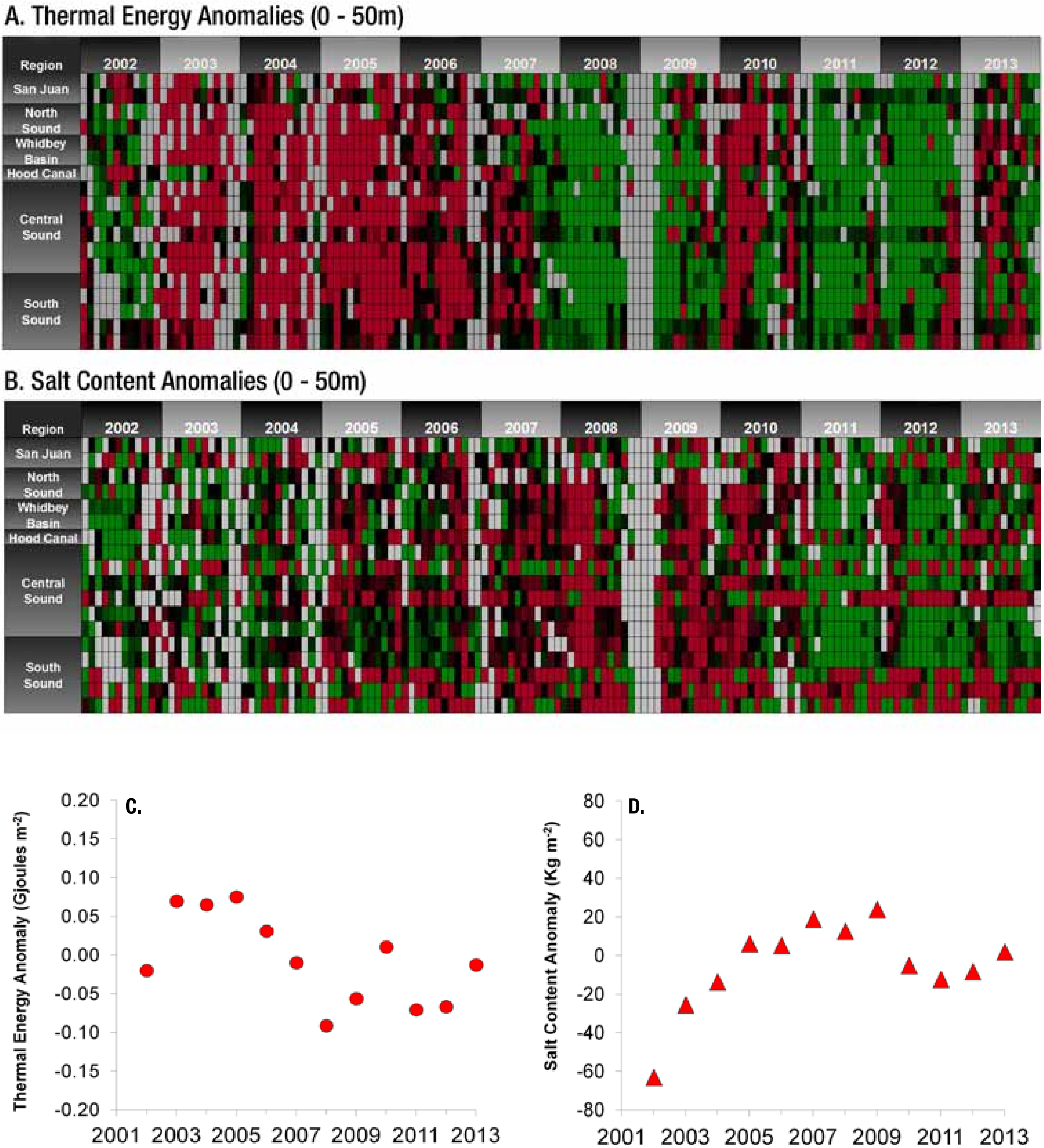
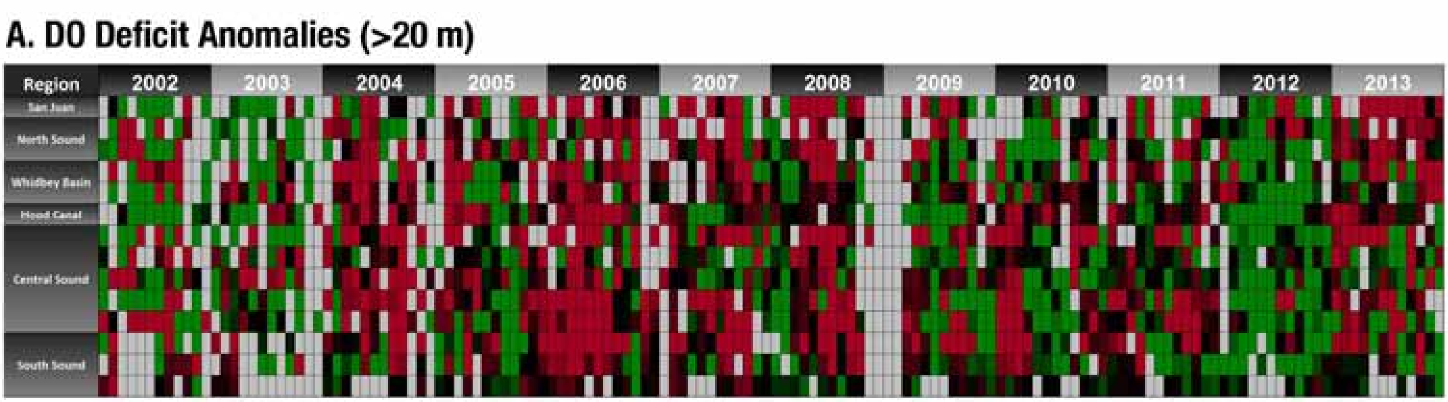


Figure 14. Heat maps of Puget Sound thermal energy (A) and salt content (B) anomalies for the 0-50 m water layer. Anomalies are calculated from site-specific monthly averages using a reference baseline established for 1999-2008. Green = lower, red = higher, black = expected, gray = no data. Puget Sound-wide annual anomalies for (C) temperature and (D) salinity in the 0-50 m water layer from 2002-2013.

ii. Dissolved oxygen:

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

Ecology reports a dissolved oxygen “deficit” to put DO measurements into an environmental context. The DO deficit is the difference between the measured value and fully saturated value, calculated using station-specific pressure, temperature, and salinity results. When the DO deficit is high, measured DO in the water column is low compared to full saturation, and when the DO deficit is low, measured DO is closer to full saturation. A heat map of monthly anomalies of the DO deficit is shown in Figure 15A for the period 2002-2013. The DO deficit for water deeper than 20 m was higher during the middle of the decade, dropped from 2009-2012, and increased again in 2013 implying that DO concentrations were lower. The DO deficit was very low in 2012 (green) indicating very favorable oxygen conditions below 20 m. A sharp shift occurred in 2013 with the DO deficit increasing to higher than normal values (red), especially at northern sites. This shift may be related to a change in boundary conditions. Higher upwelling in early 2013 corresponded to decreased oxygen in sub-surface waters. An overall Puget Sound-wide annual anomaly in the DO deficit is calculated from averaged monthly site-specific anomalies and shows that 2013 had a DO deficit higher than 2009-2012 and similar to the years 2007-2008 (Figure 15B).



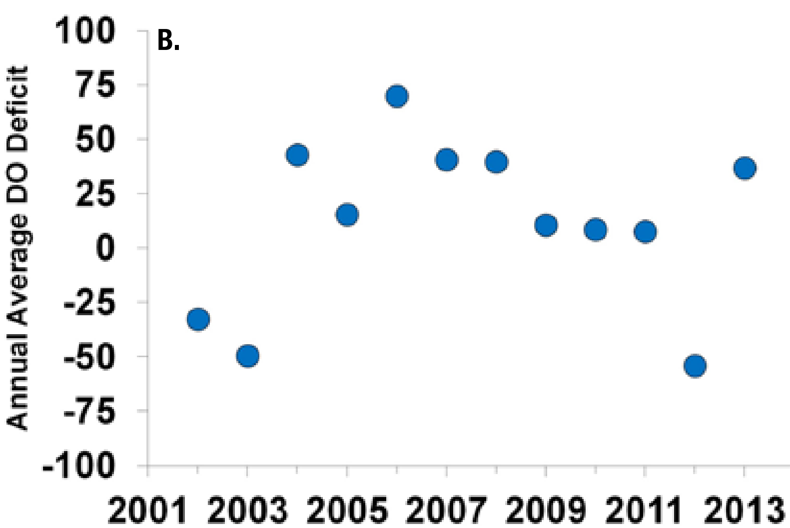


Figure 15. Puget Sound monthly DO deficit anomalies from 2002-2013 for water deeper than 20 m using a reference baseline established from 1999-2008. (A) Heat map of monthly anomalies calculated from site-specific monthly averages. Green=lower, red=higher, black=expected, gray=no data. (B) Puget Sound-wide annual anomaly of the DO deficit from 2002-2013.

iii. Nutrients and chlorophyll:

Source: Christopher Krembs (ckre461@ecy.wa.gov), Julia Bos, Carol Maloy, Skip Albertson, Mya Keyzers, and Laura Friedenberg (Ecology); https://fortress.wa.gov/ecy/publications/SummaryPages/1303081.html

Monthly anomalies in macro-nutrients have been increasing in Puget Sound over the last 15 years relative to seasonal baseline conditions established from 1999-2008 (Figure 16A). The increase of 3 μM nitrate and 0.3 μM phosphate per decade could reflect nutrient additions or indicate that nutrient pools are not assimilated by organisms. The latter case is supported by decreasing chlorophyll-*a* biomass (Figure 16B) and the negative long-term correlation of nitrate and chlorophyll-*a* (Figure 16C). Increasing macro-nutrients but otherwise steady micro-nutrients, such as silicate, imply that the overall nutrient balance availability to organisms may be changing. In 2013, nitrate and phosphate anomalies were lower than normal, interrupting the long-term increasing trend. Nevertheless, lower nutrient concentrations and higher chlorophyll-*a* in 2013 (Figure 16A, B) suggest that phytoplankton efficiently utilized the nutrient pool. The silicate-to-nitrogen ratio (Si:DIN), a potential indicator of human nitrogen inputs continues to decline by 10 units per decade (Spearman Rank Correlation rh=-0.62, p<0.05, n=15), primarily driven by changes in nitrate. This trend was interrupted in 2013, due to the lower nitrate concentrations. The decline is regionally strongest in South Puget Sound and seasonally strongest during the summer (Figure 16E). A 14-year time-averaged seasonal cycle of chlorophyll-*a* and ammonium, proxies for phytoplankton biomass and grazing activity, respectively, show that Puget Sound develops a consistent spring bloom in May followed by a peak in grazing in June. A broader late summer bloom in August is followed by moderate grazing activity in September (Figure 16D). 2013 was different because phytoplankton biomass was less impacted by grazing until April, when historically grazing impacts appear in March. Algal biomass was also higher, particularly in August, and was followed by higher grazing activity in September 2013. High overall phytoplankton biomass may have contributed to a strong and extensive bloom of *Noctiluca* that extended across the entire Central Basin in May and June (Figure 16F).

A Noctiluca bloom in Elliott Bay on June 17, 2013. Photo: Christopher Krembs.

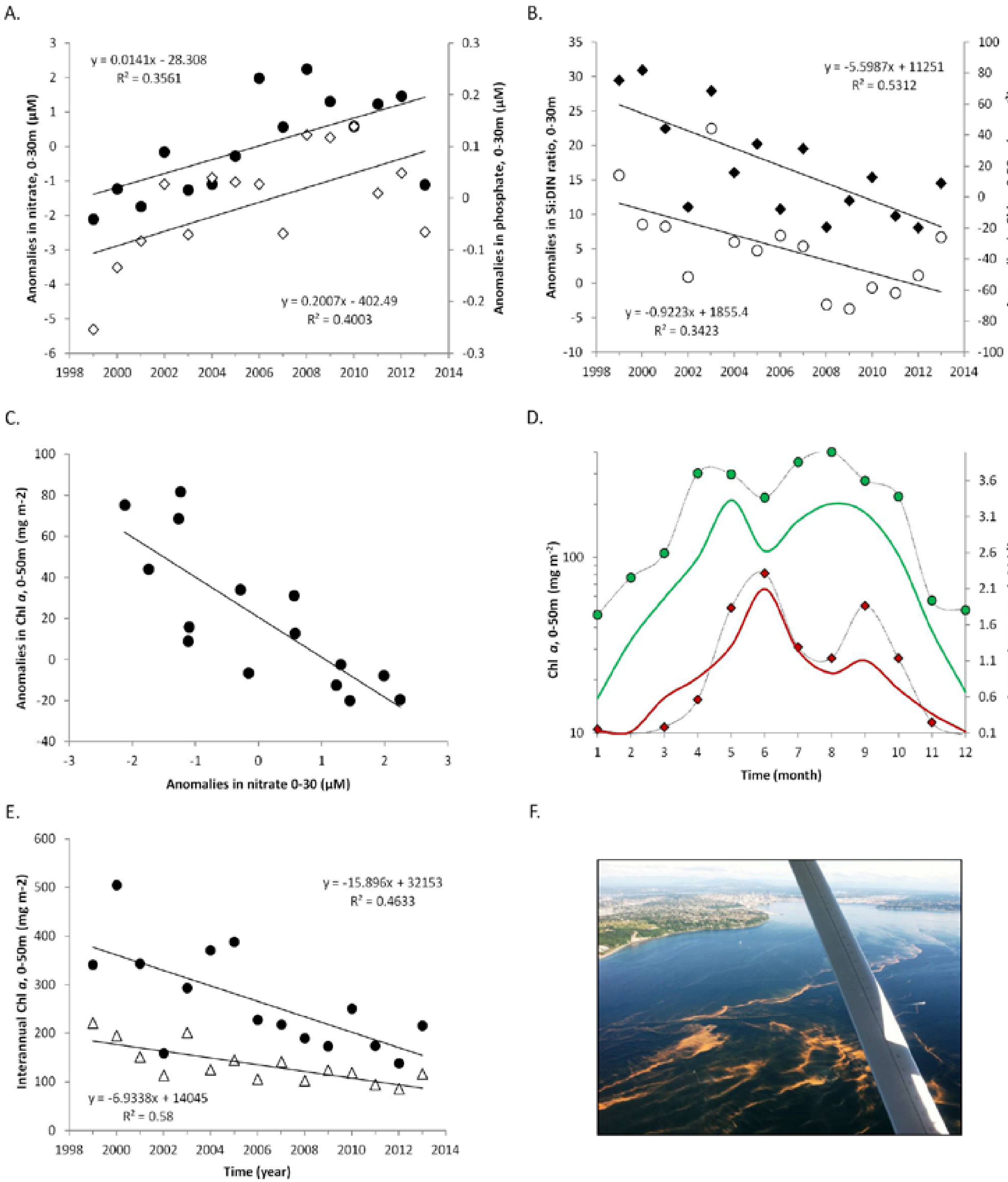


Figure 16. Puget Sound-wide annual anomalies of (A) nitrate (black circles) and phosphate (white diamond), (B) the ratio of Si:DIN (white circles) and chlorophyll-a (black diamond) over the period from 1999-2013. Correlation of Puget Sound-wide long-term anomalies for nitrate and Chl a (C). (D) Puget Sound-wide seasonality and temporal coupling between Chl a (green circles) and ammonium (red circles) for 2013, and time averaged for the years 1999-2012 (green line, Chl a; red line, ammonium). (E) Long-term trends in Puget Sound wide average phytoplankton biomass, for yearly average (triangles) and averages specific to the period July-December, highlighting a preferred decline in late summer. (F) Example of the end of strong Noctiluca bloom surfacing in Central Basin in 2013.

iv. Water mass characterization:

Source: Skip Albertson (salb461@ecy.wa.gov), Christopher Krembs, Mya Keyzers, Laura Hermanson, Julia Bos, and Carol Maloy (Ecology)

Temperature and salinity uniquely determine the density of water which drives flow between Puget Sound basins. Temperature and salinity are also signatures that suggest the origin of a water mass, along with other parameters like DO and DIN. Temperature and salinity values from profiles at stations in five basins of Puget Sound are plotted independently of depth to show dominant water masses present in 2013 (Figure 17). The Central Basin, which at 46% of the total volume of Puget Sound, is intermediate in density between South Sound and Admiralty Reach. South Sound demonstrates the most extreme range of temperatures due to its high surface area relative to its volume (i.e., it is the shallowest basin). Hood Canal has the tightest range of values for the opposite reason. Understanding the exchange of water masses between basins will help us better understand the fate and transport of human effluent as well as oceanic sources of nitrogen. This analysis uses monthly data from Ecology's long-term station monitoring network.

Basin/Water mass	1	2	3	4	5	6
Central	23.2	23.0	23.1	22.7	22.9	22.4
Whidbey	22.8	22.7	22.75	23.0		
Hood Canal	23.0	22.8	22.9	23.2		
Admiralty Reach	23.5	23.7	23.4			
South Sound	22.5	22.1	22.3			

Table 1. Density (sigma-t units) corresponding to the water masses defined in Figure 17. Water masses are arranged in descending order of volume in Puget Sound.

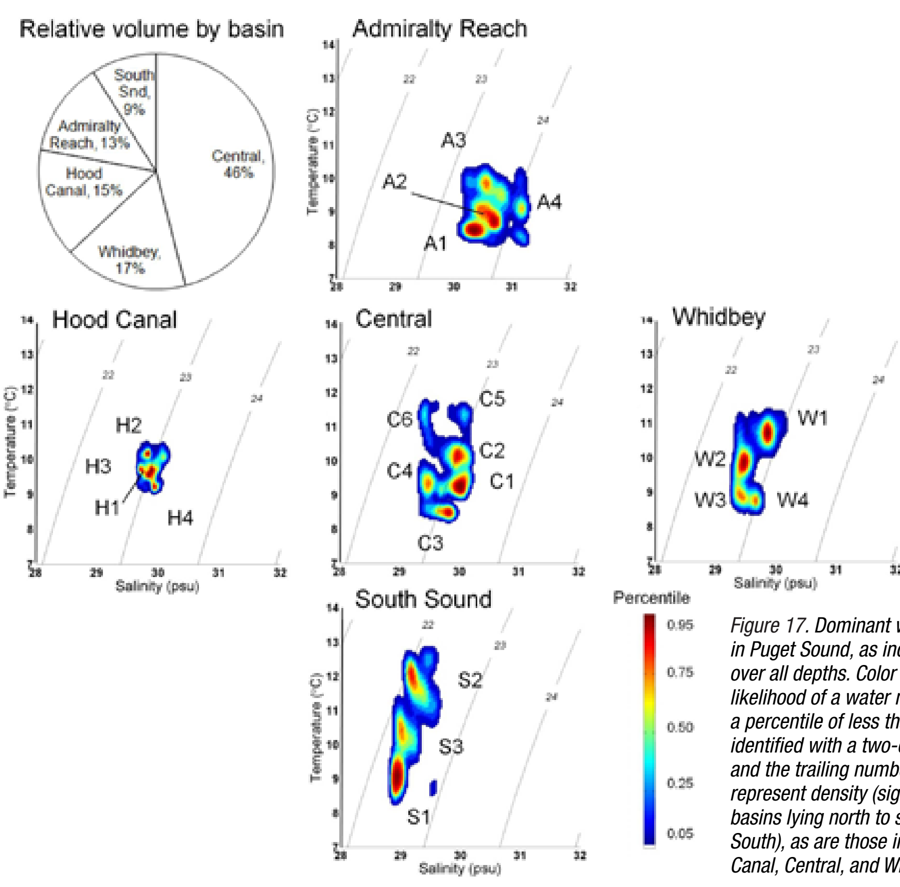


Figure 17. Dominant water masses in each of the five basins in Puget Sound, as indicated by their density signatures over all depths. Color contours indicate the frequency or likelihood of a water mass signature in 2013, white indicates a percentile of less than 0.016. Dominant water masses are identified with a two-digit code; the letter identifies the basin and the trailing number is in order of dominance. Contour lines represent density (sigma-t). The figure is arranged so that the basins lying north to south are aligned (Admiralty, Central, and South), as are those in a general west to east alignment (Hood Canal, Central, and Whidbey).

B. Puget Sound profiling buoys:

Profiling buoys provide data that describe short-term dynamics with high levels of variation and identify water masses. There are currently six ORCA (Oceanic Remote Chemical Analyzer) moorings in Puget Sound measuring water column properties at high frequencies (1 to 12 profiles per day dependent upon season) from surface to depth. Data from four moorings are presented here: southern Hood Canal (Twanoh and Hoodsport), Dabob Bay, and southern Puget Sound (Carr Inlet).

i. Temperature and salinity:

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

Temperature data at Twanoh, Hood Canal, from the previous four years (Figure 18A) show a consistent seasonal cycle every year, with interannual differences in the timing of the start and degree of warming. Waters are cool and well mixed during the winter followed by strong thermoclines developing in late spring. Strong temperature stratification persists throughout the summer, and temperatures approaching 25°C have been observed in the surface layer. As air temperatures cool in late summer and fall storms break down stratification, the water column becomes well-mixed and remains so until the following spring. On this seasonal pattern, interannual variation in timing and heat content is distinct.

During 2013, surface stratification started earlier than in previous years; a thermocline formed by the beginning of May, approximately two weeks earlier than in 2012 or 2010, and approximately three weeks earlier than 2011. Surface temperatures were higher during the mid-summer months in 2013 than in previous years. Temperature variation in the surface layer is strongly correlated with climate conditions, while deep water temperatures are mainly affected by intrusion of oceanic waters. In 2013, deep water temperatures were similar to those observed in 2010, with minimum temperatures of 7.6°C in 2013 and 8.3°C in 2010. These years were relatively warm compared to 2011 and 2012, which had minimum temperatures of 5.8 and 5.7°C respectively.

Salinity data from 2013 (Figure 18B) reveal spatial differences between mooring locations. At Twanoh and Hoodsport, both in southern Hood Canal, strong freshwater stratification above 20 m depth existed throughout much of the year due to the nearby Skokomish River discharge. Similar surface freshwater conditions exist in Dabob Bay from several freshwater inputs nearby. In contrast, Carr Inlet has no significant fresh water source creating surface stratification and inhibiting vertical mixing. The water column was generally well mixed with summer salinity values similar to those observed at other moorings. All sites exhibited increasing salinity in the deep layers (and throughout the water column at Carr Inlet) beginning in late summer and early fall continuing into the winter. In Hood Canal, this is associated with the start of the fall intrusion of oceanic water over the sill, although there is strong inter-annual variation in both the timing and magnitude of this event (Figure 18C). In South Sound, the increased fall salinity signal is less (on October 1, values at depth were ~29.8 psu at Carr Inlet vs. ~30.4 psu in Hood Canal) since the incoming oceanic waters to South Sound have mixed with Central Sound waters at mixing points such as the Narrows near Tacoma.

Zoë Parsons and Gretchen Thuesen redeploying the Point Wells ORCA mooring. Photo: Wendi Ruef.

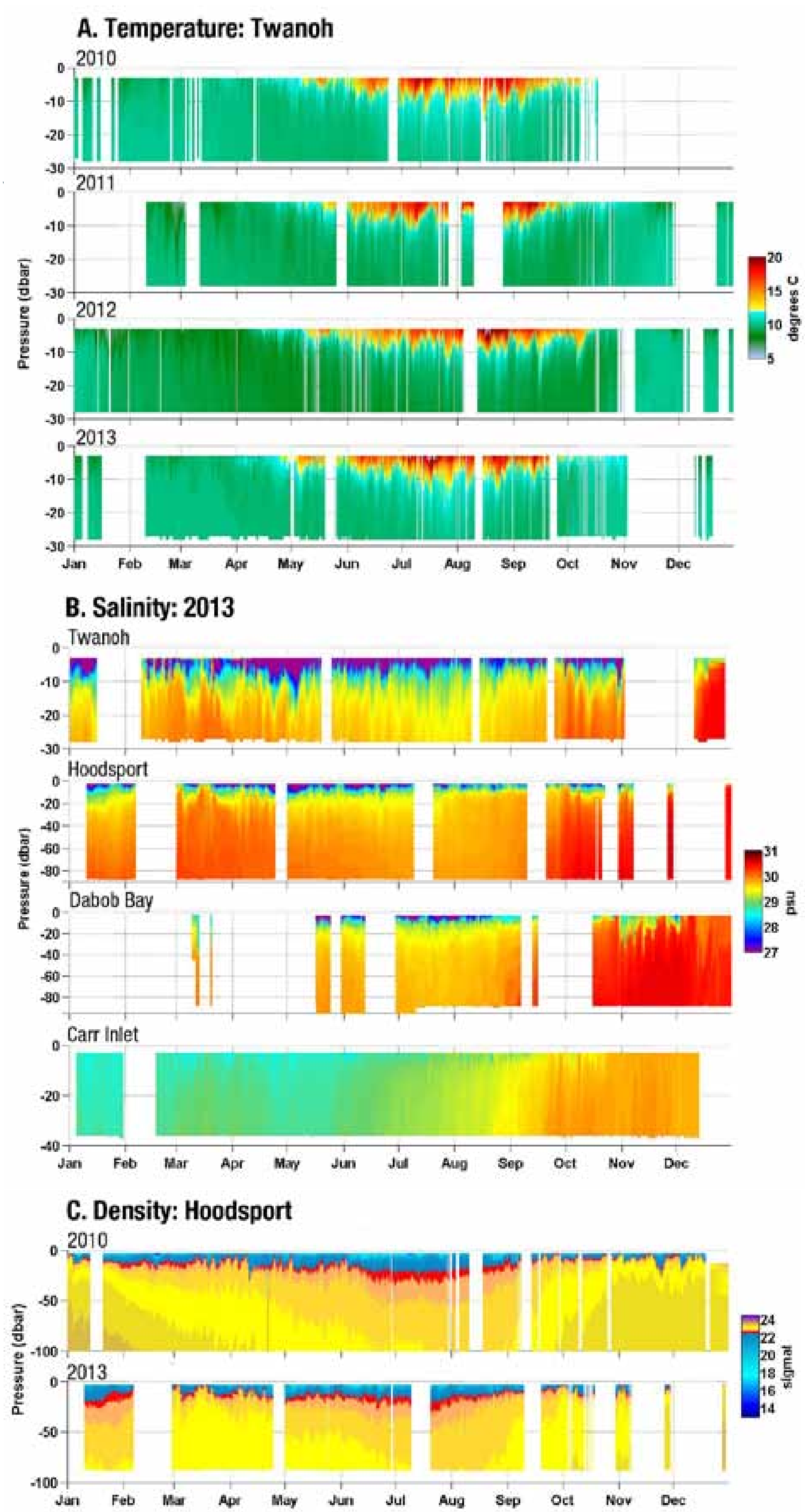
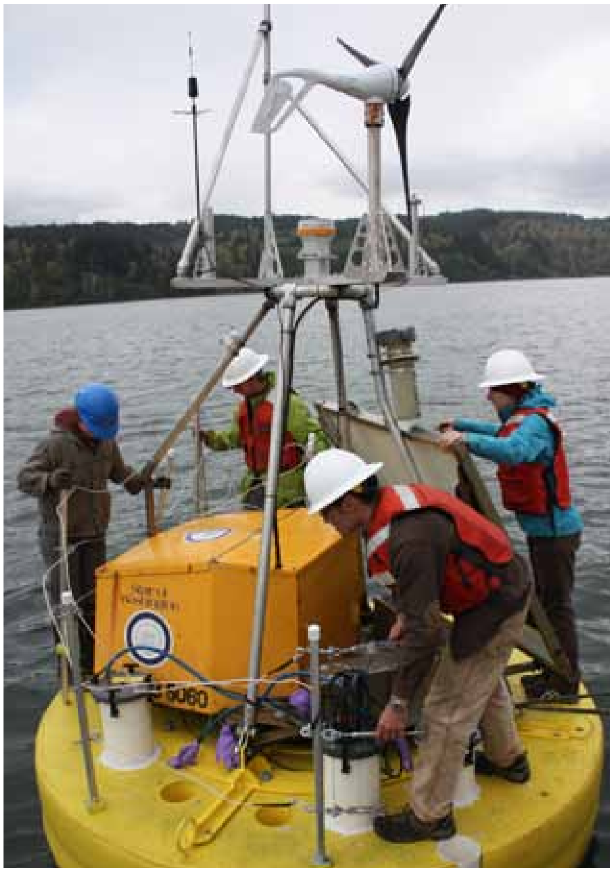


Figure 18. (A) Temperature data at Twanoh (southern Hood Canal) for 2010-2013. Note that pressure in dbars is roughly equivalent to depth in meters. (B) Salinity data from the Twanoh and Hoodsport (southern Hood Canal), Dabob Bay, and Carr Inlet (southern Puget Sound) moorings for 2013. (C) Density (sigma-t) data at Hoodsport (southern Hood Canal) for 2010 and 2013.

Above: Eric Boget preparing to deploy a mooring anchor at the Point Wells ORCA mooring. Photo: Wendi Ruef.

Below: The ORCA team installing gear on the Dabob Bay mooring. From left, Zoë Parsons, Sam Fletcher, John Mickett, Hannah Glover. Photo: Rachel Vander Giesse.



ii. Dissolved oxygen and chlorophyll:

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

Dissolved oxygen and chlorophyll concentrations at Twanoh (Hood Canal) and Carr Inlet (South Puget Sound) from June-July 2013 (Figure 19A) reveal different bloom dynamics at these two Puget Sound sites. Bloom events frequently occur at both locations during the summer, evident by co-varying oxygen and chlorophyll concentrations. Both locations had oxygen super-saturation in surface waters coupled with chlorophyll peaks, but oxygen concentrations in the bottom layer were significantly different between the sites. Bottom waters were hypoxic at Twanoh but near saturation at Carr Inlet. Chlorophyll maxima at Carr Inlet extended from the surface to 15-20 m, while chlorophyll maxima at Twanoh were primarily confined to the subsurface throughout the summer, an indication of nutrient limitation. Both Twanoh and Carr Inlet experienced large blooms at the beginning of June, but the chlorophyll layer at Carr Inlet was generally thicker throughout the summer, indicating stronger more robust blooms than those at Twanoh. Both sites had intervals with low chlorophyll concentrations and subsequently less oxygen, probably due to less phytoplankton growth. These periods indicate strong wind-mixing, lack of sunlight, or both. However, these happen at different times; early-mid June at Carr Inlet and late June at Twanoh. This suggests short-term mechanisms operating at different locations can affect the chlorophyll biomass available for grazing at a given time.

In comparison with the previous 10 years of data, oxygen concentrations at Twanoh during 2013 were average. Super-saturation in the surface layer in spring 2013 started a bit later than 2010-2012, but was more intense in June than in the previous four years.

Oceanic water intrusion (Figure 18C) has a strong effect on oxygen concentrations in southern Hood Canal. A strong intrusion of dense oceanic water will displace deeper, less oxygenated waters towards the surface while a weaker density intrusion can fail to adequately flush out the canal and replenish oxygen for the following year. An early intrusion can set up the water column so that hypoxic waters are close to and can reach the surface during fall when southern wind events advect oxygenated surface waters north. Hypoxia at depth in 2013 was moderate with no observed fish kill events; waters were more hypoxic than 2012, but less so than 2010 and 2011 (Figure 19B).

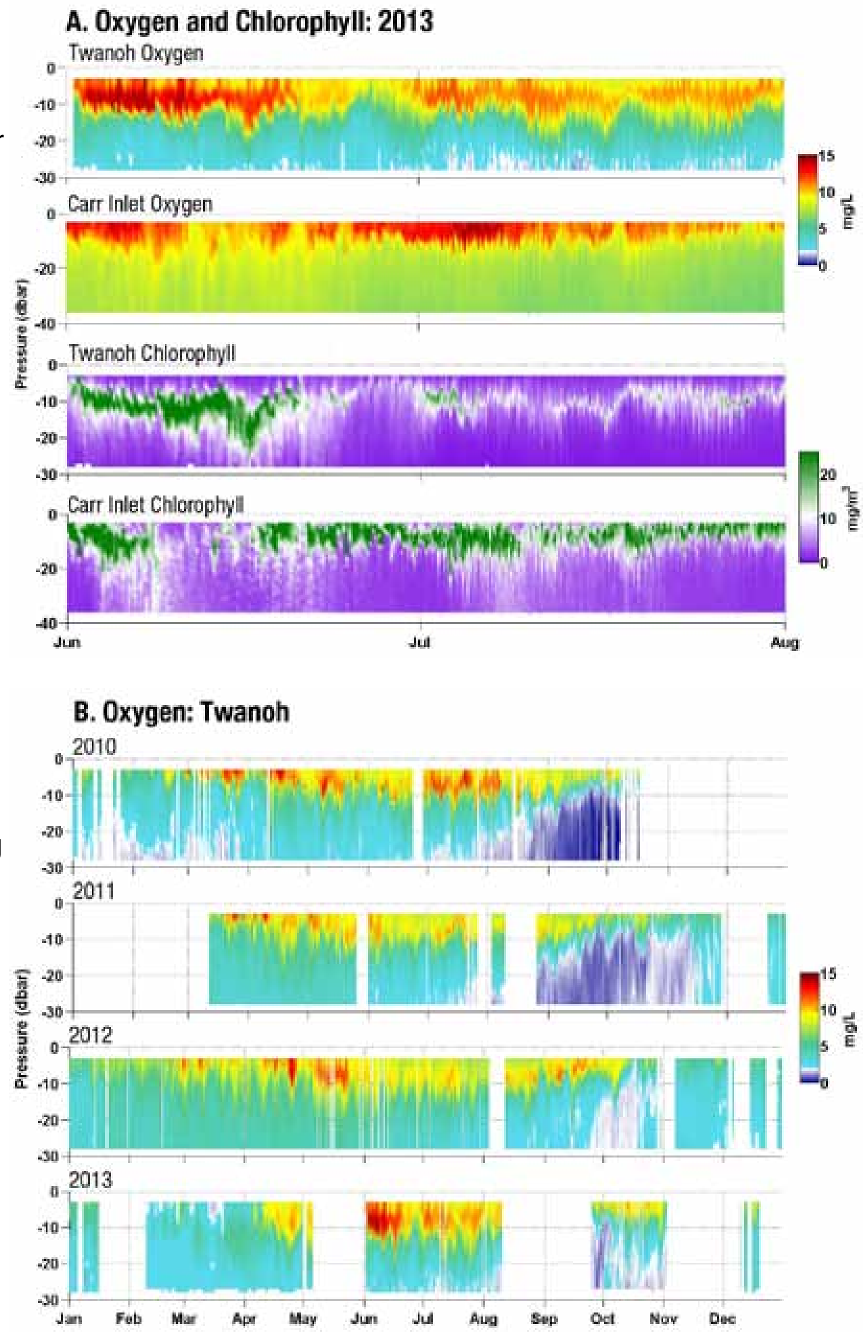


Figure 19. (A) Oxygen (upper two panels) and chlorophyll (lower two panels) concentrations at Twanoh (southern Hood Canal) and Carr Inlet (southern Puget Sound) from June through July, 2013. Note that pressure in dbars is roughly equivalent to depth in meters. (B) Oxygen data at Twanoh (southern Hood Canal) for 2010-2013. Data are colored with a white threshold at 2 mg/L; values below are shaded purple and indicate hypoxic waters.

iii. Ocean and atmospheric CO_2:

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

CO_2 sensors have measured atmospheric and surface seawater xCO_2 (mole fraction of CO_2) at three-hour intervals on surface ORCA moorings at Dabob Bay since June of 2011 and at Twanoh since July 2009. Gaps in the time-series unfortunately create imperfect overlap of seasonal observations.

Cumulatively, the observations across all years and both sites suggest a pattern of atmospheric xCO2 that tends to be elevated compared to the global average most of the time, with higher variability in summer. Relative to previous years, 2013 atmospheric xCO_2 levels appear to have been somewhat higher at both sites (Figure 20). Surface seawater xCO_2 values at both sites are mostly undersaturated with respect to the atmosphere from March/April to September/October, and more variable and frequently supersaturated in fall and winter due to upward mixing of deeper, CO_2-rich waters during storms. In 2013, surface seawater xCO_2 levels were less variable and lower overall in early fall at both Dabob and Twanoh. At Twanoh, variability in November and December was more typical, with frequent and sometimes more prolonged peaks between 1000-2000 ppm. As in previous years, a few late fall excursions of seawater xCO_2 below atmospheric values at Twanoh suggest surface primary producers were occasionally active enough to draw down CO_2 even late in the year.

In 2011 and 2012 at the Dabob Bay mooring, surface seawater xCO_2 values reached as high as ~1200 ppm. The 2013 peak value was 919 ppm, but with less than two months of observations for the year, during fall when values normally increase, it is unclear whether the annual peak value differed from previous years. Average atmospheric values increased slightly from 2011 to 2013 (407 ppm in 2011, 409 ppm in 2012, 416 ppm in 2013). While the year-to-year increase is consistent with increasing global atmospheric xCO_2, the observed magnitude of change may be affected by different seasonal coverage across the period of record.

At the Twanoh mooring, surface seawater xCO_2 is elevated more of the time during fall and winter than at Dabob Bay, with values frequently higher than 750 ppm. The highest xCO_2 values observed in the NOAA CO_2 and Ocean Acidification mooring networks have been at the Twanoh site and require additional processing to resolve the uncertainty of these high values. This processing is completed only for the 2012–2013 deployment, which includes peaks up to ~2000 ppm. Real-time data from earlier years are still being processed and likely to have peaks in the same range as those for 2013. Average atmospheric xCO_2 values increased from 2009 to 2013 (400 ppm in 2009, 401 in 2010, 407 in 2011, 407 in 2012, and 415 in 2013), with better seasonal coverage across years than at Dabob, particularly for atmospheric measurements.

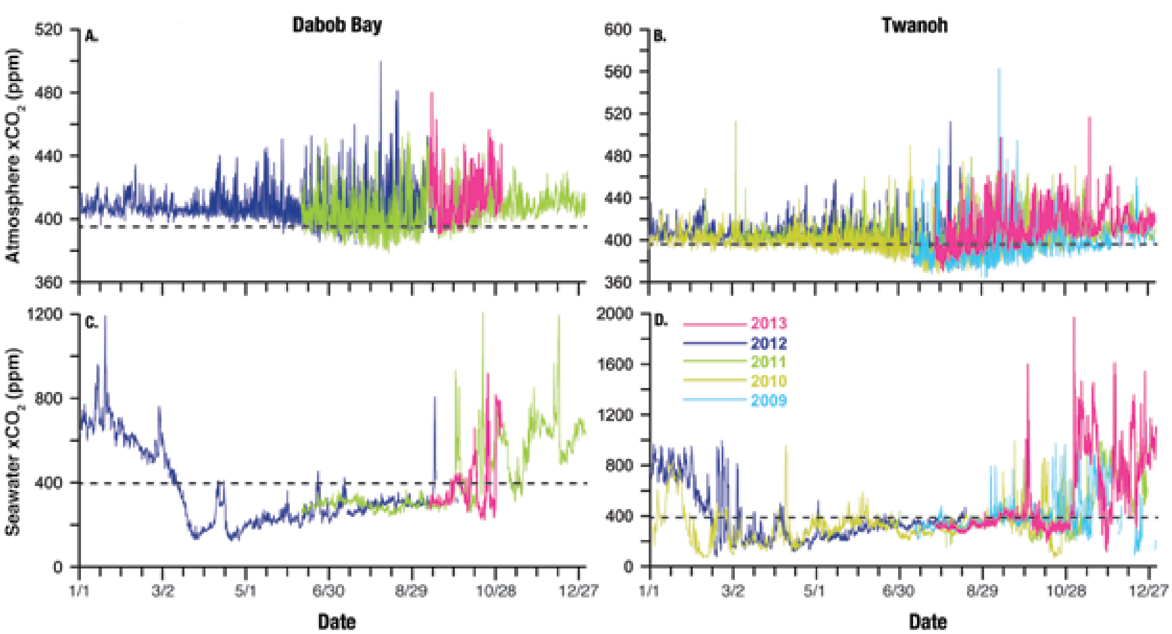


Figure 20. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater (A, B) and surface seawater at 0.5 m depth (C, D) through the full annual cycle on the surface ORCA moorings in Dabob Bay and Twanoh. Data from all deployment years are included for comparison (color key in panel D applies to all panels). Approximate 2013 global average atmospheric xCO_2 of 395 ppm is indicated with a dashed line in each panel. Data shown for 2013 at Dabob and for 2009-2012 at Twanoh have not been subjected to quality control, but typical uncertainty associated with xCO_2 measurements from these systems is <2 ppm in the range of 100-600 ppm, increases for values between 600 and 1000 ppm, and is not well constrained above 1000 ppm. Note different scales of vertical axes.

C. Central Basin long-term stations:

Focusing on the Central Basin of Puget Sound, King County collects monthly water column profile data at 12 open water sites. King County also collects monthly temperature and salinity data at 20 marine beach sites located throughout the county; http://green.kingcounty.gov/marine/CTD.aspx, http://green.kingcounty.gov/marine-buoy/.

i. Temperature and salinity:

Source: Kimberle Stark (kimberle.stark@kingcounty.gov) and Wendy Eash-Loucks (KCDNRP)

Surface temperatures (<2 m) in 2013 were either typical or slightly cooler than the long-term average (1999-2010) from January through March and then ~0.5-0.8°C cooler than normal in April (Figure 21A, B). Surface temperatures in June were 1.1-2.3°C warmer than normal at the northern Central Basin sites but variable elsewhere. Water temperatures at depth (>100 m) were generally cooler than normal throughout the year, particularly in December, with the exception of the period from August through October. Surface salinities were fairly typical in 2013 compared to the long-term average, with the exception of May and July which was fresher than normal, likely due to increased freshwater input from snowmelt. Although May is typically when freshwater input to Central Basin from snowmelt occurs, a sharp increase in river discharge was seen in unregulated rivers during the three very warm days from June 30-July 2. Deep water salinities were fresher than the long-term average in January, October, and November but fairly typical in other months. Although salinities throughout the water column in 2013 were similar to the long-term average for most months, salinities were higher than those measured in 2012 due to the wet spring that year (Figure 21C, D). In situ temperature and salinity sensors collect data at 15-minute intervals at 1 and 10-m water depths at the Seattle Aquarium. Monthly median water temperatures in 2013 were warmer throughout most the year compared to the previous five years at both depths. Surface salinities in 2013 were typical compared to previous years, with the exception of April and October which had fresher than normal values. Waters near the Seattle Aquarium are affected by discharge from the Duwamish River, particularly during large rain events such as those observed in April and late September/early October.

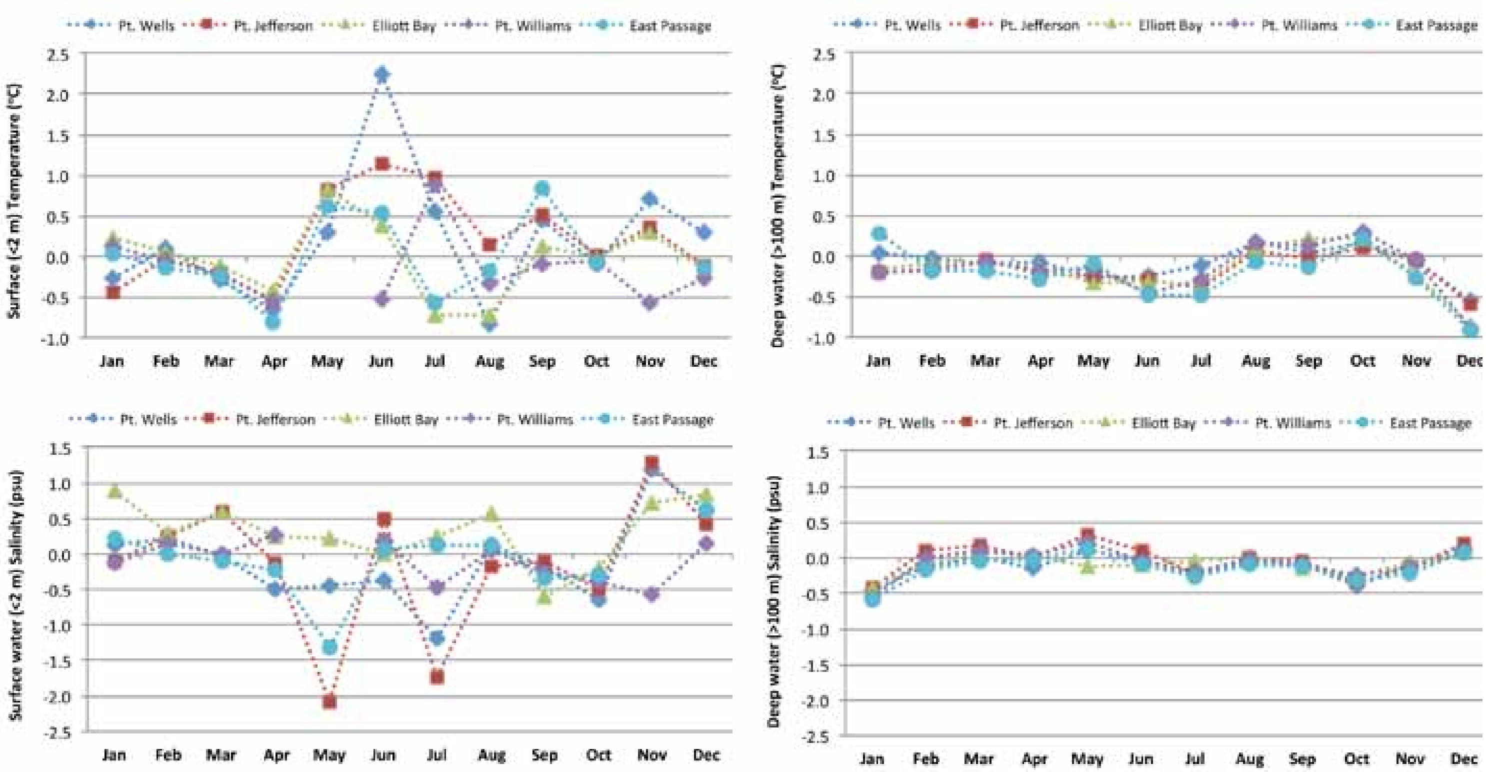


Figure 21. Monthly anomalies of temperature at the (A) surface (<2 m) and (B) depth, and salinity at the (C) surface and (D) depth for five sites in Central Basin in 2013 relative to a long-term average (1999-2010). Negative values indicate colder/fresher water than normal.

ii. Dissolved oxygen:

Source: Wendy Eash-Loucks (wendy.eash-loucks@kingcounty.gov) and Kimberle Stark (KCDNRP)

Results from monthly sampling at 12 sites in the Central Basin and 3 in situ moorings (15-minute interval data) indicate that dissolved oxygen (DO) levels in 2013 were above 5.0 mg/L throughout the year at all locations and depths, with the exception of Quartermaster Harbor and East Passage. DO levels were lowest in inner Quartermaster Harbor between September and October and dropped below 1.0 mg/L on October 14th during nighttime hours (Figure 22). Although DO levels in outer Quartermaster Harbor were lower than in open waters, and below 5.0 mg/L in the fall months, but not as low as those observed in the inner harbor. Data from both Quartermaster Harbor moorings showed substantial diurnal variation, particularly during bloom events. DO levels in bottom waters of East Passage were above 5.0 mg/L for all months with the exception of late October. In late October, DO values less than 5.0 mg/L were measured in waters between 121 and 172-m depth with the lowest value (4.7 mg/L) noted at the deepest depth. An increase in DO from primary production during the large April and August to early September phytoplankton blooms was evident in the upper 30 m of the water column at all sites in April and at most sites in September. DO measured at both the 1 and 10-m depths in Elliott Bay at the Seattle Aquarium mooring showed high DO values during April, August, and September of 2013 (Figure 22). DO concentrations at the Seattle Aquarium during these months were higher than the last 5 years, particularly in August when the abnormally large late-season bloom occurred. Figure 23 shows monthly profile data at two Central Basin sites. The profiles show lower oxygenated deep waters in the late summer and lower oxygenated water throughout the water column in the fall.

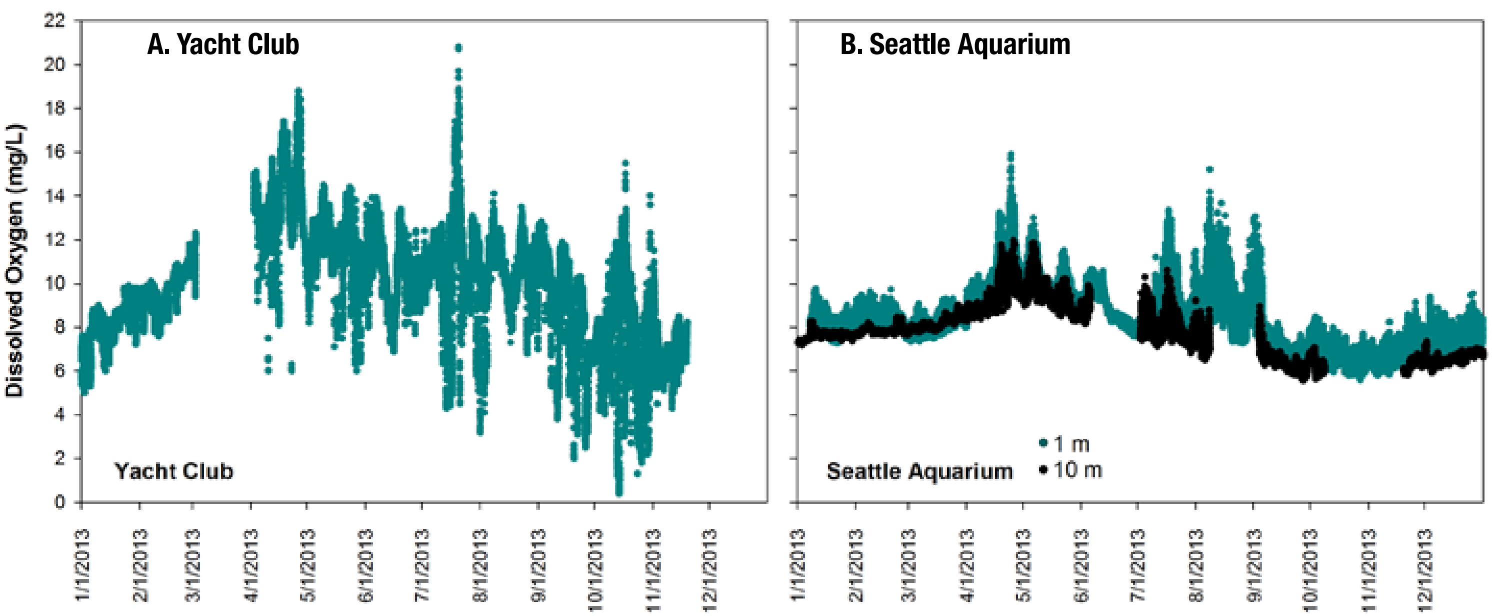


Figure 22. Dissolved oxygen levels in 2013 in inner Quartermaster Harbor (Yacht Club) at 1 m and in Elliott Bay (Seattle Aquarium) recorded every 15-minutes.

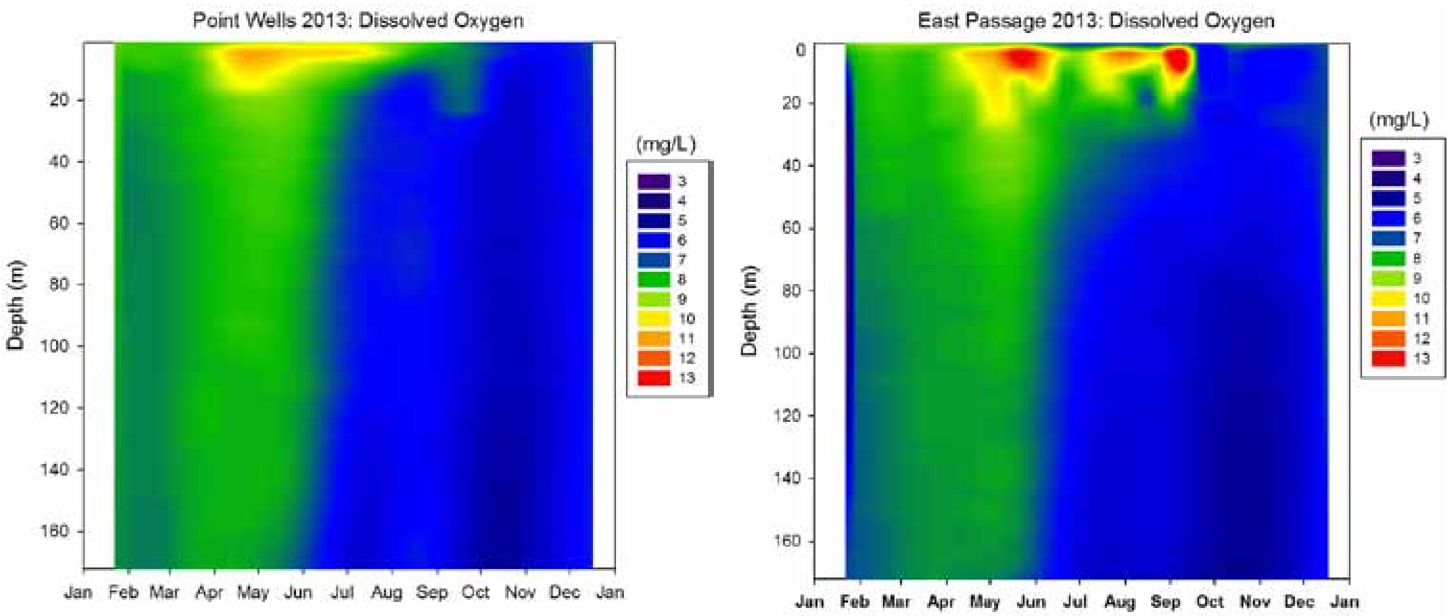


Figure 23. 2013 dissolved oxygen levels at two sites in the Central Basin. An increase in oxygen from phytoplankton blooms is evident, particularly in East Passage.

Jim Devereaux collecting King County water samples. Photo: Kimberle Stark.

King County collecting water samples and profile data. Photo: Kimberle Stark.

iii. Nutrients and chlorophyll:

Source: Kimberle Stark (Kimberle.Stark@kingcounty.gov) (KCDNRP); http://green.kingcounty.gov/marine/

Results from monthly sampling at 12 sites in the Central Basin, semi-monthly sampling at a subset of 3 sites from April through October, and 3 in situ moorings (data sampled at 15-minute intervals) reveal nutrient and phytoplankton dynamics in King County waters. The timing of the spring phytoplankton bloom in 2013 was typical, occurring in early April. The large April bloom, dominated by the diatoms *Chaetoceros* spp. and *Thalassiosira* spp., lasted throughout most of the month. An unusually large bloom occurred in August following the warmer than normal late spring and summer (June through August in particular) and was evident through early September at Point Jefferson and East Passage (Figure 24A). A decrease in nitrate/nitrite due to phytoplankton uptake and an increase in ammonia due to degradation of the bloom was observed in the water column in both surface (<2 m) and deep waters (>75 m) (Figure 24B, C). The August bloom included both diatoms and dinoflagellates but was dominated by diatoms.

Chlorophyll-*a* levels in June 2013 were lower than the long-term median using the baseline period 1997-2010. Because the phytoplankton biomass was not sufficient to draw down nutrients, nitrate/nitrite levels in June and July were higher than normal. Conversely, a large increase in ammonia in surface waters was noted in June (Figure 24D, E) in most of the Central Basin samples with the exception of the northernmost sites, Point Wells and Point Jefferson. It is suspected that a notable bloom of *Noctiluca scintillans* in the Central Basin during this time reduced chlorophyll-*a* levels due to grazing and caused the increased ammonia concentrations due to excretion as this species is known to accumulate high levels of ammonia.

Monthly nutrient concentrations at 20 beach sites in the Central Basin vary considerably and are influenced by proximity to freshwater sources, such as streams or stormwater outfalls. Overall, however, 2013 nitrate/nitrite values were lower than normal from April through September, particularly in May (relative to the 1999-2010 baseline). Higher than normal ammonia values were observed in June, August, and September.

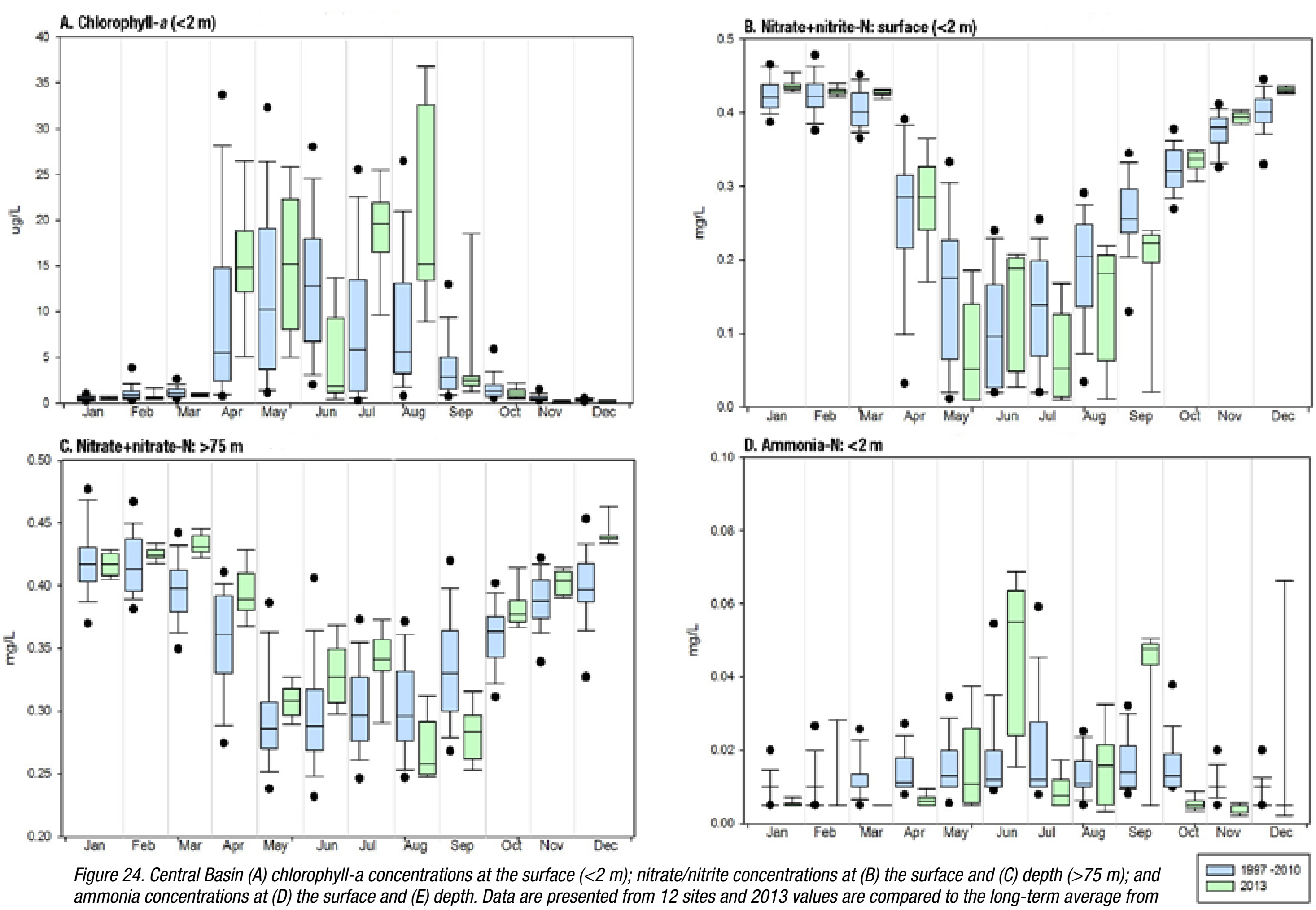


Figure 24. Central Basin (A) chlorophyll-a concentrations at the surface (<2 m); nitrate/nitrite concentrations at (B) the surface and (C) depth (>75 m); and ammonia concentrations at (D) the surface and (E) depth. Data are presented from 12 sites and 2013 values are compared to the long-term average from 1997-2010.

D. Snapshot surveys:

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

i. Salish Sea tribal canoe journey surface survey:

Source: Eric Grossman (egrossman@usgs.gov) (U.S. Geological Survey) and Sarah Grossman (sgrossman@swinomish.nsn.us) (Swinomish Indian Nation); http://www.usgs.gov/coastsalish

In its sixth year of sampling, the Tribal Journey Water Quality Project collected 23,000 surface water measurements from traditional canoes at ~20-m intervals across the Salish Sea. Data were collected from Squaxin Island, WA to Port Angeles, WA between July 16 and July 23, 2013. Measurements of the marine surface layer (1-2 m) during the annual Tribal Journey show spatial variability and trends at landscape- and site-specific scales (Figure 25). Temperatures ranged from 10.3°C in the north Central Basin (CB) to 18.8°C in the South Puget Sound Basin. Mean surface water temperatures by basin ranged from 11.8±1.0°C in the Strait of Juan de Fuca (SJF) to 16.5±0.5°C in Whidbey Basin (WB). These surface water temperatures were comparable to the average of all previous years and were reflective of the typical weather and average river flow conditions in July 2013. Mean basin salinity ranged from 21.6 PSU in WB to 30.1 PSU in SJF. Surface waters in WB persistently show the lowest mean salinity due to the large amount of freshwater input from the Skagit, Stillaguamish, and Snohomish Rivers. Mean values of dissolved oxygen in each basin were generally high ranging from 8.8±1.5 mg/L in SJF to 11.6±1.4 mg/L in south CB, but minimum values were lowest in SJF (6.6 mg/L) and north CB (6.2 mg/L). Turbidity measured within the Puyallup River plume, which extended across Commencement Bay, ranged from 20-50 FNU and was consistent with observations in previous years. Along-track variability in temperature, pH, and dissolved oxygen in south and south central Puget Sound was greater and patchier in 2013 than previous years, likely reflecting localized areas of more thorough mixing and/or upwelling of bottom waters associated with sills and/or isolated eddies. Localized effects of river plumes were notable in all water quality parameters measured.

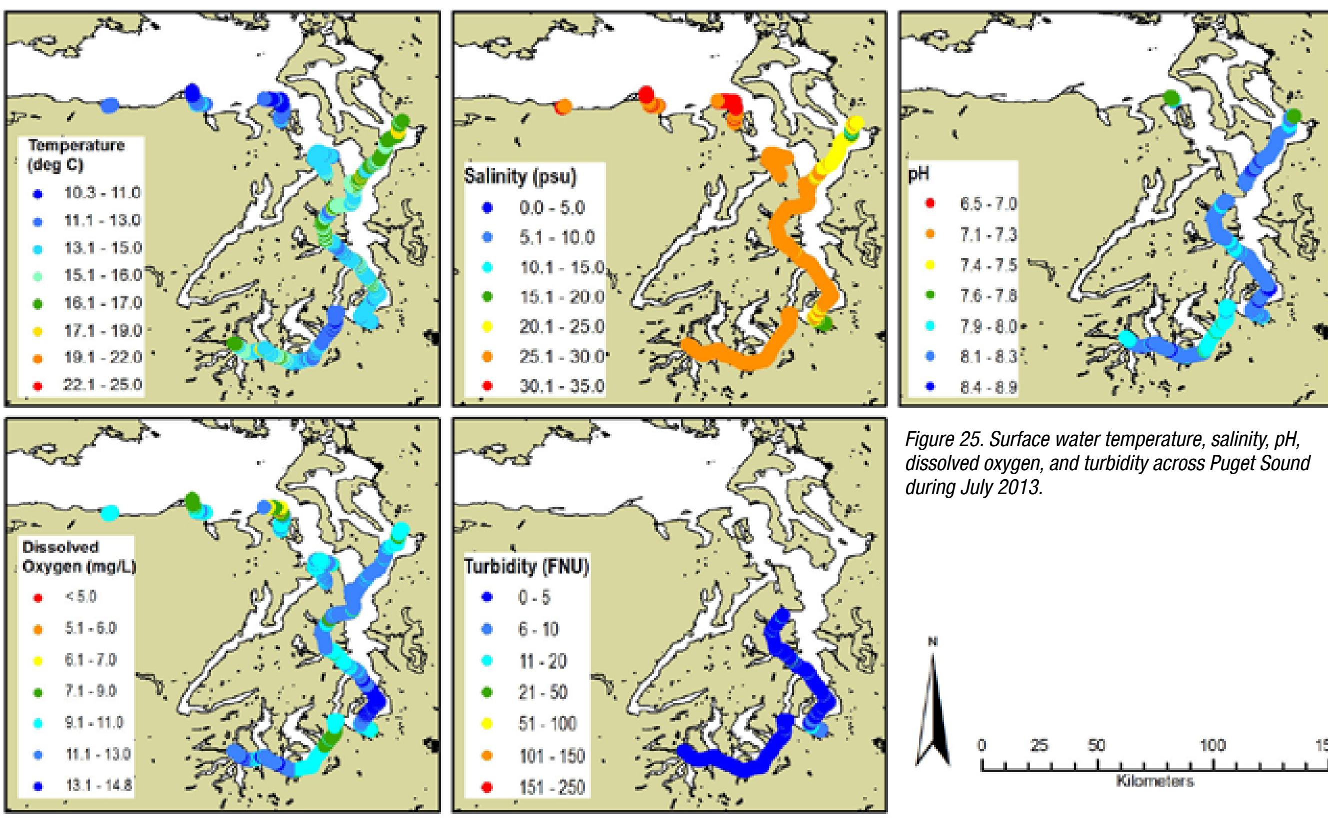


Figure 25. Surface water temperature, salinity, pH, dissolved oxygen, and turbidity across Puget Sound during July 2013.

ii. San Juan Channel/Juan de Fuca fall surveys:

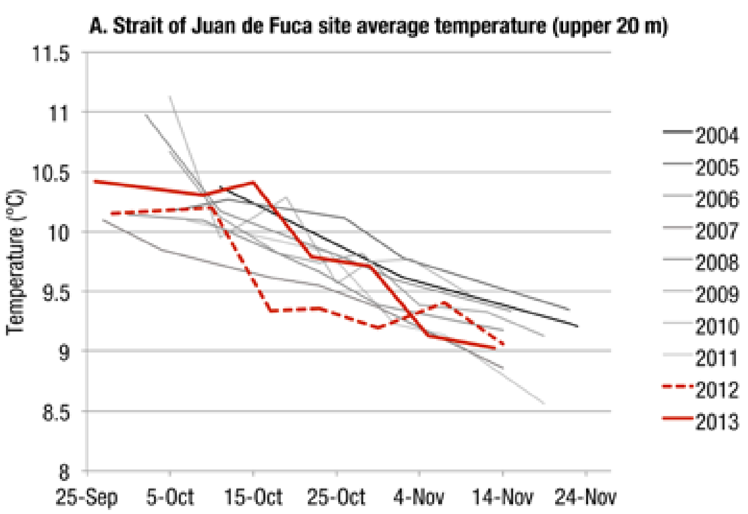
Source: Jan Newton (newton@apl.washington.edu) (APL, UW), Breck Tyler (UCSC), and Jessi Thompson (UW); http://courses.washington.edu/pelecofn/index.html

In 2004, the UW Friday Harbor Laboratories Research Apprenticeship Program started collecting a time series of pelagic ecosystem variables during fall quarter studies. Research apprentices sample two sites approximately weekly, focusing on physical and biological observations. The San Juan Channel (North) site is well-mixed with seasonal influence from the Fraser River plume, and the Strait of Juan de Fuca (South) site has classic two-layer stratification between out-flowing estuarine water and in-flowing oceanic water. The 10-year time series shows spatial and temporal differences between the two sites as well as influence from climate and river drivers and the fall transition from summer to winter conditions.

During 2013, water temperature in the upper 20 m was more variable than previous years. Temperature was warmer than the 10-year mean in mid-October, became average by late October then colder by mid-November (Figure 26A). Higher-resolution sampling in October 2012 and 2013 (not shown) showed that the upper 20 m at both stations was 0.7-1.0°C warmer and 0.5-0.7 psu fresher during 2013. As a result, surface waters were less dense in 2013 compared with 2012 when the densest waters in the series were observed.

In addition to seasonal variation, the influence of both ENSO and PDO are visible in the 10-year temperature time series. During El Niño years, water temperatures are warmer, cooler during La Niña years, and generally colder after 2007 when the PDO shifted to cool phase (Figure 26B).

Anomalies in seawater properties (temperature, salinity, and oxygen) are correlated with external drivers including ENSO, PDO, Fraser River flow, and the timing of the fall transition. However, correlations with biological observations, including plankton, seabird, and mammal abundance have been less evident, with the exception that relatively higher seabird and cetacean abundances are correlated with cooler waters observed during the La Niña/cool PDO conditions of 2010-2012. There has been no trend in fall seabird abundance or change in seabird species composition from 2006 through 2013.



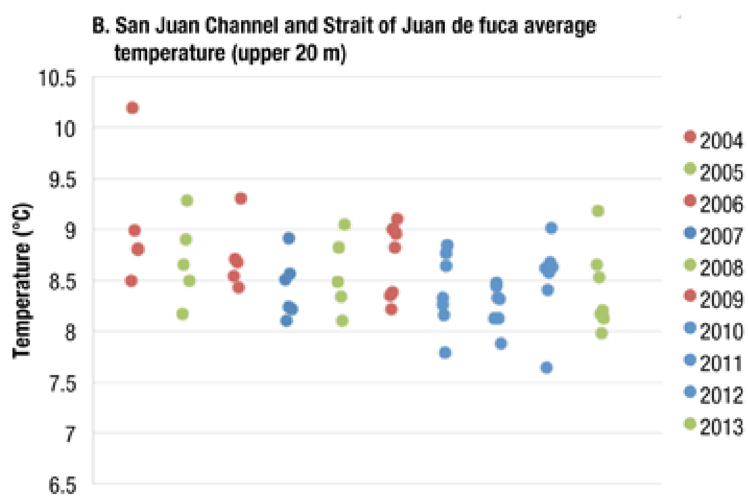


Figure 26. (A) Average seawater temperature during fall in Strait of Juan de Fuca over 10-year time series. (B) Average cruise seawater temperature (both sites) colored by ENSO status (orange = El Niño; blue = La Niña; green = neutral).

CALL-OUT: SEA STAR WASTING DISEASE

Sea stars, previously commonly called "starfish", are echinoderms and one of the most familiar marine invertebrates. There are roughly 1,500 species of sea stars that exist between the intertidal to deep abyssal depths of over 20,000 feet. Sea stars are considered a top predator and a keystone species as their diet includes many animals that have few natural predators, including sea urchins, barnacles, snails, limpets, and molluscs. Low grade disease in sea stars has been previously documented on a waxing/waning, potentially seasonal, occurrence in both captive and free ranging populations along the west and east coasts. In the past, these events have been mild and usually involved a variety of sea star species. Since October of 2013, a higher prevalence of disease in the wild population of *Pycnopodia* (sunflower sea star) near Vancouver, B.C., and the Seattle, WA, waterfront has been documented. Disease in other sea stars, such as *Pisaster* species, followed and now over 14 species have been affected. As part of a multi-institutional collaborative effort to quickly respond to this unusual mortality event in sea stars, Seattle Aquarium divers, Jeff Christianson and Joel Hollander, were able to collect both healthy and diseased stars from the waters surrounding the Seattle Aquarium in late October (Figure 27). Seattle Aquarium divers have also monitored levels of disease along the waterfront since the disease was first noted. The animals collected in late October were sampled according to a protocol carefully developed by several institutions and were sent to our collaborators in New York at Cornell University and the Wildlife Conservation Society. Investigators are looking for viral, bacterial, and other potential causes of disease and are also processing samples collected by the Vancouver and Monterey Bay Aquariums. At this time, no definitive cause of disease has been identified; however, researchers at Cornell have made headway isolating and identifying several viruses that may be involved in the disease process. Samples have also been sent to local laboratories and a local veterinary pathologist, Dr. Michael Garner of NW ZooPath, to aid in the efforts to determine the cause of disease. Determining the cause of disease in wild animals, such as sea stars, takes time due to the complexity involved in identifying normal flora versus disease-causing pathogens, as well as evaluating for factors such as environmental change (including aspects such as contaminants and changes in water quality). There have been suggestions that radiation from Japan may be involved in the sea star wasting syndrome; however, a recent report by the Washington Department of Health shows that no abnormal levels of radiation have been found in several species of fish and shellfish from the Pacific coast of Washington. Teams of marine biologists, wildlife veterinarians, microbiologists, pathologists, and others are working together to determine the cause of the unusual mortality event seen in sea stars along the western coast of the United States and Canada. Updates will be provided as information becomes available.

Author: Lesanna Lahner, DVM, MPH (l.lahner@seattleaquarium.org) (Seattle Aquarium); http://www.seattleaquarium.org

Figure 27. A healthy (left) and wasting (right) sea star. Photo: Seattle Aquarium.

Plankton

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

A. Marine phytoplankton:

Source: Gabriela Hannach (gabriela.hannach@kingcounty.gov) and Kimberle Stark (KCDNRP); http://green.kingcounty.gov/marine/photos.aspx

King County has collected and analyzed phytoplankton samples semi-monthly April to October from three locations since 2008. Point Jefferson and East Passage are deep water stations in the north and south of the Central Basin, respectively, whereas Dockton in Quartermaster Harbor is a shallow station near the entrance to an embayment with poor tidal flushing. Sample analysis has focused primarily on taxon identification and relative abundances; however, a new method to obtain quantitative data will commence in summer 2014. Diatoms typically comprise the most abundant and diverse group of primary producers in Puget Sound. Eight diatom (primarily chain-forming) and four dinoflagellate genera were identified as the most commonly encountered in 2013 samples (Figure 28). Five of the eight diatom genera and only one of the four dinoflagellate genera that were common in 2013 were also common in 2012. The proportion of diatom genera in a given sample relative to all genera identified in 2013 is compared in Figure 28 against the 2008-2012 average. In 2013, the spring April bloom in the Central Basin was dominated by diatoms and followed by a sharp drop in the diatom component during June. The large *Noctiluca scintillans* bloom observed in June may have contributed to the sharp decrease of diatom populations. In past years, dinoflagellate genera typically became prevalent during early and late summer at all locations, particularly the shallower waters of Quartermaster Harbor. However, 2013 was markedly different in that dinoflagellate populations did not become more diverse, with diatoms remaining prevalent throughout this time period at all locations. Diatoms, particularly *Chaetoceros* species, were also dominant in terms of relative cell numbers throughout the entire sampling period. Between April and September, the large, multi-specific genus *Chaetoceros* was found to be either dominant or subdominant in 83% of the samples.

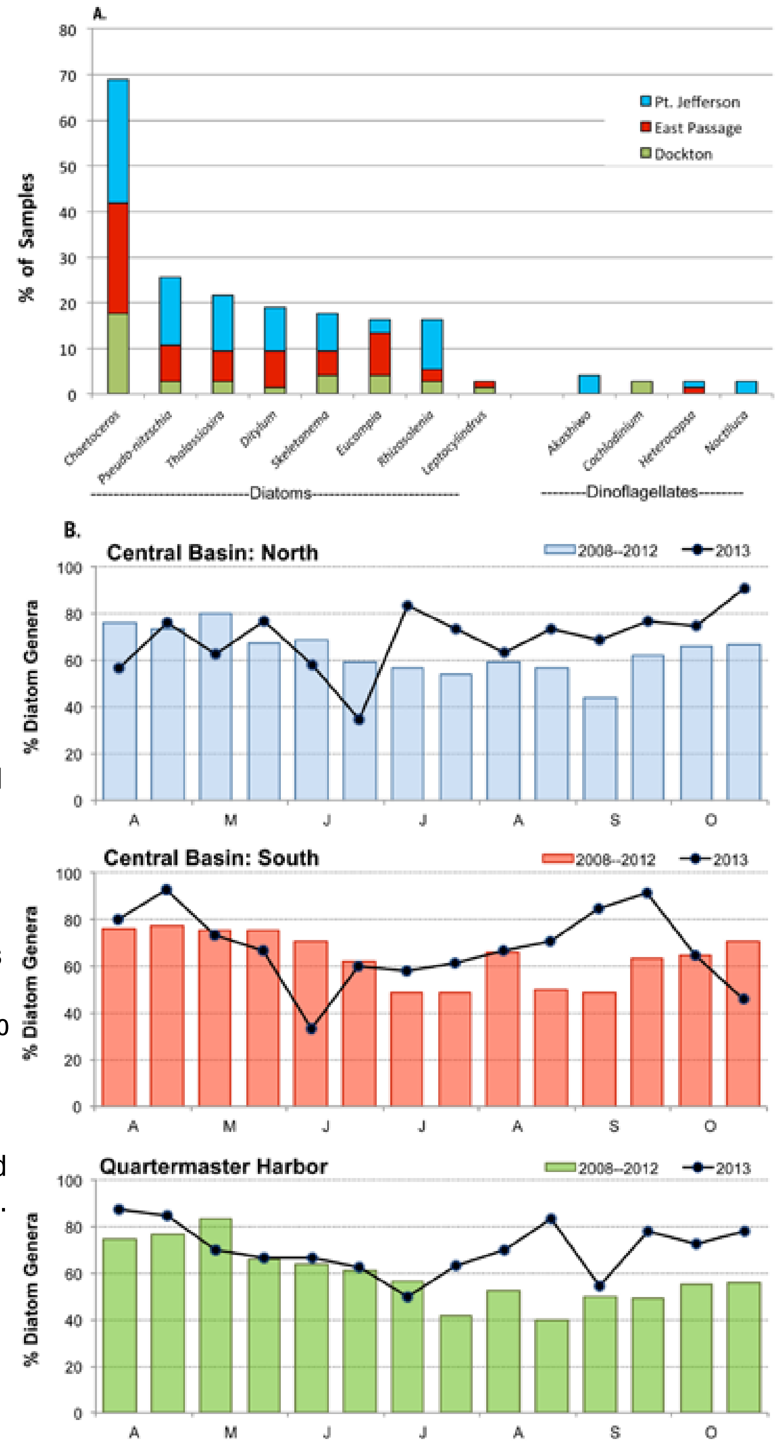


Figure 28. (A) Most abundant genera encountered in 2013, as percent of the total number of samples analyzed (n=74). These genera were considered abundant if categorized as common, subdominant or dominant (based on relative cell numbers) in the sample. During each of the nine sampling events, samples were collected from two depths at Point Jefferson and East Passage (1 m and the chlorophyll-a maximum layer) and from 1 m at Quartermaster Harbor. (B) Seasonal changes in the proportion of diatom genera at Point Jefferson (Central Basin: North), East Passage (Central Basin: South) and Quartermaster Harbor from April through October. Bars represent 2008-2012 monthly means and lines indicate 2013 values.

B. Harmful algae:

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

i. Biotoxins:

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

Source: Jerry Borchert (jerry.borchert@doh.wa.gov), and Clara Hard (WDOH); http://www.doh.wa.gov/CommunityandEnvironment/Shellfish/BiotoxinsIllnessPrevention/Biotoxins.aspx; www.soundtoxins.org

In 2013, the Washington State Public Health Laboratory (PHL) analyzed 3,279 samples for PSP toxins. There were far fewer PSP toxic events in 2013 than in 2012, with the highest value of 8,040µg/100g detected in mussels at Penrose Point Park in Pierce County. The FDA standard for PSP toxin is 80 µg/100g of shellfish tissue. In 2013, 32 commercial growing areas (29 geoduck clam tracts and 3 general growing areas) and 24 recreational harvest areas were closed due to unsafe levels of PSP toxins. A total of 1,300 samples were analyzed for domoic acid in 2013, with the highest value of 6 parts per million (ppm) detected in razor clams from Mocrocks on December 5, 2013. There were no harvest closures due to domoic acid last year. In 2013, the PHL analyzed 1920 shellfish samples for DSP toxins from areas around Washington. The highest DSP toxin measured in 2013 was 50 µg/100g in mussels from San Juan County. 11 recreational areas were closed due to DSP toxins, but no commercial growing areas. Puget Sound had several places closed to both PSP and DSP at the same time (dual closures). There were no marine biotoxin caused illnesses reported last year in Washington. WDOH collaborates with the phytoplankton monitoring group SoundToxins to detect potential marine biotoxin producing algae in Puget Sound. This early-warning system helps DOH identify and prioritize areas for additional biotoxin testing.

ii. SoundToxins:

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

The "SoundToxins" program samples phytoplankton at key locations throughout Puget Sound, reporting cell concentrations of *Alexandrium* spp., *Dinophysis* spp., *Heterosigma* sp., and *Pseudo-nitzschia* spp. This provides an early warning system for the Washington State Department of Health to prioritize shellfish toxin analysis and timely information to shellfish and finfish producers and researchers. Active monitoring sites in 2013 were: Budd Inlet, Discovery Bay, Dolphin Bay, East Sound, Fort Worden, Long Live the Kings, Manchester, Mystery Bay, North Bay, Penn Cove, Port Susan, Port Townsend, Quartermaster Harbor, Quilcene Bay, Sequim Bay, and Spencer Cove. Sampling stations are monitored weekly from April to October and biweekly during the winter months. *Alexandrium* spp. counts were low or absent from most of the sampling locations throughout 2013 with the exceptions being East Sound, Long Live the Kings, Discovery Bay, and Sequim Bay. Two sites, East Sound and Long Live the Kings, within Orcas Island reported *Alexandrium* as either common or abundant in their waters in late June. At the Sequim Bay monitoring site, *Alexandrium* spp. appeared as early as January and then was a constant presence from October 8-November 5, 2013, with cells ranging in abundance from 2,000- 3,000 cells/L. The greatest abundance of *Alexandrium* was 6,000 cells/L in Discovery Bay on October 28, 2013. *Dinophysis* spp. was identified at all monitoring stations, except at North Bay, where it was absent. The greatest amount of *Dinophysis* was reported at Discovery Bay and Sequim Bay. On July 3, Discovery Bay cell counts reached 6,000 cells/L. Throughout the month of June at Sequim Bay, *Dinophysis* was consistently above 2,000 cells/L for two weeks. *Dinophysis acuminata* was the dominant species present for the month. *Heterosigma* sp. had a variable presence among the various monitoring stations in 2013. Sites where *Heterosigma* sp. was present include: Dolphin Bay, Long Live the Kings, Manchester, Mystery Bay, Port Susan, Port Townsend, Quartermaster Harbor, Sequim Bay, and Spencer Cove. Peak abundance reached 485 cells/L at Quartermaster Harbor on July 16, 2013. *Pseudo-nitzschia* spp. were common throughout Puget Sound in 2013, including both large and small species. The highest cell concentrations were observed in Penn Cove with cell counts reaching >3,200,000 cells/L. Other locations with high cell counts include Sequim Bay (cell counts >597,000 cells/L) and Mystery Bay (cell counts >294,000 cells/L). Despite the high cell counts, no domoic acid-related shellfish closures occurred in Puget Sound during 2013.

iii. Robotic monitoring:

The Environmental Sample Processor (ESP) is a robotic biosensor that offers timely, quantitative, in-situ detection capabilities for harmful algal bloom and bacterial species. The ESP filters water samples and analyzes them onboard to detect target organisms using DNA and RNA-based technologies.

Source: Stephanie Moore (stephanie.moore@noaa.gov) (NOAA, NWFSC and UCAR), Linda Rhodes, William Nilsson (NOAA, NWFSC), Annie Cox, Steven Hallam (UBC), Kevan Yamahara, James Birch, Brent Roman, Roman Marin III, Christina Preston, Scott Jenson, and Chris Scholin (MBARI); http://www.nwfsc.noaa.gov/research/datatech/tech/esp.cfm

In summer 2013, four ESPs were deployed for ~60 days total at a tribal shellfish and finfish hatchery in Lummi Bay and a commercial shellfish farm in Samish Bay hosted by the Lummi Nation and Taylor Shellfish Farms, respectively. The main objective was to assess ESP-enabled detection of HABs in support of proactive fisheries management efforts. The devices were configured to sample daily at the daytime high tide and were operational from June 20-August 18, 2013, in Lummi Bay and from July 16-September 7, 2013, in Samish Bay. Target HAB species detected by the ESP were *Heterosigma akashiwo, Alexandrium* spp., and *Pseudo-nitzschia* spp. Validation samples were taken periodically to confirm ESP data. The fish-killing algae, *H. akashiwo*, was intermittently detected at the Lummi Bay site and confirmed the ESP's ability to detect HAB species at low cell densities before they are able to contaminate or harm shellfish and finfish and threaten public health or economic interests (Figure 29). This ability makes the ESP a useful tool for early warning of HAB events. *Alexandrium* spp. and *Pseudo-nitzschia* spp. were not detected at the Lummi Bay site and none of the HAB targets were detected at the Samish Bay site during the deployment period. Near-real time (i.e., ~3 hours) results from the ESP were made available to decision-makers via the NOAA NWFSC website and the NANOOS Data Visualization System.

Preparing the Environmental Sample Processor for deployment. Photo: Stephanie Moore.

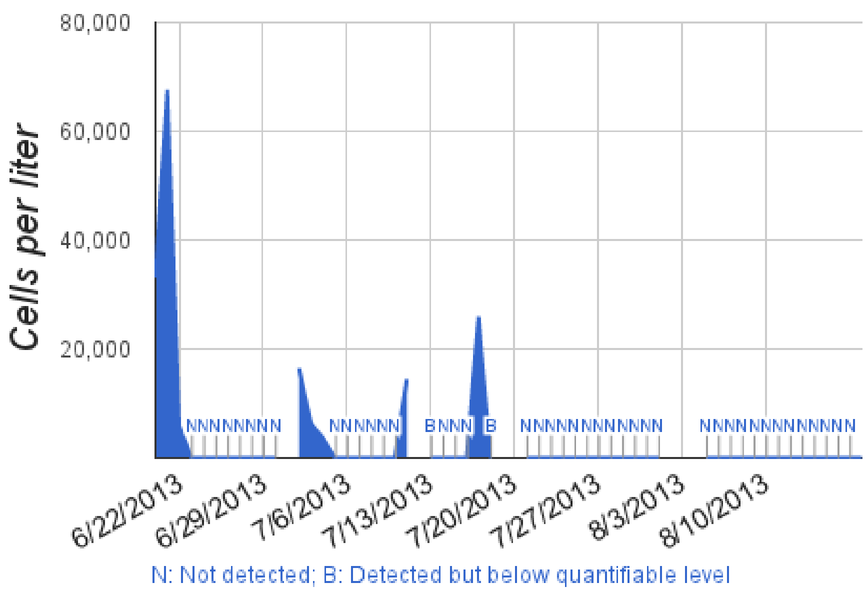


Figure 29. Heterosigma akashiwo cell abundance at Lummi Bay.

iv. *Alexandrium* species cyst mapping:

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

Source: Cheryl Greengrove (cgreen@uw.edu), Julie Masura (UWT), Stephanie Moore (NOAA, NWFSC and UCAR), Brian Bill (NOAA, NWFSC), and the PS-AHAB group; http://www.tiny.cc/psahab

The PS-AHAB (Puget Sound Alexandrium Harmful Algal Bloom) program, funded by NOAA/ECOHAB, seeks to understand environmental controls on the benthic (cyst) and planktonic life stages of the toxic dinoflagellate *Alexandrium catenella*, and evaluate the effects of climate change on the timing and location of blooms. This includes detailed mapping of overwintering cysts at 99 stations throughout Puget Sound. Highest surface sediment cyst abundances in 2011, 2012 and 2013 were found in Bellingham Bay (north), in bays on the western side of the central main basin, and in Quartermaster Harbor (south). Abundances in 2013 remained the same as 2012 for Quartermaster Harbor, but were lower in Bellingham Bay and the bays on the west side of the main basin than the previous year, which in turn were all lower than observed concentrations in 2011. Compared to a 2005 survey (Horner et al. 2011), the 2011-2013 Bellingham Bay "seed bed" is new, whereas Quartermaster Harbor cyst concentrations decreased by an order of magnitude. In a related study funded by Washington Sea Grant, cysts from surface sediments at thirty 2012 PS-AHAB stations were evaluated for their germination potential with results ranging from 16 to 66% viability. To date, no relationship between cyst viability and cyst appearance has been detected. These results will be used to inform a model to explore the possibility of providing seasonal *Alexandrium catenella* bloom forecasts.

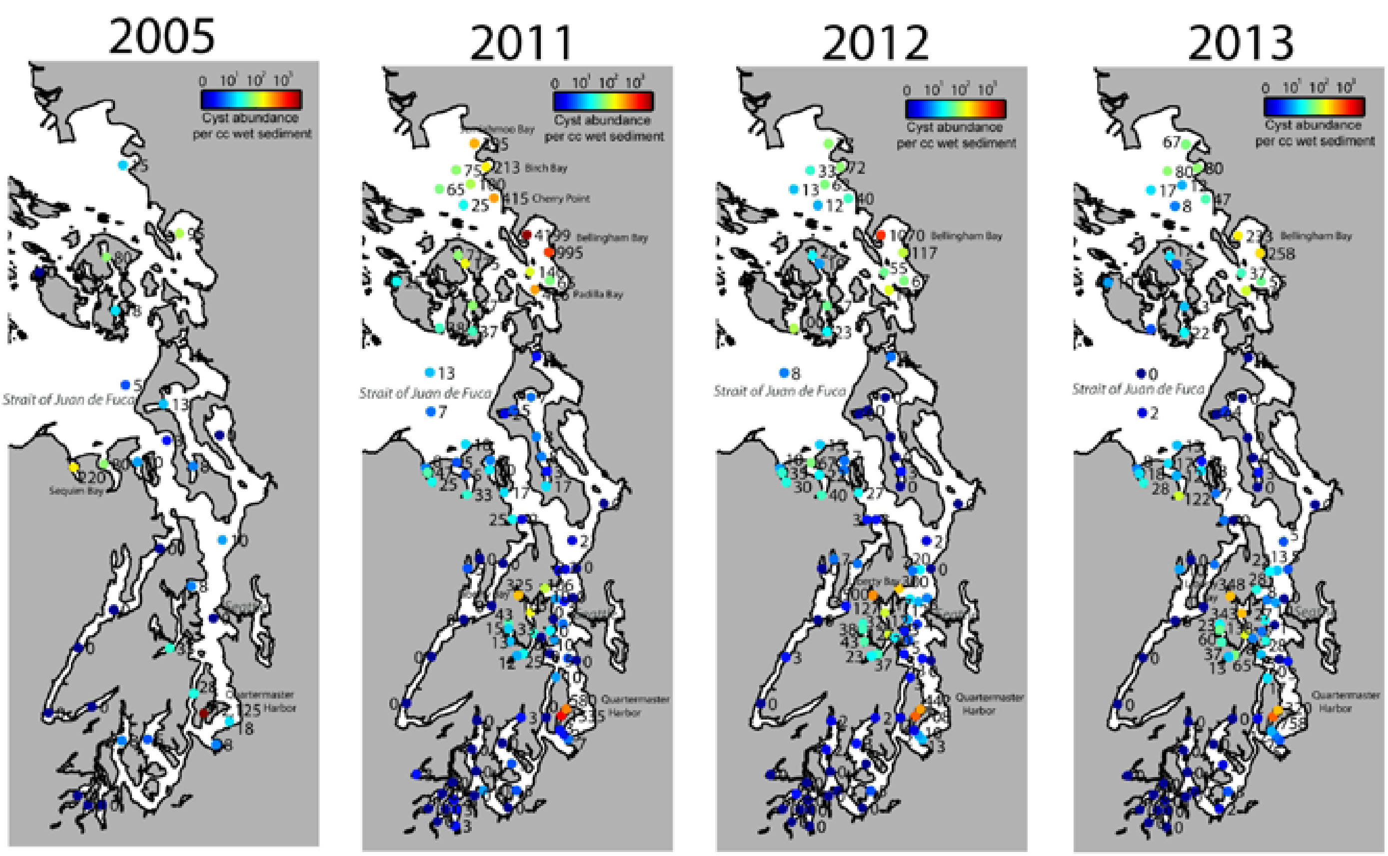


Figure 30. Alexandrium catenella surface sediment cyst distribution maps for winter Puget Sound surveys (number of cysts/cc wet sediment).

CALL-OUT: QUARTERMASTER HARBOR FISH KILL

Several hundred dead and dying shiner surfperch in inner Quartermaster Harbor were reported by a citizen on July 17, 2013. Quartermaster Harbor is a shallow, southward facing bay bordered by Vashon-Maury Island that connects to the Puget Sound Central Basin. It has a shallow inner harbor (average depth of 6 m) and a deeper outer harbor (average depth of 12 m with a range from 11-46 m) (King County 2014). While low DO levels (<2.0 mg/L) have been observed in Quartermaster Harbor during August and September the past several years, particularly in the inner harbor, this was not the cause of the fish kill - high temporal resolution (15-minute interval) DO data from King County's in situ moorings located in the inner (Quartermaster Yacht Club) and outer (Dockton Park) harbors indicated that waters were not hypoxic at the time of the fish kill. A SoundToxins volunteer who collects weekly phytoplankton samples in Quartermaster Harbor observed that the harmful species *Heterosigma akashiwo* was present in a 20 µm net tow sample collected from Dockton in Quartermaster Harbor on July 9. *H. akashiwo* were observed at low densities (i.e., reported as "present") in whole water samples on July 16, on July 17 at 12:40 pm at 200,000 cells/ml, and on July 17 at 2:30 pm at 1,500,000 cells/ml. Winds were from the north on July 16 with a shift to winds from the south on the 17th. *H. akashiwo* is a harmful algal bloom species that has been linked to fish kills. The exact cause of toxicity is not known, but gill irritation and/or damage is suspected to be the causal factor of fish death. The SoundToxins Program is a partnership of Washington state shellfish and finfish growers, environmental learning centers, Native American tribes and Puget Sound-area volunteers. The program is designed to provide early warning of harmful algal bloom events in order to minimize health risks and economic losses to Puget Sound fisheries. Semi-monthly sampling at Dockton conducted by King County showed *H. akashiwo* was not present in samples collected on July 2. Following notification of the fish kill, King County collected water samples from both the inner and outer harbors on July 17. The samples contained dense concentrations of *H. akashiwo* (Figure 31). Although it was not determined conclusively to be the cause of the fish kill, it is believed that the warm weather was a factor that likely promoted the bloom. *H. akashiwo* often blooms in Puget Sound during the warm summer months, but most blooms are not concentrated enough to cause fish kills. King County issued a press release following the fish kill and encouraged people who observed additional dead or dying fish to contact SoundToxins. No additional fish deaths were observed subsequent to the initial die-off and *H. akashiwo* was not present in samples analyzed on August 6 in the outer harbor.

Authors: Kimberle Stark (kimberle.stark@kingcounty.gov), Gabriela Hannach (KCDNRP), and Vera Trainer (NOAA, NWFSC)

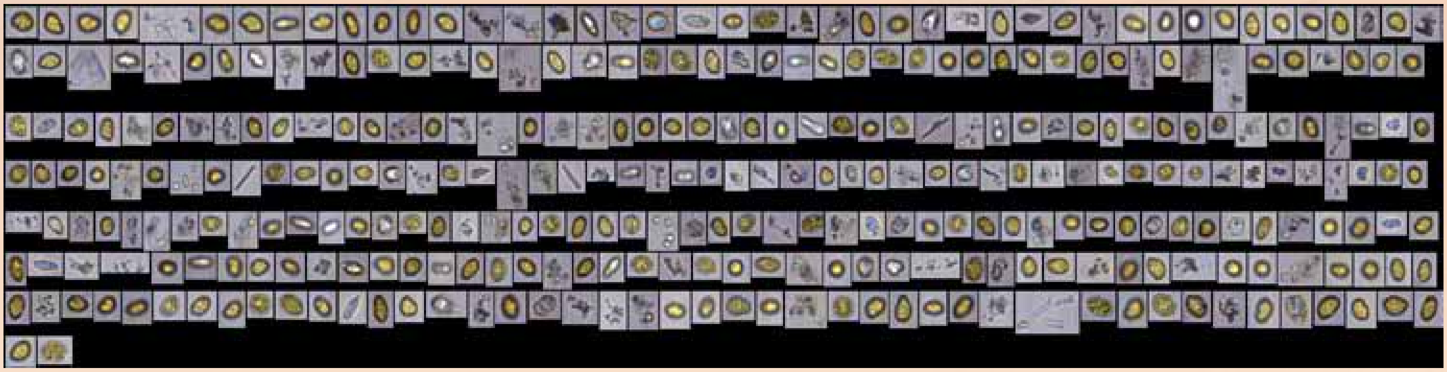


Figure 31. Composite of FlowCam images for the 12-17 mm ABD (area based diameter) size fraction of the Dockton sample that was collected July 17 (L58254-5 at MSWH01, not in LIMS). Heterosigma cells dominate the size fraction.

Bacteria and pathogens

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

A. Fecal indicator bacteria:

i. Puget Sound recreational beaches:

Source: Debby Sargeant (debby.sargeant@ecy.wa.gov) and Julianne Ruffner (Ecology & WDOH); http://www.ecy.wa.gov/programs/eap/beach/

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 beaches for fecal bacteria (enterococcus) and to notify the public when results exceed EPA's swimming standards. Beaches are selected from throughout the Puget Sound and Washington's coast. BEACH coordinates weekly monitoring from Memorial Day (May) to Labor Day (September) with local and county agencies, tribal nations, and volunteers. Our program is 100% funded by EPA. In 2013, 60 Puget Sound beaches were sampled including 43 beaches considered "core beaches" (beaches that are consistently sampled from year to year). Figure 32 represents the percentage of all monitored Puget Sound beaches meeting the EPA's water quality standards for enterococcus (allowing for one exceedance exception) from 2004 through 2013. 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.

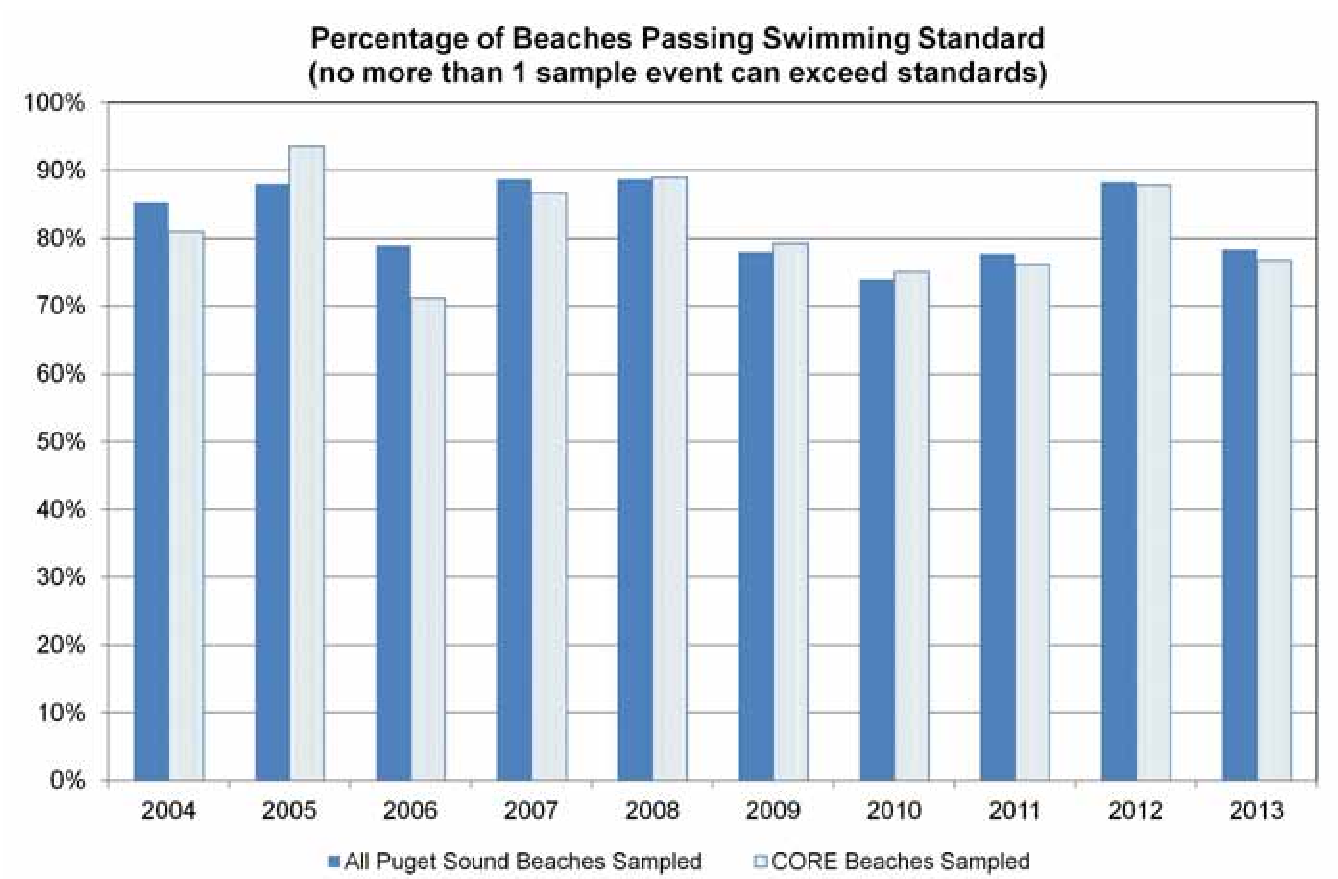


Figure 32. Percent of all monitored Puget Sound beaches and all core beaches (monitored each year) that met EPA's swimming (enterococcus bacteria) standards during the 2004-2013 period.

ii. Central Basin stations:

Source: Scott Mickelson (scott.mickelson@kingcounty.gov) (KCDNRP); http://green.kingcounty.gov/marine/

King County conducts monthly water quality monitoring at 14 offshore locations in the Central Puget Sound Basin. Samples were collected from the 1-m depth at six ambient and eight outfall stations in 2013. Ambient stations are chosen to reflect ambient environmental conditions, while outfall stations are located at King County wastewater outfalls, both treatment plants and CSOs. Data were compared to Washington State marine water quality standards – a geometric mean standard of 14 CFU/100 ml with no more than 10% of the samples used to calculate the geometric mean exceeding 43 CFU/100 ml (peak standard). Fecal coliform data collected in 2013 show that all 14 offshore stations passed both the geometric mean and peak standards during all 12 months, continuing a trend seen over many monitoring years.

King County also monitors fecal coliforms in monthly water samples collected from 20 beach stations along the western shoreline of the county and on Vashon and Maury Islands. In 2013, 10 of 20 beach monitoring stations met the geometric mean standard during all 12 months. Of these 10 stations, 4 stations also met the peak standard. Nine of 20 stations failed both the geometric mean and peak standards during 2013. Seven of these nine stations are located near freshwater inputs, either creeks/rivers (five stations) or stormwater outfalls (two stations). The highest number of individual excursions beyond the peak standard occurred in March (7 stations). Rainfall during the March sampling event totaled 0.85 inches over the sampling day and two previous days. Figure 33 compares 2013 fecal coliform monitoring data from King County marine beaches to previous monitoring years, showing the percentages of monitoring stations that passed the geometric mean and peak standards.

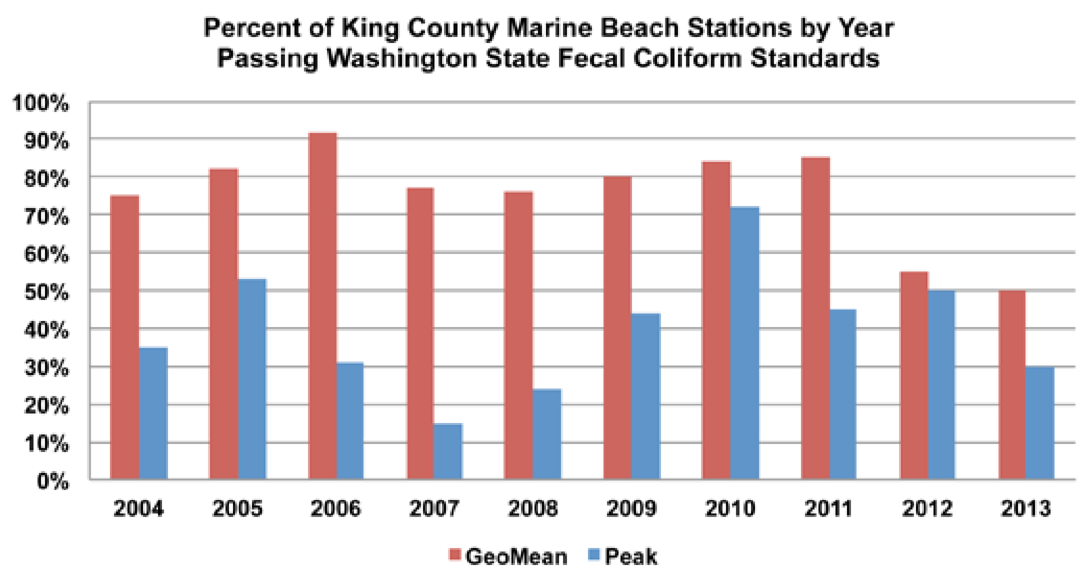


Figure 33. Percent of King County marine beach stations passing fecal coliform standards from 2004 through 2013.

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 U.S. A large outbreak of Vp-related illnesses occurred in 2006, and in spite of the implementation of stringent post-harvest controls the number of confirmed cases has remained elevated relative to the time period of observation before the 2006 outbreak. Genetic markers for virulent strains of Vp work well in other areas of the U.S., but are not effective in Puget Sound, significantly challenging health authorities.

Source: Laura Wigand (laura.wigand@doh.wa.gov) (WDOH); http://www.doh.wa.gov/CommunityandEnvironment/Shellfish.aspx

Vibrio parahaemolyticus (Vp) is a naturally occurring marine bacteria found in oysters that can cause gastrointestinal illness in humans. *Vp* populations increase rapidly with temperature and can reach levels that cause illness in the summer months. The Washington State Department of Health uses three strategies to control *Vp* related illnesses: monitoring *Vp* levels in oysters; reducing the time allowed between harvest and temperature control for the commercial shellfish industry during May through September; and closing growing areas to oyster harvest when illnesses occur. In addition to collecting oyster samples for *Vp* testing, current weather conditions, air, water and tissue temperatures, and salinity are also recorded. From June to September 2013, 311 samples were collected from 28 sites and analyzed for the presence of *Vp* (total and potentially pathogenic). The highest values were from sites in Hood Canal where some samples tested greater than 110,000 MPN/g tissue (Figure 34). In 2013 there were 88 laboratory-confirmed and epidemiologically-linked illnesses due to the consumption of oysters contaminated with *Vp*. Seventy nine cases came from commercially-harvested oysters and nine were from recreationally-harvested oysters. The majority of illnesses occurred among individuals who consumed raw oysters in July and August, which is consistent with historic illness occurrence. Fifteen shellfish growing areas in Puget Sound were closed during 2013 due to high *Vp* levels or the occurrence of *Vp*-related illnesses associated with the areas.

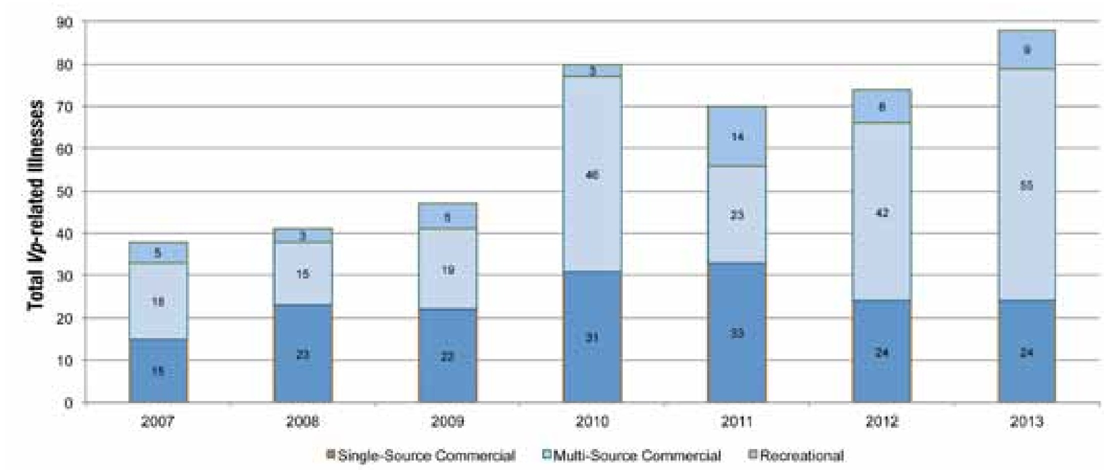


Figure 34. Vp-related illnesses for both commercially and recreationally harvested oysters.

CALL-OUT: PUGET SOUND'S NEARSHORE PELAGIC FOODWEB

In 2003, the Northwest Fisheries Science Center (NWFSC) observed dramatic differences in the relative abundance of small pelagic fishes and jellyfish across Puget Sound, suggesting different pelagic food web structure in different areas of the Sound. In 2011, the NWFSC followed up on this result with a greatly expanded study of lower to middle trophic levels in the near shore pelagic food web of greater Puget Sound. Monthly sampling occurred at 79 sites in six major sub-basins: Admiralty Inlet, Hood Canal, South Sound, Central Basin, Whidbey Basin, and "Rosario Basin" (areas in and around Padilla and Bellingham Bays) over the seven most productive months of the year (April-October). Measurements included abiotic water column variables, nutrients, primary production metrics, and heterotrophic microbes, zooplankton, and fish and jellyfish. This comprehensive approach provided a unique opportunity to examine spatial variation in multiple foodweb attributes over the year. Chlorophyll-*a* and fluorescence (primary production proxies) were positively associated with heterotrophic abundance and production, while all four of these biotic measures displayed strong inverse relationships with dissolved nutrients (Figure 35A). These observations suggest microbes were effectively regulating inorganic nitrogen and phosphorous concentrations. The abundance of picophytoplankton was positively associated with cyanobacterial (*Synechococcus* spp.) abundance, the abundance of low nucleic acid bacteria, and silicic acid concentration, but negatively associated with pH across the six oceanographic basins surveyed, indicating coordinated fluctuations of microbial subsets and abiotic conditions. Hence, while these patterns were coherent across all sites in Puget Sound (large panels in Figure 35A), they varied markedly among the different basins of Puget Sound (smaller panels), particularly in Hood Canal and Whidbey Basin. This basin-level variation appears to structure biological communities in predictable ways. Multivariate techniques were used to examine spatial patterns in environmental metrics (e.g., water column metrics and nutrients) and compare these to biological community structure in three groups of organisms: bacterial diversity (determined by DNA profiling), zooplankton (sampled with nets of two different mesh sizes), and fish and jellyfish (sampled in surface trawls). Following from patterns in Figure 35A, environmental metrics exhibited strong spatial structure which was repeated at different trophic levels (Figure 35B). The structures of bacterial communities displayed strong differences among basins, with convergent patterns between adjacent oceanographic basins over time and the highest similarities occurring in the fall. Hood Canal, however, was distinct from other basins in bacterial community structure. These same patterns were observed in zooplankton and fish and jellyfish: communities in South Sound, Central basin, and Admiralty Inlet shared stronger similarity, and differed from Hood Canal, Whidbey and Rosario Basins. These observations highlight the value of integrated measurements in evaluating lower trophic levels of pelagic food webs. More importantly, the strong spatial differences observed in this study indicate that target conditions or current status of ecosystem health cannot be uniform across greater Puget Sound. These are critical considerations for management of the Puget Sound ecosystem, and further analysis of these results in the context of other studies will improve our understanding of the causes for observed patterns across Puget Sound.

Authors: Correigh Greene (correigh.greene@noaa.gov), Casimir Rice, and Linda Rhodes (NOAA, NWFSC)

F.V. Coral Sea and R.V. Harold W. Streeter performing flow meter calibrations. Photo: Anne Baxter.

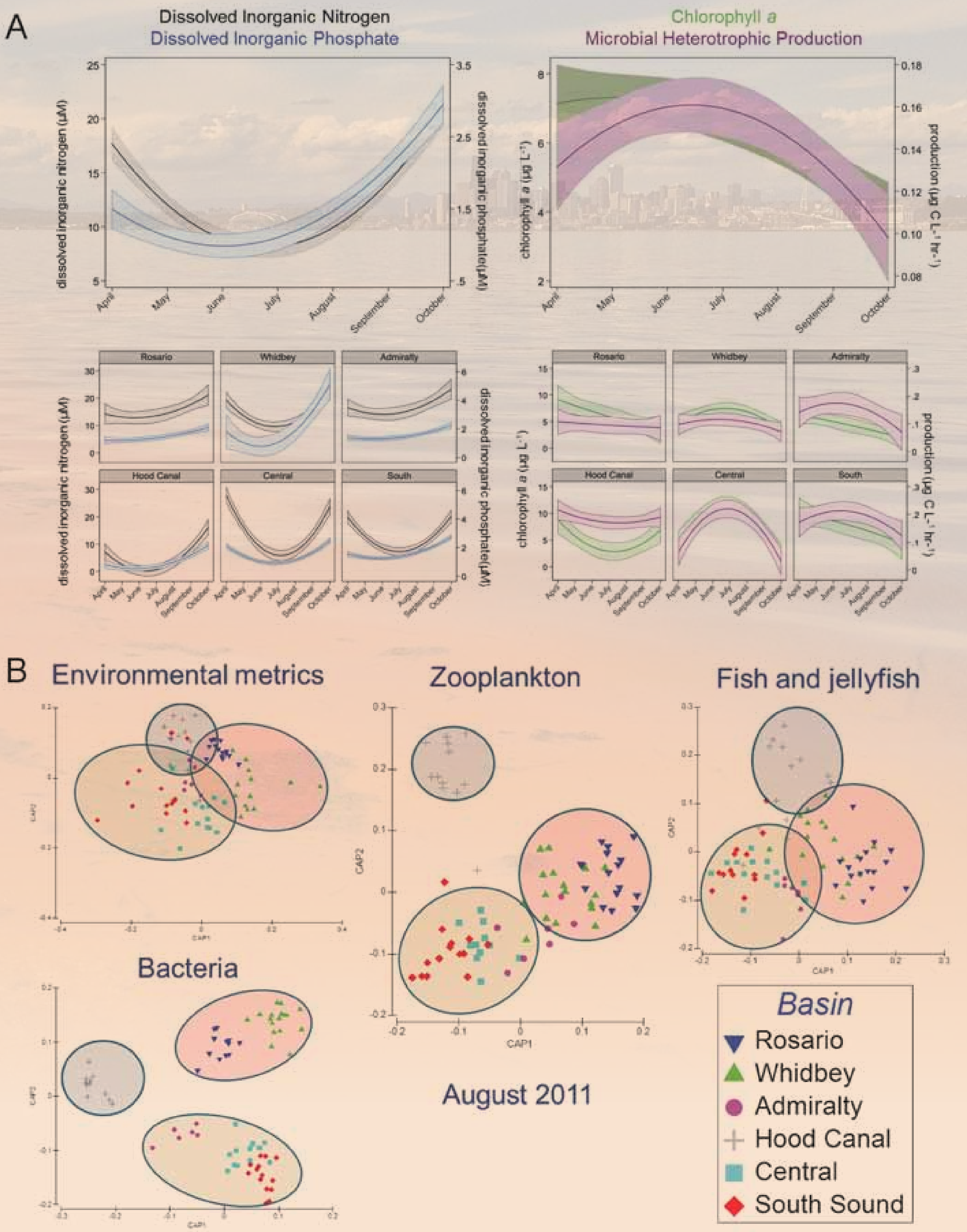


Figure 35. (next page) A. Seasonal trends for dissolved inorganic nutrients (nitrogen in black and phosphate in blue) and microbial indicators (chlorophyll-a in green and heterotrophic production in purple) for all sites in Puget Sound (upper graphs) and by sub-basins (lower graphs) in 2011. Plots are best regressions ± 95% confidence intervals. B. Multivariate analysis of sub-basin differences in environmental metrics, bacterial diversity, zooplankton taxa, and fish and jellyfish species captured in August 2011. Canonical analysis of principal coordinates explores the hypothesis of sub-basin differences by maximizing basin differences in observations (each point is a sampling site) and mapping them in two unitless axes.

Marine birds and mammals

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

A. Pigeon Guillemot – burrow count and breeding success study on Protection Island:

Source: Sue Thomas (sue_thomas@fws.gov) (USFWS, Washington Maritime Refuge Complex) and Lee Robinson (retired USFWS); http://www.fws.gov/washingtonmaritime/

Approximately 16,000 pigeon guillemots (*Cepphus columba*) can be found in the Salish Sea. Of this total, up to 1,500 can be found on Protection Island, one of the top five sites in Washington for this species. Approximately 150 breeding pairs have been counted, island-wide. 2013 marked the third year of a breeding success study of pigeon guillemot in natural cavities (such as hollow driftwood logs) and artificial nest boxes. Of 26 total nests observed, 10 were located in driftwood (38%); 1 in grass (4%); and 15 in artificial nest boxes (58%). The majority of nests (19; 73%) contained two eggs. Breeding success was slightly higher in 2013 than 2012, with observed chick mortalities (n=6) closer to normal compared to last year. Preliminary results show that success in driftwood nests was approximately 29%, while success in artificial nest boxes reached 58%. The one grass nest in the study area failed, likely due to the proximity of gull nests. Success in driftwood nests was higher than average for the last two years while success for nest boxes fell close to average for a long term study of breeding success in artificial nest boxes on the island between 1995-2010. As in the first two years of this study, all nests from previous years had filled in with driftwood, were not in use, or were inaccessible during the 2013 breeding season. We are currently analyzing the precision of criteria used to calculate breeding success. During the 2014 breeding season, we plan to conduct an additional island-wide burrow count and a diet study of guillemot chicks.

B. Rhinoceros auklet – long-term reproductive success:

Source: Scott Pearson (scott.pearson@dfw.wa.gov) (WDFW), Peter Hodum (University of Puget Sound), and Thomas Good (NOAA, NWFSC); http://wdfw.wa.gov/conservation/research/projects/seabird/rhinoceros_auklet/

Rhinoceros auklets (*Cerorhinca monocerata*) have been designated a marine bird indicator species for the Puget Sound Partnership Vital Signs program. As such, long-term data on population trends, reproductive success, and diet are critical to informing the Vital Signs monitoring process. We have been monitoring these parameters at three colonies, Protection and Smith Islands in the Salish Sea and Destruction Island on the Outer Coast, since 2006, 2012, and 2008, respectively. In this update, we focus on reproductive success measures from Protection Island and compare recent results to those from the mid-1970s. In 2013, burrow occupancy, or the percentage of burrows that are reproductively active in a given season, was slightly lower (61.7%) than the mean occupancy between 2006-2012 (71.7 ± 5.1%) and was the lowest rate recorded since 2006 (Figure 36). Hatching success in 2013, however, was marginally higher than the 2006-2012 mean (90.7% vs. 85.2 ± 2.4%, respectively). Overall, fledging success (81.3%) in 2013 was comparable to 2006-2012 values (80.1 ± 5.0%). Compared to the mid-1970s (1975 and 1976), burrow occupancy, hatching success and fledging success in the 2013 breeding season were all similar. The mean values from 2006-2013 were also similar to those from the mid-1970s, although burrow occupancy rates since 2006 have been slightly higher. These results indicate a remarkable inter-decadal consistency in reproductive success parameters for the Protection Island rhinoceros auklet breeding population despite increasing anthropogenic stressors in the Salish Sea ecosystem.

Rhinoceros auklet adult returning to the colony to provision its chick. Photo: Peter Hodum.

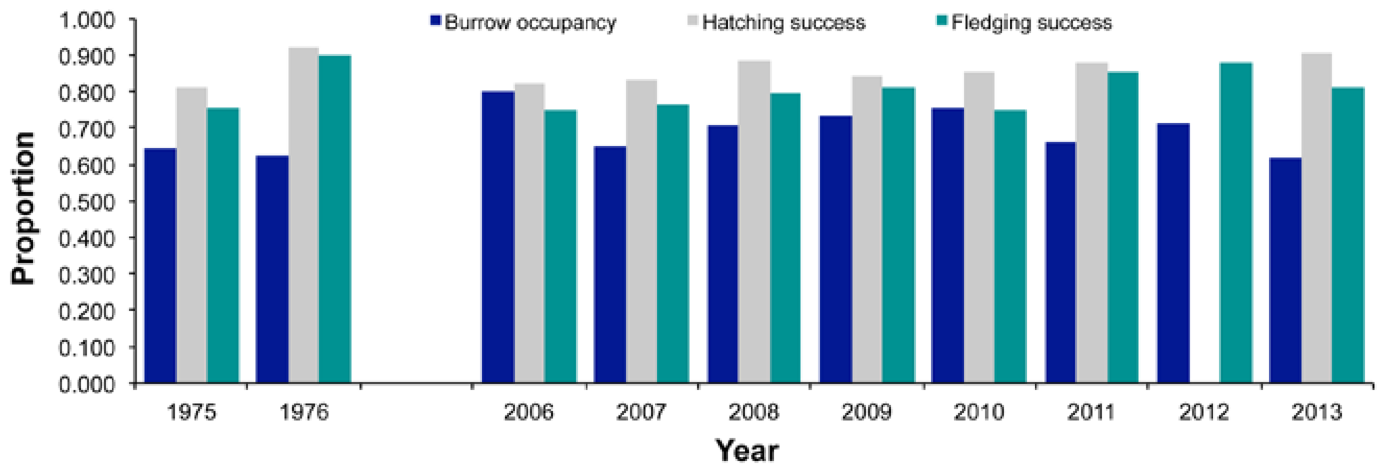


Figure 36. Temporal comparison of reproductive success parameters for the Protection Island rhinoceros auklet breeding population between the mid-1970s and the 2006-2013 breeding seasons. Burrow occupancy is defined as the proportion of burrows reproductively active in a given season. Hatching success is the proportion of eggs laid that produce nestlings, and fledging success is the proportion of eggs laid that produce fledglings.

C. Wintering marine birds:

Source: Joseph Evenson (joseph.evenson@dfw.wa.gov), Bryan Murphie, and Tom Cyra (WDFW); http://wdfw.wa.gov/; http://wdfw.wa.gov/conservation/research/staff/evenson_joe.html

WDFW has flown aerial surveys annually since 1994 to monitor trends in abundance indices of wintering marine birds throughout the Salish Sea within Washington's boundaries. Each year, December through January, roughly 7,000 km of transects are surveyed that cover essentially all shoreline (running parallel to shore) and sample the offshore waters utilizing saw-tooth transects. Estimates reported should be used as indices of abundance, and not actual population estimates, as corrections for detection rates have not yet been applied. This summary includes only a selection of the species monitored by this survey, including some sea ducks, ruddy duck, and western grebe.

There is a declining trend for most species from the mid-1990s through 2014 (Figure 37). The 2014 (Dec 2013-Jan 2014) estimate of 54,103 for scoters (*Melanitta perspicillata, M. deglandi, M. americana*) was similar to 2013, continuing recent increases from the low recorded in 2010 (42,317). However, the 2014 estimate is 57% below the high recorded in 1995 (125,287). Goldeneye (*Bucephala clangula, B. islandica*) show a similar trend as the scoters, in that the short term trend is increasing. The 2014 count (24,575) was up 20% from the low recorded in 2011(20,461), but was 54% below the high recorded in 1995 (53,273). Mergansers (*Lophodytes cucullatus, Mergus serrator, M. merganser*) have been relatively stable over all years. The merganser estimate this year was the highest on record (20,762), and has recovered to the 1995 level, since the low recorded in 1998. The western grebe (*Aechmophorus occidentalis*) estimate of 9,099 represents a 92% decline from the high recorded in 1995 (120,850), and was the lowest estimate recorded for this species since the survey began in 1994. The ruddy duck (*Oxyura jamaicensis*) estimate this year was the 2nd lowest recorded (465) representing a decline of 94% from the high recorded in 1994 (6,233).

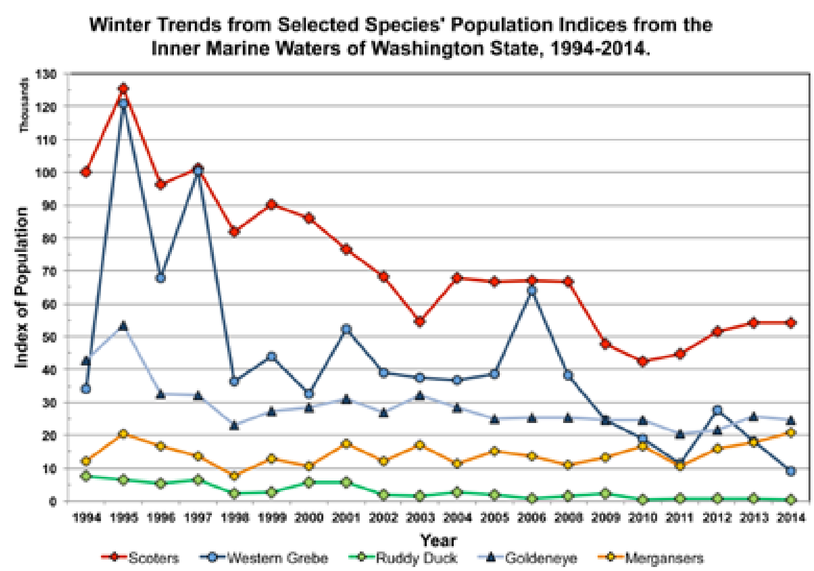


Figure 37. Winter trends from selected species' population indices from the inner marine waters of Washington State, 1994-2014.

D. Harbor porpoise:

Source: Aileen Jeffries (aileen@pacificbio.org) and Cindy R. Elliser (Pacific Biodiversity Institute); www.pacificbio.org

Population dynamics of the harbor porpoise, *Phocoena phocoena*, in the Salish Sea are poorly understood. The population was abundant in the 1950s, dropped dramatically by 1992 but now, may be rebuilding. Using passive acoustic monitors (PAM) combined with citizen science observations since 2009, the Pacific Biodiversity Institute's (PBI) Harbor Porpoise Project is developing a baseline of information about this little known species. Data on the presence of porpoises and their patterns of occurrence in Burrow's Pass (between Burrows Island and Fidalgo Island) are reported here for 2011-2013.

Land-based observation data were collected by trained, volunteer citizen scientists at Burrows Pass. A PAM was placed on a buoy off the NE point of Burrow's Island. Harbor porpoise sightings and echolocations have been recorded. Visual observations document the porpoises' presence, on average, more than 40% of the time. They are seen in small groups averaging 2-5, but single individuals were not uncommon. The porpoises showed a clear diurnal pattern, with increased presence at night (Figure 38A). They were present year-round, but had a seasonal pattern with increased presence from September to mid-March (Figure 38B). They were seen traveling, foraging, and swimming synchronously with calves. This study site appears to be an important area for the porpoises based on behavior, lifecycle events, and time present.

PBI has initiated a photographic identification study of the porpoises which will allow us to develop information about their density, range, and movements. We have begun to identify individuals based on natural scars and coloration patterns (Figure 38C), and have re-sighted at least one individual over multiple years. This identification along with our ongoing visual observations and acoustic monitoring (including expansion to other study sites) will continue to provide information that will help guide conservation, direct marine resource management, and contribute to restoring the harbor porpoise population.

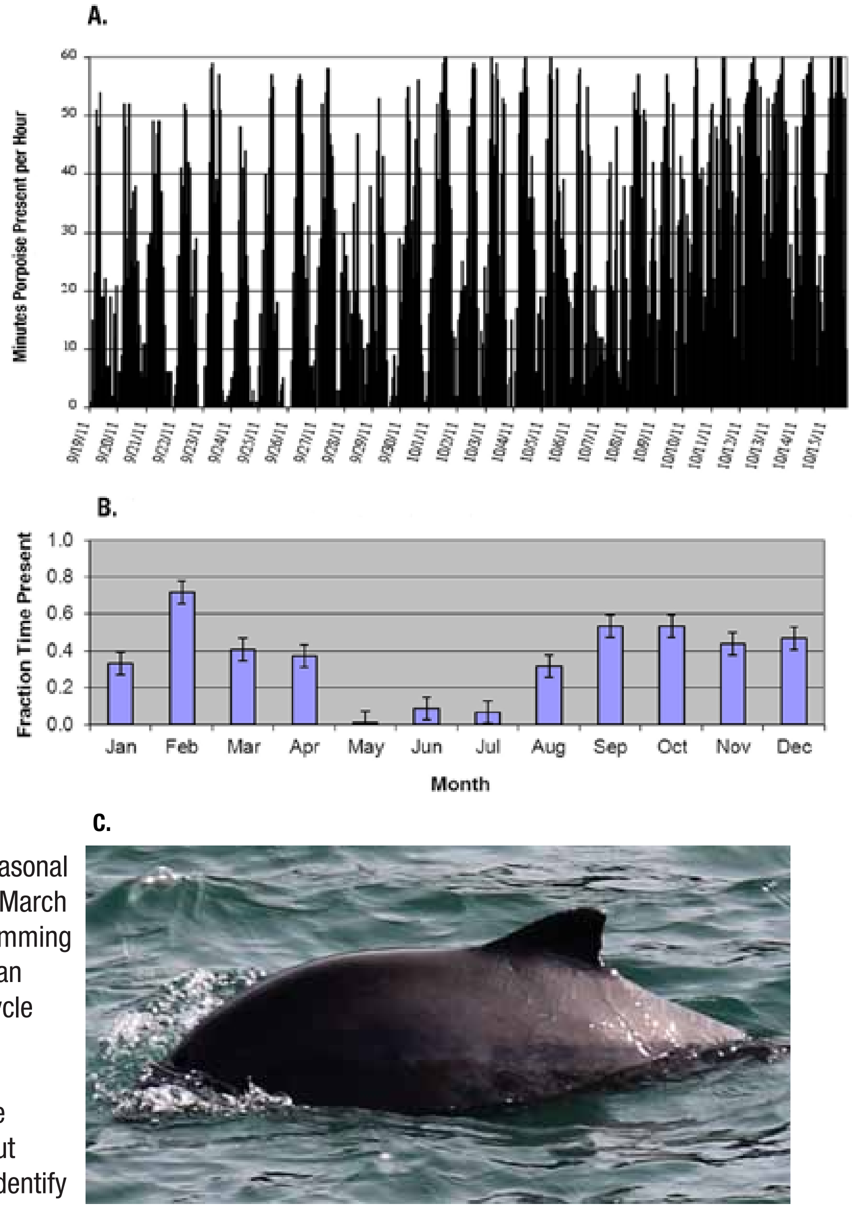


Figure 38. Data from 2011 are shown here, however these results were consistent through 2012 and 2013. (A) Minutes per hour porpoises were present shows diurnal cycle with peak occurrence at night. (B) Porpoises were present year-round, but showed increased occurrence seasonally during September to mid-March. (C) Using fin shape, nicks and scars and coloration patterns we have begun to identify harbor porpoises like this individual, named Nip.

E. Southern Resident killer whales – salmon-eating killer whales shifting from a resident to transient species?

Source: Scott Veirs (scott@beamreach.org) (Beam Reach Marine Science and Sustainability School); http://www.beamreach.org/2014/04/18/2013-year-southern-resident-killer-whales-transient

2013 was an unusual year for Southern "resident" killer whales and Pacific salmon. Most noticeably, the Southern Residents returned to the Salish Sea later in the spring than normal, continuing a trend seen during April and May over the last decade (Figure 39). Also, throughout the summer the whales were present less than normal and the duration of their visits to the Salish Sea were abbreviated. One possible explanation for these shifts is a scarcity of the killer whales' primary summertime prey, Fraser River Chinook salmon (Hanson et al., 2010). This hypothesis is supported by the Albion test fishery on the Fraser River, if the Chinook salmon counts there are used as a proxy for availability of Chinook in the Salish Sea. The 2013 counts show that the Chinook runs returned later than in the last 25 years and, along with 2012, had the smallest end-of-season totals of the last 25 years. The cumulative Chinook counts in 2013 reached average historic levels about 6 weeks late and only ~1000 Chinook were sampled throughout 2013, compared to >3,500 in the peak years of 2001 and 2003.

In contrast, on the Columbia River in 2013, 80-year record returns were counted at the Bonneville dam fish ladder. If these counts are taken as a proxy for the availability of Columbia Chinook in the outer coastal waters of Washington State, then prey abundance there may have been at record levels. Combined with evidence from killer whale studies (satellite tags, prey samples, and acoustic detections) indicating that some Southern Residents seek Columbia salmon during the springtime, the fish count and inland sighting patterns of 2013 may indicate a transition for the urban estuary known as the Salish Sea; from one with "resident" orcas to one with southern "transient" fish-eating orcas.

A Southern Resident killer whale breaches in the San Juan Islands with Mount Baker in the background. Photo: Beam Reach.

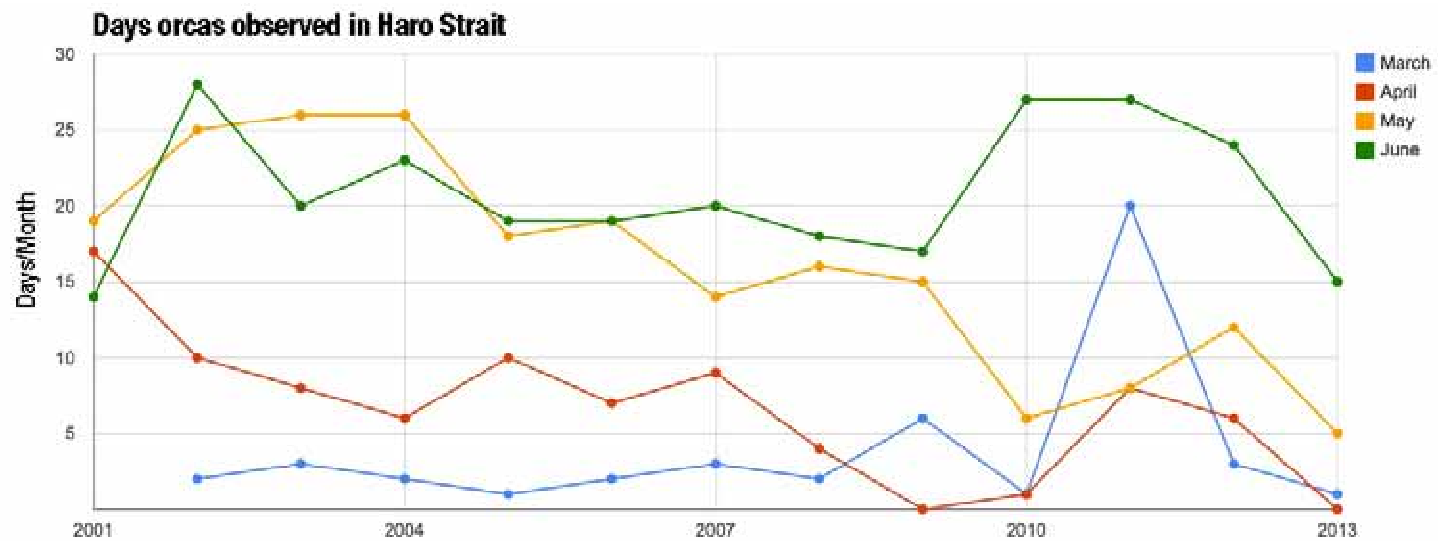


Figure 39. Year-to-year trends (2001-2013) in the number of days/month that Southern Resident killer whales were sighted in Haro Strait (off the west side of San Juan Island) based on the sighting archives of Orca Network. Data are shown in different endangered Southern Resident killer whales arrived later and were present less in the Salish Sea in colors for the months of March-June. 2013, possibly because Fraser River Chinook were scarce while Columbia Chinook were abundant.

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Acronyms

APL	Applied Physics Laboratory
ATG	Atmospheric Sciences and Geophysics building
BEACH	Beach Environmental Assessment, Communication and Health
CTD	Conductivity Temperature Depth
DO	Dissolved Oxygen
DSP	Diarrhetic Shellfish Poisoning
EC	Environment Canada
ECOHAB	Ecology and Oceanography of Harmful Algal Blooms Program
Ecology	Washington State Department of Ecology
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
ESP	Environmental Sample Processor
FCU	Fecal Coliform Unit
HAB	Harmful Algal Bloom
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
KCDNRP	King County Department of Natural Resources and Parks
MPN	Most Probable Number
MSMP	Marine Sediment Monitoring Program
NANOOS	Northwest Association of Networked Ocean Observing Systems
NEMO	Northwest Enhanced Moored Observatory
NOAA	National Oceanic and Atmospheric Administration
NPGO	North Pacific Gyre Oscillation
NWFSC	Northwest Fisheries Science Center
OCNMS	Olympic Coast National Marine Sanctuary
ORCA	Oceanic Remote Chemical Analyzer
OWSC	Office of the Washington State Climatologist
PAR	Photosynthetically Active Radiation
PAM	Passive Acoustic Monitor
PBI	Pacific Biodiversity Institute
PDO	Pacific Decadal Oscillation
PFEL	Pacific Fisheries Environmental Laboratory
PHL	Washington State Public Health Laboratories
PMEL	Pacific Marine Environmental Laboratory
PRISM	Puget Sound Regional Synthesis Model
PS Partnership	Puget Sound Partnership
PSEMP	Puget Sound Ecosystem Monitoring Program
PSI	Pacific Shellfish Institute
PSP	Paralytic Shellfish Poisoning
SAFS	School of Aquatic and Fisheries Sciences
SWFSC	Southwest Fisheries Science Center
TEC	Thermal Energy Content
TJWQP	Tribal Journey Water Quality Project
UCAR	University Corporation for Atmospheric Research
UCSC	University of California, Santa Cruz
USFWS	United States Fish and Wildlife Service
UW	University of Washington
UWT	University of Washington-Tacoma
Vp	*Vibrio parahaemolyticus*
WCC	Washington Conservation Corps
WDFW	Washington Department of Fish and Wildlife
WDOH	Washington State Department of Health
WSG	Washington Sea Grant