Growth and survival of forage fish and juvenile salmon in response to oceanographic variability in the northern California Current, including the Salish Sea

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Trends in Nutrient Over-Enrichment in Puget Sound

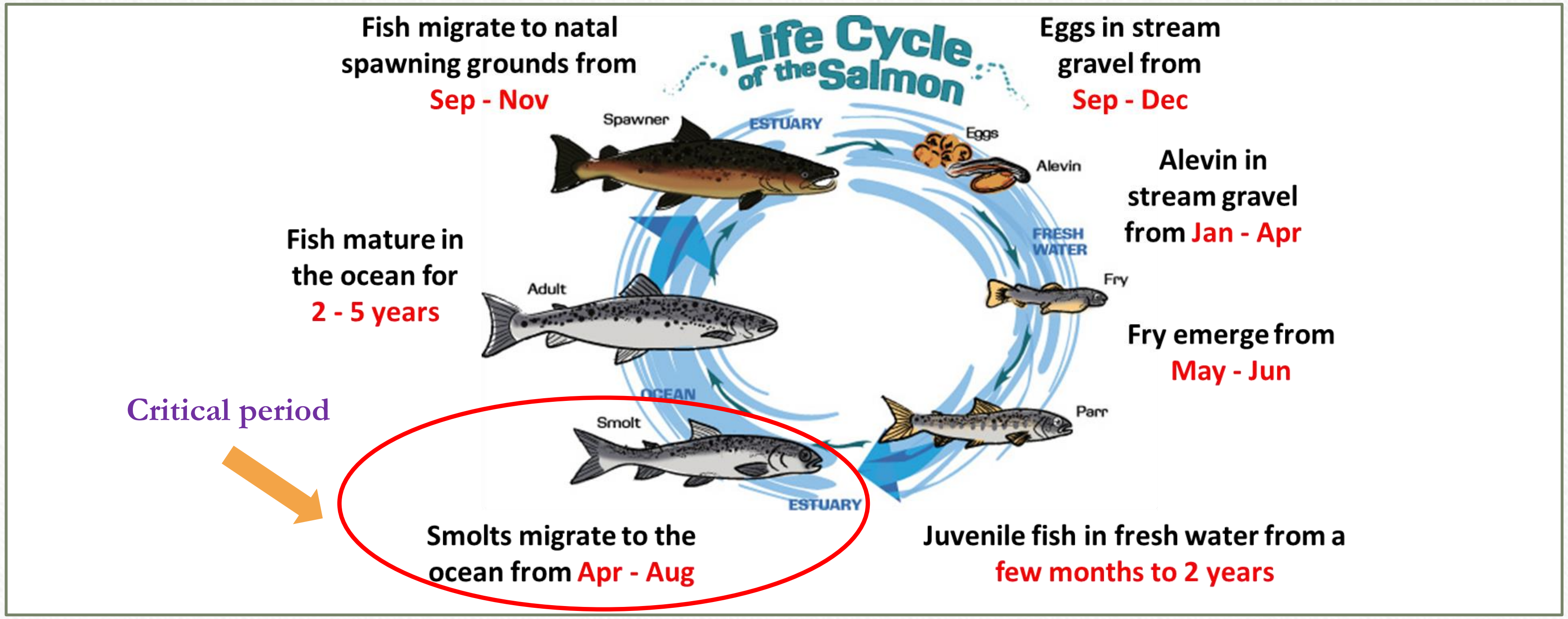
- Physiological and behavioral changes in salmonids and forage fish in response to low DO conditions in the marine environment

- Marine food web changes in response to shifts in marine water quality

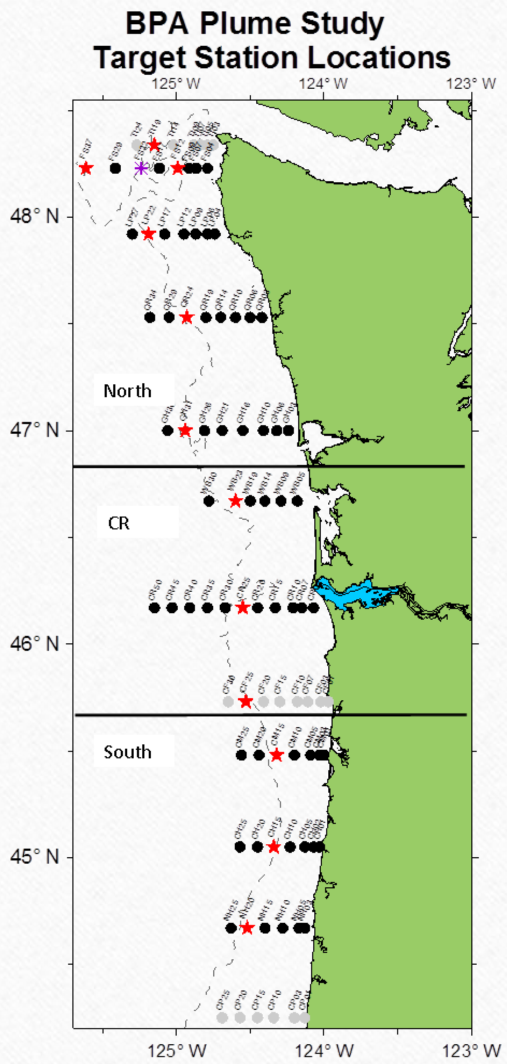
Outline

- Current understanding of salmon and forage fish marine survival
- Factors affecting food web and growth
- Climate change impacts in the North Pacific
- Examples from Puget Sound

A *critical period* in the life history of Pacific salmonids when mortality is high and variable



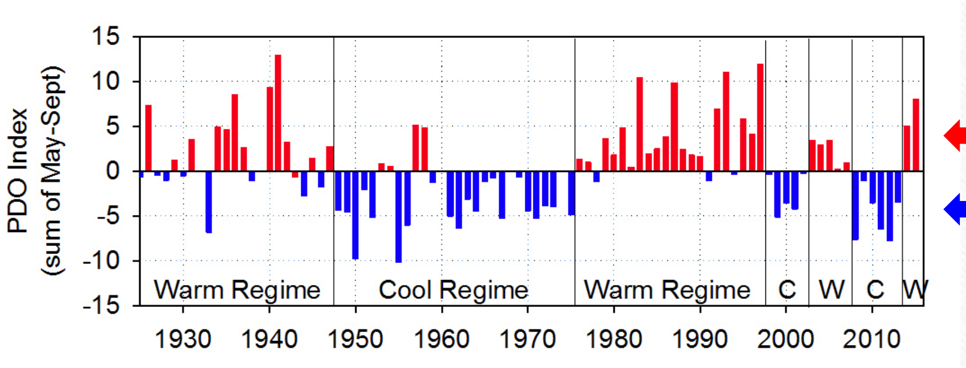
Pearcy 1992; Beamish 2018



Sampling of Juvenile Pacific Salmon 1998-2017

- Juvenile salmon ecology studied for the past 20 years
- Understand marine growth, migration, and survival
- Informs salmon conservation, recovery, harvest management
- Early warning ***indicators*** of ocean conditions that affect salmon survival

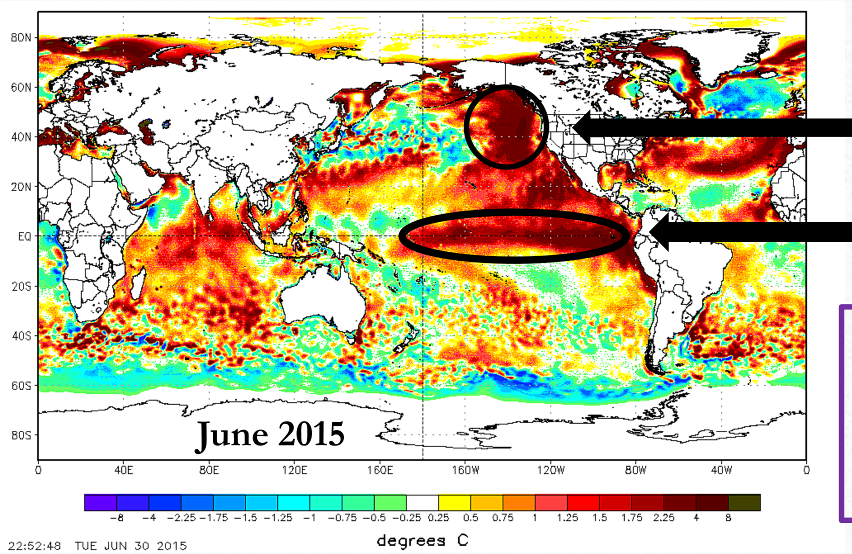
Basin-Scale Ocean/Atmospheric Indicators



Pacific Decadal Oscillation (PDO)

Positive Phase = Warm, **bad** for salmon

Negative Phase = Cool, **good** for salmon



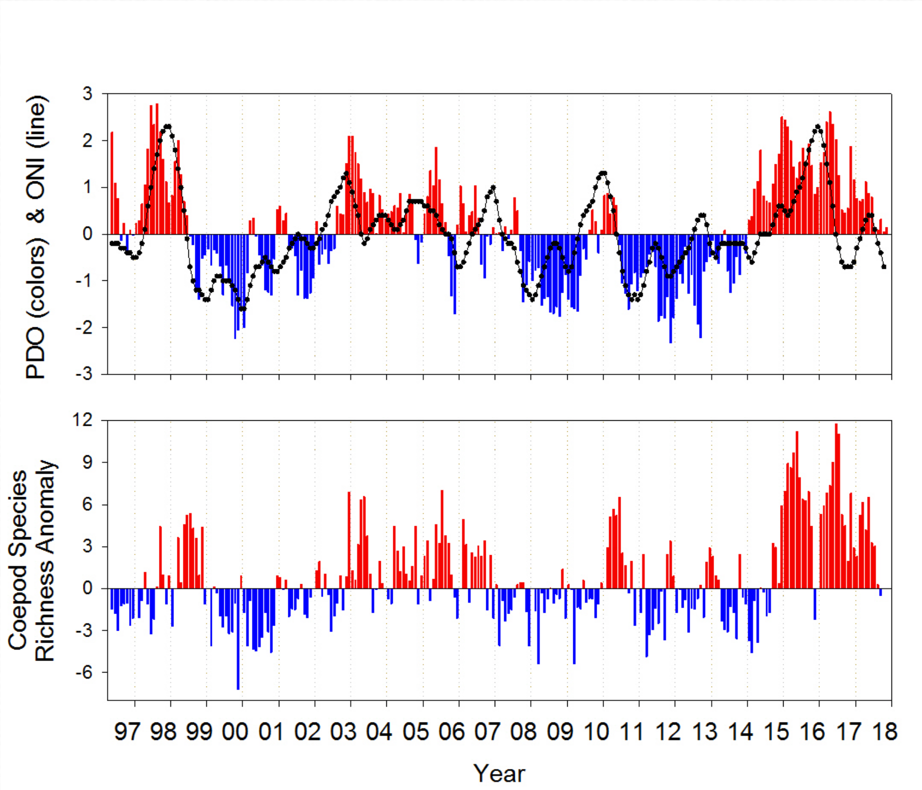
Marine Heatwave 2014 – 2016

The Warm Blob

El Niño Southern Oscillation (ENSO)

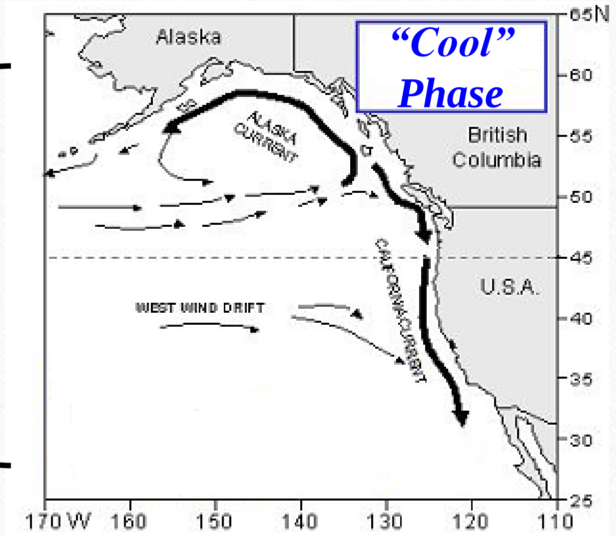
Most (<5%) salmon that enter the ocean do not survive. Why? Prey quality, availability, competition, predators, disease

PDO and Copepods



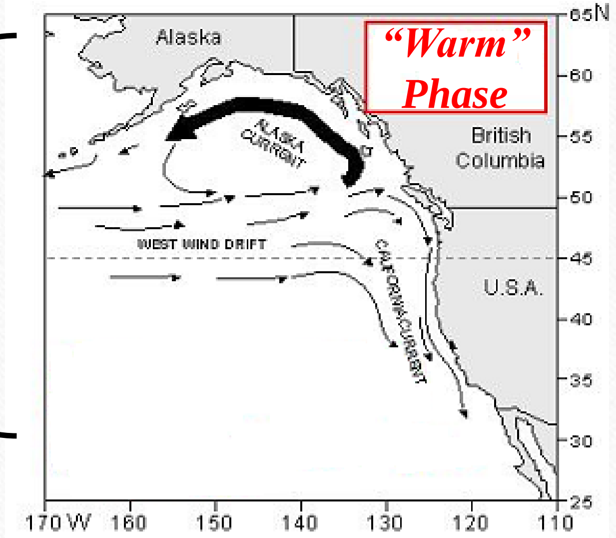
Cool Phase ➔

Transport of boreal coastal copepods into NCC from Gulf of Alaska

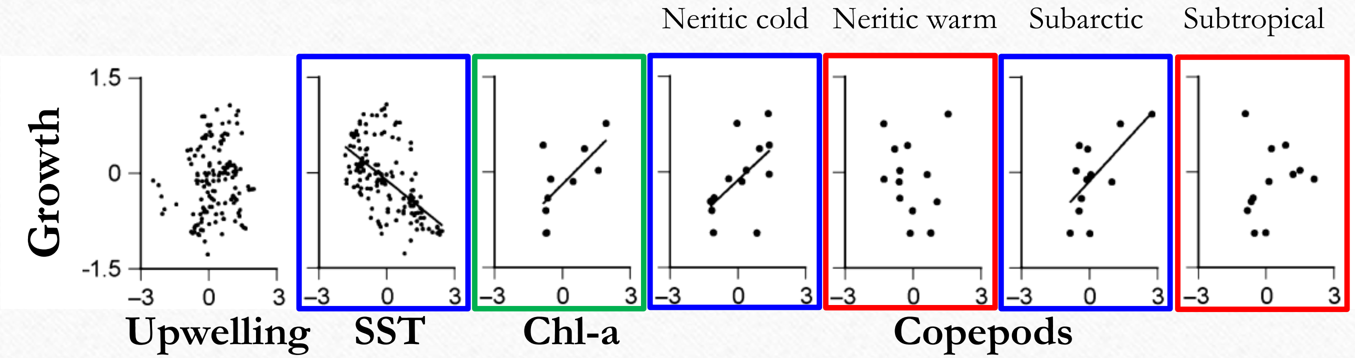


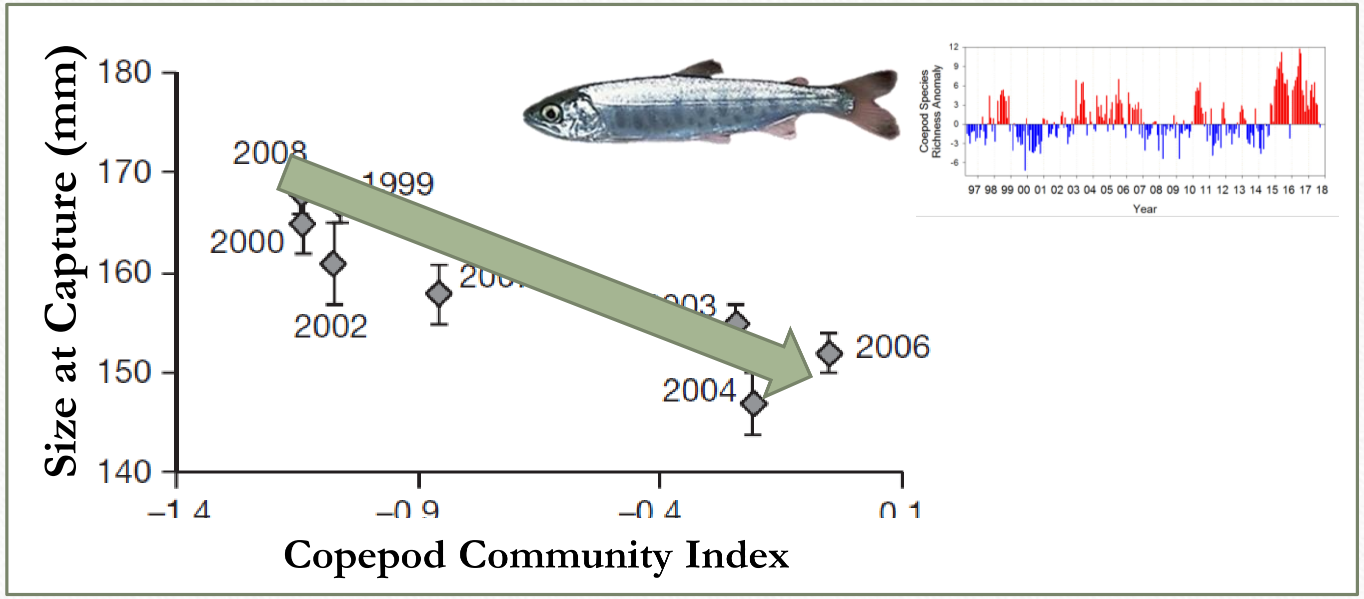
Warm Phase ➔

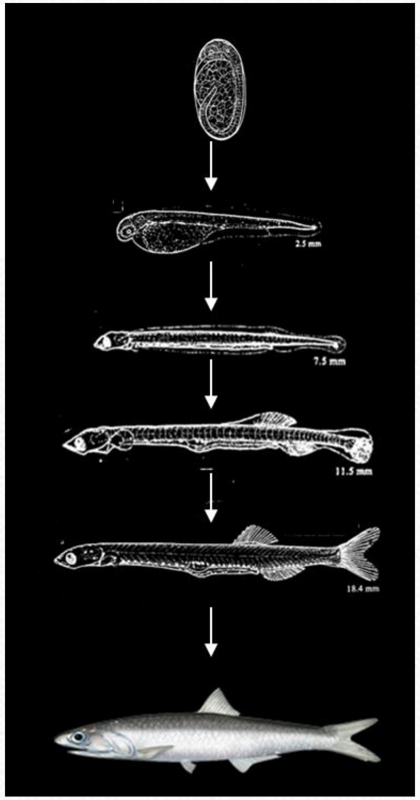
Transport of sub-tropical copepods into NCC from Transition Zone offshore



Growth positively related to abundance of cold water copepods

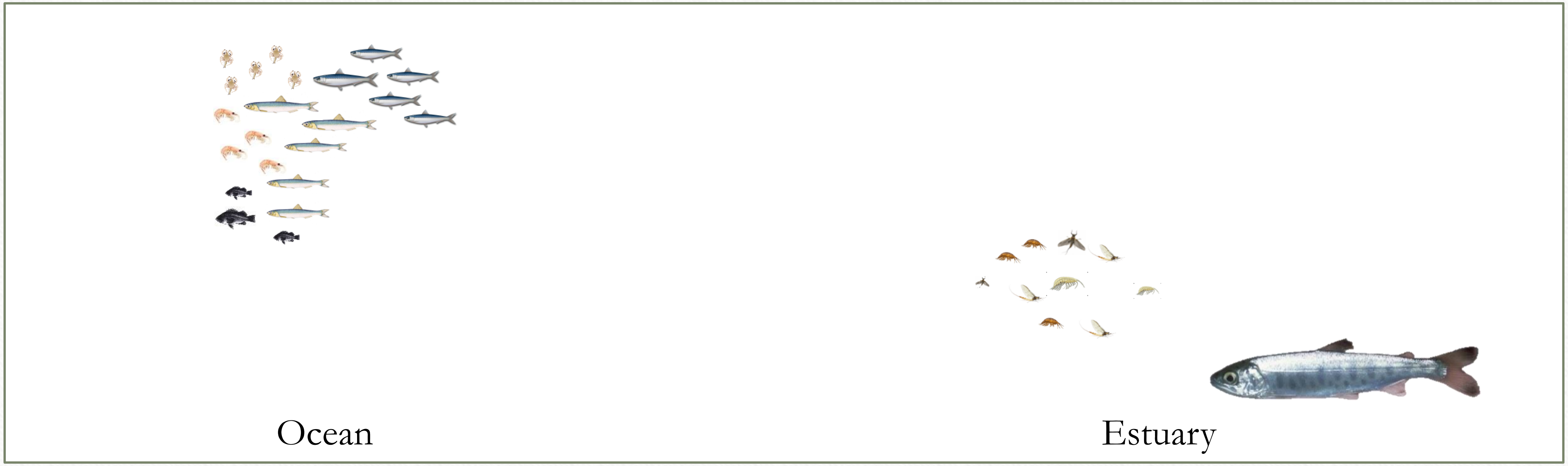






Takahashi et al. 2012; Tomaro et al. 2012

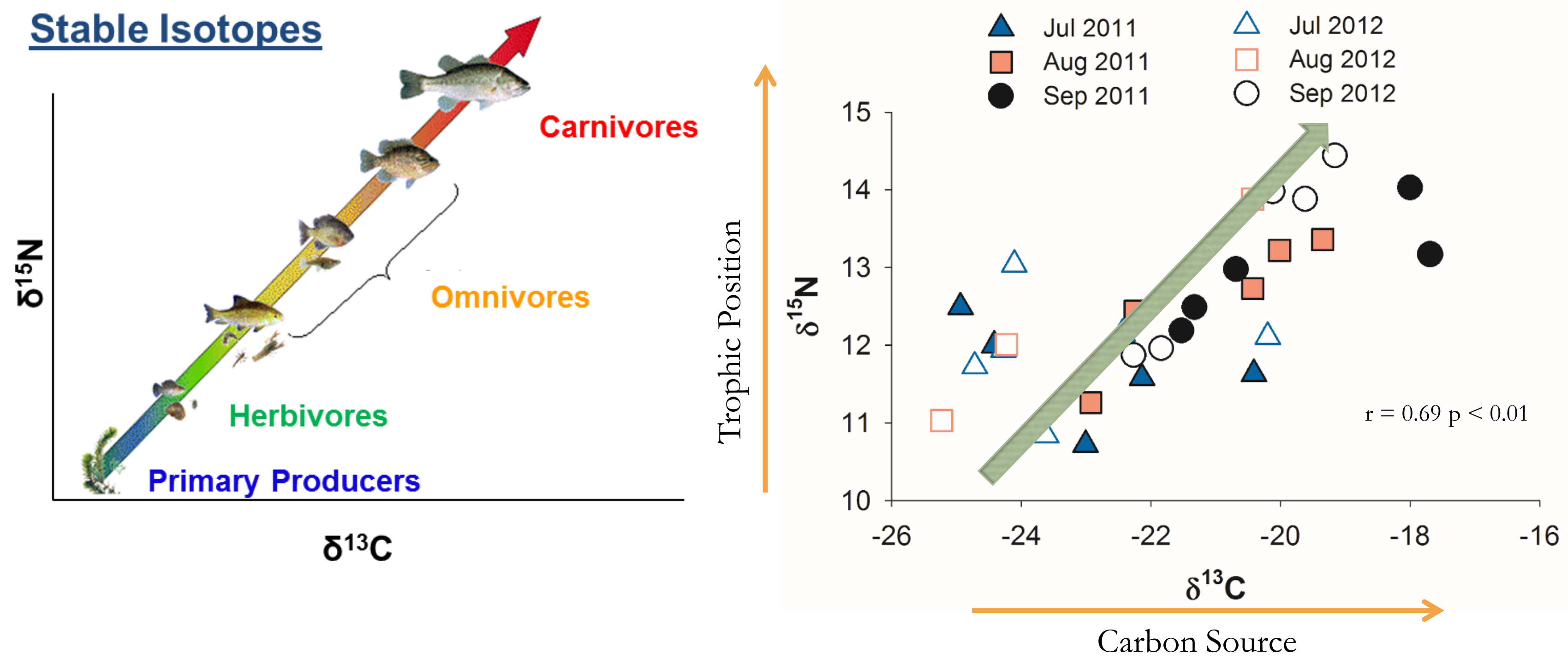
Ontogenetic shift in diet upon ocean entry



Larger size or faster growth may have an advantage: “bigger-is-better” and “growth-mortality” hypotheses

Anderson 1988; Miller et al. 1988; Brodeur et al. 1991; Litz et al. 2017

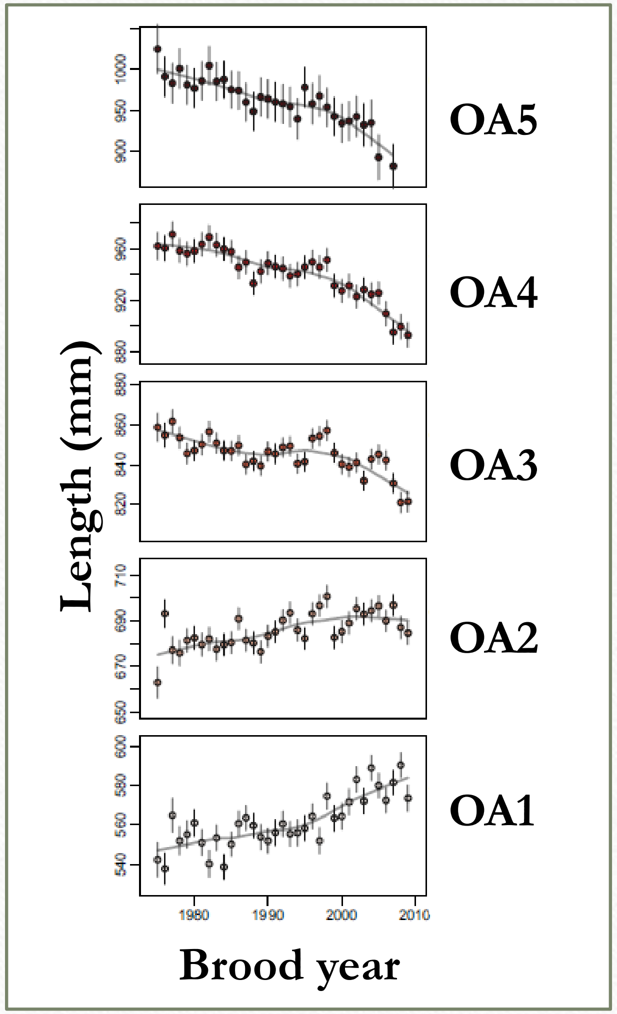
Both δ¹³C and δ¹⁵N *increase* through time as salmon begin feeding more heavily on forage fish



Litz et al. 2017

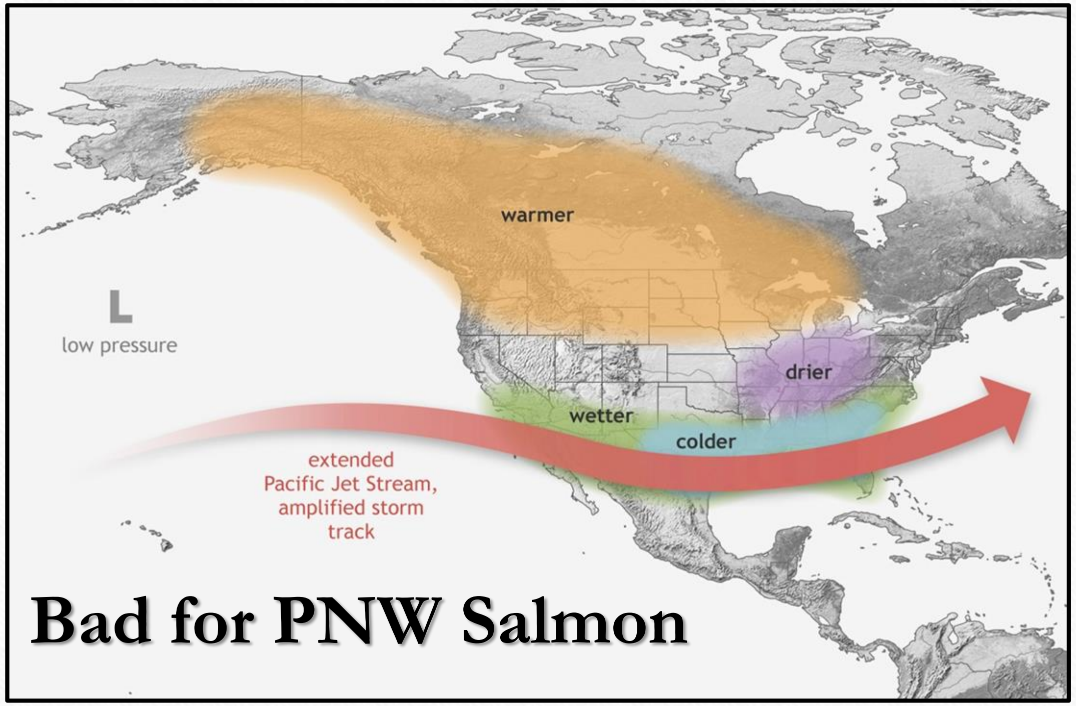
Chinook salmon size-at-age is changing along the west coast

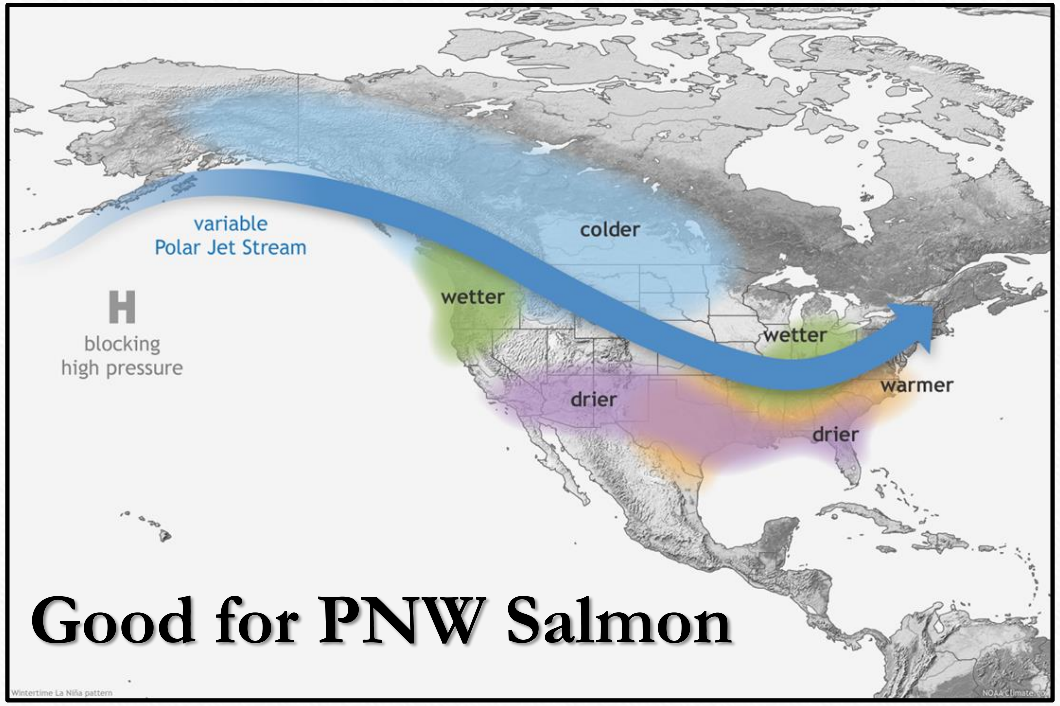
- Size-selective harvest
- Environmental changes that affect growth and mortality
- Hatchery practices – density dependent effects
- Increased competition
- Predation by marine mammals



Ohlberger et al. 2018

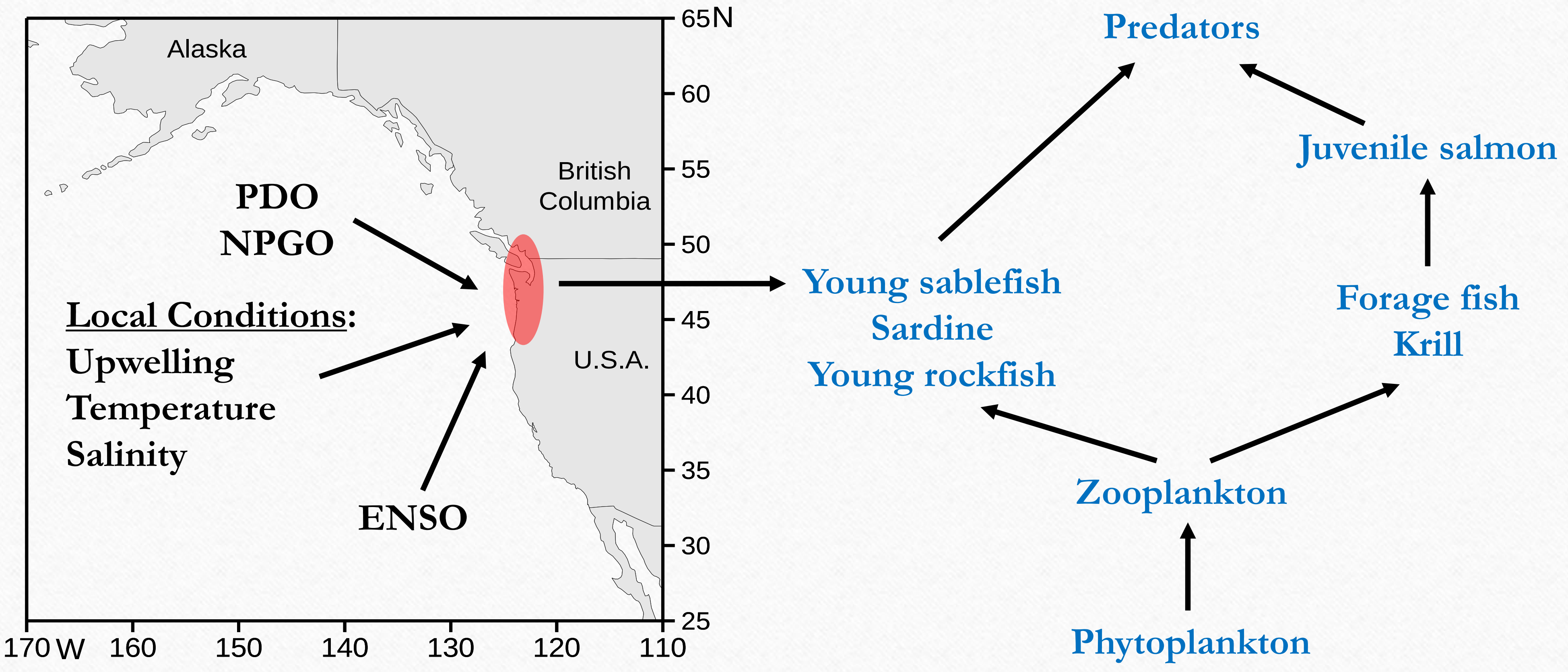
Typical El Niño and La Niña patterns





www.climate.gov

Variations in salmon marine survival correlates with variations in ocean conditions



Peterson et al. 2014

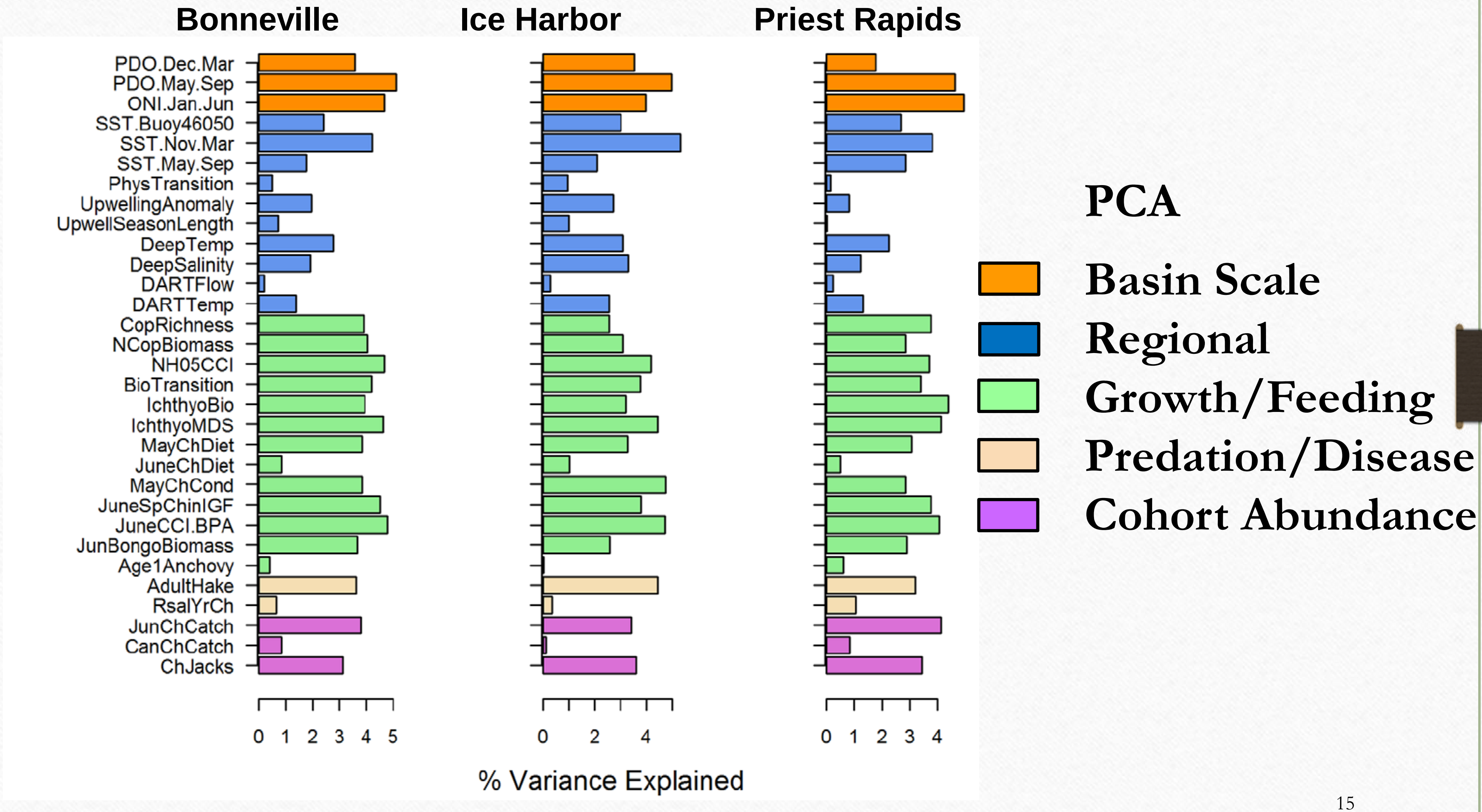
Salmon Indicators 1998 - 2017: Bad → Good

		Year																			
	Ecosystem Indicators	*1998*	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*
Basin-scale physical indices	PDO (Sum Dec-March)	17	6	3	12	7	19	11	15	13	9	5	1	14	4	2	8	10	20	18	16
	PDO (Sum May-Sept)	10	4	6	5	11	16	15	17	12	13	2	9	7	3	1	8	18	20	19	14
	ONI (Average Jan-June)	19	1	1	6	13	15	14	16	8	11	3	10	17	4	5	7	9	18	20	12
Regional physical indices	46050 SST (°C; May-Sept)	16	9	3	4	1	8	20	15	5	17	2	10	7	11	12	13	14	19	18	6
	Upper 20 m T (°C; Nov-Mar)	19	11	8	10	6	14	15	12	13	5	1	9	16	4	3	7	2	20	18	17
	Upper 20 m T (°C; May-Sept)	16	12	14	4	1	3	20	18	7	8	2	5	13	10	6	17	19	9	15	11
	Deep temperature (°C; May-Sept)	20	6	8	4	1	10	12	16	11	5	2	7	14	9	3	15	19	18	13	17
	Deep salinity (May-Sept)	19	3	9	4	5	16	17	10	7	1	2	14	18	13	12	11	20	15	8	6
Regional biological indices	Copepod richness anom. (no. species; May-Sept)	18	2	1	7	6	13	12	17	15	10	8	9	16	4	5	3	11	19	20	14
	N. copepod biomass anom. (mg C m^{-3}; May-Sept)	18	13	9	10	3	15	12	19	14	11	6	8	7	1	2	4	5	16	20	17
	S. copepod biomass anom. (mg C m^{-3}; May-Sept)	20	2	5	4	3	13	14	19	12	10	1	7	15	9	8	6	11	17	18	16
	Biological transition (day of year)	17	8	5	7	9	14	13	18	12	2	1	3	15	6	10	4	11	20	20	16
	Ichthyoplankton biomass (log (mg C 1000 m^{-3}); Jan-Mar)	20	11	3	7	9	18	17	13	16	15	2	12	4	14	10	8	19	5	6	1
	Ichthyoplankton community index (PCO axis 1 scores; Jan-Mar)	9	13	1	6	4	10	18	16	3	12	2	14	15	11	5	7	8	17	20	19
	Chinook salmon juvenile catches (no. km^{-1}; June)	18	4	5	15	8	12	16	19	11	9	1	6	7	14	3	2	10	13	17	20
	Coho salmon juvenile catches (no. km^{-1}; June)	18	7	12	5	6	2	15	19	16	4	3	9	10	14	17	1	11	8	13	20
	Mean of ranks	17.1	7.0	5.8	6.9	5.8	12.4	15.1	16.2	10.9	8.9	2.7	8.3	12.2	8.2	6.5	7.6	12.3	15.9	16.4	13.9
	Rank of the mean rank	20	6	2	5	2	14	16	18	11	10	1	9	12	8	4	7	13	17	19	15

1998 = Worst Score

2008 = Best Score

Survival associated with physical and biological indicators

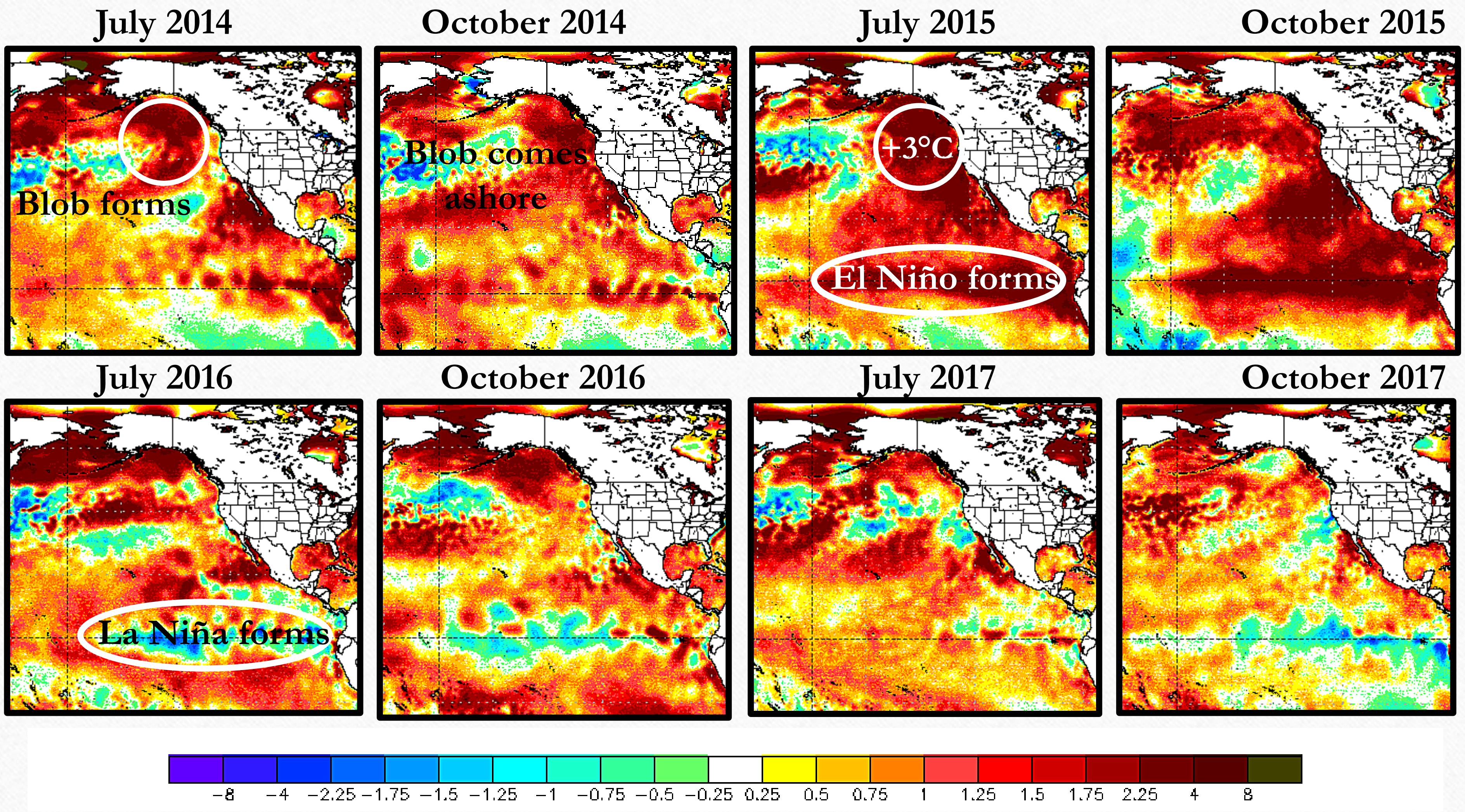


Burke et al. 2013

Puget Sound Indicators

- NOAA IEA Salmon Indicators
- Puget Sound Partnership
- Long Live The Kings Salish Sea Marine Survival Project

THE BLOB



Bond et al. 2015

Biological Responses to the Warm Ocean

2015

Harmful algal blooms shut down crab and clam fisheries CA – AK

Reductions in zooplankton and changes to jellyfish community

Tropical fish caught in the PNW

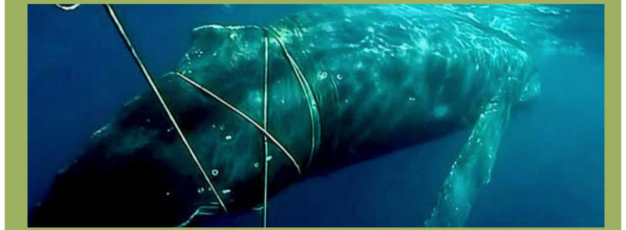
Whales feeding in estuaries

2016

Pelagic red crabs wash ashore

Food web changes continue

Anchovy increase in Salish Sea



Whales nearshore; entangled in fishing lines

2017

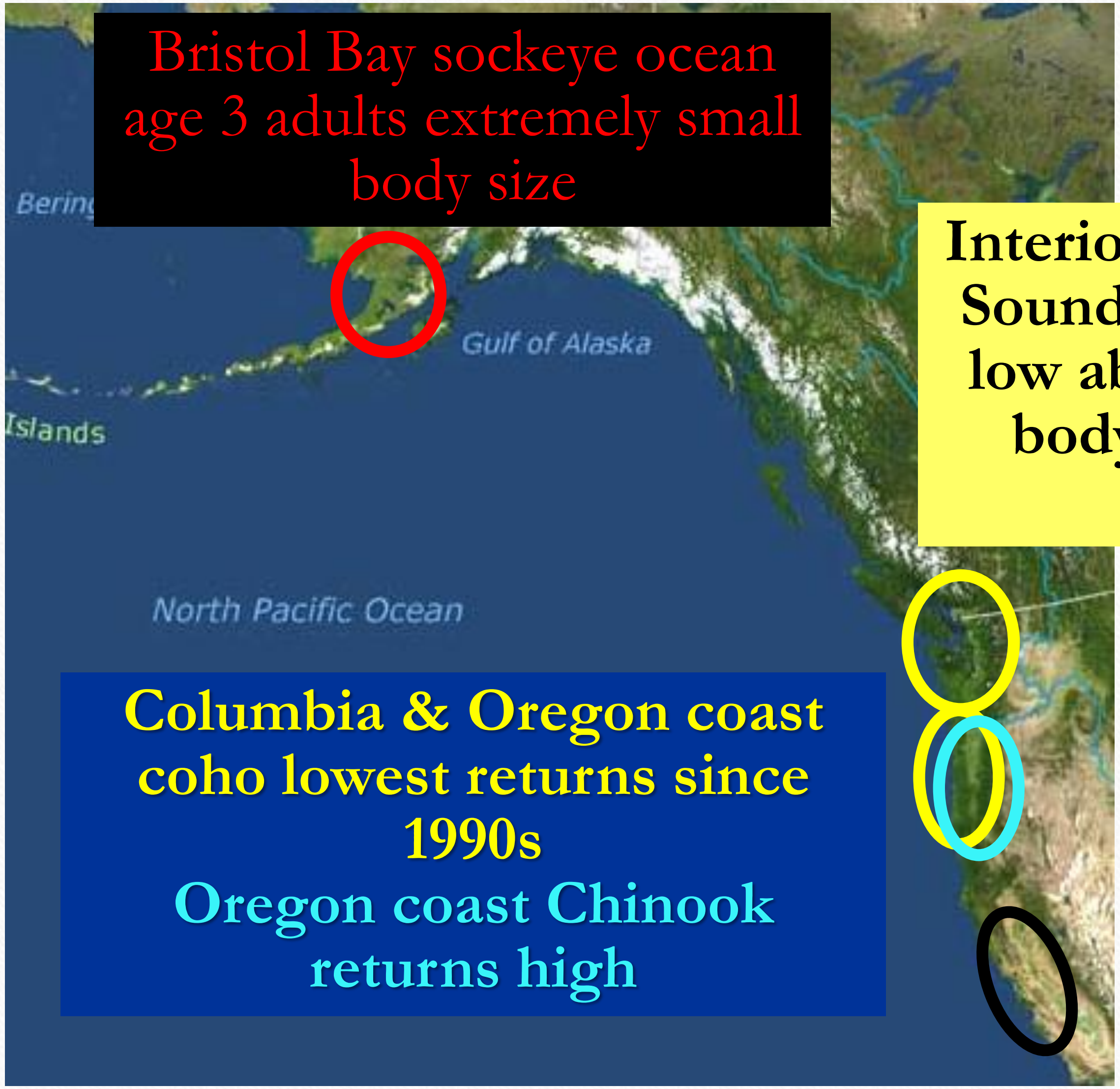
Pyrosomes explode in N Pacific

Sea bird die offs in Bering Sea

Pacific cod collapse in Gulf of AK

Sea lion abundance increasing in PNW

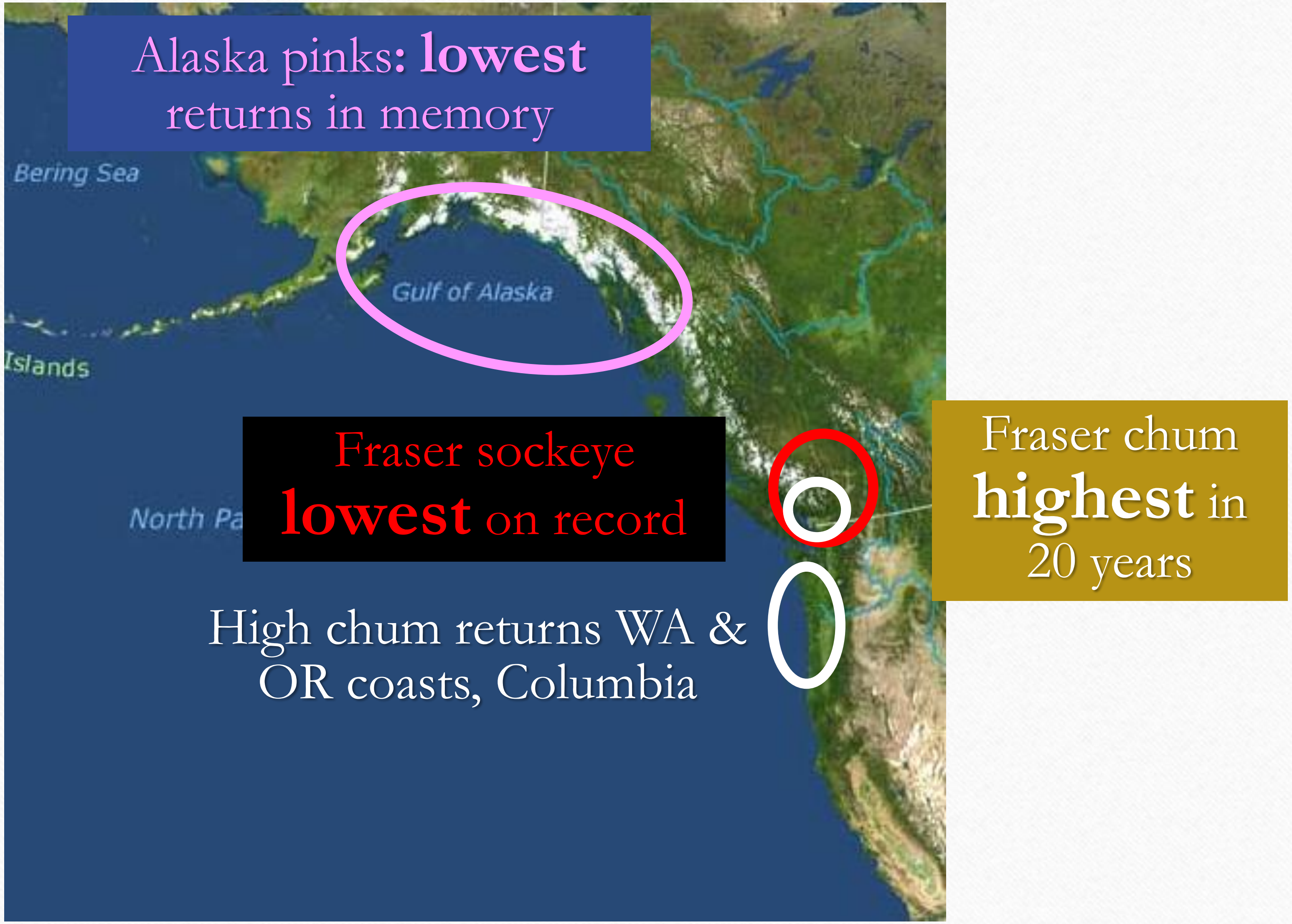
Unusual salmon observations in **2015**



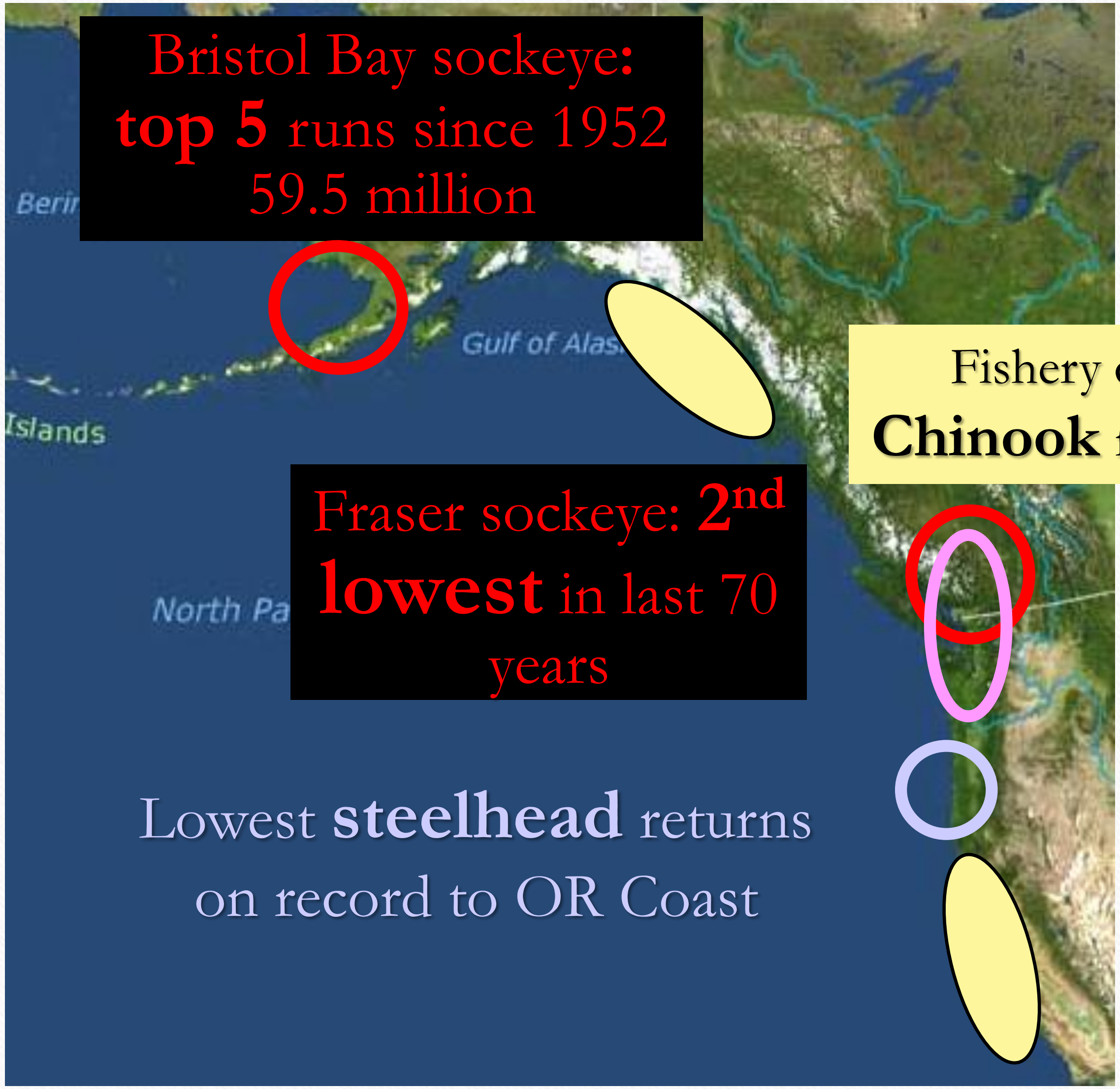
Interior Fraser & Puget Sound coho extremely low abundance, small body size, and low fecundity

Extremely low downstream survival Central Valley Chinook & steelhead (drought)

Unusual salmon observations in **2016**



Unusual salmon observations in **2017**

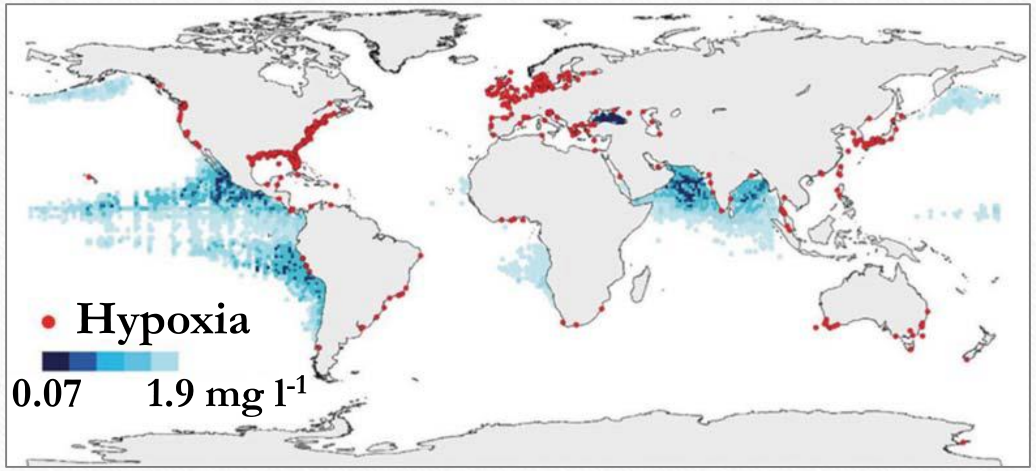


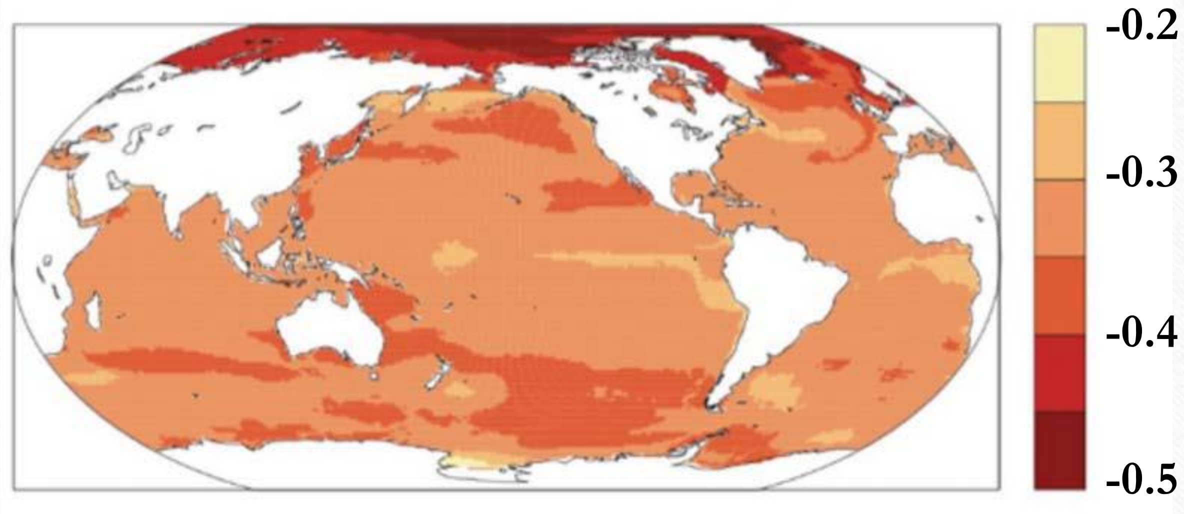
Highest **chum** harvest ever in Alaska

Fishery closures for **Chinook** from CA to BC

Fraser and PS **pinks**: lowest run in decades

Impacts of climate change on fisheries and aquaculture





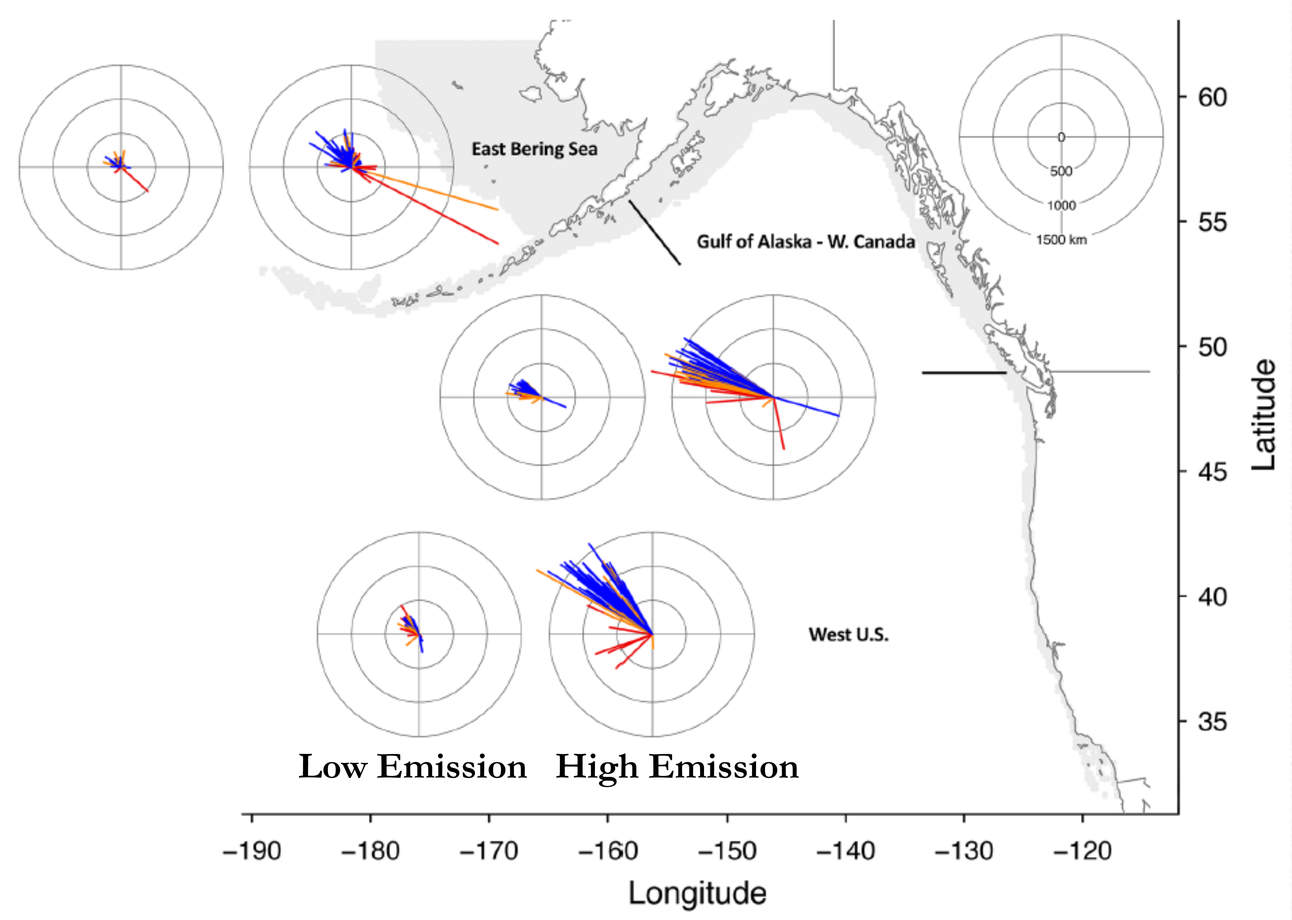
Coastal sites where nutrients have caused O_2 declines <2 mg l^{-1}

Median change in surface pH from 1850 – 2100 = 0.2-0.3

FAO Technical Paper 2018

Species on the west coast have highest projected magnitude shift in distribution: >1000 km

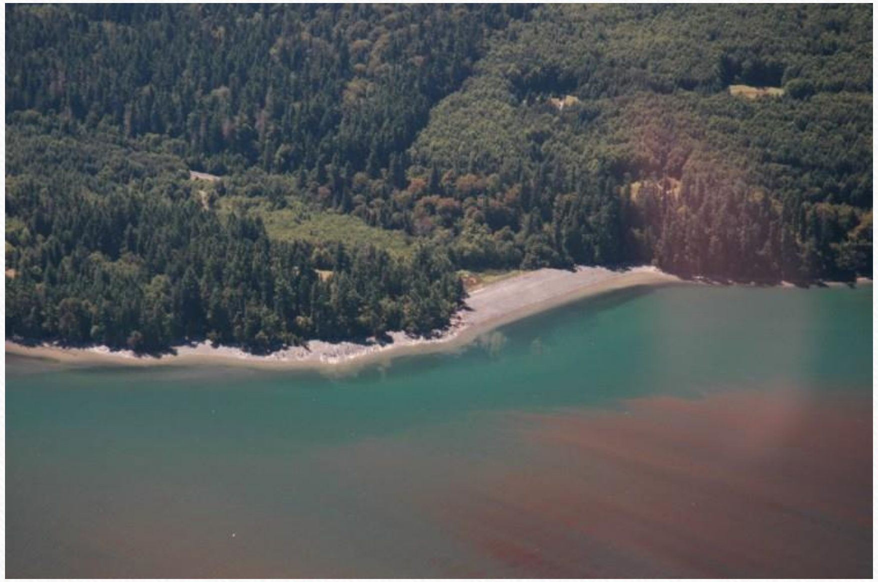
- Extreme events more frequent
- Warming waters
- Ocean acidification
- Low dissolved oxygen
- Spatial and temporal shifts



Holsman et al. 2018; Morley et al. 2018

Impacts of ocean acidification on marine fish

- Increased fish-killing harmful algae
- Direct effects:
  - -behavioral disruption
  - -increased boldness?
- Indirect effects:
  - -shell-forming zooplankton
  - -fecundity



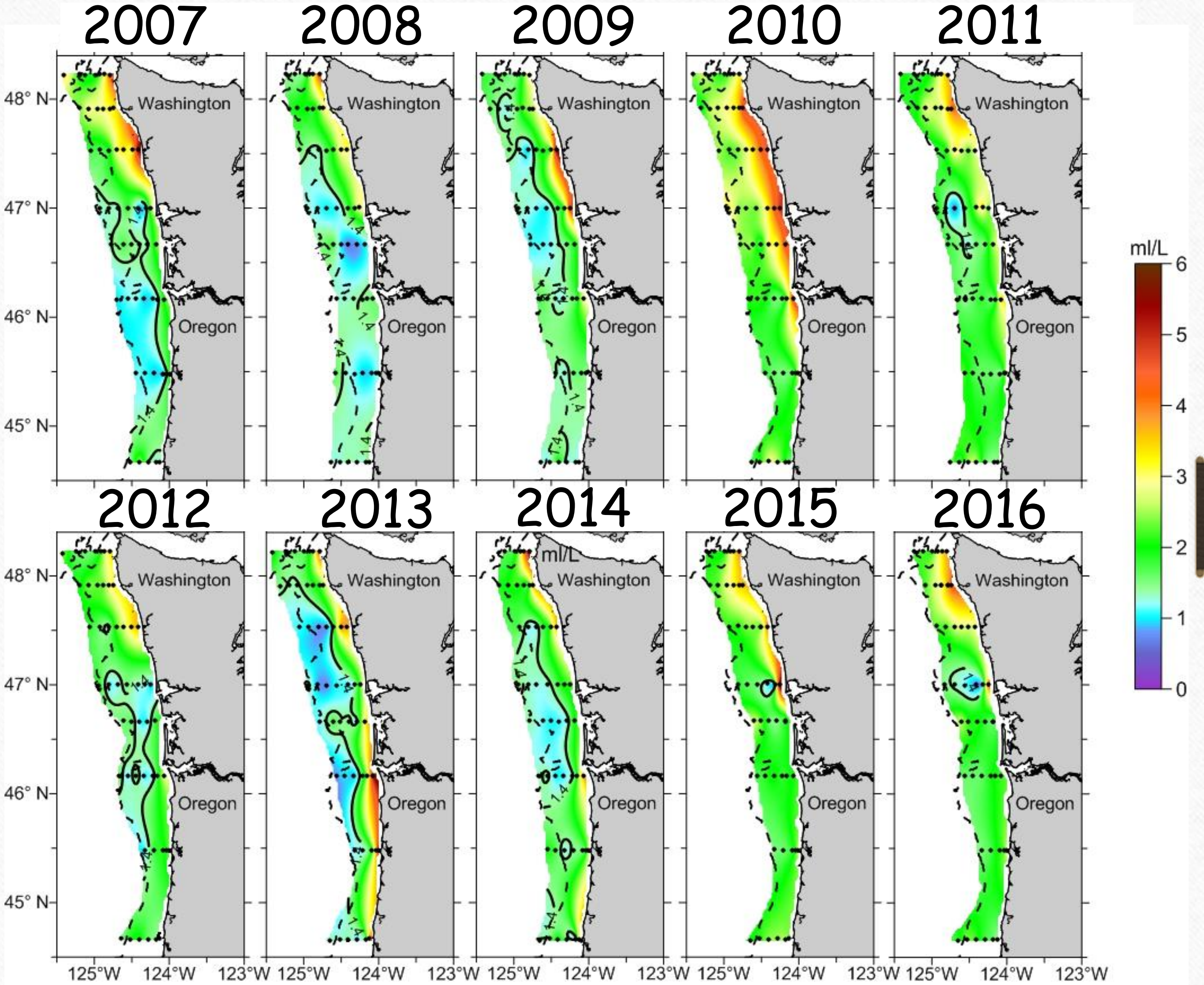
Heterosigma akashiwo bloom in northern Puget Sound (Photo: V. Trainer)

Rensel 2007; Hurst et al. 2013; Feely et al. 2016

June 2007 – 2016 Minimum Oxygen

Low DO (<1.4 ml l^{-1}) related to climate events

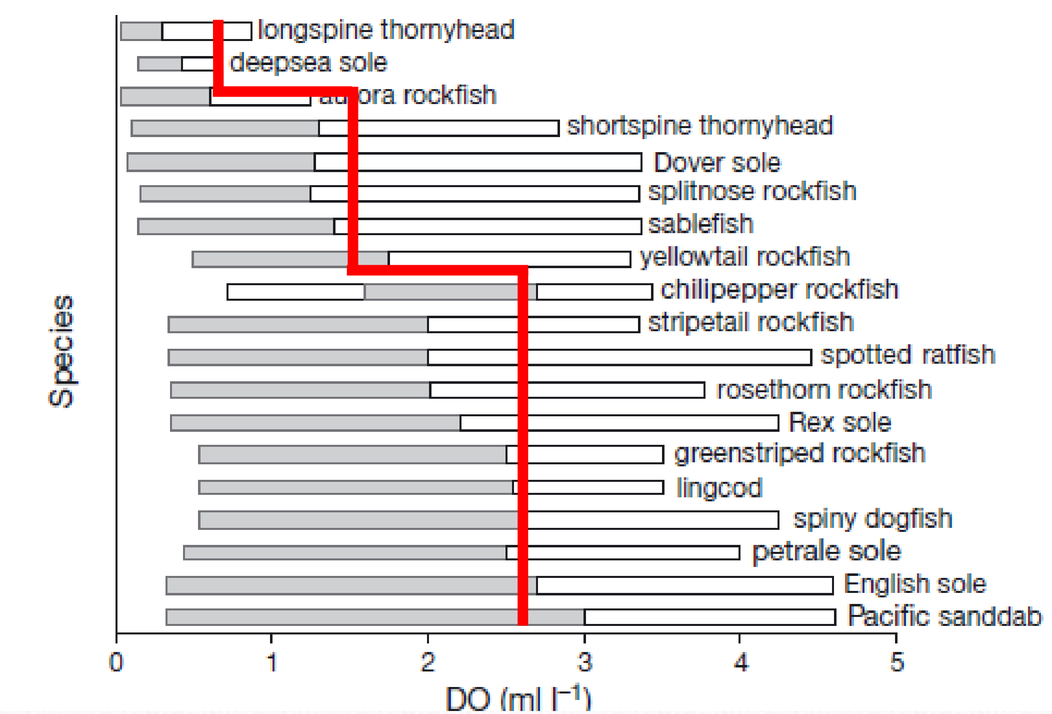
Decreased solubility + increased stratification = reduced subsurface ventilation



C. Morgan, OSU

Restricted range of common demersal fish

- Synergistic effects from changes in temperature, ocean acidification and reduced DO
- Flatfishes, roundfishes, and shelf rockfishes will move away from areas with severe hypoxia



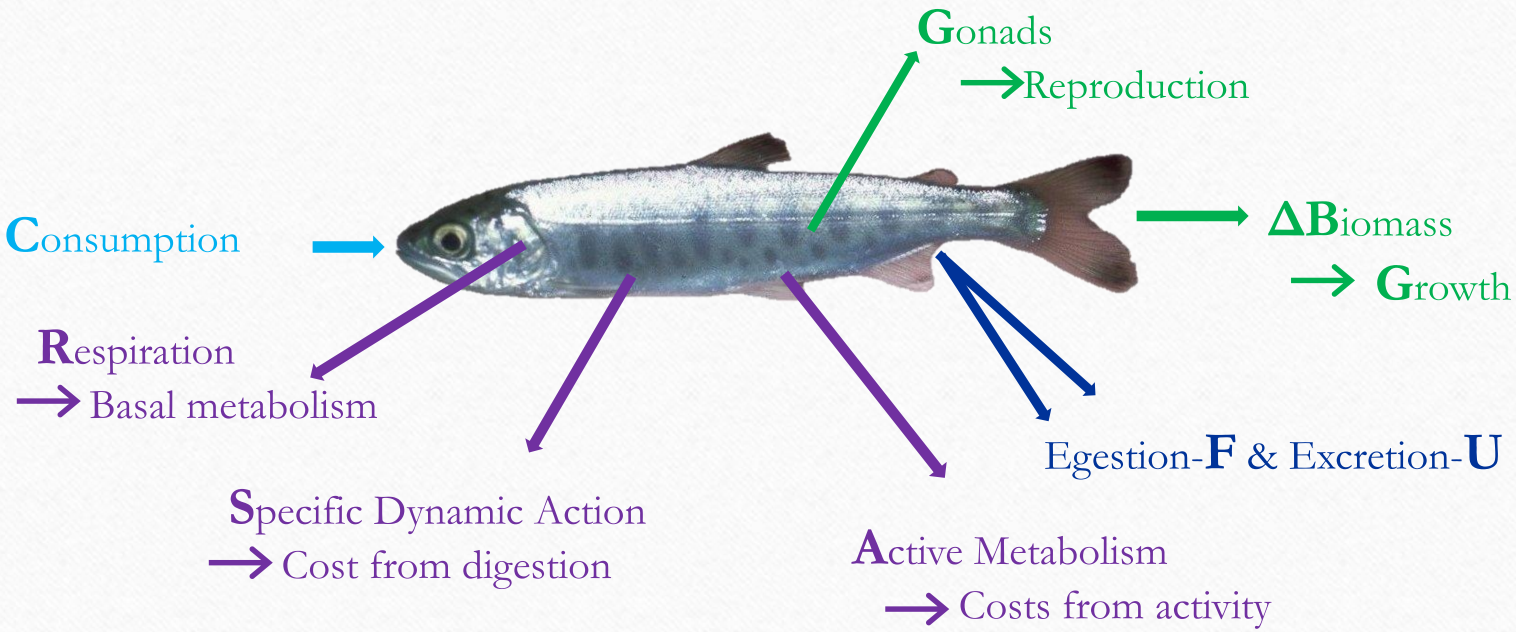
Keller et al. 2017

Impacts of declining DO on marine fish

- Increased mortality
- Physiological impairment
- Displacement out of hypoxic waters
- Habitat compression
- Altered predator-prey relationships
- Changes in foraging dynamics

Keller et al. 2017

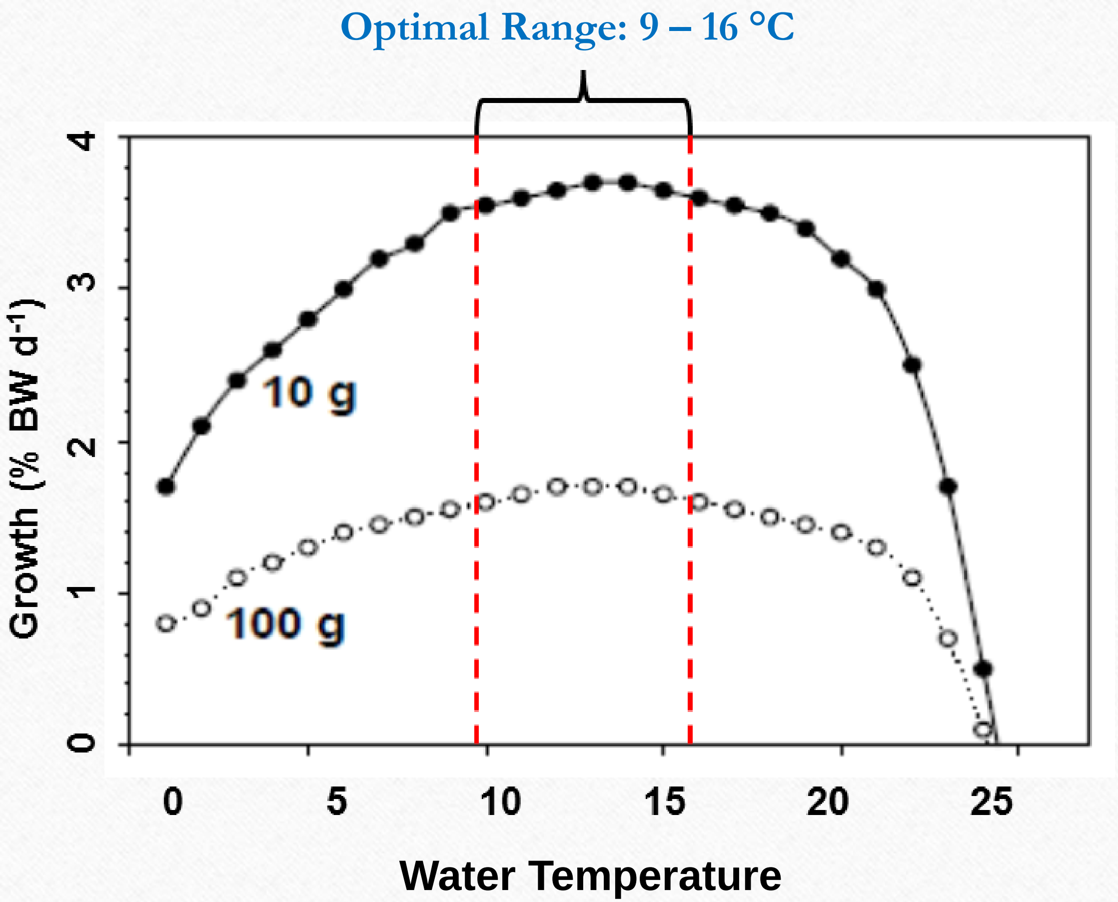
Bioenergetics Model:



$$C = (R + A + S) + (F + U) + (\Delta B)$$

Optimal DO and temperature range for salmon growth

Level of Effect	DO (mg l^{-1})
None	8
Slight	6
Moderate	5
Severe	4
Acute	3



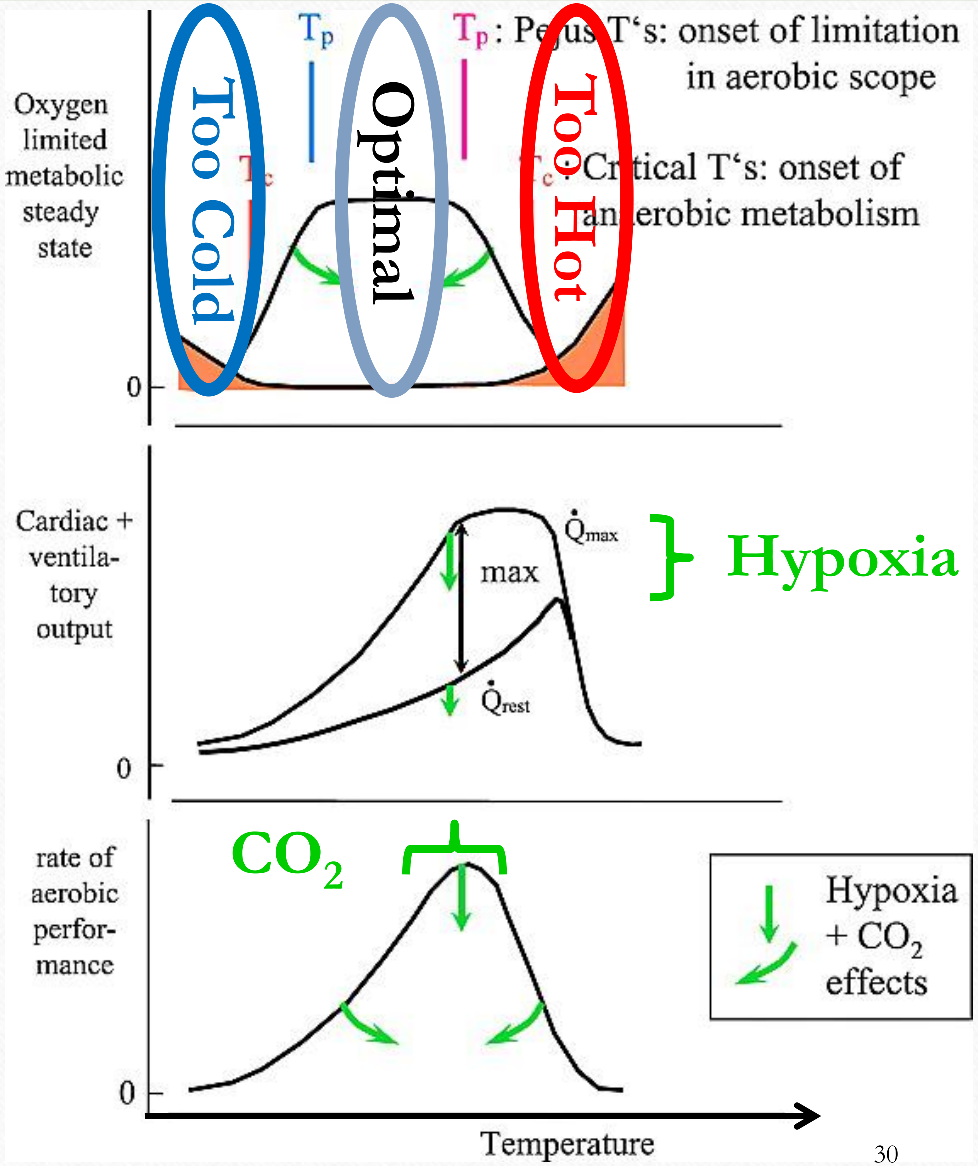
Carter 2005; Beauchamp 2009

Physiological Studies

- Preferred range: 12 - 15° C
- Physiological Stress: >16 – 18° C
- Lethal Temperature : >21 - 28° C

Enhanced CO_2 and Hypoxia

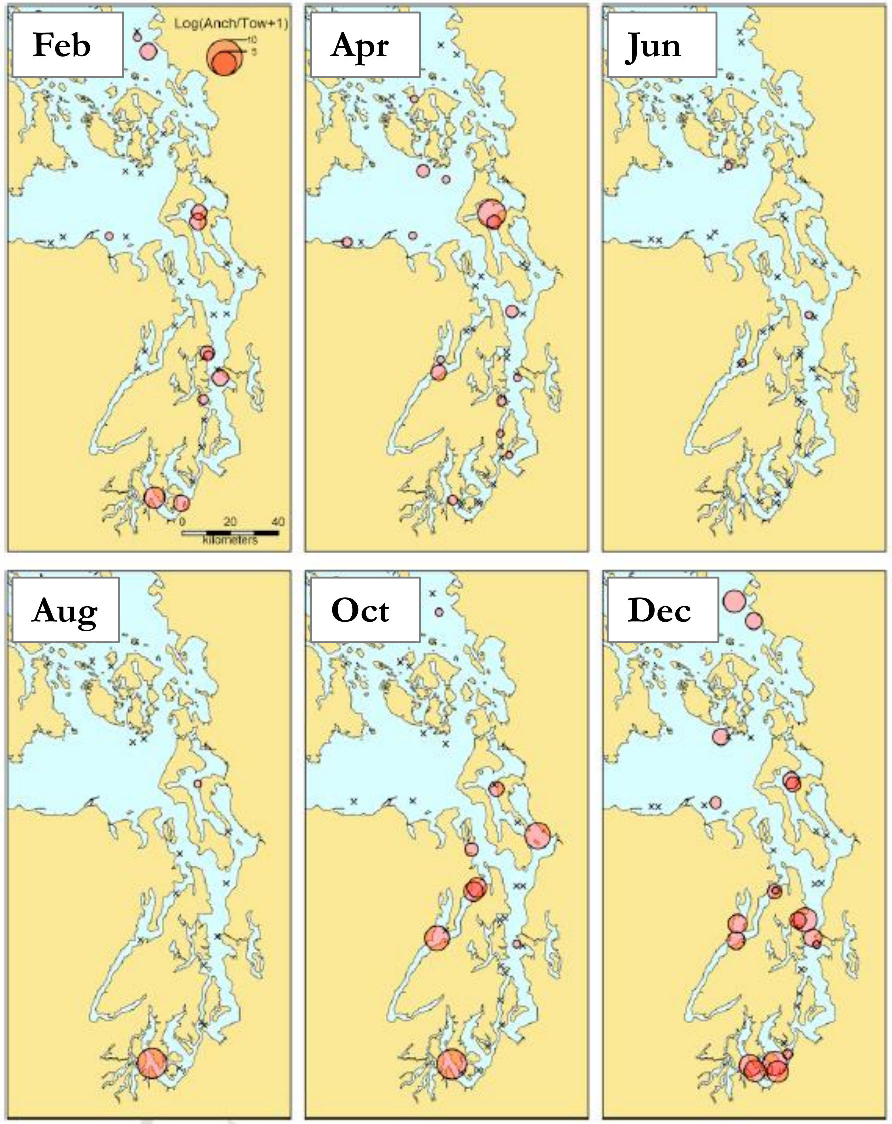
- Thermal tolerance is narrowed
- Metabolic scope reduced



Pörtner et al. 2005

Increased anchovy abundance in Puget Sound 2014-2016

- Surveys conducted by WDFW in 2016
- Anchovy present in all major basins
- Largest catches in South Sound in Oct/Dec
- Larval/post-larval catches in Skagit Bay
- Benefits resident salmon



Duguid et al. 2018

Reports of mass die-offs:

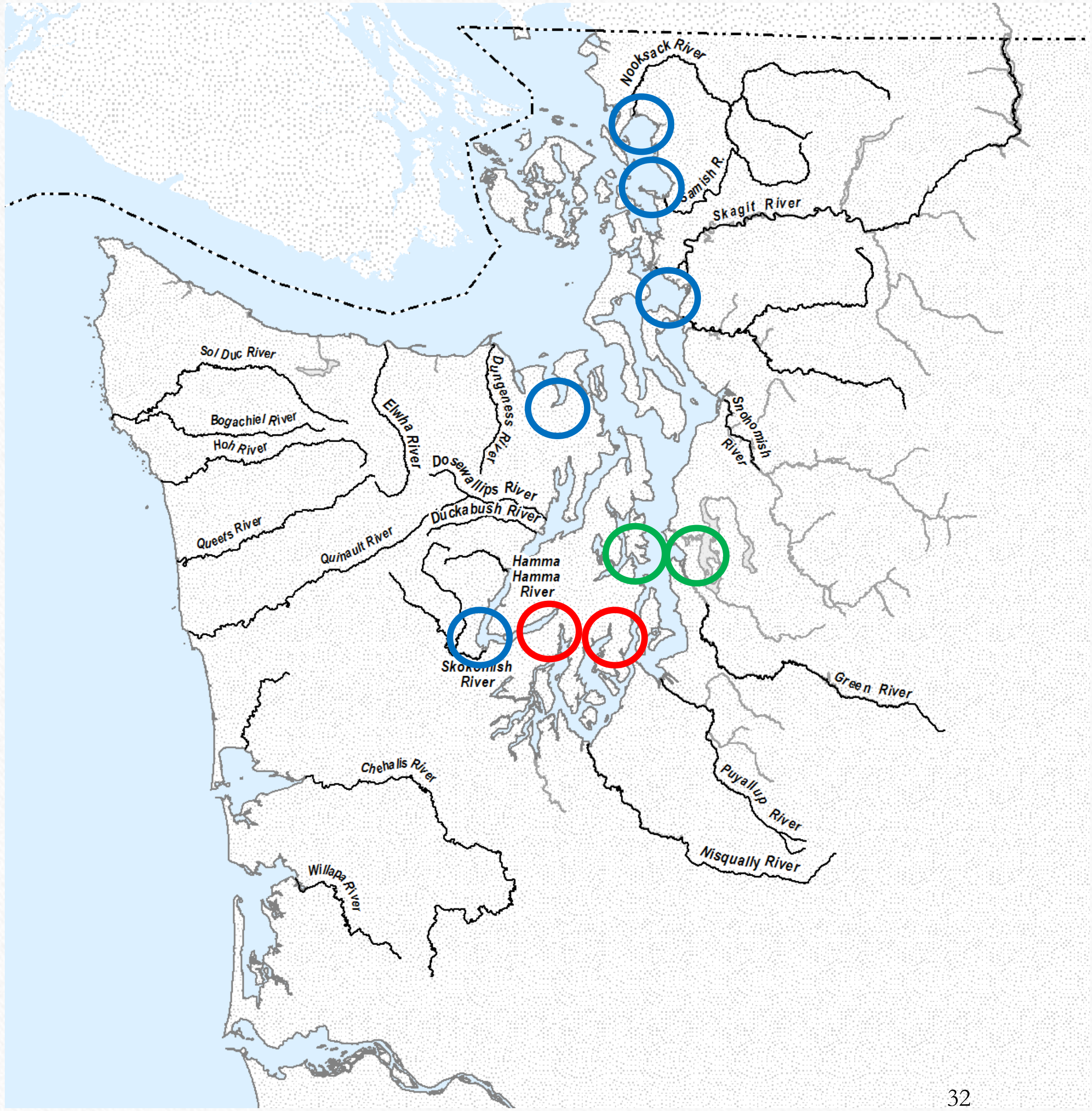
South Sound:

- Case Inlet
- Carr Inlet

Central Sound:

- Elliott Bay
- Eagle Harbor

- Southern Hood Canal
- Whidbey Basin
- Padilla Bay
- Discovery Bay
- Bellingham Bay



D. Lowry, WDFW

Causes of mass die-offs

Warm water and/or low DO

Shallow bays

Summer

Large tidal exchanges

No indication of Viral Hemorrhagic Septicemia (VHS)

Herding behavior by marine mammals

Summary

- Puget Sound is part of the larger Salish Sea and impacted by physical and biological interactions occurring at larger scales
- Reduced DO must be considered along with synergistic effects of increased temperature and ocean acidification
- Climate change impacts impacting the physiology (aerobic capacity, metabolism, etc.) and behavior of marine fish will also affect phenology (timing), spatial range, and ecological interactions (predator-prey interactions)
- Require better understanding of capacity for species to adapt

Acknowledgements

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