WA Shellfish Initiative

Blue Ribbon Panel on Ocean Acidification

Science White Paper

What is the role of the Science White Paper?

1. Serve as the basis for the Panel's Research & Monitoring recommendations
2. Inform the Panel's Policy recommendations

Science White Paper Development

April:

- Draft outline shared with tribal & state agencies
- Panel scientists tasked with:
  - Reviewing *published* science
  - Identifying information gaps & needs
  - Identifying monitoring & research to address needs

May:

- Synthesize information
- Draft chapters 1-6

June:

- First draft (preliminary figures; some info gaps)
- Review by Panel members & external experts

July/August:

- Incorporate feedback on Chapters 1-6
- Draft Chapter 7 (based on Research & Monitoring recommendations)

August/Sept:

- Approve final Draft Chapters 1-7

Ocean Acidification in Washington Science White Paper

Richard Feely, Terrie Klinger, Jan Newton, Jennifer Ruesink, Shallin Busch, Carolyn Friedman, George Waldbusser and Simone Alin and Christopher Krembs

Meg Chadsey, Panel Coordinator

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- Ch 6: Habitats and Ecosystems

Ch1. Introduction to Ocean Acidification in Washington State Waters

Definition: Ocean acidification (OA) is the reduction of pH in the oceans over an extended period of time, typically decades or longer, caused primarily by the uptake of carbon dioxide from the atmosphere.

What do we KNOW about OA in the global open ocean?

In the open ocean, the **rate of acidification is more than 10 times faster** than at any time over the past 300 million years:

- average pH decrease: 0.02 pH units/decade
- average aragonite saturation state (Ω_{arag}) decrease: 3.5%/decade

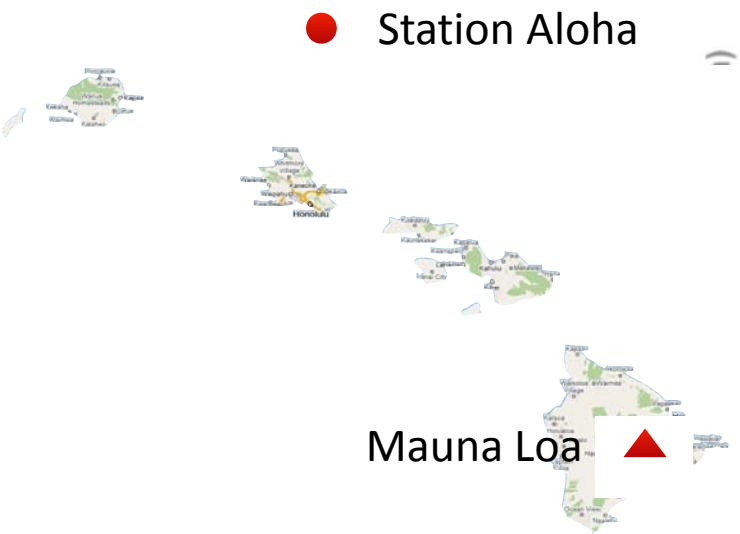
The average acidity (the H^+ concentration) of the oceans **has increased by about 30%**. By the end of this century, the acidity of the oceans could increase by as much as 100-150%.

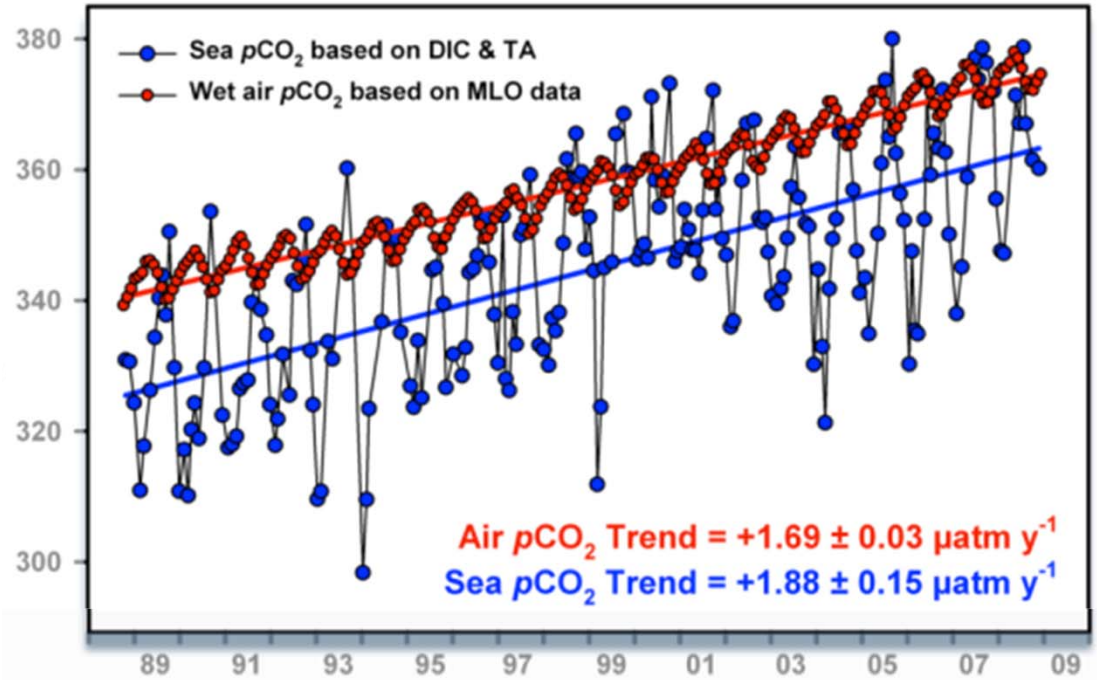
The average $\mathbf{\Omega_{arag}}$ **will drop below the current range** of variability **within 12-40 years**.

The oceans are undergoing dramatic, long-term chemistry change

Carbon Changes at the Hawaii Ocean Time-series (HOT) site

pCO_2 is the 'partial pressure' of CO_2





Surface water pCO_2 is increasing at about the same rate as atmosphere

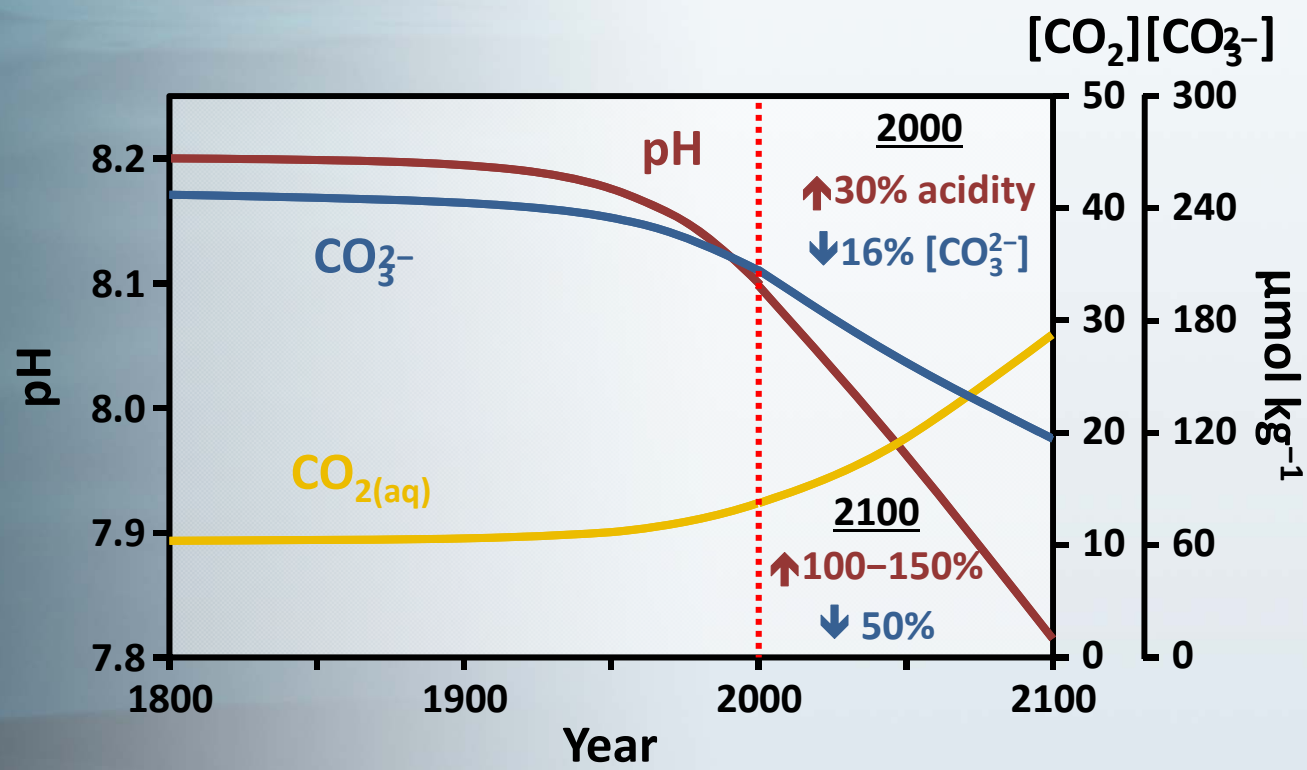
We see a commensurate decrease in pH with the rise in surface water pCO_2

Doney, Science 2010
Dore et al., PNAS 2009

Ocean Acidification

$$CO_2 + H_2O \rightarrow H^+ + HCO_3^- \qquad H^+ + CO_3^{2-} \rightarrow HCO_3^-$$

$$CO_2 + H_2O + CO_3^{2-} \Leftrightarrow 2HCO_3^-$$



Wolf-Gladrow et al. (1999)

Saturation State

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

calcium carbonate calcium carbonate

Saturation State

$$\Omega_{phase} = \frac{[Ca^{2+}][CO_3^{2-}]}{K^*_{sp,phase}}$$

$\Omega > 1$ $CaCO_3$ precipitates

$\Omega = 1$ equilibrium

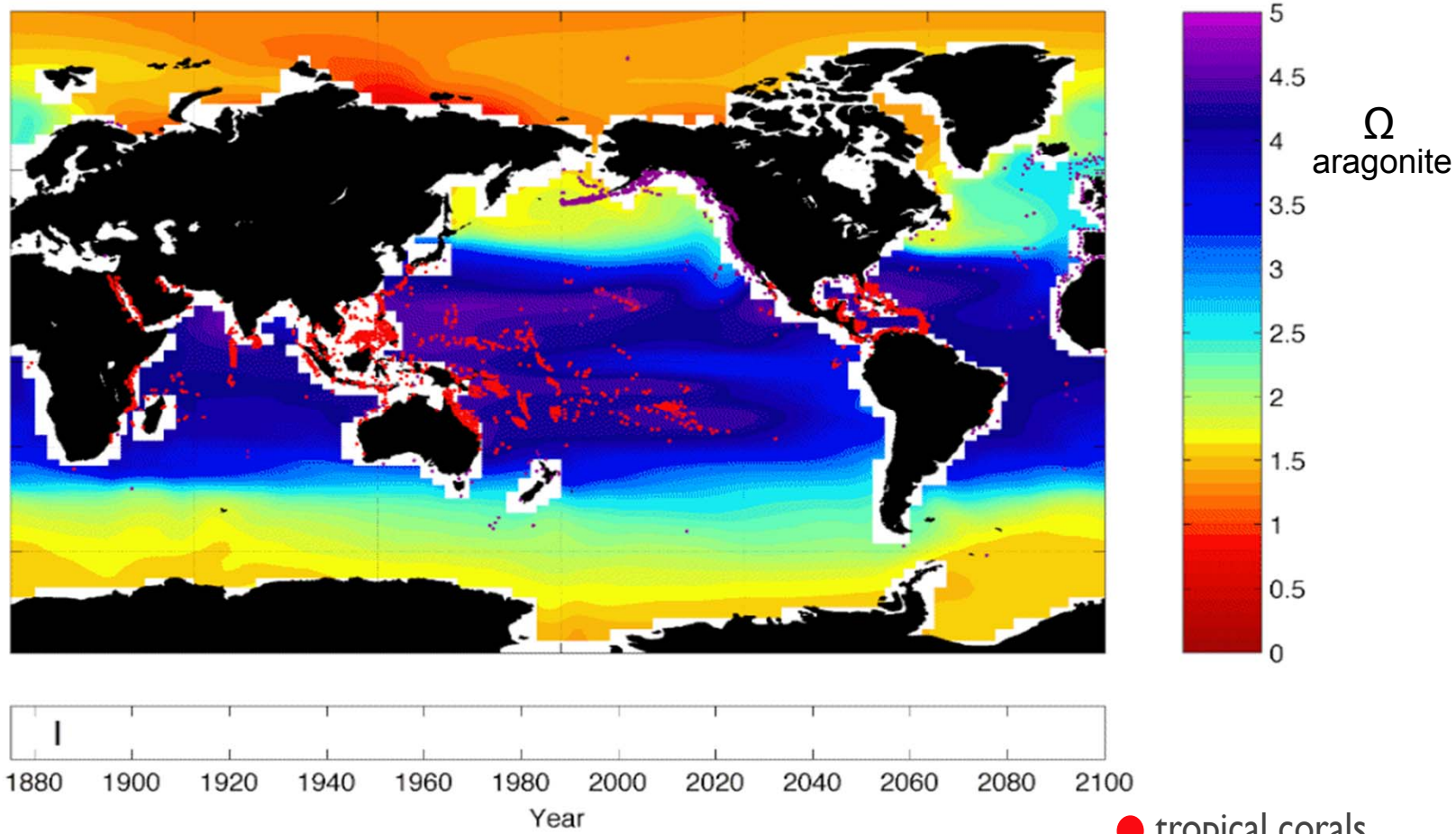
$\Omega < 1$ $CaCO_3$ dissolves

Common carbonate minerals:

aragonite (more soluble) and calcite (less soluble)

Predictions of Ocean Acidification in the Global Oceans

Projections



Aragonite Saturation State (Ω)

blue = good for calcification

red = bad

tropical corals

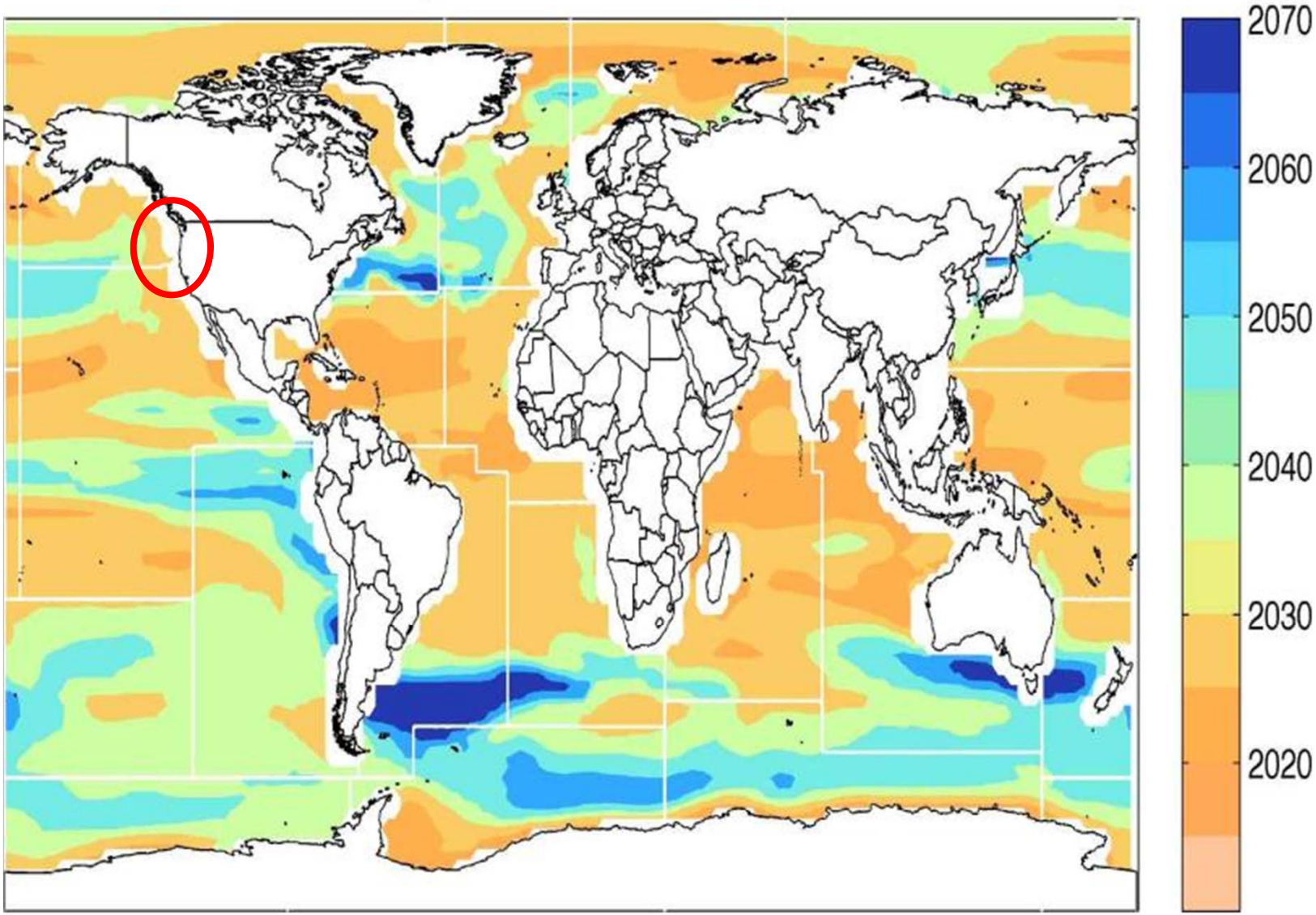
deep-water corals

after Feely et al (2009) with Modeled Saturation Levels using NCAR CCSM3 model

Calcification rates in the tropics may decrease by 30% over the next century

Date when range of aragonite saturation is entirely different from that of 2010

Ocean CO_2 Chemistry



Cooley et al., 2012

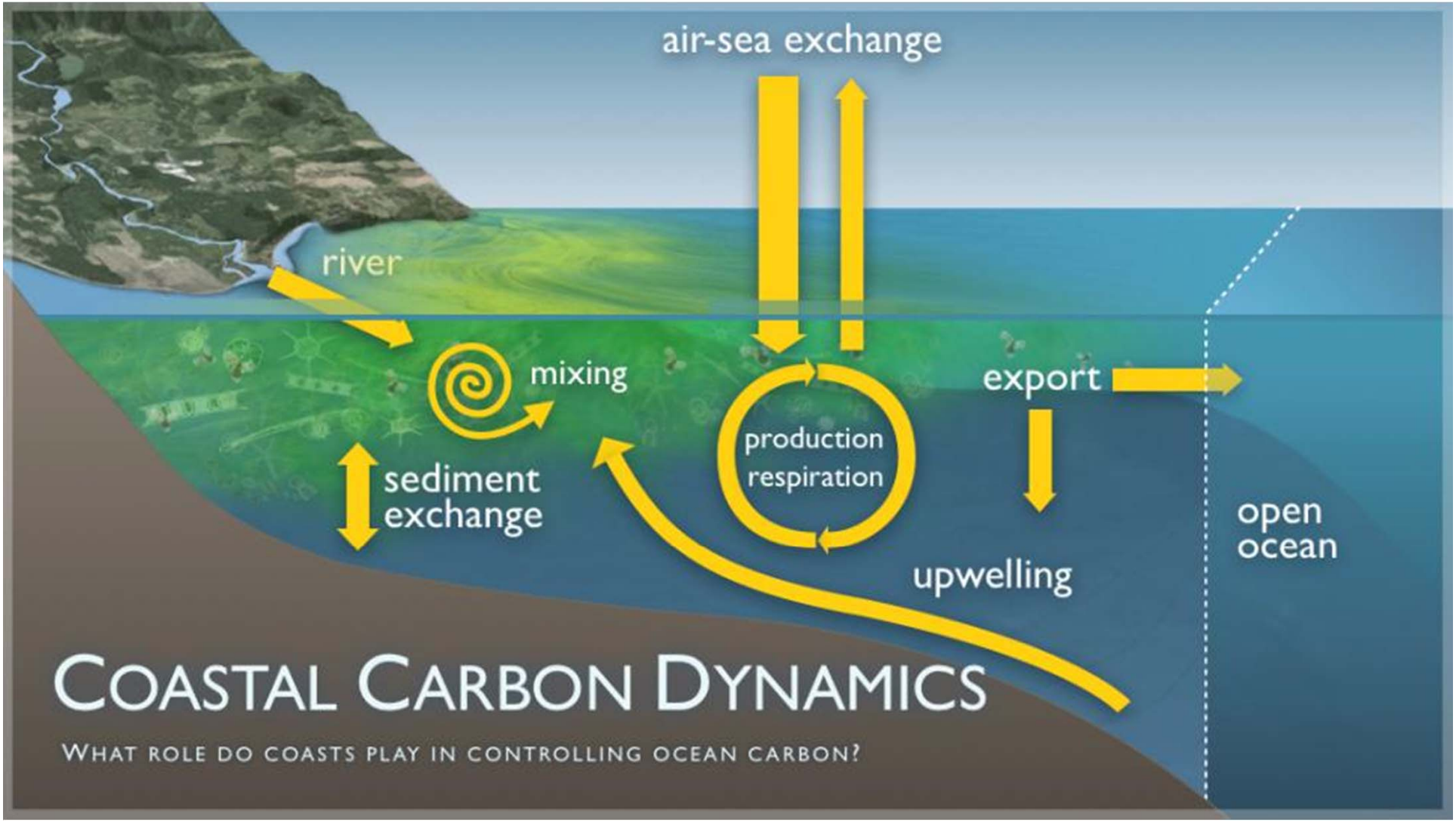
Ch1. Introduction to Ocean Acidification in Washington State Waters

Definition: Ocean acidification (OA) is the reduction of pH in the oceans over an extended period of time, typically decades or longer, caused primarily by the uptake of carbon dioxide from the atmosphere.

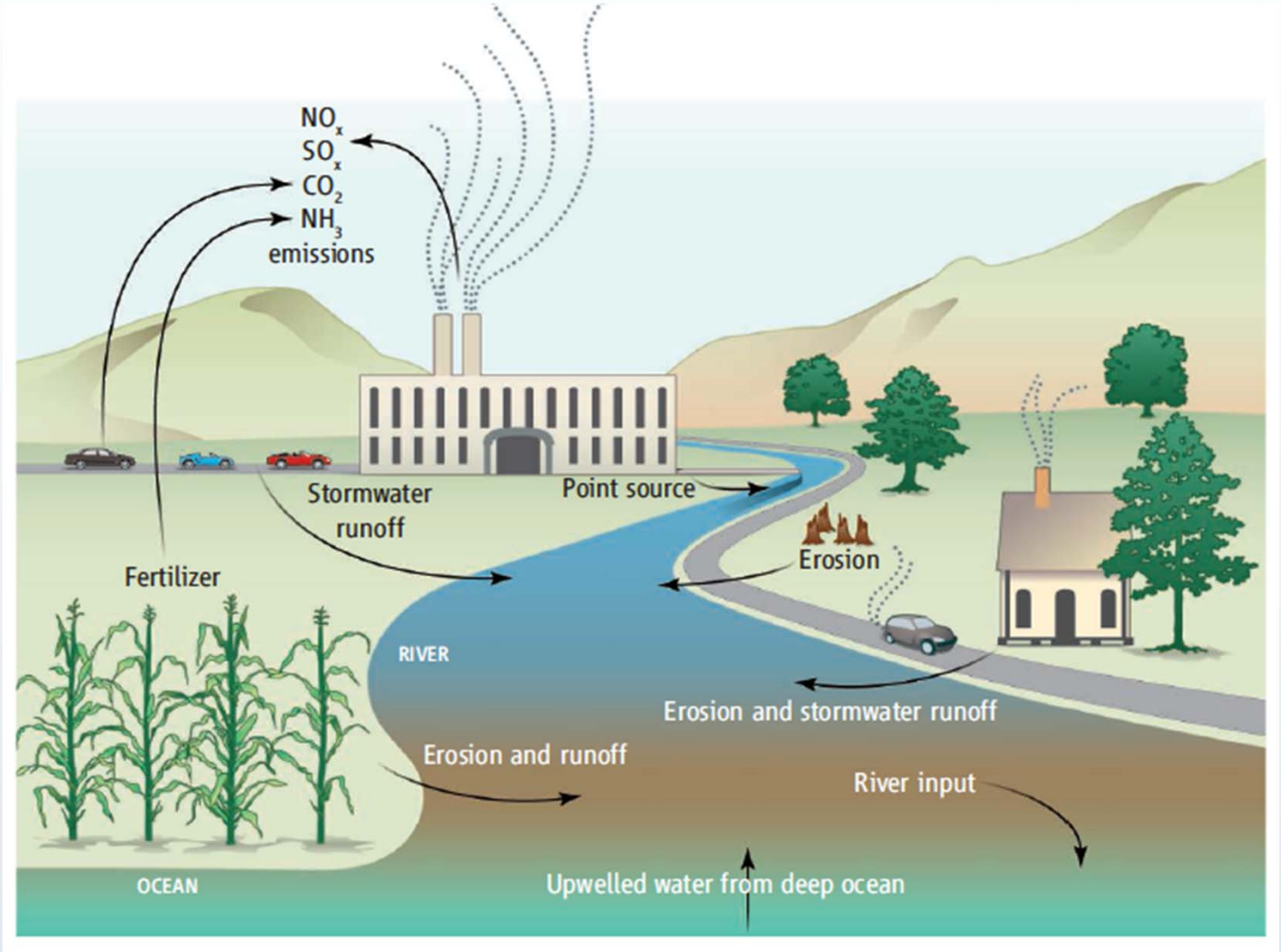
- The **average rate of acidification is >10 times faster** than at any time over the past 300 million years.
- The **average acidity** of the oceans **has increased by about 30%**, and could increase by 100-150% by 2100.
- The **average aragonite saturation state decline drops below the normal range** of variability **within 12-40 years**.

What do we KNOW about OA in Washington waters?

- **Washington State waters are particularly vulnerable** to decreased pH from ocean acidification because upwelling, hypoxia, NO_X/SO_X, and watershed inputs of nutrients also affect water chemistry. The **relative contributions** of each of these drivers to reduced pH and aragonite saturation state is **still uncertain**.
- **Evidence for OA in Washington**:
  - **<u>Outer Coast</u>:** Observed to have **corrosive waters shoaling upwards** (currently within 20-100 meters of surface **during summer upwelling** events)
  - **<u>Puget Sound</u>**: Observed to have **even lower pH conditions in late summer due to the combined effects of acidification, upwelling, hypoxia, and watershed inputs of nutrients.**
- **Freshwater inputs** contribute to lower pH and decreased aragonite saturation in local river estuaries.


air-sea exchange
river
mixing
sediment
exchange
production
respiration
export
upwelling
open
ocean
COASTAL CARBON DYNAMICS
WHAT ROLE DO COASTS PLAY IN CONTROLLING OCEAN CARBON?

Terrestrial factors that contribute to acidification



Kelly et al., Science (2011)

Ch 2. Ocean Acidification on the Outer Washington Coast

What do we KNOW about OA on the Washington coast?

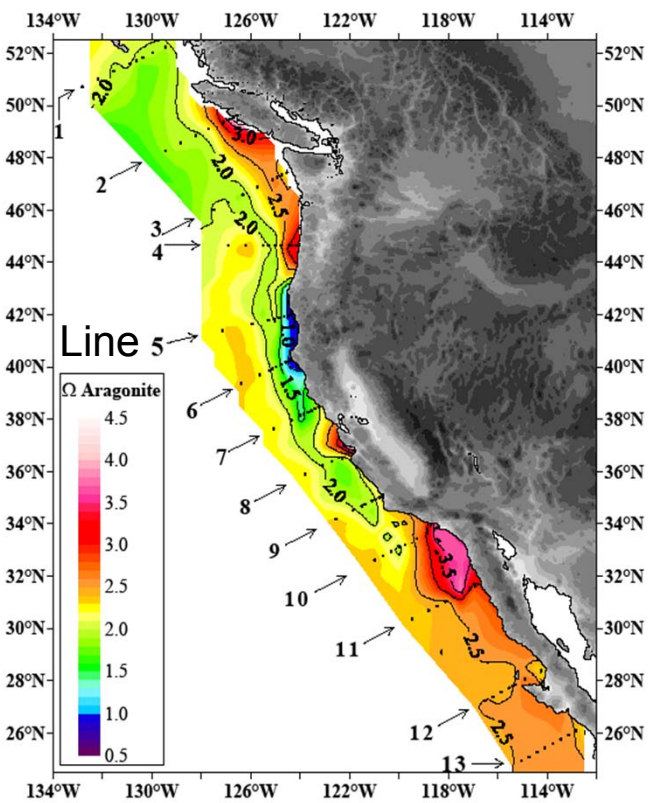
- **INTERIOR OCEAN NATURALLY CO_2-RICH**: Deeper waters are naturally high in pCO_2, particularly in the North Pacific
- **ANTHROPOGENIC CO_2 INCREASE**: Human CO_2 fingerprint is apparent as oceanic data shows an increase in pCO_2 and a decrease in aragonite saturation.
- **UPWELLING HAPPENS:** Seasonal upwelling brings corrosive waters to shallower depths during summer.
- **OA ALREADY EVIDENT**: Corrosive waters found at mid-shelf between 20 and 120 m.
- **OTHER FACTORS**:
  - Columbia River plume influences pCO_2 and productivity in near-surface layer
  - Coastal hypoxia is sign of high respiration and thus higher pCO_2 in subsurface waters

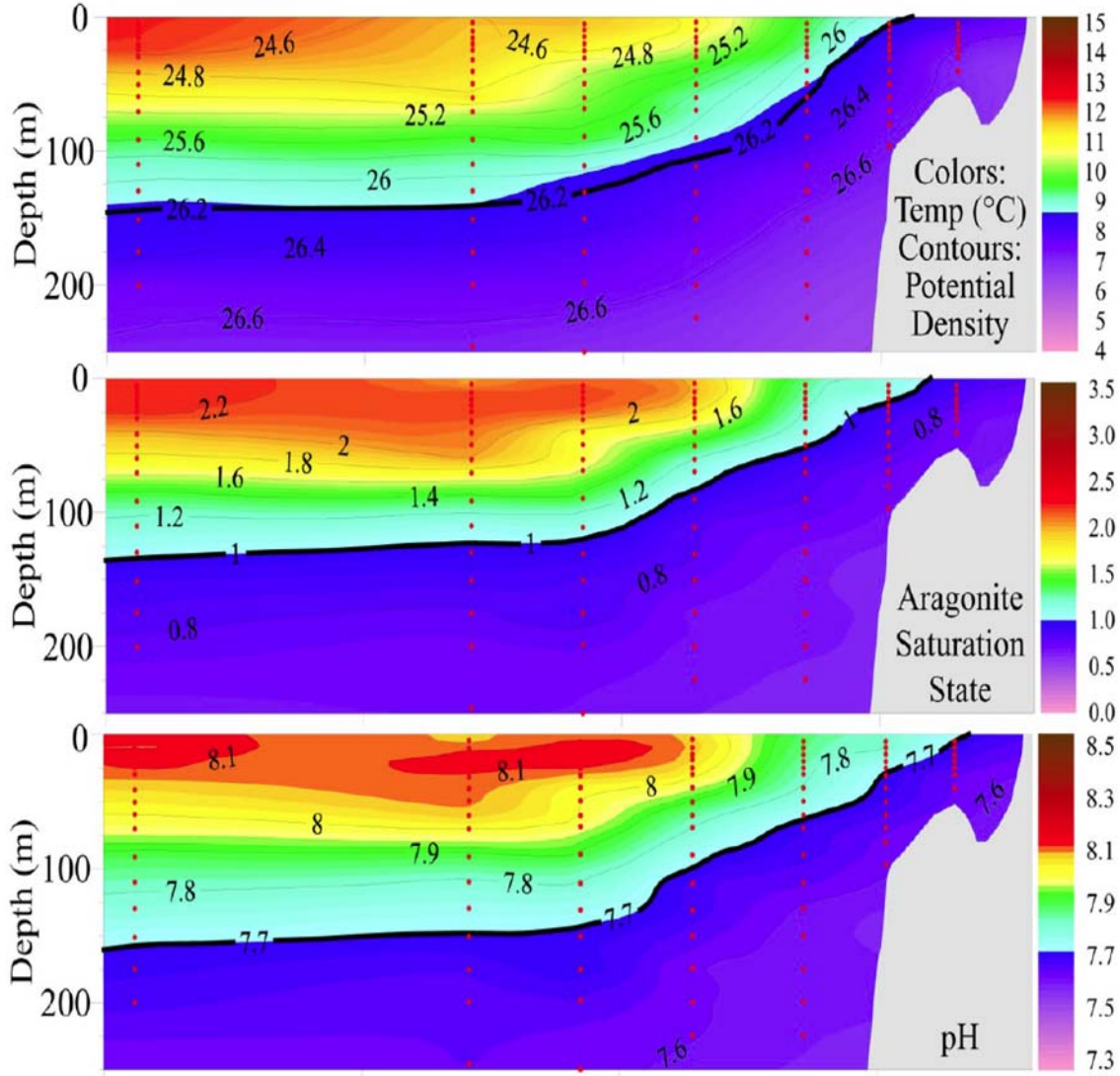
Coastal waters corrosive earlier than predicted, due to combination of regional factors that reduce pH and aragonite saturation state.

NACP West Coast Survey Cruise

11 May - 14 June 2007

Vertical sections from Line 5 –
Pt. St. George, CA





Feely et al., Science, 2008

Ch 2. Ocean Acidification on the Outer Washington Coast

What do we KNOW about OA on the Washington coast?

- **INTERIOR OCEAN NATURALLY CO_2-RICH**
- **ANTHROPOGENIC CO_2 INCREASE**
- **UPWELLING HAPPENS**
- **OCEAN ACIDIFICATION ALREADY EVIDENT**
- **OTHER FACTORS**: Columbia River plume; coastal hypoxia

What do we NEED to KNOW?

- **QUANTIFY DRIVERS**: Document spatial and temporal patterns in pCO_2 and pH and quantify what is driving the observed variation
- **BUDGET**: Basic understanding of carbon sources and sinks
- **COLUMBIA RIVER PLUME EFFECT**: Quantify effect of plume on pCO_2 and pH

Ch 2. Ocean Acidification on the Outer Washington Coast

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What do we NEED to KNOW?

- **QUANTIFY DRIVERS**
- **BUDGET**
- **COLUMBIA RIVER PLUME EFFECT**

What do we need to DO?

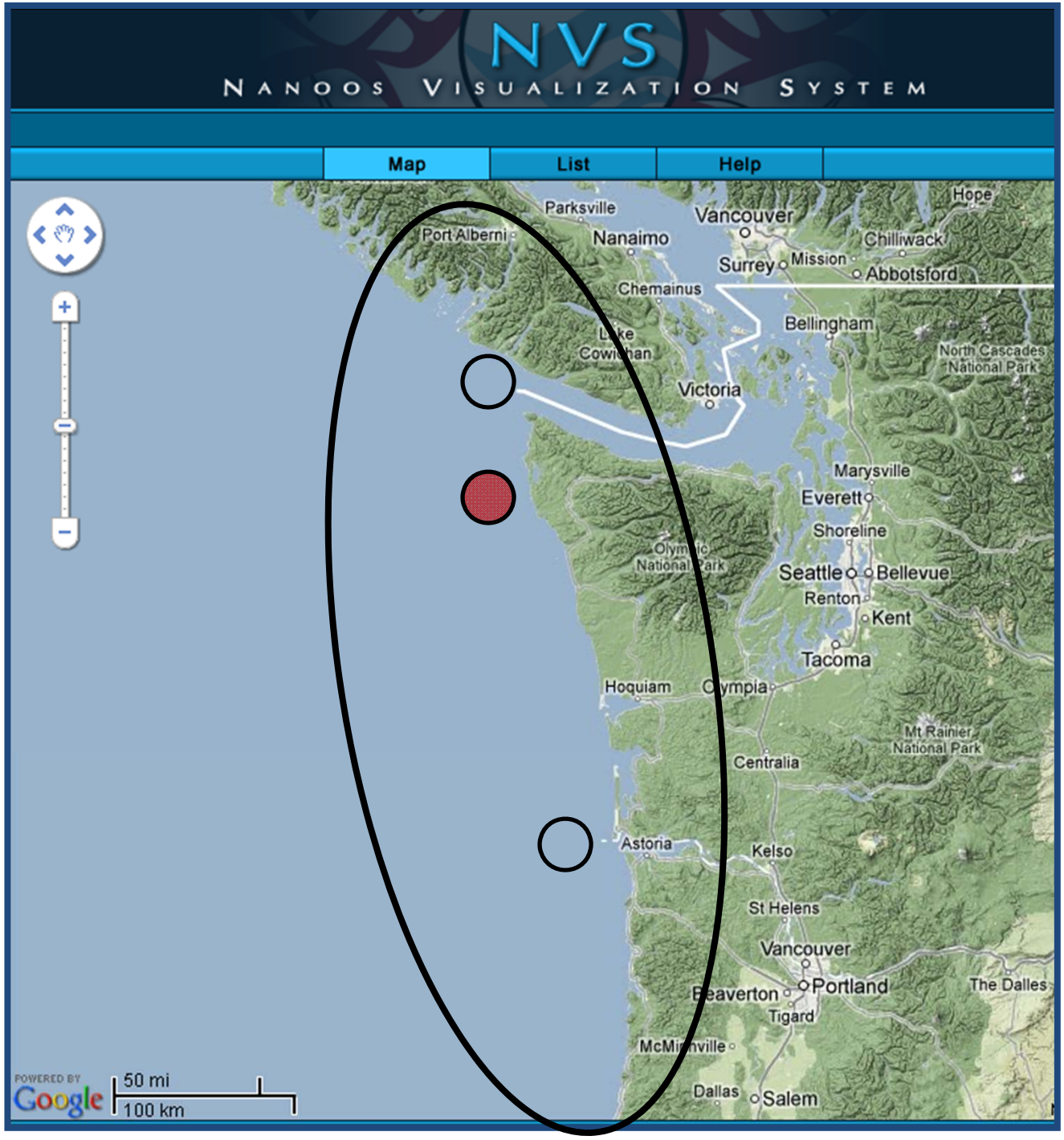
- **QUANTIFY CARBON SOURCES AND SINKS**
- **SUSTAIN SURVEY OBSERVATIONS TO IMPROVE PREDICTIVE RELATIONSHIPS FOR ESTIMATING pH & Ω**
- **SUSTAIN HIGH RESOLUTION TIMESERIES IN KEY LOCATIONS** e.g., La Push, mouth of Columbia R, mouth of Strait Juan de Fuca
- **CONDUCT COUPLED PHYSICS/CHEMISTRY/BIOLOGY MEASUREMENTS**
- **CONDUCT PROCESS STUDIES TO ADDRESS ABOVE UNKNOWNS**
- **ANALYZE AND MODEL DATA FOR PREDICTIVE FORECASTING**

OA data:

= UW buoy & NOAA sensors: *La Push*

= need temporal coverage

= surveys for predictive capability



Ch 3. Puget Sound and Strait Juan de Fuca

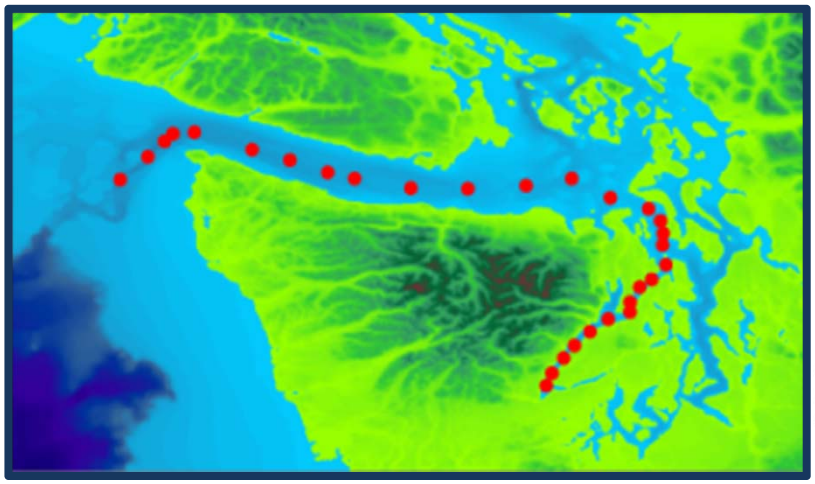
What do we KNOW about OA in Puget Sound and the Strait?

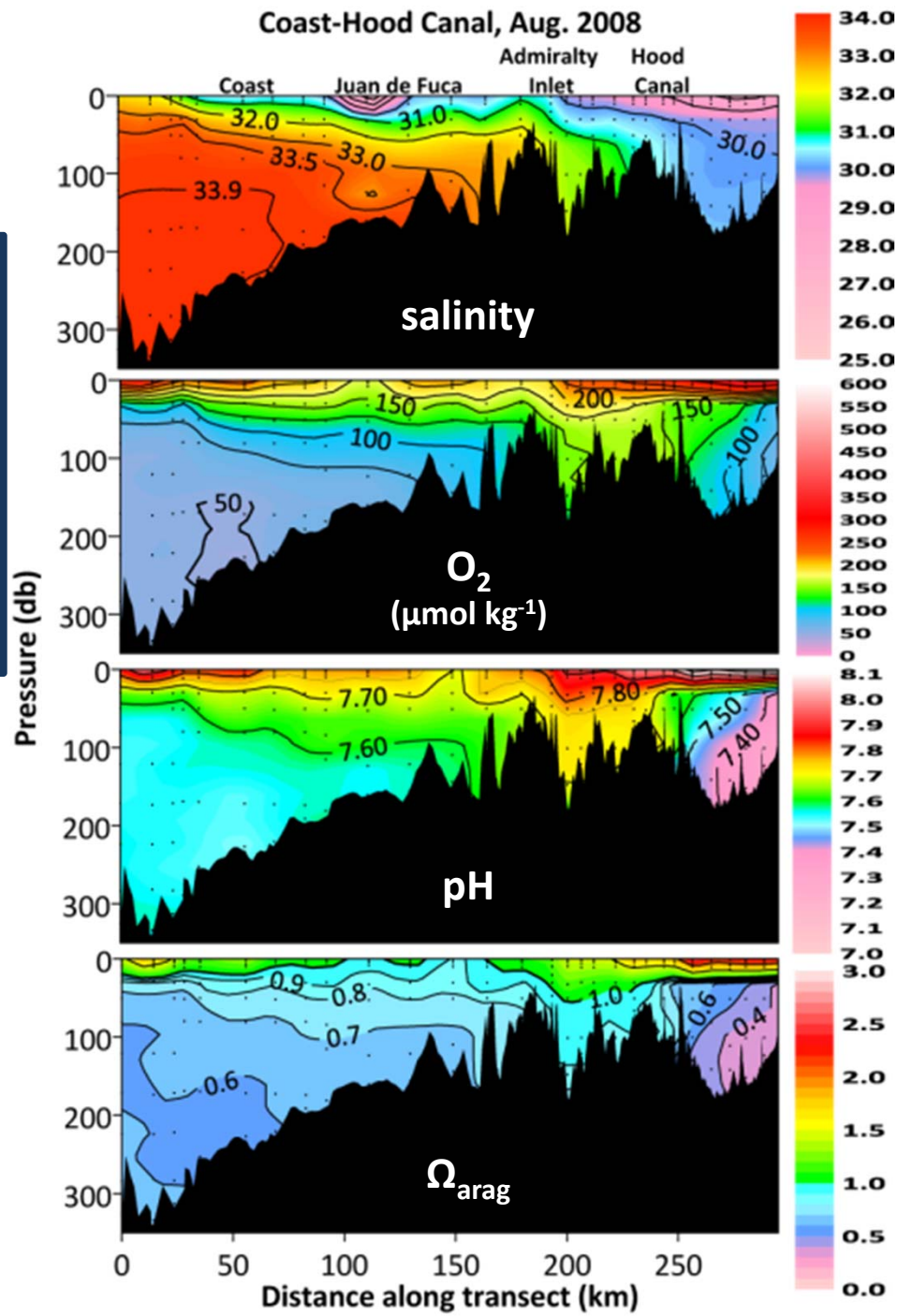
- **THE OCEAN RULES**:
  - Strong signal from oceanic input, enters at depth.
  - Nature of ocean input varies seasonally and interannually.
- **PUGET SOUND IS RETENTIVE**:
  - Waters stay in some parts of Puget Sound for a long time due to sills that 'reflux' water back into Puget Sound.
  - Flushing influenced by density difference between freshwater and oceanic inputs; this varies within Puget Sound and annually.
- **NITROGEN INPUT INCREASE**:

  Human nutrient fingerprint in marine waters apparent in WA Ecology data (3 µM nitrate increase over 10 years); implies respiration may be in excess of natural signal
- **OA EVIDENT**:
  - Subsurface waters in Puget Sound are undersaturated with respect to aragonite.
  - OA estimated to be 24-49% of CO_2 increase in Hood Canal; remaining change results from remineralization of organic matter due to natural or anthropogenically stimulated respiration processes within Puget Sound.
  - UW/NOAA data show pCO_2 is highly variable in space and time.

Variation strong, but deeper waters observed corrosive; oceanic signal evident but influence by nutrients cannot be dismissed.

Summer 2008 transect: WA Coast to Hood Canal

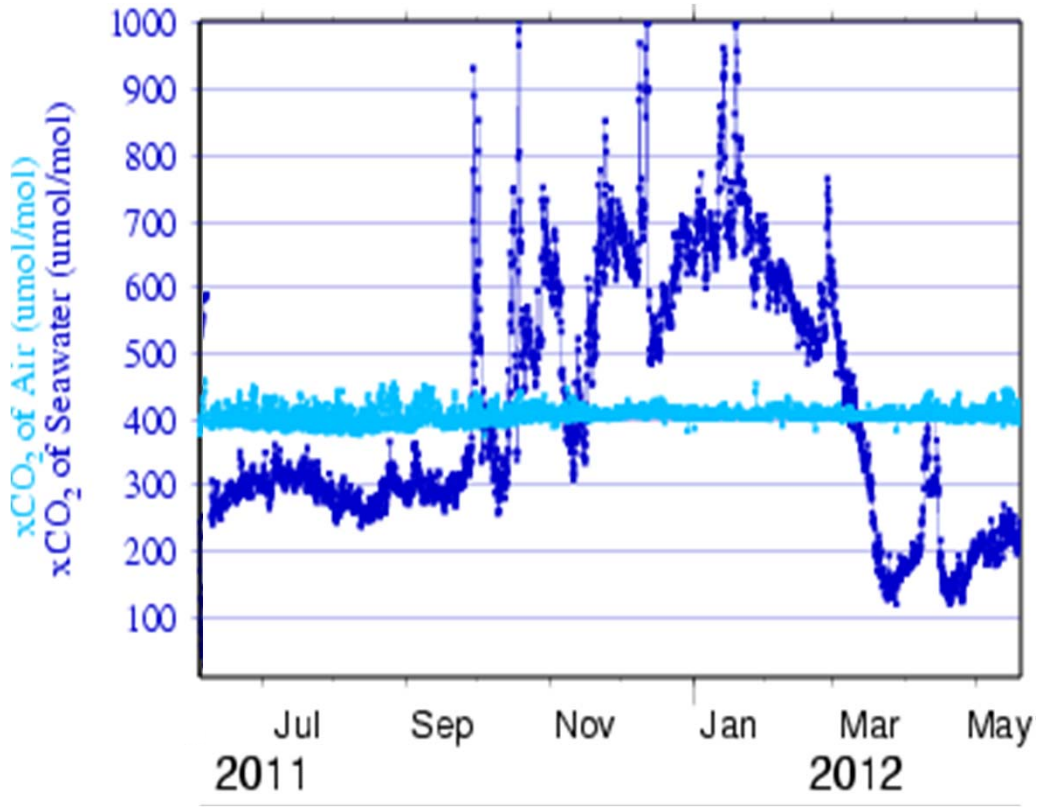




Corrosive undersaturated water (Ω<1.0) occurs below 20 m in Hood Canal, but is sometimes mixed upward into the surface layer during high-wind conditions.

Feely et al. (2010) ESTUARINE AND COASTAL SHELF SCIENCE

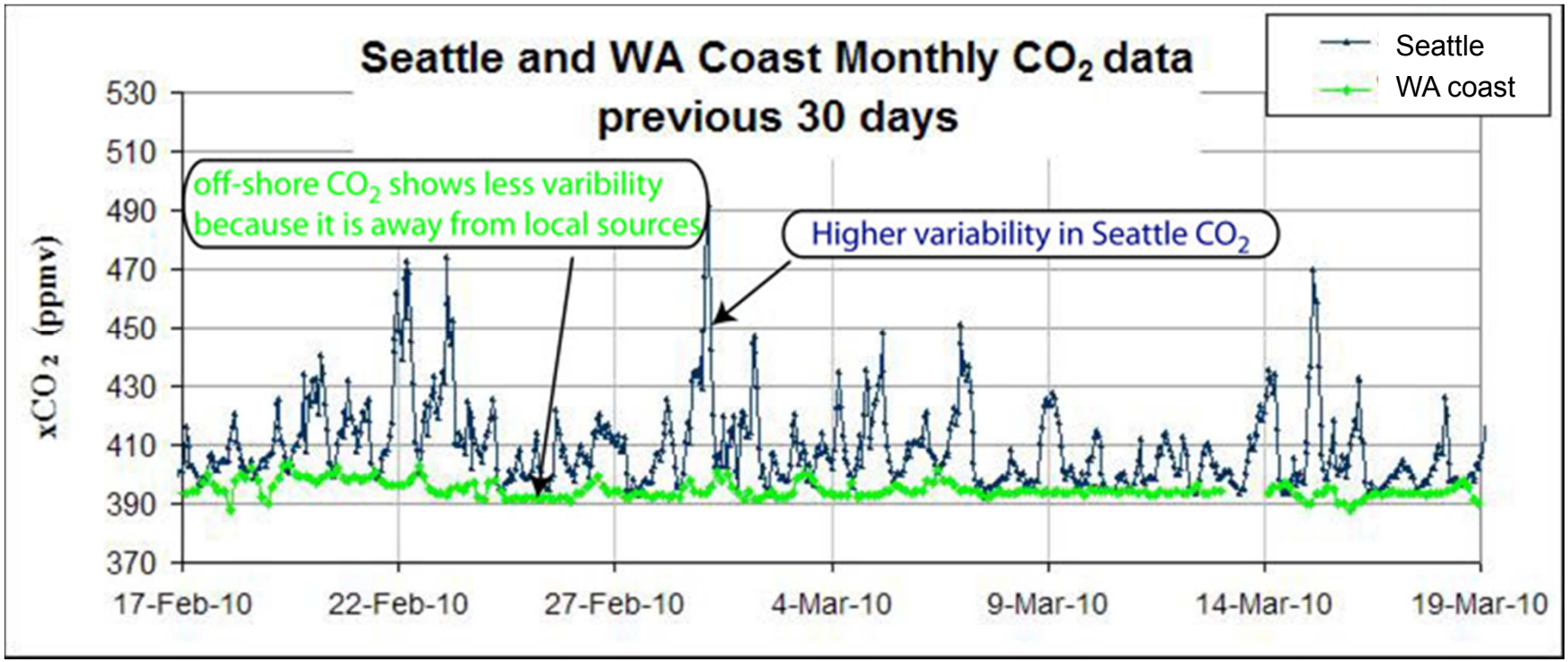
Higher seawater CO_2 associated with wind-driven local upwelling of deeper waters



NOAA data from UW-NANOOS buoy

Higher atmospheric CO_2 associated with urban corridor: effect on Puget Sound?

Seattle vs. Coast



Graphics provided by Ellen Lettvin, Pacific Science Center: NOAA-PMEL data, exhibited in Pacific Science Center CO_2 kiosk and in collaboration with Chris Sabine NOAA PMEL

Ch 3. Puget Sound and Strait Juan de Fuca

What do we KNOW about OA in Puget Sound and the Strait?

- THE OCEAN RULES
- PUGET SOUND IS RETENTIVE
- NITROGEN INPUT INCREASE
- OA EVIDENT

What do we NEED to KNOW?

- **QUANTIFY DRIVERS:** Document spatial and temporal patterns in pCO_2 and pH and quantify what is driving the observed variation
- **BUDGET**: Basic understanding of carbon sources and sinks; including assessment of NO_X/SO_X regionally and freshwater effect on pH
- **NITROGEN LOAD EFFECT:** Quantify effect of nitrogen loading on pCO_2 and pH
- **ATMOSPHERIC CO_2 EFFECT**: Quantify effect of regional atmospheric CO_2 on local seawater pCO_2 and pH

Ch 3. Puget Sound and Strait Juan de Fuca

What do we KNOW about OA in Puget Sound and the Strait?

- THE OCEAN RULES
- PUGET SOUND IS RETENTIVE
- NITROGEN INPUT INCREASE
- OA EVIDENT

What do we NEED to KNOW?

- QUANTIFY DRIVERS
- BUDGET
- NITROGEN LOAD EFFECT
- ATMOSPHERIC CO_2 EFFECT

What do we need to DO?

- **QUANTIFY CARBON SOURCES AND SINKS**
- **OBTAIN HIGH QUALITY, REGIONALLY DIVERSE SURVEY DATA TO DEVELOP PREDICTIVE RELATIONSHIPS (pH and Ω)**
- **SUSTAIN HIGH RESOLUTION TIMESERIES IN KEY LOCATIONS** such as boundary, basins, nearshore, and river mouths
- **CONDUCT COUPLED PHYSICS/CHEMISTRY/BIOLOGY MEASUREMENTS**
- **CONDUCT PROCESS STUDIES TO ADDRESS ABOVE UNKNOWNS**
- **ANALYZE AND MODEL DATA FOR PREDICTIVE FORECASTING**

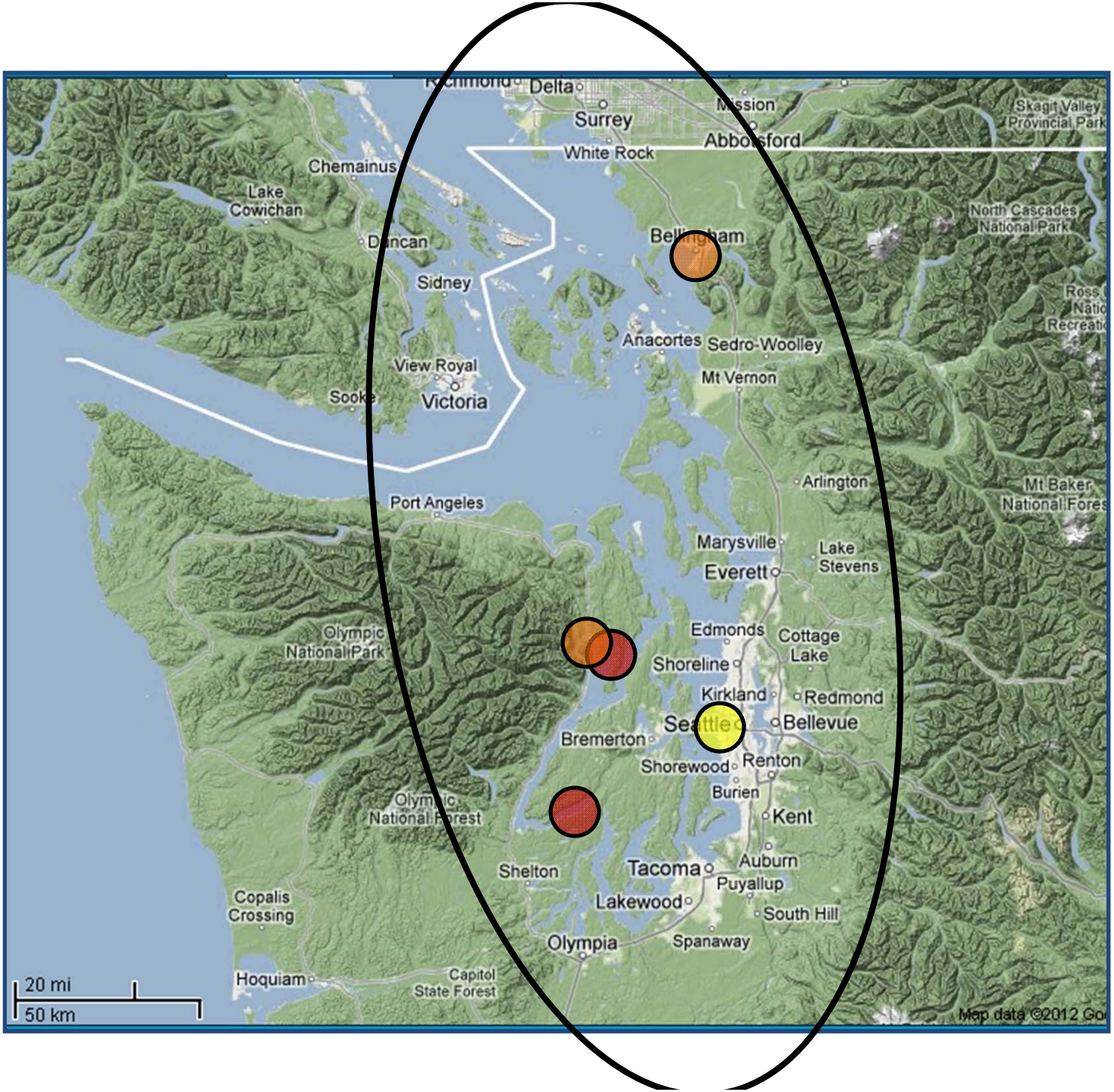
OA data:

= UW buoy & NOAA sensors:
Twanoh, Dabob

= Shellfish sensors:
Dabob, Lummi

= NOAA sensor:
Seattle Aquarium

= need coupled bio-phys-chemical sampling and spatial/ temporal variation



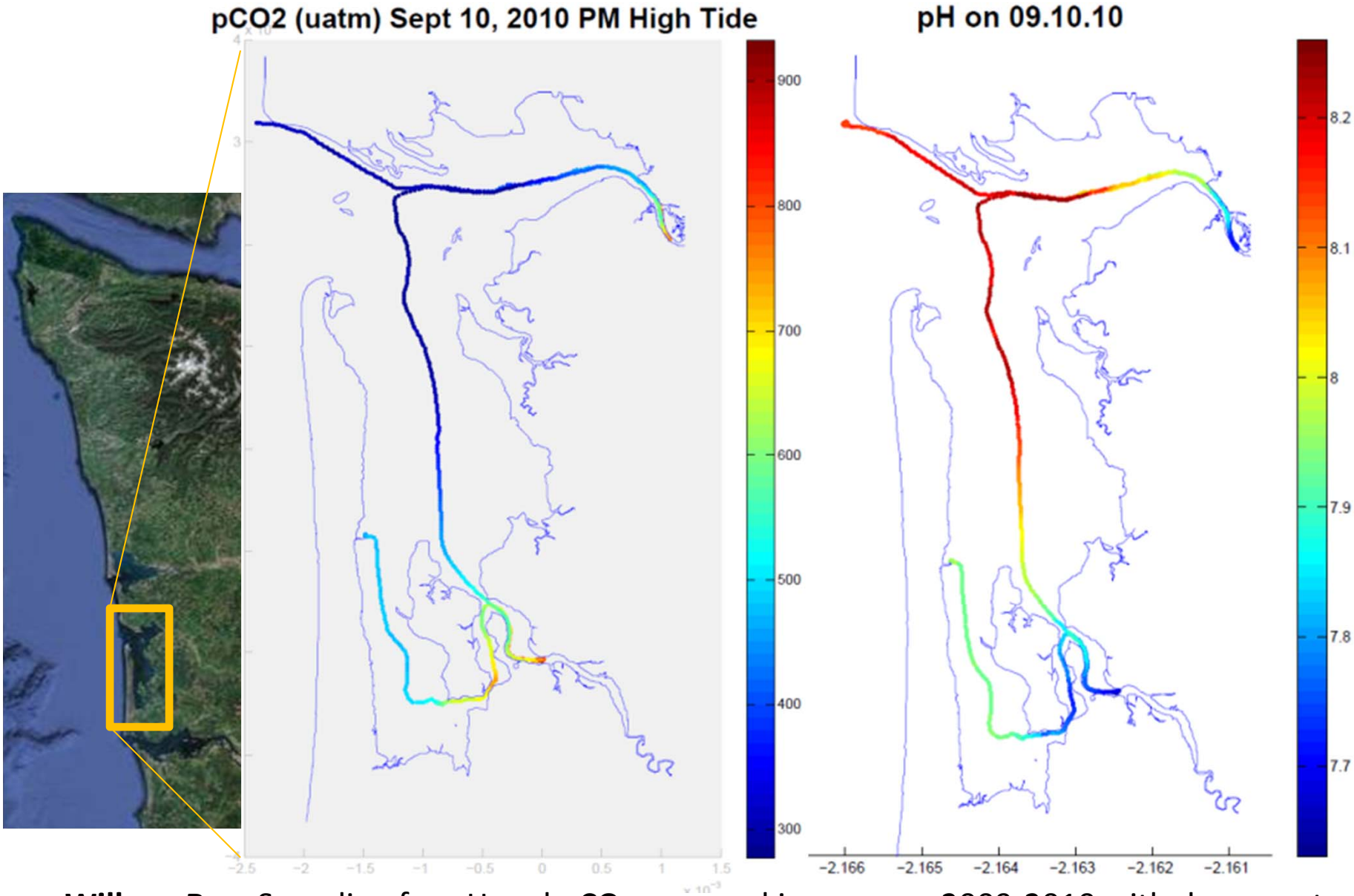
Ch 4. Columbia River and Shallow Estuaries

What do we KNOW about OA in the Columbia & Shallow Estuaries?

- **COLUMBIA R. IS UNIQUE AND HUGE:** Turbid waters, little productivity and nitrogen, but lots of iron and silicate.
- **SHALLOW ESTUARIES OFTEN MIXED:** Vertical gradients instead of horizontal gradients; balance of river flow and tides.
- **FRESHWATER INFLUENCE:** River input; some evidence for low pH in low salinity waters in Willapa Bay
- **RIVERS BRING LAND INFLUENCE:** Particles, dissolved organics, and nutrients in river water from natural and human influences all can lead to reduced pH and aragonite saturation, and increased pCO_2
- **SHALLOWNESS AMPLIFIES BIOLOGY:** Shallow estuaries, both within Puget Sound and on the outer coast, can be highly productive (benthic photosynthesizers), with very high respiration rates and CO_2 production.

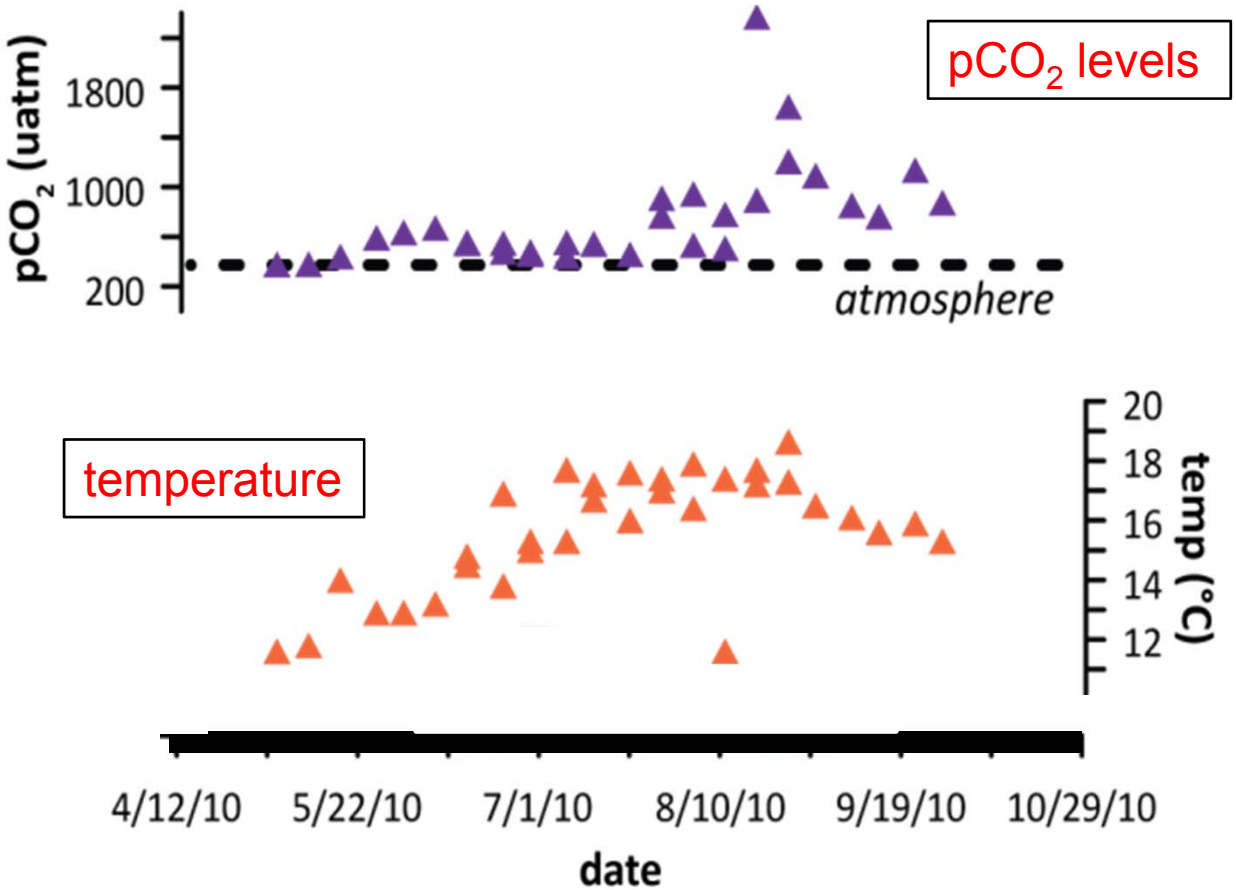
Freshwater and land use influences strong in these estuaries.

Freshwater input associated with lower pH



Willapa Bay: Sampling for pH and pCO_2 occurred in summer 2009-2010 with documented watershed carbon inputs *(Ruesink and Trimble, unpublished)*

Higher pCO_2 associated with high respiration ?



Totten Inlet: Sampling for temperature, salinity, pH and pCO_2 and oyster larvae spatfall occurred during summer 2009-2010 *(Alin et al., unpublished)*

Ch 4. Columbia River and Shallow Estuaries

What do we KNOW about OA in the Columbia River and Shallow Estuaries?

- COLUMBIA R. IS UNIQUE AND HUGE
- SHALLOW ESTUARIES OFTEN MIXED
- FRESHWATER INFLUENCE
- RIVERS BRING LAND INFLUENCE
- SHALLOWNESS AMPLIFIES BIOLOGY

What do we NEED to KNOW?

- **QUANTIFY DRIVERS**: Document spatial and temporal patterns in pCO_2 and pH and quantify what is driving the observed variation
- **BUDGET**: Basic understanding of carbon dioxide sources and sinks, especially differentiating relative contributions of local respiration vs. oceanic input effects on pCO_2 levels
- **FRESHWATER EFFECT:**
  - Effect of freshwater on pH measurement
  - Evaluate correlation between pH and salinity
- **LAND USE EFFECT:** Quantify effect of land use practices such as timber extraction, dike removal, restoration

Ch 4. Columbia River and Shallow Estuaries

What do we KNOW about OA in the Columbia River and Shallow Estuaries?

- COLUMBIA R. IS UNIQUE AND HUGE
- SHALLOW ESTUARIES OFTEN MIXED
- FRESHWATER INFLUENCE
- RIVERS BRING LAND INFLUENCE
- SHALLOWNESS AMPLIFIES BIOLOGY

What do we NEED to KNOW?

- QUANTIFY DRIVERS
- BUDGET
- FRESHWATER EFFECT
- LAND USE EFFECT

What do we need to DO?

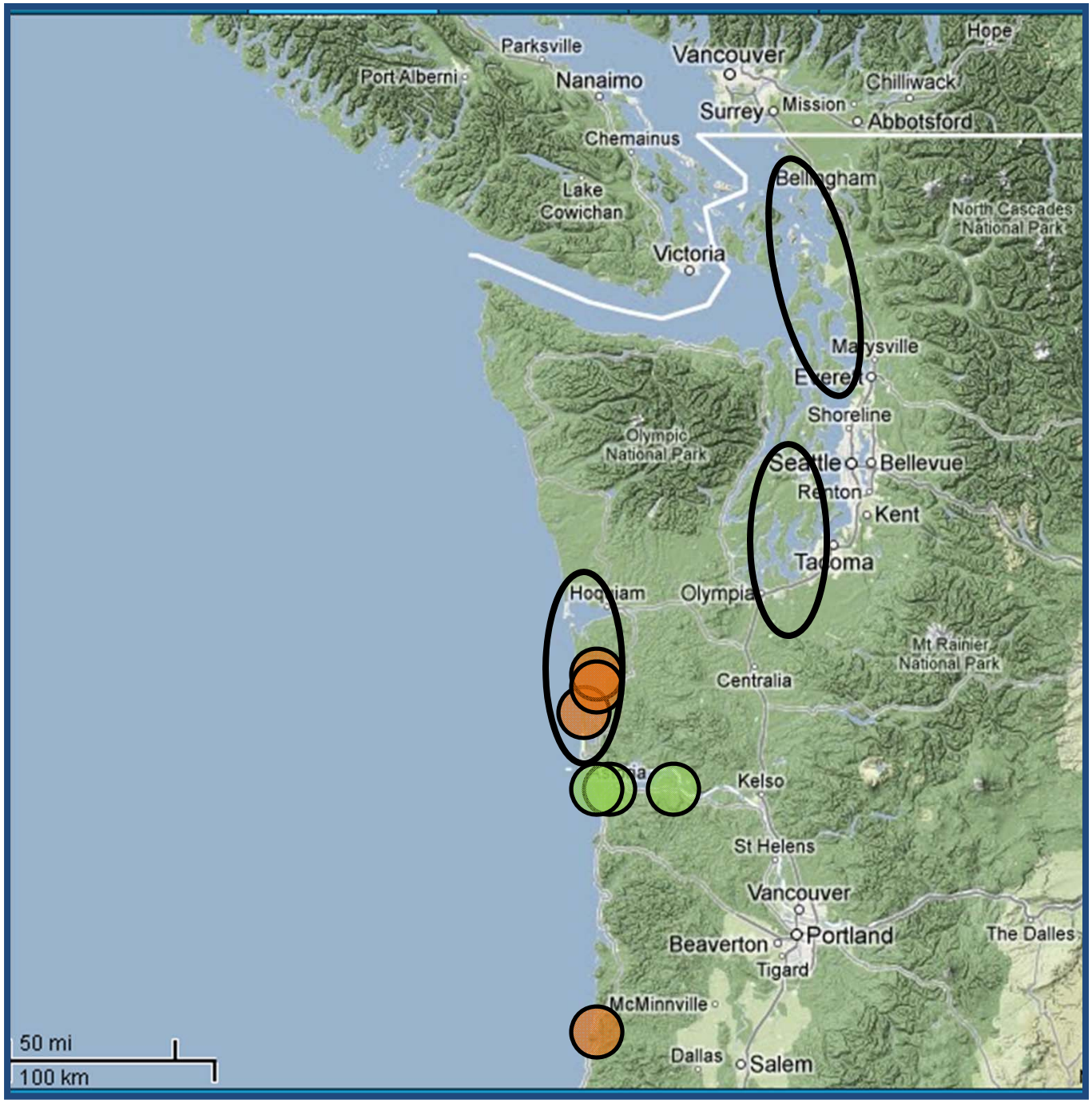
- **SUSTAIN HIGH QUALITY, REGIONALLY DIVERSE SURVEY DATA FOR PREDICTIVE RELATIONSHIP DEVELOPMENT**
- **SUSTAIN HIGH RESOLUTION TIMESERIES IN KEY LOCATIONS** such as along Columbia R. salt gradient, key estuary types based on land-use, hydrography
- **CONDUCT COUPLED PHYSICS/CHEMISTRY/BIOLOGY MEASUREMENTS** (Willapa, Totten)
- **CONDUCT PROCESS STUDIES TO ADDRESS ABOVE INFO NEEDS**
- **ANALYZE AND MODEL DATA FOR PREDICTIVE FORECASTING**

OA data:

= Shellfish sensors:
Willapa (3), Lummi, Netarts Bay

= CMOP NSF STC sensors:
Columbia R. (3)

= need coupled bio-phys-chemical sampling and document spatial and temporal variation



Distinctive Influencing Factors

Outer Coast

- Upwelling
- Columbia R plume effect (?)

Puget Sound/Strait

- Oceanic input
- Nutrient addition effect (?)
- Local atmospheric effect (?)

Columbia/shallow

- Terrestrial input
- Freshwater influence (?)

- ***Diversity of factors and degree of human influence***
- ***The biology that exists in these different environments faces different OA-related pressures***

Chapter 5. Species, Populations, and Communities

What Do We KNOW?

- **BIOLOGICAL RESPONSES ARE LESS PREDICTABLE and LESS CONSISTENT** than physical and chemical changes
- The nature of **BIOLOGICAL RESPONSE VARIES BETWEEN ORGANISMS;** negative responses are common, especially among calcifying species

Chapter 5. Species, Populations, and Communities

What Do We KNOW?

- **PHYTOPLANKTON:** responses vary, suggest sensitivity to OA and (some) capacity for genetic adaptation
- **ZOOPLANKTON:** Pteropods and copepods show negative responses to OA
- **OYSTERS:** Larval stages show negative responses to OA, with variation; other molluscs also respond negatively
- **FISH:** Direct responses, behavioral changes, and food web interactions all can occur

Chapter 5. Species, Populations, and Communities

Recent Research Suggests that…

- **NUTRITIVE VALUE** of phytoplankton could decline
- **TOXICITY** of harmful algae could increase
- **INCIDENCE OF DISEASE** could increase
- **INTERACTIONS WITH OTHER FACTORS** (temperature, nutrients, etc.) will intensify some responses
- **FUNDAMENTAL PROCESSES** (e.g., fertilization, early development, calcification) could be affected
- **SURPRISES WILL OCCUR:** many findings are unexpected

Chapter 5. Species, Populations, and Communities

What Do We NEED to Know?

- How will **LOCAL SPECIES** respond changes in *average* seawater chemistry? *Variation* in seawater chemistry?
- Which species and groups are at **HIGHEST RISK?**
- How will **FOOD WEBS** be affected**?**
- Where is genetic **ADAPTIVE CAPACITY** highest? lowest?
- Can we build **PREDICTIVE MODELS?**
- What are **STRATEGIES FOR MITIGATION** of biological impacts?

Chapter 5. Species, Populations, and Communities

What Do We Need to DO?

- **DETERMINE RESPONSE** of species & life stages across a range of seawater conditions
- **CHARACTERIZE VARIATION in RESPONSE** and capacity for adaptation
- **BUILD PREDICTIVE MODELS**
- **TEST APPLICATIONS** for local mitigation of biological impacts
- **ESTABLISH SITES** for long-term observation

Chapter 6. Habitats and Ecosystems

What Do We KNOW?

- **ORGANISMS IN DIFFERENT HABITATS WILL SUFFER DIFFERENT EXPOSURE:** upwelling systems, deep fjords, semi-isolated bays will differ in the expression of OA

- **ORGANISMS IN DIFFERENT HABITATS COULD RESPOND DIFFERENTLY:** prior history could influence biological response

- **BIOLOGICAL PROCESSES FEED BACK TO CHEMISTRY:** e.g., photosynthesis & respiration can influence pH on day/night basis and over longer periods

Chapter 6. Habitats and Ecosystems

Recent Research Suggests that…

- **ADDITIVE STRESSORS WILL EXACERBATE IMPACTS:** warmer temperatures, nutrient enrichment, hypoxia, and others create "packages of stressors"
- **FOOD WEBS** could substantially change
- **AQUATIC VEGETATION** could modulate local response

Chapter 6. Habitats and Ecosystems

What Do We NEED to Know?

- Which habitats or systems are at **UNACCEPTABLE RISK** of change due to ocean acidification?
- Can risk be **REDUCED? HOW?**
- Do **STRATEGIES FOR MITIGATION** of habitat and ecosystem impacts exist?

Photo: Jon Erickson

Chapter 6. Habitats and Ecosystems

What Do We Need to DO?

- **DETERMINE VULNERABILITY** of key habitats & systems
- **BUILD RESILIENCE,** especially in vulnerable habitats
- **PRESERVE RESILIENCE** and mitigation potential across habitats and systems
- **DEVELOP AND TEST** new mitigation strategies
- **ESTABLISH SITES** for long-term observation

Summary

- **Ocean chemistry is changing and will continue to change**
- **Biological processes will respond** to changes in ocean chemistry
  - Biological responses will vary according to taxon, life history, genetic diversity, capacity for adaptation, etc.
  - Multiple stressors will modify, exacerbate effects
  - Biological processes will feed back to and modify ocean chemistry
  - Fundamental biological principles point to general responses across taxa, habitats and ecosystems
- **More detail is provided in Science White Paper**