# puget sound marine waters

2011 overview



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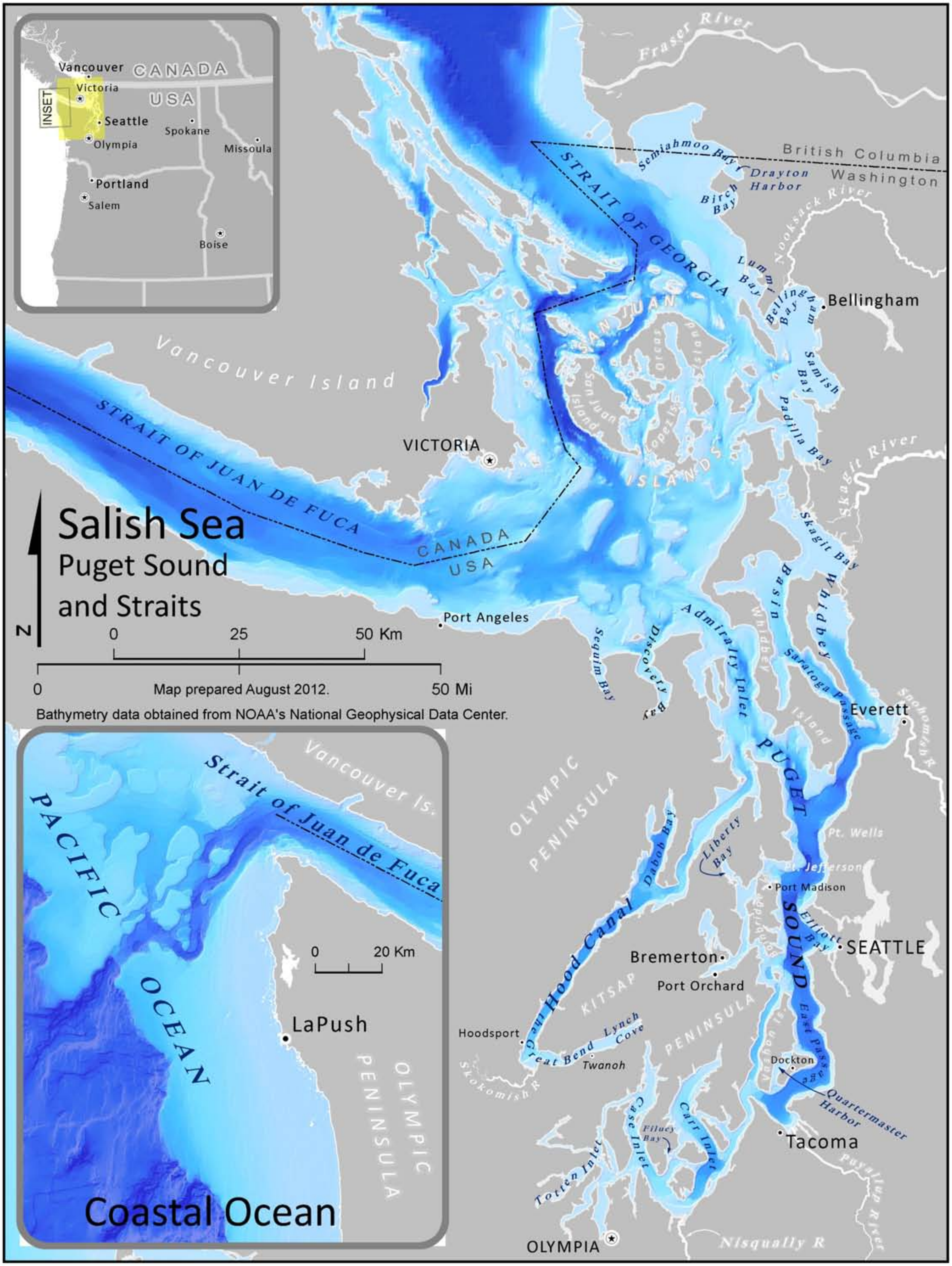

Salish Sea
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Map prepared August 2012.
Bathymetry data obtained from NOAA's National Geophysical Data Center.
Vancouver
CANADA
USA
Victoria
INSET
Seattle
Spokane
Olympia
Missoula
Portland
Salem
Boise
Fraser River
British Columbia
Washington
Semiahmoo Bay
Drayton Harbor
Birch Bay
STRAIT OF GEORGIA
Nooksack River
Lummi Bay
Bellingham Bay
Bellingham
SAN JUAN ISLANDS
San Juan Island
Orcas Island
Lopez Is.
Samish Bay
Padilla Bay
Vancouver Island
STRAIT OF JUAN DE FUCA
VICTORIA
Skagit River
CANADA
USA
Skagit Bay
Port Angeles
Sequim Bay
Discovery Bay
Admiralty Inlet
Whidbey Basin
Whidbey Island
Saratoga Passage
Everett
Snohomish R.
PUGET SOUND
OLYMPIC PENINSULA
Dabob Bay
Liberty Bay
Pt. Wells
Pt. Jefferson
Port Madison
Elliott Bay
SEATTLE
Hood Canal
Bremerton
Port Orchard
KITSAP PENINSULA
Hoodsport
Great Bend
Lynch Cove
Twanoh
Skokomish R.
Dockton
East Passage
Quartermaster Harbor
Case Inlet
Carr Inlet
Filucy Bay
Tacoma
Puyallup River
Totten Inlet
OLYMPIA
Nisqually R
Vancouver Is.
Strait of Juan de Fuca
PACIFIC OCEAN
0 20 Km
LaPush
OLYMPIC PENINSULA
Coastal Ocean

2011 overview

harmful algae

water quality

bacteria

climate & weather

shellfish

ocean acidification

dissolved oxygen

# puget sound marine waters

Editors: Stephanie Moore, Rosa Runcie, Kimberle Stark, Jan Newton and Ken Dzinbal

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

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## About PSEMP

The Puget Sound Ecosystem Monitoring Program **(PSEMP)** is a collaboration of monitoring professionals, researchers, and data users from state, federal, tribal, 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 a overview of 2011 marine water quality and conditions in Puget Sound from comprehensive monitoring and observing programs. The report focuses on the marine waters of Puget Sound south of Admiralty Inlet and Deception Pass. However, additional selected conditions are also included due to their influence on Puget Sound waters (e.g., selected climate indices and conditions along the outer Washington coast and north of Admiralty Inlet).*

The objective of the report is to collate and distribute the valuable physical, chemical, and biological information obtained from various monitoring and observing programs in Puget Sound. Based on mandate, need, and expertise, these various efforts employ different approaches and tools that cover various temporal and spatial scales. For example, ship surface surveys yield good horizontal spatial coverage, but lack depth information; regular station occupation over time is needed to identify long-term trends, but can miss shorter term variation associated with certain drivers; moorings with high resolution temporal coverage can be used to understand dynamics and identify shorter term drivers, but have limitations in their spatial domain. However, collectively, the information representing various temporal and spatial scales can be used to improve the ability to connect the status, trends, and drivers of ecological variability in Puget Sound marine waters. By identifying and connecting trends and anomalies from each of the monitoring programs, this report adds significant value to the individual datasets and enhances our understanding of this complex ecosystem. We present here that collective view for the year 2011.

Data summaries were compiled by the Puget Sound Ecosystem Monitoring Program's (PSEMP) Marine Waters Workgroup, which includes members from various federal, state, academic, local, tribal, and industry sources. This report helps the Workgroup to (i) develop an inventory of the current monitoring programs in Puget Sound and conduct a gap analysis to determine how well these programs are meeting priority needs; (ii) update and expand the monitoring results reported in the Puget Sound dashboard indicators (http://www.psp.wa.gov/vitalsigns/index.php); and (iii) improve transparency, data sharing, and 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.

Field work near the ORCA buoy deployed near Twanoh in southern Hood Canal. Photo credit: Robert Hubley.

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**Front cover and section photo credits:** Simone Alin, Duane Fagergren, Gabriela Hannach, Ruth Howell, and Su Kim.

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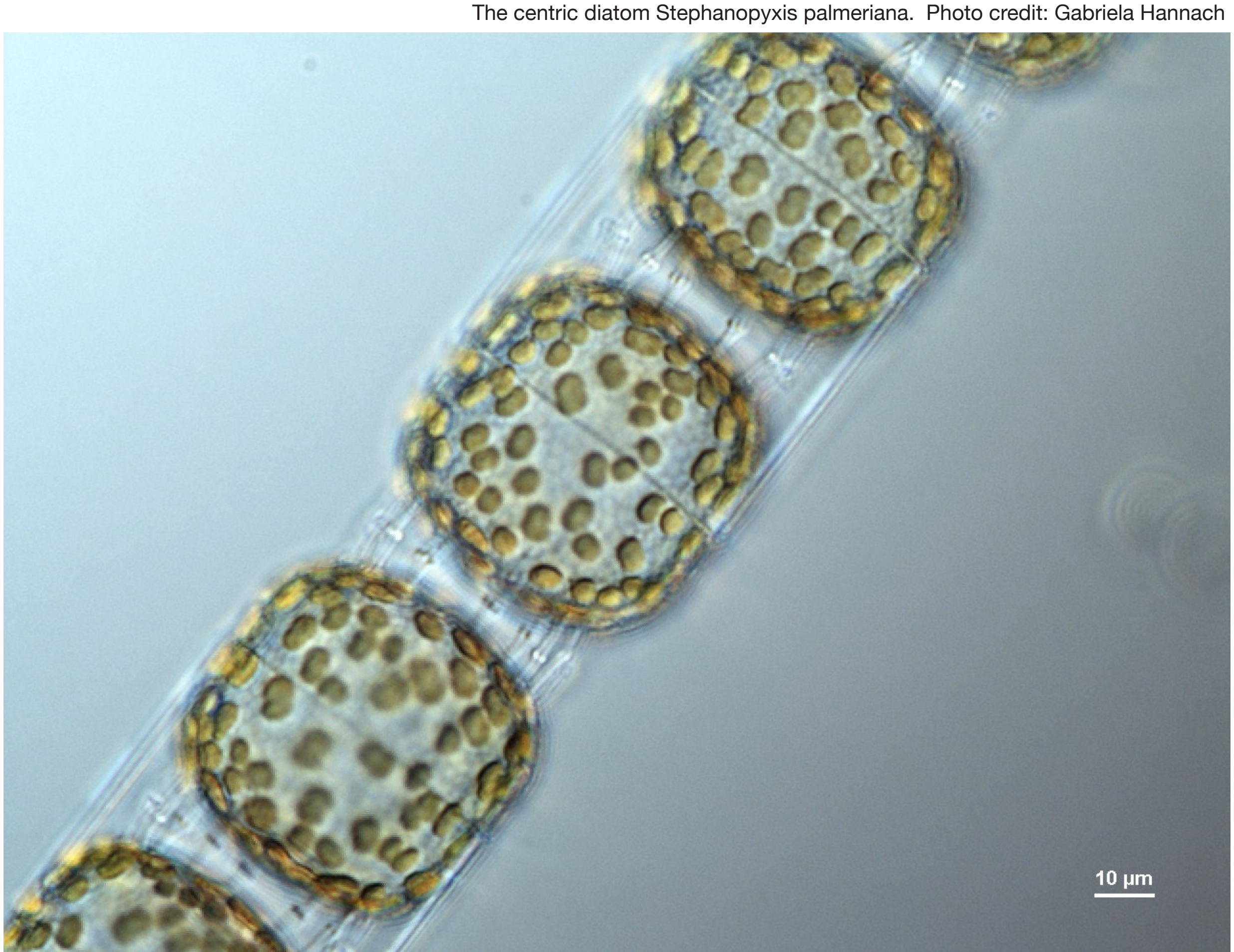
The centric diatom Stephanopyxis palmeriana. Photo credit: Gabriela Hannach



# Executive Summary

## Large-scale climate variability and wind patterns:

- **El Niño-Southern Oscillation (ENSO):**
    - A strong La Niña developed in 2010 with negative values not seen since 1955 and the mid 1970's, and persisted through spring 2011. ENSO-neutral conditions prevailed in June-July. La Niña returned in August and strengthened in September.

- **Pacific Decadal Oscillation (PDO):**
    - The PDO index was negative in 2011, and became strongly negative in July.

- **Upwelling Index (UI):**
    - The upwelling index was below average from March through November 2011, with March and September showing considerably stronger than normal downwelling.

    - The spring transition occurred later than usual (June) and the fall transition was early (between August and September).

## Local climate and weather:

- 2011 featured historic climate anomalies over the Pacific Northwest and Puget Sound, with record low temperatures from April through June and unusual wetness from March through May.

## Coastal ocean and Puget Sound boundary conditions:

- **Coastal ocean:**
    - Data from a new buoy off the coast of WA near La Push during summer 2011 revealed short-term variation in water properties that was responsive to wind forcing.

    - A phytoplankton bloom that occurred in mid-August was coincident with the onset of south (upwelling favorable) winds and a weakened current.

- **Puget Sound boundary conditions:**
    - Water masses at depth in Admiralty Inlet were slightly fresher, with lower dissolved oxygen during late winter/early spring 2011 compared to the same period the previous year.

## River inputs:

- South Puget Sound river flows were generally above normal during the first half of the year while flows in North Puget Sound rivers were above normal from late-June to September.

- Fraser River flows were much higher than average from May to September due to snowmelt from a larger than usual snowpack.

## Water quality:

- **Temperature and salinity:**
  - » Long-term monthly profiling stations exhibited colder and fresher conditions for 2011, with the lowest values observed since 1999.
  - » Surface temperatures in central Puget Sound were 1-2°C cooler in May and June 2011, compared to the previous year.
  - » Warm/fresh water associated with Fraser and Skagit River flows were evident in the Strait of Juan de Fuca and in Triple Junction.
  - » Relative to 2005-2011, high temporal resolution profiling buoys observed the lowest seawater densities in Hood Canal in 2011 and revealed substantial interannual variation in the timing, intensity, and duration of high salinity intrusions during fall.
  - » High spatial resolution transects in early October show a distinct transition in water properties from the Strait (oceanic influence: cool, salty, with low dissolved oxygen at depth) over the sill at Admiralty Inlet (well-mixed) and into the various interior basins (Main, Whidbey, and Hood Canal). Patterns observed were:
    - Localized upwelling of subsurface intermediate depth waters with low temperature and low oxygen content was observed in Southern Hood Canal around the Great Bend, presumably stimulated by southerly winds.
    - Particle load was highest at depth in all basins but also in the surface waters of Hood Canal.
  - » Tribal canoe journey data in July 2011 show that Whidbey basin had lower surface salinity compared to past years and higher surface temperatures compared to other basins.

- **Nutrients and chlorophyll:**
  - » The timing of the 2011 spring bloom varied in the different basins of Puget Sound (historically observed as early as February and as late as May).
    - High temporal resolution profiling data showed that the spring bloom occured earlier than usual in southern Hood Canal.
    - In the Main Basin, the spring bloom was delayed until May and higher than usual growth-limiting nutrients were observed in April.
    - In Quartermaster Harbor (small bay in Main Basin), the 2011 spring bloom was not delayed compared to previous years; typical conditions were observed with nitrate depletion occurring from May to August (longer than the period of nitrate depletion observed in the open waters of Main Basin).
  - » Ammonia levels were lower than usual in 2011, except for June and July (Main Basin) and August (Sound-wide). The high values of ammonia in June and July followed a large phytoplankton bloom in May and June that had high abundances of *Noctiluca scintillans.*
  - » A long-term (since 1999) increasing trend in nitrate concentrations (and decreasing trend in *Si:N* ratio – indicating a non-oceanic nitrogen source) was observed.
- **Dissolved oxygen:**
  - » Dissolved oxygen in Puget Sound was higher (i.e., oxygen concentrations were closer to saturation) in 2011 compared to the 1999 to 2010 record.
  - » In the main stem of Hood Canal, dissolved oxygen was average in 2011 relative to a data record of 29 years representing the 1950s, 1960s, 1990s and 2000s. 2011 started and ended with concentrations just under 5 mg/L and had a minimum just over 3 mg/L.
  - » In Lynch Cove (i.e., southern Hood Canal), hypoxia was observed during fall with many samples under 1 mg/L, suggesting that the annual flushing was slow to reach the Lynch Cove area and respiration was significant; however, no fish kills were observed.
    - Interannual variation in hypoxia in the mainstem of Hood Canal appears to be linked with flushing from higher density oceanic intrusions.
  - » Dissolved oxygen in Quartermaster Harbor was similar to previous years in the 2008 to 2011 record.

- **Ocean acidification and carbon chemistry:**
  - » High spatial resolution transects in early October 2011 revealed conditions to be corrosive (pH < 7.75 (seawater scale, $pH_{SWS}$) and under-saturated with respect to aragonite ($\Omega_{arag}$ < 1) throughout the water column from the Strait of Juan de Fuca to the Great Bend.
    - The lowest values for $pH_{SWS}$ and $\Omega_{arag}$ observed to date in Puget Sound were measured at a station in The Great Bend of Hood Canal during this cruise and appear to be a result of local production and respiration processes in Lynch Cove.
  - » High-frequency measurements at the Lummi Nation Shellfish Hatchery showed fluctuations in pH (NBS scale, $pH_{NBS}$) associated with time, tide, and salinity.

## Plankton:

- **Phytoplankton**
  - » Spring diatom blooms were delayed at open water stations in the Main Basin, consistent with the cooler, wetter, and cloudier spring weather pattern.
  - » Fall diatom blooms were less conspicuous at open water stations in the Main Basin and delayed in Quartermaster Harbor.
- **Harmful algae**
  - » Highest *Alexandrium* spp. cyst concentrations were found in Bellingham Bay, Birch Bay and Semiahmoo Bay in the north, Port Madison, Liberty Bay and Port Orchard on the west side of Main Basin and Quartermaster Harbor.
    - Quartermaster Harbor cyst concentrations were an order of magnitude less compared to a 2005 survey, and a new “seed bed” area developed in Bellingham Bay.
  - » *Alexandrium* spp. vegetative cell counts were low or absent throughout most of the Sound in 2011.
  - » *Pseudo-nitzschia* cells were present throughout the entire year at most sites with blooms occurring as early as May and as late as September 2011.
  - » *Dinophysis* was the species that attracted the most attention during the summer of 2011, when the first documented illnesses in the U.S. due to the consumption of shellfish contaminated with Diarrhetic Shellfish Poisons (DSP) triggered a shellfish growing area closure and recall of shellfish from Sequim Bay.

- Dinophysis cell counts were greater than 50,000 cells per liter at the peak of the Sequim Bay bloom in July.

- **Biotoxins:**
  » DSP toxins were detected in Sequim Bay shellfish at levels up to 160 µg per 100 g of tissue in 2011 (the European regulatory limit for DSP is 16 µg/100 g).

  - There were three reported illnesses in 2011 from the consumption of Sequim Bay shellfish.

  » Paralytic Shellfish Poisoning (PSP) toxin levels were lower in 2011 compared to 2010.

  - The highest recorded value in 2011 was 954 µg/100 g (the regulatory limit for PSP is 80 µg/100 g), but there were no reported PSP illnesses.

  - There were 8 commercial sub-tidal geoduck clam tracts, 2 commercial general growing areas, and 29 recreational harvest areas closed in 2011 due to PSP toxins.

## Bacteria and pathogens:

- **Fecal indicator bacteria:**
  » The percentage of shellfish growing areas with low fecal pollution (indicated by fecal coliform bacteria) improved from 1.4% in 2010 to 2.1% in 2011. Fecal pollution at the 36 most affected shellfish growing areas has dropped significantly since 2003.

  » In 2011, just over 75% of the marine beaches monitored for enterococcus bacteria as part of the Beach Environmental Assessment, Communication and Health (BEACH) Program met the EPA water quality standard of 104 cfu/100 ml (similar to 2009 and 2010).

- ***Vibrio parahaemolyticus:***
  » There were 43 confirmed illnesses in 2011 due to the consumption of shellfish contaminated with *Vibrio parahaemolyticus* – the number of illnesses decreased from the 71 confirmed cases in 2010.

## Shellfish resources:

- The cold spring of 2011 caused a delay in phytoplankton growth, which in turn limited hatchery shellfish seed production.

# Large-scale climate variability and wind patterns

*Large-scale patterns of climate variability can strongly influence Puget Sound's marine waters. 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. Both patterns of climate variability influence the temperature of Puget Sound's marine waters. Warm temperature anomalies produced during the winter of warm phases of ENSO and PDO typically linger for 2 to 3 seasons, but for PDO these anomalously warm waters can reemerge 4 to 5 seasons later (Moore et al., 2008b).*

## A. El Niño-Southern Oscillation (ENSO):

*Source: Rosa Runcie (Rosa.Runcie@noaa.gov) (NOAA, SWFSC); http://www.cdc.noaa.gov/people/klaus.wolter/MEI/mei.html, http://www.cpc.noaa.gov/products/analysis_monitoring/enso_advisory/*

The Multivariate ENSO Index (MEI) reflects the behavior of ENSO using 6 main observed variables in the tropical Pacific. Positive values of the MEI indicate warm phases (El Niño) and negative values indicate cool phases of ENSO (La Niña). The MEI turned strongly negative in April 2010, reaching large negative values not seen since 1955 and the mid-1970s (Figure 1A). A transition from La Niña to ENSO-neutral conditions occurred during May 2011. During June and July 2011, ENSO-neutral conditions continued and were reflected in the overall pattern of small sea surface temperature (SST) anomalies across the equatorial Pacific Ocean. La Niña conditions returned in August 2011 due to the strengthening of negative SST anomalies across the eastern half of the equatorial Pacific Ocean. During September and October 2011, La Niña conditions strengthened as indicated by increasingly negative SST anomalies across the eastern half of the equatorial Pacific Ocean. November and December 2011, La Niña conditions continued across the eastern and central equatorial Pacific Ocean. MEI values from 2005 to 2011 are shown in Figure 1B.

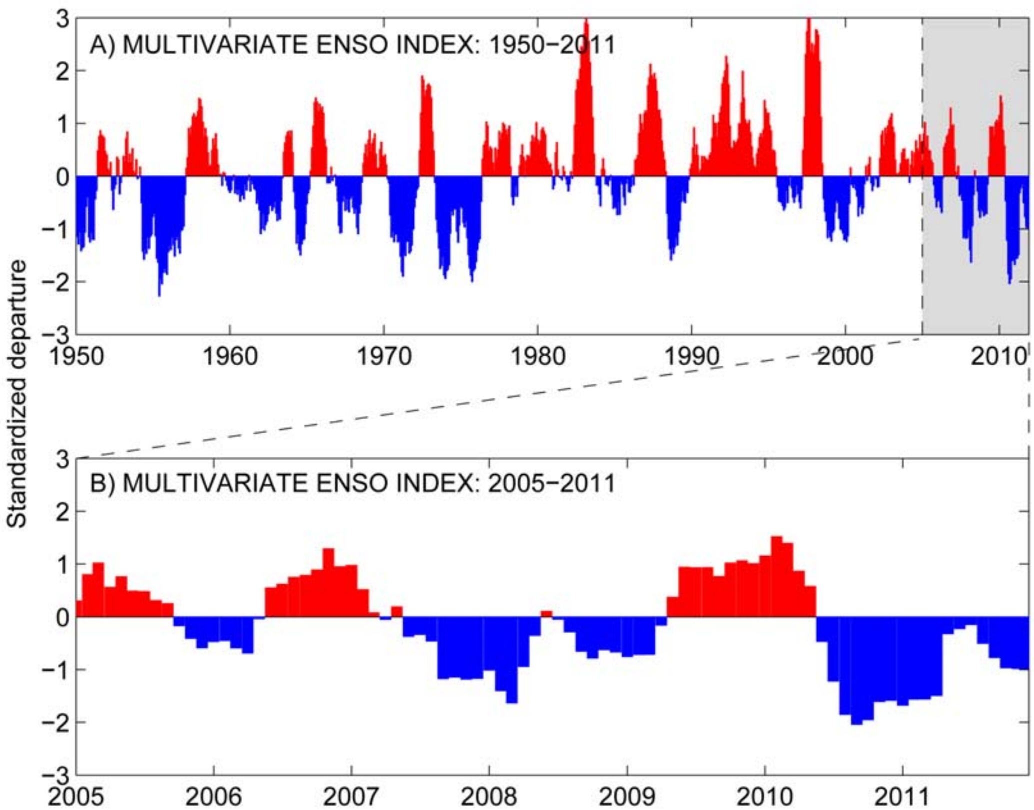



**Figure 1.** NOAA Physical Sciences Division attempts to monitor ENSO by basing the Multivariate ENSO Index (MEI) on the six main observed variables over the Pacific. These six variables are: sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky. Monthly values of the MEI are shown from (A) 1950 to 2011 and (B) 2005 to 2011.

## B. Pacific Decadal Oscillation (PDO):

*Source: Jerrold Norton (Jerrold.G.Norton@noaa.gov) (NOAA); http://jisao.washington.edu/pdo/PDO.latest*

The Pacific Decadal Oscillation (PDO) is considered a long-lived ENSO like pattern of Pacific climate variability based on sea surface temperature measurements north of 10°N. The PDO index is positive when there are positive SST anomalies along the coast and extending 1500 km off of western North America and negative SST anomalies farther offshore and in the central and western North Pacific. Negative PDO index values indicate the reverse pattern where the positive anomalies are offshore and negative SST anomalies are characteristic of coastal regions. Negative SST anomalies have persisted in the northeastern Pacific Ocean over the last 19 months (Figure 2B). The November PDO value is strongly negative (-2.33) and the lowest since December 1961, but statistically comparable negative values occurred in the last quarters of 1990 and 1999 (Figure 2A). These strongly negative values occur during runs of negative monthly PDO indices. Only about 25% of PDO values were positive from January 2007 to December 2011.

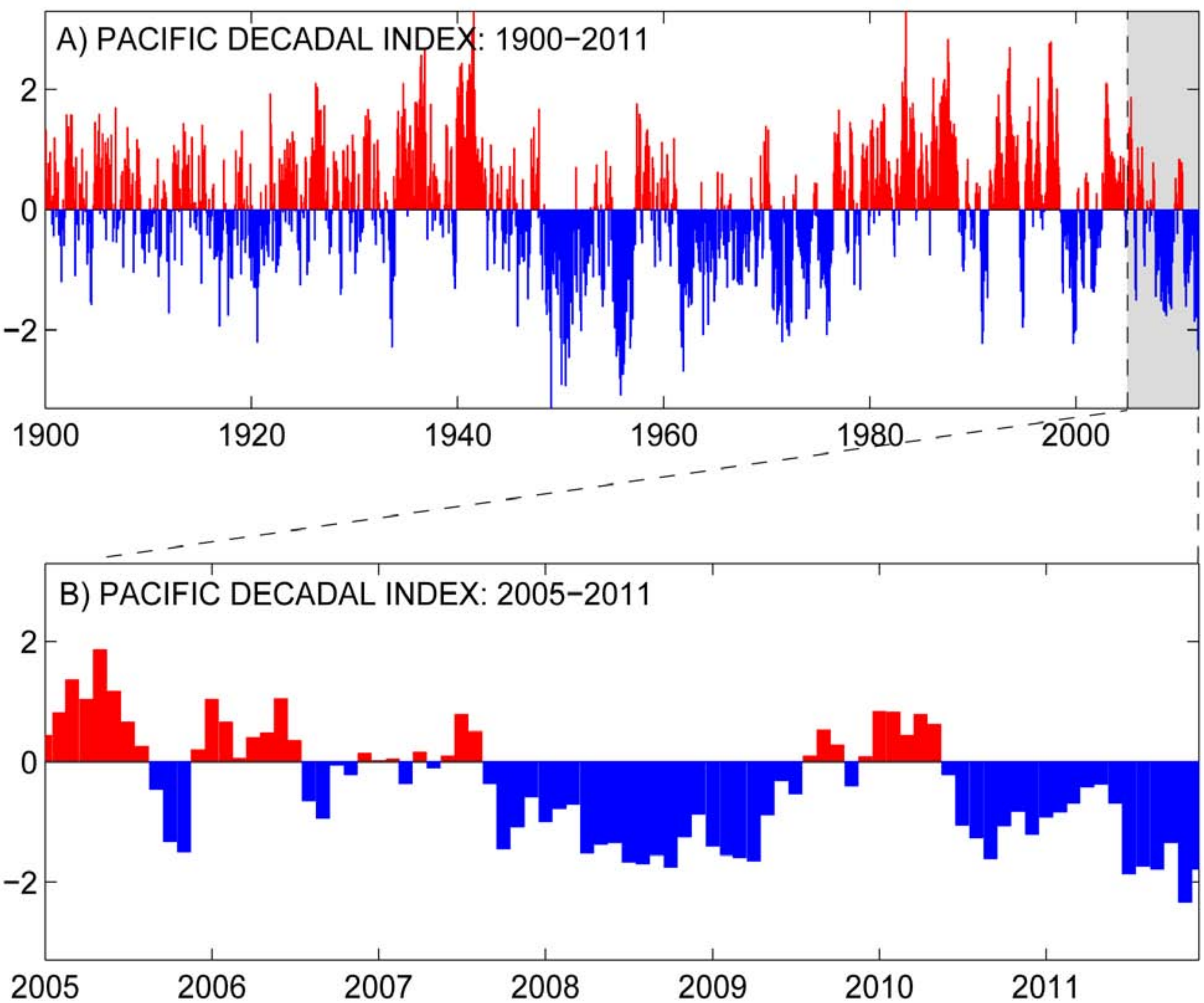



Figure 2. Monthly values of the Pacific Decadal Oscillation (PDO) index from (A) 1900 to 2011 and (B) 2005 to 2011.

*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.*

## C. Upwelling index:

*Source: Skip Albertson (skip.albertson@ecy.wa.gov), Julia Bos, Christopher Krembs (Ecology), and NOAA: http://www.pfeg.noaa.gov/products/pfel/modeled/indices/upwelling/upwelling.html*

Upwelling winds were generally less than median historic values during the 2011 upwelling season (i.e., April to September in Pacific Northwest) but within expected historic ranges (Figure 3). Winter downwelling was slightly weaker than the median historic values during January, February and December 2011, but exceptionally strong downwelling occurred in March and September.

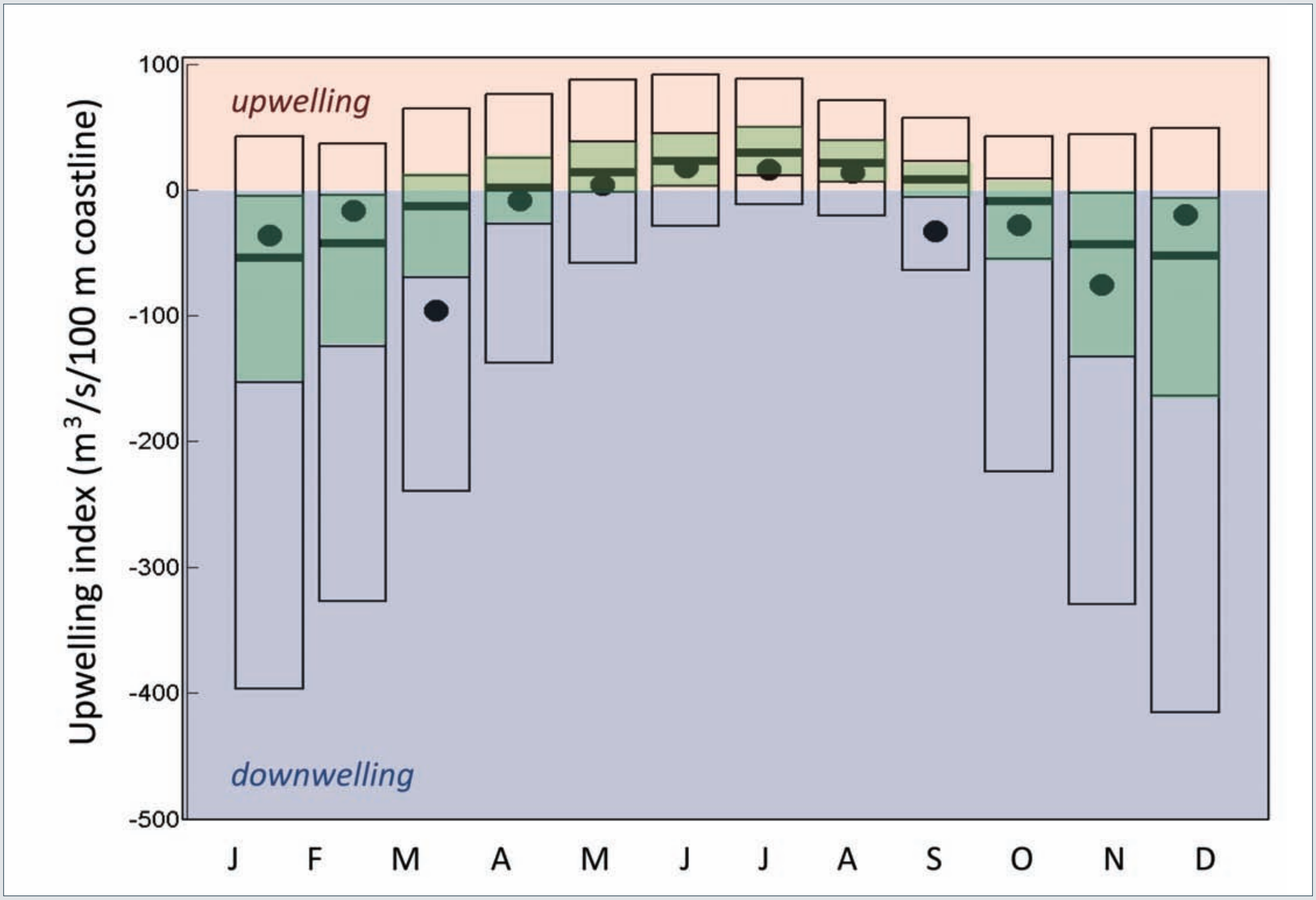



**Figure 3.** Monthly values of the coastal upwelling index at 48°N and 125°W for 2011 (filled circles). Values in the red/blue portion of the plot indicate upwelling/downwelling conditions, respectively. Historic monthly values are used to calculate the median (i.e., 50th percentile) which is depicted by the solid black lines, and the interquartile ranges (i.e., the range of values defined by the 25th and 75th percentiles) are depicted by the green box. If an observed value for a particular month occurs outside of the interquartile range (implying that values outside of this range occur less than 50% of the time), Ecology consider it to significantly differ from the historical norm. The larger box surrounding the interquartile range represents the 5th and 95th percentiles.

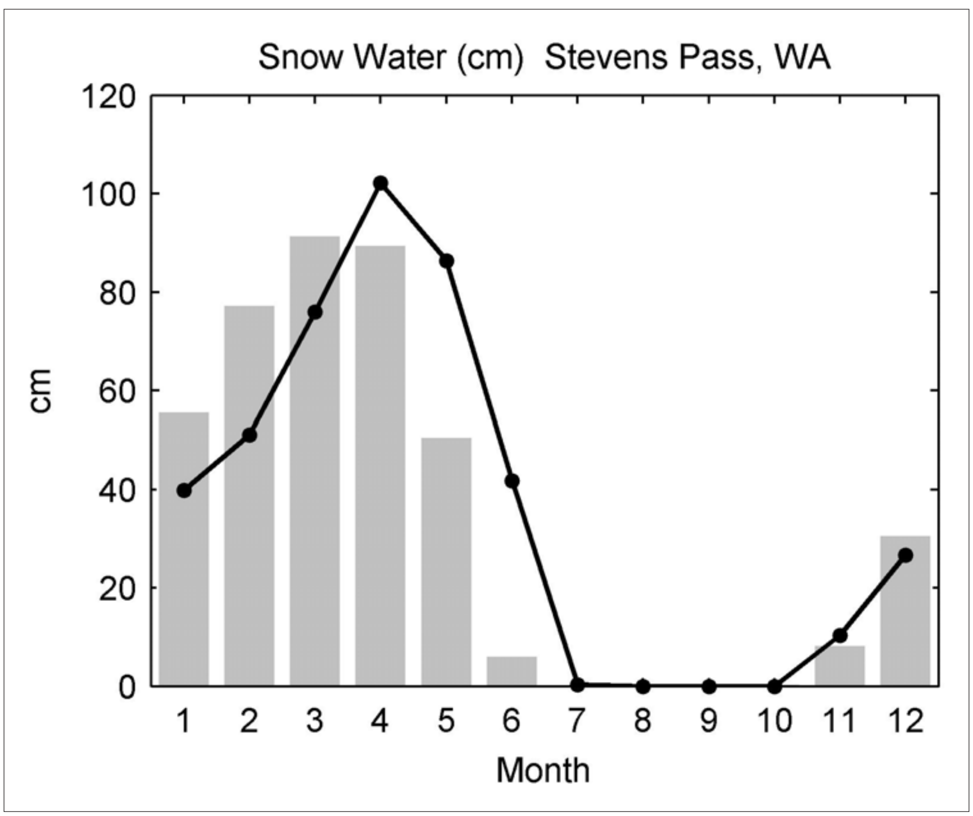
# Local climate and weather

*Local climate conditions typically exert an even stronger influence on Puget Sound marine water conditions compared to large-scale patterns of climate variability. Variation in local air temperature has been found to best explain variations in Puget Sound water temperature (Moore et al., 2008b).*

## A. Regional air temperature and precipitation:

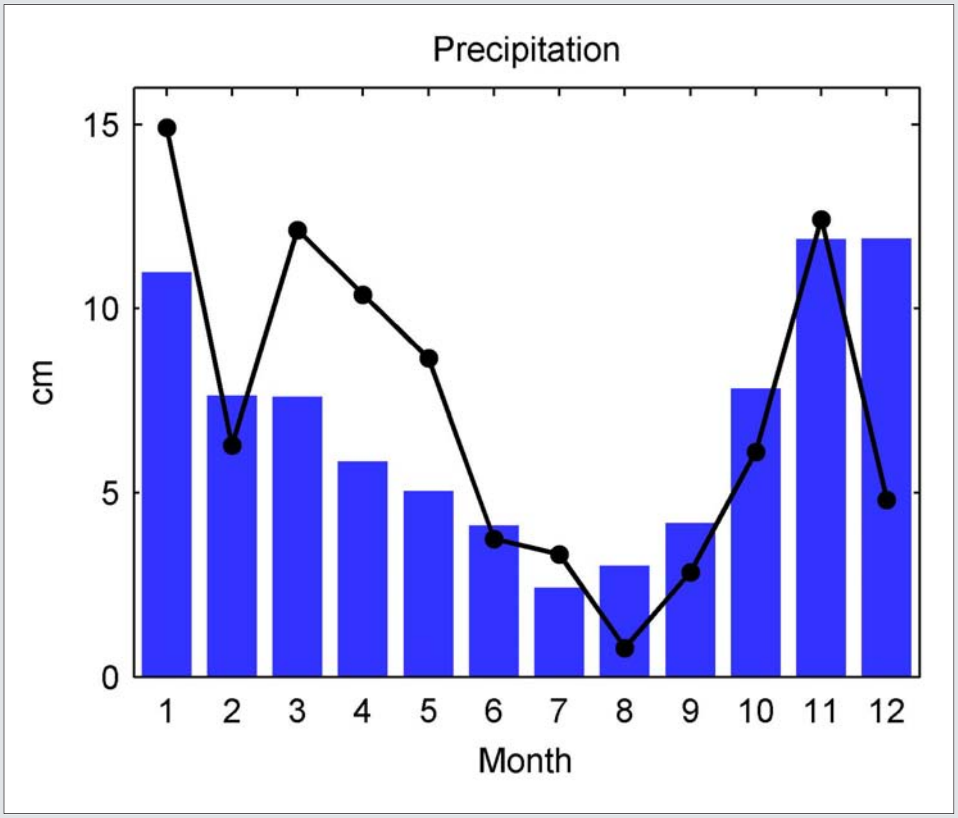
*Source: James A. Johnstone (jajstone@u.washington.edu) (UW, JISAO)*

The calendar year of 2011 featured historic climate anomalies over the Pacific Northwest and Puget Sound. At the onset of 2011, a major La Niña event was underway, leading to expectations of cool, wet conditions. The first two months of the year saw near-average precipitation and temperatures, however, snow pack conditions in the northern Cascades were below normal (Figure 4, this page, panel below). By March, a deep, persistent region of low atmospheric pressure (i.e., troughing) took hold over the NE Pacific, prolonging typical winter weather into the spring months, and maintaining cool, wet conditions into summer. The early snow pack deficits in the northern Cascades were rapidly recovered in spring, becoming surpluses from April through June. The Southern Oscillation Index reached its highest February to April average in recorded history, dating back to 1866. The unusual springtime conditions over Puget Sound were generally consistent with winter La Niña impacts, but remarkable in their magnitude and late arrival.



The unusual jet stream configuration continued into early summer, with continued troughing seen over the Pacific Northwest and enhanced ridging over the eastern US. This pattern produced record low April to June temperatures over much of the Pacific NW, and widespread record highs over the southern US (dating back to 1900). Over Puget Sound, below-average temperatures continued in every month through July, effectively delaying the onset of summer by a month (Figure 4, this page, top and bottom panels).

In the tropics, the strong La Niña event decayed over summer, and then reemerged in late 2011. Over Puget Sound, the second half of 2011 was slightly drier than normal, with continued below-average temperatures, in part due to cool conditions in the coastal ocean. The year of 2011 saw below normal temperatures around Puget Sound during 10 of 12 months, highlighted by the remarkable anomalies of spring and early summer.



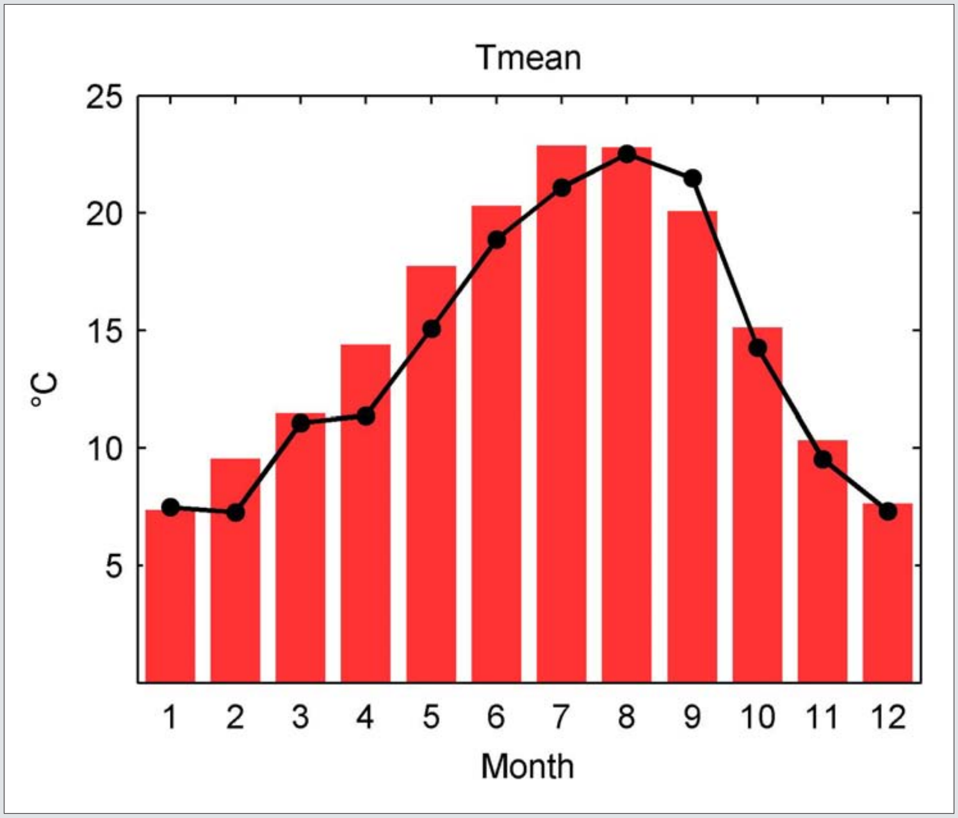




Figure 4. Monthly climatology and 2011 weather conditions for the Puget Sound region. Bars show the monthly mean values; dotted lines indicate 2011 values. Opposite page: Snow water equivalent, Stevens Pass, WA SNOTEL site. This page, top: Monthly precipitation averaged over six long-term Puget Sound stations from the US Historical Climate Network (Bellingham, Blaine, Everett, Olga, Port Townsend, and Seattle). This page, bottom: Monthly mean temperature averages from the same six long-term Puget Sound stations.

## B. Local air temperature and solar radiation:

*Source: Skip Albertson (skip.albertson@ecy.wa.gov), Julia Bos, and Christopher Krembs (Ecology)*

Air temperature and solar radiation anomalies at Everett (north) and Olympia (south) are shown in Figure 5. Cold air temperature anomalies were seen in the north and south Puget Sound basin were observed for much of the year, especially from March until August 2011. Solar radiation was generally lower than normal, especially from January to May 2011.

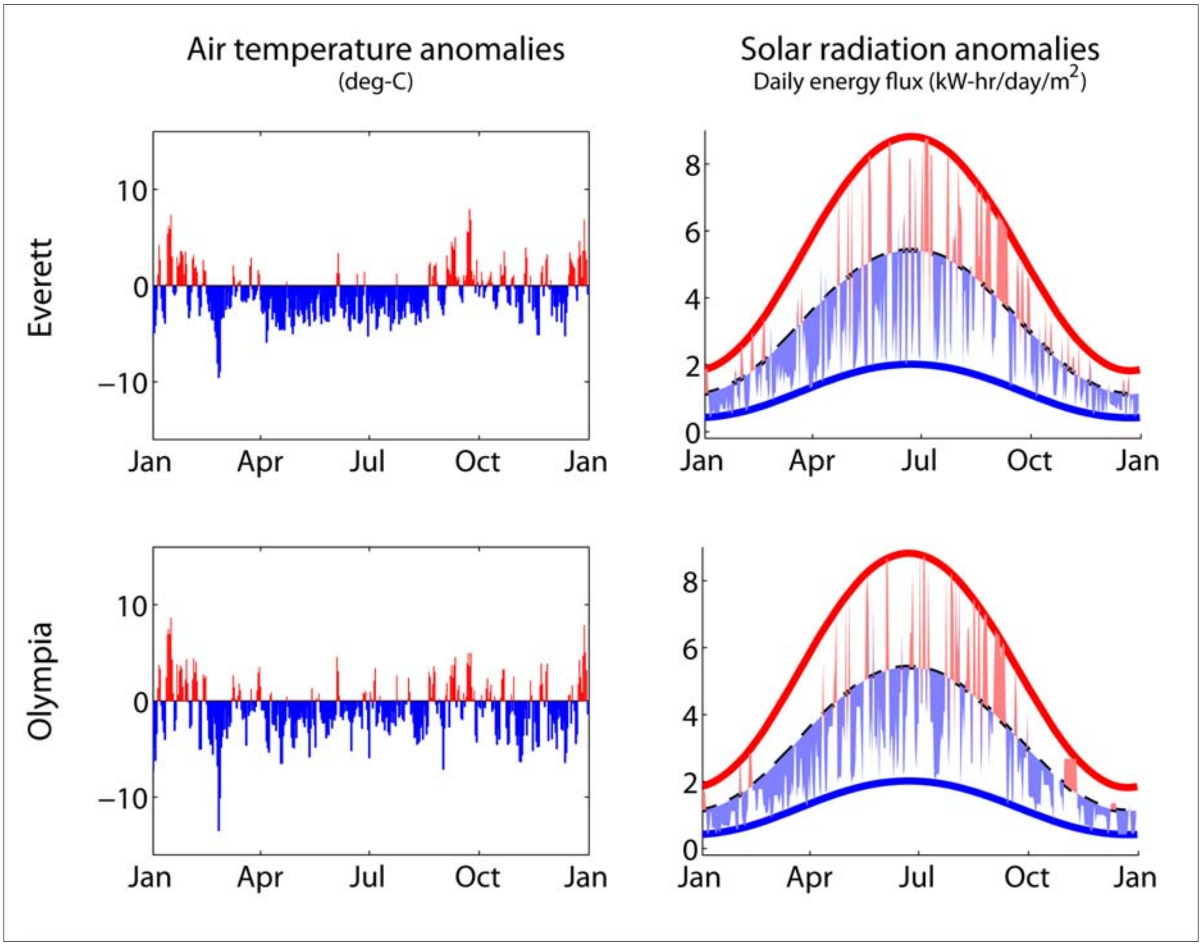



Figure 5. Air temperature (left panel) and solar radiation (right panel) anomalies at Everett and Olympia for 2011.

# 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. Coastal ocean:

*Source: Matthew Alford, Jan Newton (newton@apl.washington.edu), John Mickett (UW, APL), and Al Devol (UW). http://www.nanoos.org and http://wavechasers.uw.edu*

Two new buoys deployed off the WA coast near La Push to be sustained as part of NANOOS allowed observation for the first time of internal wave dynamics off the WA coast and the response from variables such as chlorophyll, oxygen and nitrate. During late summer 2011, Alford et al. (2012) observed a rich, variable internal wave field that appeared to be modulated in part by a coastal jet and its response to the region's frequent wind reversals. The temperature, salinity, and density stratification generally responded in the expected way to these low-frequency wind shifts, with upwelling following each wind burst by one to two days (Figure 6). Also evident was a response in the dissolved oxygen, nitrate, and chlorophyll. Because each of these variables depends on biological as well as physical processes, they are considerably more complex than the physical variables. For example, the record begins with high nitrate and low oxygen in the mixed layer, and nearly no measurable chlorophyll. A bloom appeared on August 13, coincident with the onset of south winds and weakened current, evidenced by high chlorophyll. Reduced nitrate and increased oxygen followed, which is consistent with phytoplankton growth. The data reveal the importance of internal tide displacements that were observed to heave chlorophyll, oxygen, and nitrate fields up and down as the bloom developed. As upwelling resumed, density isopycnals were brought upward, but nitrate suddenly increases in the upper 30 m on August 22, implying a lateral transport. These dynamics indicate the importance of short-term processes on water conditions. A longer time record will be welcome to study longer-term processes and inter-annual differences.


Colin Smith, UW ORCA buoy technician, works to service weather sensors on the profiling buoy off Pt. Wells in the Main Basin of Puget Sound. These buoys are solar powered and utilize a winch (blue box) to lower a water sensor package for temperature, salinity, oxygen, chlorophyll and other variables. Data are relayed in near real-time. Photo credit: Allan Devol

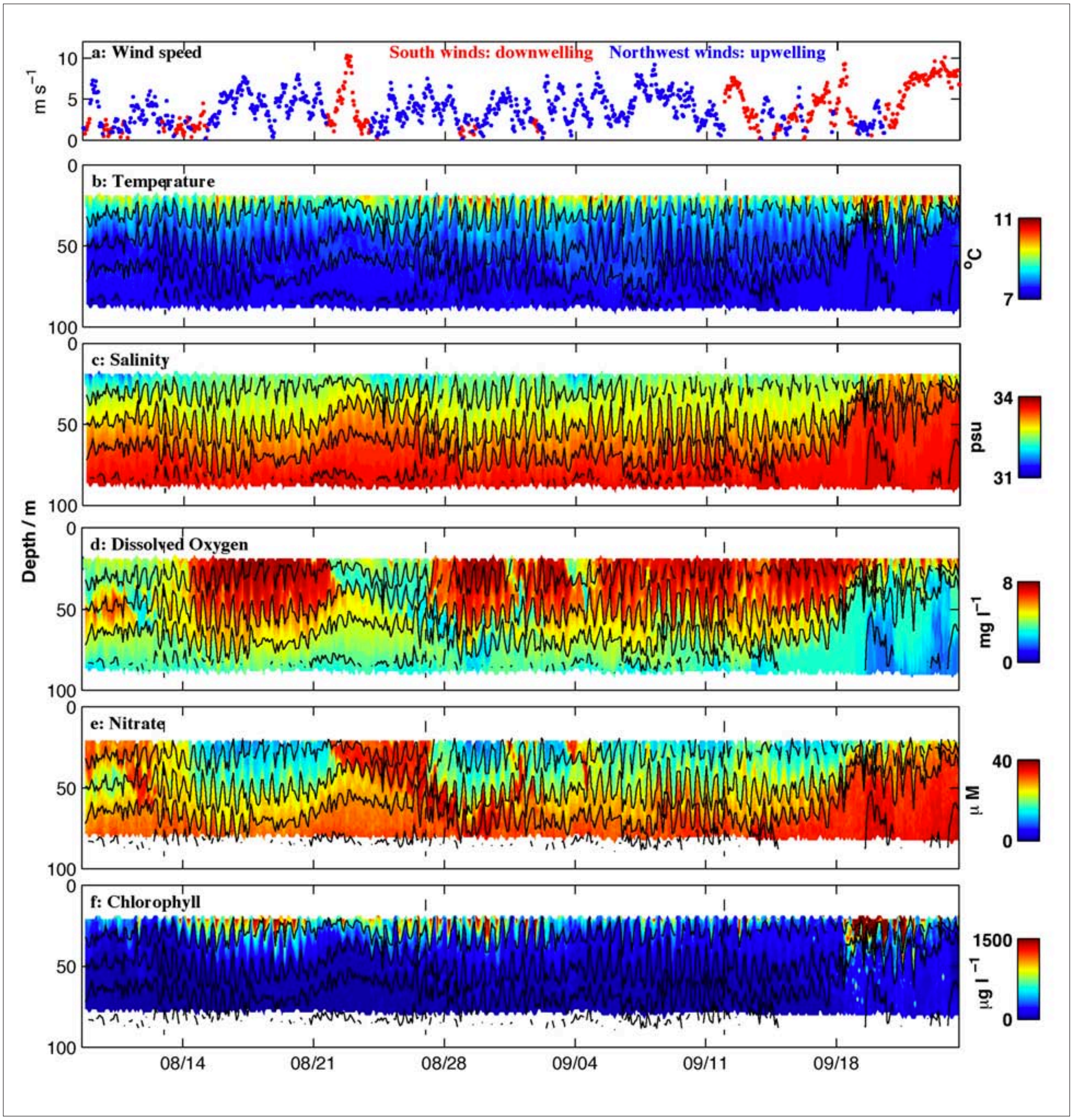



Figure 6. Profile data from the NANOOS profiling buoy at La Push, WA, during August-September of 2011. Modified from Alford et al., 2012 (TOS).

*Admiralty Inlet connects the Strait of Juan de Fuca to Puget Sound. Conditions at depth at Admiralty Inlet are representative of the water masses coming into the Sound from the coastal ocean. These conditions are responsive to the tides and upwelling winds.*

## B. Admiralty Inlet:

*Source: Christopher Krembs (christopher.krembs@ecy.wa.gov), David Mora, Julia Bos (Ecology), and Jim Thomson (APL)*

A marine mooring at Admiralty Inlet revealed that water masses were slightly fresher, with lower dissolved oxygen during late winter/early spring (November 2010 to April 2011), compared to the same period the previous year (Figure 7). Daily conditions at Admiralty Inlet are most homogenous during the late winter/early spring period and most variable in the summer/fall period (May to November). Largest variability in daily observations of oxygen and salinity across Admiralty Reach occurred during the summer/fall period. The variability in these observations reveals differences in outgoing and incoming water masses. The highest salinity and lowest dissolved oxygen values are seen during late summer and are roughly comparable in value for 2010 and 2011; however, the daily ranges of 2011 measurements showed greater variability. The association of highest salinity/lowest dissolved oxygen conditions with incoming tides is not shown in this plot.

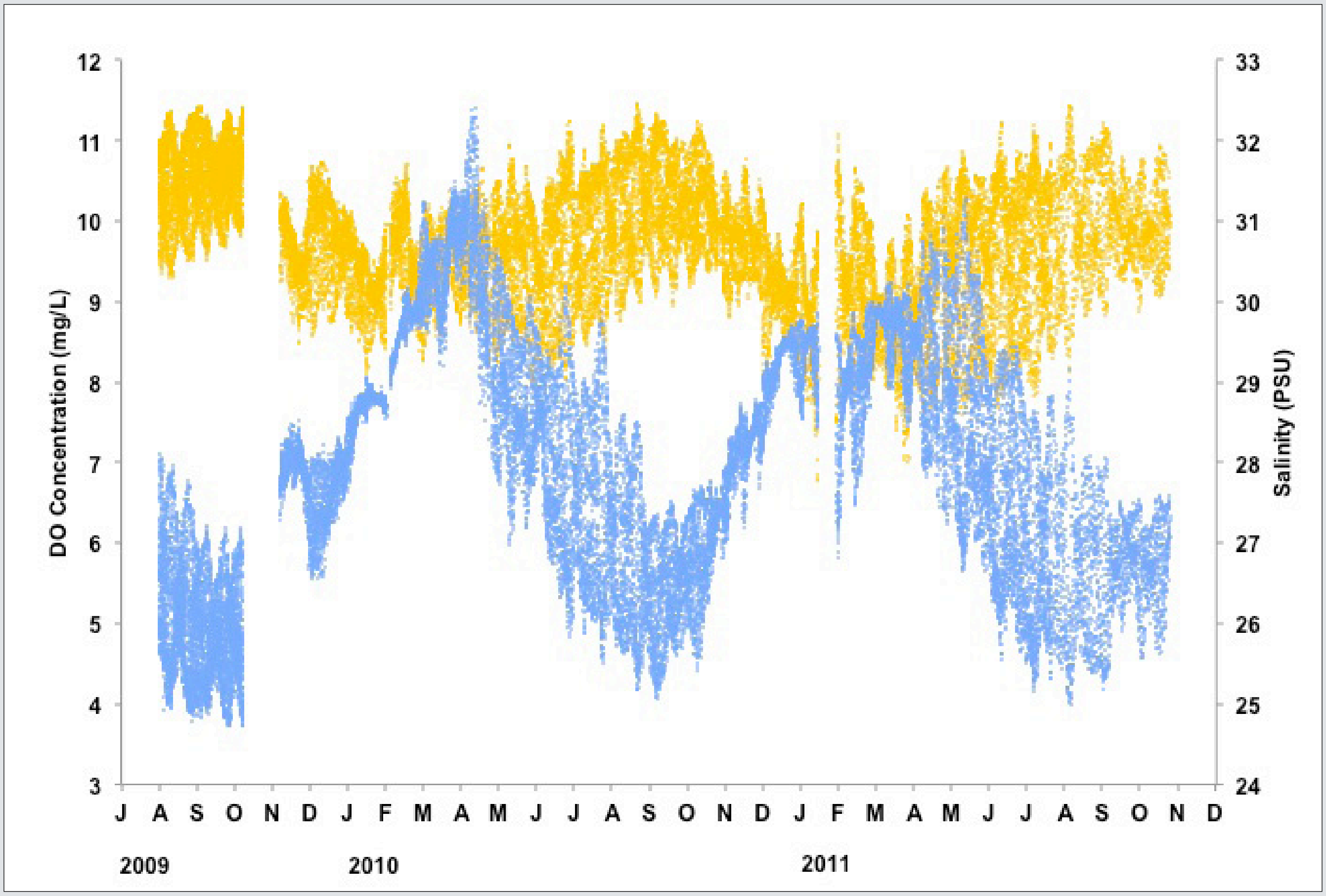



Figure 7. Admiralty Inlet 2010-2011 bottom-mounted mooring data showing dissolved oxygen concentration (blue) and salinity (gold) measured in 30 minute intervals at 65 m depth.

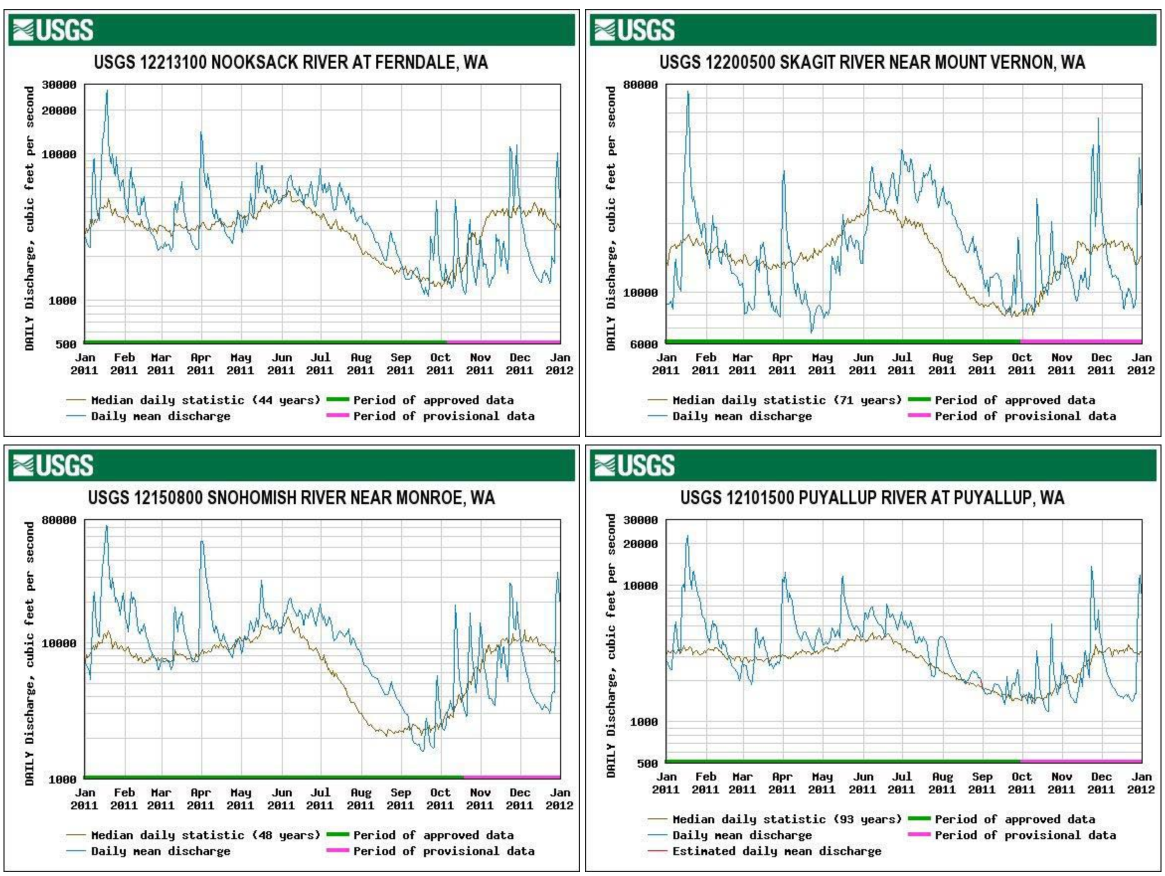
# River inputs

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

## A. Puget Sound rivers:

*Source: Ken Dzinbal (ken.dzinbal@psp.wa.gov) (PSP); and U.S. Geological Survey; http://waterdata.usgs.gov/nwis/uv/?referred_module=sw*

South Puget Sound river flows were generally above normal during the first half of the year while flows in North Puget Sound rivers were above normal from late-June to September (Figure 8).



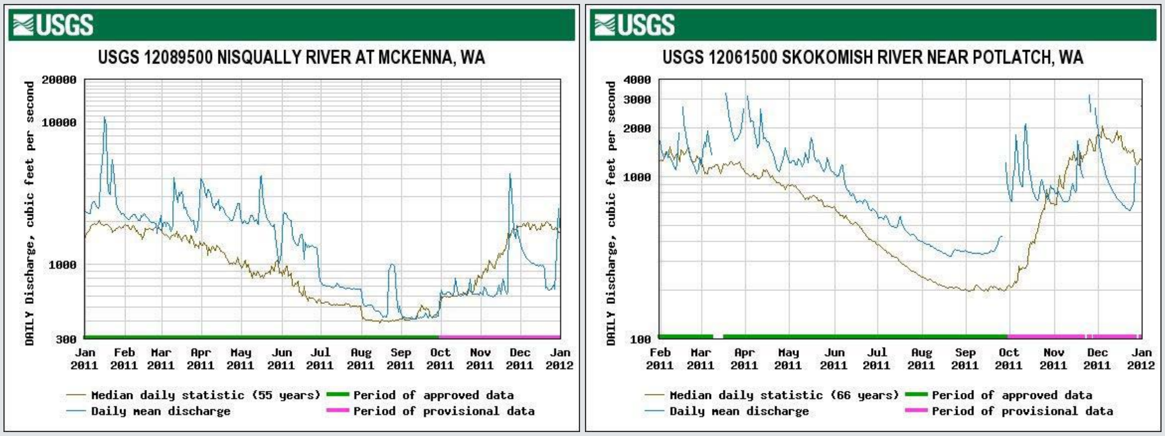



Figure 8. Daily river discharge at sites in the Nooksack, Skagit, Snohomish, Puyallup, Nisqually, and Skokomish Rivers for 2011. Median values from historic records are also shown.

## B. Fraser River:

*Source: Brandon Sackmann (brandon.sackmann@ecy.wa.gov) (Ecology); and EC; http://www.wateroffice.ec.gc.ca/*

Fraser River flows were similar to long-term climatologic averages from January to May 2011 (Figure 9). From May to September, snowmelt from a larger than usual snowpack resulted in much higher than average flows, with values exceeding the 75th percentile. By October river flow returned to more typical values.

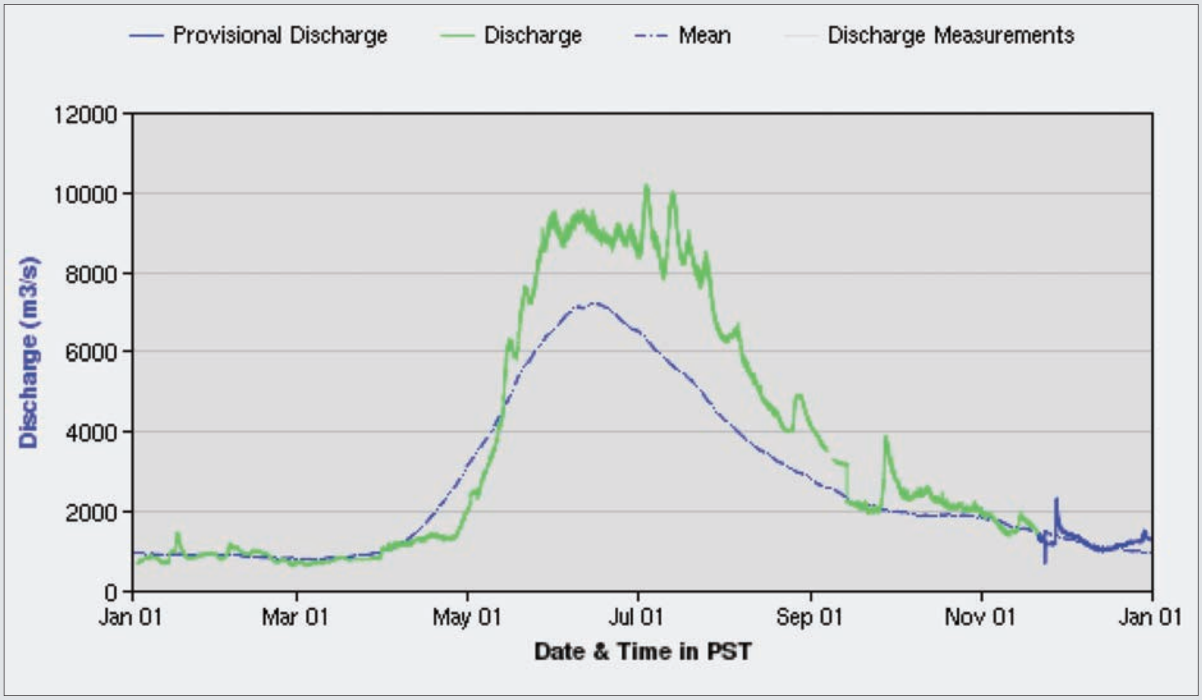



Figure 9. Daily Fraser River discharge at Hope for 2011. The mean values from historic records are also shown.

# Water quality

*The most basic water quality measurement, temperature and salinity 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.*

## A. Temperature and salinity:

### i. Puget Sound long-term stations:

*Source: Julia Bos (julia.bos@ecy.wa.gov), Christopher Krembs, Mya Keyzers, Laura Friedenberg, and Carol Maloy (Ecology)*

The Washington State Department of Ecology's long-term stations in Puget Sound have the temporal coverage and precision needed to identify long-term trends. The Puget Sound stations exhibited colder and fresher conditions for 2011, with new minimum values occurring compared to the 1999 to 2010 climatological record (Figure 10).

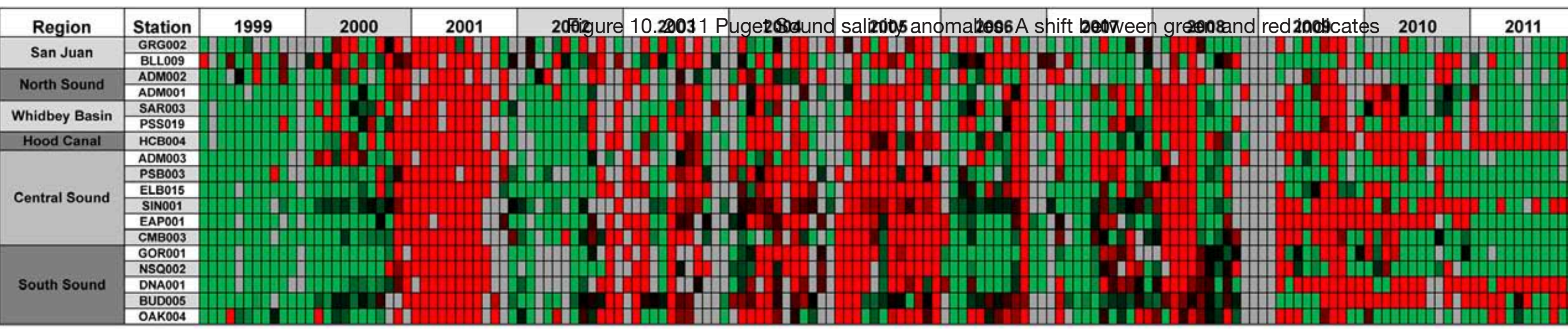
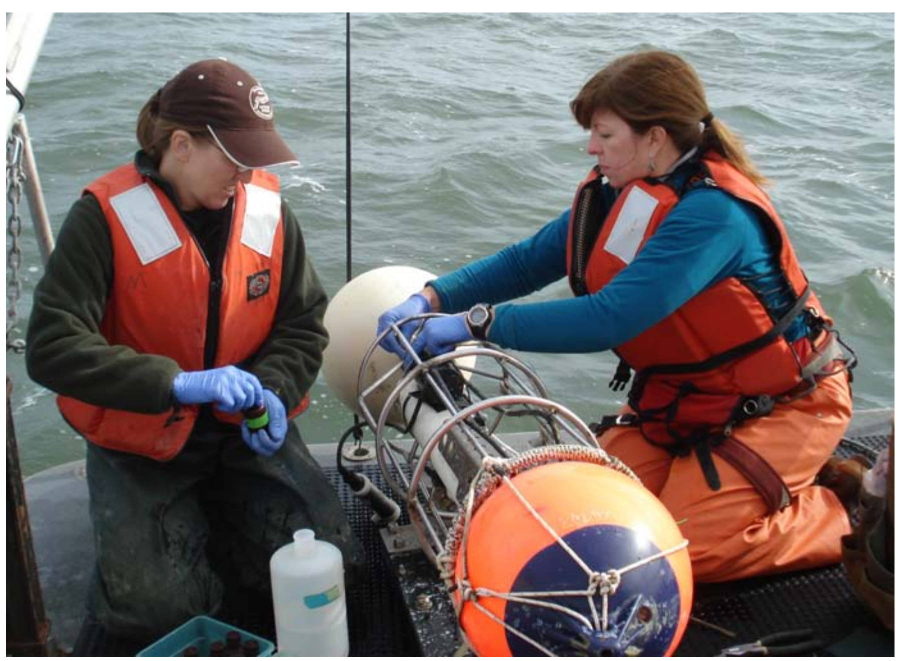



Figure 10. 2011 Puget Sound salinity anomalies. A shift between green and red indicates saltier (red) or fresher (green) conditions. Each cell represents a monthly median salinity concentration for continuous profiles from 0 to 50 meters depth. Anomalies are defined as falling outside the inter-quartile (25th to 75th percentile) range for site and seasonal specific historic data since 1999. Color indicates anomalies: red < IQR, green > IQR and black = expected (within IQR) values. Grey fields denote no data available.



Suzan Pool (left) and Julia Bos (right) of Ecology's Marine Monitoring Unit deploying a serviced sensor package moored to a channel marker. Photo credit: Ecology's Marine Monitoring Unit.

### ii. Victoria Clipper transect:

*Source: Brandon Sackmann (brandon.sackmann@ecy.wa.gov), Christopher Krembs, and Julia Bos (Ecology)*

Providing a highly spatially defined transect in the Main Basin of Puget Sound, the Victoria Clipper (http://www.clippervacations.com/ferry/vesselinformation) runs 80 mi between Seattle (47.6°N) and Victoria, B.C. (48.4°N) (Figure 11A). Ecology has equipped the vessel with a Turner Designs C3 fluorometer measuring sea surface temperature, *in vivo* chlorophyll *a* fluorescence, turbidity, and colored dissolved organic matter fluorescence to gain information on surface water dynamics. Surface temperatures in 2011 were minimal in late February to early March (~8°C) and maximal in late August to early September (>15°C). Temperatures in Central Puget Sound were 1 to 2°C cooler in May and June 2011, compared to the previous year (Figure 11B). Strong temperature gradients during summer were observed near the Triple Junction (warm/fresh water entering central Puget Sound from Whidbey Basin) and the entrance to Puget Sound near Admiralty Inlet with modulations driven by spring/neap tidal mixing. Warmer temperatures associated with Fraser River water were evident in the Strait of Juan de Fuca (48.1 to 48.4°N) during periods of neap tides/reduced tidal mixing (Figure 11B and C).

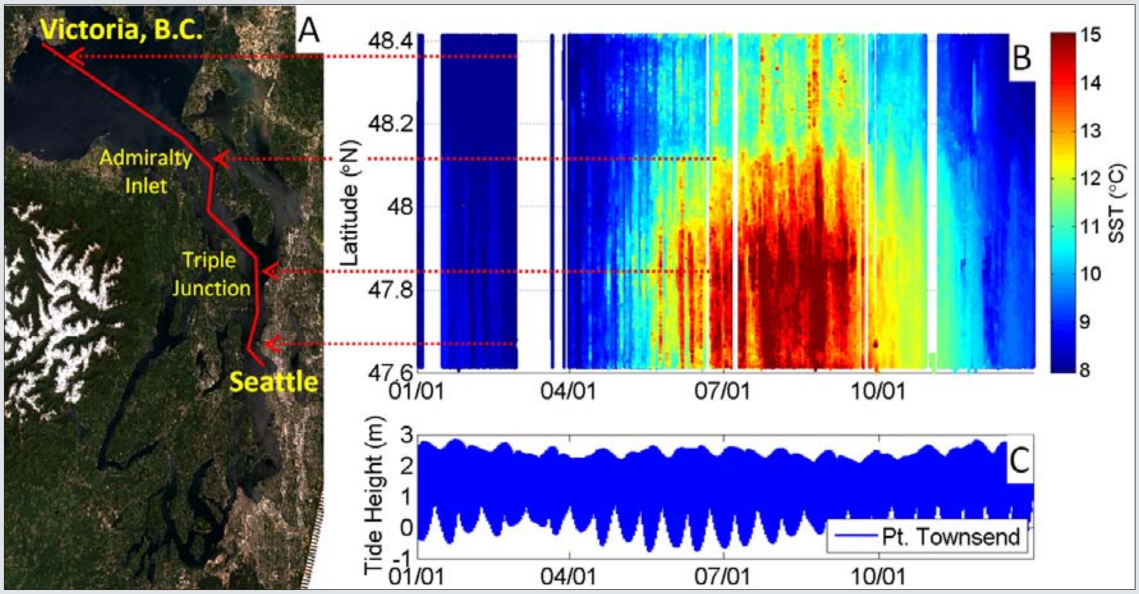



Figure 11. (A) Orientation of the Victoria Clipper transect. (B) SST gradient from Elliott Bay to Strait of Juan de Fuca. (C) Spring/neap tide variability

### iii. ORCA profiling buoys:

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

Profiling buoys provide high-resolution depth-defined data that can illuminate short-term dynamics and identify water masses. Currently there are 6 ORCA (Oceanic Remote Chemical Analyzer) moorings throughout Puget Sound measuring water column properties at high temporal resolution from surface to depth. Temperature, salinity and density from the Twanoh mooring in southern Hood Canal are plotted for the last six years in Figure 12. Seasonal variability in water masses is evident in both the temperature and salinity data. These time series indicate different flushing regimes, which are stimulated by the annual intrusion of oceanic water entering the Puget Sound primarily in the fall. There is substantial interannual variation in the timing, intensity, and duration of the high salinity intrusions. While there is a data gap in late 2010 through early 2011 due to required maintenance, 2011 appears to have less dense waters in general.

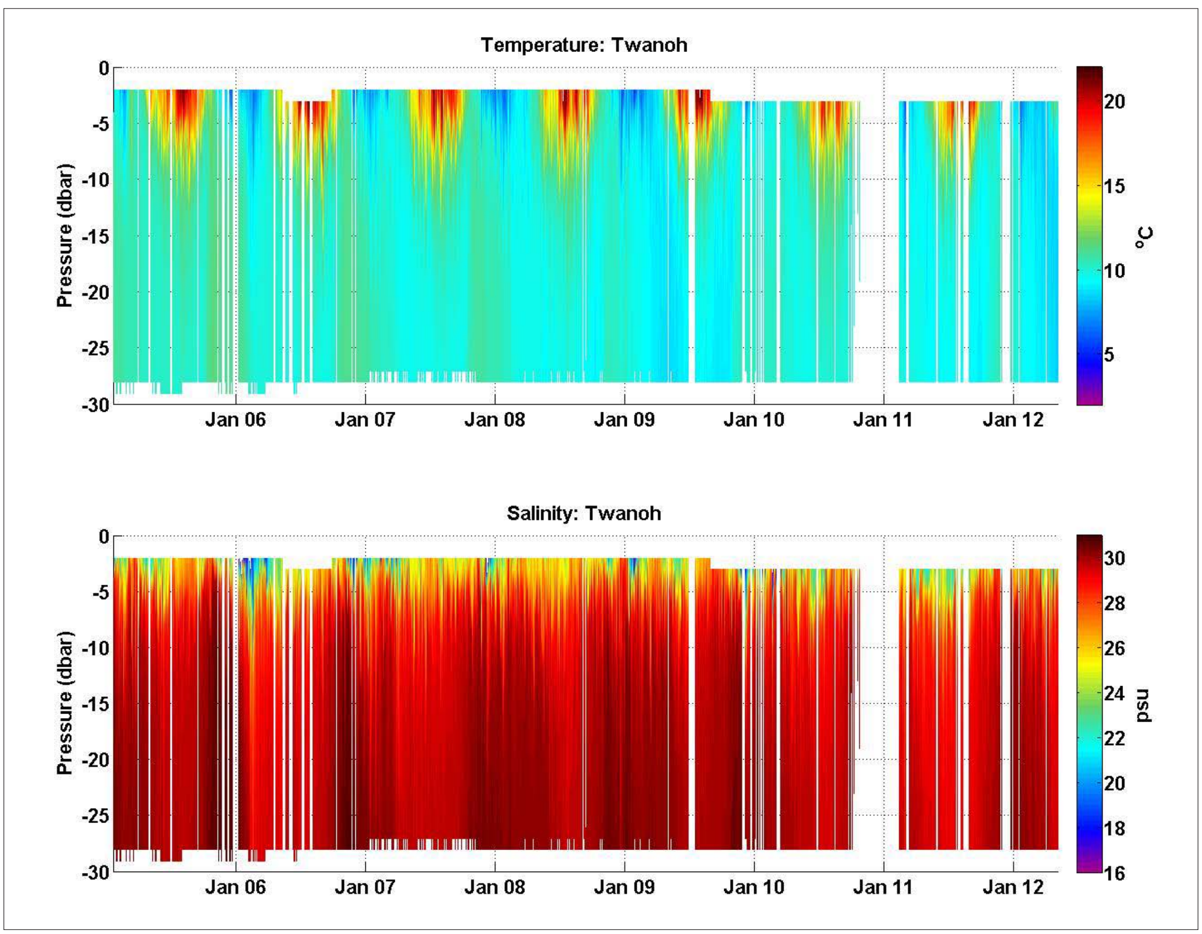



Figure 12. Temperature, salinity and density from the Twanoh mooring in southern Hood Canal for the last six years. Pressure in dbar is roughly equivalent to depth in meters.

### iv. King County Department of Natural Resources & Parks marine waters:

*Source: Kimberle Stark (Kimberle.Stark@kingcounty.gov) (KCDNR)*

Focusing in on sub-regions, King County maintains several monitoring stations within the Main Basin of Puget Sound to assess the county's water quality. An increase in freshwater throughout the Main Basin of Puget Sound in 2011 from the wet spring and subsequent increased riverine input was observed at all sampling sites as indicated by salinity. Water column profile data show that the entire water column was fresher than in previous years, even at sites with depths of 200 meters. Figure 13 shows profile data from a sampling site at Point Wells in the northern Main Basin. The pattern shown is representative of other sites.

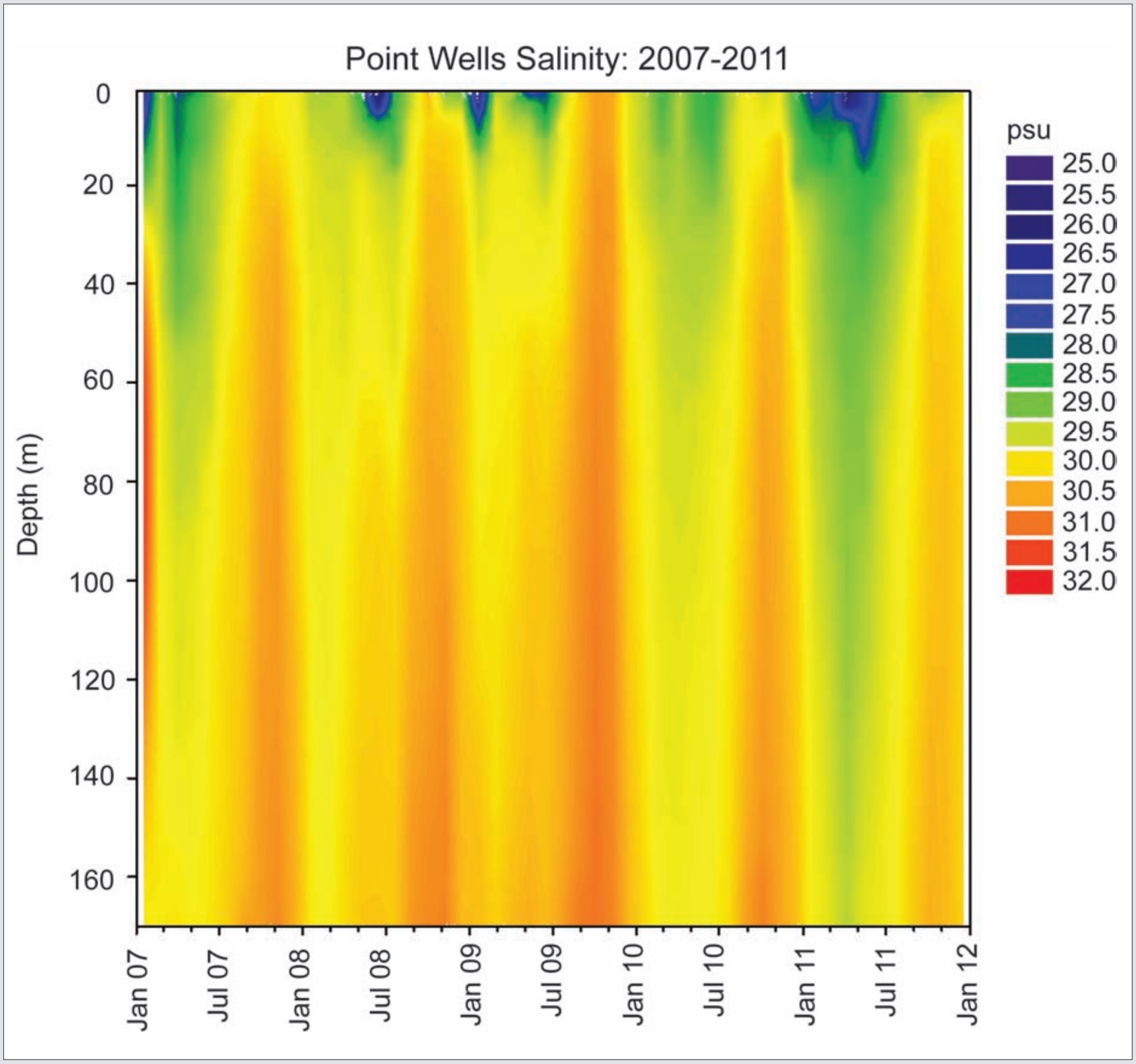



Figure 13. Contours of monthly water column salinity profile data for a northern Central Basin site (Point Wells) showing the increased freshwater input during the wet spring months for the last five years.

### v. Salish Sea surface waters – tribal journey water quality project:

*Source: Eric Grossman (egrossman@usgs.gov) (U.S. Geological Survey) and Sarah Grossman (Swinomish Indian Tribal Community)*

July 2011 marked the fourth year that Coast Salish canoe families from Canada and the United States participated in the mapping of surface water temperature, salinity, pH, dissolved oxygen, and turbidity at 10-second (~20 m) intervals along their ancestral highways, the coastal waters of the Salish Sea (http://www.usgs.gov/coastsalish). Their journeys provide a highly spatially defined snapshot of local surface conditions in Puget Sound and local rivers. In 2011 a total of 25,905 data points were collected along 450 km of marine waters while 2,493 measurements were made along 87 km of the Skagit River (Figure 14). In marine waters, the canoes typically travel in early morning and mid-afternoon along the near shore and occasionally cross deeper bays, channels and fjords. The data provide a unique snapshot of conditions and provide insight to summer conditions when ecosystems are influenced by near peak annual warming, declining stream flow, moderate to high coastal upwelling, and generally high productivity.

Surface temperatures of marine waters were generally cool (ranging 8.9 to 24.5°C) and overall lower (mean of 13.5±2.2°C) than values observed during the 2008 to 2010 surveys (Akin and Grossman, 2009; 2010), possibly reflecting the neutral ENSO, negative PDO, average upwelling, and higher than normal Fraser, Skagit, and Snohomish River flow conditions that characterized the Salish Sea region in July 2011 (Figure 14). Surface temperatures in 2011 were 2 to 4°C warmer in Whidbey Basin (15.4±1.3°C) than in North, Central and South Puget Sound and ~5°C warmer than river inputs (e.g. the Skagit River was 10.4±1.1°C) which were higher than normal with respect to discharge (Figure 14). Surface water salinity for the Washington portion of the study area was 4 to 5 psu fresher than in previous years, likely reflecting higher fluvial runoff and low to moderate coastal upwelling. Salinity was lowest in Whidbey Basin, which has shown the most interannual variability. Salinity in North Central and South Central Puget Sound basins was lower in 2011 than other years but not in South Puget Sound or Hood Canal. Dissolved oxygen in surface water in 2011 ranged from 5.2 to 15.0 mg/L. All of the dissolved oxygen readings below 6.0 mg/L were recorded in the Strait of Juan de Fuca. The surface water temperature of the Skagit River ranged from 7.7 to 12.1°C. Dissolved oxygen ranged from 10.5 to 12.3 mg/L.

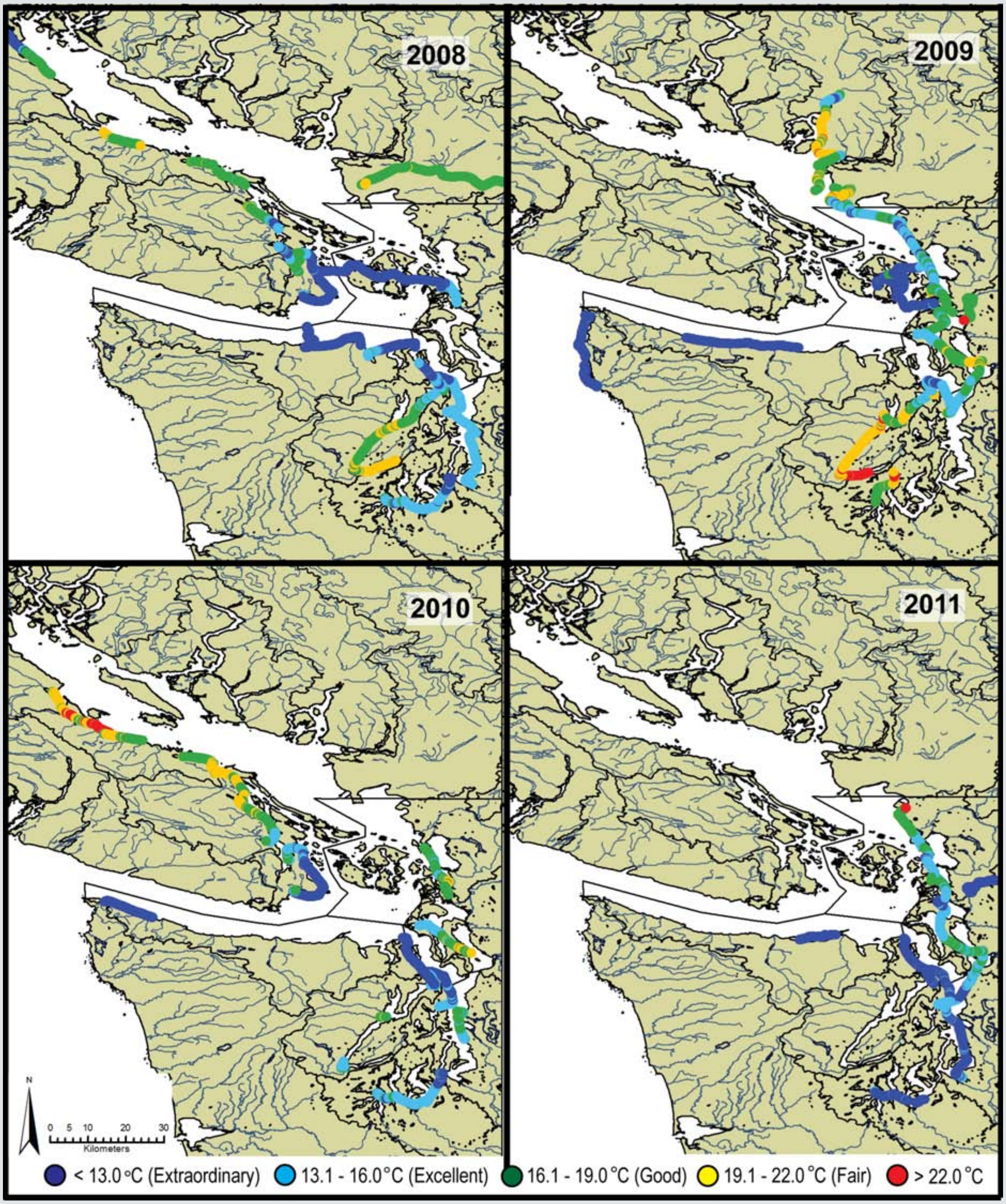



Figure 14. Map showing the results of surface temperature measurements during the 2008 to 2011 TJWQP mapped by Washington State Marine Water Quality Standard classifications.

Variation in surface temperature in Puget Sound (North, Central, South basins) was lower in 2011 compared to 2008 and 2009. 2011 showed steadily increasing temperature with distance south, despite little variability in and apparent influence by salinity (Figure 15). It is interesting to note that when San Juan and Whidbey Basin surface salinity has been low (2010 and 2011) temperatures have been high, despite higher than normal freshwater inputs that have been 3 to 5°C colder than receiving waters. The greatest variability in dissolved oxygen has also been observed in San Juan and Whidbey Basins which also showed lower values in 2008 and 2009 (warmer years with stronger upwelling) than 2010 and 2011.

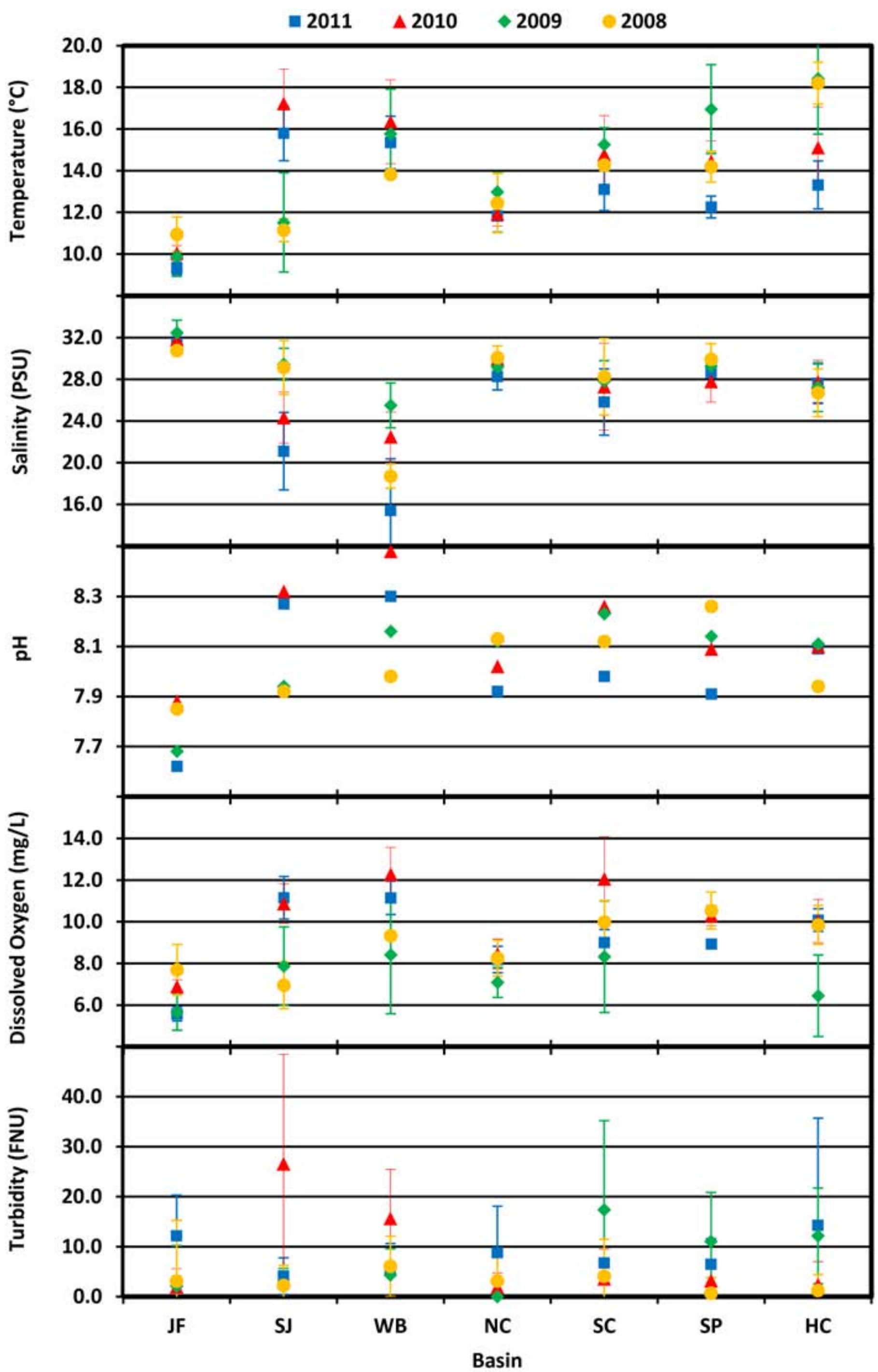



**Figure 15.** Plots showing mean and (1 standard deviation) ranges for surface temperature, salinity, and dissolved oxygen and median pH by basin in Washington waters for 2008 to 2011. JF=Strait of Juan de Fuca, SJ=San Juan Islands, WB=Whidbey Basin, NC=North Central Basin, SC=South Central Basin, SP=South Puget Sound, HC=Hood Canal.

### vi. PRISM-NANOOS cruise:

*Source: Jan Newton (newton@apl.washington.edu) (APL-UW) and Mark Warner (UW); http://www.nanoos.org*

Another highly spatially defined snapshot of Puget Sound conditions are the repeat hydrography cruises throughout Puget Sound, capturing both horizontal and depth variation. Since 1998, the University of Washington has sponsored student cruises aboard its research vessel, the *R/V Thomas G. Thompson*. The students are trained to run the sampling equipment and conduct surveys throughout Puget Sound, covering its major basins: Hood Canal, Whidbey Basin, South Puget Sound, and the Main Basin. The data have been used to calibrate circulation models (Sutherland et al., 2011) and for interpretation of climate influences (Moore et al., 2008a and b). Figure 16 shows temperature and salinity data plotted in sections (depth versus distance) for the October 2011 cruise. All transects start in the Strait of Juan de Fuca, go through Admiralty Inlet and then into the Main Basin, Hood Canal, and Whidbey Basin. Cold and salty water can be seen at depth outside the Admiralty Inlet sill, originating from the ocean. While fall is a time of downwelling, with typically warmer, fresher input from the ocean, relative to the internal waters of Puget Sound these oceanic waters are still seen to be colder and saltier (and with less oxygen content). Another striking feature is the cold (and low oxygen) water in the Great Bend region of Hood Canal (Figure 16 B and E). Skagit River influence on salinity is clearly seen in Whidbey Basin (Figure 16 C and F).

*R/V Thomas G. Thompson.*
Photo credit: ECOHAB PNW

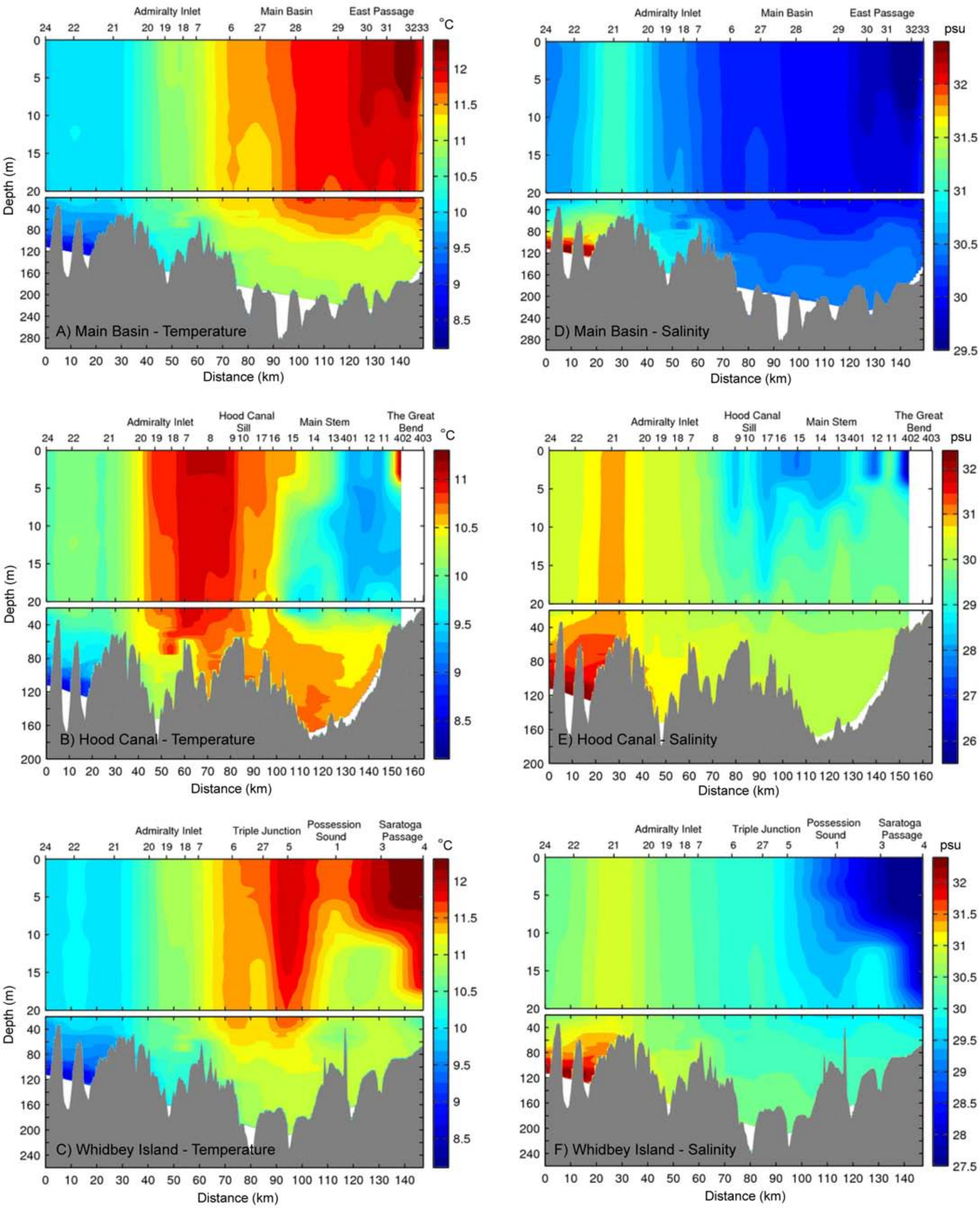



Figure 16. Sections from the UW October 2011 PRISM-NANOOS cruise showing temperature in (A) Main Basin, (B) Hood Canal, and (C) Whidbey Basin, and salinity in (D) Main Basin, (E) Hood Canal, and (F) Whidbey Basin.

*Nutrients and chlorophyll give insight to the production at the base of the food web. Phytoplankton are assessed by monitoring chlorophyll, their photosynthetic pigment. In Puget Sound, like most marine systems, nitrogen nutrients are sometimes limiting. On a mass balance, the major source of nutrients is from the ocean; however, rivers and human sources also contribute especially to surface waters.*

## B. Nutrients and chlorophyll:

### i. Puget Sound long-term stations – nutrient trends:

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

Ecology's long-term stations have been used to identify a nutrient trend in Puget Sound. Despite significantly different physical conditions that added freshwater to Puget Sound in 2011, average yearly nitrate levels ($NO_3$) in Puget Sound continue to increase (Figure 17). This continues the significant 13-year increasing trend in growth-limiting macronutrients (Figure 18A). Significant negative trends in the *Si:N* ratio indicate that oceanic conditions are not contributing to nutrient increases within Puget Sound (Figure 18B).

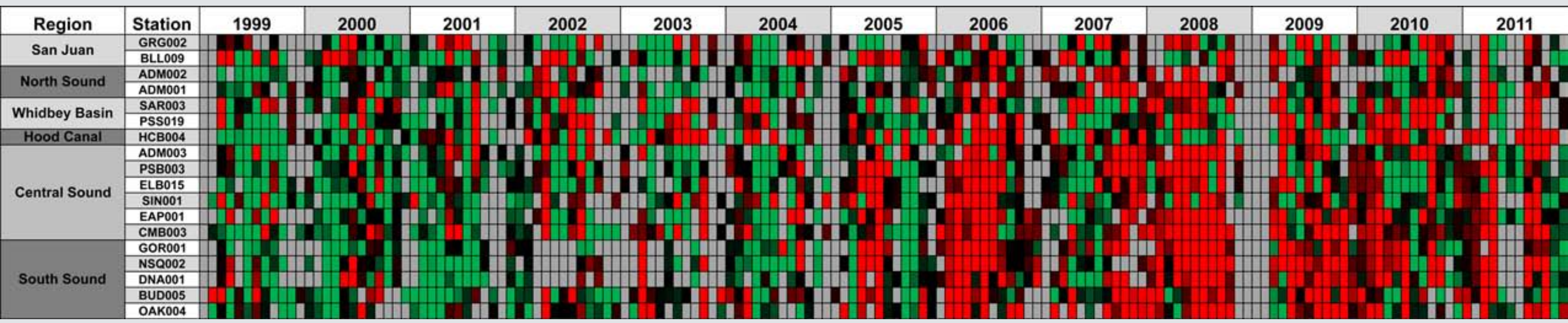



Figure 17. Monthly variability in nitrate concentration for stations in Puget Sound from 1999-2011. A shift from a prevalence of green to red cells indicates significant nitrate increases over the last 10 years. Each cell represents a monthly median nitrate concentration for samples from 0, 10 and 30m depths. Anomalies are defined as falling outside the inter-quartile (25th to 75th percentile) range for site and seasonal specific historic data since 1999. Color indicates anomalies: red < IQR, green > IQR and black = expected (within IQR) values. Grey fields denote no data available.

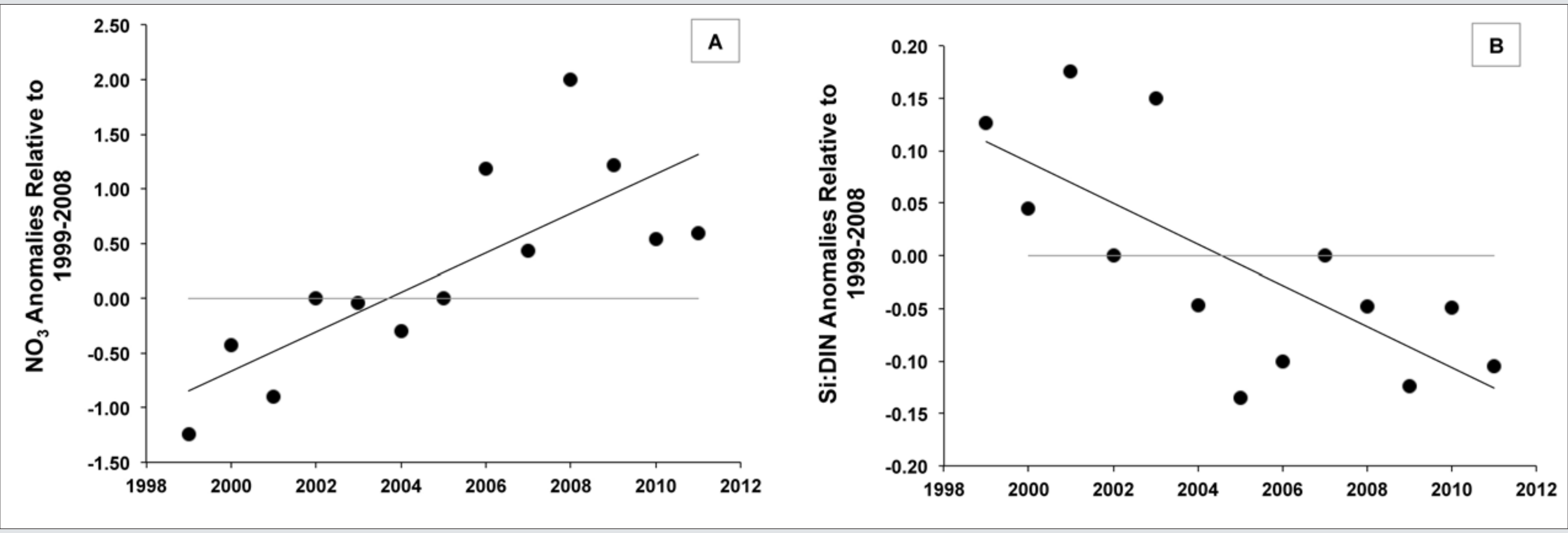
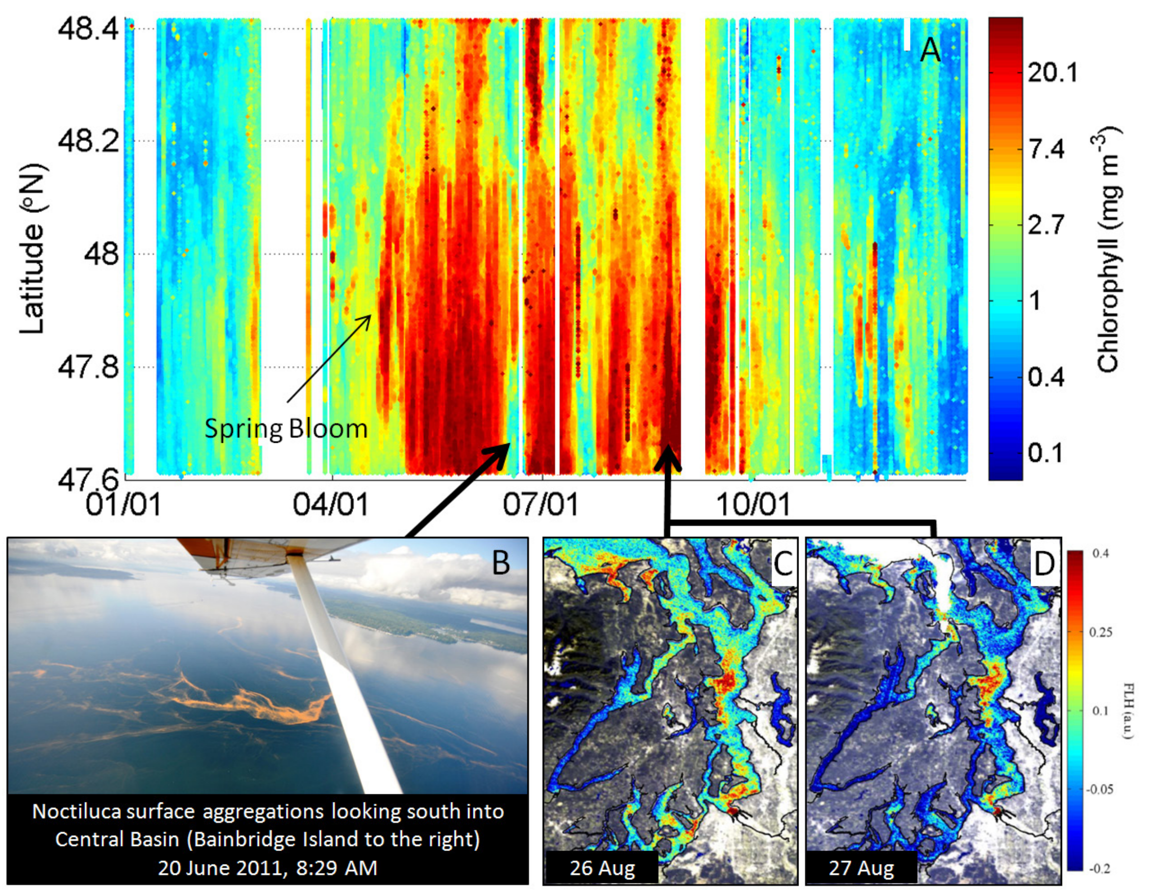



Figure 18. 1999 to 2011 yearly averaged Puget Sound-wide A) nitrate ($NO_3$) anomalies, and B) *Si:N* ratio anomalies.

### ii. Victoria Clipper transect and remote sensing:

*Source: Brandon Sackmann (brandon.sackmann@ecy.wa.gov), Christopher Krembs, and Julia Bos (Ecology)*

The highly resolved spatial transect over time along the Victoria Clipper track have revealed algal bloom dynamics. These are most powerful for understanding short-term variation when used in concert with satellite remote sensing. In Central Puget Sound during 2011 the first strong algal bloom was observed during April. Both ferry and MERIS satellite ocean color from 23 April 2011 suggest that this spring bloom was associated with a plume of Whidbey Basin water (http://www.ecy.wa.gov/programs/eap/mar_wat/eops/clipper.html). Throughout the summer growing season surface algae concentrations near Admiralty Inlet and in the Strait of Juan de Fuca were modulated by spring/neap tidal mixing with higher algae concentrations being observed during periods of reduced mixing/neap tides (Figure 19A). Two brief ‘clearing’ events (reduced turbidity and chlorophyll a fluorescence) occurred in late June and early July. During the first event, aerial surveys revealed a widespread Noctiluca bloom (Figure 19B). These events were associated with reduced near-surface dissolved oxygen concentrations, as measured by a UW/APL ORCA mooring deployed at Point Wells (47.761°N; data not shown). In late August to September an intense algae bloom was observed in the western portion of central Puget Sound off of Bainbridge Island. Satellite data provided spatial context for this large and long-lived algae bloom (Figure 19C and D).




bloom in Central Puget Sound. MERIS Fluorescence Line Height (FLH) images indicating significant blooms on (C) August 26 and (D) August 27, 2011.

Colored dissolved organic matter (CDOM) fluorescence is normally higher in the freshwater that enters Puget Sound from local rivers. Pulses of freshwater water entering Puget Sound from Whidbey Basin (Figure 20A) can affect water quality throughout Admiralty Inlet and the northern portion of Central Puget Sound. CDOM concentrations in the Strait of Juan de Fuca (48.1 to 48.4°N) are maximal during summer, when peak flows from the Fraser River are observed (Figure 20B).

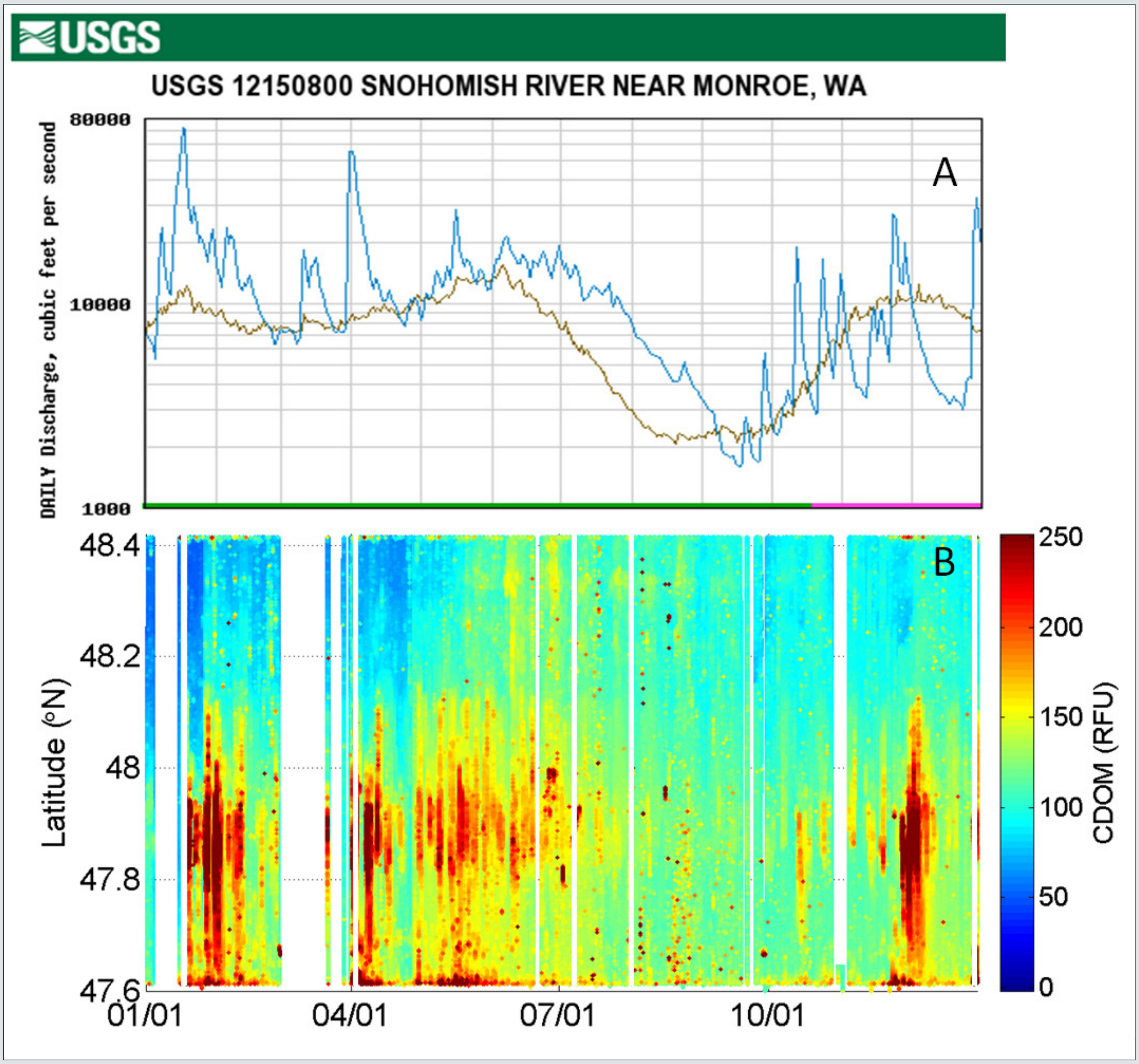



Figure 20. (A) 2011 Snohomish River discharge (blue) and historical average (brown). (B) CDOM (Colored Dissolved Organic Matter) fluorescence along Clipper transect from Elliott Bay to Victoria, B.C.

### iii. ORCA profiling buoys:

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

Because of the high-frequency monitoring aspect of ORCA profiling buoys (multiple times a day) differences in phytoplankton bloom dynamics can be compared between basins. In Figure 21, chlorophyll concentrations from 2011 are plotted from the main basin of Puget Sound (Point Wells), southern Puget Sound (Carr Inlet), and southern Hood Canal (Hoodsport and Twanoh). Differences between southern Hood Canal and other stations are observed in both the timing of the spring bloom and nutrient limitation of the bloom. The start of the spring bloom in 2011 is significantly earlier in the year in southern Hood Canal versus the main basin and south Sound. Nutrient limitation of surface phytoplankton, as evidenced by the presence of a subsurface chlorophyll maximum, is observed within weeks in southern Hood Canal; Carr Inlet appears to be somewhat nutrient limited beginning in August, and Point Wells does not experience significant nutrient limitation.

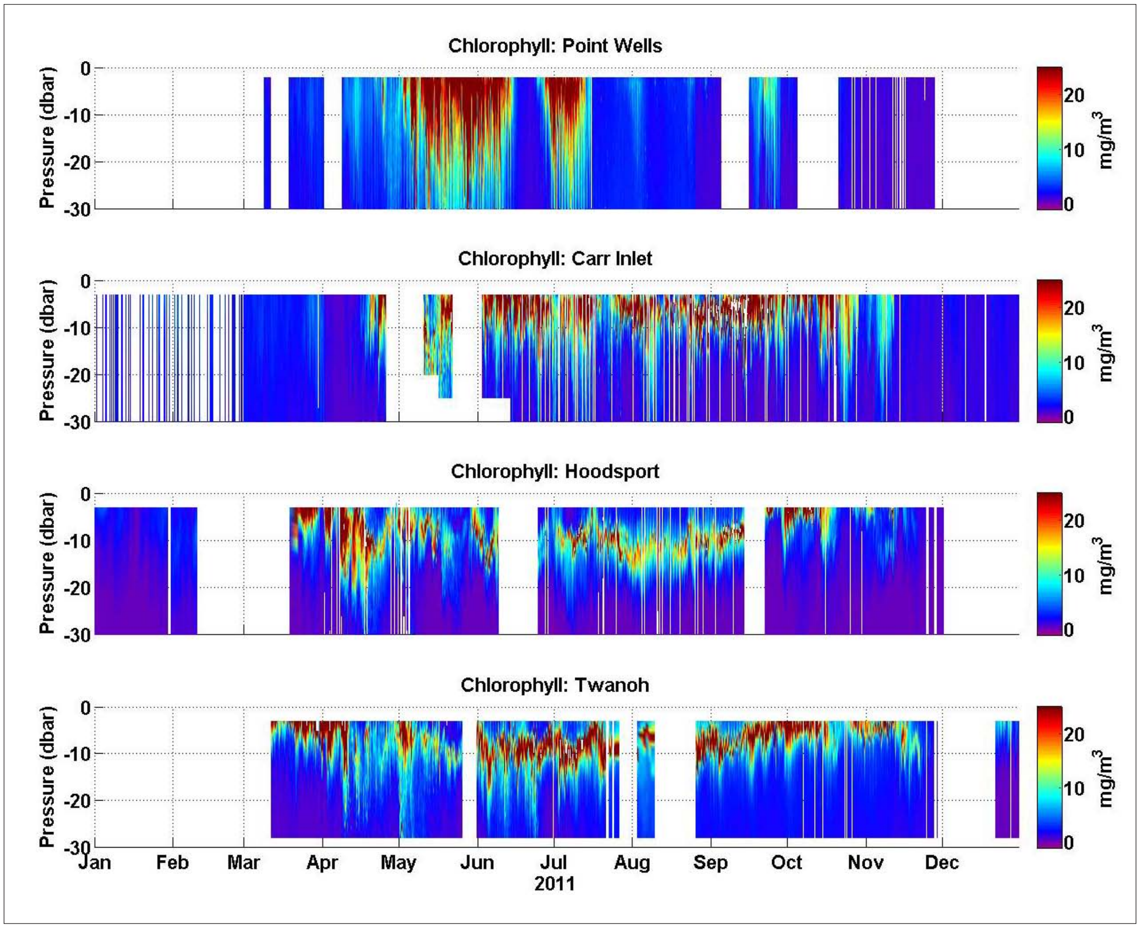



Figure 21. Chlorophyll a concentrations from 2011 are plotted from the main basin of Puget Sound (Point Wells), southern Puget Sound (Carr Inlet), and southern Hood Canal (Hoodsport and Twanoh). Pressure in dbar is roughly equivalent to depth in meters.

### iv. King County Department of Natural Resources & Parks marine waters:

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

Focusing on the Main Basin of Puget Sound, results from monthly sampling at 12 open water sites, bi-weekly sampling at three locations from March through October, and three in situ moorings reveal bloom dynamics in King County waters.

The effects of the cold, wet spring in 2011 can be seen in the water column data. The spring phytoplankton bloom usually occurring in late March/early April and consisting primarily of diatoms was delayed until late April and May, dependent upon location. Based upon chlorophyll-*a* data, the bloom was delayed until May for most open water locations. This delay resulted in increased nutrients, nitrate+nitrite and silica in particular, in surface waters during April due to the lack of phytoplankton uptake (Figure 22). A large phytoplankton bloom occurred throughout the Central Basin in May and had dissipated by late June, based on results of bi-weekly sampling at three locations. Another large bloom occurred in the first week in July but was absent by mid-July. Ammonia concentrations were elevated in June and July throughout the Central Basin due to degradation of the large blooms. Overall, phytoplankton blooms in 2011 did not follow the typical pattern observed in prior years.

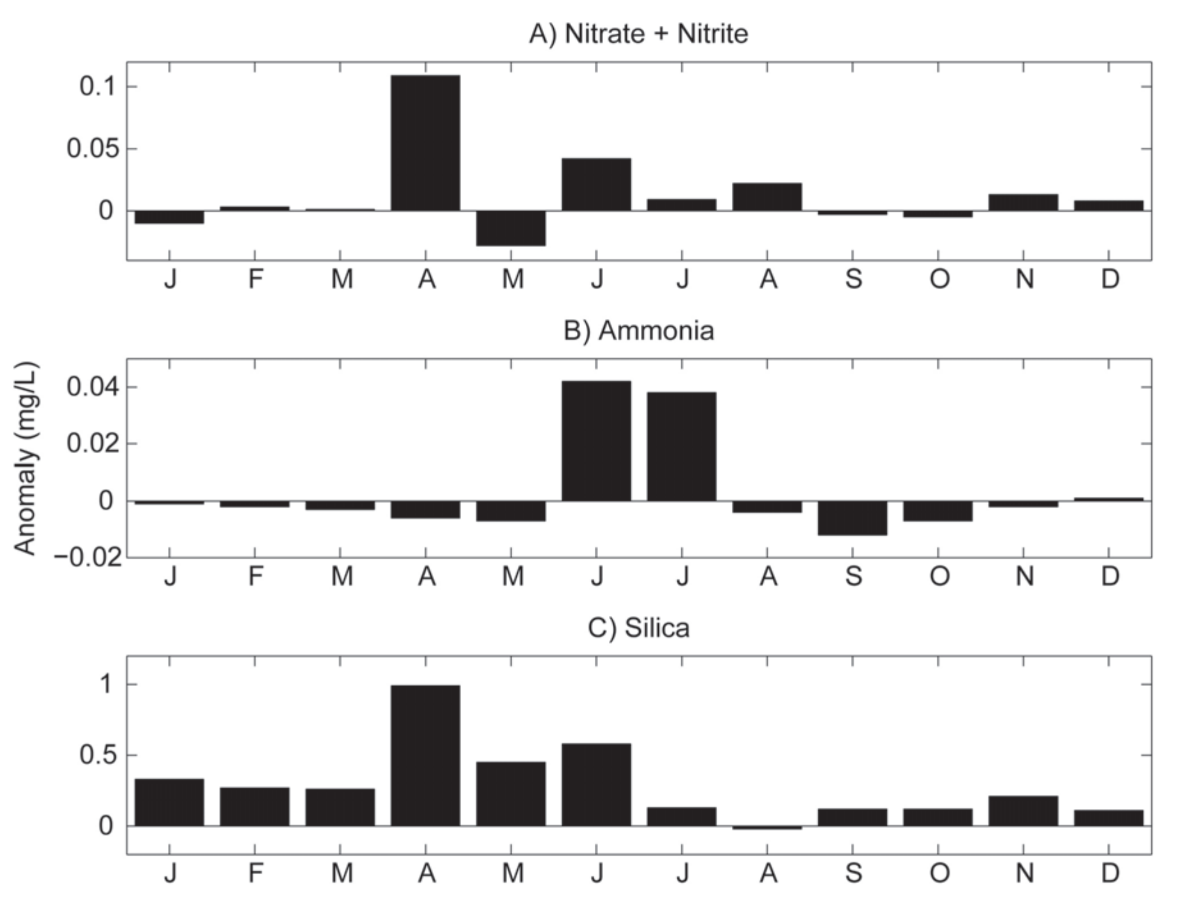
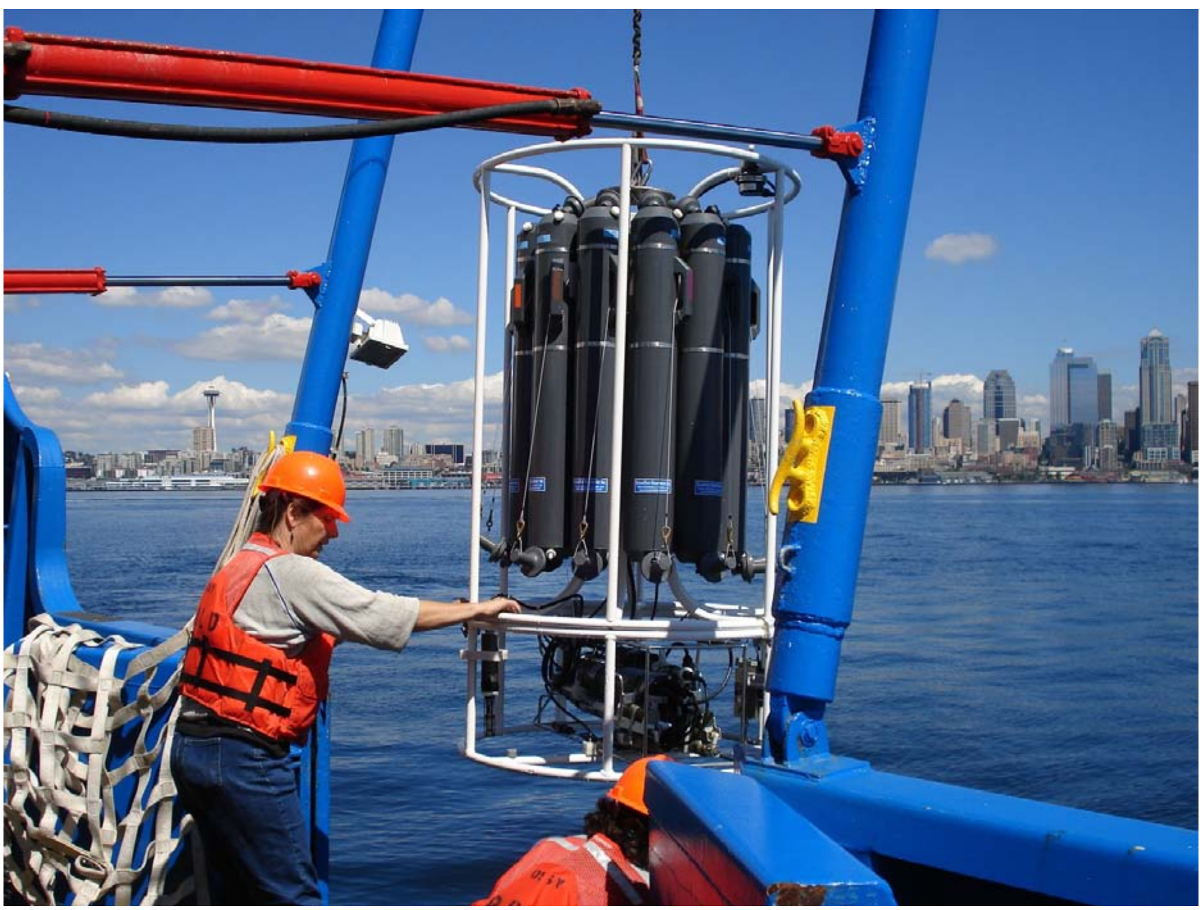



**Figure 22.** These figures show 2011 anomalies for 12 open water sites for (A) nitrate and nitrite, (B) ammonia, and (C) silica. Anomalies were calculated using a 12-year dataset for surface waters <2 m. The positive nitrate+nitrite and silica anomalies in April are due to the lack of phytoplankton uptake. The silica figure also reflects the increased riverine input in 2011. Positive ammonia anomalies in June and July are due to the prior months phytoplankton blooms degradation.

### v. PRISM-NANOOS cruise:

*Source: Jan Newton (newton@apl.washington.edu) (UW, APL) and Mark Warner (UW); http://www.nanoos.org*

The hydrographic sections from the PRISM-NANOOS cruise show interesting features in chlorophyll distributions during October 2011. Figure 23 shows chlorophyll and transmissivity data plotted in sections (depth versus distance) from the October 2011 PRISM-NANOOS cruise. All transects start in the Strait of Juan de Fuca, go through Admiralty Inlet and then into the Main Basin, Hood Canal, and Whidbey Basin. A striking feature is the water in the Great Bend region of Hood Canal that is very low in particles and chlorophyll (also cold and low oxygen), indicating its deep origin. Also seen is the strong phytoplankton bloom in Hood Canal, as indicated by chlorophyll-a landward of the Great Bend toward Lynch Cove (20 µg/L), that is much higher than that seen in Whidbey Basin at Saratoga Passage (4 µg/L) and in the Main Basin at East Passage (6 µg/L).



Jan Newton (UW, APL) retrieves a CTD-rosette sampling package at a station offshore from downtown Seattle during a PRISM cruise on Puget Sound on the EPA's Ocean Survey Vessel Bold in August 2008. Photo credit: Simone Alin, NOAA

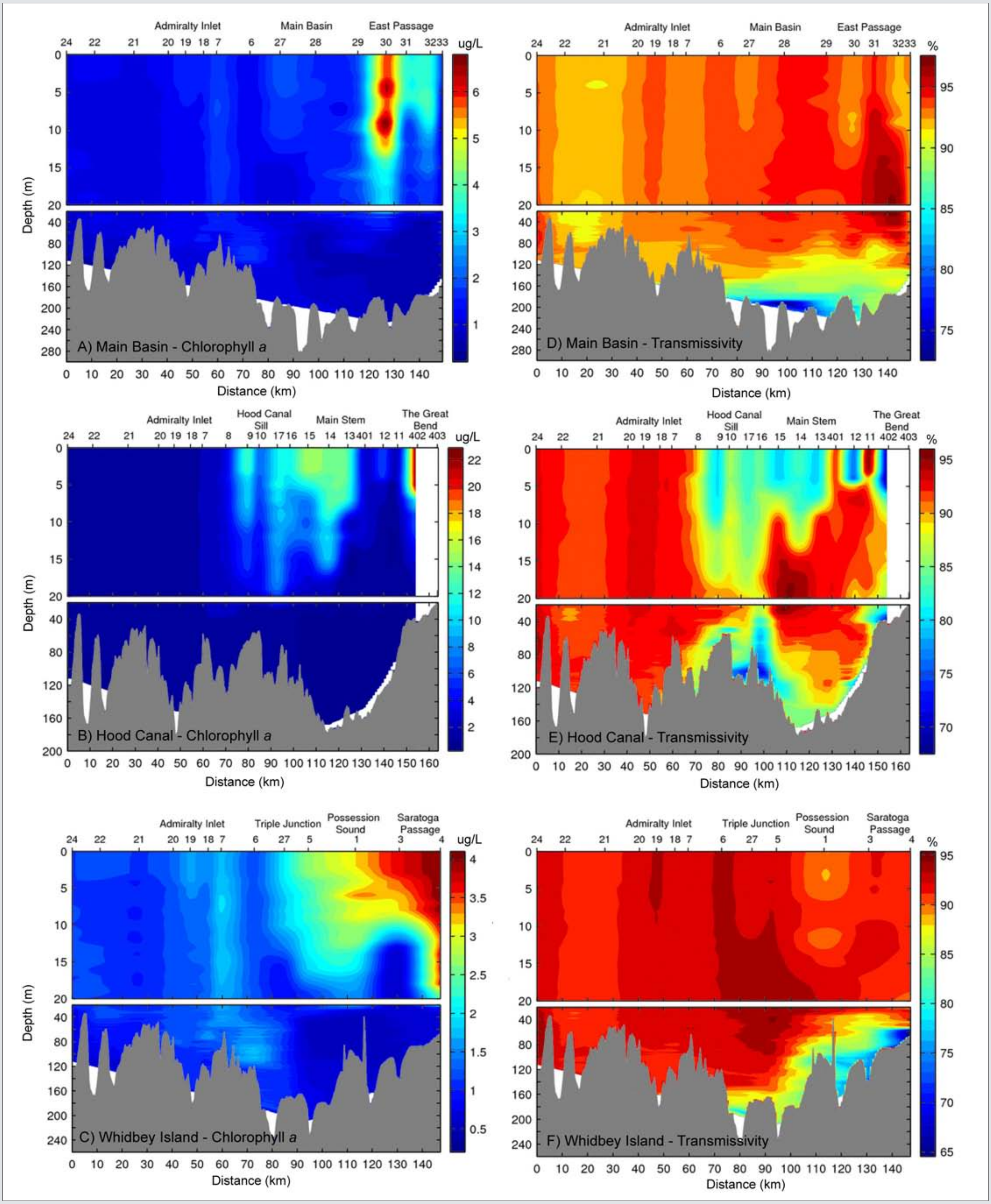



Figure 23. Sections from the UW October 2011 PRISM-NANOOS cruise showing chlorophyll in (A) Main Basin, (B) Hood Canal, and (C) Whidbey Basin, and transmissivity in (D) Main Basin, (E) Hood Canal, and (F) Whidbey Basin.

## Dissolved oxygen in Hood Canal:

Dissolved oxygen in the deep waters of southern Hood Canal goes through a seasonal cycle reflecting the physical and biological processes which control its distribution. The deep waters of Hood Canal are replaced approximately once per year around the end of summer. The “new” deep waters are dense (salty) waters that have recently upwelled along the coast and traveled through the Strait of Juan de Fuca to Admiralty Inlet. The dissolved oxygen content of these waters is typically higher than those within Hood Canal, but they are much lower than the concentration would be if these waters were in oxygen equilibrium with the atmosphere. This seasonal flushing displaces older, oxygen-poor water in Hood Canal upwards and results in a mid-depth dissolved oxygen minimum through Hood Canal, representing the older waters being pushed up and sandwiched between the top layer and the “new” deeper waters. The oxygen minimum can be found just below the pycnocline (density gradient just below the surface layer) over much of this region. Mixing of the mid-depth waters with colder, fresher waters during winter and into spring increases the average dissolved oxygen of southern Hood Canal. Near the time of the spring phytoplankton bloom, the dissolved oxygen concentrations in the deep waters begin to decrease. This is because the demand for dissolved oxygen for respiration of the sinking organic matter is greater than the supply of dissolved oxygen from waters flowing over the sill. The flushing slows greatly during the summer months until the intrusion of the higher density upwelled water again occurs in the late summer. During this late summer period the oxygen inventory is typically at its lowest.

Author: Mark Warner

*Dissolved oxygen in Puget Sound’s marine waters is quite variable spatially as seen by Sound-wide sections. Dissolved oxygen has been intensively monitored in Hood Canal in response to severe hypoxia causing large fish kills in 2003 and 2006. South Puget Sound also experiences problems due to low dissolved oxygen levels. Various Puget Sound inlets with restricted flushing, such as Quartermaster Harbor, also develop hypoxia.*

## C. Dissolved oxygen:

### i. ORCA profiling buoys:

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

With the exception of southern Hood Canal, hypoxic conditions were not observed at any of the buoy locations during 2011 (Figure 24). The two southern most buoys in Hood Canal, however, showed extensive periods of hypoxia. Southern Hood Canal has been the subject of extensive sampling over the last 5 years in response to an apparent increase in the intensity and duration of seasonal deep water hypoxia as well as the frequency of fish kill events. Many of the fish kill events have been observed near the Hoodsport mooring. Dissolved oxygen concentrations observed at Hoodsport were not as intensely hypoxic during 2011 in comparison with the previous 5 years. A typical pattern for southern Hood Canal is for deep water oxygen concentrations to decrease over the course of the summer with the fall intrusion of oceanic water pushing this hypoxic layer closer to the surface, a condition that leaves the area vulnerable to a fish kill. In order to compare 2011 to other recent years and put it in perspective to the typical pattern, oxygen profiles from the Hoodsport mooring in southern Hood Canal from 2006 to 2011 are plotted to highlight hypoxia in Figure 24. Oxygen concentrations are contoured with high concentrations indicted by warm colors and low concentrations indicated by cool colors. The color scale turns to white at 2 mg/L, a common threshold for the definition of hypoxia, and fades to dark purple as concentration values reach 0 mg/L. Both 2006 and 2010 were years with low oxygen concentrations throughout in the lower water column and a layer of hypoxic water near the surface by late summer; fish kill events were observed in both years. In contrast, oxygen concentrations in 2007 to 2009 were relatively high, and while oxygen minima formed in late summer near the surface, the oxygen concentrations were higher than in 2006 or 2010, and no fish kill events were observed. Oxygen concentrations in 2011 were in the middle of the spectrum. Patterns were remarkably similar to those observed during 2010, with a layer of low oxygen forming at depth over the summer and gradually expanding up near the surface by late summer. However, the intensity of hypoxia was less than in 2010, and no fish kill events were observed.

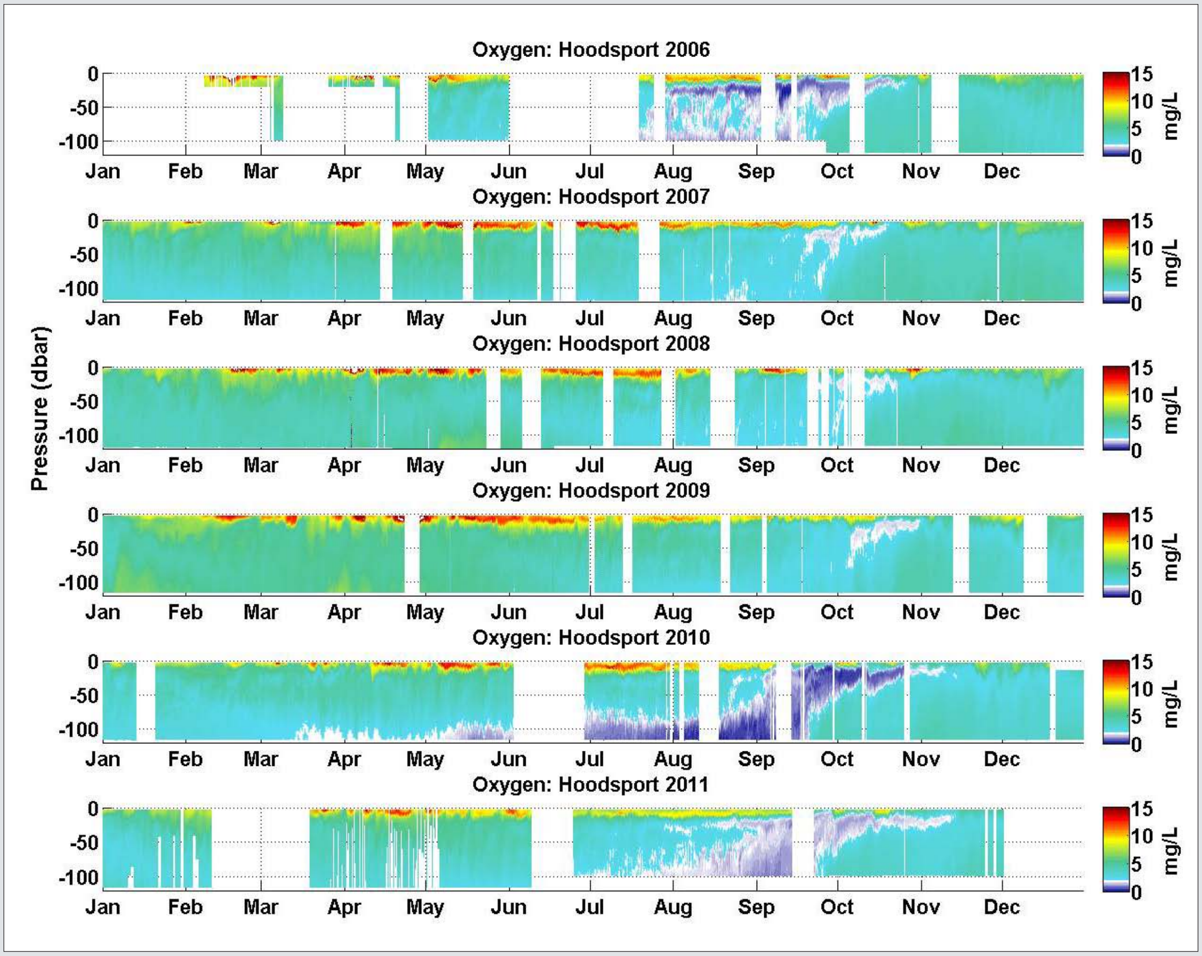



**Figure 24.** Oxygen profiles from the Hoodsport mooring in southern Hood Canal from 2006 to 2011. Pressure in dbar is roughly equivalent to depth in meters.

### ii. Puget Sound Long-Term Stations – DO deficit:

*Source: Julia Bos (julia.bos@ecy.wa.gov), Christopher Krembs, Mya Keyzers, Laura Friedenberg, and Carol Maloy (Ecology)*

The Washington State Department of Ecology measures dissolved oxygen concentration monthly at core stations in Puget Sound. These measurements are used to calculate the amount of oxygen required to saturate portions of the water column that are under-saturated with respect to oxygen. The total amount of oxygen required to saturate the water column is referred to as the "DO deficit". When DO saturation is high, the deficit is low, and when DO saturation is low, the deficit is high. Figure 25 shows the DO deficit from 1999 to 2011. In general, the DO deficit in Puget Sound was lower than usual in 2011, implying that DO levels were closer to saturation compared to previous years.

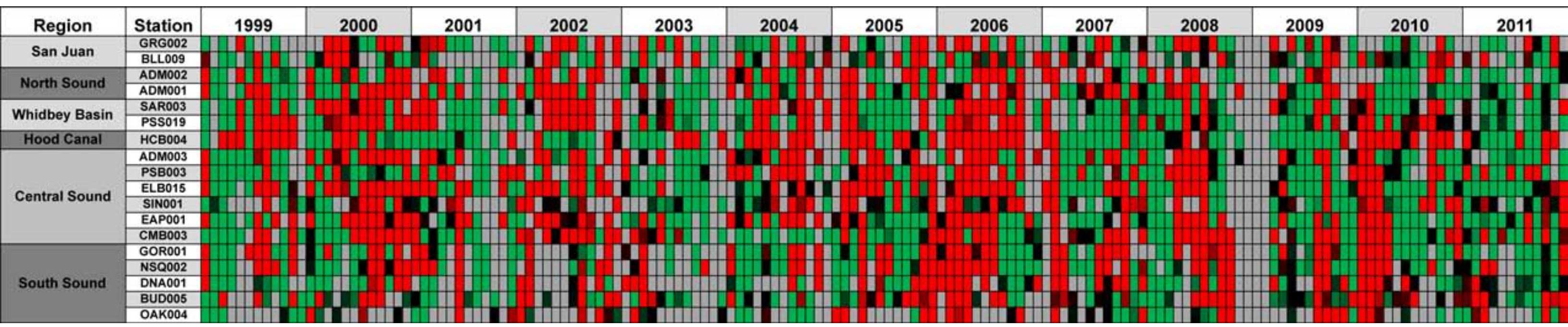



Figure 25. Monthly anomalies of the DO deficit for Puget Sound stations from 1999 to 2011 over a depth of 0 to 50 m. Each cell represents the difference in the DO deficit compared to a historical baseline median value. Red = higher than the historical median and represents waters with a greater DO deficit (i.e., low DO). Green = lower than the historical median and represents waters with a lower DO deficit (i.e., high DO). Black = expected (close to median) values. Grey = no data available.

### iii. PRISM-NANOOS cruise:

Source: Jan Newton (newton@apl.washington.edu) (UW, APL) and Mark Warner (UW); http://www.nanoos.org

The PRISM-NANOOS hydrographic sections show basin differences in oxygen content. Figure 26 shows oxygen data plotted in sections (depth versus distance) for the October 2011 PRISM-NANOOS cruise. All transects start in the Strait of Juan de Fuca, go through Admiralty Inlet and then into the Main Basin, Hood Canal, and Whidbey Basin. Clearly seen is the low oxygen water (also cold and salty) found at depth outside the Admiralty Inlet sill, originating from the ocean. Low oxygen water (also low in particles and chlorophyll) can also be seen in the Great Bend region of Hood Canal. Notably at the time, these waters extend all the way to the surface, with oxygen values of ~3 mg/L in contact with the surface. Fall 2011 had some sunny weather prior to the cruise, but had strong southerly winds during the cruise that are known to cause localized upwelling of deep waters. This phenomenon sometimes can result in fish kills, but the 2011 oxygen concentration being upwelled (2 to 3 mg/L) was not low enough to result in mortality.

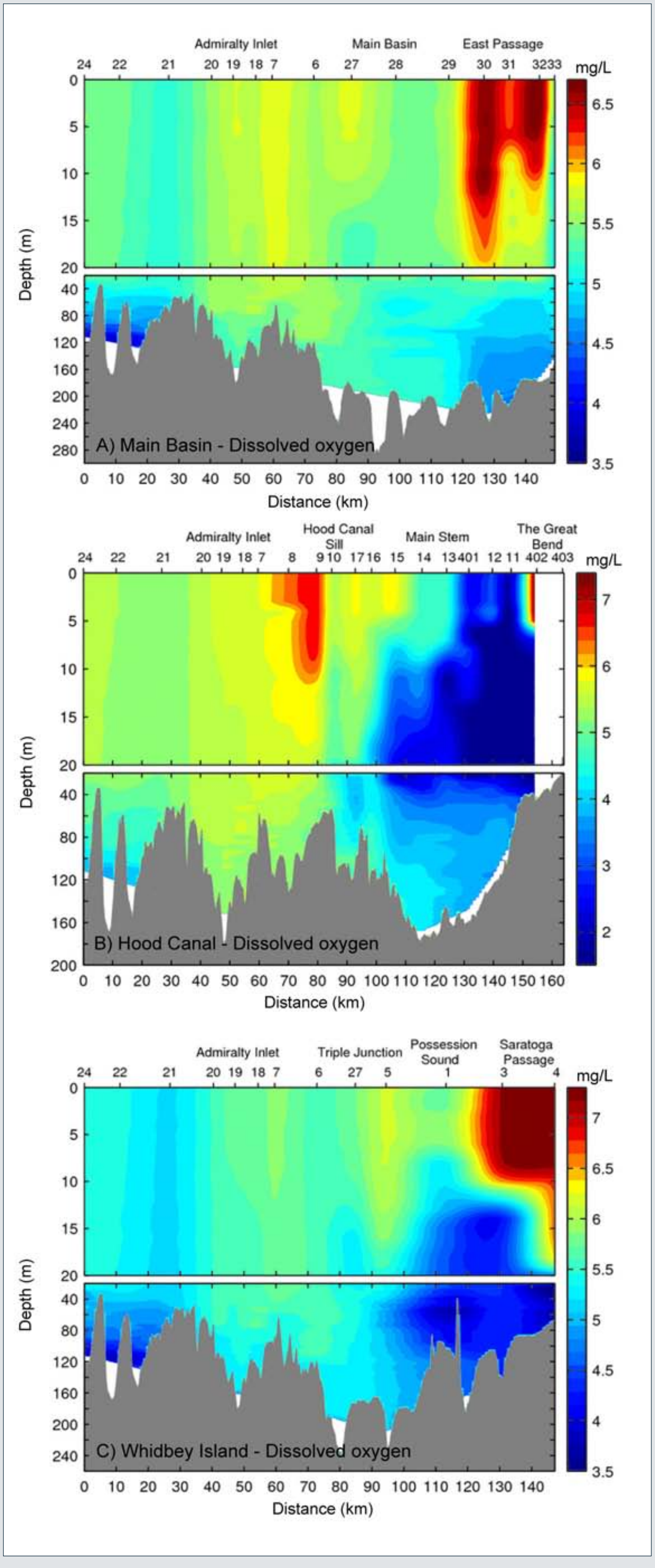



Figure 26. Dissolved oxygen sections from the UW October 2011 PRISM-NANOOS cruise in (A) Main Basin, (B) Hood Canal, and (C) Whidbey Basin.

### iv. Hood Canal oxygen inventory:

*Source: Mark Warner (warner@u.washington.edu) (UW) and Jan Newton (UW, APL)*

The seasonal pattern in dissolved oxygen in the main stem of Hood Canal is shown in Figure 27. In contrast to 2009, which started out with comparatively high oxygen (>6 mg/L) and ended relatively low (~4 mg/L), or 2010, which started out comparatively low (4 mg/L), had a minimum of <3 mg/L, and ended average (4.5 mg/L), 2011 was a very average year relative to the full data record of 29 years representing the 1950s, 1960s, 1990s and 2000s. The year 2011 started out and ended with concentrations just under 5 mg/L and had a minimum just over 3 mg/L. There were no cases of fish kills reported in southern Hood Canal during 2011. The annual cycle in the DO concentrations in Lynch Cove is similar to that from the main stem of Hood Canal, showing higher variation during spring than during fall (Figure 28). However, when assessing interannual variability, 2011 appears to be a low oxygen year during fall with many values under 1 mg/L. This suggests that the annual flushing was slow to reach the Lynch Cove area and respiration was significant.

Credits: Oxygen inventory calculation (Figure 27) by Mark Warner, University of Washington; data interpretation by Mark Warner and Jan Newton, University of Washington. The data from the 1950s and 1960s are from Collias et al., 1966. The data from the 1990s and some of the 2000s are from the University of Washington PRISM program. The data from much of the 2000s are from the Hood Canal Dissolved Oxygen Program as implemented by the Hood Canal Salmon Enhancement Group. Graphic and data interpretation by Jan Newton and Corinne Bassin, University of Washington. The data are from the Hood Canal Dissolved Oxygen Program as implemented through the Hood Canal Salmon Enhancement Group by Dan Hannafious and Renee Rose. Data can be accessed at http://www.nanoos.org.

Jan Newton, Mark Warner, and others prepare to install solar panels on a newly deployed ORCA mooring. Photo credit: Wendi Ruef

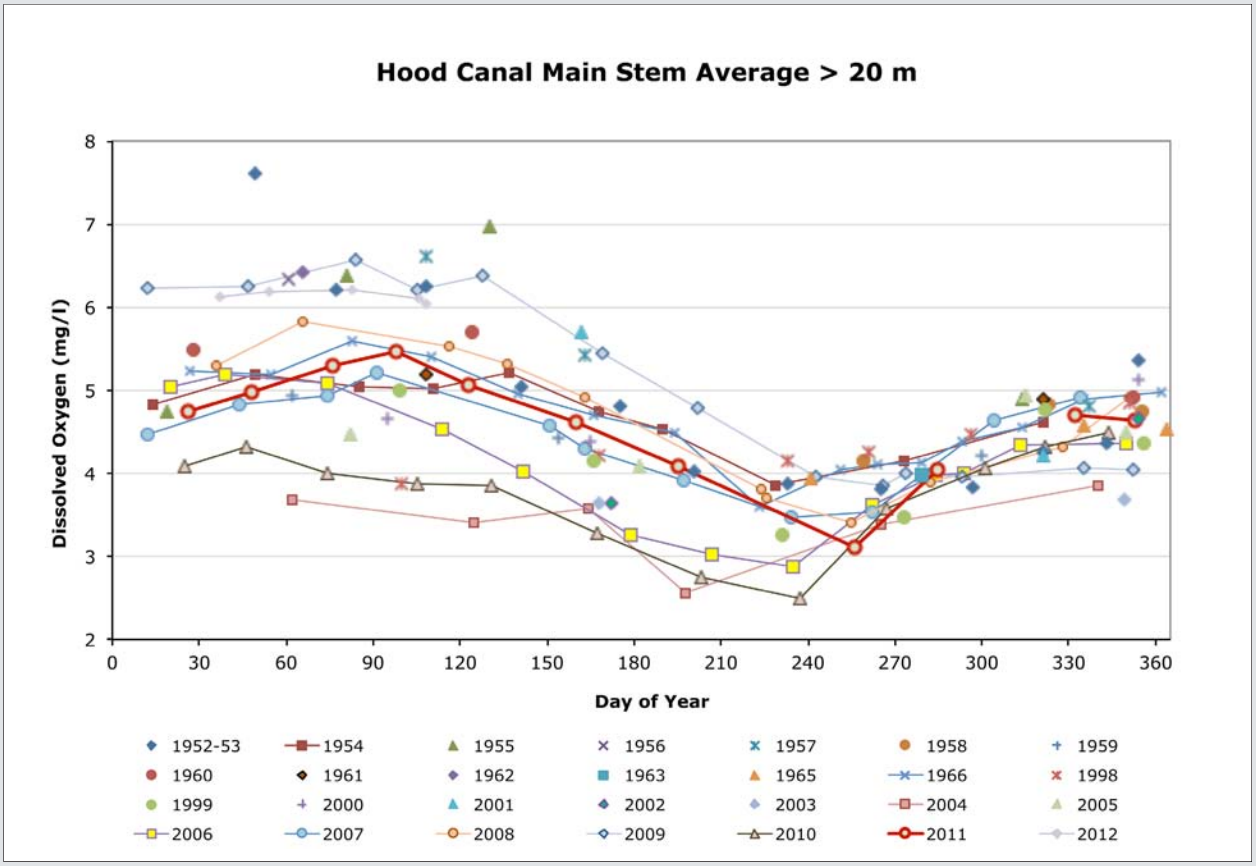



Figure 27. The average dissolved oxygen concentration in the water below 20 meters depth in the region between Dabob Bay and the Great Bend (PRISM Station 11) plotted versus the day of the year. There are two important aspects of this figure to note: the annual cycle in the dissolved oxygen concentrations and the interannual variability.

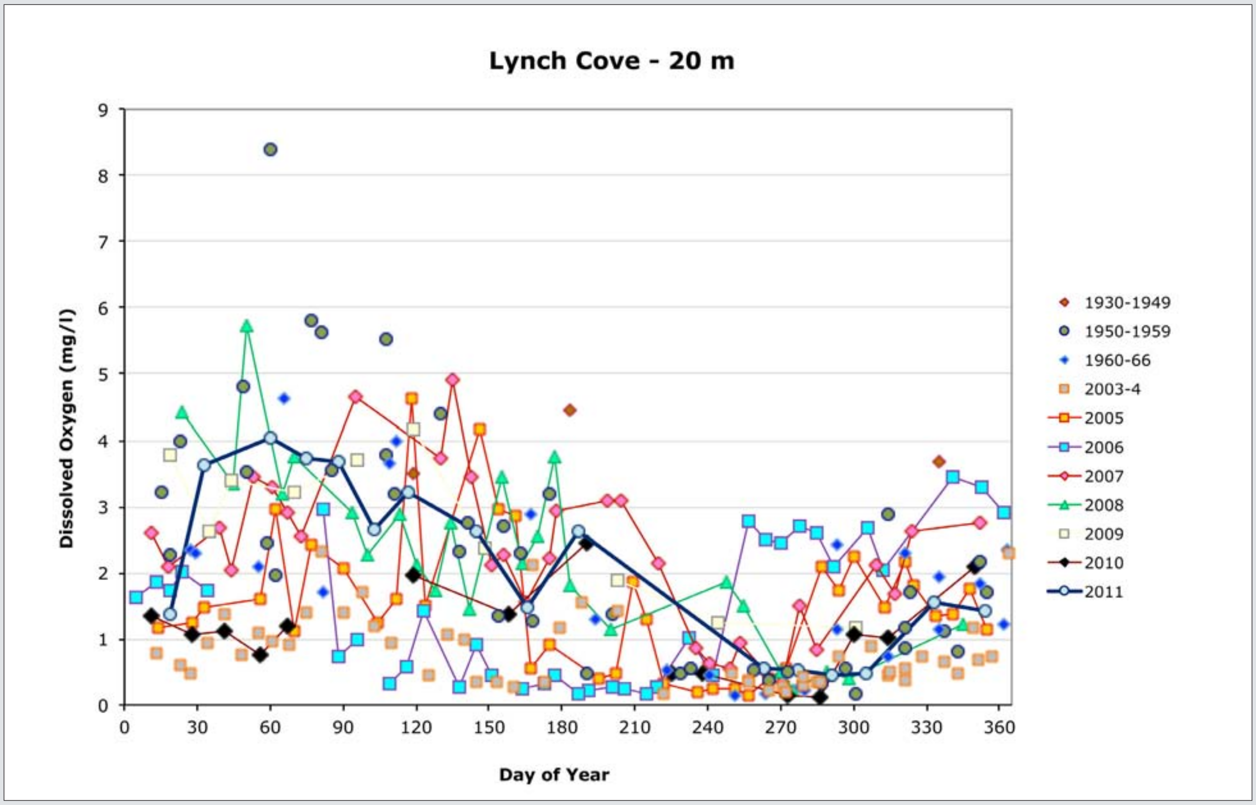



Figure 28. This dissolved oxygen concentration at depth (~1 m above sea bed) at the HCDOP mid-channel Lynch Cove station plotted versus the day of the year.

### v. Oxygen in Quartermaster Harbor:

*Source: Cheryl Greengrove (UWT) and Kimberle Stark (KCDNR)*

Dissolved oxygen has been monitored at nine locations in Quartermaster Harbor since 2006. The University of Washington Tacoma (UWT) collects monthly water column profile data at seven stations throughout the harbor and King County (KCDNR) collects single-depth in situ data at two dock sites and discrete data from two depths at the same sites. A four-year study is currently underway in Quartermaster Harbor to determine the role, if any, nitrogen plays in low dissolved oxygen events observed in the harbor. The project website can be accessed at http://www.kingcounty.gov/environment/watersheds/central-puget-sound/vashon-maury-island/quartermaster-nitrogen-study.aspx.

Monitoring results over the last six years indicate that oxygen is lowest in the late summer through fall in the shallow, inner harbor. High DO values are seen in March and April due to the production during the spring phytoplankton bloom. The 2011 spring bloom was not delayed in Quartermaster Harbor as was seen at open water Central Basin sites and DO results from 2011 were similar to previous years.

Figure 29 shows a composite of DO in Quartermaster Harbor is compiled from the two dockside moorings located at Dockton (7-m depth) in the outer harbor and the Yacht Club in the inner harbor (1-m depth) that record DO at 15-minute intervals. Quartermaster Harbor has an aquatic use designation of "extraordinary" by the Washington State Department of Ecology, which sets the DO standard at 7 mg/L. Although DO values routinely fall below this standard in the late fall months, exceptionally low levels – near and below 2.0 mg/L – have been observed during this season. Figure 29A shows 2011 inner harbor (Yacht Club) data for the entire year. Figure 29B expands one week of this time series during the fall to show the impact of phytoplankton photosynthetic diurnal variation on DO in the water column on short time scales. It is also important to note that monthly daytime discrete sampling of oxygen at these locations misses the extreme lows in DO that can occur on a daily basis due to this process. Figure 29C shows DO in the outer harbor (at Dockton) from 2009 to 2011. Note there is a downward trend in oxygen at this location from April to September in all years. Figure 29D shows only 2011 DO data at Dockton and the sharp increases in DO due to phytoplankton productivity. Both the inner and outer harbor 2011 time series follow the same pattern of decreasing oxygen over the same time period, consistent with the two previous years. The two data series also show similar higher frequency variability, though the outer harbor appears to slightly lag behind the inner harbor DO signal and the inner harbor has greater extreme events. In situ data are available at http://green.kingcounty.gov/marine-buoy/.

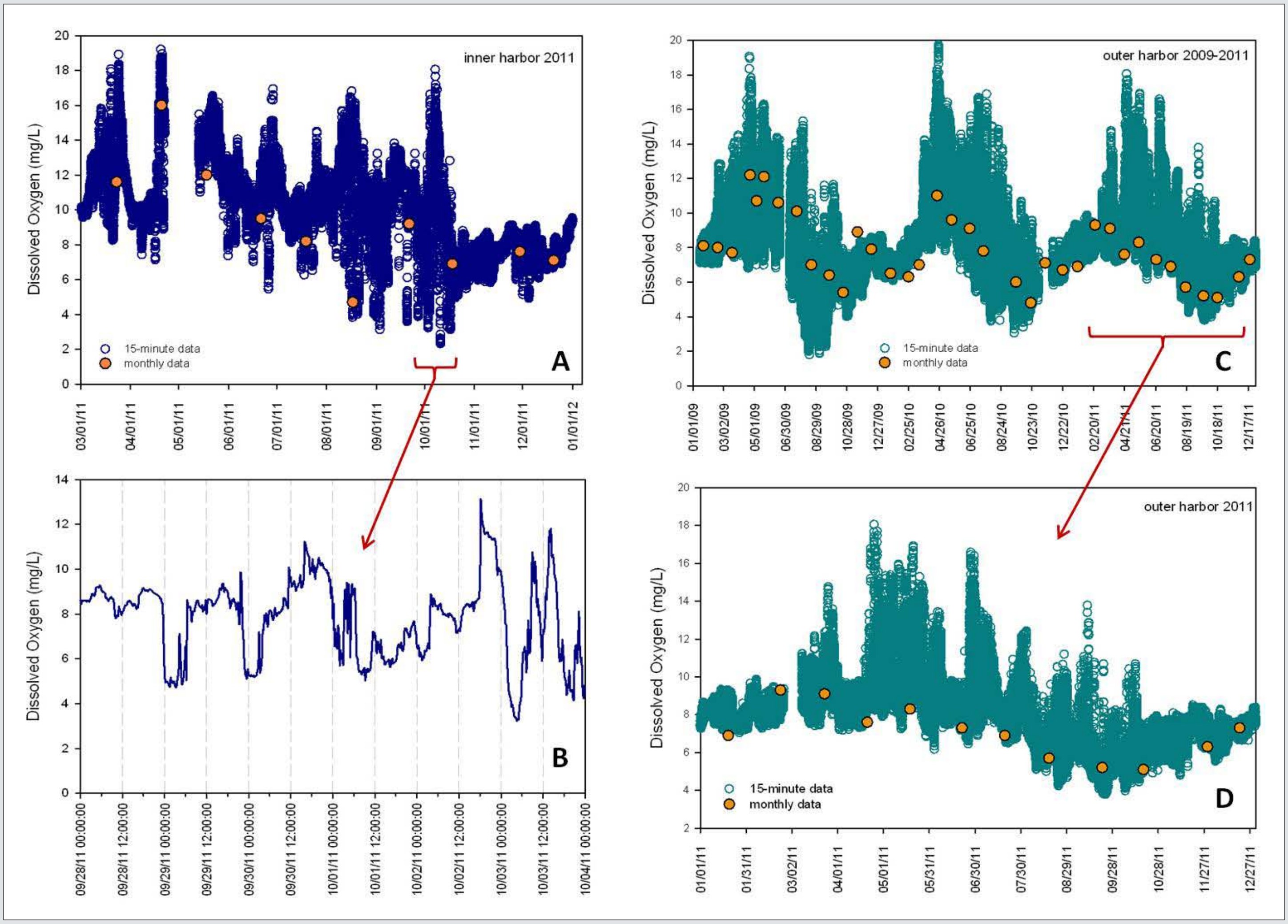



Figure 29. Dissolved oxygen (mg/L) in Quartermaster Harbor compiled from two dockside moorings at Dockton (7-m depth) in the outer harbor and the Yacht Club (1-m depth) in the inner harbor.

Dr. Cheryl Greengrove preserving a dissolved oxygen sample. Photo credit: Kimberle Stark.

UW-T researchers lowering sensors to collect water column profile data. Photo credit: Cheryl Greengrove.

Ocean acidification (OA) is a threat that is only starting to be assessed in Puget Sound. Excess carbon dioxide in the atmosphere from human activities is partially absorbed by the oceans, resulting in a lower pH. Estuarine processes, both natural and human-mediated can also increase the carbon dioxide content and lower the pH of marine waters. Coastal upwelling also brings deeper, more corrosive waters to the surface. Thus, Puget Sound is influenced by a variety of drivers of OA, which has ramifications for marine food webs generally, and shellfish in particular. Many shellfish species secrete aragonite shells as larvae, a process which is impeded under corrosive conditions for many species.

## D. Ocean acidification and carbon chemistry:

### i. Carbon chemistry surveys:

*Source: Simone Alin (Simone.R.Alin@noaa.gov), Richard Feely, Chris Sabine (NOAA, PMEL), Adrienne Sutton (UW, JISAO & NOAA, PMEL), and Jan Newton (UW, APL)*

In order to assess the effects of ocean acidification on the Puget Sound ecosystem, inorganic carbon measurements have been added to select existing observational programs. Starting in 2008, NOAA/PMEL has measured dissolved inorganic carbon concentrations and total alkalinity on UW PRISM-NANOOS cruises and used these data to calculate other inorganic carbon parameters, such as pH (measured on the seawater scale, $pH_{SWS}$) and the saturation states for the aragonite and calcite forms of the biomineral calcium carbonate (Ω values). In addition, moored autonomous sensors for measuring the partial pressure of carbon dioxide ($pCO_2$) were installed on ORCA moorings in Dabob Bay and at the southern end of Hood Canal, near Twanoh, in July 2010 and July 2009, respectively. $pCO_2$ measurements are only made at the surface (~1 m depth).

PRISM-NANOOS cruise observations: The first surveys of carbon chemistry to assess ocean acidification in Puget Sound were conducted in February and August 2008. During the winter in 2008, the entire water column in both the Main Basin and Hood Canal was corrosive, meaning that they were undersaturated with respect to the aragonite form of the biomineral calcium carbonate (to be undersaturated, aragonite saturation ($\Omega_{arag}$) is less than 1, corresponding to a $pH_{SWS}$ of less than 7.75) (Feely et al., 2010). During the summer in 2008, aragonite saturation and $pH_{SWS}$ values in the upper ~20 m were substantially higher, due to biological drawdown of $CO_2$, while deeper waters (>20 m depth) hovered just above or below the saturation threshold ($\Omega_{arag}$=1) in the Main Basin and were substantially lower than 1 (undersaturated) in Hood Canal bottom waters, especially at the southern end of the basin (minimum $\Omega_{arag}$<0.4, minimum $pH_{SWS}$ = 7.35; Feely et al., 2010).

Since the initial surveys in 2008, carbon measurements have been repeated on October cruises in 2009, 2010, and 2011 at stations running from the Strait of Juan de Fuca through Hood Canal (carbon analyses were conducted on a limited number of stations due to lack of funding for this work). Data for 2011 are shown in Figure 30. Because of the extremely low $pH_{SWS}$ and $\Omega_{arag}$ values seen in southern Hood Canal during the 2008 cruises, subsequent cruise sampling was extended to a site around the Great Bend toward Lynch Cove (PRISM station 402). In all three October surveys, the entire water column from the Strait of Juan de Fuca to the Great Bend was undersaturated with respect to aragonite and corrosive ($\Omega_{arag}$<1, $pH_{SWS}$ <7.75; Alin and Feely, unpublished data). During all October cruises, the cruise-wide minimum values observed for $pH_{SWS}$ and $\Omega_{arag}$ were seen at station 402. $pH_{SWS}$ and $\Omega_{arag}$ values through Hood Canal were comparable to or lower than those observed in August 2008 during the 2009 and 2011 October cruises. Slightly higher values were seen in October 2010 in the deep Hood Canal waters as compared with August 2008. The lowest values measured to date in Puget Sound were seen in October 2011 at station 402, with a $pH_{SWS}$ of 7.06 and minimum $\Omega_{arag}$ of 0.19. The minimum $pH_{SWS}$ and $\Omega_{arag}$ values at station 402 occurred at water depths of ~5–10 m in all three years (2009–2011) and appear to be the result of the combined influences of mixing of deep, $CO_2$-rich water from the Hood Canal basin along with strong production and respiration in surface waters in eutrophic Lynch Cove region.

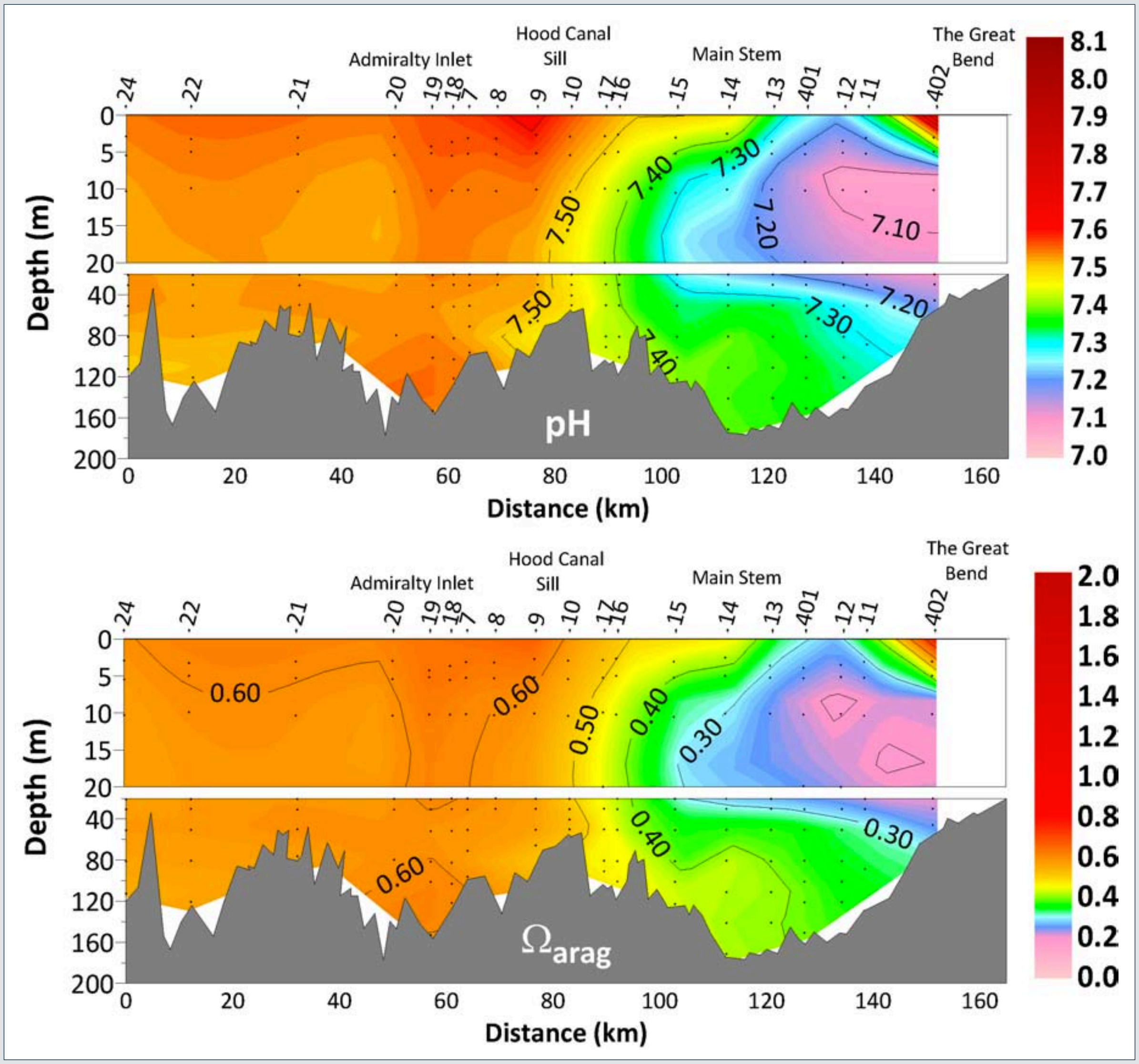



Figure 30. $pH_{SWS}$ and aragonite saturation profiles from the Strait of Juan de Fuca to The Great Bend from the October 2011 UW PRISM-NANOOS cruise.

## The fundamentals of inorganic carbon chemistry:

Carbon dioxide ($CO_2$) naturally exchanges between the atmosphere and the surface of the ocean. The ocean absorbs roughly a quarter of the approximately 10 gigatons of carbon emitted into the earth's atmosphere through human activities each year. As the anthropogenic $CO_2$ in the atmosphere is absorbed into the surface ocean, it combines with water molecules to form carbonic acid ($H_2CO_3$), which subsequently dissociates to form hydrogen ions ($H^+$) and bicarbonate ions ($HCO_3^-$). The resulting long-term increase in acidity ($H^+$ concentration) in the surface ocean, driven primarily by this uptake of anthropogenic $CO_2$, is called "ocean acidification." Since acidity is measured on the pH scale (an inverse, logarithmic scale, $pH = -\log[H^+]$), an increase in acidity (or increase in H+ concentration) is manifested as a decrease in pH. Since the preindustrial era, average global surface ocean pH has decreased by 0.11 pH units, corresponding to an average increase in acidity of 29%. Ocean uptake of $CO_2$ emissions through the 21st century is expected to decrease surface ocean pH by a total of about 0.3–0.4 pH units, which is equivalent to a 100–150% increase in acidity since preindustrial times (Orr et al., 2005).

One important effect of the increase in acidity is that hydrogen ions combine with carbonate ions ($CO_3^{2-}$) at surface seawater pH values to form additional bicarbonate ions (the dominant species of $CO_2$ at typical surface seawater pH). Many biological organisms may be affected physiologically by changes in $CO_2$ (typically measured as the partial pressure of $CO_2$, or $pCO_2$), $H^+$, and/or $CO_3^{2-}$ concentrations in seawater. The "inorganic carbon system" is comprised of the concentrations of $CO_2$, $H_2CO_3$, $HCO_3^-$, $CO_3^{2-}$, and H+, as well as other parameters such as calcium carbonate saturation states.

Organisms that synthesize hard parts out of calcium carbonate biominerals, such as aragonite or calcite, must extract calcium and carbonate ions from seawater in order to do so ($Ca^{2+} + CO_3^{2-} \Rightarrow CaCO_3$ (solid)). To get a relative sense of how easy or difficult it will be for organisms to synthesize their hard parts, chemists use calcium carbonate saturation states as an index:

$$\Omega_{phase} = [Ca^{2+}][CO_3^{2-}]/K_{sp}'$$

where Ω is the saturation state of calcium carbonate, phase refers to the form of calcium carbonate (typically aragonite or calcite), $[Ca^{2+}]$ is the calcium ion concentration, $[CO_3^{2-}]$ is the carbonate ion concentration, and $K_{sp}'$ is the apparent solubility product for the relevant calcium carbonate phase and is a function of temperature, salinity, and pressure. For Ω values above one, calcium carbonate is supersaturated; at one, saturation conditions are at equilibrium; and below one, conditions are undersaturated or corrosive to the relevant form of solid $CaCO_3$.

Author: Simone Alin

**Moored pCO2 observations:** Preliminary 2011 data shown in Figure 31 include only those from June 1 to December 31 due to questionable data quality during preceding periods. Atmospheric $pCO_2$ values at both Dabob Bay and Twanoh remained relatively constant around 400 µatm through the 2011 record. Surface seawater $pCO_2$ was substantially undersaturated with respect to the atmosphere at Dabob Bay continuously from June 1 until late September (average = 294 ± 22 µatm), reflecting the biological drawdown of $CO_2$ and consistent with the production of $O_2$ near the surface evident in ORCA $O_2$ profiles in Hood Canal (Figure 24). At the end of September, deeper, $CO_2$-rich water was mixed to the surface, elevating $pCO_2$ values above atmospheric values, where they remained for most of the rest of the year, with peaks up to nearly 1000 µatm during strong mixing events. At Twanoh, surface seawater $pCO_2$ was also undersaturated on average between June and the end of September, but there were excursions above atmospheric values during this time, unlike at Dabob (average = 343 ± 37 µatm). The same mixing event was evident in late September at Twanoh, and surface water $pCO_2$ values spiked to >800 µatm. Unlike at Dabob, however, surface $pCO_2$ values returned below atmospheric values for the following several weeks, perhaps reflecting the uptake of upwelled nutrients associated with the late September mixing event. After mid-November, surface water $pCO_2$ values at Twanoh remained quite elevated through the rest of 2011, with values frequently >800 µatm.

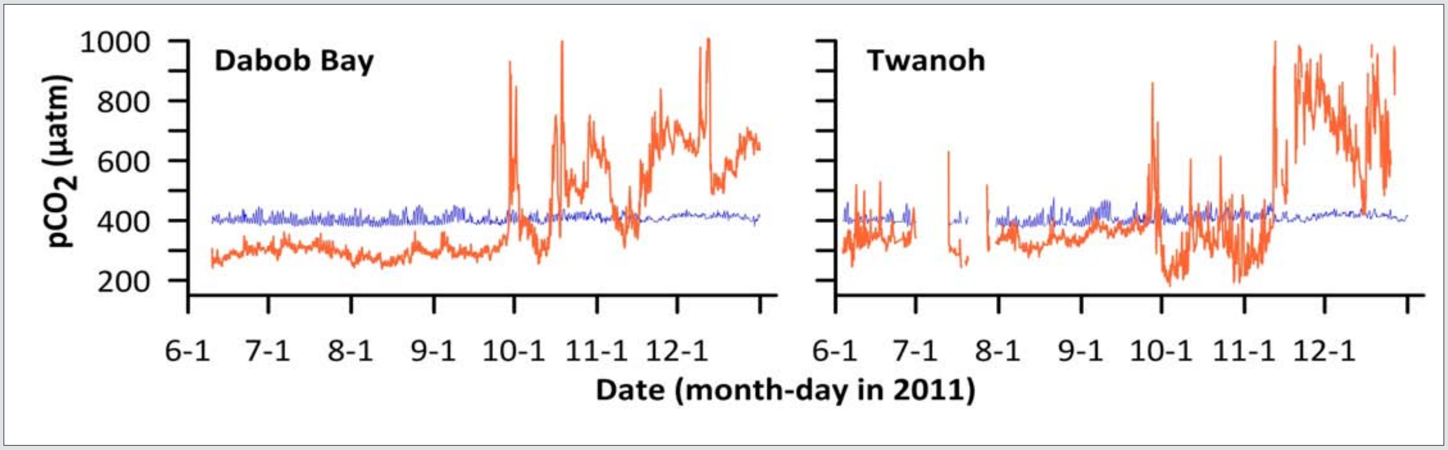



Figure 31. Moored time series measurements of $pCO_2$ in air (blue, ~1 m above water surface) and water (orange, ~1 m below water surface) at Dabob Bay and Twanoh ORCA buoy sites in Hood Canal.

### ii. Totten Inlet:

*Source: Andy Suhrbier (PSI), Simone Alin (NOAA, PMEL), Jan Newton (UW, APL)*

Totten Inlet, a key shellfish growing area for mussels, clams and oysters, also houses shellfish nurseries, a hatchery, oyster brood stock repositories, and a natural population of Olympia oysters. NOAA, the Puget Sound Restoration Fund (PSRF), Pacific Shellfish Institute (PSI) and University of Washington scientists have studied this area during the past three years to better understand water chemistry and how it pertains to Olympia oyster reproduction and settlement. Data from 2009 and 2010 samples point to a dynamic link between larval settlement, phytoplankton production, and carbon chemistry. To further evaluate tidal and diel fluctuations at this site, volunteers from PSI collected nutrient, dissolved oxygen and inorganic carbon samples every two hours for full diel cycles on June 29 and September 9, 2011. Significant water chemistry fluctuations were observed at the study site during these dates and appeared to be related to tidal and solar variations throughout the diel cycle.

Pacific Shellfish Institute (PSI) scientists have been assisting Lummi Nation Shellfish Hatchery (Lummi) staff in water quality monitoring starting in early 2011. Lummi staff collect weekly $CO_2$, dissolved oxygen (DO), nutrient and bacteria samples while PSI staff maintain a YSI 6600 water quality meter at the hatchery intake located inside Lummi Lagoon. Carbon chemistry analyses have yet to be completed. Data show seasonal differences in temperature, pH (measured on the NBS scale, $pH_{NBS}$), and DO, as well as high-frequency variation (Figure 32). Diel fluctuations are present due to both tidal height and the photosynthesis and respiration of algae. Variation associated with tidal height is profound, as a tidal gate is breached at high water, bringing in water from Lummi Bay to the intake; this breach and its high salinity signal are associated with a reduction in $pH_{NBS}$ (Figure 33). There is a potential link between oyster larvae performance at the hatchery and water chemistry, though project partners await carbon chemistry results before defining the relationships.

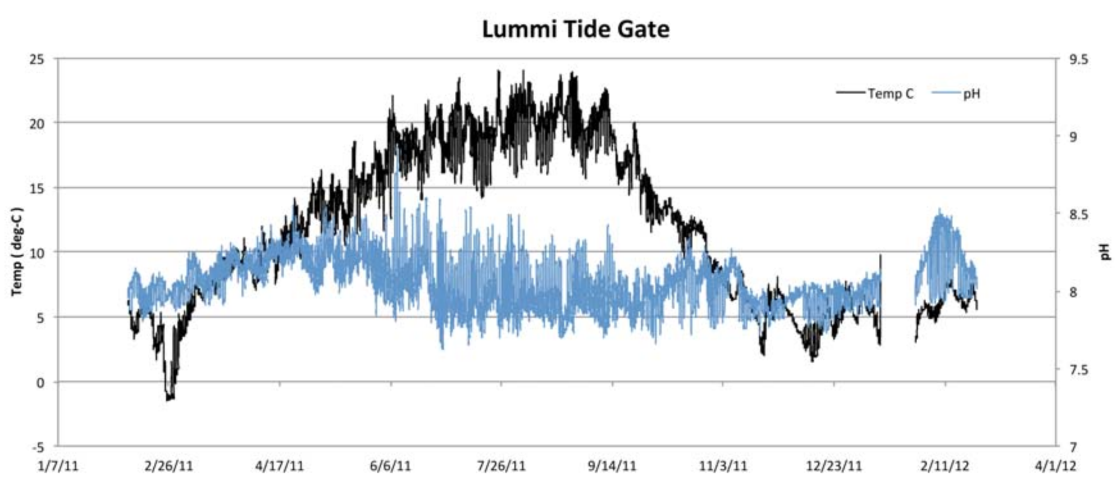



Figure 32. Temperature and $pH_{NBS}$ at the Lummi tide gate in 2011.

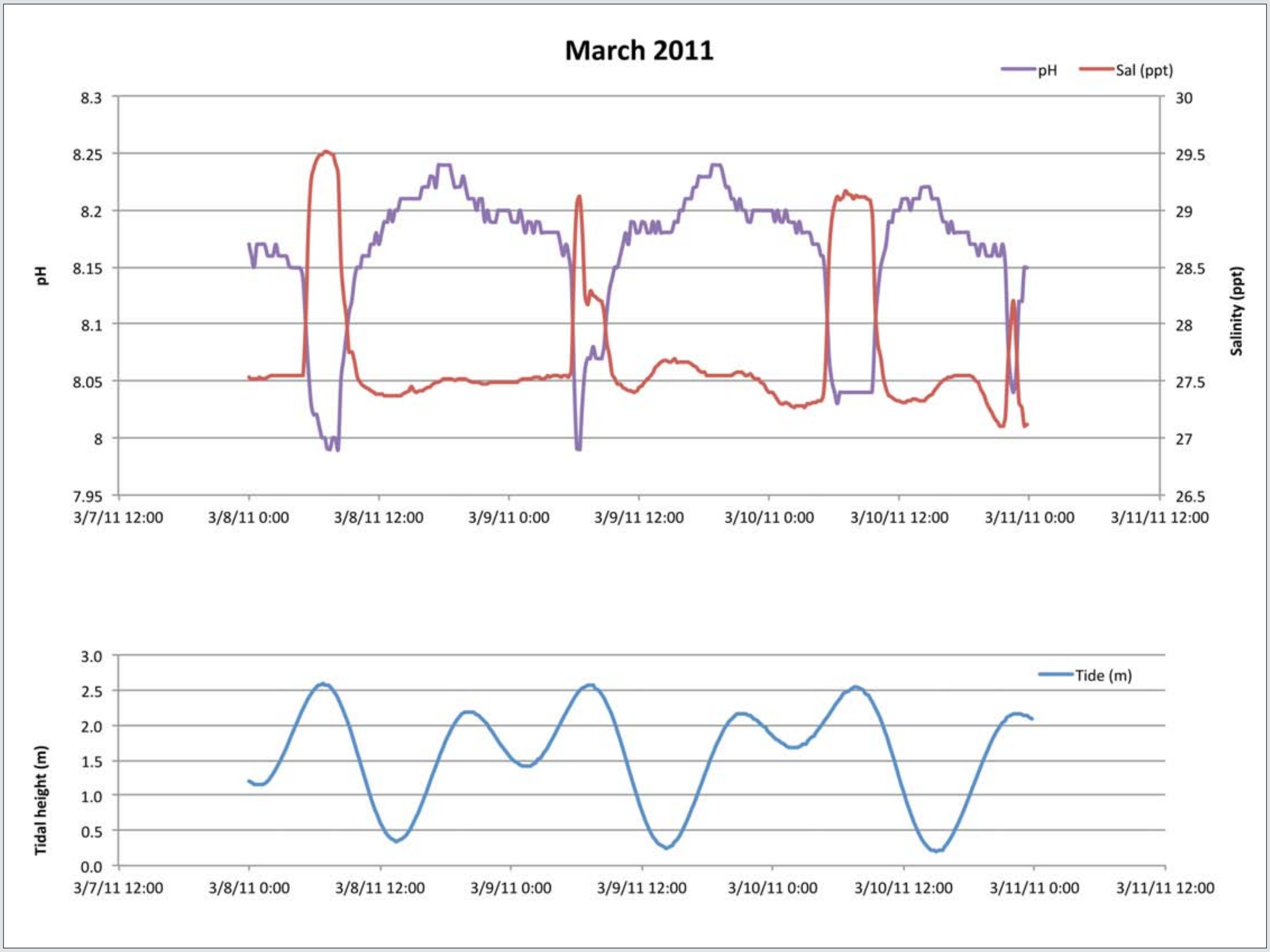
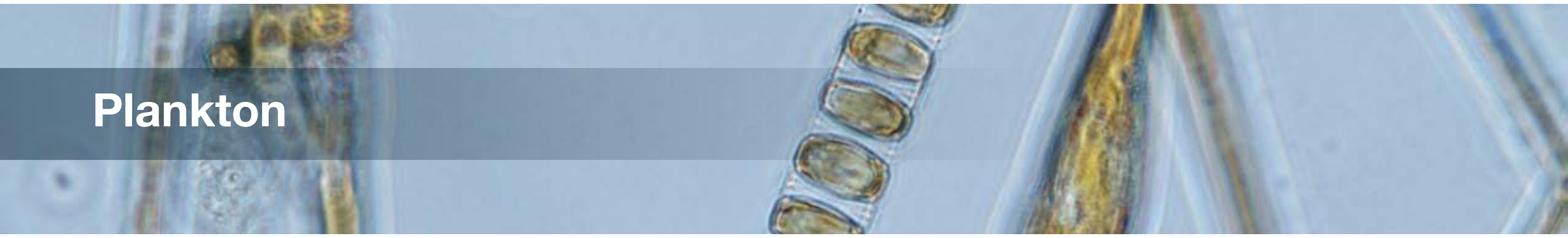



Figure 33. Salinity (ppt), tide (m), and $pH_{NBS}$ at the Lummi tide gate in March 2011.



# 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 can provide early warning of deteriorating or changing ocean conditions that can affect entire ecosystems.*

## A. Marine phytoplankton – King County Department of Natural Resources & Parks marine waters:

*Source: Kimberle Stark (Kimberle.Stark@kingcounty.gov), Gabriela Hannach (KCDNR), Cheryl Greengrove (UWT), and Stephanie Moore (NOAA, NWFSC)*

Phytoplankton samples were collected bi-weekly in 2011 during the March-through-October bloom season from three Central Basin locations: northern open water (Point Jefferson), southern open water (East Passage), and Quartermaster Harbor, a shallow embayment with limited flushing. Data gathered included taxon richness (number of species or genera as an indicator of biodiversity), frequency of occurrence (used as a relative indicator for long-term changes in species composition), and relative abundance (identifies taxa as dominant, subdominant, or present according to relative cell numbers and used to recognize the major primary producers and bloom-forming species).

Diatom species/genus richness was greatest from March to May and lowest from the end of July to early September as dinoflagellate populations increased. The majority of dinoflagellate taxa were observed from late August to early September. In 2011, the dinoflagellate species *Ceratium fusus* was dominant at all three sites throughout September.

As in previous years, diatoms dominated throughout most of the 2011 sampling season at all three sites, hyalochaete *Chaetoceros* and *Thalassiosira* species most frequently comprising the dominant group. However, 2011 was notably different from the previous three years in that no diatom species dominated at the open water stations until late April for the southern location and early May for the northern site. Monthly chlorophyll-a data also indicated a delay in the spring phytoplankton bloom at the open water sites along with an absence of a late summer bloom typical of previous years. This chlorophyll-*a* pattern noticeably follows the proportion of diatom genera present and reflects the role of diatoms as the main primary producers in this system (Figure 34). While spring 2011 chlorophyll-*a* data for Quartermaster Harbor are not atypical, *in vivo* fluorescence data collected at 15-minute intervals at this embayment site in 2011 suggests that the spring phytoplankton bloom was also delayed.

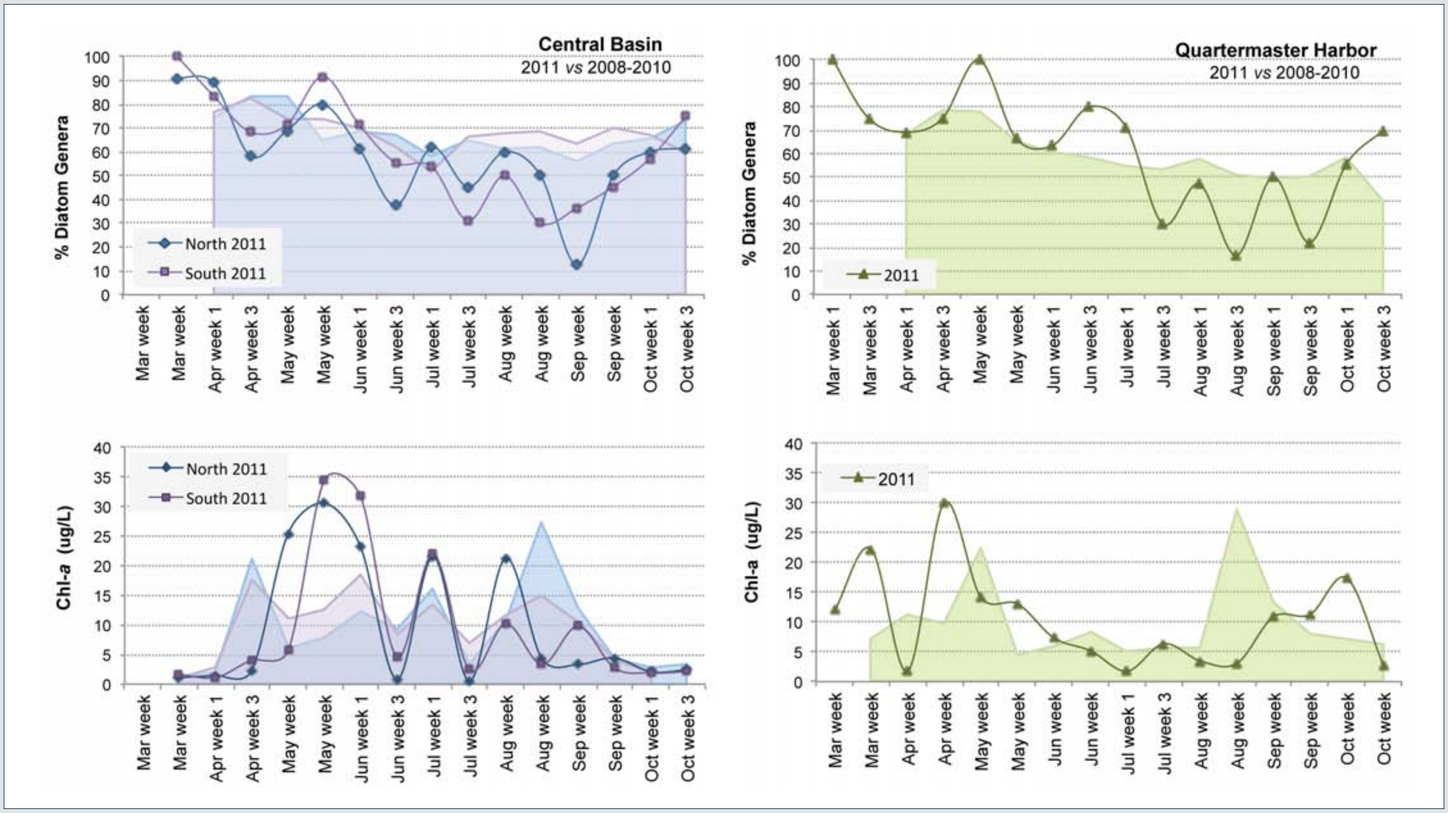



**Figure 34.** Seasonal progression in the proportion of diatom genera and chlorophyll-*a* values at three locations in the Central Basin, showing 2011 data and the 2008-2010 average for surface waters (<2 m). Lines show 2011 data and shaded areas represent the 2008-2010 average (blue: north open water, purple: south open water, green: Quartermaster Harbor).


The centric diatom *Chaetoceros eibenii*. Photo credit: Gabriela Hannach.

*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*

Intense bloom of both harmful and non-harmful algae infront of Poulsbo. Photo credit: Megan Black.

## B. Harmful algae:

### i. SoundToxins:

*Source: Teri King (guatemal@u.washington.edu) (WSG)*

SoundToxins partners sample phytoplankton at key locations throughout Puget Sound, provide an early warning of harmful algal blooms for the Washington State Department of Health to prioritize shellfish toxin analysis, and communicate timely information to shellfish and finfish producers and researchers. Sampling stations are monitored weekly from April to October and bi-weekly during the winter months. Cell concentrations of *Alexandrium* spp., *Pseudo-nitzschia* spp. and *Dinophysis* spp. are reported via an online database at www.soundtoxins.org. SoundToxins is jointly administered by NOAA's Northwest Fisheries Science Center and Washington Sea Grant in partnership with community volunteers, shellfish and fish farmers, environmental learning centers and tribes.

*Alexandrium* spp. counts were low or absent throughout most of the sampling sites in 2011. Paralytic shellfish toxins measured in sentinel mussels above the regulatory level were detected by WDOH in May and June at Birch Bay, but phytoplankton cell counts did not show levels of *Alexandrium* spp. on the days sampled during these toxic shellfish events.

*Pseudo-nitzschia* spp. cells were present throughout the entire year with blooms occurring as early as May and as late as September 2011 at the various sampling locations. Many samplers reported the presence of *Pseudo-nitzschia* spp. cells into the end of December. No domoic acid related closures were made by the WDOH in Puget Sound in 2011. This indicates that the *Pseudo-nitzschia* spp. monitored by SoundToxins members were not high toxin producers.

*Dinophysis* was the taxon that attracted the most attention during the summer of 2011 when illnesses due to shellfish consumption triggered a shellfish growing area closure and recall of shellfish from Sequim Bay. *Dinophysis* spp. are dinoflagellates known to produce toxins associated with diarrhetic shellfish poisoning (DSP) causing gastrointestinal problems including diarrhea in humans. Regional species include *D. acuminata, D. acuta, D. fortii, D. norvegica, D. rotundata* and *D. parva.* Monitoring suggests that *D. acuminata* is the major toxin producer in Puget Sound. SoundToxins volunteers detected the presence of *Dinophysis* spp. in the water column at levels greater than 50,000 cells per liter at the peak of a bloom in Sequim Bay in July 2011 (Figure 35). Subsequent analysis of shellfish tissues by the FDA lab in Alabama showed DSP levels up to 160-micrograms/100 g of shellfish tissue, where the regulatory closure level for DSP is 16-micrograms/100 g of tissue or greater. WDOH had not been monitoring for DSP toxins prior to 2011 but will now routinely monitor for the toxins in shellfish, guided by SoundToxins observations of *Dinophysis* spp.

During the Sequim Bay *Dinophysis* spp. bloom in July, samplers also noted the presence of *Protoceratium reticulatum*, a known yessotoxin producer. Although yessotoxin has shown toxic effects in model mice, there is still controversy over whether or not this toxin poses a threat to humans. In 2012, volunteers will keep an eye on this species, alerting WDOH and NOAA when the species is present.

In 2012, changes to the SoundToxins program include a new database that enhances the ability of volunteers to report data and users to receive data, increased attention to *Heterosigma* concentrations, and improved volunteer coordination.

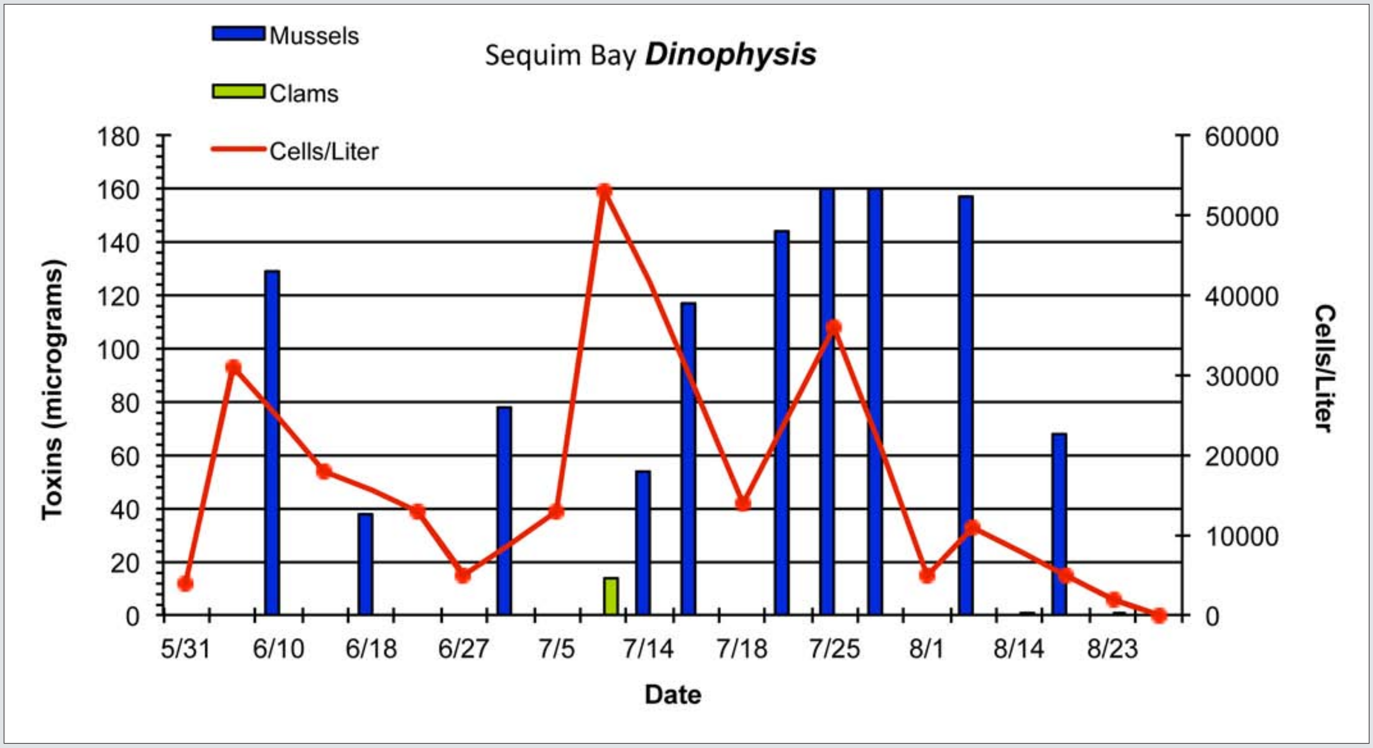
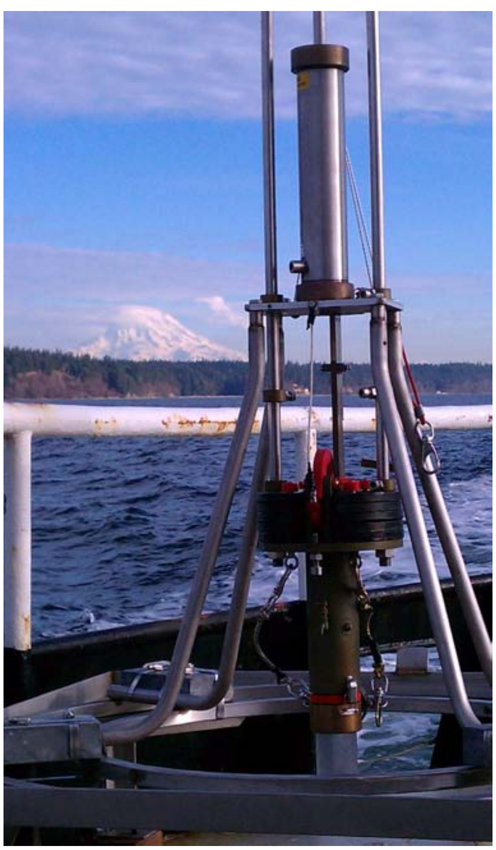



Figure 35. DSP toxins in mussels and clams and *Dinophysis* spp. cells counts in Sequim Bay from May through August 2011. Note that oysters were also sampled on August 14 and August 23, 2011, but DSP levels were low (0 and 0.4 micrograms, respectively).

*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.*



The craib corer is used to collect sediment from the bottom of Puget Sound during the winter to map the distribution of cysts of *Alexandrium*. Photo credit: Stephanie Moore.

### ii. *Alexandrium* species cyst mapping:

*Source: Cheryl Greengrove (cgreen@u.washington.edu), Julie Masura (UWT), and Stephanie Moore (NOAA, NWFSC) http://www.tiny.cc/psahab*

One of the objectives of the three year Puget Sound Alexandrium Harmful Algal Bloom (PS-AHAB) study is to map interannual variations in *A. catenella* cyst distribution in Puget Sound. The first year surface sediment *A. catenella* cyst distribution mapping survey was completed in winter 2011. Figure 36 shows the concentration of cysts/cm$^3$ in the upper 0-1 cm of surface sediments from 98 stations throughout all of Puget Sound, the Strait of Juan de Fuca and the San Juan Islands. Highest cyst concentrations were found in Bellingham Bay, Birch Bay and Semiahmoo Bay in the north, Port Madison, Liberty Bay and Port Orchard on the west side of the main basin and Quartermaster Harbor in central Puget Sound. Quartermaster Harbor cyst concentrations are an order of magnitude less compared to a 2005 survey (Horner et al. 2011), and a new "seed bed" area has developed in Bellingham Bay.

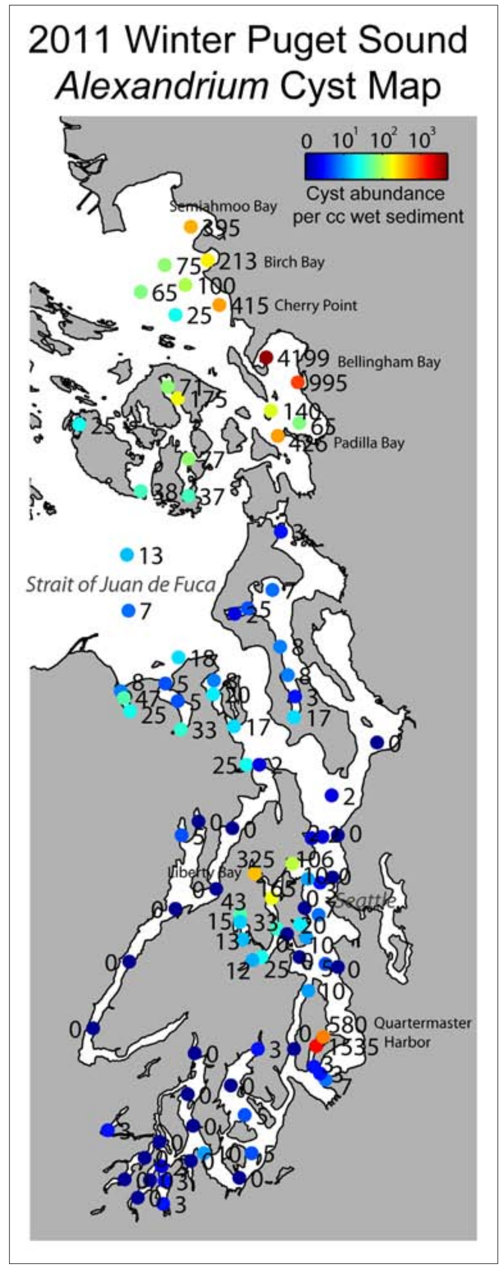



Figure 36. 2011 winter Puget Sound *Alexandrium* cyst map.

*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.*

## C. Biotoxins:

*Source: Jerry Borchert (jerry.borchert@doh.wa.gov) (WDOH)*

In 2011, the Washington State Public Health Laboratory analyzed 2,804 samples for PSP toxins. PSP toxins were lower in 2011 compared to 2010, with the highest value of 954 ug/100g detected in mussels from Bainbridge Island. The Federal Drug Administration (FDA) standard for PSP toxin is 80 ug/100g of shellfish tissue. In 2011, 10 commercial growing areas (8 geoduck clam tracts and 2 general growing areas) and 29 recreational harvest areas were closed due to unsafe levels of PSP toxins. No PSP illnesses were reported.

A total of 1,201 samples were analyzed for domoic acid in 2011, with the highest value of 2 parts per million (ppm) detected in razor clams off the Washington coast. There were no commercial or recreational harvest closures due to domoic acid and no ASP illnesses were reported.

Three DSP illnesses were reported in 2011 in Washington State – these were the first documented cases in US history. WDOH did not have access to the necessary equipment to conduct DSP toxin testing prior to this outbreak, but subsequently sent approximately 40 samples to the FDA Laboratory in Alabama for analysis. Although there is currently no US regulatory limit for DSP toxins, the WDOH has adopted the European Action Level of 16 ug/100 g of shellfish tissue. The highest DSP toxin measured in 2011 was 160.3 ug/100g in mussels from Sequim Bay. One commercial growing was closed in 2011 due to DSP toxins. Technicians at the WDOH have now been trained in DSP toxin testing and will begin monitoring for this biotoxin in 2012.

# Bacteria and pathogens

*Fecal coliform bacteria are indicators of contamination by sewage and the potential presence of other pathogenic organisms. Fecal coliform standards in shellfish growing areas are established to prevent sewage contamination of shellfish that may be consumed raw.*

## A. Fecal coliforms – shellfish growing area classification:

*Source: Tim Determan (Tim.Determan@doh.wa.gov) (WDOH)*

The Washington State Department of Health Office of Shellfish and Water Protection collects and analyzes fecal coliform data to protect shellfish consumers from eating contaminated shellfish, and to analyze status and trends in fecal pollution in shellfish growing areas of Puget Sound. The Department developed a fecal pollution index (FPI) as a simple tool to quantify fecal pollution impact. The FPI is a unitless number that ranges from 1.0 (100% of 90th percentiles are GOOD, i.e., negligible impact) to 3.0 (100% of 90th percentiles are BAD, maximum impact). A detailed description of the FPI and most recent data report can be found at http://www.doh.wa.gov/Portals/1/Documents/4400/332-120-PugetSound-statrend-11.pdf.

Figure 37 shows the proportions of sampling stations in each FPI category for 2011. Sampling stations are located mostly in intertidal and subtidal zones in areas ranging from remote to residential-light industrial land use. Highly urban areas are not included. There are five FPI categories. Areas with the highest FPI impacts scores are Filucy Bay and Drayton Harbor. Sites with low FPI increased from 1.4% of stations in 2010 to 2.1% of stations in 2011. The remaining categories remained relatively unchanged. Figure 38 shows that fecal pollution at the 36 most affected shellfish growing areas has dropped significantly over time. The degree of fecal pollution impact in 2011 continues a trend that began in 2003.

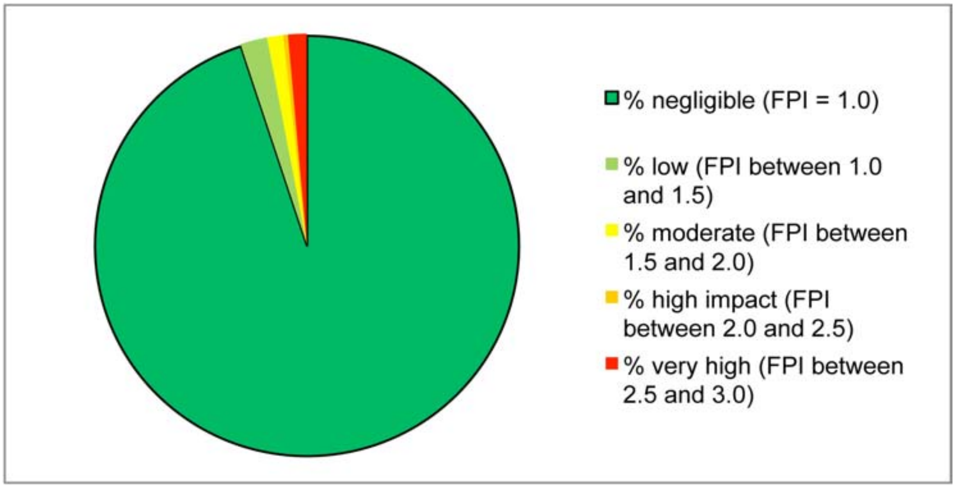



Figure 37. Proportions of sampling stations (n=1459 among 96 shellfish growing areas throughout Puget Sound) in each FPI category for 2011.

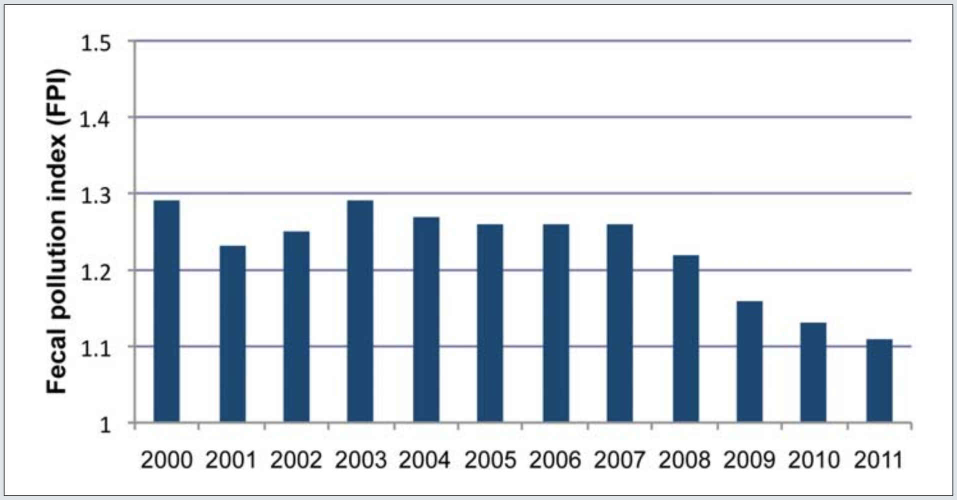



Figure 38. Trends in fecal pollution at the 38 most affected shellfish growing areas since 2000.


WDOH staff (Tim Determan, Jule Schultz) collecting a water sample in a shellfish growing area for fecal coliform bacteria analysis. Photo credit: Celita Johnston.

*Enterococcus is a bacteria found in the gut of humans as well as other warm blooded animals. It is an efficient bacterial indicator of water quality and contamination by sewage. High levels of Enterococci can cause swimming-associated gastrointestinal illness.*

## B. Enterococcus – BEACH program:

*Source: Julie Lowe (jlow461@ecy.wa.gov) (Ecology & WDOH)*

The Beach Environmental Assessment, Communication and Health (BEACH) Program is a coordinated effort between the Departments of Health and Ecology and is funded by the Environmental Protection Agency. This program coordinates saltwater monitoring at *high risk* swimming beaches in Puget Sound and Washington's coast; therefore, samples are not representative of average conditions in all of Puget Sound. The goal of our program is to monitor beaches for bacteria and notify the public when results exceed EPA standards.

Figure 39 shows the percentage of all monitored Puget Sound beaches meeting EPA water quality standards for enterococcus (allowing for one exceedance exception). The Puget Sound Partnership's dashboard indicator goal is that by 2020, all monitored beaches meet human health standards.

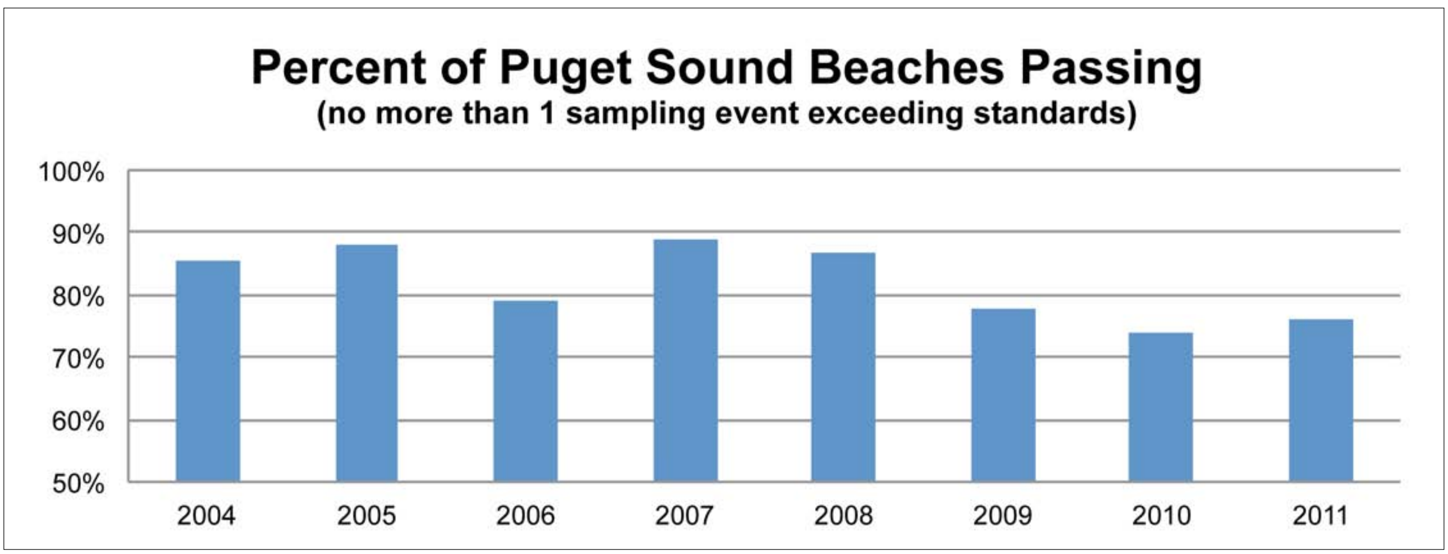


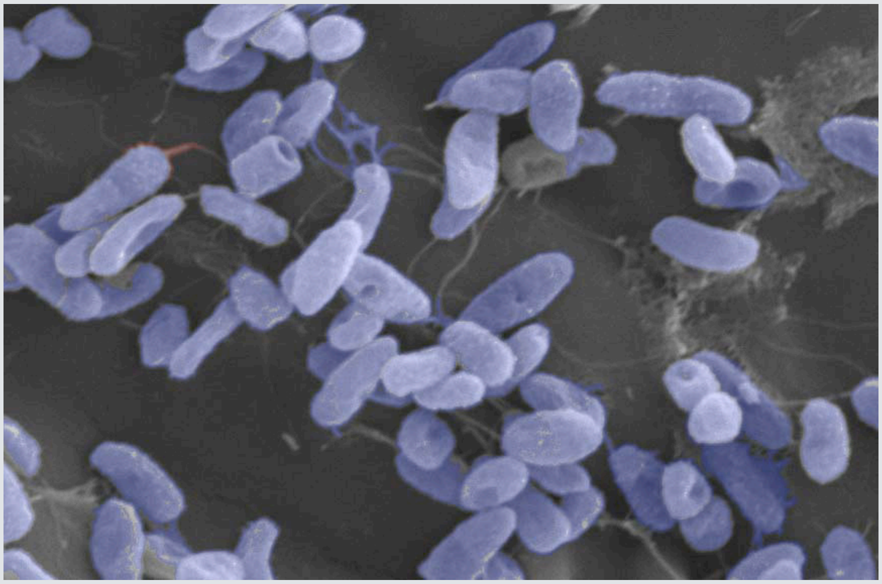

Figure 39. This graph represents the percent of all monitored Puget Sound beaches meeting EPA water quality standards for enterococcus (allowing for one exceedance exception). The dashboard indicator goal is that all monitored swimming beaches meet human health standards.

*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.*

## C. *Vibrio parahaemolyticus*

*Source: Rohinee Paranjpye (Rohinee.Paranjpye@noaa.gov) (NOAA, NWFSC) and Richard Lillie (WDOH)*

In Washington State, *Vp*-related illnesses are controlled by monitoring the populations (total and potentially pathogenic) of these bacteria in oysters from shellfish growing areas in Hood Canal from June to September by the Washington State Department of Health, Office of Shellfish and Water Protection (WDOH). Water temperature and salinity, two environmental parameters known to influence concentrations of these bacteria are also monitored in these growing areas. In 2011, there were 43 confirmed *Vp*-related illnesses. This was lower than the 71 confirmed illnesses reported in 2010.



*Vibrio parahaemolyticus.* Photo credit: Rohinee Paranjpye & Carla Stehr.


# Shellfish resources

*Shellfish improve water quality, transfer food energy to higher trophic levels, and provide cultural, social, spiritual, economic, and health benefits. Shellfish health is directly related to water quality and can be strongly affected by changes in temperature and pH. Shellfish harvesting closures can occur when harmful algae bloom and contaminate shellfish with biotoxins or when Vibrio parahaemolyticus concentrations in tissues exceed regulatory limits for human consumption.*

*Source: Paul Williams (pwilliams@suquamish.nsn.us) (Suquamish Tribe)*

Shellfish harvest amounts for Puget Sound are shown in Figure 40. These values can be multiplied by the value of each species to show the direct economic value. Other benefits are less tangible (e.g., recreation, ecosystem services) but are arguably of equal or greater value.

Historic harvest records reflect management strategies as well as ecosystem effects. In the 1980's and early 1990's sea cucumbers were managed without harvest limits and over-harvested. Therefore, in some areas we can fairly accurately back-calculate the original sea cucumber biomass. Crab are managed by size and sex restrictions and harvest continues until most legal sized males are removed each year – crab harvests have shown a remarkable increase.

Meteorological and oceanographic conditions influence survival and transport of the pelagic larval stages of shellfish, but those pathways are poorly understood. Hatcheries are a good place to observe some of these impacts. For example, the cold spring of 2011 caused a delay in phytoplankton growth and resulted in decreased hatchery production.

Harvest amounts of naturally occurring intertidal clams and oysters, as well as shellfish produced in aquaculture operations, were not available for this report but will be included in subsequent reports. The data used in this summary were generated using fish receiving ticket databases maintained by the Northwest Indian Fish Commission and the Washington State Department of Fish and Wildlife.

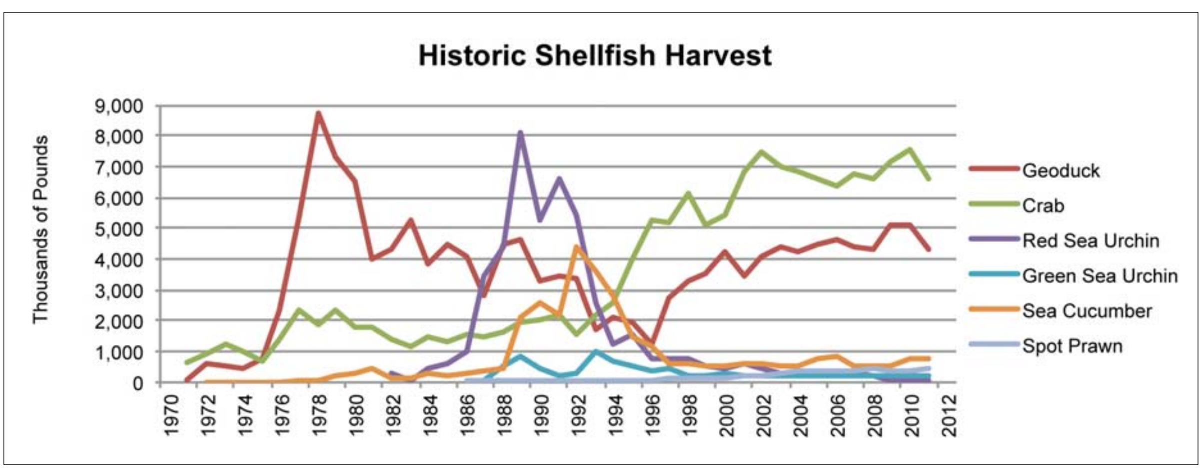



Figure 40. Historic harvest summary of six economically important shellfish species in Puget Sound.

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## Acronyms:

| | |
|---|---|
| APL | Applied Physics Laboratory |
| BEACH | Beach Environmental Assessment, Communication and Health |
| EC | Environment Canada |
| JISAO | Joint Institute for the Study of the Atmosphere and Ocean |
| KCDNR | King County Department of Natural Resources and Parks |
| NANOOS | Northwest Association of Networked Ocean Observing System |
| NOAA | National Oceanic and Atmospheric Administration |
| NWFSC | Northwest Fisheries Science Center |
| ORCA | Oceanic Remote Chemical Analyzer |
| PMEL | Pacific Marine Environmental Laboratory |
| PRISM | Puget Sound Regional Synthesis Model |
| PSI | Pacific Shellfish Institute |
| PSP | Puget Sound Partnership |
| SWFSC | Southwest Fisheries Science Center |
| UW | University of Washington |
| UWT | University of Washington-Tacoma |
| Ecology | Washington State Department of Ecology |
| WDOH | Washington State Department of Health |
| WSG | Washington Sea Grant |