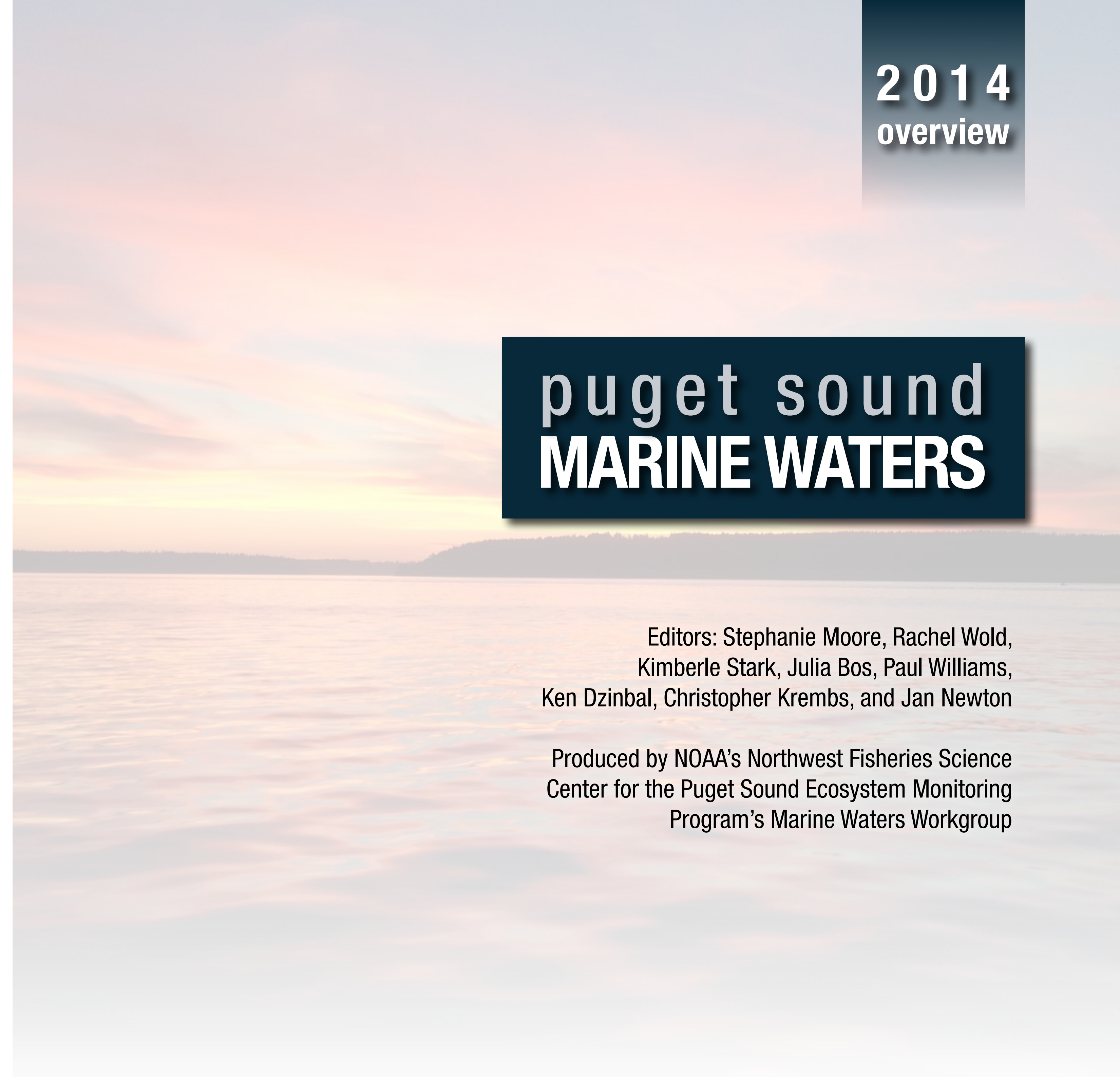
2014 overview

puget sound MARINE WATERS

PSEMP
Puget Sound Ecosystem Monitoring Program

NOAA FISHERIES



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puget sound MARINE WATERS

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Center for the Puget Sound Ecosystem Monitoring
Program's Marine Waters Workgroup

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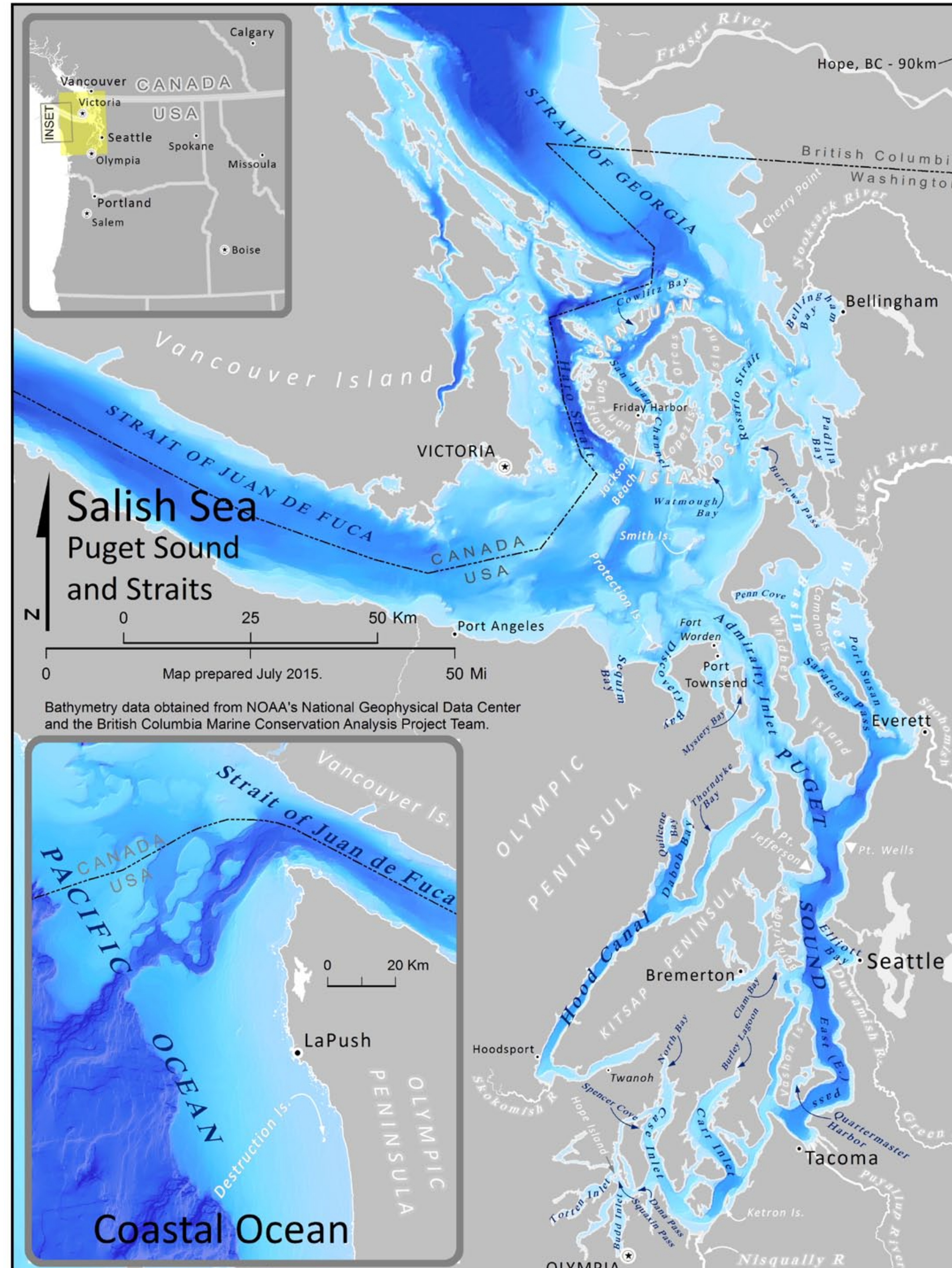

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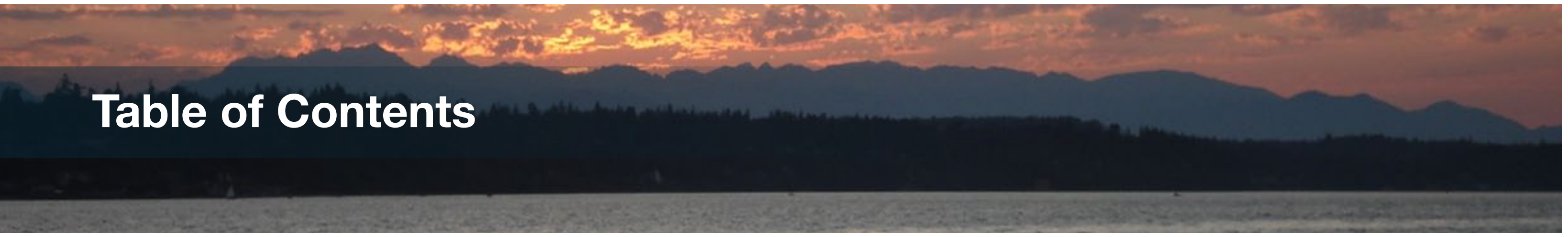

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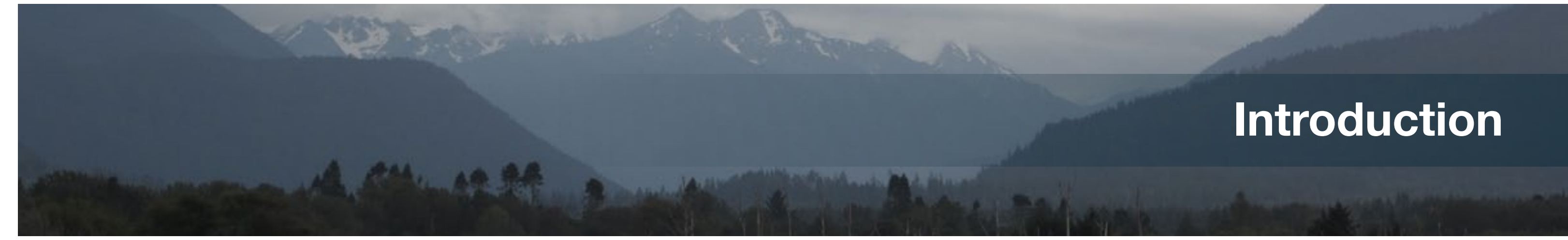
About PSEMP

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, including the oceanic, atmospheric, and terrestrial influences and drivers affecting the Sound. For more information about PSEMP and the Marine Waters Workgroup, please visit: *https://sites.google.com/a/psemp.org/psemp/*.



Introduction

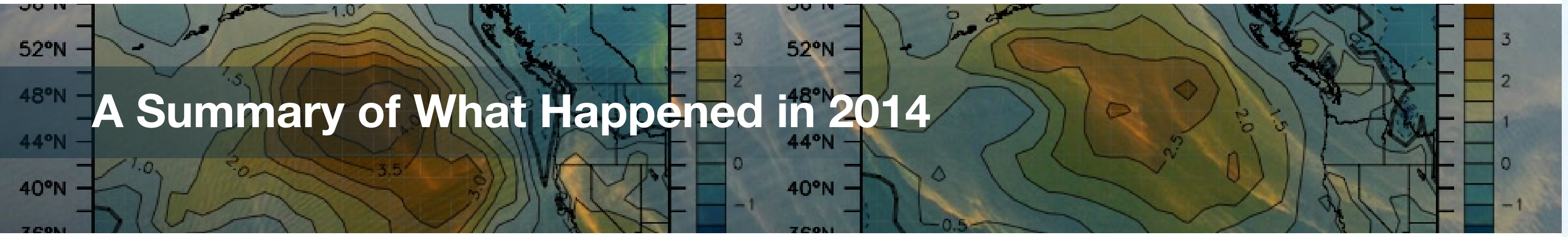
This report provides an overview of 2014 marine water quality and conditions and associated biota in Puget Sound from comprehensive monitoring and observing programs. The report focuses on the marine waters of greater Puget Sound. Additional selected conditions are also included due to their influence on Puget Sound waters, such as selected climate indices and conditions along the outer Washington coast. This is the fourth 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 2014.

The data and interpretations presented here are the proceedings of an annual effort by the PSEMP Marine Waters Work Group to compile and cross-check observations collected across the marine waters of greater Puget Sound during the previous year. Data quality assurance and documentation remains the primary responsibility of the individual contributors. All sections of this report were individually authored and contact names and information have been provided. The editors managed the internal cross-review process and focused on organizational structure and overall clarity. This included crafting a synopsis in the Executive Summary that is based on all of the individual contributions and describes the overall trends and drivers of variability and change in Puget Sound's marine waters during 2014.

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 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 System (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 2014

FROM THE EDITORS:

The collective view of Puget Sound's marine water environment and some of its associated biota in 2014 is presented here in the context of factors that drive variation, such as large-scale climate patterns, coastal upwelling, and regional weather. It is important to document and understand regional drivers and patterns so that water quality data may be interpreted with these variations in mind, to better attribute human effects versus natural variations and change. We show the conditions from a variety of observations and approaches in order to derive a general overview of the year 2014. Our message to decision makers, policy makers, managers, scientists, and the public who are interested in the health of Puget Sound follows.

In contrast to 2013, which in many ways was an average year, 2014 was a year with notable departures from average. The major story of 2014 is the influence of the warm northeast Pacific Ocean surface waters known as the "Blob" on Puget Sound. This ocean phenomenon was mainly driven by atmospheric conditions, primarily weaker winter winds that did not cool surface ocean waters as much as usual (see call-out box: *Development and evolution of the "Blob" in the NE Pacific*), coupled with the strengthening of the positive (warm) phase of the Pacific Decadal Oscillation (PDO). The ocean's response to these atmospheric forcings was an increase in water temperatures much higher than normal, in some cases unprecedented for the time records we present. How this response developed over time and space in Washington's marine waters and the strong effect these ocean conditions had on Puget Sound permeates much of this year's overview, though other events or extremes were also important in the narrative of 2014.

As might be expected with the positive PDO phase, the Puget Sound regional annual air temperature was warmer than normal; notably, on an annual basis 2014 ranks as the second warmest year since records began in 1895. Sunlight was stronger than normal, and especially so during summer months. Monthly Puget Sound weather also showed extremes, with a very dry January, a wet and very cold February, the wettest March on record, and a warmer than average fall. February was the only month in 2014 that was not warmer than normal. While the region saw strong forcing from the "Blob" and PDO, the ENSO status was neutral and upwelling was normal during 2014.

The normal upwelling pattern is why the warm NE Pacific waters did not reach the Washington coast and Puget Sound until fall, when the seasonal winds shift to downwelling favorable. With this shift to downwelling conditions, NE Pacific surface ocean waters move shoreward, instead of being pushed offshore and replaced by cool deep waters as happens during upwelling. When that shift (i.e., the Fall Transition) occurred, buoys at La Push registered water temperature anomalies (anomaly = departure from mean) as high as 6 °C above that seen in past records. Continuing the journey into the Puget Sound estuary, much warmer than average waters were observed during fall in the eastern Strait of Juan de Fuca, where waters at depth (incoming Pacific waters) were actually warmer than surface waters (exiting Puget Sound waters), an observation not seen in the 11-year record. This same pattern (anomalously warm deep temperatures) was first observed in November in Central Puget Sound.

The Puget Sound estuary is not only influenced by oceanic input, but also that from rivers. Coinciding with regional precipitation patterns, river flows generally exceeded historic means during spring 2014, dropped to normal levels during summer, then rose to higher than average values during fall and early winter before returning to normal. Salinity in Puget Sound reflected this alternating pattern, with both fresher and saltier than normal conditions observed, depending on location and timing.

Zoë Parsons, Hannah Glover, Keith Magness and John Mickett standing by ready to recover Cha'ba during the fall 2014 recovery cruise on the R/V T. G. Thompson. Photo: Jacob Wenegrat

Water temperatures within Puget Sound began colder than normal, a legacy from the cold fall 2013 and the very cold February 2014 conditions, but warmed the rest of the year, with unprecedented maxima based on the 16-year record in all locations except Hood Canal. These warm seawater temperatures were influenced by warm summer air temperatures, high solar radiation, and the arrival of the "Blob" in fall 2014. The exception, Hood Canal, was influenced by uncharacteristically cold seawater that appeared to be caused by weather-forced local deep water formation (very cold surface waters that became so dense they sank) in response to the very cold February air temperatures. Even though this phenomenon occurred in February, these cold waters persisted until fall. On an annual basis, water masses in Puget Sound were warmer and saltier everywhere except Hood Canal where they were colder. The localized deep water formation in Hood Canal also sheds light on why this was the only Puget Sound basin with a very low annual DO deficit relative to other years, because when the cold surface waters sank they had high oxygen content.

Aside from Hood Canal, the annual oxygen content throughout Puget Sound was similar to 2013; with lower oxygen concentrations than during 2009-2012 but higher oxygen concentrations than during 2006-2008. Although oxygen content in deep waters was lower than normal during the fall, surface waters had higher oxygen concentrations than normal, particularly during spring and late fall, reflecting production from large phytoplankton blooms. Fewer than normal oceanic intrusions entered Puget Sound from the Strait of Juan de Fuca, likely due to lower than normal Fraser River summer discharge. This had the effect of keeping overall oxygen concentration higher than what would have occurred with more oceanic intrusions during the upwelling season, as upwelled waters have lower oxygen content.

The arrival of the "Blob" into Puget Sound during fall caused a quick change in many of the conditions afore noted. Oxygen in lower Hood Canal rapidly went from higher than average to hypoxia which persisted through the end of the year, a condition not seen in the 10-year record. The low river discharge, the lack of oceanic intrusions, and the lower density of the fall intrusions (due to warmer temperatures) likely contributed to the lack of flushing of lower Hood Canal, resulting in the persistence of hypoxia. Fall hypoxia was also observed in Quartermaster Harbor.

The warm, sunny weather throughout the year was a boon to phytoplankton blooms, with diatoms dominant. Overall, phytoplankton biomass was higher during 2014, with large, chain-forming diatoms dominating. In the Central Basin, spring diatoms were dominated by a different species than in other years. Compared to previous years both spring and fall blooms were larger; the fall bloom was unusually large and coincided with warmer fall temperatures and more solar radiation.

Algal biotoxins associated with PSP and DSP were evident, with 58 closures and PSP closures in two new areas (Dabob and Quilcene Bays) historically considered biotoxin free. Despite the high numbers of closures, no illnesses were recorded, likely due to active monitoring and effective communication. However, encounters with *Vibrio* pathogens (e.g., 81 cases of tainted oyster consumption) and fecal coliform bacteria (e.g., 14 of 20 King County beaches) continued to affect human health this year.

With colleagues studying fish, seabirds, and marine mammals we continue efforts to understand how these water and plankton conditions affected the food web. A new zooplankton time series began in 2014 with initial key observations of strong seasonal cycles in abundance, high variability between sites, and differences in the zooplankton community between basins. Forage fish abundance and condition were not optimal during 2014 but varied over time and by region: in the north, Cherry Point herring stocks showed 90% decline in abundance relative to 1973 while southern Squaxin stocks held steady, and others showed a 20% decline compared to the 10-year record; Pacific Sand lance showed lower abundance and condition than the previous four years. In contrast, the abundance of harbor porpoise indicates a strong recovery relative to the 1960-1990s. Rhinoceros auklet reproductive success appeared to be relatively stable. Much more analysis of relationships between species and environmental conditions is needed.

This brief synopsis describes patterns in water quality and conditions and associated biota observed during 2014 and their association with large-scale ocean and climate variations and weather factors. The data compilation and analysis presented in the annual "Puget Sound Marine Water Overview", which began in 2011, offers the opportunity to evaluate the strength of these relationships over time and is a goal of the PSEMP Marine Waters Work Group.

Coscinodiscus curvatulus. Photo: Gabriela Hannach

Highlights from 2014 Monitoring

Large-scale climate variability and wind patterns

- El Niño-Southern Oscillation (ENSO)
  - » ENSO was neutral for the 2014 calendar year, though heading toward a weak El Niño at the close of the year.
- Pacific Decadal Oscillation (PDO)
  - » PDO was positive the entire year and strengthening.
- North Pacific Gyre Oscillation (NPGO)
  - » NPGO began to trend negatively in October 2013, suggesting lower primary productivity.
- Upwelling index
  - » Upwelling winds were mostly normal. In September and October stronger than normal downwelling occurred, coinciding with the movement of anomalously warm Pacific Ocean water into Puget Sound.

Local climate and weather

- Puget Sound annual average air temperature for 2014 was much warmer than normal, particularly in the fall, ranking as the 2nd warmest year since records began in 1895.
- Annual total precipitation was above normal for the 2014 calendar year, with some extremes in monthly anomalies; most notable were a drier than normal January, a wet and cold February that brought much-needed precipitation to the region, the wettest March on record.
- Solar radiation was higher than normal, especially during summer.

Coastal ocean and Puget Sound boundary conditions

- Coastal ocean
  - » Anomalously warm Pacific Ocean water of the “Blob” moved onto the shelf off La Push following the fall transition to downwelling-favorable winds, resulting in ocean temperature anomalies greater than 6º C observed at some depths from the Chá Bă and NEMO-subsurface moorings.
  - » Both record high (March) and record low (summer) surface seawater xCO_2 values were observed in 2014 at Chá Bă. Since the time series began in 2010, average surface seawater xCO_2 values for mid-July to mid-October have declined each year.

River inputs

- Coinciding with regional precipitation patterns, river flows generally exceeded historic mean flows in spring of 2014, dropped to normal levels through the summer, then rose above mean flows again in fall and early winter.

Water quality

- Temperature and salinity
  - » For the calendar year of 2014 the most common water masses were warmer and saltier compared to historic ranges for Puget Sound, except in Hood Canal, where it was colder.
  - » Fewer oceanic intrusions entered Puget Sound from the Strait of Juan de Fuca due to lower than normal Fraser River summer flow. Consequently, DO concentrations remained higher in Puget Sound despite upwelling off the coast.
  - » Puget Sound was colder than normal in early 2014, a legacy from fall 2013 conditions, and then dramatically warmed during the rest of the year, with new 16-year maximum temperatures observed everywhere expect Hood Canal.
  - » Central basin surface water temperatures (<2 m) were generally colder than the baseline average (1999-2010) from January through May and significantly cooler than normal (0.5-1.4ºC) in June. Bottom waters were warmer than normal (1.0 to 1.8ºC) in November.
  - » Eastern Strait of Juan de Fuca waters were the warmest (>1ºC at the surface and more than that at depth) in an 11-year record in fall 2014, consistent with the inbound transit of water from the “Blob”. These waters were also fresher and are the only observation in the record where water properties did not vary substantially over depth.
  - » Salinity in the San Juan Islands and North Sound was the highest observed since 2010, yet fresher conditions persisted for much of the year in the other Puget Sound basins
  - » Central Basin surface salinities (<2 m) were fairly typical in 2014 compared to the baseline average (1999-2010), with the exception of March, November, and December, which were fresher than normal due to freshwater input from precipitation.
  - » Strong upper water column stratification was observed at Point Jefferson and East Passage between March and early June, which has not been observed before.
  - » The water column in Bellingham Bay became warmer, fresher and more stratified as the calendar year progressed towards summer. This trend reverses from summer to late fall. Short-term disruption of summer stratification may occur as a result of changes in Nooksack river flow, tidal exchange, and weather fronts.

- Nutrients and chlorophyll
  - » The long-term trend of increasing nitrate and phosphate concentrations and decreasing chlorophyll changed in 2013 and 2014. A negative but persistent relationship between nutrients and phytoplankton biomass illustrates the importance of the lower food web in controlling dissolved nutrient pools in the water column. Chlorophyll *a* (biomass) displayed a different pattern in 2014 compared to the previous 14 years with a broader spring bloom and a smaller late summer bloom.
  - » The timing of the 2014 spring phytoplankton bloom in the Central Basin was typical, occurring in early April.
  - » An unusually large and longer than normal fall bloom occurred in the Central Basin from early September through October and was dominated by *Chaetoceros* spp.
  - » Chlorophyll levels in the Central Basin were higher in 2014 than in previous years.
  - » A sharp decrease in nitrate+nitrite levels in September and October were noted in the Central Basin coinciding with the anomalous late fall bloom
- Dissolved oxygen
  - » In 2014, lower than normal DO was observed mainly in North, Central, and South Sound. In contrast, Hood Canal had a very low DO deficit relative to previous years implying that oxygen conditions, albeit low, had improved temporarily.
  - » In the deep basin of Hood Canal, uncharacteristically cold seawater with high oxygen content appeared to be caused by weather-forced local deep water formation during winter.
  - » Late season hypoxia was persistent in southern Hood Canal through the end of the year.
  - » DO concentrations in Quartermaster Harbor fell below 1.0 mg/L in late September.
  - » DO in Central Basin surface waters was higher than the long-term baseline average as a result of primary production and slightly below normal in bottom waters.
  - » Warmer than normal Central Basin bottom waters in November and December coincided with lower than normal DO in bottom waters during those months.
- Ocean and atmospheric CO_2
  - » As in past years, average atmospheric and surface seawater xCO_2 values and variability were higher at Hood Canal sites compared to the offshore Chá Bă site. Surface seawater xCO_2 at Hood Canal sites followed similar seasonal patterns to previous years, with the highest values occurring in early winter or fall, decreasing to the lowest values of the year in late winter or early spring.

Plankton

- Phytoplankton
  - » The chain-forming diatoms *Chaetoceros*, *Thalassiosira*, and *Rhizosolenia* were the most abundant genera at the six Central Basin sites sampled in 2014.
  - » Seasonal phytoplankton species succession was characterized by a double spring bloom and an unusually large, extended fall diatom bloom coinciding with late fall warm temperatures.
  - » The *Chaetoceros* dominated spring community observed in previous years changed to a *Thalassiosira* dominated spring community in 2014, and an unusually extended period of *Chaetoceros* dominance was observed in the fall
  - » Dinoflagellate populations remained small throughout the year with the exception of a fall *Akashiwo sanguinea* bloom in Quartermaster Harbor.
  - » Zooplankton monitoring was initiated throughout Puget Sound in 2014, with sampling conducted by several tribes and agencies following protocols developed as part of the Salish Sea Marine Survival Program. Strong seasonal cycles in abundance, high variability among sites, and differences in zooplankton communities among basins were observed.
- Harmful algae and biotoxins
  - » PSP and DSP toxins resulted in 31 commercial growing area closures and 27 recreational harvest area closures but caused no illnesses while domoic acid remained below regulatory limits in 2014.
  - » Quilcene and Dabob Bays in Hood Canal closed for the first time ever due to PSP toxins with the highest value of 12,688 µg/100g detected in mussels at Quilcene Bay marina. This closure was the result of an unprecedented bloom of the harmful algae *Alexandrium* in Dabob and Quilcene in September and October 2014.
  - » *Alexandrium* spp. cell counts in marine waters were low or absent from most of the SoundToxins monitoring sites throughout 2014 with the exceptions being East Sound and Sequim Bay. *Pseudo-nitzschia* spp. were common throughout Puget Sound, with the highest cell counts observed in Sequim Bay and Discovery Bay. *Dinophysis* spp. were identified at all monitoring sites, except at Burley Lagoon, Dabob Bay, and Port Susan, with highest cell abundances

in Discovery Bay and Sequim Bay. *Heterosigma* sp. had variable presence among monitoring sites. *Akashiwo sanguinea* had a strong presence at several locations including Quartermaster Harbor, Totten Inlet, Budd Inlet, North Bay, Spencer Cove, Clam Bay, Fort Worden, and Mystery Bay.

- » Mapping of *Alexandrium* cysts in January 2015 found an order of magnitude higher concentration of cysts in the surface sediments Quilcene and Dabob Bays, indicating the formation of a new seedbed following the unprecedented bloom in September and October 2014.

Bacteria and pathogens

- » In 2014, 88% of the 60 Puget Sound beaches, and 86% of the core beaches monitored for the BEACH program had less than two swimming closures or advisories during the swimming season.
- » All King County offshore monitoring stations in the Central Basin passed the Washington State geometric mean and peak standards for fecal coliforms during 2014.
- » Fourteen of 20 monitoring stations at marine beaches in King County failed the geometric mean, peak fecal coliform standards, or both. Exceedances of the peak standard occurred most often during months with high rainfall prior to sampling.

- *Vibrio parahaemolyticus*
  - » There were 81 laboratory-confirmed and epidemiologically-linked illnesses in 2014 due to the consumption of oysters contaminated with *Vibrio parahaemolyticus* (76 from commercially harvested oysters and 5 from recreationally harvested oysters).

Marine birds and mammals

- Rhinoceros auklet
  - » Rhinoceros auklet breeding populations in the Salish Sea had similar reproductive success rates and diet composition in 2014 as they had in recent previous years, 2005-2013, as well as in the 1970s.
- Wintering marine birds
  - » Seabird species richness was similar to previous surveys with the exception of October 2013 when more pelagic species were seen in Puget Sound.
- Harbor porpoise
  - » Aerial surveys indicate harbor porpoise have made a remarkable recovery and return to Puget Sound with very preliminary analyses resulting in an estimated density of 0.695/km^2 and abundance of 1,832 (CV=0.17).
  - » Acoustic and land-based observations of harbor porpoises in northern Puget Sound from 2011-2014 show seasonal changes in distribution with winter concentrations in Burrows Pass and summer concentrations in Admiralty Inlet. Burrows Pass has been identified as a stronghold for harbor porpoises.

Fish

- Herring
  - » Pacific herring, critical to the Puget Sound ecosystem, have declined in abundance since monitoring began in the 1970s, with several stocks exhibiting a sharply decreasing trend over the past 3-7 years.
- Sand lance
  - » Sand lance in the San Juan archipelago were in poorer condition and showed reduced total abundance in 2014 compared to previous years, and the populations suggest a cyclic pattern in terms of age group composition.

Large-scale climate variability and wind patterns

Large-scale patterns of climate variability, such as El Niño-Southern Oscillation (ENSO) the Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO), can strongly influence Puget Sound's marine waters. 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 than usual coastal ocean temperatures and drier than usual winters. The opposite is generally true for cool phases of ENSO and PDO. ENSO climate cycles usually persist 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.climate.washington.edu

ENSO was in the neutral state for nearly all of the 2014 calendar year, but began building toward a weak El Niño at the end of the year. For both indicators mentioned here (i.e., the ONI and MEI), 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 from January through August with the most negative value of -0.59 °C in January (Figure 1). ONI values became positive in September and strengthened through the end of the calendar year, with the highest value of 0.74 °C in November. The other commonly used indicator, the Multivariate ENSO Index (MEI), shows a tendency for positive values, approaching weak El Niño values in May through September. The index was positive for the entire calendar year except for January and February, which had an average index of -0.29. The highest value of 0.97 was recorded in May.

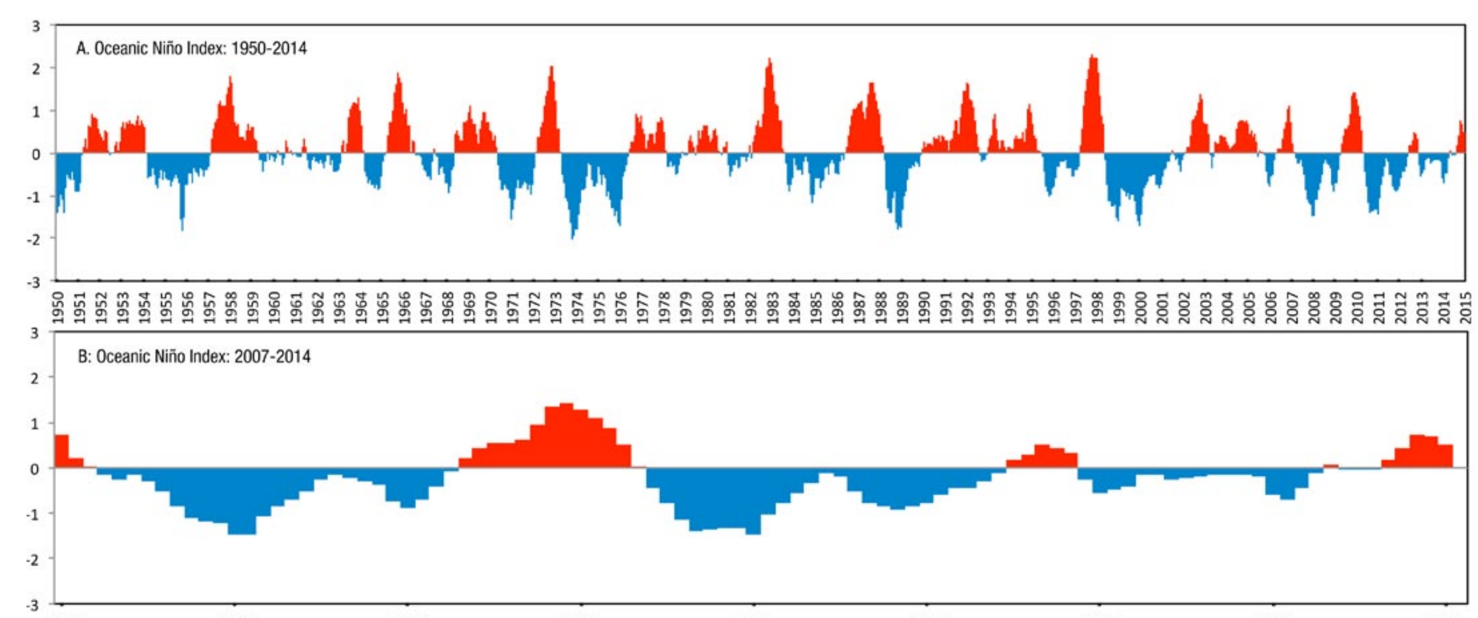


Figure 1. Oceanic Niño Index (ONI) values from (A) 1950-2014 and (B) 2007-2014.

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 was in the positive phase for the entire 2014 calendar year, which has been a shift from previous years (Figure 2); the PDO had been in the negative phase for the vast majority of the months since September 2007. The index shifted from negative (-0.41) in December 2013 to positive (0.30) in January 2014 and positive values continued to strengthen. The highest index value, of 2.51, for the calendar year was in December, which is an extremely high value for the time of year. The PDO values at the end of 2014 are comparable to the highest positive values in any month since 1950, as shown in Figure 2. The positive phase of the PDO is associated with southerly winds and warmer water along the Pacific coast of Washington State.

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), Julia Bos and Skip Albertson (Ecology); http://www.ecy.wa.gov/programs/eap/mar_wat/index.html

NPGO values were mostly positive from 1998-2012 with the exception of 2005-2007 when monthly values were negative (Figure 3). Since October 2013, however, NPGO values trended negatively and this trend continued in 2014. Declining NPGO values suggest that primary productivity is decreasing along Washington's coastline and within the California Current System.

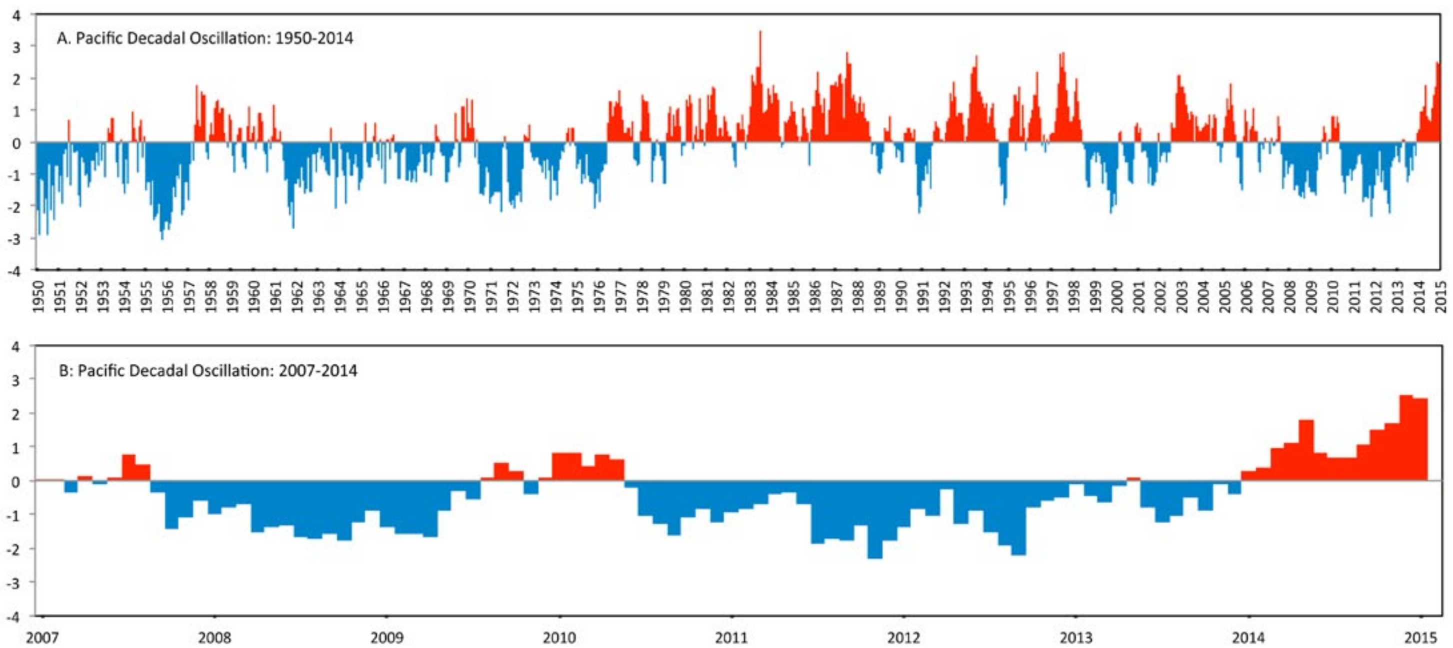


Figure 2. Monthly values of the Pacific Decadal Oscillation (PDO) Index from (A) 1950-2014 and (B) 2007-2014.

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

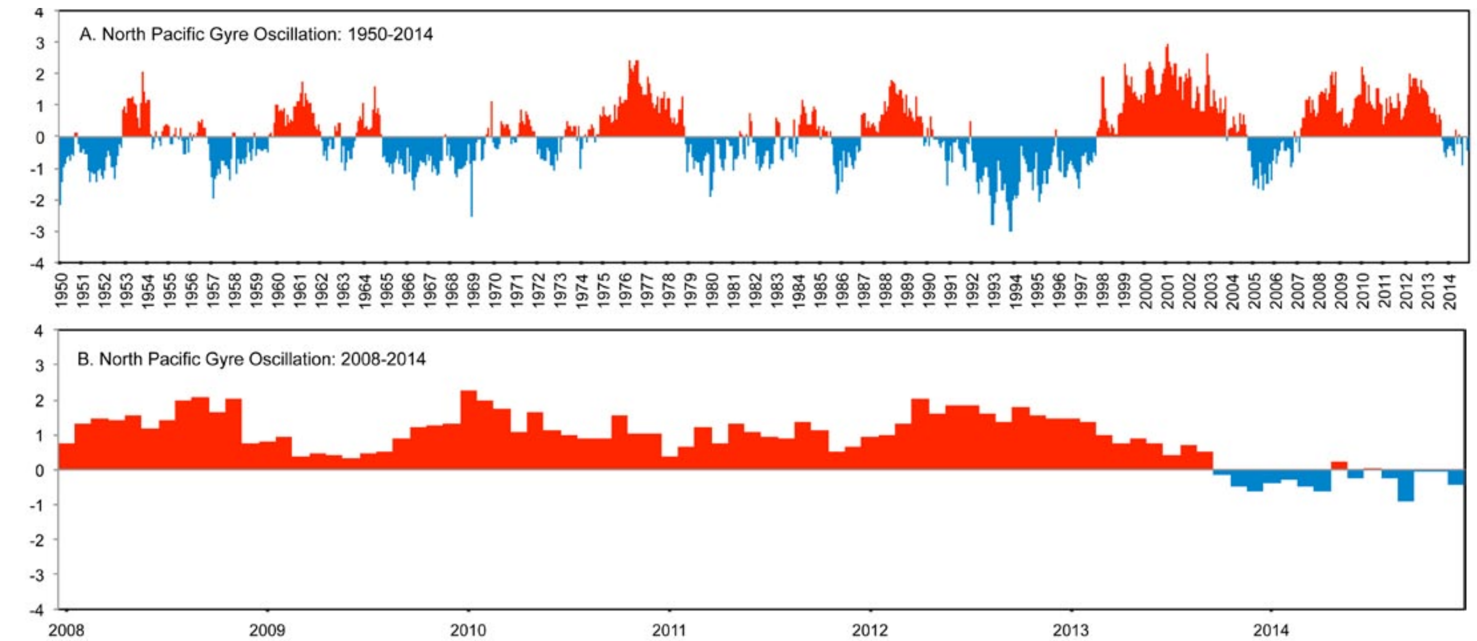


Figure 3. Monthly values of the North Pacific Gyre Oscillation index (NPGO) from (A) 1950-2014 and (B) 2008-2014.

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, Julia Bos, Mya Keyzers, Laura Hermanson, and Carol Maloy (Ecology); http://www.ecy.wa.gov/programs/eap/mar_wat/index.html

Upwelling favorable winds (i.e. winds from the north) on the outer Washington coast are an important driver for bringing deep ocean water into the Strait of Juan de Fuca and Puget Sound. This upwelled water is relatively cold and salty, with low oxygen, low pH, and high nutrient concentrations. The typical upwelling season for the Pacific Northwest is from April through September, while downwelling typically occurs during winter.

Monthly mean values of the upwelling index at 48ºN and 125ºW in 2014 were mostly within historic (1967-present) interquartile ranges except in September and October when coastal upwelling was significantly reduced (Figure 4). This coincided with large-scale warming of NE Pacific Ocean surface water in late summer ("the Blob") and resulted in a large influx of this warm surface water coming onshore and entering Puget Sound.

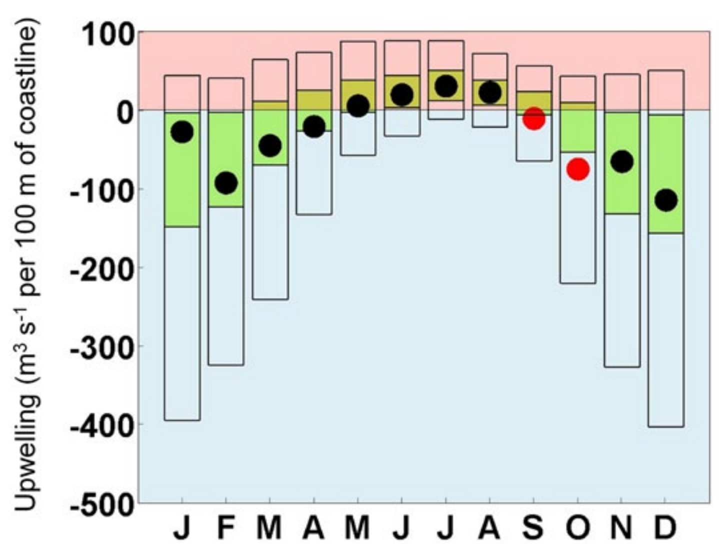


Figure 4. For communication purposes, monthly mean values of the PFEL coastal upwelling index for 2014 (red and black dots) are presented in historical statistical context based on index values at 48ºN, 125ºW from 1967-2013. The box plot extent represents 5th and 95th percentiles with the inter-quartile range between the 25th and 75th percentiles shaded green. Values falling outside 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

CALL-OUT BOX: Development and evolution of the “Blob” in the NE Pacific

Remarkably high sea surface temperatures developed in the northeast Pacific Ocean (NEP) during the winter of 2013-2014. This mass of warm water, which became known as the “Blob”, can be attributed to a highly unusual atmospheric circulation pattern that was also associated with seasonal weather anomalies in North America. Here we show the evolution of the sea surface temperature (SST) anomalies from the latter part of 2013 through 2014, and discuss implications for the marine ecosystem.

A sequence of 3-month SST anomalies, in terms of SD (standard deviation or standard departure) from normal, is shown in Figure 5. During summer months (July, August, September) of 2013, the NEP was considerably warmer than normal. The warming continued into fall (October, November, December) of 2013 in association with strong and positive sea level pressure (SLP) anomalies in the NEP. This meant fewer precipitation-bearing storms for the US west coast, especially California (Seager et al. 2014). Flow from the north downstream of the NEP SLP anomaly delivered abnormally low temperatures to the Great Lakes region (Hartmann 2015). Bond et al. (2015) showed that the warm NEP could be attributed largely to the weak winds over the NEP, leading to weak surface fluxes from the ocean to the atmosphere and anomalous warm horizontal advection. The result was extreme SST anomalies of greater than 4 SD above normal near 45 °N, 145 °W (Figure 5) during JFM 2014.

An abrupt change in the regional atmospheric circulation occurred in the second week of February 2014. The atmospheric forcing during the spring months (April, May, June) of 2014 caused some spreading out of the warm anomaly and a decrease in its maximum intensity. The summer (July, August, September) of 2014 brought a moderation of positive SST anomalies in the coastal zone from Vancouver Island to northern California, and an increase of positive anomalies in the Southern California Bight. These changes appear to be linked to upwelling (downwelling) favorable wind anomalies in the north (south). The last map shown for fall (October, November, December) of 2014 indicates the presence of strongly positive anomalies extending from off the coast of California into the southern Bering Sea, and negative anomalies in the southwestern portion of the domain. This is a signature of the positive phase of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997).

The anomalous atmospheric forcing of the NEP appears to be attributable in part to a teleconnection pattern driven by deep cumulus convection in the western tropical Pacific (Seager et al. 2014, Hartmann 2015). Full understanding of the cause(s) of the recent fluctuations in the climate of the NEP variability is lacking, but intrinsic variability certainly plays a part.

The abnormally warm waters have had impacts on the marine ecosystem of the NEP. In particular, low near-surface chlorophyll concentrations occurred in the NEP during the late winter and spring of 2014 (Whitney 2015), apparently because the vertical mixing of nutrients was suppressed due to the enhanced thermal stratification. At the time of this writing, the full repercussions of the recent warming are unknown. Previous expressions of the PDO have had major and wide-ranging impacts on the marine ecosystem; recent developments are receiving a great deal of attention from fishery-based oceanographers along the west coast. This kind of extreme event does represent a special opportunity to determine how the ocean’s biochemical properties respond to changes in the physical environment.

Authors: Nick Bond (nab3met@u.washington.edu) (UW), and Meghan Cronin (NOAA, PMEL)

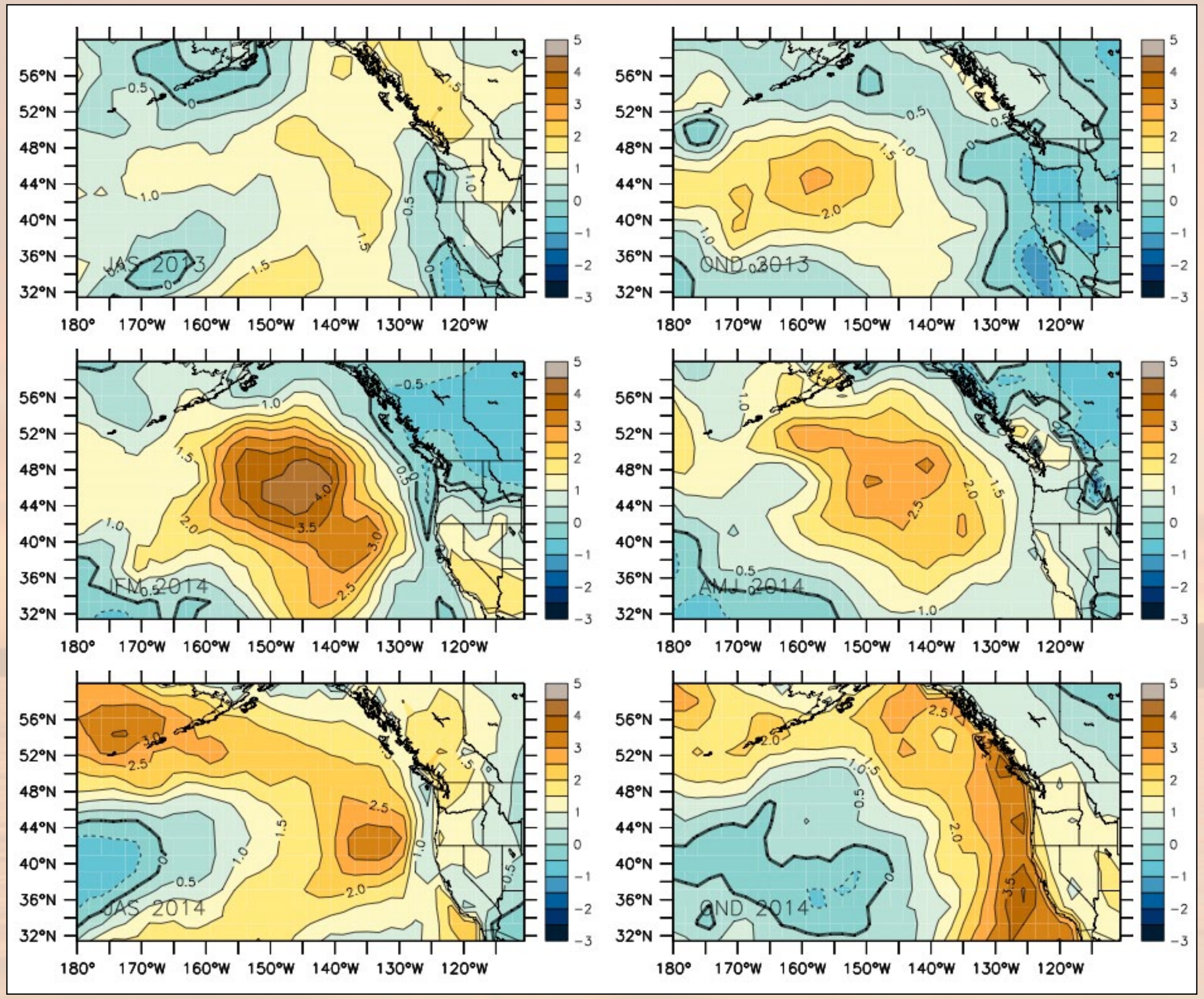
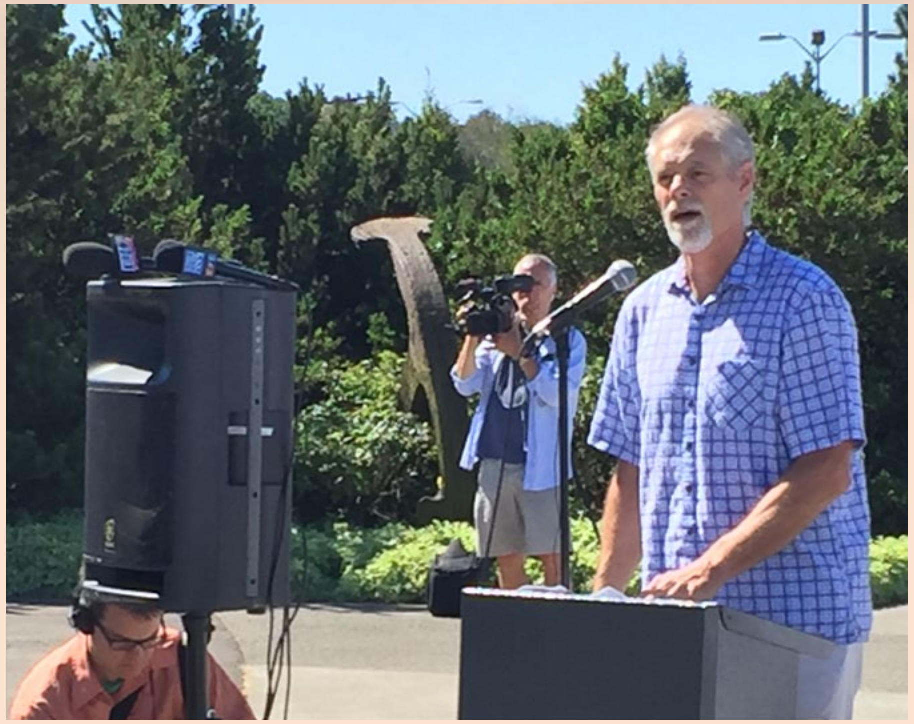
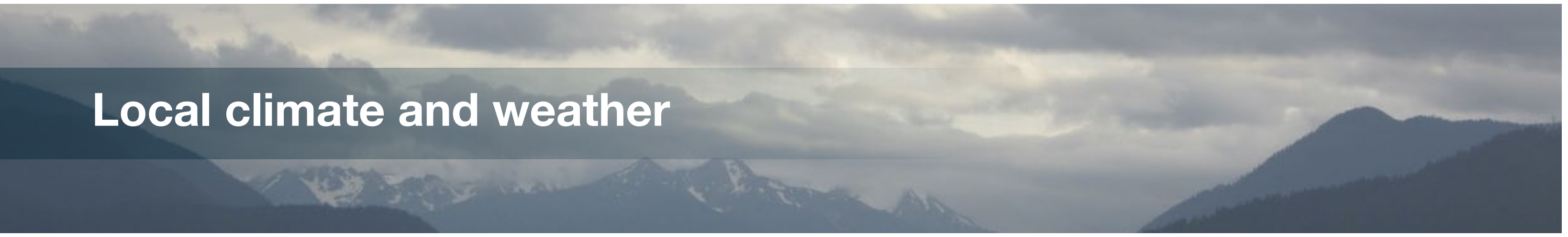


Figure 5. Surface temperature anomalies in units of standard deviations from the 1981-2010 climatological mean for JAS 2013 (upper left); OND 2013 (upper right); JFM 2014 (middle left); AMJ 2014 (middle right); JAS 2014 (lower left); and OND 2014 (lower right).



Nick Bond describing the “Blob” at a media event. Photo: Ruth Howell.



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 2014 calendar year, Puget Sound conditions were much warmer than normal with wetter than normal conditions compared to the 1981-2010 climate averages. Washington State is divided into 10 climate divisions based on similar average weather conditions within a region (http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php). This summary uses data from the Puget Sound Lowlands division that encompasses most of the Puget Sound.

The 2014 average temperature for this division was 0.9 °C (1.7 °F) warmer than the 1981-2010 normal and ranked as the 2nd warmest year since records began in 1895. It was also the warmest year for the region in the past decade, with 2004 as the next most-recent year that was nearly as warm. Total annual precipitation (134.8 cm) was higher than normal, at about 119% of normal. Both the temperature and the precipitation anomalies are spatially consistent throughout the Puget Sound region for the calendar year.

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 6 shows monthly temperature and precipitation anomalies for the Puget Sound relative to the 1981-2010 normals. Nearly every month was on the warmer side of normal except for February and November. The largest temperature anomaly occurred in October, with average temperatures ~2.6 °C warmer than normal. A ridge of high pressure dominated in January causing the drier than normal conditions, but a large shift in the weather pattern occurred in February, ushering in cooler temperatures and higher than normal precipitation that eased drought concerns on the state level by bringing much-needed snow to the mountains. The wetter pattern continued into March with a large precipitation anomaly (over 11 cm above normal), ranking as the wettest March on record. October was another wet month for the region, with storms often accompanied by warm temperatures.

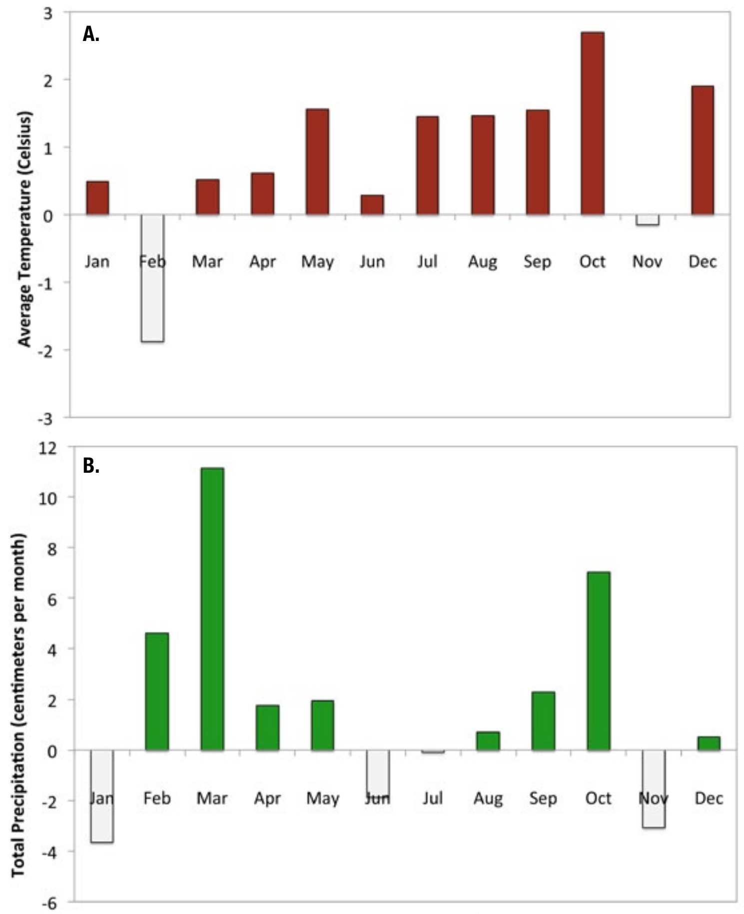
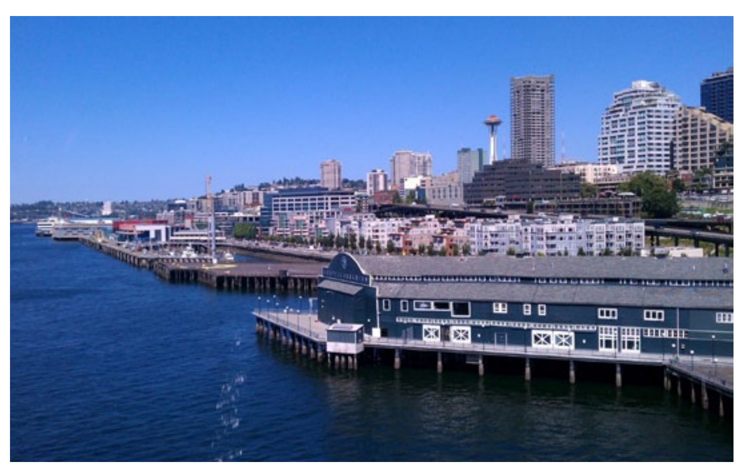


Figure 6. Monthly anomalies for (A) temperature (°C) and (B) precipitation (cm) for the Puget Sound Lowlands climate division in Washington State for the 2014 calendar year. Anomalies are relative to 1981-2010 climate normals.

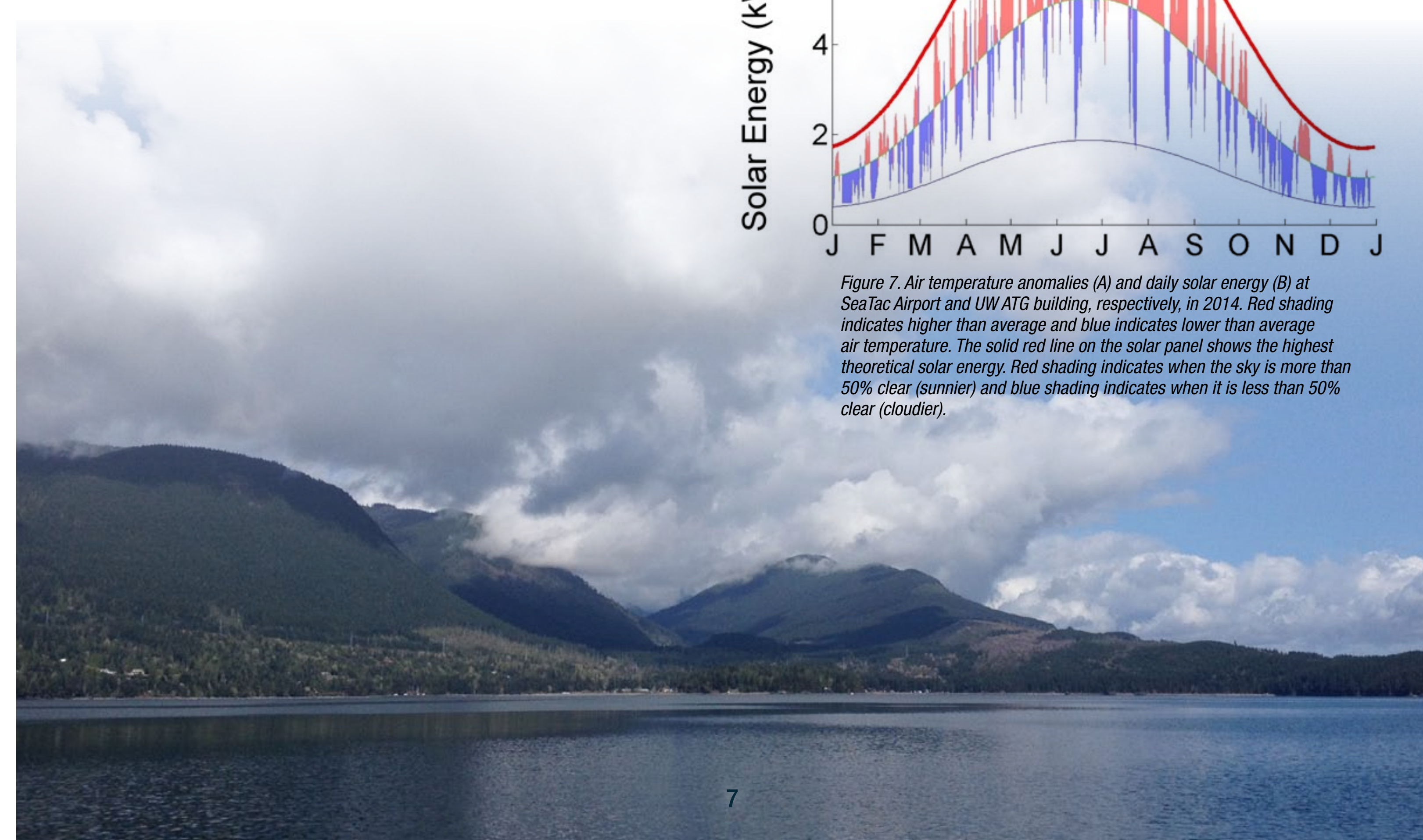


Seattle Waterfront. Photo: Stephanie Moore.

B. Local air temperature and solar radiation

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

Air temperatures at long-term monitoring sites in 2014 were often significantly warmer than normal, with the exception of February, when a strong low temperature event occurred. Figure 7A shows anomalies in daily air temperature at Sea-Tac Airport, relative to a 1971-2000 historical baseline period. Warmer air temperatures were accompanied by lower cloud cover and sunnier days. Anomalies of daily solar energy flux measured by a PAR sensor, located at the UW Atmospheric Sciences building (ATG) were generally above normal levels (Figure 7B, red shaded area). Solar fluxes reached seasonally high levels from May to September, and often approached the theoretical maximum, resulting in a sunnier summer overall in 2014 (Figure 7B, solid red line).



Clouds over Hood Canal. Photo: Rachel Wold

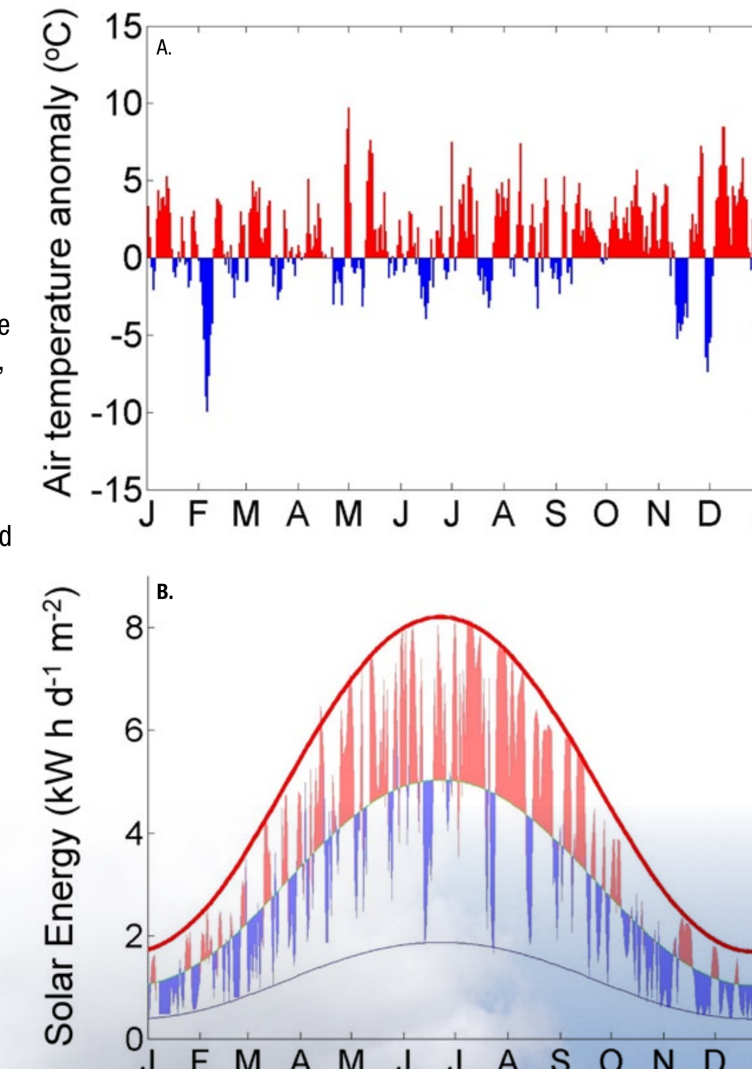
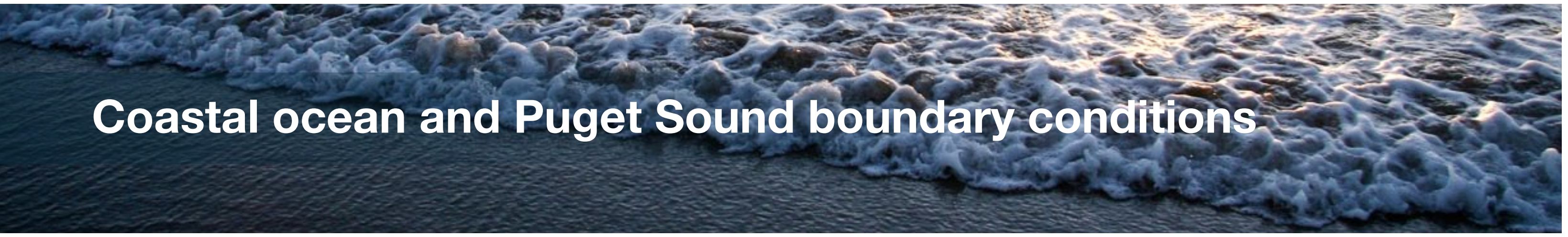


Figure 7. Air temperature anomalies (A) and daily solar energy (B) at SeaTac Airport and UW ATG building, respectively, in 2014. Red shading indicates higher than average and blue indicates lower than average air temperature. The solid red line on the solar panel shows the highest theoretical solar energy. Red shading indicates when the sky is more than 50% clear (sunnier) and blue shading indicates when it is less than 50% clear (cloudier).



Coastal ocean and Puget Sound boundary conditions

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

A. NW Washington Coast water properties

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

Observations spanning late June through late October 2014 from two NANOOS/UW moorings mid-shelf on the NW Washington Coast indicate that ocean conditions (T, S, DO, chlorophyll a) in this region were similar to previous observations (2011-2013) for most of this period with a two notable exceptions: summertime deep oxygen was lower and early fall temperature was dramatically higher (Figure 8A,C).

Deep DO was on average about 1 mg l^{-1} lower than previous observations dating back to 2011. DO dropped to 1 mg l^{-1} from roughly 3 mg l^{-1} in July before rising again in mid-September (Figure 8A). Unlike 2013, the 2014 record does not show any rapid, short-lived (<1 week) extreme drops in DO, which during August 2013 co-occurred with dead crabs at Ruby Beach.
A robust correlation between shelf wind direction, the currents, and changes in deep DO, was observed in 2014, as it was in 2013. Somewhat counter-intuitively upwelling favorable winds (from the northwest), produced local *increases* in deep DO, and downwelling-favorable winds (from the southeast) produced *decreases* (Figure 9A,B,D). This could be due to advection of a north-south DO gradient with lower DO to the south that moves northward to the mooring site. This is also consistent with past observations (Connolly et al., 2010). The relationship between winds/currents and DO reversed after extended downwelling and an episode of very strong, nearly full-depth northward currents (>0.3 m s^{-1}) lasting over a week in late September (Figure 9B,D). This extended, strong northward flow may have flushed low DO water past the mooring site. Thus, during this strong downwelling event, DO levels at the mooring site first dropped, then increased again, presumably as the low DO water advected away from the site. The observed current speed and duration relative to the expected low-DO patch size (Connolly et al. 2010) support this mechanism.

For much of the summer, temperatures were normal despite anomalously warmer surface water offshore in the NE Pacific. This highlights the complex interplay between ocean basin-scale anomalies ("the Blob") and local oceanographic processes (upwelling). Near-surface (3 m) ocean temperatures remained near average, staying below 14 ºC for much of the summer (Figure 8C). However, following a strong, extended downwelling-favorable wind event driving northward currents in late September (Figure 9A,B), upper ocean temperatures rapidly increased from ~9 ºC to more than 14 ºC (Figure 9C). After a 2-week period of weak and variable winds, another strong downwelling event brought "the Blob" further ashore, increasing this warm layer to >50 m depth and elevating temperatures above 15 ºC, more than 6 ºC above 2013 observations for this period at mid-depths (20-60 m) (Figure 9A,C).

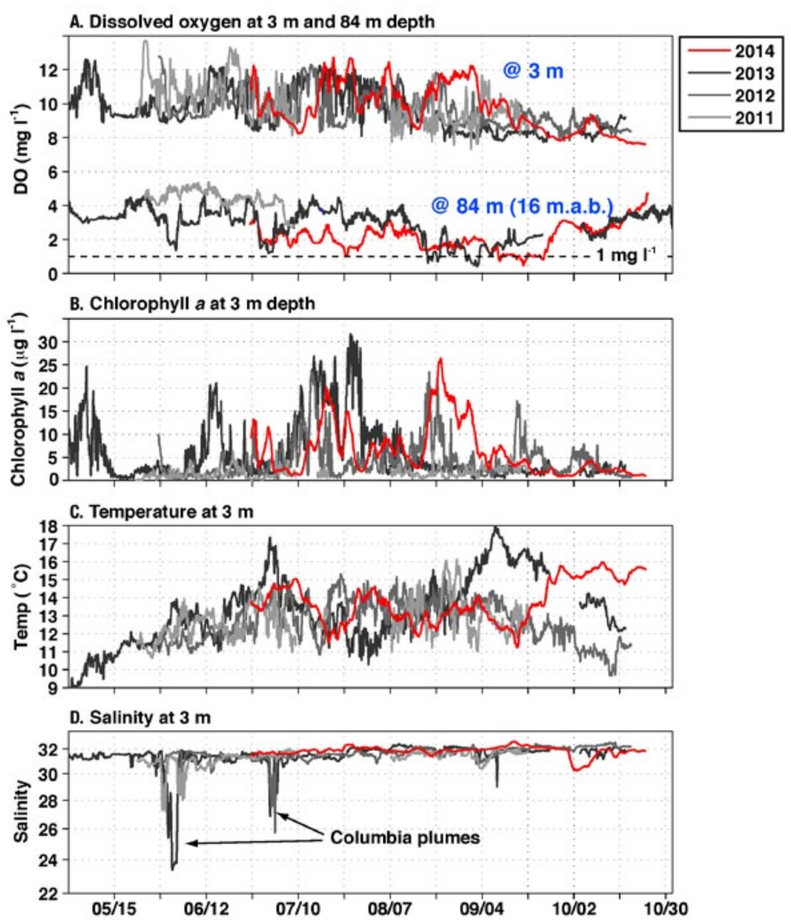


Figure 8. Interannual comparison of observations at the Chá Bă mooring, 13 nautical miles WNW of La Push at 47º58' N, 124 º57' W.

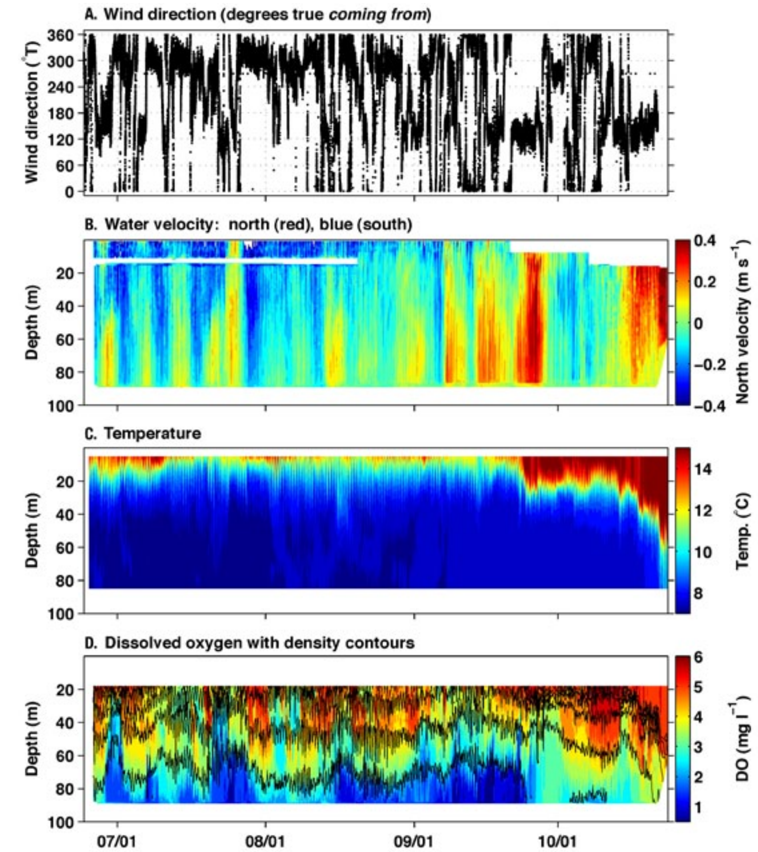


Figure 9. 2014 NEMO/ Chá Bă observations: (A) wind direction showing the direction the wind is blowing from, (B) north (red)/south (blue) current velocities, (C) temperature, (D) dissolved oxygen with density contours overplotted.

Deploying the Chá Bă mooring. Photo: Diego Sorrentino

B. Ocean and atmospheric CO_2

Source: Simone Alin (simone.r.alin@noaa.gov), Christopher Sabine, Richard Feely (NOAA, PMEL), Adrienne Sutton, Sylvia Musielewicz (UW, JISAO), Jan Newton, and John Mickett (UW, APL); http://www.pmel.noaa.gov/co2/story/La+Push; PMEL contribution number 4354

A carbon dioxide (CO_2) sensor has measured atmospheric and surface seawater xCO_2 (mole fraction of CO_2) at three-hour intervals on the surface Chá Bă mooring since 2010, mostly from spring through fall. The 2014 deployments were the first to span a full winter. Atmospheric xCO_2 ranged from 385 to 436 ppm (parts per million), with an average value of 400±7 ppm (±SD), which was 3 ppm higher than the global marine surface average for 2014 (Figure 10). Surface seawater xCO_2 varied between 66 and 654 ppm, with an average of 310±81 ppm. While surface seawater conditions were on average lower than atmospheric xCO_2 during the 2014 deployment, both the lowest and the highest seawater xCO_2 values seen to date at this site were recorded in 2014. The highest seawater xCO_2 was observed in late March and likely reflects a winter storm mixing deep water to the surface. Over the following week, xCO_2 fell to 180 ppm. Relative to previous deployments (2010–2013), the peak 2014 surface seawater xCO_2 value was somewhat higher than typical, but unlike previous years occurred in winter rather than summer. In contrast, the peak value during upwelling season (May-September) was lower than all previous years at 445 ppm (cf. Alin et al. 2014).

Since the original deployment, the most complete and continuous xCO_2 records were collected from mid-July through mid-October for all years. Average July–October surface seawater xCO_2 values have declined over time, while average atmospheric xCO_2 values have typically increased by 1–5 ppm per year (Table 1).

	2010	2011	2012	2013	2014
Atmosphere	388±6	387±7	392±8	394±7	395±7
Seawater	353±87	332±76	297±51	281±67	276±72

Table 1. Average (±SD) mid-July to mid-October xCO_2 values in surface seawater and the atmosphere at Chá Bă mooring from 2010 to 2014 (in parts per million, ppm).

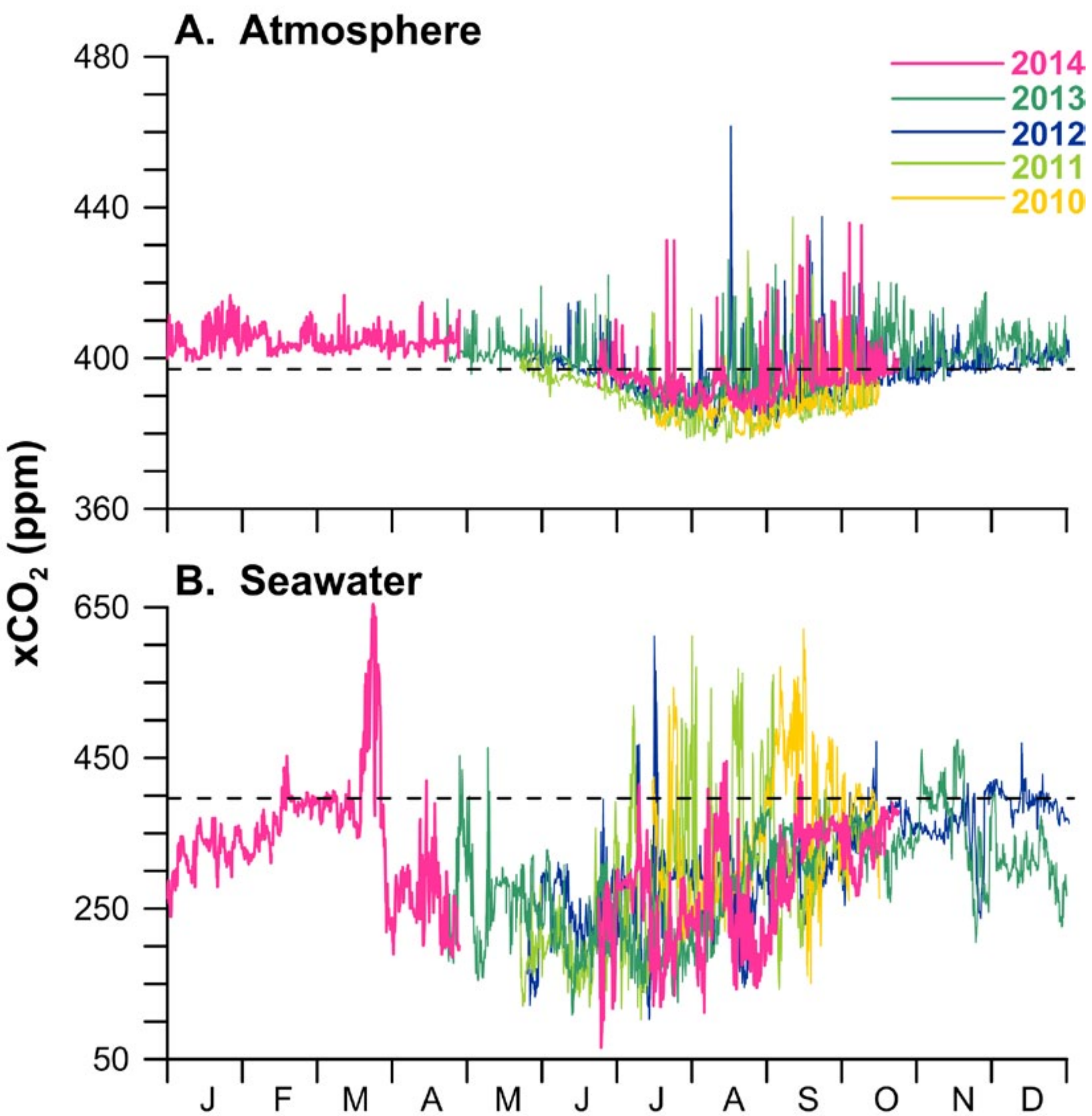
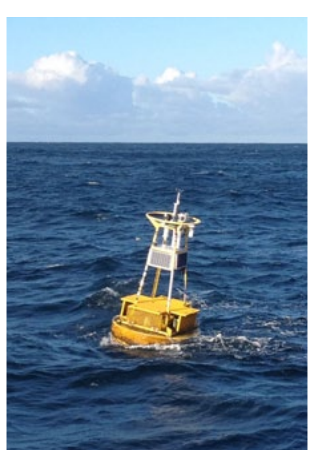


Figure 10. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater (A) and surface seawater at 0.5 m depth (B) from January through the full annual cycle at the surface Chá Bă mooring off La Push, WA. Data from all deployment years are included for comparison (color key in panel A applies to both panels, data available in: Sutton, et al. 2011). Approximate 2014 global average atmospheric xCO_2 of 397 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.



Chá Bă mooring off the coast of La Push. Photo: Rachel Wold

Deploying the Chá Bă mooring. Photo: Diego Sorrentino

River inputs

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

A. Fraser River

Source: Ken Dzinbal (ken.dzinbal@psp.wa.gov) (PS Partnership) and Environment Canada; https://wateroffice.ec.gc.ca/index_e.html

The Fraser River is the largest single source of freshwater to the Salish Sea, accounting for roughly two-thirds of all river inflow. The normal flow regime is characterized by a single, early summer discharge peak (Figure 11). Fraser River waters can strongly influence conditions in the Strait of Juan de Fuca including the water entering Puget Sound through Admiralty Inlet. In 2014, Fraser River discharge was normal from January through April, then rose above long-term mean levels in May, with an extreme peak late in the month. This peak occurred approximately two weeks earlier than average. Summer flows dropped to slightly below average until October, followed by a second pulse of above average flows in November and December.

B. 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. In contrast to the Fraser, 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 in mid-fall with the onset of winter storms and rain and extending through the winter. In 2014, flows exceeded long-term median levels in spring (March through May/June), dropped to average levels through summer, then rose above average discharge levels through fall and early winter. The Nisqually River varied somewhat from this overall pattern, with above average discharge measured through the summer followed by a small pulse of above average flows in late November and December.

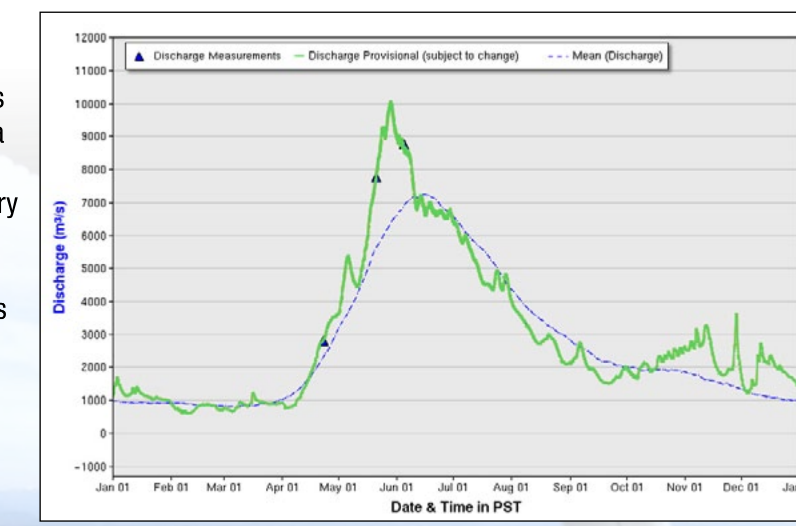


Figure 11. Fraser River daily discharge (m^3/s) at Hope, B.C. for 2013, compared to the mean value from long-term records (1912-2014). (Note 1 m^3/s = 35.3 cfs).

Sediment-laden water entering Port Susan, Stillaguamish River Estuary (Whidbey Basin). Photo: Christopher Krembs

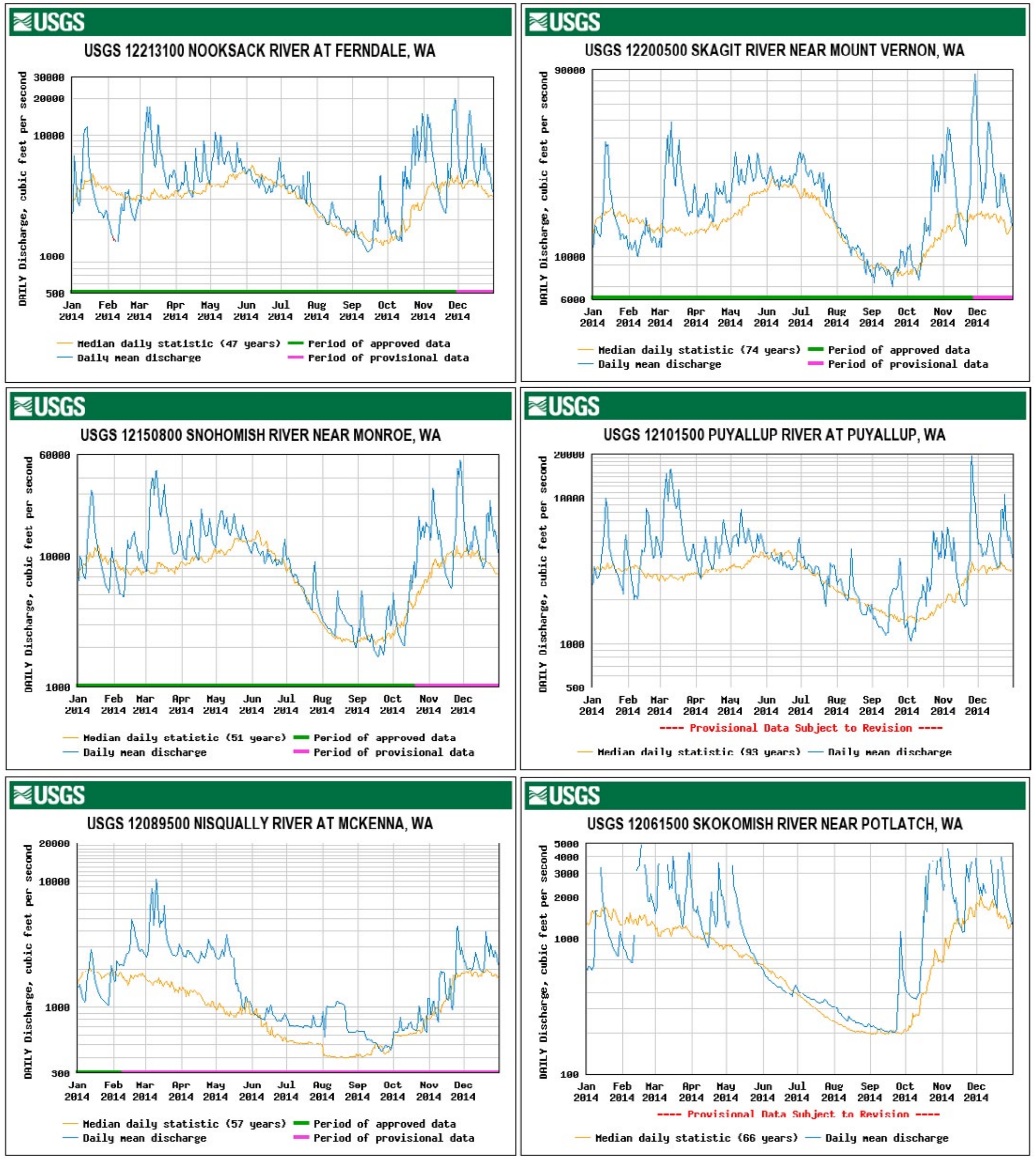


Figure 12. Daily discharge (cfs) at stations in Nooksack, Skagit, Snohomish, Puyallup, Nisqually, and Skokomish Rivers in 2014, compared to long-term median values. Note the period of record varies and is indicated separately for each station.

CALL-OUT BOX: Floating kelp

Floating kelp canopies on the water's surface make up the most visible constituent of the Salish Sea's kelp community. These beds are composed primarily of bull kelp (*Nereocystis luetkeana*) and giant kelp (*Macrocystis pyrifera*). They represent a fraction of the 23 kelp species found locally, which occur predominately in submerged beds. Kelp provides critical biogenic habitat and is an important source of primary production to both nearshore and deepwater ecosystems.

The Washington Dept. of Natural Resources has monitored floating kelp canopies using aerial photography since 1989 along the Strait of Juan de Fuca and Pacific Ocean coast, a region with substantial floating kelp. Imagery is collected annually during low tide in late summer, the season of maximum canopy extent. In 2014, canopy area declined 34% relative to 2013 (Figure 13). Decreases were greatest along the western Strait of Juan de Fuca, the sub-region with the majority of the canopy area. The decreases in 2014 continue a general decline in kelp canopy area since the maximum measured throughout the monitoring record in 2000. The 2014 estimate is similar to the lowest values measured in 1989 and 1997, and represents both a loss relative to 2000 and a return to previous levels.

In 2014, bull kelp canopy area decreased 47% range-wide, while giant kelp decreased 25%. Year-to-year changes are generally greater in bull kelp, an annual species, while the perennial giant kelp shows greater stability. Bull kelp is generally an inferior competitor, and often responds with large declines to stressors and rapid increases in favorable conditions.

Floating kelp responds strongly to climate. High water temperature and low nutrient concentrations associated with El Nino and warm phases of the PDO are linked to decreases in kelp (Graham et al., 2007). In 2014, positive (warm) ONI and PDO anomalies corresponded with kelp decreases. Also, extremely high ONI and PDO values in 1997 corresponded to a minimum in kelp extent. However, other patterns argue against a simple coupling between floating kelp abundance and climate indices. Greater declines near the Elwha River since 2011 are likely associated with the Elwha River dam removal, where massive sediment outflows have decreased light availability and increased sediment supply. Since dam removal began, kelp canopy area decreased by 67% near the Elwha River, in comparison to a decrease of 49% throughout the study area. While the spatial extent of impacts from the plume is not known, kelp canopy decreases along the Pacific coast in 2013 and 2014 suggest that other factors are also contributing to declines.

Grazers, such as sea urchins, affect kelp abundance. On the Pacific coast, sea otters have been important predators of sea urchins since their reintroduction in 1970 and along the Strait of Juan de Fuca, commercial harvest affects sea urchin numbers. Recently, sea star wasting syndrome may have increased grazer populations by reducing sea star predation.

The effects of ocean acidification on algal communities are largely unknown but will likely come through changes in the abundances of calcified herbivores such as urchins, limpets, and abalone (Harley et al. 2012).

Author: Helen Berry (helen.berry@dnr.wa.gov) and Pete Dowty (WA Dept. of Natural Resources); http://www.dnr.wa.gov/ResearchScience/Topics/AquaticHabitats/Pages/aqr_nrsh_kelp_monitoring.aspx

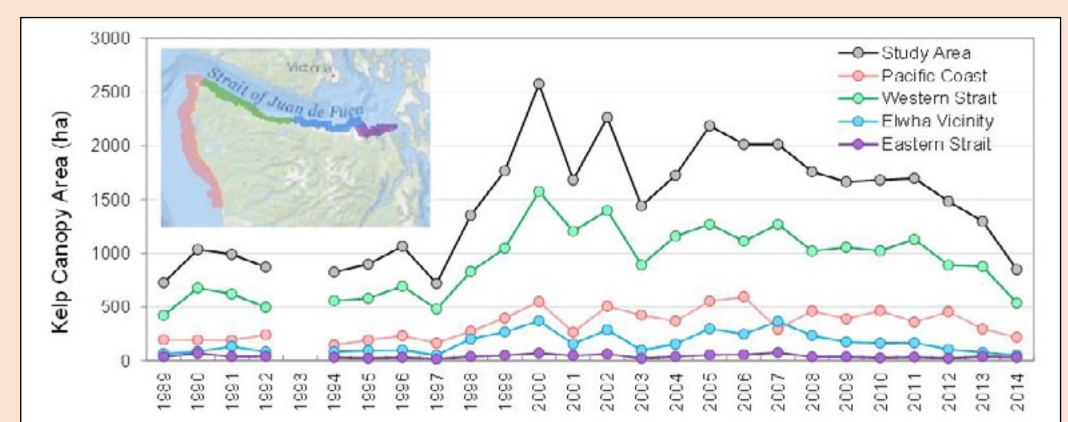


Figure 13. Floating kelp canopy area along the Strait of Juan de Fuca and Washington's Pacific Ocean coast (1989-2014).

Floating Kelp in Puget Sound. Background photo: Erin Spencer

Water quality

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.

After a storm in Admiralty Inlet. Photo: Rachel Wold

A. Puget Sound long-term stations

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, Skip Albertson, Mya Keyzers, Laura Hermanson and Carol Maloy (Ecology)

In early 2014, temperature and salinity conditions at Ecology's long-term station network were colder and saltier, a legacy from anomalous conditions that were first observed in October 2013. During early spring, temperatures warmed rapidly, first in the San Juan Islands, North Sound, and Whidbey Basin and extending to the rest of Puget Sound by summer. At the end of 2014, temperatures were anomalously warm with new 16 year site-specific maximum temperatures observed throughout all Puget Sound basins. Hood Canal, in contrast, remained colder. Salinity in the Puget Sound basins was lower than normal (i.e., fresher) in 2014 starting in the spring, while salinity in the San Juan Islands and Hood Canal remained high for most of 2014.

Anomalies calculated from historical site-specific baselines are used to display results across Ecology's station network (as heat maps). Thermal energy (heat) content in the 0-50 m layer of the water column started lower (colder) through early spring of 2014, then increased (turned warmer) in March (Figure 14A). Puget Sound-wide annual anomalies in 0-50 m temperature and salinity for all of Ecology's monitoring stations are calculated from averaged monthly site-specific anomalies. These summarized data show that there was more thermal energy in the system in 2014 compared to 2011-2013, reminiscent of 2007 and 2010 (Figure 14C). Salt content in the 0-50 m upper water column was higher in 2014 compared to 2010-2013, but not as high as the period 2005-2009 (Figure 14D).

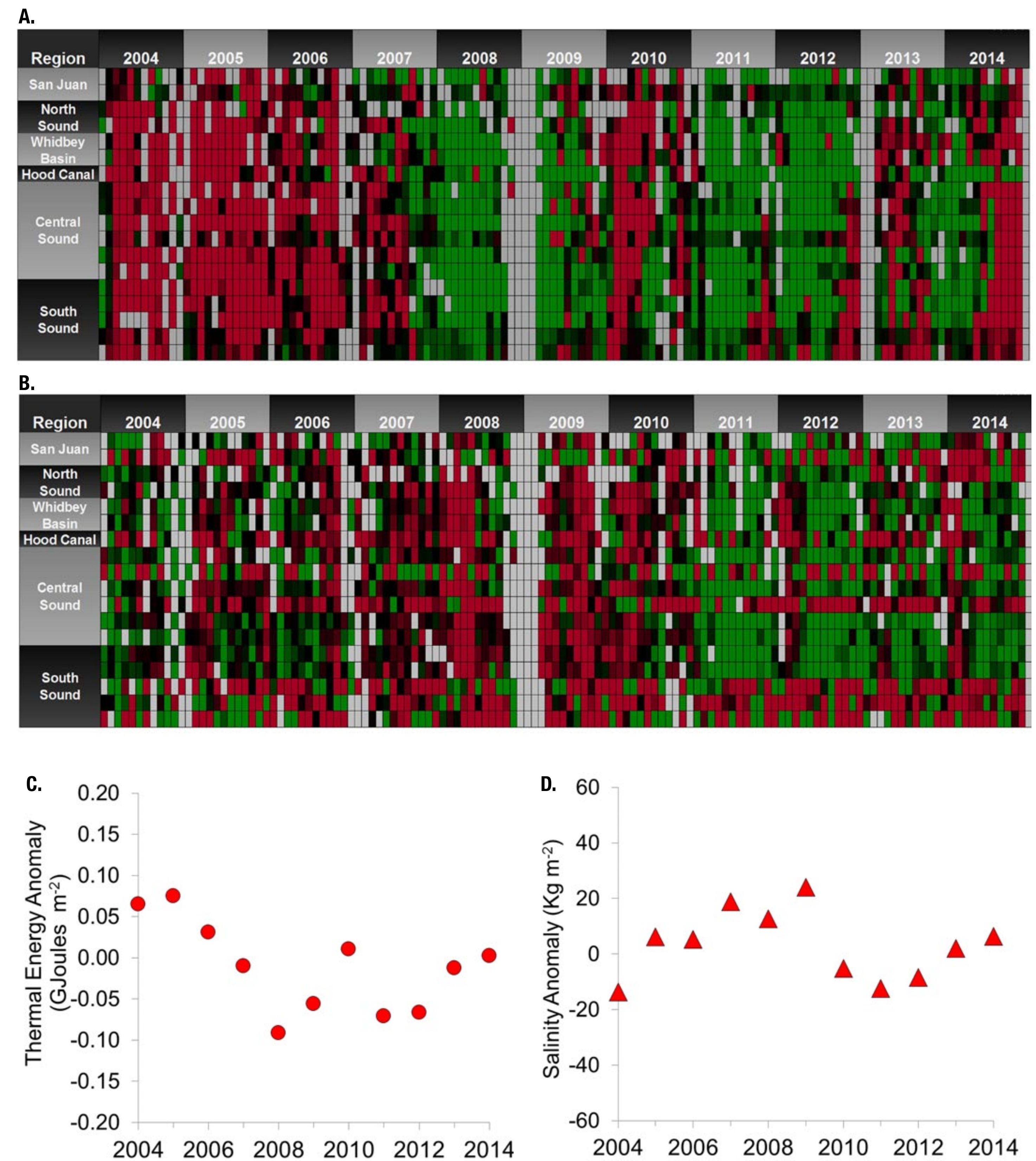


Figure 14. Heat maps of Puget Sound thermal energy (A) and salt content (B) anomalies for the 0-50 m upper water layer. Anomalies are calculated from site-specific monthly averages using a reference baseline established for 1999-2008. Green = lower, red = higher, black = expected, gray = no data. Puget Sound-wide annual anomalies for (C) temperature and (D) salinity in the 0-50 m water layer from 2002-2014.

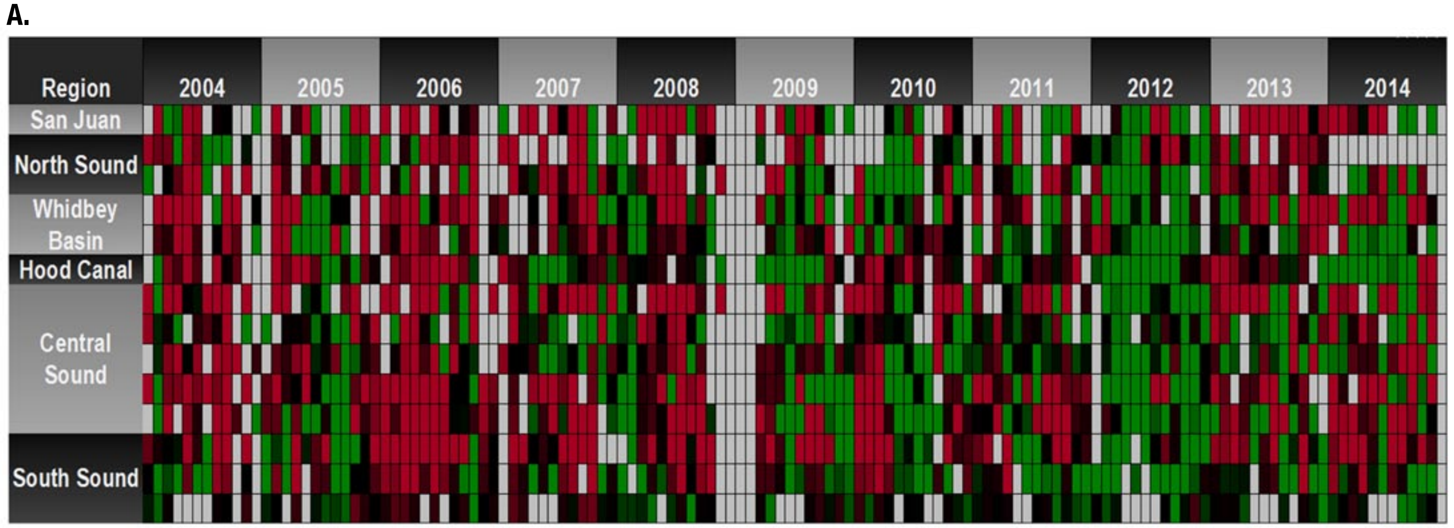
ii. Dissolved oxygen

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

In order to put dissolved oxygen (DO) measurements into a Puget Sound-wide context, Ecology reports a dissolved oxygen (DO) “deficit”. The DO deficit is the difference between the measured value and fully saturated value, calculated using site-specific pressure, temperature, and salinity results. When the DO deficit is high, measured DO in the water column is low (i.e., there is a large deficit between the amount of oxygen in the water and the amount that it could hold if it was fully saturated), and when the DO deficit is low, measured DO is closer to full saturation. A Puget Sound-wide annual anomaly in the DO deficit is calculated from averaged monthly site-specific anomalies.

A heat map of monthly anomalies of the DO deficit for water deeper than 20 meters is shown in Figure 15A for the period 2004-2014. The DO deficit was high during the middle of the decade, decreased from 2009-2012, and increased in 2013 and 2014. The DO deficit was very low in 2012 (green) indicating very high oxygen conditions below 20 m. In 2013, a shift occurred in the DO deficit with higher than normal values (red) observed, especially at northern sites. These low DO conditions continued into 2014. This shift may be related to a change in boundary conditions that was first observed in 2013 and is strongly evident at the San Juan and North Sound stations. Although lower oxygen conditions were more pronounced at Central and South Sound sites in 2014, this trend was not observed in Hood Canal or south Whidbey Basin. The anomaly in the DO deficit shows that while 2014 had a lower DO deficit than 2013 and 2006-2008, it remained elevated compared to 2009-2012 (Figure 15B).

A.



B.

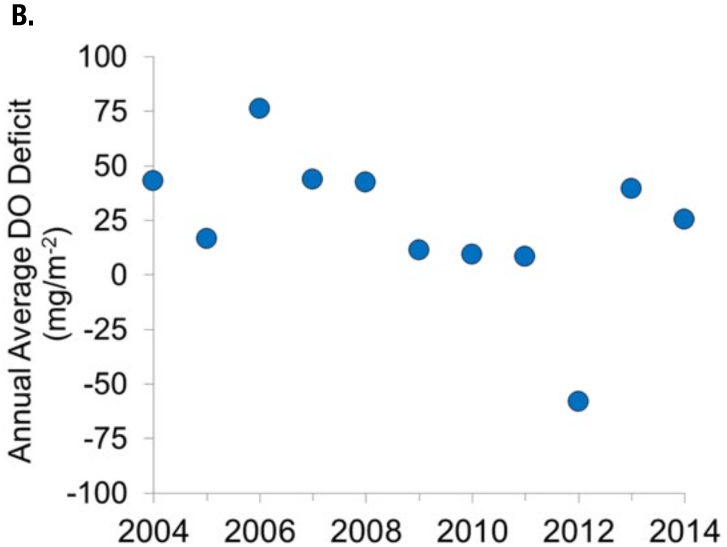


Figure 15. Puget Sound monthly DO deficit anomalies from 2004-2014 for water deeper than 20 m using a reference baseline established from 1999-2008. (A) Heat map of monthly anomalies calculated from site-specific monthly averages. Green=lower, red=higher, black=expected, gray=no data. (B) Puget Sound-wide annual anomaly of the DO deficit from 2004-2014.

iii. Nutrients and chlorophyll

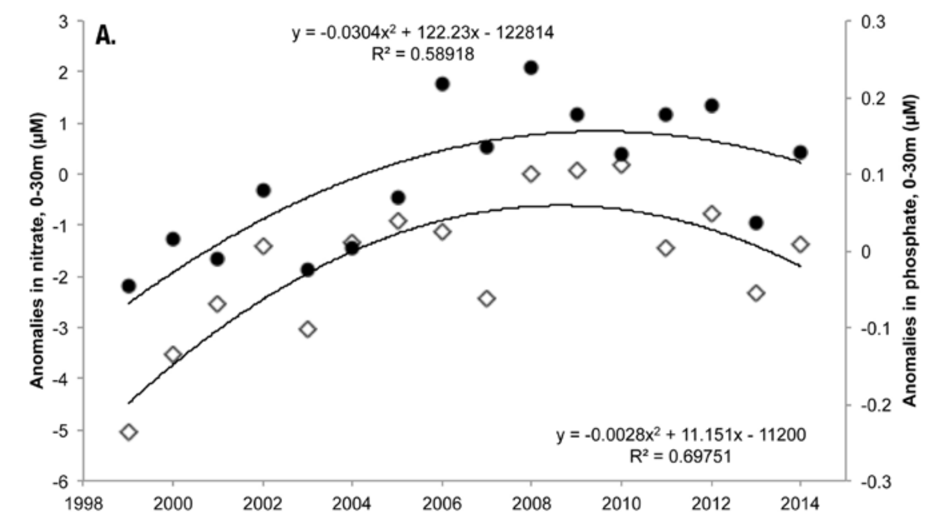
Source: Christopher Krembs (ckre461@ecy.wa.gov), Carol Maloy, Julia Bos, Mya Keyzers, and Laura Hermanson (Ecology)

Starting in 1999 and continuing for more than a decade, monthly anomalies in the macro-nutrients nitrate and phosphate from Ecology’s Puget Sound monitoring stations increased (Figure 16A). In 2013 and 2014, these anomalies started to decline. Increasing macronutrients (3 μM nitrate and 0.3 μM phosphate per decade) occurring in conjunction with otherwise stable micro-nutrients, such as silicate, may indicate that the overall nutrient balance is changing and food web shifts are occurring in Puget Sound. This is also suggested by the decline in chlorophyll *a* (Figure 16B) and a robust but negative correlation of nitrate and chlorophyll a over 15 years (Figure 16C). In 2014, nitrate and phosphate anomalies were close to baseline conditions. Yet a consistent negative correlation between nitrate and chlorophyll *a* (Figure 16C) persisted under these fluctuating conditions illustrating a strong dependency between the two variables.

We suggest that food web shifts, rather than nutrient additions, are driving the observed changes. The silicate-to-nitrogen ratio (Si:DIN), a potential indicator of human nitrogen inputs (Figure 16B) declined by 10 units per decade until 2013, primarily driven by changes in nitrate. This trend was reversed for 2013 and 2014, due to the lower nitrate concentrations (and higher phytoplankton biomass).

A 14-year time-averaged seasonal cycle of chlorophyll *a* and ammonium, proxies for phytoplankton biomass and dissolved organic nitrogen remineralization, respectively, reveal a unique pattern across Ecology’s entire Puget Sound station network with the spring bloom starting early in March, remaining strong into May followed by increased ammonium in June (Figure 16D). The pattern in 2014 was very different, with a broader spring bloom and a smaller late summer bloom without the typical decline in June.

Aerial observations showed that the *Noctiluca* bloom in June was smaller compared to previous years. The increase in ammonium was also remarkably different, with an uncharacteristic peak in August through October that coincided with warmer water temperatures. The 15-year trend of a weakening late-summer bloom continued, (Figure 16E) while the spring bloom strength remained unchanged (data not shown).



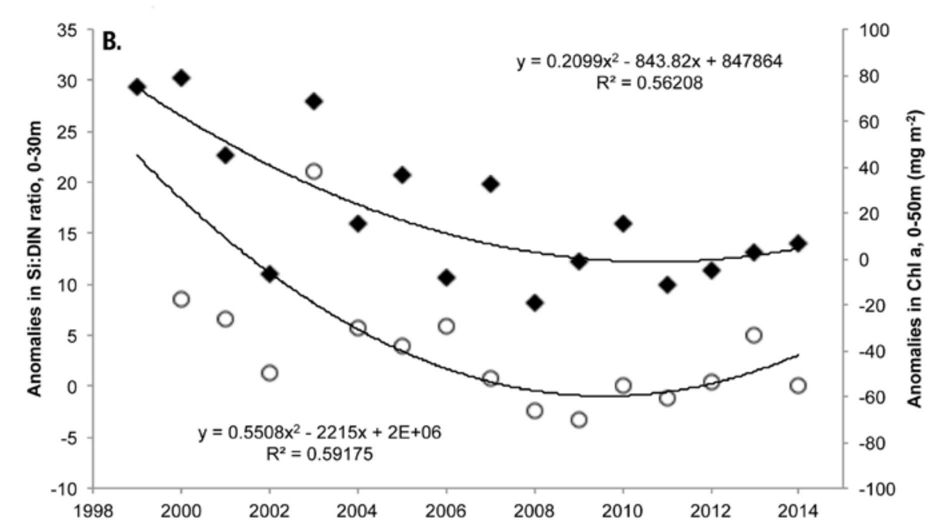
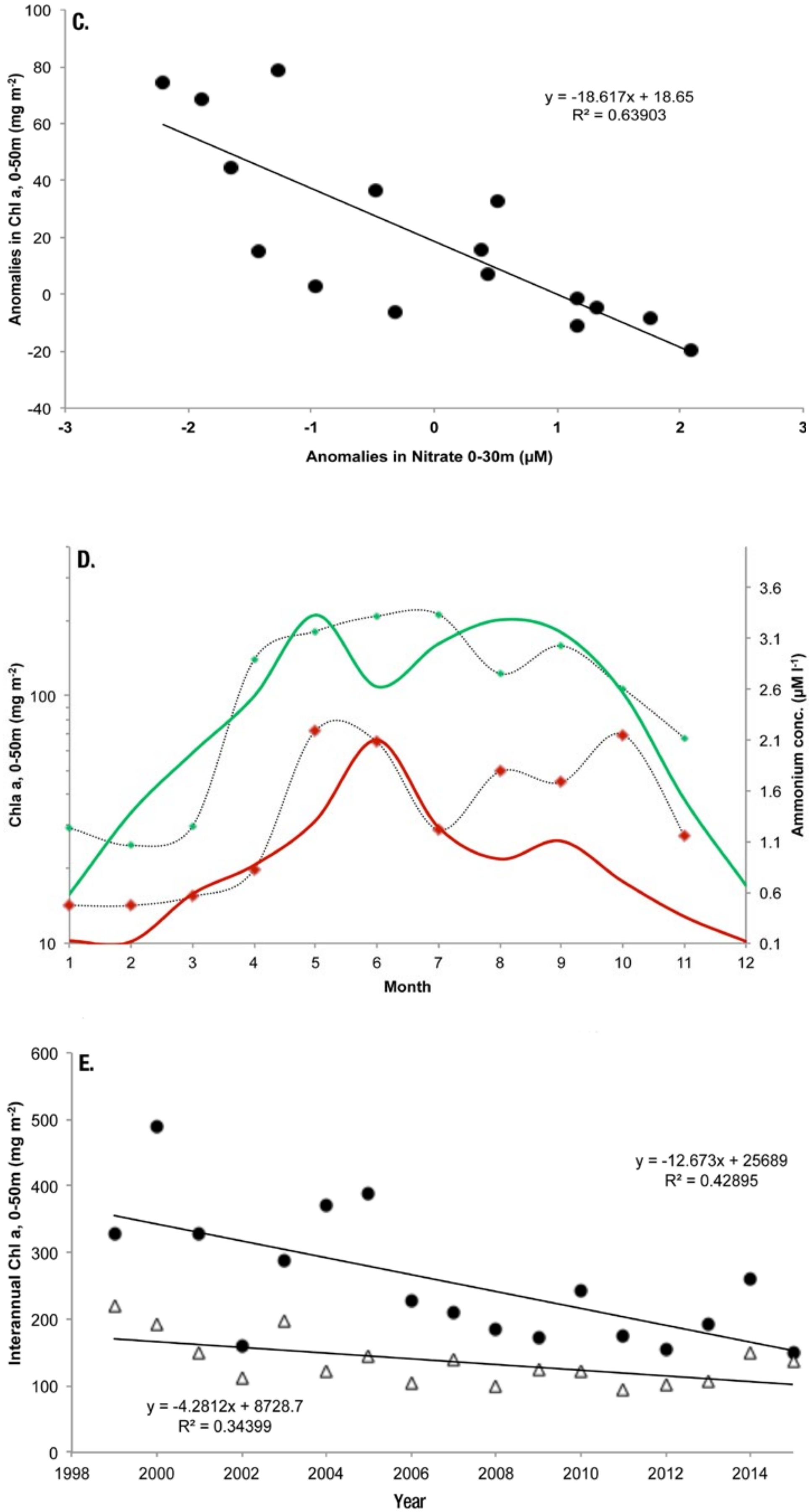


Figure 16. Puget Sound-wide annual anomalies of (A) nitrate (black circles) and phosphate (open diamond), (B) the ratio of Si:DIN (open circles) and chlorophyll a (black diamonds) over the period from 1999-2014.

Figure 16. (C) Correlation of Puget Sound-wide long-term anomalies for nitrate and Chl a. (D) Puget Sound-wide seasonality and temporal coupling between Chl a (green diamonds) and ammonium (red diamonds) for 2014 , and long term monthly averages based on 1999-2013 values (green line, Chl a; red line, ammonium). (E) Long-term trends in Puget Sound wide average phytoplankton biomass, with annual averages (triangles) and averages specific to the July-December period (circles), highlighting a pronounced decline during the late summer and fall period.

Deployed CTD in Admiralty Inlet. Photo: Rachel Wold



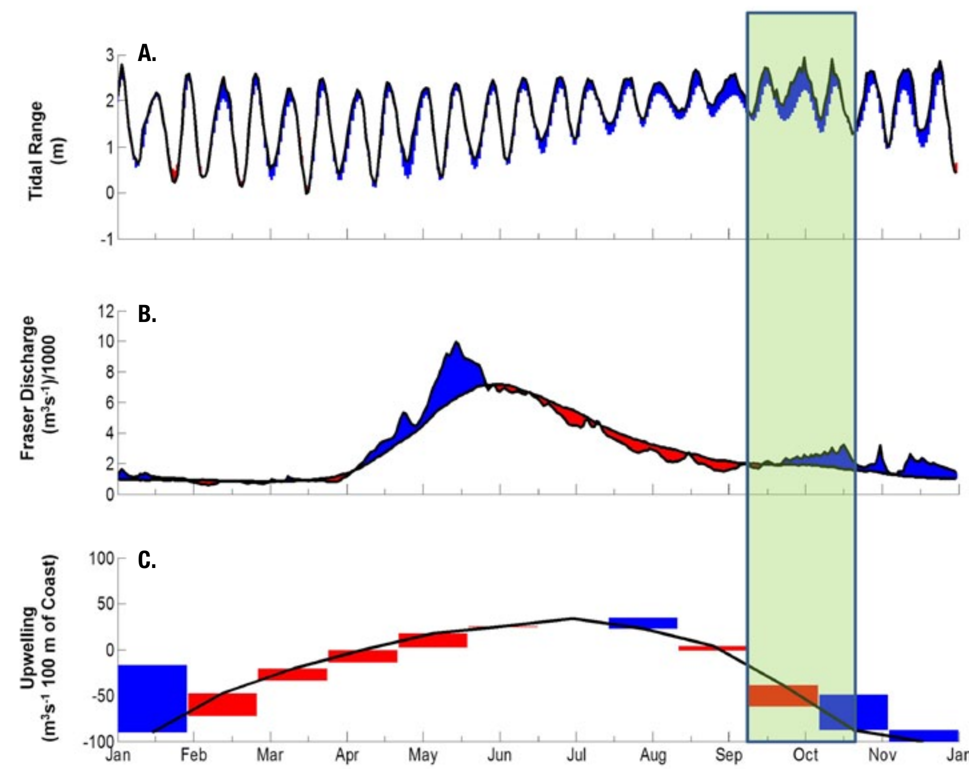
iv. Water mass characterization

Source: Skip Albertson (salb461@ecy.wa.gov), Christopher Krembs, Julia Bos, Mya Keyzers, Laura Hermanson and Carol Maloy (Ecology), and R. Walt Deppe (U. Hawaii at Manoa)

Water mass characteristics are important for understanding water transport and circulation in Puget Sound. Depending on their densities (determined by temperature and salinity), water masses may mix or stratify (i.e., form layers), setting up dynamics that influence flushing, water quality, and the marine food web.

Basin	T (ºC)	S (psu)	Density as sigma-t (kg/m³)	DO (mg/l)
Central	11.0-12.0	30.0-30.3	22.8-23.1	7.3 +/- 0.0
Whidbey	9.5-11.5	29.4-29.8	22.5-22.8	5.3 +/- 0.5
Hood Canal	8.2-9.3	29.3-30.4	22.8-23.6	5.6 +/- 1.6
Admiralty Reach	10.0-1.0	30.0-30.7	22.7-23.5	7.3 +/- 0.3
South Puget Sound	12.0-13.1	29.0-29.7	21.8-22.3	7.1 +/- 0.4

Table 2. Density and oxygen characteristics of the most common water masses observed during 2014 in each of the Puget Sound basins, ordered by basin volume.



Water masses in Puget Sound were generally warmer and saltier during 2014 (Table 2) compared to historic ranges from 1999-2013 (data not shown). The exception was Hood Canal, where the dominant water mass shown was colder throughout most of the year and slightly denser compared with water in adjoining Admiralty Reach.

Intrusions of dense water into Puget Sound require several conditions to align; upwelling along the coast, strong estuarine circulation (driven by rivers), and exchange across the shallow sill at Admiralty Reach (Deppe 2013). Water exchange across the sill is linked to the character of the tides, occurring more readily during conditions of minimal tidal mixing around the equinoxes (Geyer and Cannon 1982). In 2014, water exchange driven by the Fraser River flow was lower than normal from June until the beginning of September. The shaded region shown in Figure 17 indicates when conditions aligned that were favorable for intrusions, blue coloration indicates intrusion-favorable anomalies for all factors. Because of drought-related reductions to the Fraser River flow, intrusions were more favorable after offshore winds shifted to downwelling conditions in late September, which brought the warm ocean water "Blob" (page 4) on to the shelf and into Puget Sound.

Figure 17. (A) Tidal range at Port Tonwsend, (B) Fraser River flow at Hope Station 08MF005 and (C) upwelling winds along the WA coast at 48 °N. Black lines indicate average conditions, red fill indicates lower than expected conditions, and blue fill indicates greater than expected conditions for 2014. The superimposed green shaded area indicates when intrusions of upwelled water were most likely to occur during 2014 according to the Intrusion Index (Deppe et al. 2013).

B. Puget Sound profiling buoys

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

i. Temperature and dissolved oxygen

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

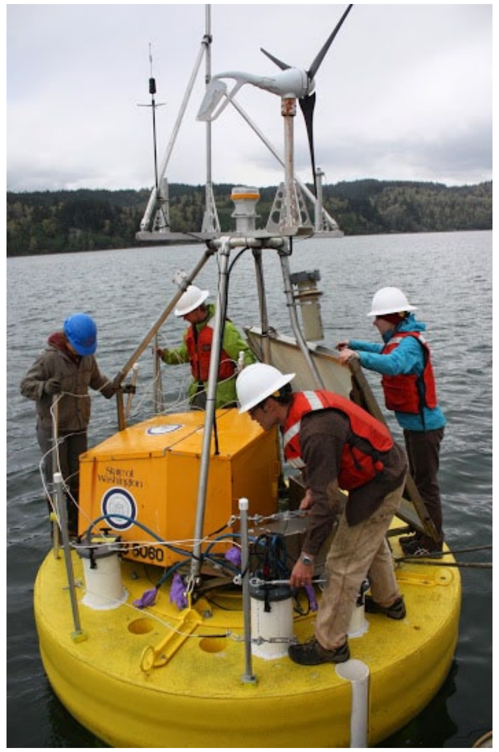
Observations from the UW ORCA mooring program, with high-frequency (> daily) full-depth profiles over the full water column at six locations show that Puget Sound waters experienced large temperature and dissolved oxygen anomalies during 2014, though the character of these anomalies was strikingly different between Hood Canal and other Puget Sound basins.

Temperature anomalies at both Twanoh in southern Hood Canal and Carr Inlet in South Sound reveal a large contrast between the two sites, with colder than normal deep waters at Twanoh that persist for the entire year, yet warmer than normal waters at Carr all year, with the exception of February (Figure 18A,B). The other ORCA sites outside of Hood Canal also had warmer than normal waters for much of the year. As water from the warm "blob" (see page 4) did not appear on the coast until fall of 2014, the local warming in Puget Sound may have been largely due to local weather. Fairly strong (~2ºC) warm anomalies were observed in the surface waters of Twanoh but were pulsed, short-lived and were typically constrained to above 15 m.

The most notable observations in 2014, however, were the uncharacteristically cold, high-dissolved oxygen anomalies seen in the deep basin water of Hood Canal, which were present at the beginning of the year and intensified through the winter and early spring. Values of both temperature and dissolved oxygen were nearly two standard deviations below and above, respectively, the 10-year observational means (Figure 18C,D) and close to the coldest and most oxygenated water observed to date.

The pattern revealed by the high temporal resolution data indicate these conditions formed in response to strong forcing from local weather. October 2013 through February 2014 was a period of extreme atmospheric forcing in Washington, with a persistent high pressure ridge, well below normal precipitation levels (>13-inch deficit) (Figure 19A) and several extended (>1 week) periods of very cold air temperatures (<0ºC) (Figure 19B). During December 2013, ORCA Dabob observations show rapid full-water column cooling and oxygenation at the same time the water column de-stratified (i.e. seawater density was the same top to bottom; Figure 19C,D). The coincidence of these observations with the dry, cold weather conditions and the calculated heat-loss estimates from local meteorological observations strongly suggests a linked mechanism. A large increase in observed surface salinity likely due to low precipitation along with rapid cooling of the sea surface due to cold, dry and windy conditions, together increased surface water density to the point that it sank rapidly, displacing and mixing with the resident deep water within Hood Canal, resulting in very cold, highly-oxygenated waters that penetrated to all depths. This deep cold anomaly persisted year-round.

In October the deep oxygen anomaly became negative at Hoodsport. Likely this is attributable to the dynamics of the annually-occurring fall oceanic intrusion. 2014 data show this started weakly and the main intrusion pulse occurred a month later than usual (Figure 18D). This change in the strength and timing of the intrusion likely resulted in less fall flushing in Lower Hood Canal, leading to lower than typical dissolved oxygen levels at Twanoh in the late fall (Figure 20) which have continued into early 2015. The weak, late intrusion also resulted in persistence of the deep water cold anomaly, as it reduced the replacement of the resident waters by the warmer but saltier oceanic intrusion waters.



The ORCA team adding the final touches to the newly-refurbished Dabob ORCA mooring in April 2014. Photo: Rachel Wold

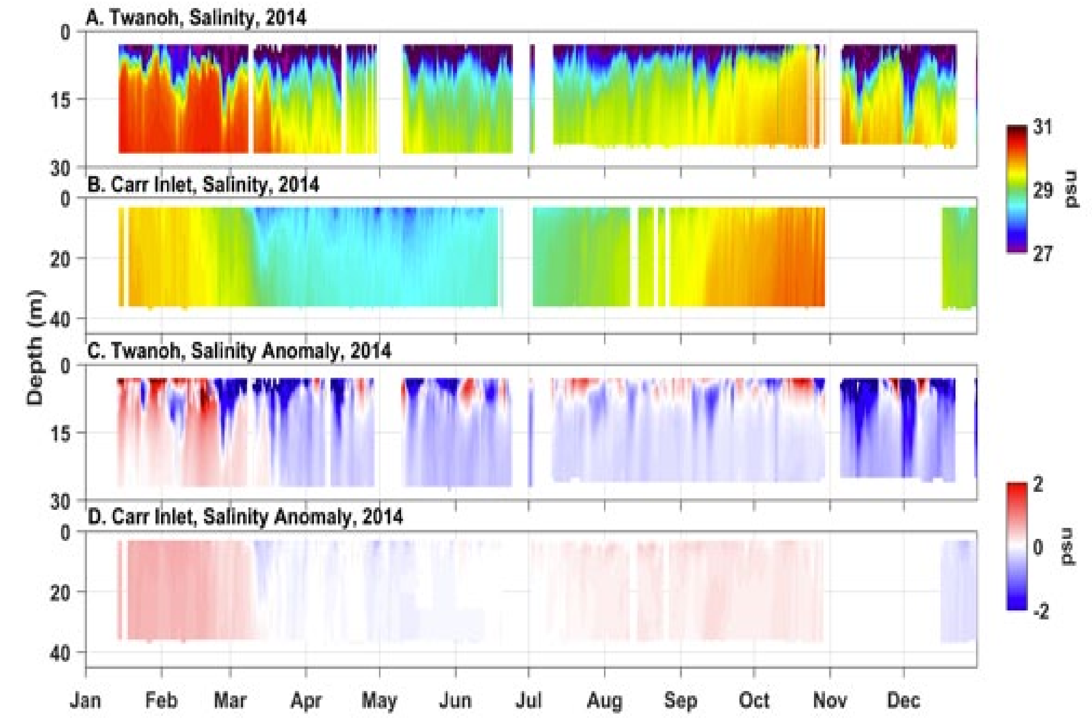


Figure 18. Top two panels: temperature anomalies (2014 - climatology) for Twanoh and Carr Inlet. Data are colored with a white threshold at 0, with red indicating warmer and blue indicating colder than historical average conditions. Bottom two panels: 2014 (red line) and climatology (dark blue line) for Hoodsport temperature and oxygen at 80 meters; darker shaded area is +/- 1 std dev from the climatology; lighter shaded area is +/- 2 std dev from the climatology.

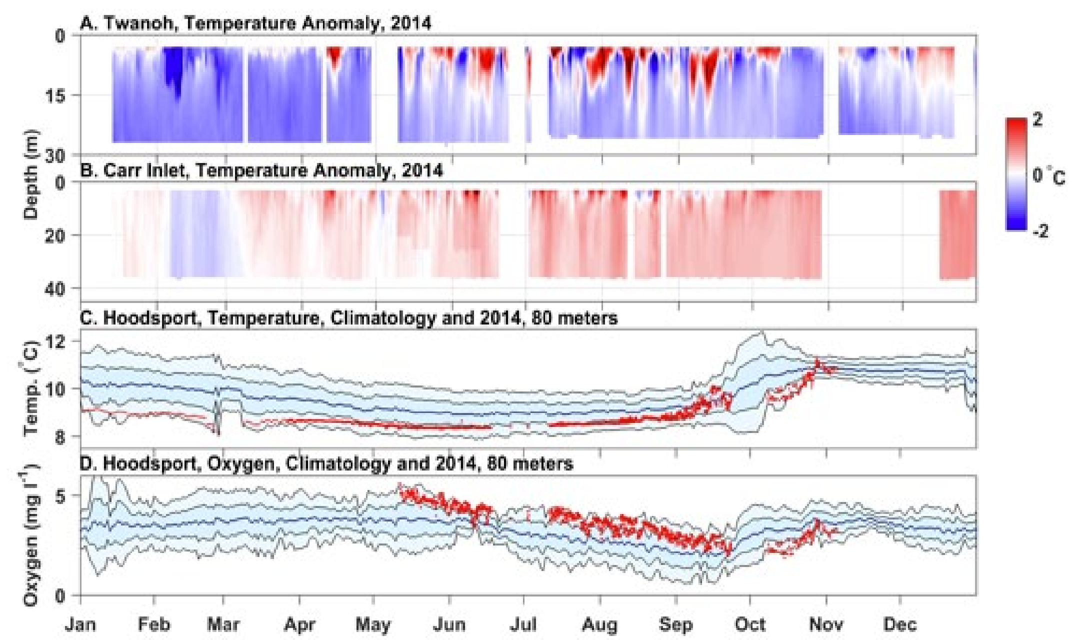


Figure 19. (A) cumulative precipitation starting October 1, 2013 at UW Atmospheric Sciences (black) compared to SEATAC climatology (red) and (B) air temperature at Atmospheric Sciences (black) compared to climatological highs and lows. Lower two panels: (C) Dabob ORCA buoy depth-time colored contours of water temperature with line contours of dissolved oxygen concentration over-plotted, and d) colored and line contours of density from the Dabob mooring.

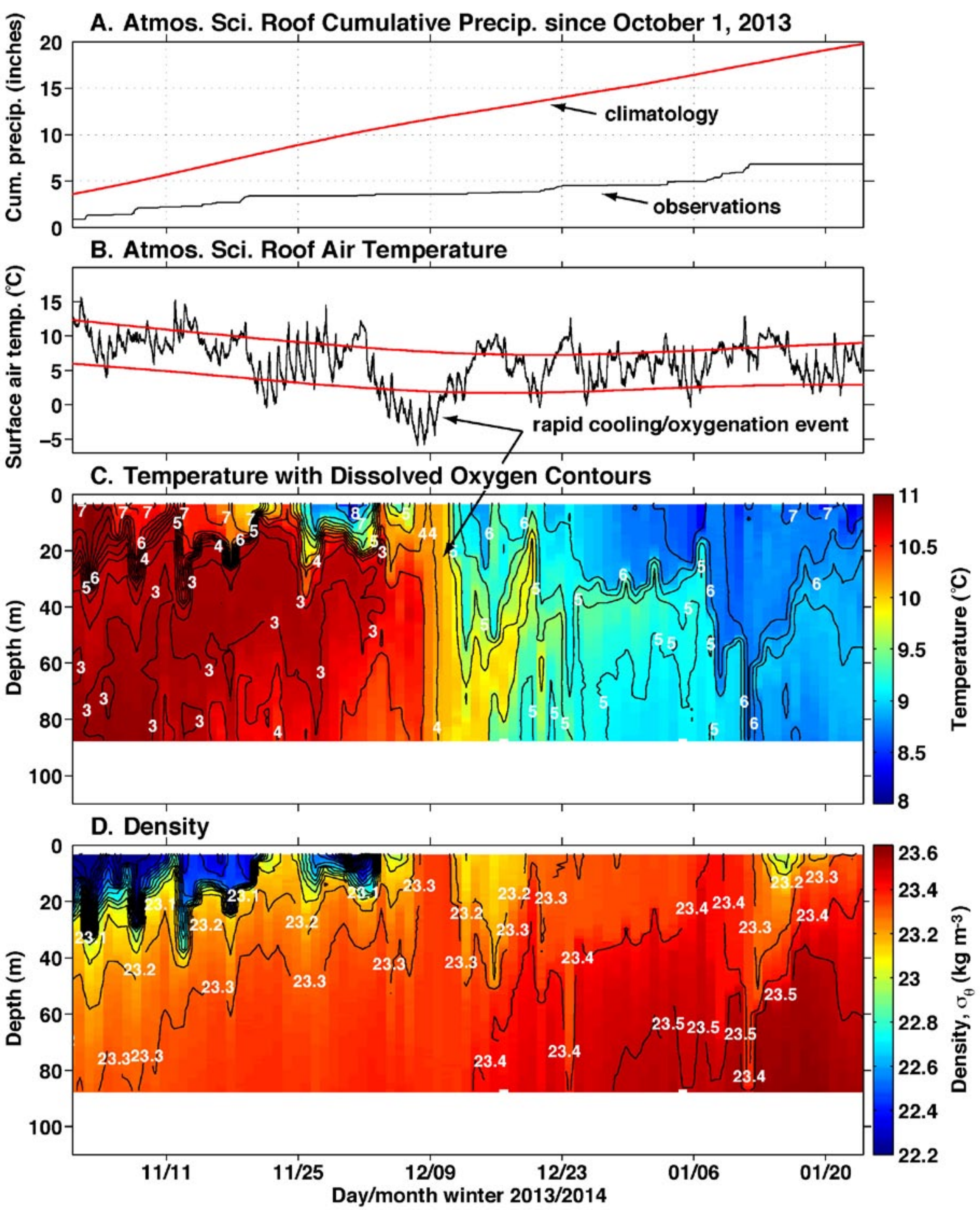


Figure 20. Oxygen data at Twanoh (southern Hood Canal) for 2010-2014. Data are colored with a white threshold at 2 mg/L; values below the threshold are shaded purple and indicate hypoxic waters.

ii. Salinity

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

While salinity at each Puget Sound basin is affected by ocean, watershed, and weather forcing, UW ORCA buoy's high-resolution profile data facilitate insights between basins. We compare Twanoh in southern Hood Canal to Carr Inlet in South Sound, both sites that are far from the entrance to Puget Sound but in different basins. Twanoh began 2014 saltier than Carr Inlet, but by fall the two locations had similar salinities (Figure 21A,B). This pattern is revealed further by the anomalies, which for both locations switch from salty to fresh in mid-March but then anomalies at the sites diverge around July; at Twanoh the fresh anomaly persists, whereas at Carr it fades to a weak salty anomaly during the summer and fall (Figure 21C,D). The salinity anomaly pattern in the first half of the year at both sites is consistent with regional precipitation patterns, which began 2014 much lower than normal and rapidly transitioned to above normal. While regional precipitation patterns may explain some of the salinity anomalies, other factors, such as mixing and proximity to rivers, appear to affect these basins differently.

In Hood Canal, higher than normal near-surface salinities early in the year were likely due to the large precipitation deficit noted above. This salty anomaly rapidly transitioned to a fresh anomaly during April-May (as seen at Twanoh, Figure 21C), associated with an extended period of above normal local precipitation.

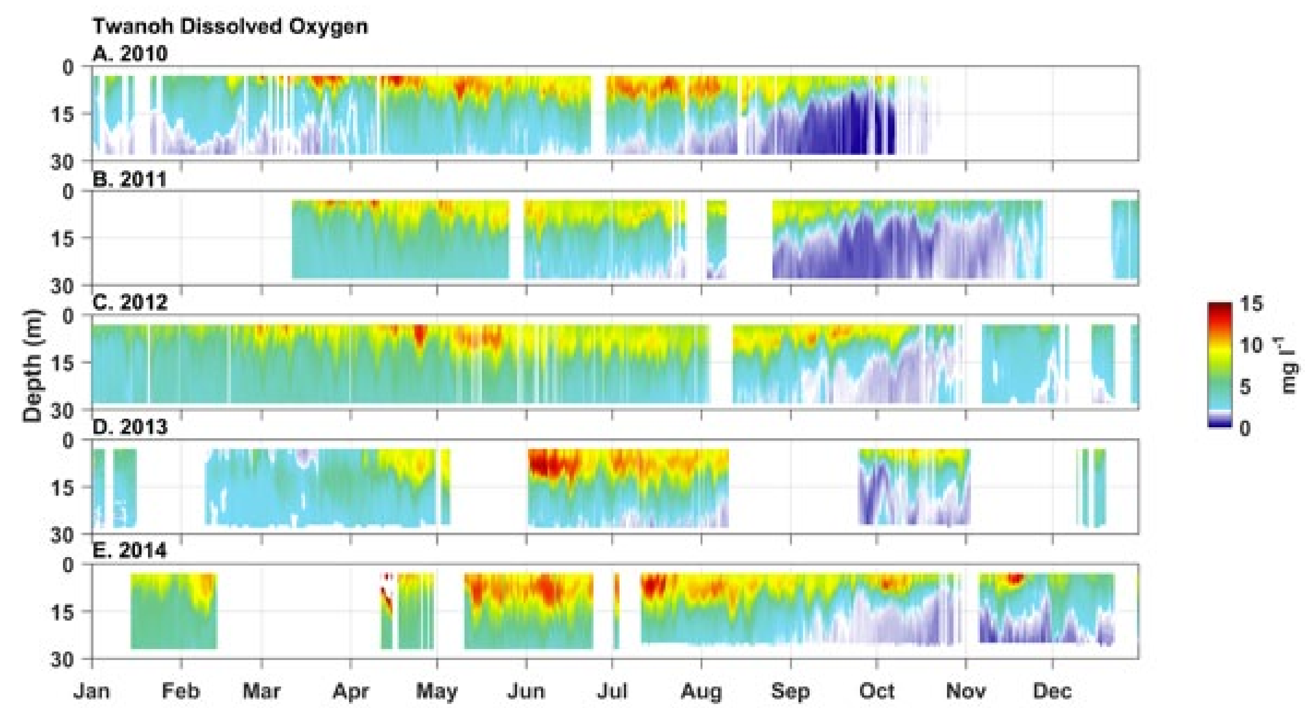


Figure 21. Top two panels: salinity data for Twanoh and Carr Inlet for 2014. Bottom two panels: salinity anomalies (2014 - climatology) for Twanoh and Carr Inlet. Data are colored with a white threshold at 0, with red indicated more saline and blue indicating less saline than historical average conditions.

iii. Ocean and atmospheric CO_2

Source: Simone Alin (simone.r.alin@noaa.gov), Christopher Sabine, Richard Feely (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; PMEL contribution number 4354

Carbon dioxide 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. At both sites, 2014 had the most complete time-series of any year to date (Figure 22). Observational gaps across years at each site make comparisons among years challenging, therefore, the focus is on comparisons across sites for 2014.

Both Dabob and Twanoh sites reflect the regionally elevated xCO_2 relative to global averages of marine surface air and the Chá Bă mooring site (Figure 22). Across winter and fall months (i.e., January–March and October–December 2014), atmospheric xCO_2 averaged 412±9 ppm (±SD) at Dabob and was even higher at Twanoh, with an average of 419±12 ppm. Spring and summer average values were lower but variability was higher, with 407±15 ppm at Dabob and 414±15 ppm at Twanoh. In comparison, fall-winter atmospheric xCO_2 at Chá Bă averaged 403±5 ppm and the global marine surface average was 397.3 ppm. Spring-summer Chá Bă atmospheric values were 396±7 ppm, with the global average falling at 396.7 ppm.

Surface seawater xCO_2 at both Dabob and Twanoh follows similar seasonal patterns to previous years, with the highest values occurring in early winter or fall, decreasing to the lowest values of the year in late winter or early spring, and remaining mostly undersaturated (below atmospheric values) throughout summer and early fall. Averaged winter and fall xCO_2 at Dabob was 537±189 ppm and 521±255 ppm at Twanoh (though gaps in the Dabob time-series and preliminary fall data at Twanoh may bias these numbers). Spring-summer xCO_2 averages and variability were substantially lower at both sites, with 278±101 ppm at Dabob and 336±114 ppm at Twanoh. In comparison, the winter/fall and spring/summer averages at Chá Bă were 361±62 and 264±66 ppm.

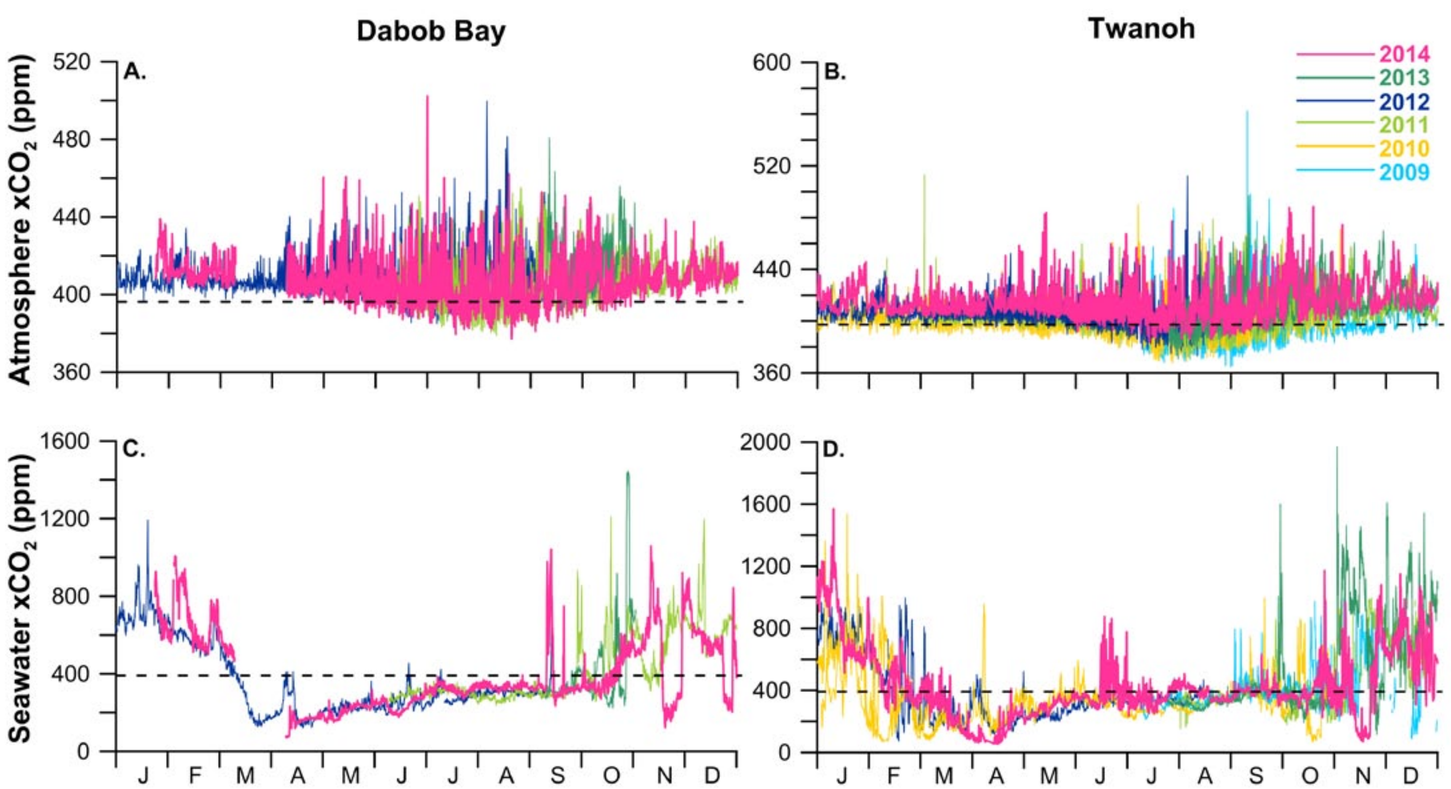


Figure 22. The mole fraction of carbon dioxide (xCO_2) in air at 1.5 m above seawater (A,B) and surface seawater at 0.5 m depth (C,D) in Dabob Bay and Twanoh in 2014. Data from previous years are included for comparison. Dabob data available in: Sutton et al. 2011). Approximate 2014 global average atmospheric xCO_2 of 397 ppm is indicated with a dashed line in each panel. Data shown for Dabob Bay at the end of 2014 and for Twanoh 2009–2012 have not been subjected to quality control, but typical uncertainty associated with quality controlled xCO_2 measurements from these systems is <2 ppm for the range 100–600 ppm, increases for values between 600 and 1000, and is not well constrained above 1000 ppm.

C. Central Basin long-term stations

Focusing on the Central Basin of Puget Sound, King County collects twice 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://green2.kingcounty.gov/marine-buoy/default.aspx, http://green2.kingcounty.gov/marine/Monitoring/OffshoreCTD.

i. Temperature and salinity

Source: Kimberle Stark (kimberle.stark@kingcounty.gov) (KCDNRP)

Open water surface temperatures (<2 m) for the Central Basin in 2014 were generally colder than the baseline average (1999-2010) from January through May, and about 0.5 to 1.4ºC cooler than normal during June (Figure 23A). However, surface temperatures from July through December were warmer than normal, particularly in October when air temperatures were 2.8ºC warmer than normal. Water temperatures at depth were primarily colder than normal between January and July but warmer than normal September through December. Bottom waters in November were markedly warmer than the baseline average, with temperatures ranging from 1.0 to 1.8ºC above normal.

Surface salinities were fairly typical in 2014 compared to the baseline average (1999-2010), with the exception of March, November, and December when fresher than normal surface waters were observed due to large precipitation events. Over nine inches of rain was recorded in March at SeaTac airport, which was 5.3 inches above normal. Although November and December were drier than normal, there were significant rain events on or just prior to sample collection days. Deep water salinities observed throughout 2014 were similar to previous years. Strong upper water column stratification due to fresher water was observed at Point Jefferson and East Passage (Figure 23B) between March and early June, which has not been seen in prior recorded years.

In situ temperature and salinity sensors (15-minute interval data) at both 1 and 10 m water depths at the Seattle Aquarium show that waters are affected by discharge from the Duwamish River, particularly during large rain events. Temperature and salinity at both depths in 2014 followed a similar pattern to open waters in the Central Basin, although lower surface salinities from freshwater input were more evident at this location. Waters at the 10 m depth also showed warmer than normal temperatures, particularly between September and October (Figure 23C).

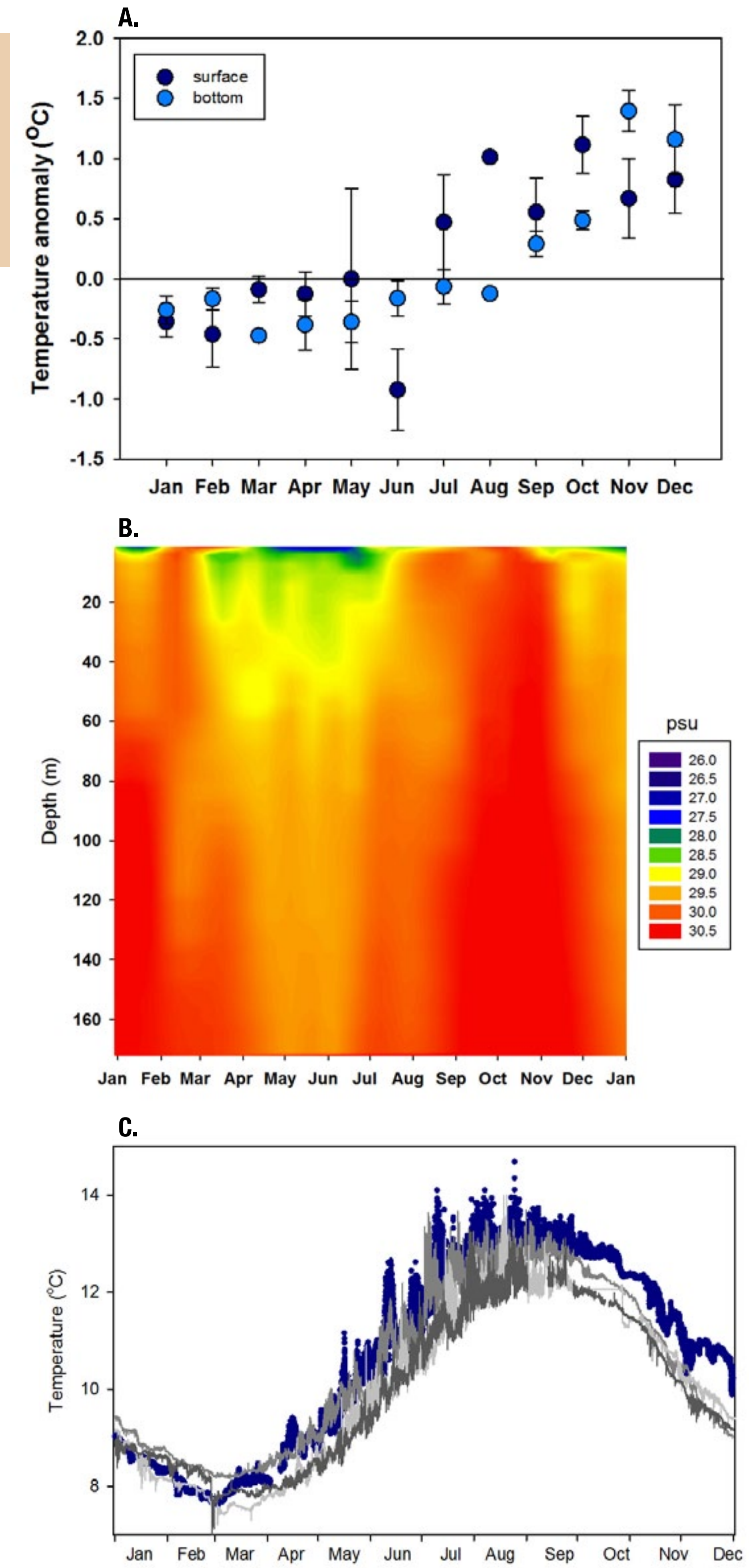


Figure 23. (A) Mean of 2014 temperature anomalies for seven sites at surface(<2m) and depth relative to a baseline average (1999-2010). (B) Salinity at East Passage throughout the water column. (C) Continuous water temperature observations at 10 m depth at the Seattle Aquarium for 2011, 2012, 2013 and 2014.

ii. Dissolved oxygen

Source: Kimberle Stark (Kimberle.stark@kingcounty.gov) and Wendy Eash-Loucks (KCDNRP); https://green2.kingcounty.gov/marine-buoy/default.aspx; http://green2.kingcounty.gov/marine/Monitoring/OffshoreCTD

Results from monthly sampling at 12 sites and 4 in situ moorings (15-minute interval data) in the Central Basin indicate that DO levels in 2014 were above 5.0 mg/L throughout the year at all locations and depths, with the exception of East Passage and Quartermaster Harbor. DO concentrations in bottom waters at East Passage were 4.8 and 4.9 mg/L in early October and November, respectively. DO levels in inner Quartermaster Harbor were both highest and lowest in late September during a large phytoplankton bloom (Figure 24A). During daytime hours DO was above 22.0 mg/L; however, during nighttime hours concentrations dropped below 1.0 mg/L reflecting a lack of photosynthesis and high respiration. Although DO in outer Quartermaster Harbor was lower than in open waters, and below 5.0 mg/L from late summer to fall (<2.0 mg/L in early August), values were not as low as those observed in the inner harbor. Data from both Quartermaster Harbor moorings showed substantial diurnal variation, particularly during bloom events.

An increase in oxygen from primary production during phytoplankton blooms was evident in surface waters at most sites. DO measured at both the 1 m and 10 m depths in Elliott Bay at the Seattle Aquarium mooring showed high oxygen values during April and at other times that corresponded with high chlorophyll levels (Figure 24B). Overall, DO in surface waters was higher than the long-term baseline average (1999-2010) most of the year at all sites, particularly in April, May, September, and October during large phytoplankton blooms.

For most sites, DO in bottom waters in 2014 was slightly below normal (~1.0 mg/L) between Jan—April and October—December. The November and December anomalies coincided with warmer than normal bottom waters, and DO at all sites in November and December was below the long-term average for each site.

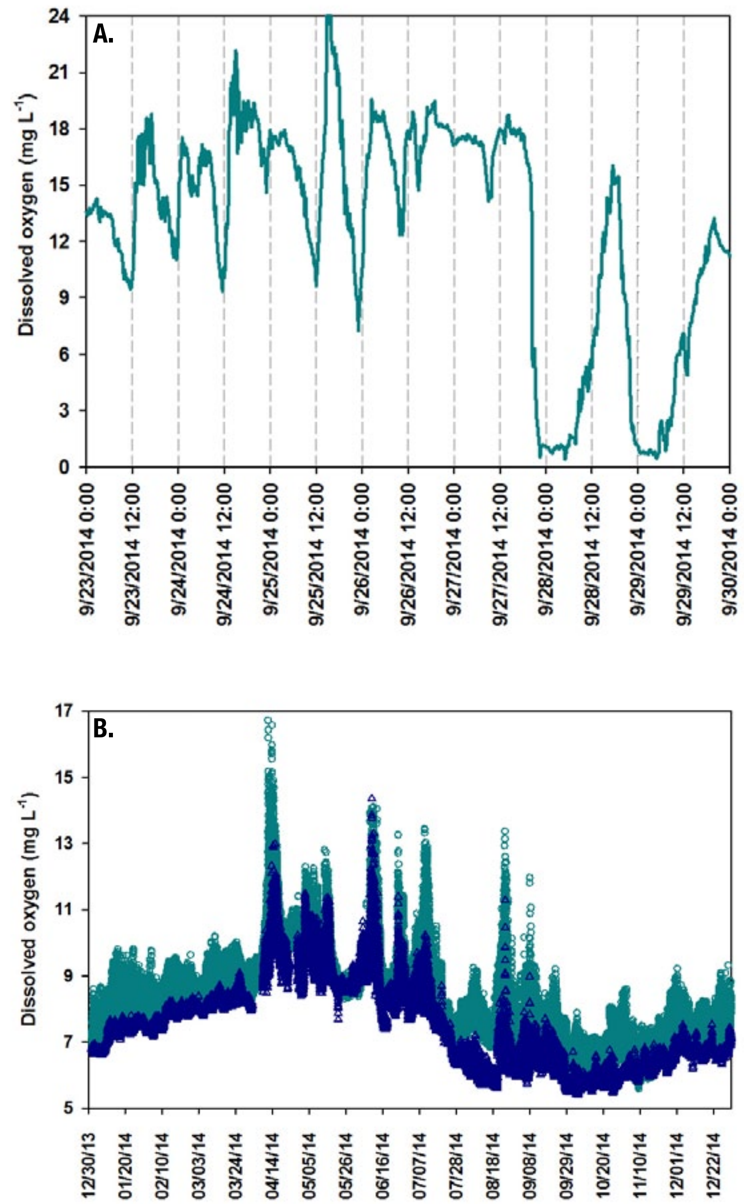


Figure 24. Dissolved oxygen concentrations in 2014 in inner Quartermaster Harbor (Yacht Club) during a 1-week period in September (A), and at the Seattle Aquarium throughout the year (B). Data were recorded every 15-minutes.

iii. Nutrients and chlorophyll

Source: Kimberle Stark (Kimberle.Stark@kingcounty.gov), Amelia Kolb (KCDNRP), and Gabriela Hannach (KCEL); http://green.kingcounty.gov/marine/

Results from monthly (January-April, December) and twice monthly (May-November) sampling at 12 sites and 2 in situ moorings (15-minute intervals) in the Central Basin show that the timing of the 2014 spring phytoplankton bloom was typical, occurring in early April. The large April bloom, dominated by the diatoms *Thalassiosira* spp. and *Chaetoceros* spp., declined at most stations by the end of April but increased again in early May at most sites and then subsided by mid-May. Smaller blooms in early June and July were followed by a much larger and longer than normal fall bloom dominated by *Chaetoceros* spp. The fall bloom, which occurred in early September at the northern sites and later that month at most other sites, extended through October – an unusual occurrence that has not been seen in prior years. Overall, mean annual chlorophyll levels were higher in 2014 compared to previous years due to the large spring and fall blooms (Figure 25A).

Nutrient levels were highly variable between sampling events in 2014. Seasonal decreases in surface (< 2m) nitrate+nitrate levels were consistent with phytoplankton uptake; this decrease was particularly sharp in September and October during the anomalous late fall bloom (Figure 25B). Nitrate+nitrite was depleted below detectable levels at East Passage in early April, May, and June coinciding with the large spring blooms. Levels were also below detection in early May at a few other sites. Nitrate+nitrite levels in surface waters were replenished near the end of each month (April, May, and June). Silica levels were influenced by freshwater input, with unusually high levels observed in both surface and deep waters in March following heavy rainfall. Silica values in surface waters were somewhat lower than normal in April, September, and October likely the result of uptake by diatoms (Figure 25C). Ammonia levels sharply increased at most sites towards the end of May and continued throughout June (Figure 25D). At East Passage, a large increase in ammonia was also seen in late May, but the increase in ammonia levels occurred later in the year (from July through September) compared to previous years.

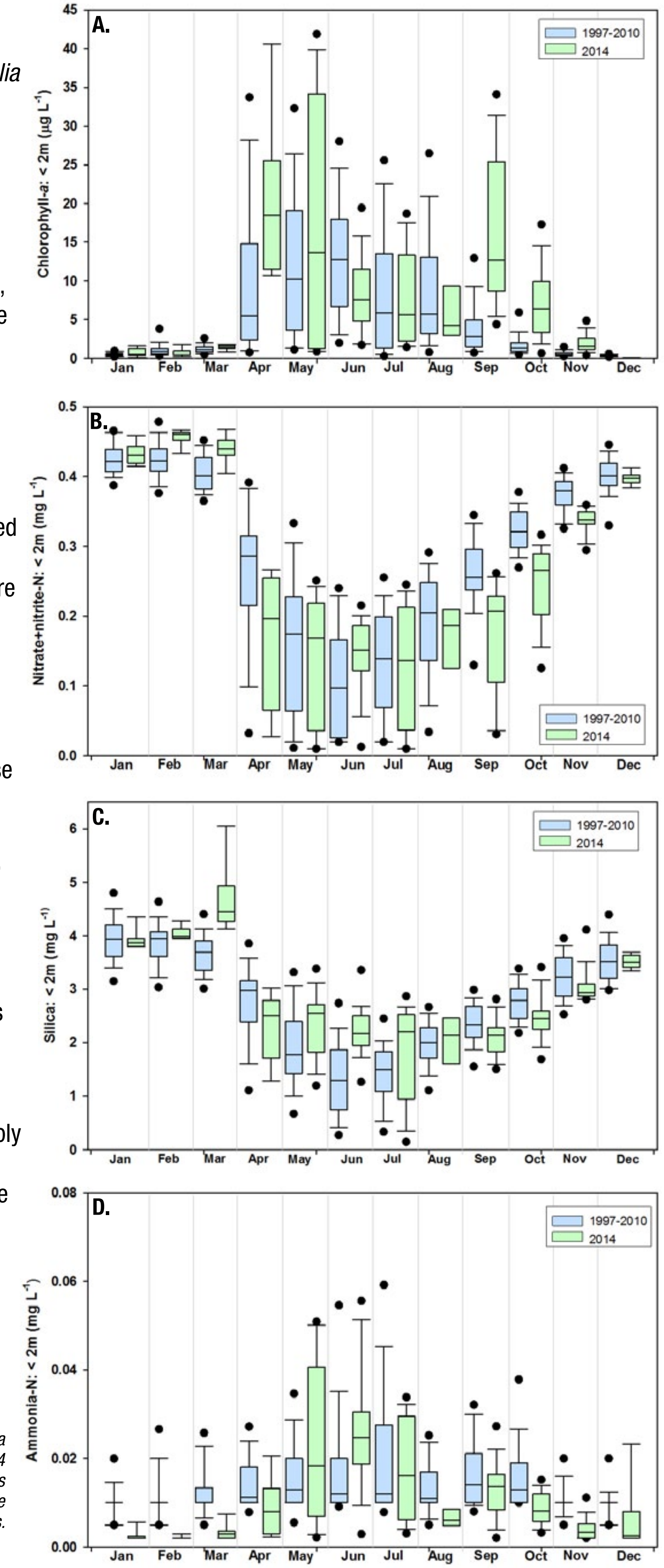


Figure 25. Surface water (A) chlorophyll-a, (B) nitrate/nitrite, (C) silica and (D) ammonia levels at 12 sites in the Central Basin for 2014 compared to the long-term baseline. The line within the box denotes the median, box boundaries are 25th & 75th percentiles, whiskers are 10th & 90th percentiles, and points the 5th & 95th percentiles.

D. North Sound surveys

i. Bellingham Bay stratification

Source: Jude Apple (japple@padillabay.gov) (WWU), Natasha Christman (UW), Robin Kodner and Ciara Asamoto (WWU), Susan Blake (WSU; WSG), and Jeff Campbell (formerly NWIC)

Over the past several years, faculty and students at Western Washington University (WWU) and the Northwest Indian College (NWIC) have studied water quality, nutrients and dissolved oxygen dynamics in Bellingham Bay. Temperature and salinity observations from water column profiles collected in central Bellingham Bay during 2014 reveal a transition to a warmer, fresher and more stratified water column from January through July, followed by a return to colder, more saline water in late fall (Figure 26A). This is generally representative of observations in 2013, which revealed similar timing and magnitude of Nooksack river flow to 2014. Noteworthy aspects of water column structure during 2014 include fresher surface waters in March associated with springtime Nooksack River flow and strong stratification in summer months evidenced by water column measurements extending from cold, salty bottom waters to warmer, fresher surface waters (Figure 26A; yellow, red, orange; bottom waters on the right and surface waters on the left side of the figure).

Water column stratification, calculated as the difference in density between surface water and at 15 m depth, was variable throughout the year, with stronger stratification generally observed in July and August (Figure 26B). This pattern in stratification in Bellingham Bay is similar to that observed during 2013 (data not shown). A short-term disruption of summer stratification was observed on July 2, 2014, which may have been driven by a combination of Nooksack river flow, tidal exchange, and atmospheric frontal systems. In the days preceding this event, Nooksack River flow was high (i.e. >7000 cfs), tidal exchange was high (i.e. spring tides), and the region was experiencing a low pressure front (i.e. 1000 mbar) with consistent winds from the south. This combination of conditions may have produced enough energy to mix the water column and disrupt the strong stratification that usually occurs during summer months in Bellingham Bay.

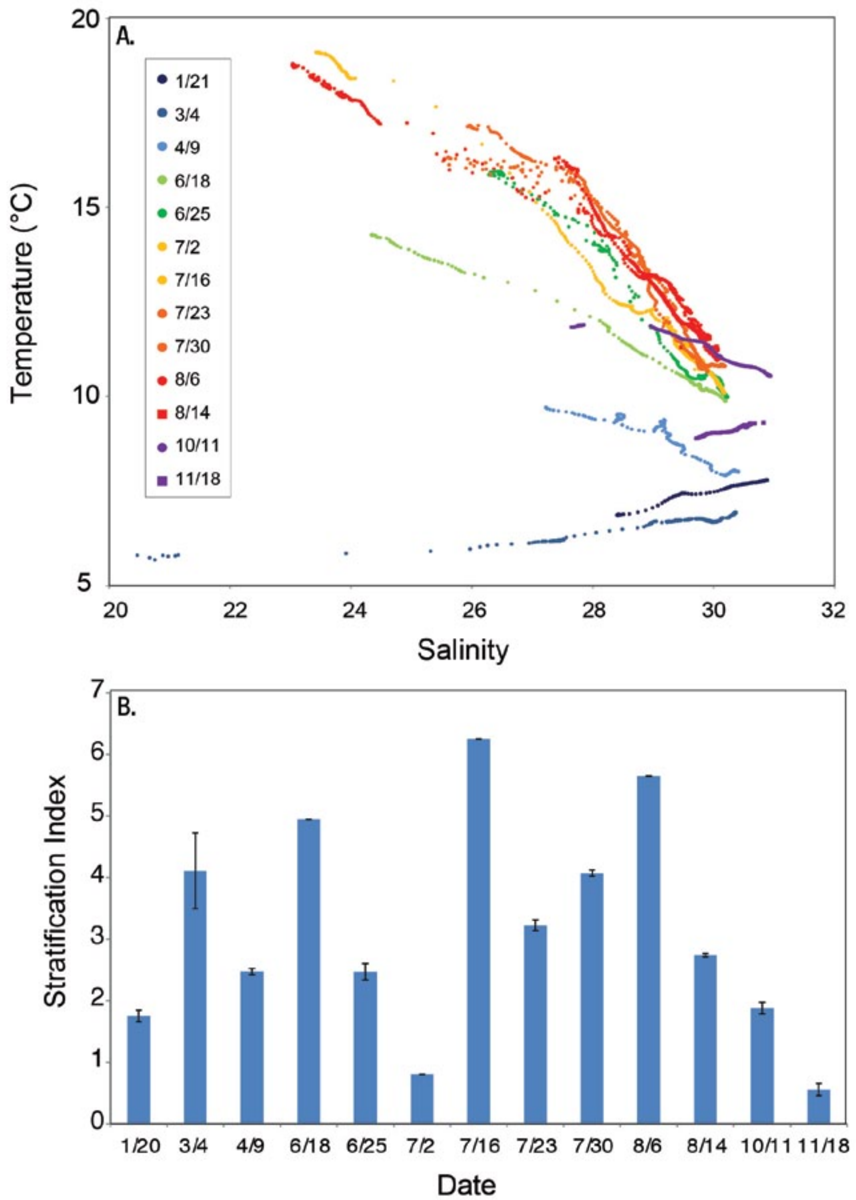


Figure 26. (A) Temperature-Salinity plot of water column profiles collected in Bellingham Bay during 2014. Data points from each profile generally represent a transition from colder, saltier bottom waters (lower right) to warmer, fresher surface waters (upper left). (B) Water column stratification indices (i.e. $\sigma_{T(15m)} - \sigma_{T(1m)}$) calculated for water column profiles represented in panel A.

ii. Padilla Bay temperature and salinity

Source: Jude Apple (japple@padillabay.gov), Heath Bohlman, Nicole Burnett, and Suzanne Shull (Padilla Bay NERR); http://www.padillabay.gov; http://cdmo.baruch.sc.edu/

Padilla Bay National Estuarine Research Reserve is a shallow embayment north of Puget Sound (see page 30 for more details). The Reserve maintains long-term monitoring stations throughout the bay which provide continuous measurements of water quality parameters. Temperature is highly variable in Padilla Bay, with an annual range from 1.7 °C to 22.2 °C (Figure 27A) and daily fluctuations approaching 10 °C in summer months. This relatively large temperature range is attributed in part to shallow waters and extensive mudflats that facilitate solar heating and cooling of surface waters in summer and winter, respectively. Water temperature is also variable on longer time scales, with annual anomalies over the past two decades revealing periodic shifts between warmer and cooler phases (Figure 27B). Although there is considerable diel and monthly variability in temperature, climate-associated conditions may be the primary factor driving long-term temperature variability. Annual temperature anomalies were well correlated with annual mean PDO values, with a strong secondary correlation with warm versus cool phase ENSO conditions.

Long term (2001-2014) analysis of salinity reveals that surface waters in more recent years have been fresher relative to the early 2000's, as evidenced by a general decrease in mean annual salinity anomalies during this period (Figure 27C). Despite fresher conditions in 2014, surface water salinity remained relatively high throughout most of the year (i.e. annual mean = 28.5 ± 1.3). This high salinity was punctuated by freshwater intrusion events in early January and mid-March during periods of elevated flow from Nooksack River, followed by episodic decreases in salinity during summer months (i.e. June-August) which appear to be driven by high discharge from Fraser River and subsequent transport of this freshwater to Padilla Bay.

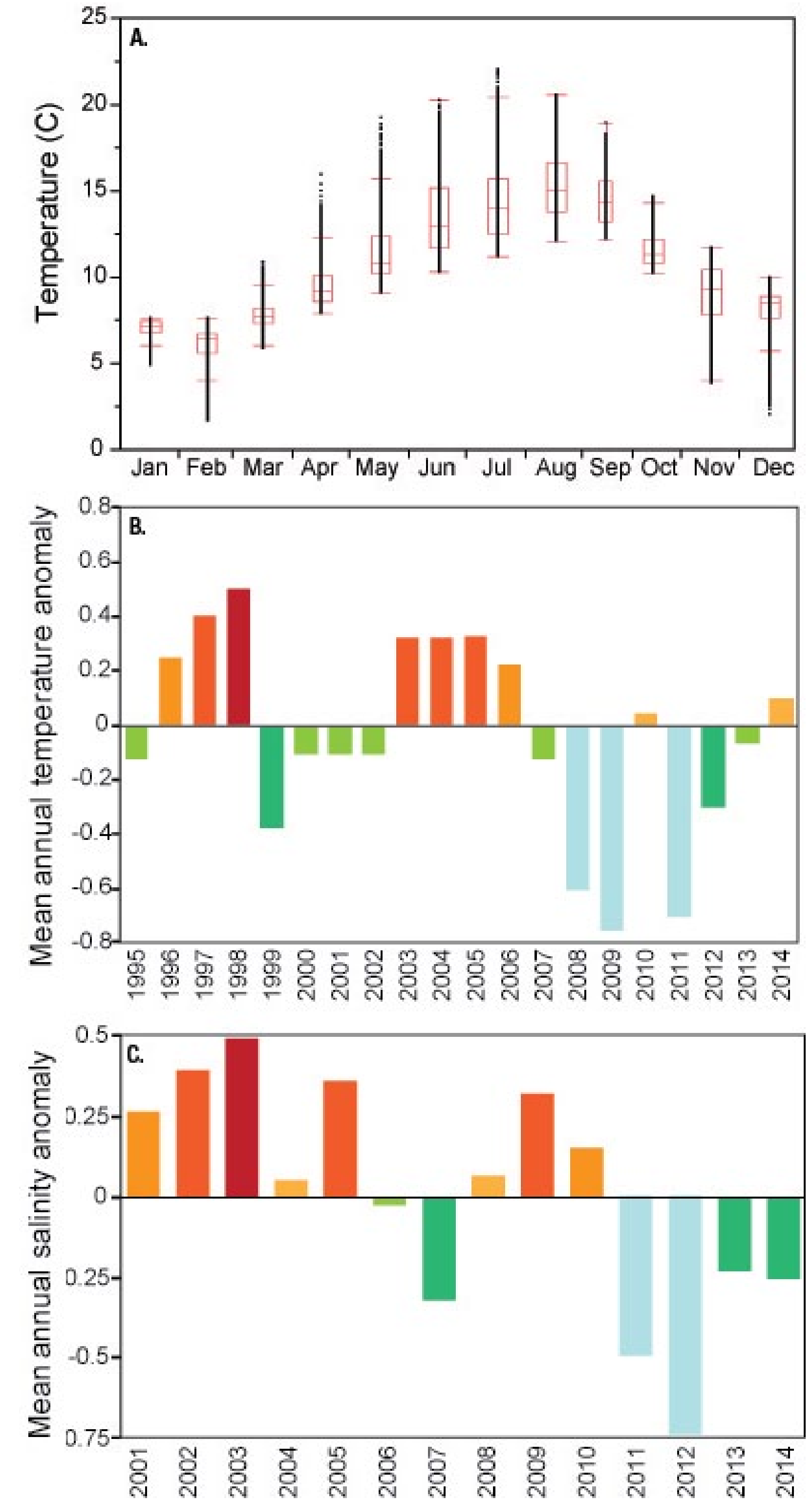


Figure 27. Temporal variability of water temperature and salinity in Padilla Bay, including A) monthly variability of surface water temperature and annual anomalies in B) temperature and C) salinity based on a 20 year mean.

E. Snapshot surveys

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

i. San Juan Channel/Juan de Fuca fall surveys

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

The University of Washington Friday Harbor Laboratories Research Apprenticeship Program has maintained a time-series of pelagic ecosystem variables during fall quarter (September-November) since 2004. Research apprentices sample two sites approximately weekly. 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 strongest signal in the 11-year temperature record was observed at both stations during 2014. Figure 28 shows temperature versus salinity from the sea surface to ~80 m at the South station measured during the first week of November 2004-2014. The November 2014 temperature was more than a full degree Celsius above the previous warmest waters. Prior to 2014 the warmest years typically were El Niño years and the coldest years typically were La Niña years. An exception is 2005, which had particularly weak coastal upwelling and warm sea temperatures (GRL 2006; Bond et al. 2015).

November 2014 conditions were unique in two ways: higher than typical seawater temperatures and little variation from surface to depth. The entire water column was ~11 degrees Celsius, which is 1-2 and 1.5-3 degrees warmer than typical surface and deep waters, respectively. The 2014 deep water salinity was fresher than typical by 0.5-2 PSU. These characteristics are consistent with a source from the "Blob", a large NE Pacific water mass that was anomalously warm and fresh. As described in the boundary condition section, the typical fall transition from upwelling to downwelling in late October was associated with the sudden appearance of the anomalously warm waters along the coast. These waters would be drawn in via the Strait through estuarine circulation; their observation at the South station in early November is consistent with that dynamic. The effect of the widespread warm waters on regional biological organisms is still under study, but the 2014 harbor porpoise abundance was lowest in the 11-year record and seabird abundance was one of the lower years.

Sample collection aboard the R/V CentenniaL. Photo: Breck Tyler

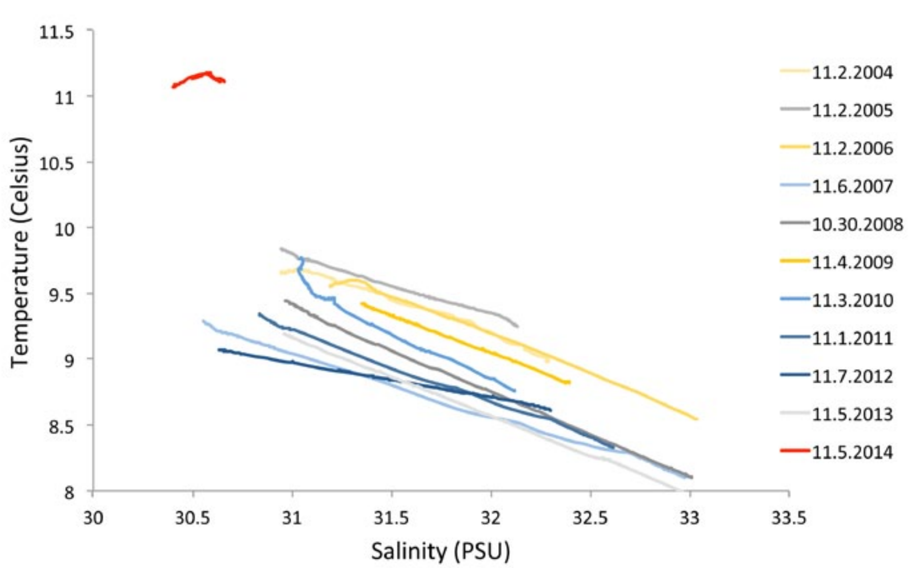


Figure 28. Temperature versus salinity from 80 m to the surface at the South station in the eastern Strait of Juan de Fuca during the first week of November. Deep waters (coldest and saltiest) are found on the right. Color coding shows: yellow=El Niño years; blue=La Niña years; gray=neutral years.

CALL-OUT BOX: Monitoring of intertidal habitats at Padilla Bay

Padilla Bay National Estuarine Research Reserve (PBNERR) was established in 1980 as a living laboratory to monitor and research estuarine ecosystems. An integral part of research at Padilla Bay is long-term monitoring to investigate changes in ecosystem status and function. In 2009, the Reserve began monitoring rocky intertidal habitats in Padilla Bay as part of the Multi-Agency Rocky Intertidal Network (MARINe) and in 2011 an annual monitoring program was established to document changes in resident eelgrass (i.e. native *Zostera marina* and non-native *Zostera japonica*). Below we provide an overview of data from these two monitoring programs and the insight they reveal into the success and challenges facing intertidal ecosystems in Puget Sound.

Intertidal Monitoring I: Decline of Rocky Intertidal Sea Star Populations in Padilla Bay

Monitoring of sea stars and other rocky intertidal populations (i.e. barnacles, macroalgae, motile invertebrates) has been conducted at four permanent sample sites on two islands located on the western edge of Padilla Bay. Long-term data from this effort provide a mechanism to track changes in populations, community structure, and responses to natural or human-induced disturbances. One such change evident in our data is the dramatic mortality of the Ochre Star (*Pisaster ochraceus*) that occurred between June and Sept 2014 (Figure 29A). *P. ochraceus*, the dominant sea star at the Padilla Bay monitoring sites, decreased in abundance by 93% (i.e. 78 to 5 individuals) throughout our study area in 2014. This mortality has been attributed to the recent outbreak of Sea Star Wasting Syndrome (SSWS) which was initially documented in our region in the summer of 2013, and quickly spread throughout the NE Pacific Coast and Salish Sea. The current outbreak of SSWS has been observed from Baja California through Alaska and collectively, has been characterized as one of the largest marine disease outbreaks on record (Hewson et al. 2014). Through continued monitoring of the sites at Padilla Bay we hope to document changes in community structure and/or recovery of these populations in subsequent years.

Motile Invert sampling at the Fucus monitoring plot, Hat Island. Right photo: Heath Bohlmann

Pisaster ochraceus, Saddlebag Island. Background photo: Heath Bohlmann

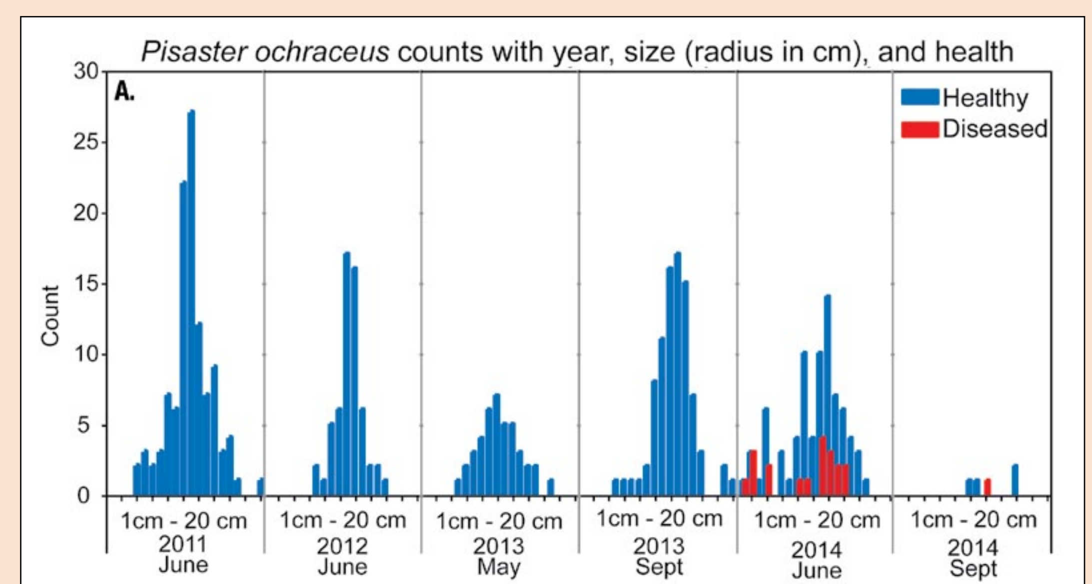
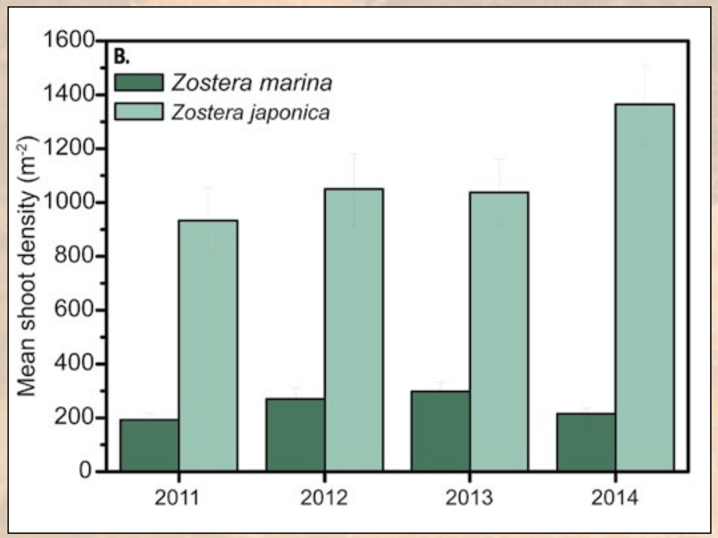
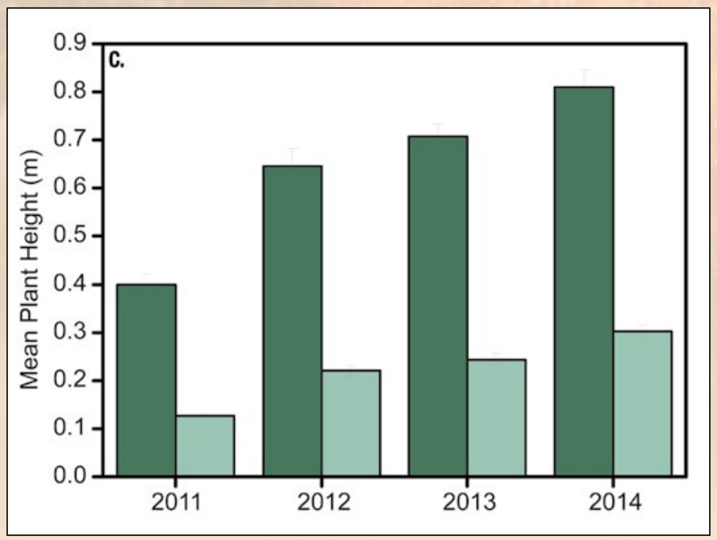
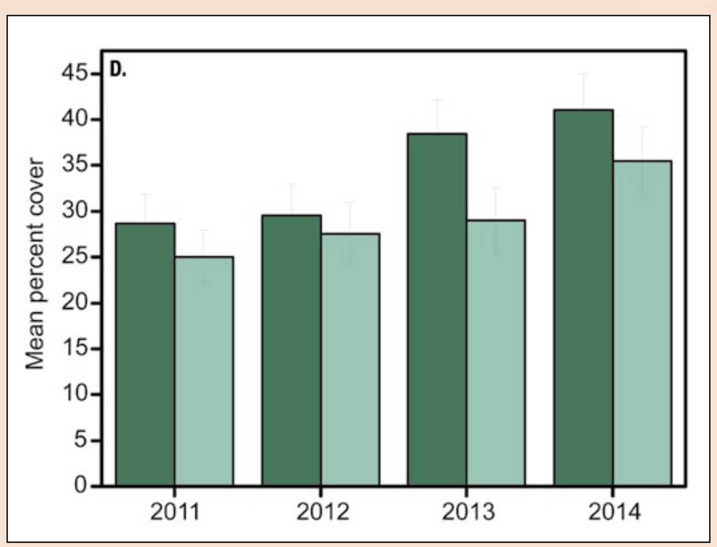


Figure 29. (A) Sea star abundance and size distribution at rocky intertidal sites in Padilla Bay. (data source: http://cdmo.baruch.sc.edu/).







Intertidal Monitoring II: Changes in Eelgrass Growth and Performance

Data derived from over 100 permanent plots along three 3km transects reveal that density of *Z.japonica* increased substantially from 2013 to 2014 (i.e. 1036 to 1363 shoots m-2) while that of *Z.marina* declined slightly during the same period (i.e. 296 to 213; Figure 29B). In contrast, plant height and percent cover of both *Z.marina* and *Z.japonica* experienced an upward trend, although the change in percent cover was not as dramatic (Figure 29B,C). Using long-term monitoring data at Padilla Bay (described elsewhere in this report), we investigated factors (i.e. temperature, light availability) that may explain patterns in eelgrass growth and performance. Mean water temperature and surface light measurements (PAR millimoles/m2) increased, while mean water depth (relative to station datum) decreased over the four-year period. Collectively, changes in PAR and water depth (Figure 29D) suggest higher levels of irradiance available for plant productivity. These data provide evidence that *Zostera* spp. may be responding positively to the transition from cooler, lower light conditions measured in 2011 to more favorable growing conditions in subsequent years.

Author: Jude Apple (japple@padillabay.gov), Heath Bohlmann, Nicole Burnett, and Suzanne Shull (Padilla Bay NERR); http://www.padillabay.gov/; http://www.marine.gov/; http://www.eeb.ucsc.edu/pacificrockyintertidal/data-products/sea-star-wasting/

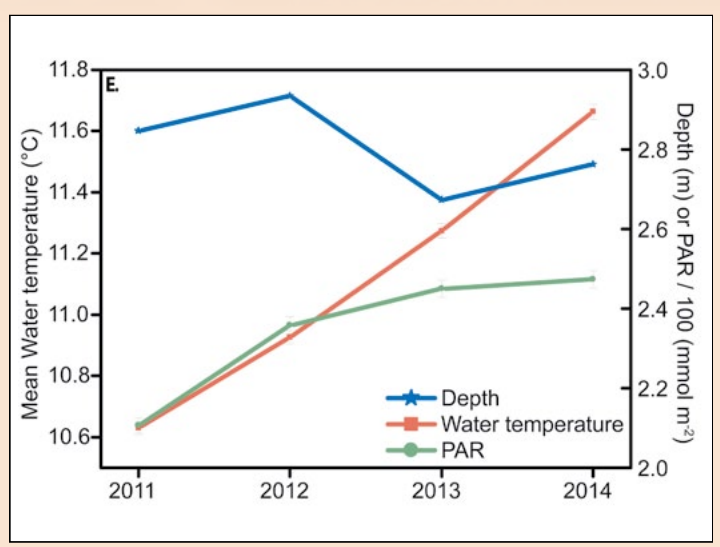
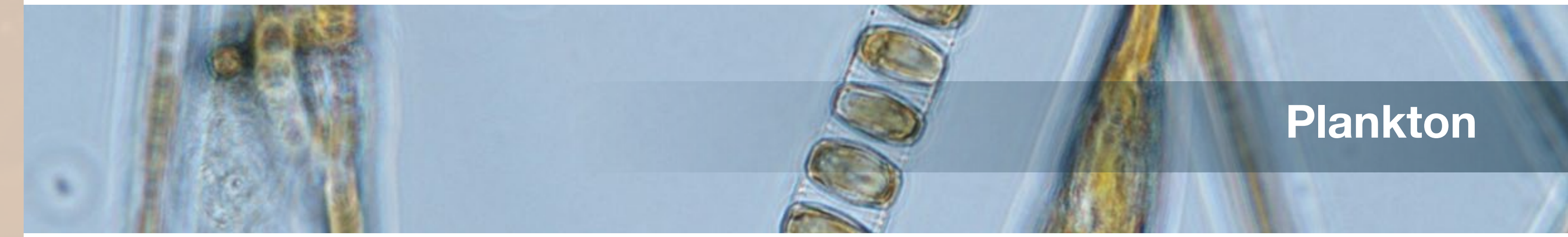


Figure 29. Annual means of Zostera marina and Zostera japonica (B) shoot density, (C) plant height, and (D) percent cover; and (E) annual means for water temperature, depth, and PAR in Padilla Bay (data source: http://cdmo.baruch.sc.edu/).



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), Amelia Kolb (KCDNRP) and Lyndsey Swanson (KCEL); http://green.kingcounty.gov/marine/photos.aspx

King County has analyzed phytoplankton samples semi-monthly in the Puget Sound Central Basin since 2008, using a semi-quantitative method that focuses on taxon identification and relative abundance. In May of 2014, the program was expanded from 3 to 8 stations, incorporating a new method of quantitative analysis that uses an imaging particle analyzer (FlowCAM) to assess 5-300 µm particle abundance and biovolume.

Chain-forming diatoms were frequently the dominant taxa observed in 2008-2014. Of the seven most abundant diatom genera identified in 2014 (Figure 30A) the large, chain forming *Chaetoceros* and *Thalassiosira* dominated the spring and fall blooms. Dinoflagellate abundance and biovolume remained small at all sites except in the fall in Quartermaster Harbor. *Noctiluca* was not as prevalent in 2014 as it was in 2013, based on qualitative observations. As in previous years, blooms of the dinoflagellates *Akashiwo* and *Heterocapsa* were observed at a few locations. Of note is a conspicuous reduction in spring and fall taxonomic richness in Quartermaster Harbor compared to previous years.

Anomalous climate conditions in 2014 likely influenced the seasonal timing and magnitude of blooms. High precipitation in spring caused increased stratification at many sites, creating conditions that may have favored an intense spring diatom bloom, soon followed by a second bloom event starting in June. Figure 30A illustrates subsequent transition to a diverse, low biovolume summer community, followed by an unusually large, extended fall diatom bloom – likely related to unusually warm water temperatures observed well into November.

A 6-year analysis of the relative abundances of taxa shows whole community shifts in 2014 compared to previous years, particularly in fall. Diatom communities shifted significantly from *Chaetoceros*-dominated spring communities in previous years to a *Thalassiosira*-dominated spring community in 2014, and an unusually extended period of *Chaetoceros* dominance in the fall (Figure 30A,B).

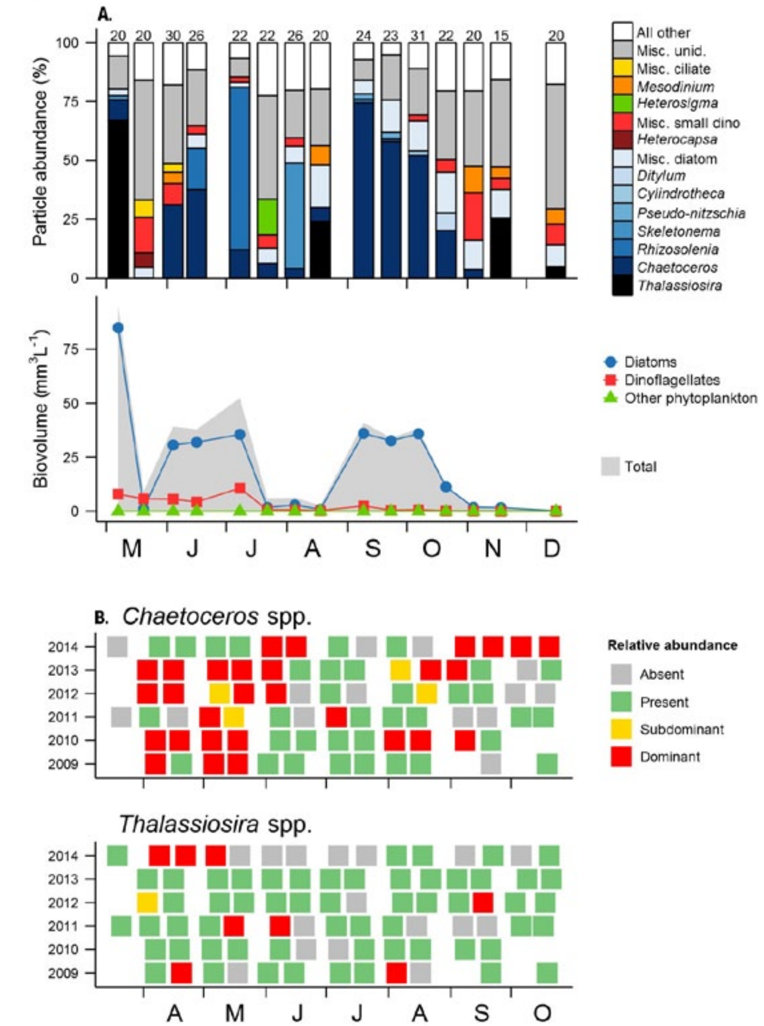


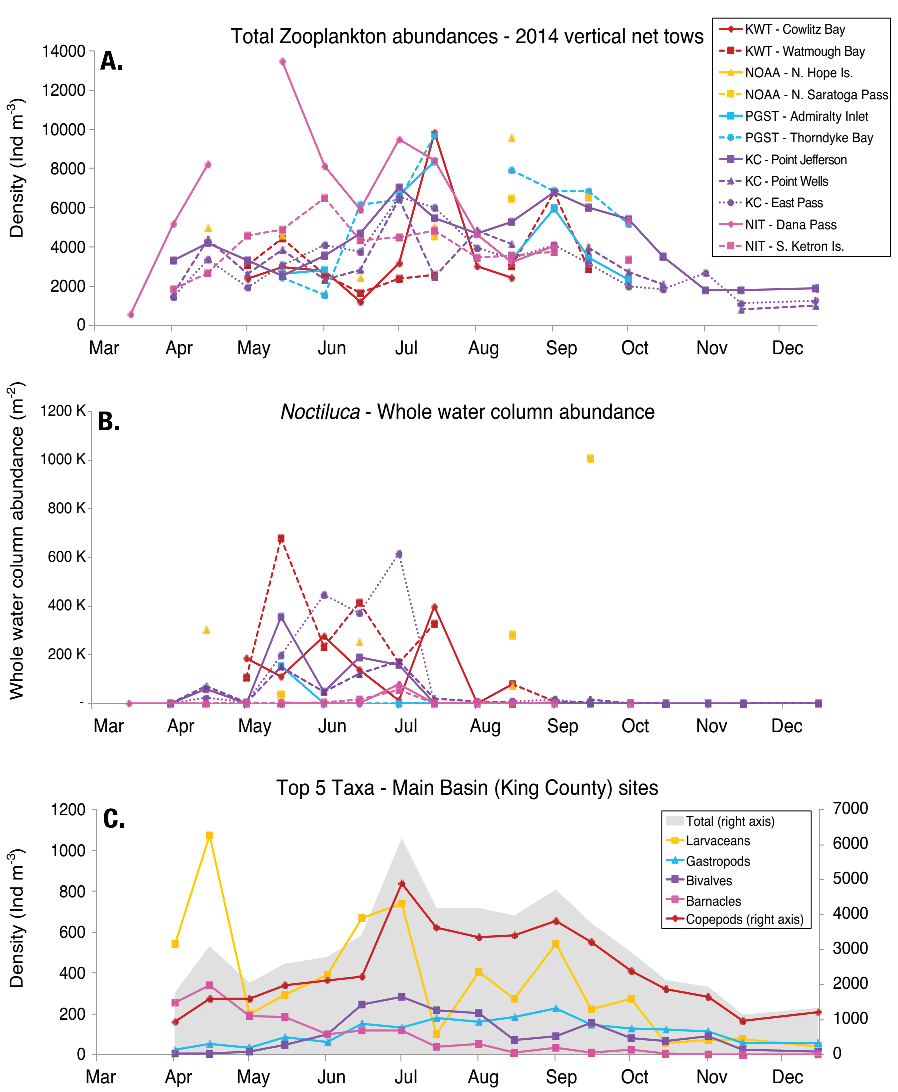
Figure 30. (A) FlowCAM-generated percent contribution of five most abundant taxa (top panel) and biovolume of main groups (lower panel) in 2014. Plotted values are means for six mainstem sites in the Central Basin. Numerals above bars indicate total number of taxa. Note that "Particle abundance" may refer to whole chains, fragments, or individual cells imaged. (B) Six-year relative abundance values show 2014 spring bloom at Pt. Jefferson dominated by Thalassiosira spp. rather than Chaetoceros spp. as in prior years (similar findings at East Passage).

B. Zooplankton

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

2014 was the first year of the new Puget Sound Zooplankton Monitoring Program. A large group of collaborators conducted the sampling including: King County (KC), the Nisqually Indian Tribe (NIT), the Tulalip Tribe, KWIÁHT, the Port Gamble S'Klallum Tribe (PGST), and NOAA, with funding from Long Live the Kings and King County. Most locations were sampled bi-weekly from April through mid-Sept; King County continued through December. Data shown here were collected with 60-cm diameter, 200-μm mesh plankton nets towed vertically from 5 m off the bottom (or a max. of 200 m in deep water) to the surface. Samples were taxonomically analyzed to species and life stage for most organisms.

Zooplankton density and seasonal timing varied across the locations sampled. Overall, copepods as a group were the most numerous taxa everywhere as is typically the case in marine waters. Larvaceans, various meroplankton (e.g., barnacles, bivalves, crabs), siphonophores, and amphipods were also abundant. The heterotrophic dinoflagellate, *Noctiluca*, was highly abundant during late spring and early summer. Ordination of the full meso-zooplankton species composition (which does not include *Noctiluca*) showed differences in community structure among basins. Axis 3 carried 55.4% of the community variance: taxa that were most strongly correlated with Axis 3 were the copepods *Acartia longiremis*, *Pseudocalanus moultoni*, copepodites (a larval stage) of those genuses, and cladocerans, all of which were negatively correlated with the axis; *Paracalanus parvus* and the siphonophores *Muggiaea* were positively correlated.



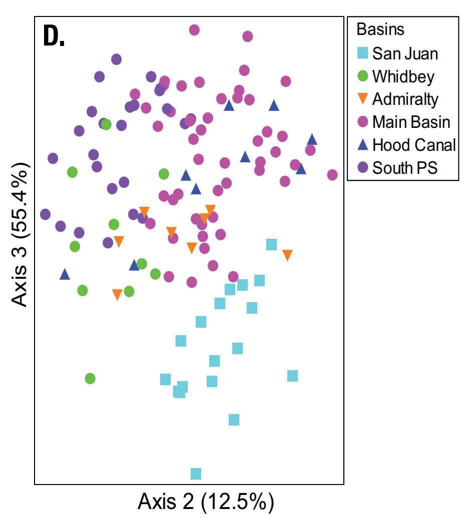


Figure 31. (A) Seasonal cycle of total mesozooplankton (as density, # m⁻³) at each station. (B) Seasonal cycle of whole water column abundance of the dinoflagellate, Noctiluca (as # m⁻²). (C) Total abundance (gray area) and abundance of the top five taxa averaged over the three King County sites in Main Basin; note that total and copepod abundances are on the right axis. (D) Non-metric multi-dimensional scaling (NMDS) ordination of the zooplankton community showing the axes that carried the greatest portion of variance in community structure, with samples symbol-coded by basin (each point is a single sample).

C. 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.

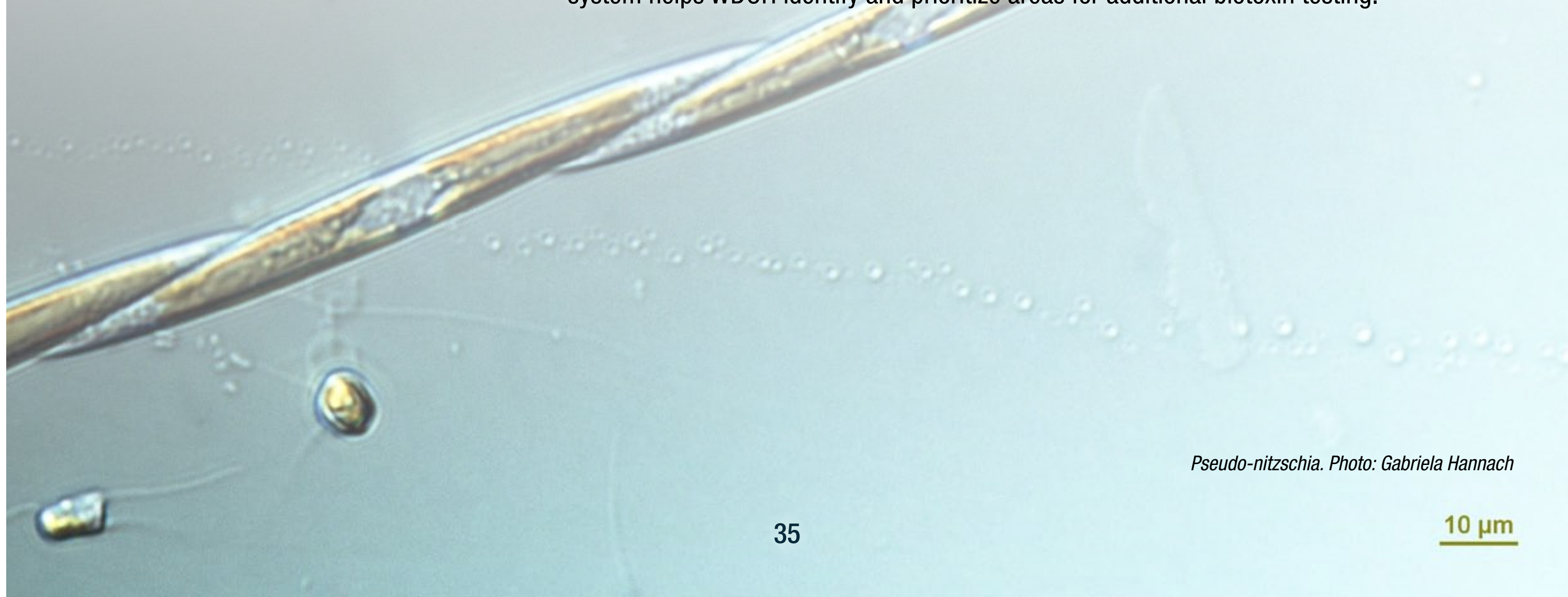
Source: Jerry Borchert (jerry.borchert@doh.wa.gov), and Clara Hard (WDOH); http://www.doh.wa.gov/CommunityandEnvironment/Shellfish/BiotoxinsIllnessPrevention/Biotoxins.aspx

In 2014, the Washington State Public Health Laboratory (PHL) analyzed 3,255 samples for PSP toxins. PSP toxic events were concentrated with high levels in a few small regions rather than Puget Sound wide. Quilcene and Dabob Bays closed for the first time ever due to PSP toxins with the highest value of 12,688 μg/100g detected in mussels at Quilcene Bay marina in Jefferson County on September 23. The FDA standard for PSP toxin is 80 μg/100g of shellfish tissue. In 2014, unsafe levels of PSP toxins caused 29 commercial (24 geoduck clam tracts and 5 general growing areas) and 17 recreational harvest areas to be closed.

A total of 1,362 samples were analyzed for domoic acid in 2014, with the highest value of 6ppm detected in razor clams from Long Beach on January 8. There were no harvest closures due to domoic acid last year.

In 2014, the PHL analyzed 2,112 shellfish samples for DSP toxins. The highest DSP toxin measured in 2014 was 180 μg/100g in mussels from Sequim Bay in Clallam County. The FDA standard for DSP toxin is 16 μg/100g of shellfish tissue. DSP toxins caused 10 recreational and 2 commercial growing areas closures. 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 groups SoundToxins and ORHAB to detect potential marine biotoxin producing algae in Washington. This early-warning system helps WDOH identify and prioritize areas for additional biotoxin testing.



Pseudo-nitzschia. Photo: Gabriela Hannach

ii. SoundToxins

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

SoundToxins partners' sample phytoplankton at key locations throughout Puget Sound, with a focus on harmful algal bloom species, and report cell concentrations of *Alexandrium* spp., *Dinophysis* spp., *Heterosigma* sp., and *Pseudo-nitzschia* spp. in an online database. This provides an early warning system for the Washington Department of Health to prioritize shellfish toxin analysis and provide timely information to shellfish and finfish growers and researchers. Active monitoring sites in 2014 included: Budd Inlet, Burley Lagoon, Dabob Bay, Discovery Bay, East Sound, Fort Worden, Clam Bay, Mystery Bay, North Bay, Penn Cove, Port Susan, Port Townsend, Quartermaster Harbor, Sequim Bay, Spencer Cove, and Totten Inlet.

Alexandrium spp. counts were low or absent from most sampling locations throughout 2014 with the exceptions of East Sound and Sequim Bay. *Alexandrium* appeared in early February in Sequim Bay lasting until November. East Sound volunteers reported *Alexandrium* as common in August and September. The greatest abundance of *Alexandrium* was at the Sequim Bay monitoring site, with cells reaching 9,000 cells/L on September 16.

Dinophysis spp. was identified at all monitoring stations, except at Burley Lagoon, Dabob Bay, and Port Susan. Burley Lagoon and Dabob Bay started data collection in September therefore it is possible that *Dinophysis* could have been present earlier in the year at those sites. The greatest numbers of *Dinophysis* were reported at Discovery and Sequim Bays. On June 11, Discovery Bay cell counts reached 180,000 cells/L. Throughout August, *Dinophysis* was consistently above 5,000 cells/L with the highest level reaching 33,000 cells/L in Sequim Bay and was subsequently closed due to high DSP toxin levels all month.

Heterosigma akashiwo had a variable presence among the monitoring stations in 2014. Sites where *H. akashiwo* was present include: Clam, Discovery, Mystery and Sequim Bays, East Sound, Port Townsend, and Spencer Cove. Peak abundance reached 3.09 million cells/L in Sequim Bay on July 8th.

Pseudo-nitzschia spp. were commonly sighted all year long throughout Puget Sound in 2014 with the highest abundance observed in Sequim Bay, reaching 237,000 cells/L on May 14. Other locations with high cell counts include Port Susan on August 21 (187,000 cells/L) and Discovery Bay on May 21 (170,000 cells/L).

SoundToxins participated in NOAA's summer *Azadinium* pilot sampling study in hopes to gain a better understanding of where *Azadinium* and azaspiracids are present within Puget Sound. Very low but detectable concentrations of *A. spinosum*, *A. obesum* and *A. poporum* were found in whole water collected from Puget Sound.

Akashiwo sanguinea has had a strong presence at several locations including Quartermaster Harbor, Totten Inlet, Budd Inlet, North Bay, Spencer Cove, Clam Bay, Fort Worden, and Mystery Bay this year. Blooms began in late August and skipped around throughout Puget Sound through December. Totten Inlet had a consistently heavy population of *A. sanguinea* with cells reaching up to 2.72 million cells/L at the end of October.

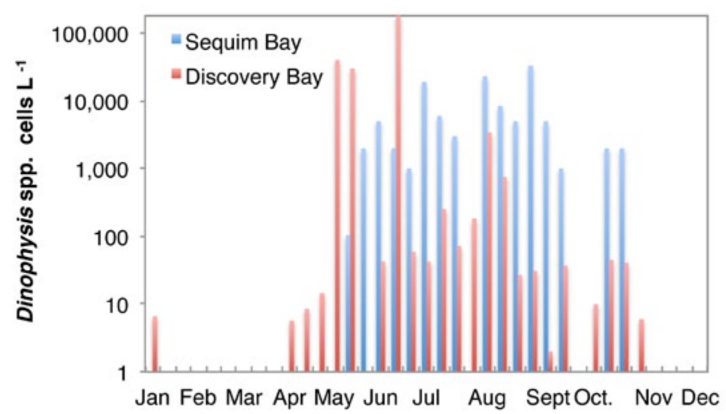
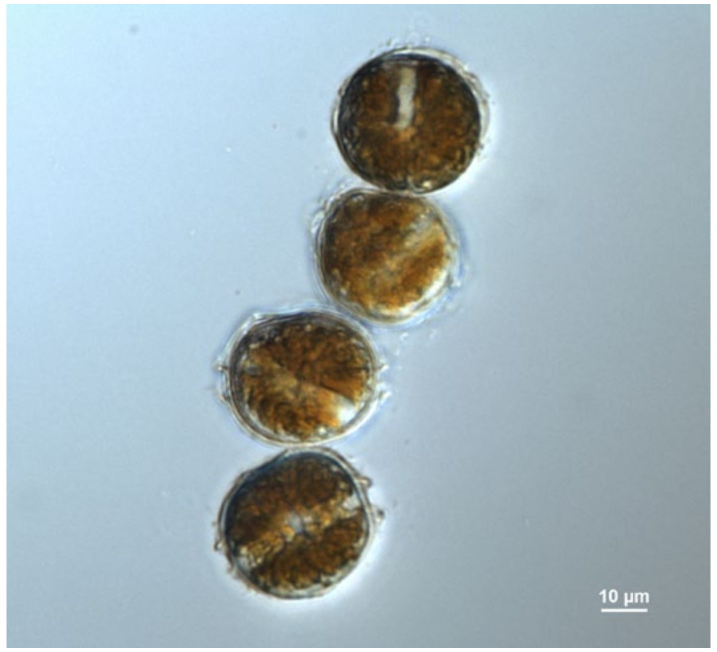


Figure 32. Dinophysis spp. abundance at Sequim Bay and Discovery Bay during 2014.



Alexandrium catenella. Photo: Gabriela Hannach

iii. *Alexandrium* species cyst mapping

The dinoflagellate 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; UCAR); http://www.tiny.cc/psahab

Emergency cyst mapping was conducted in response to concern that the unprecedented *Alexandrium* bloom in Quilcene and Dabob Bays formed a new seed bed that could increase bloom risk in the area during the 2015 season and beyond. Mapping took place January 17-20, 2015 and was supported in part by the NOAA ECOHAB Program and Penn Cove Shellfish. Previous cyst mapping efforts in 2011, 2012 and 2013 found zero or very low concentrations of cysts in the area; the highest concentration observed was 10 cysts/cc wet sediment in Quilcene Bay in 2013. In January 2015, an order of magnitude greater concentration of cysts was observed; up to 120 and 180 cysts/cc wet sediment in Quilcene Bay and Dabob Bay, respectively. These results were distributed widely to shellfish growers, health managers, and the SoundToxins monitoring program with a recommendation to increase vigilance for monitoring cells and toxins during the 2015 season and beyond in this area.

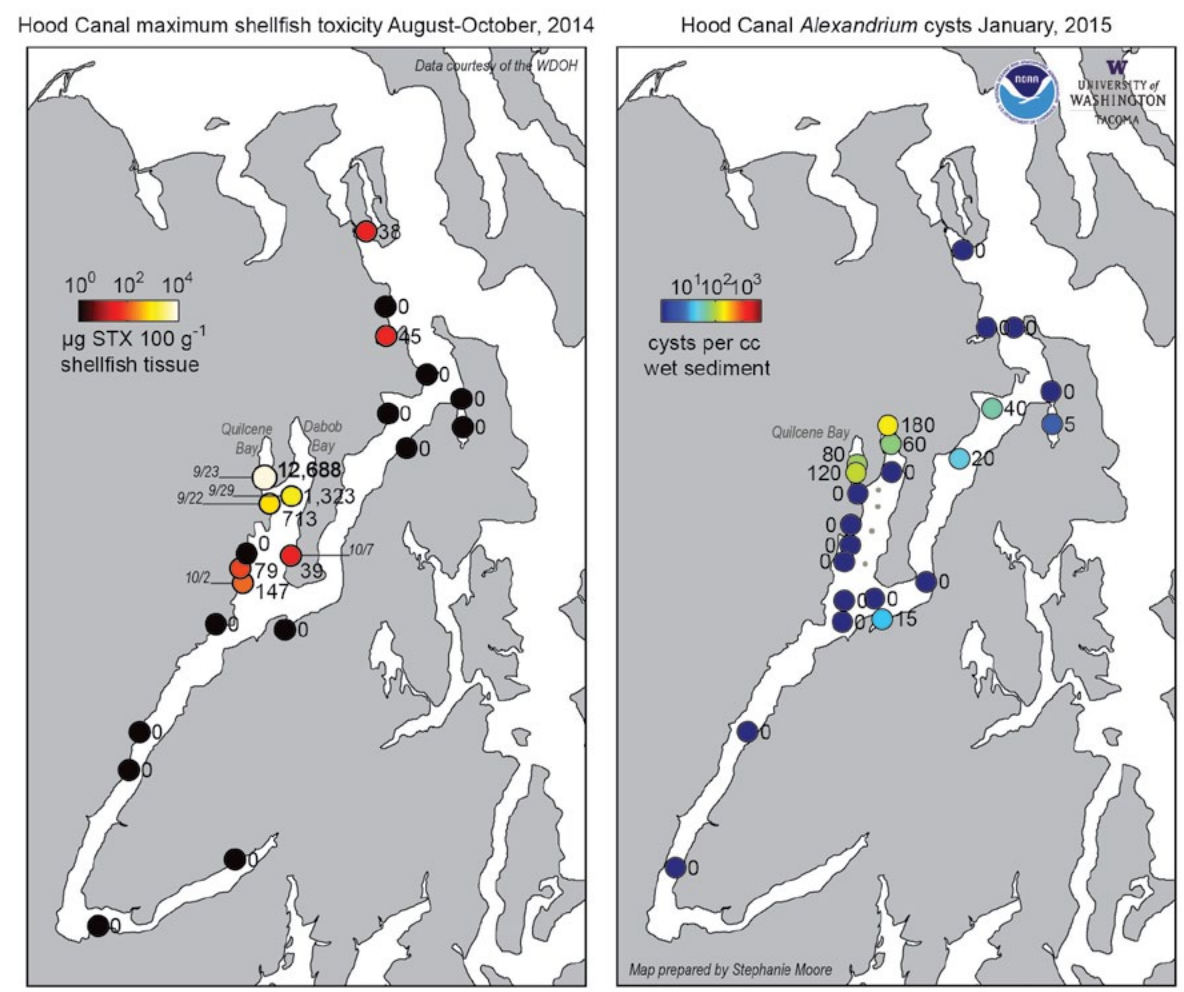


Figure 33. Maximum shellfish toxicity (ug STX/100 g) in Hood Canal from August-October 2014 (WDOH) and Alexandrium cysts/cc wet surface sediment in Hood Canal from January 2015 collected during the emergency cyst mapping survey.

Bacteria and pathogens

A. Fecal indicator bacteria

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

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/; http://www.ecy.wa.gov/programs/eap/beach/AnnualReport.html

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 or bi-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 2014, 60 Puget Sound beaches were sampled including 43 "core" beaches (beaches that are consistently sampled from year to year). Figure 34 represents the percentage of all monitored Puget Sound beaches and core beaches that had less than two swimming closures or advisories during the swimming season from 2004 through 2014. 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.

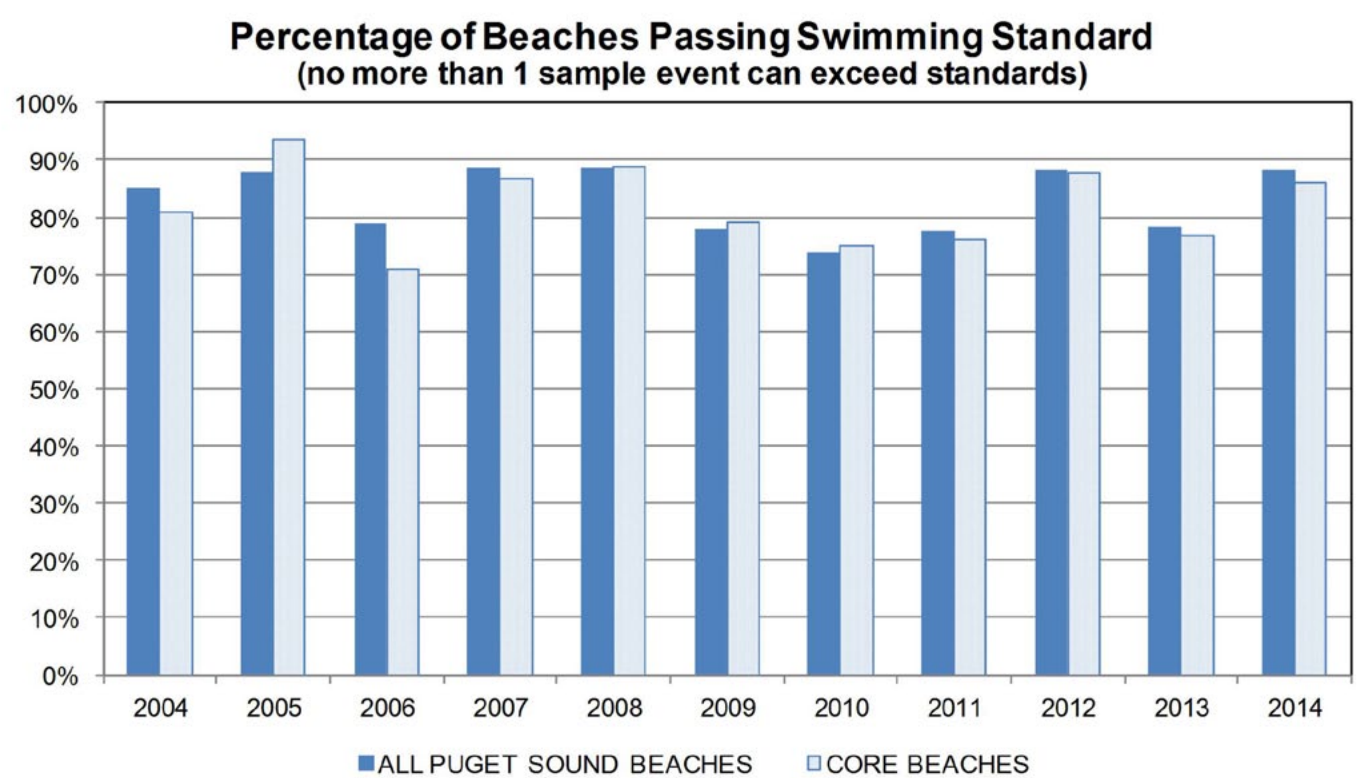


Figure 34. Percent of all monitored Puget Sound beaches and all core beaches (monitored frequently) that had less than two swimming closures or advisories during the 2004-2014 beach season.

ii. Central Basin stations

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

King County conducts water quality monitoring at 14 offshore locations in the Central Puget Sound Basin. Samples were collected twice-monthly from May thru November and monthly from January through April and December from the 1 m depth at six ambient and eight outfall stations. Ambient station locations were chosen to reflect ambient environmental conditions, while outfall stations are located 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 colony forming units (CFU) per 100 mL with no more than 10% of samples used to calculate the geometric mean exceeding 43 CFU/100 mL (peak standard). Fecal coliform data collected in 2014 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 monthly at 20 beach stations along the western shoreline of the county and on Vashon and Maury Islands. In 2014, nine of 20 beach monitoring stations met the geometric mean standard during all 12 months (Figure 35A). Of these nine stations, four also met the peak standard and were the only stations to do so. The highest number of peak exceedances occurred during the months of July, September, and October (> 10 station exceedances), and overall concentrations were higher than in previous years during these months (Figure 35B). These exceedances corresponded to periods of heavy rainfall. In July, samples were collected on a day with 0.76 inches of rainfall after more than three weeks without rain. Similarly, there was 1.52 inches of rainfall over the sampling day and the previous day in September after little rain prior, and 1.26 inches of rainfall during the sampling day in October.

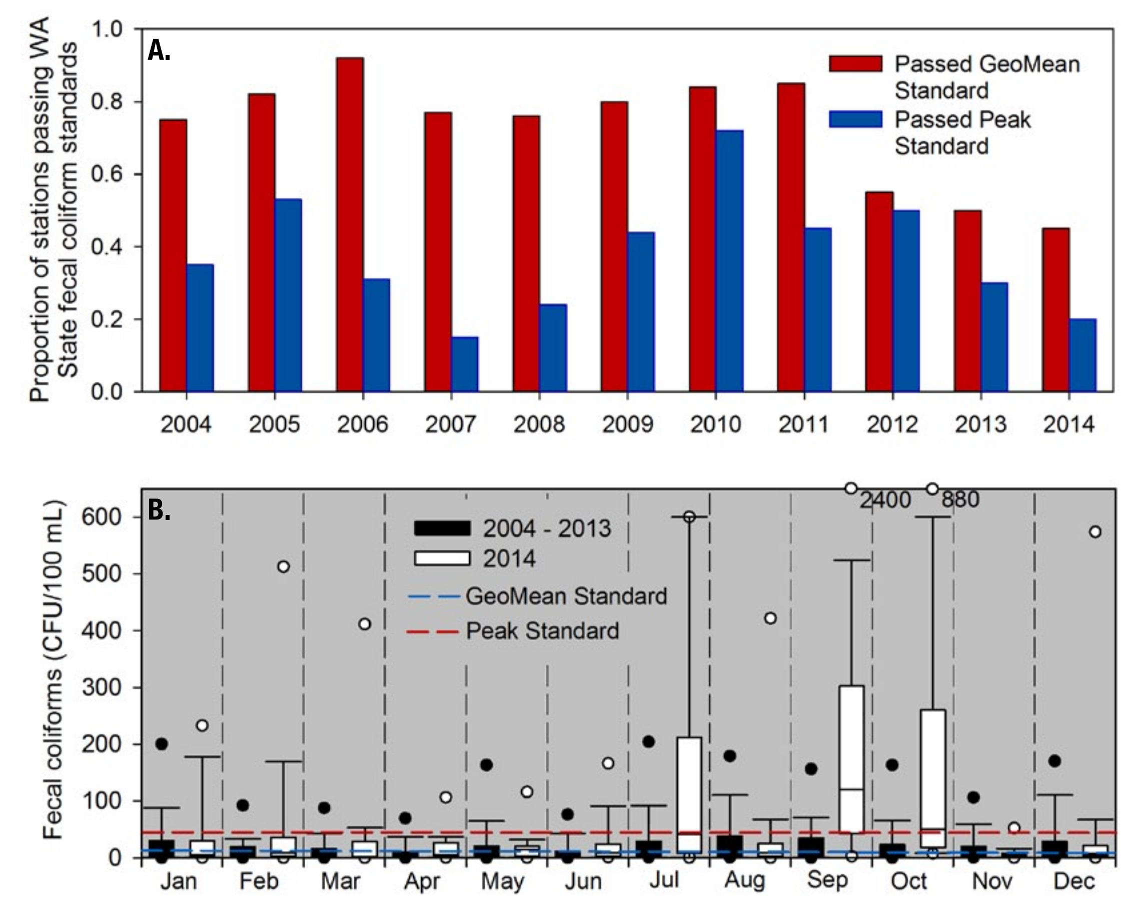


Figure 35. King County marine beach fecal station fecal coliform data: (A) Proportion of beach stations passing fecal coliform standards in 2004 through 2014; (B) Monthly fecal coliform concentrations at all beach sites in 2014 compared to 2004 through 2013 data.

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 Johnson (laura.johnson@doh.wa.gov) (WDOH); http://www.doh.wa.gov/CommunityandEnvironment/Shellfish.aspx

Vibrio parahaemolyticus (Vp) is a naturally occurring marine bacterium found in oysters that can cause gastrointestinal illness in humans. *Vibrio parahaemolyticus* 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 high *Vp* levels or 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 2014, 270 samples were collected from 24 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. In 2014 there were 81 laboratory-confirmed and epidemiologically-linked illnesses due to the consumption of oysters contaminated with *Vp*. Seventy six cases came from commercially-harvested oysters and five 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. Eighteen shellfish growing areas in Puget Sound were closed during 2014 due to high *Vp* levels or the occurrence of *Vp*-related illnesses associated with the areas.

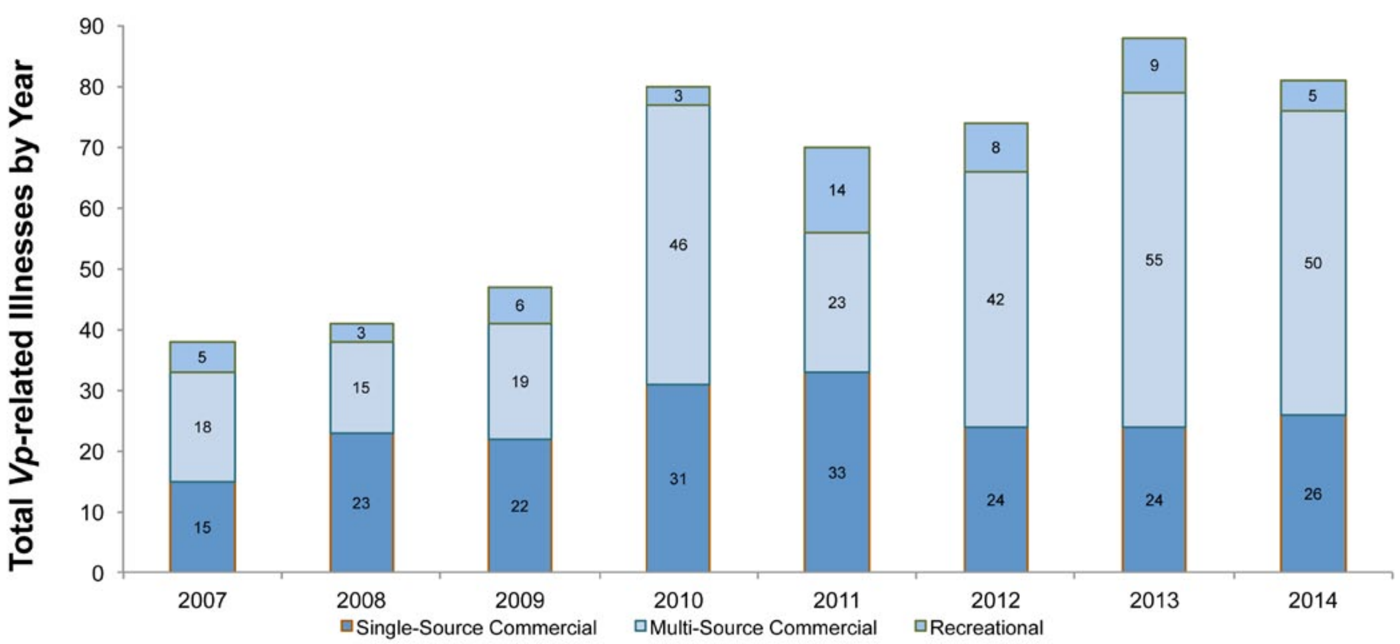
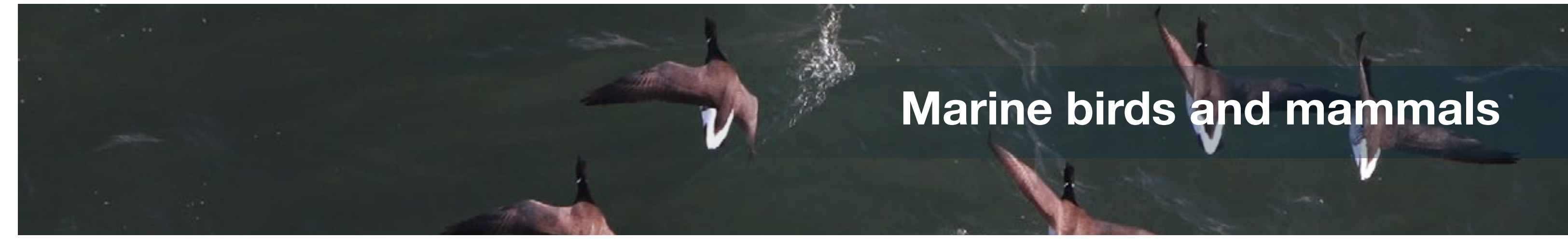


Figure 36. Vp-related illnesses for both commercially and recreationally harvested oysters.



Marine birds and mammals

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

A. Rhinoceros auklet – 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/index.html

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 2014, burrow occupancy, or the percentage of burrows that are reproductively active in a given season, was similar (69%) to the mean occupancy between 2006-2013 (70 ± 6%). Hatching success in 2014 was marginally higher than the 2006-2013 mean (91% vs. 86 ± 3%, respectively). Overall, fledging success (88%) in 2014 was higher than the average 2006-2014 values (80 ± 5%). Compared to the mid-1970s (1975 and 1976), burrow occupancy, hatching success and fledging success in the 2014 breeding season were all similar. The mean values from 2006-2014 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.

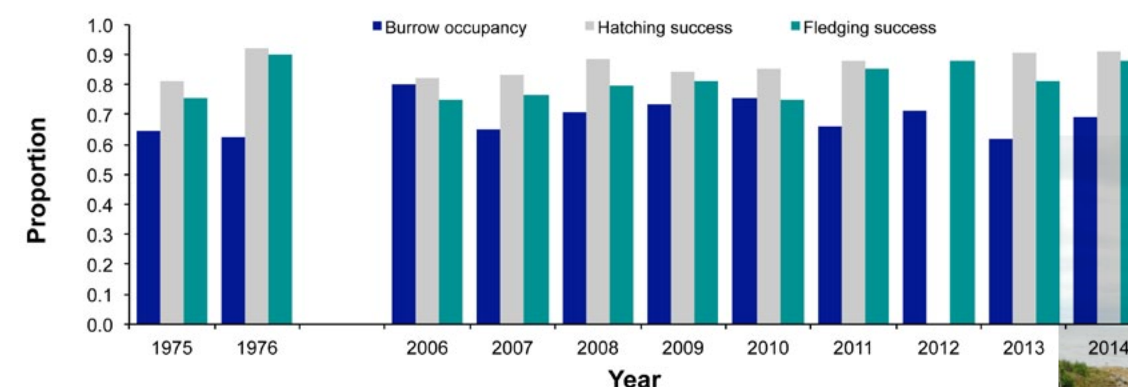


Figure 37. Temporal comparison of reproductive success parameters for the Protection Island rhinoceros auklet breeding population between the mid-1970s and the 2006-2014 breeding seasons. Burrow occupancy is defined as the proportion of burrows reproductively active in a given season. Hatching success is the proportion of eggs laid that produce nestlings, and fledging success is the proportion of eggs laid that produce fledglings.

Probing a burrow with an infrared, fiber optic probe to determine the burrow's status (e.g., does it have an egg?). Photo: Peter Hodum

B. Wintering marine birds

Source: Jerry Joyce (JerryJoyce@MoonJoyce.com) (Moon Joyce Resources), Toby Ross (Seattle Audubon Society), and Nathalie Hamel (PSP); http://www.seattleaudubon.org/sas/WhatWeDo/Science/CitizenScience/PugetSoundSeabirdSurvey

The Seattle Audubon's Puget Sound Seabird Survey is a citizen-science program that uses expert bird watchers to systematically count and identify birds from the water line out to a distance of 300 meters from October to April each year. The program is designed to monitor the winter migration and the overwintering community of marine birds as species diversity is typically highest during this period. The program started in 2008 with most effort focused on the east shore of Central and South Puget Sound and has since expanded to Admiralty Inlet, the Strait of Juan de Fuca, and the west shore of Puget Sound.

Data summarized are from the longest established sites (*n* = 62), located predominately in Central and South Puget Sound, where 339-377 surveys were conducted each survey season between 2009 and 2014. As the dataset grows over time and includes data from more diverse locations, results will be more representative of the entire Puget Sound region.

Species richness (the number of species present in a community) provides an indication over time of how well the Puget Sound region supports the diverse demands of marine birds. In the short term, species richness may be sensitive to local and regional oceanographic and climatic forces.

Fifty-four species were observed during the 2013-2014 survey season with species richness peaking in November with 37 species (Figure 38). While this was similar to previous years, species richness in October 2013 was significantly higher in part due to the presence of some pelagic species that have rarely (Cassin's Auklet, Parasitic Jaeger) or never (Pomarine Jaeger) been seen in previous surveys. Overall, the three most abundant species seen were surf scoters, buffleheads, and horned grebes, respectively, and January 2014 had the highest overall bird count with close to 3,000 observed.

Common Merganser sampling the food web during a seabird survey. Photo: Kim Stark

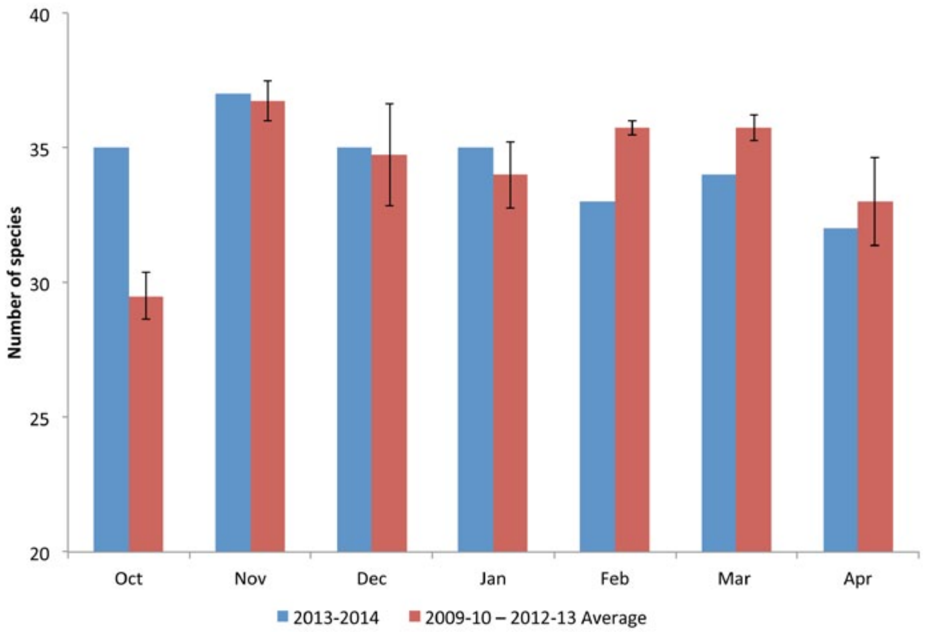


Figure 38. Average monthly species richness at 62 sample locations for the 2013/14 season and compared with the 2009/10 to 2012/13 survey monthly average species richness. Error bars are the standard error.

Marine birds and mammals (cont.)

C. Harbor porpoise

i. Aerial surveys I

Source: Joseph Evenson (joseph.evenson@dfw.wa.gov) (WSFW), David Anderson and John Calambokidis (Cascadia Research Collective); http://wdfw.wa.gov/; http://wdfw.wa.gov/conservation/research/staff/evenson_joe.html

We document the progressive return of harbor porpoise (*Phocoena phocoena*) to Puget Sound based on WDFW winter aerial waterfowl surveys conducted from 1994 to 2014. Harbor porpoise were considered the most common cetacean in the inland waters of Washington State in the 1940s including Puget Sound, but had almost completely disappeared from waters south of Admiralty Inlet by the 1960s and remained absent through the 1990s. While reports from the public and opportunistic observations in the mid to late 2000s indicated their apparent return, these reports did not provide a clear understanding of the timing and extent of this shift. Based on recent analyses of the annual winter waterfowl aerial surveys and information from past surveys done in the 1990s and 2000s, we show that the return of harbor porpoise to Puget Sound was part of an overall increase in their occurrence in Washington inland waters with a progressive shift in distribution extending into Puget Sound. While the cause of their disappearance and return is not known, it may be related to changes in local fisheries. Reduced mortalities associated with (especially) gill net fisheries are likely allowing harbor porpoise populations to recover and return to their full former range. Coincident with the return of harbor porpoise, the surveys show a progressive decline in Dall's porpoise in the same waters. This appears related to the return of harbor porpoise and possible competition between the two species which typically occupy different habitats. Harbor porpoise generally occupy more coastal, shallow waters while Dall's porpoise usually occur more offshore. The return of harbor porpoise to Puget Sound and their overall increase in inland waters is a positive indicator for the recovery of this ecosystem.

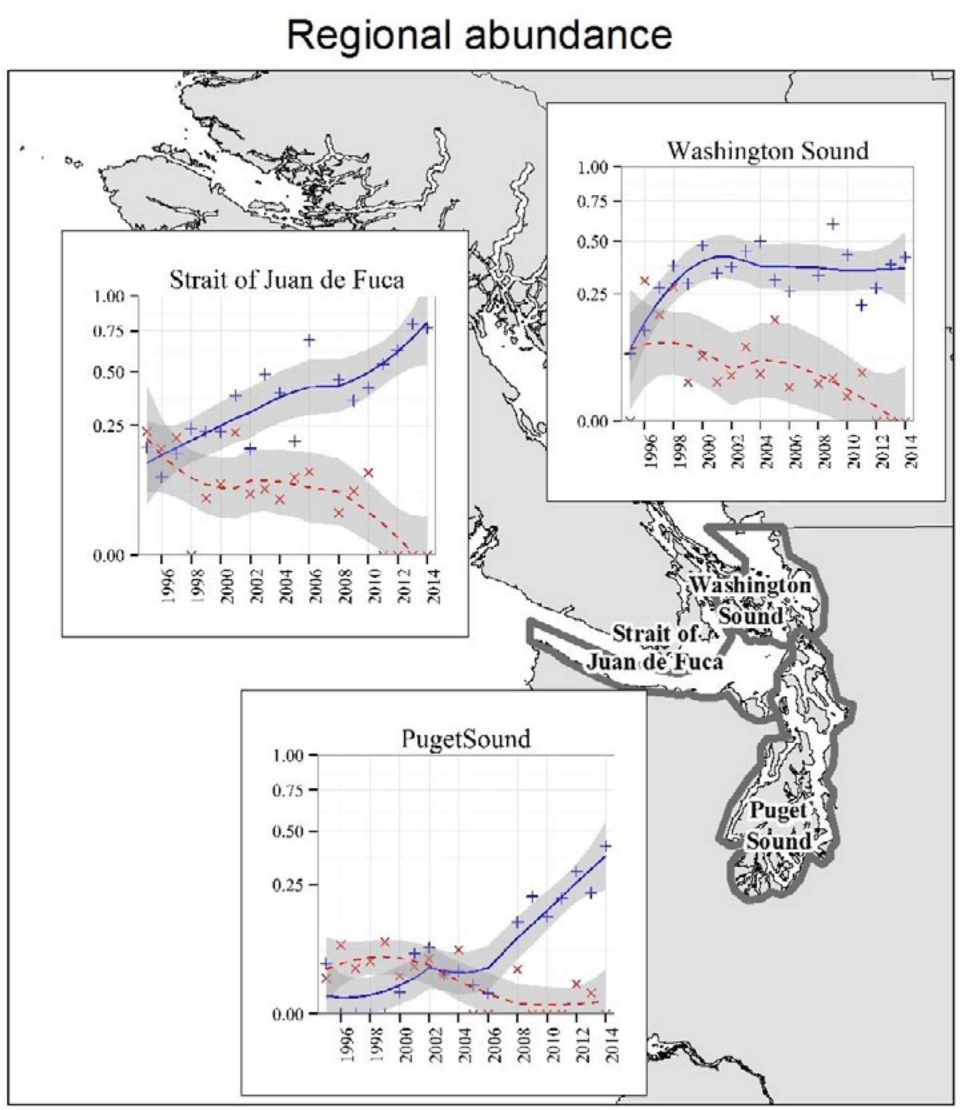


Figure 39. Trends in harbor and Dall's porpoise in three different regions of Washington inland waters based on WDFW winter waterfowl aerial surveys. Graphs show animals per surveyed sq km. Blue = harbor porpoise; Red = Dall's porpoise.

Four harbor porpoises photographed 21 July 2014 in Puget Sound. Photo: Mark Deakos NMFS permit 15569

ii. Aerial surveys II

Source: Mari A. Smultea (mari@smulteasciences.com) (Smultea Environmental Sciences), Thomas A. Jefferson (Texas A&M University), Sarah Courbis (Smultea Environmental Sciences), and David Streckler (Entiat. River Technologies); http://www.smulteasciences.com

Harbor porpoises were historically common in Puget Sound, but abundance declined, with none sighted in 1994 (Carretta et al. 2014). Recent sightings and strandings raised the question of possible repopulation of Puget Sound. We have been conducting systematic aerial surveys for marine mammals in eight sub-regions of Puget Sound, funded by the U.S. Navy. Thus far, surveys have been conducted in August 2013, July 2014 (Figure 40), September 2014, January 2015, and April 2015. When marine mammals are observed, group size, number of calves or pups (individuals <½ an adult size), behavior state (mill, travel, rest), heading, and minimum and maximum spacing of individuals within groups (i.e. “cohesion” based on body lengths) are recorded. Photographs are used to confirm species, calf/pup presence, and group size.

As of January 2015, a total of 19,407 km of trackline had been surveyed, resulting in 744 harbor porpoise groups totaling an estimated 1,748 individuals. Very preliminary analyses based on data from Aug 2013 and July 2014 result in an estimated late summer density of 0.695/km^2 and abundance of 1,832 (95% CI of 1,312-2,558, CV=0.17). These estimates are corrected for missed animals using g(0) estimated by Laake et al. (1997). An exploratory flight into the Strait of Juan de Fuca in Sept 2014 resulted in harbor porpoise sightings as well. Survey work and data analyses for this project are ongoing.

In summary, harbor porpoises are back in Puget Sound! Preliminary analyses are indicating that harbor porpoises are present in all seasons, most areas (even south of Tacoma), and in relatively large numbers. Other marine mammal species observed during our surveys include harbor seals for which abundance and density estimates have not been calculated since 1999 (Jeffries et al. 2003), Steller sea lions, California sea lions, Risso’s dolphins, minke whales, killer whales and feeding gray whales.

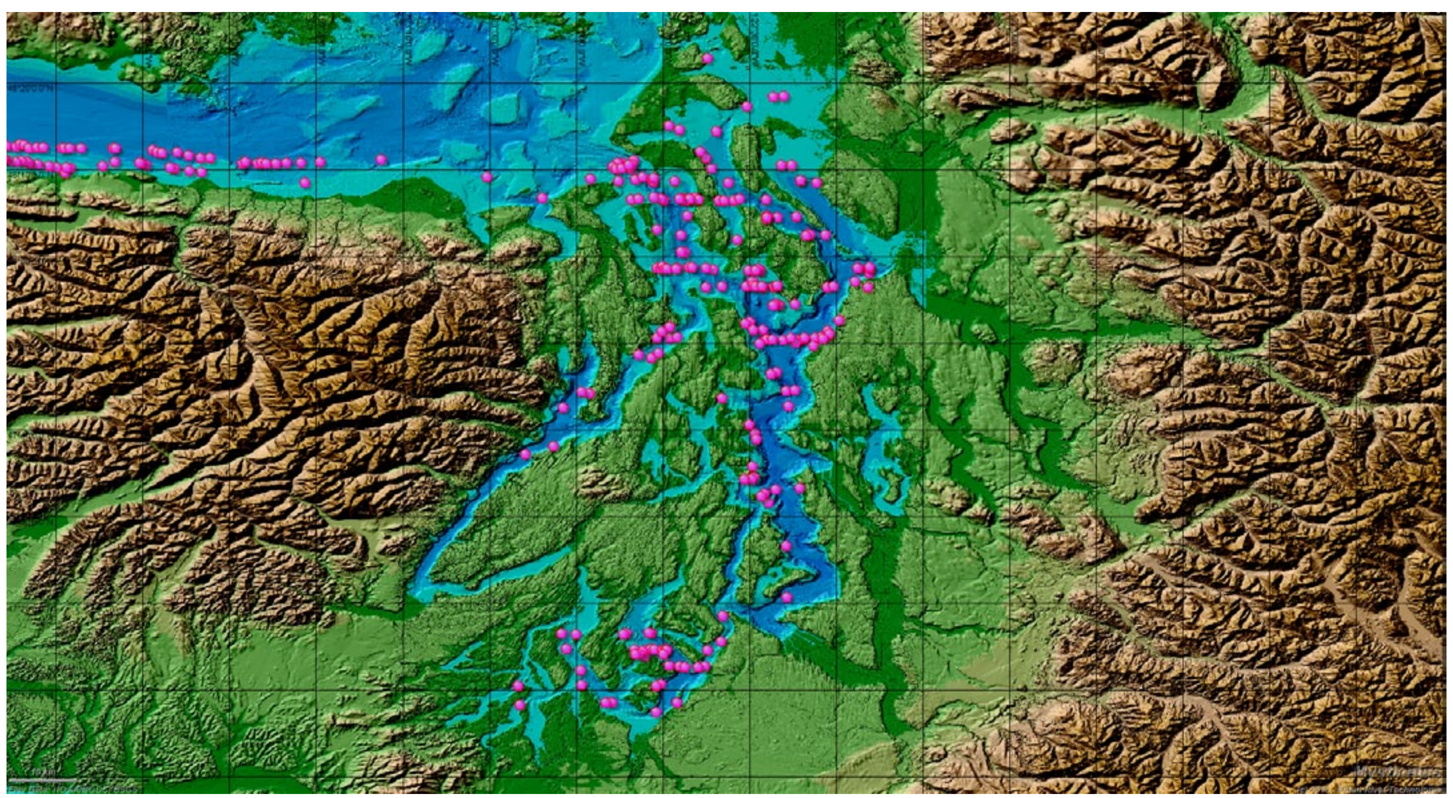


Figure 40. Example map showing harbor porpoise groups seen during July 2014.

iii. Movement and distribution

Source: Aileen Jeffries (aileen@pacificbio.org); http://www.pacificbio.org

Population dynamics of the harbor porpoise, *Phocoena phocoena*, in the Salish Sea are poorly understood. It is listed as a Candidate Species of Concern in Washington. The population was abundant in the 1950s, dropped dramatically by 1992, then began rebuilding. Using passive acoustic monitors combined with citizen scientist volunteer observations since 2009, the Pacific Biodiversity Institute’s Harbor Porpoise Project is expanding information about this little known species. Data on 2014 seasonal movements and distribution shows winter concentrations of harbor porpoise in Burrows Pass and summer concentrations in Admiralty Inlet. This information is helping us understand seasonal changes in harbor porpoise habitat use. Passive Acoustic Monitors were used to continuously record the fraction of time harbor porpoise were present at Burrow’s Pass, Rosario Strait, and Admiralty Inlet in 2014. Porpoises occurred year-around in Burrows Pass and Rosario Strait, but their presence in Burrows Pass peaked during winter months (September - March) while presence in Rosario Strait peaked in September and October. In contrast, harbor porpoise were rarely observed in Admiralty Inlet during winter months but showed a marked increase in presence in June, July and August. (Figure 41).

We are examining these data to understand how seasonal changes affect harbor porpoise choice of habitat. We are also studying how calving events, which occur primarily in June and July, may be part of this movement. The porpoises’ regular, high presence in Burrows Pass suggests this is a stronghold for the porpoises based on behavior, lifecycle events and continuous time present.

In the coming year we will be relating movement and distribution to forage and calving requirements.

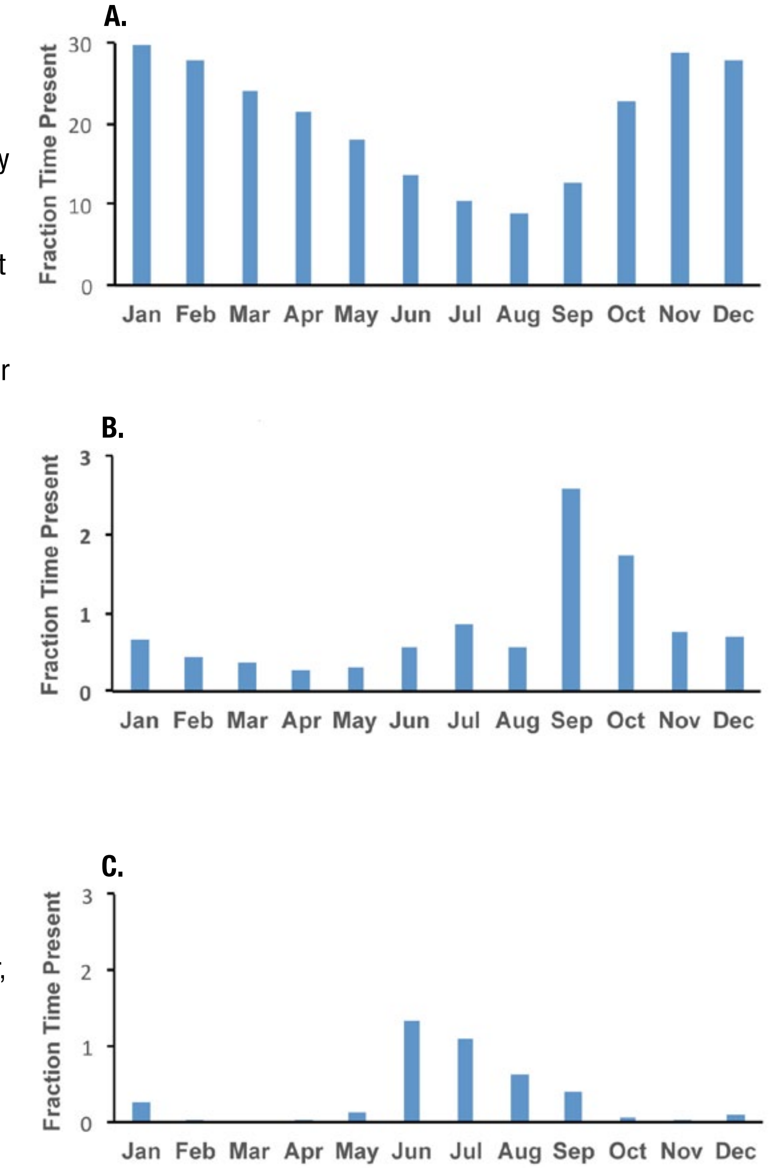


Figure 41. Seasonal differences in harbor porpoise presence in (A) Burrows Pass, (B) Rosario Strait, and (C) Admiralty Inlet, in 2014 (note differences in Y-axis scale).

Harbor porpoise are most often seen alone but may arrive in groups of two or three. Photo: Steven Gnam

CALL-OUT BOX: Winter movements of endangered Southern Resident killer whales in the Salish Sea

The frequent occurrence of endangered Southern Resident killer whales (SRKWs) in the Salish Sea throughout the summer months has been well documented over the past 40 years. Between June and September, this population typically spends most of their time in Haro Strait and the southern Strait of Georgia. As well, the whales periodically transit to the outer coast through the Strait of Juan de Fuca. However, the whales' occurrence patterns apparently change during the winter as they are infrequently seen in inland waters. Unfortunately, the extent to which this is due to them not being present, or not being observed due to limited day-length and/or inclement winter, is unclear. Since 2012 we have attempted to address this data gap by deploying satellite-linked transmitters on six SRKWs. Three of these tags were deployed on members of J pod between late December and mid-February of 2012, 2014, and 2015 (Figure 42). Two of the three tags remained attached for 28 (L87, travels with J pod) and 50 days (J27) which allowed for a four and six week assessment of their movements. The location data showed that the whales displayed remarkably similar occurrence patterns in 2014 and 2015. What was particularly striking about their travels was that in both years the whales remained primarily within the Salish Sea, despite being rarely observed. Additionally, it was apparent that the areas the tagged whales visited differed from their summer distribution. Although the whales commonly transit through the Strait of Juan de Fuca and Haro Strait in the summer, other areas were used that are not visited during that time of year: Puget Sound, and in particular, the northern Strait of Georgia. These new data illustrate the multi-season importance of the Salish Sea to a portion of the SRKW population.

Authors: M. Bradley Hanson (brad.hanson@noaa.gov), and Candice K. Emmons (NOAA, NWFSC), Gregory S. Schorr (Cascadia Research Collective) and Damon M. Holzer (NOAA, NWFSC)

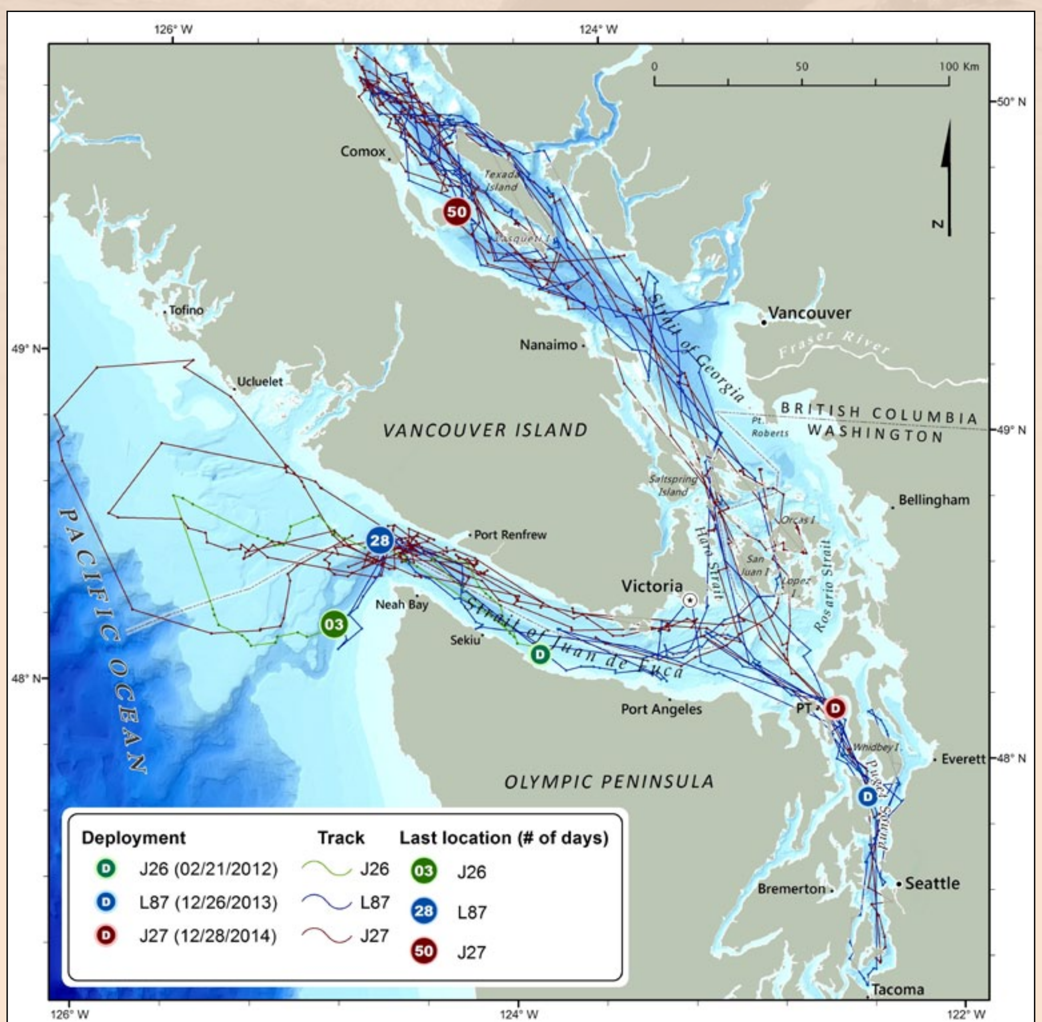


Figure 42. Movement tracks of three Southern Resident killer whales from J pod tagged with satellite-linked transmitters.

SRKWs in Puget Sound. Background photo: Candice Emmons

A. Pacific herring

Source: Dayv Lowry (dayv.lowry@dfw.wa.gov), Kurt Stick and Adam Lindquist (WDFW); http://wdfw.wa.gov/conservation/research/projects/marine_fish_monitoring/herring_population assessment/index.html

Pacific herring (*Clupea pallasi*) are a vital component of the marine food web and an indicator species of overall Puget Sound health. These small, prolific fish are prey for a variety of birds, fish and marine mammals throughout their entire life cycle. Herring stocks are defined by spatiotemporal isolation of spawning activity, and 21 stocks typically spawn annually in Puget Sound. Stock assessment is based on annual estimates of the tonnage of spawning adults (spawning biomass). Two methods have been used by WDFW since the 1970s to provide quantitative estimates of herring spawning biomass: spawn deposition surveys (vegetation rake surveys) and acoustic/trawl surveys, but acoustic/trawl surveys were eliminated in 2009. Detailed methods and results are presented in periodic WDFW reports (e.g., Stick and Lindquist 2009; Stick et al. 2014).

Genetic studies have concluded that the Cherry Point and Squaxin Pass herring stocks are demographically distinct, but that all other sampled stocks in Puget Sound are genetically homogenous (Beacham et al. 2001; Small et al. 2005; Mitchell 2006). Here, status is presented for the Cherry Point and Squaxin Pass stocks independently, and for all other stocks in aggregate. Despite significant interannual variation, the number of herring in the Squaxin Pass stock and Other Stocks complex have been relatively stable over the past 40 years. However, in 2014 the biomass of the Other Stocks complex was nearly 20% below its 10-year average of ~9,500 tons, while the biomass of the Squaxin Pass stock remained more stable. The spring-spawning Cherry Point stock in North Puget Sound, however, has declined by over 90% since 1973 and remained near record low levels in 2014. Concerns continue regarding declines in herring biomass, and the resultant ecosystem-wide impacts of this reduction in prey abundance.

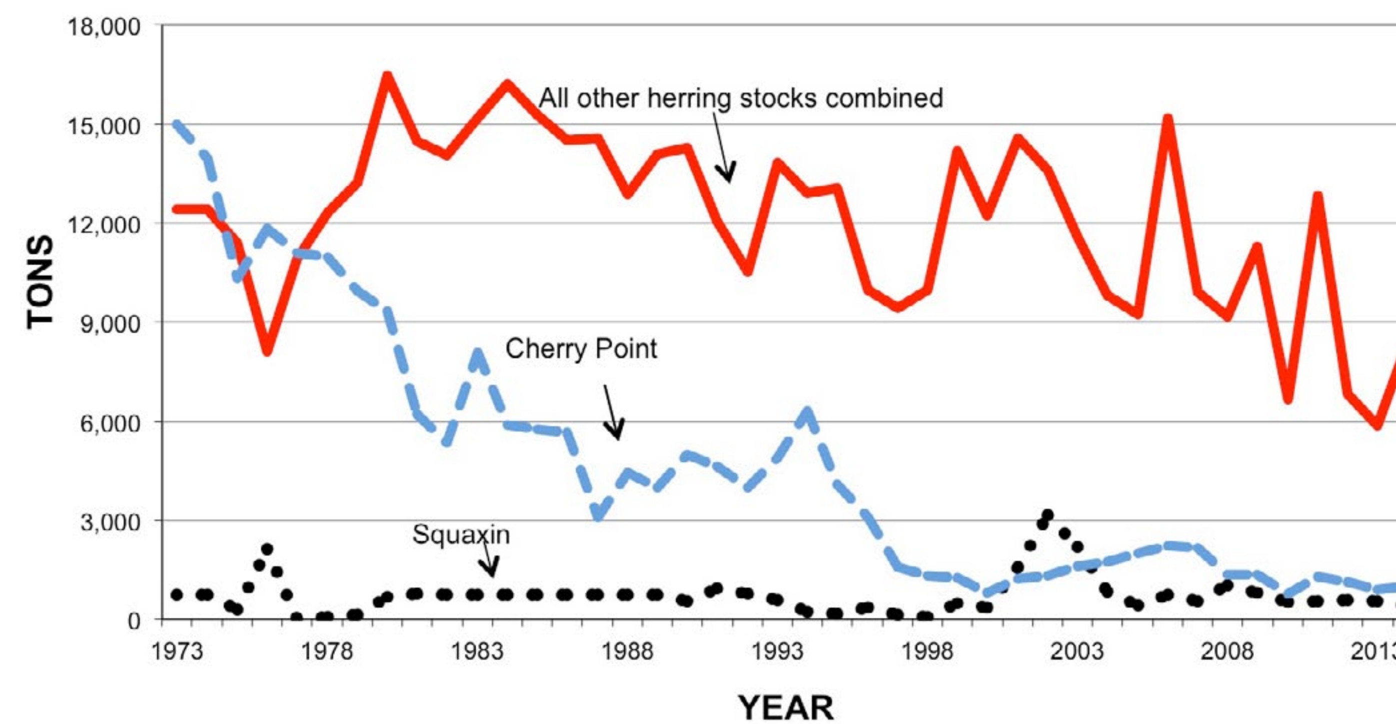


Figure 43. Estimated spawning biomass of Pacific Herring in Puget Sound since 1973. Series represent three genetically distinct populations: the Cherry Point Stock in northern Puget Sound; the Squaxin Pass Stock in southern Puget Sound; and the Other Stocks Complex, composed of the remaining 19 stocks. Since monitoring began, a substantial decline can clearly be seen for the once dominant Cherry Point Stock.

B. Sand lance

Source: Olivia Graham (ojgraham@mac.com), Matthew Baker, Kailee Bynum, Emily Burke, Jan Newton, and W. Breck Tyler (UW, FHL); http://depts.washington.edu/fhl/

Spatiotemporal variation in abundance, conditions, and age groups was assessed for Pacific sand lance (*Ammodytes personatus*) in the San Juan archipelago in the fall of 2014. Sand lance were collected from Jackson Beach (JB) and the San Juan Channel (SJC), and were compared to historical data from 2010-2013 to determine seasonal and inter-annual patterns.

Within the fall 2014 season, sand lance abundance increased at both sites consistent with the timing of sand lance winter dormancy (Robards et al. 1999). At Jackson Beach, sand lance were most abundant in 2012, less abundant in 2013, and declined to their lowest recorded abundance in 2014. In the San Juan Channel, sand lance declined from an estimated 111 million in 2011 to just 38 million in 2014.In 2014, sand lance at both locations were in greatly reduced condition compared to the previous two years. However, SJC sand lance were in better condition in 2014 than those at JB, suggesting that there may have been different environmental conditions that influenced survivorship and growth between the sites.

Age groups were determined based on the fork lengths for individuals and were based on Wyllie-Echeverria's length-age categories (unpublished data 2010). Both locations had alternating years that were dominated by young or old sand lance. Even years (2010, 2012, 2014) had predominantly smaller, younger sand lance whereas odd years had primarily larger, older sand lance (2011, 2013; Figure 44). Across all years, JB sand lance were younger (years 0-1) than those from the SJC (years 0-3), suggesting that JB is a rearing site for younger fish. Overall, the results suggest that sand lance abundance is lower than in previous years, and that the population may demonstrate year class strength.

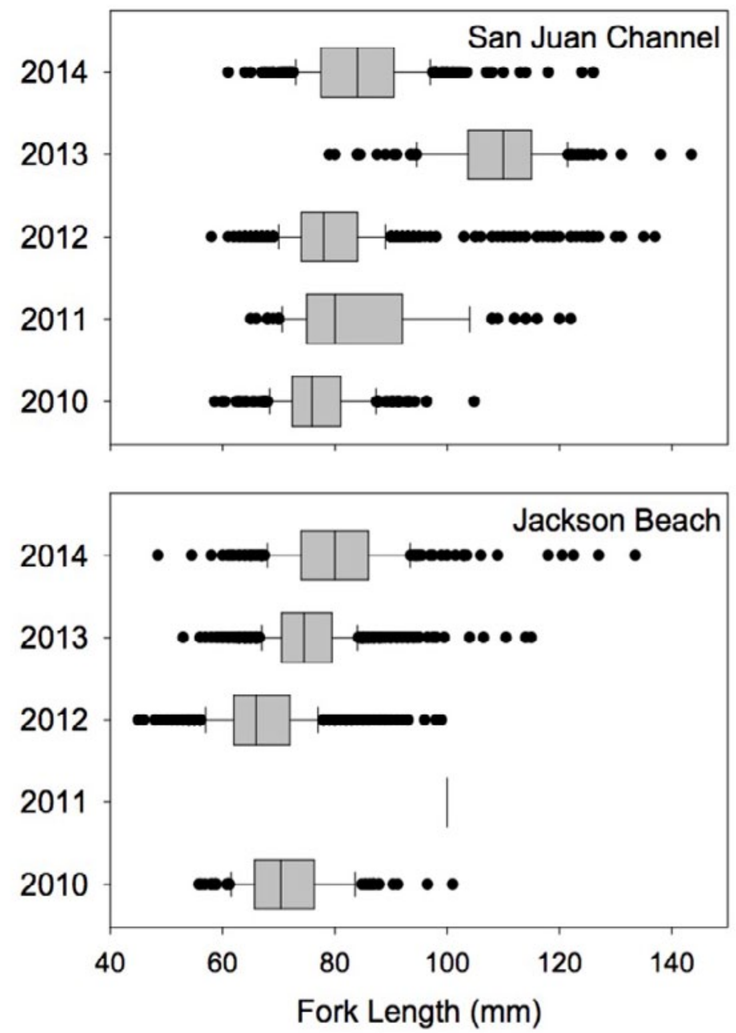


Figure 44. Fork length distributions (mm) for sand lance caught in the San Juan Channel (SJC) and at Jackson Beach (JB) from 2010-2014. Middle bars within boxes represent median values and 90% of data are within the whiskers.

Students aboard the R/V Centennial sampling from a Van Veen Grab collection. Photo Breck Tyler

CALL-OUT BOX: Puget Sound Steelhead marine survival research

In 2013, the Washington Department of Fish and Wildlife and the Puget Sound Partnership initiated an effort to determine why juvenile steelhead are dying in Puget Sound (Steelhead Marine Survival Workgroup 2014). This collaborative effort involves federal agencies, Puget Sound Treaty Tribes, and academic representatives. It is coordinated by the nonprofit Long Live the Kings and is a component of the Salish Sea Marine Survival Project. Nine studies were implemented in the initial 2014 research phase. These studies are not complete but initial findings suggest: Steelhead smolt-to-adult (marine) survival rates were lower in Puget Sound than on the coast or lower Columbia River. The best predictor of marine survival rates for all regions combined was the spring upwelling index. However, the best predictors for Puget Sound were adult herring abundance (positive correlation) and harbor seal abundance (negative). The correlation with herring abundance could be a predator buffer effect, or possibly herring and steelhead are similarly affected by another factor.

Similar to previous studies, we observed high mortality (>80%) in the Puget Sound marine environment. A reciprocal transplant, acoustic telemetry study comparing Nisqually and Green River wild steelhead showed mortality is primarily a function of distance traveled through Puget Sound and not a result of population or river condition. Mortality was highest from river mouths to Admiralty Inlet and was much lower in the rivers and Strait of Juan de Fuca.

Predation was identified as the likely proximate driver of mortality. However, the primary predator has not been confirmed, and it's uncertain whether or not increased predator abundance, poor fish condition, or other ecosystem dynamics are driving the predation of steelhead. A literature review suggested harbor seals and cormorants are the most likely predators. An acoustic telemetry study of encounter rates between seals and steelhead showed a large number of encounters, although no specific predation events were observed by harbor seals outfitted with receivers. However, we did observe atypical acoustic tag behavior (e.g. stationary detections near seal haul out sites) suggesting tagged steelhead may have been consumed and the tag deposited by the predator.

Fish condition was also evaluated as a potential contributing or underlying driver of steelhead mortality. Results suggest that toxic contaminants aren't a primary factor driving survival. However, the parasite *Nanophyetus* was prevalent in steelhead collected from both the Green and Nisqually Rivers, and was particularly intense in the Nisqually population. High *Nanophyetus* prevalence in steelhead in the lower rivers and marine environment suggest the parasite may be contracted as steelhead migrate downstream and into Puget Sound. A saltwater challenge of heavily infected steelhead suggested that marine entry itself would not kill infected fish; however, further investigation into the effect of *Nanophyetus* on swimming performance and, thusly, predator avoidance, is warranted.

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Steelhead smolt. Photo: Morgan Bond

Tulalip Tribe and NOAA staff seining the Snohomish Estuary for juvenile steelhead and salmon. Background photo: Long Live the Kings

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Acronyms

APL	Applied Physics Laboratory
ASP	Amnesic Shellfish Poisoning
ATG	Atmospheric Sciences and Geophysics building
BEACH	Beach Environmental Assessment, Communication and Health
cfs	cubic feet per second
CFU	Colony Forming Unit
CTD	Conductivity Temperature Depth
DO	Dissolved Oxygen
DSP	Diarrheic Shellfish Poisoning
ECOHAB	Ecology and Oceanography of Harmful Algal Blooms Program
Ecology	Washington State Department of Ecology
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
FDA	US Food and Drug Administration
FHL	Friday Harbor Laboratories
HAB	Harmful Algal Bloom
JB	Jackson Beach
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
KC	King County
KCDNRP	King County Department of Natural Resources and Parks
KCEL	King County Environmental Laboratory
MARINe	Multi-Agency Rocky Intertidal Network
MPN	Most Probable Number
$m^3 s^{-1}$	Cubic Meters per Second
NANOOS	Northwest Association of Networked Ocean Observing System
NERR	National Estuarine Research Reserve
NEMO	Northwest Enhanced Moored Observatory
NIT	Nisqually Indian Tribe
NMDS	Non-metric Multi-dimensional Scaling
NOAA	National Oceanic and Atmospheric Administration
NPGO	North Pacific Gyre Oscillation
NWFSC	Northwest Fisheries Science Center
NWIC	Northwest Indian College
ONI	Oceanic Nino Index
ORCA	Oceanic Remote Chemical Analyzer
OWSC	Office of the Washington State Climatologist
PAR	Photosynthetically Active Radiation
PBI	Pacific Biodiversity Institute
PBNERR	Padilla Bay National Estuarine Research Reserve
PDO	Pacific Decadal Oscillation
PGST	Port Gamble S'Klallam Tribe
PFEL	Pacific Fisheries Environmental Laboratory
PHL	Washington State Public Health Laboratory
PMEL	Pacific Marine Environmental Laboratory
PS Partnership	Puget Sound Partnership
PSEMP	Puget Sound Ecosystem Monitoring Program
PSP	Paralytic Shellfish Poisoning
S	Salinity
SJC	San Juan Channel
SSWS	Sea Star Wasting Syndrome
T	Temperature
UCAR	University Corporation for Atmospheric Research
UW	University of Washington
UWT	University of Washington-Tacoma
Vp	*Vibrio parahaemolyticus*
WDFW	Washington Department of Fish and Wildlife
WDOH	Washington State Department of Health
WSG	Washington Sea Grant
WWU	Western Washington University