Mechanisms and trends in ocean transport of nutrients and low DO water to the Salish Sea and Puget Sound

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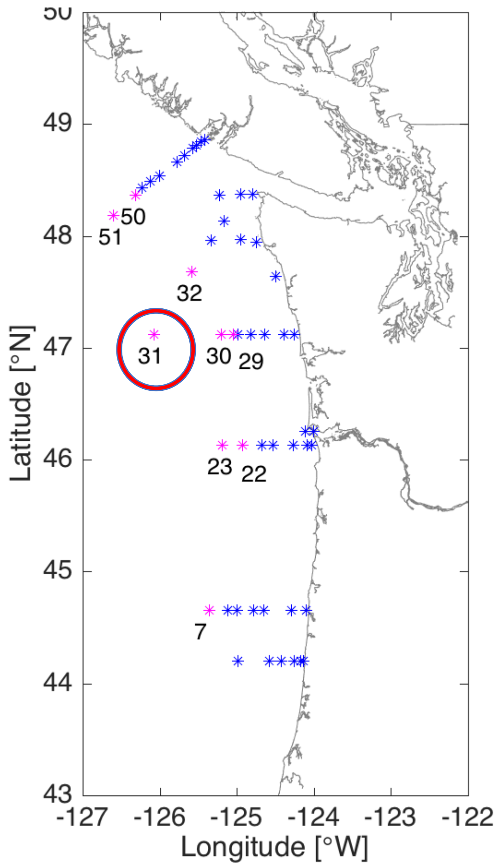
Motivation:
Why focus on mouth of Juan de Fuca?

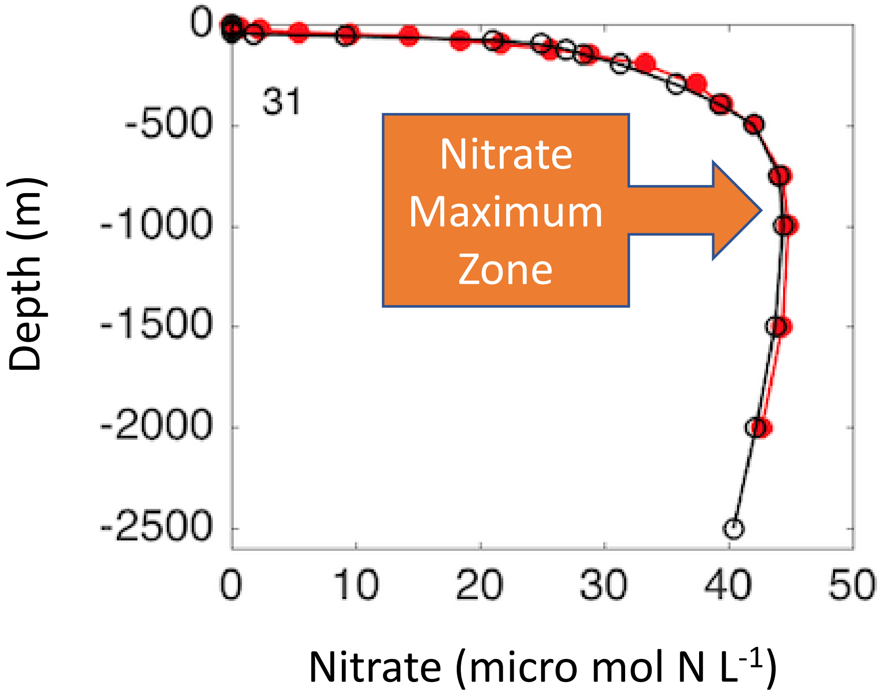
- The deep, inflowing branch of the estuarine exchange flow in the Strait of Juan de Fuca delivers 95% of the total Nitrate coming into the Salish Sea
- Mackas and Harrison (1997 ECSS)
  - Ocean source: 2,600,000 kg/d
- Mohamedali et al. (2011 Ecology Report)
  - WWTPs: 70,000 kg/d
  - Rivers: 30,000-100,000 kg/d
  - PS Rivers peak N loading in winter
  - Fraser peak N loading in summer

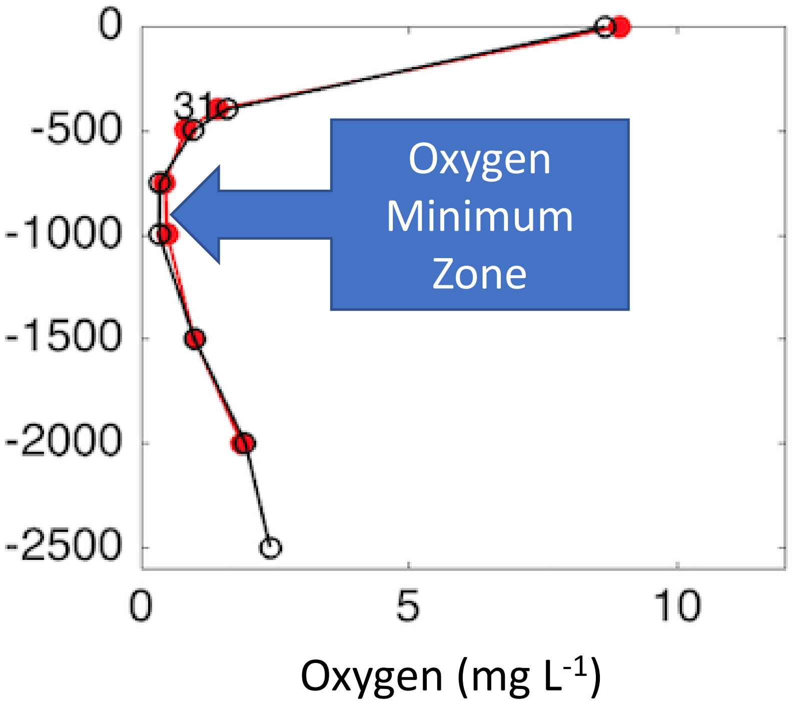
Other Main Points

- The exchange flow is strongest in the summer, and often reverses in the winter.
- During upwelling winds the source waters of the JdF inflow are from as deep as 300 m, below the shelf break, and come through the Juan de Fuca Canyon which cuts across the shelf.
- The inflow also has low DO, nearly hypoxic in the summer.
- The DO of the source water has declined by 20% over the past 40 years.

There is a lot of High-Nitrate, Nearly-Anoxic water offshore below the shelf break (NOAA Casts 2016)





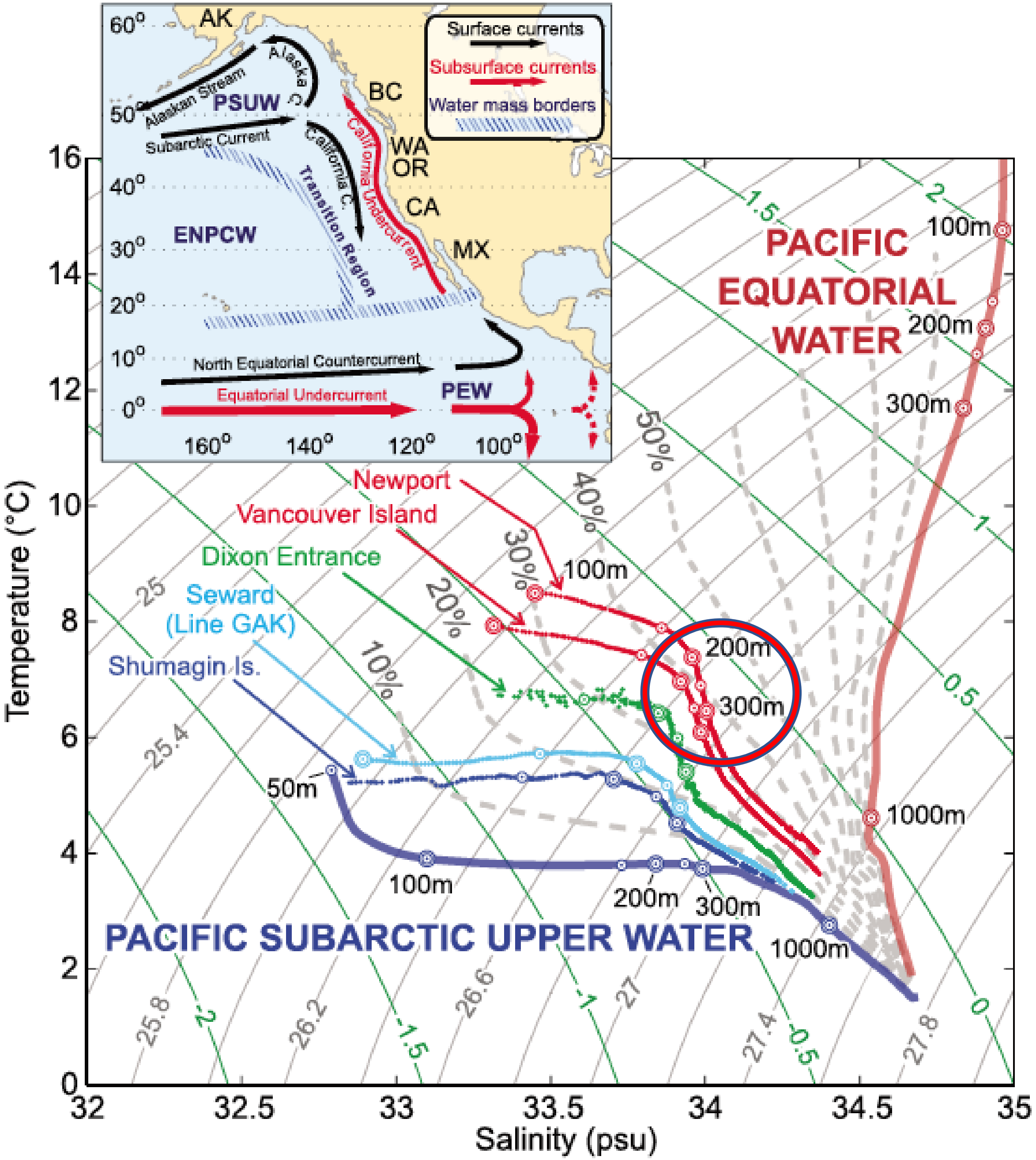


Hypoxia = 2 (mg L^{-1})

Reflects the accumulated remineralization of organic matter

This water is a 40:60 mixture of Pacific Equatorial Water coming north in the California Undercurrent, and Pacific Subarctic Upper Water from the NW Pacific

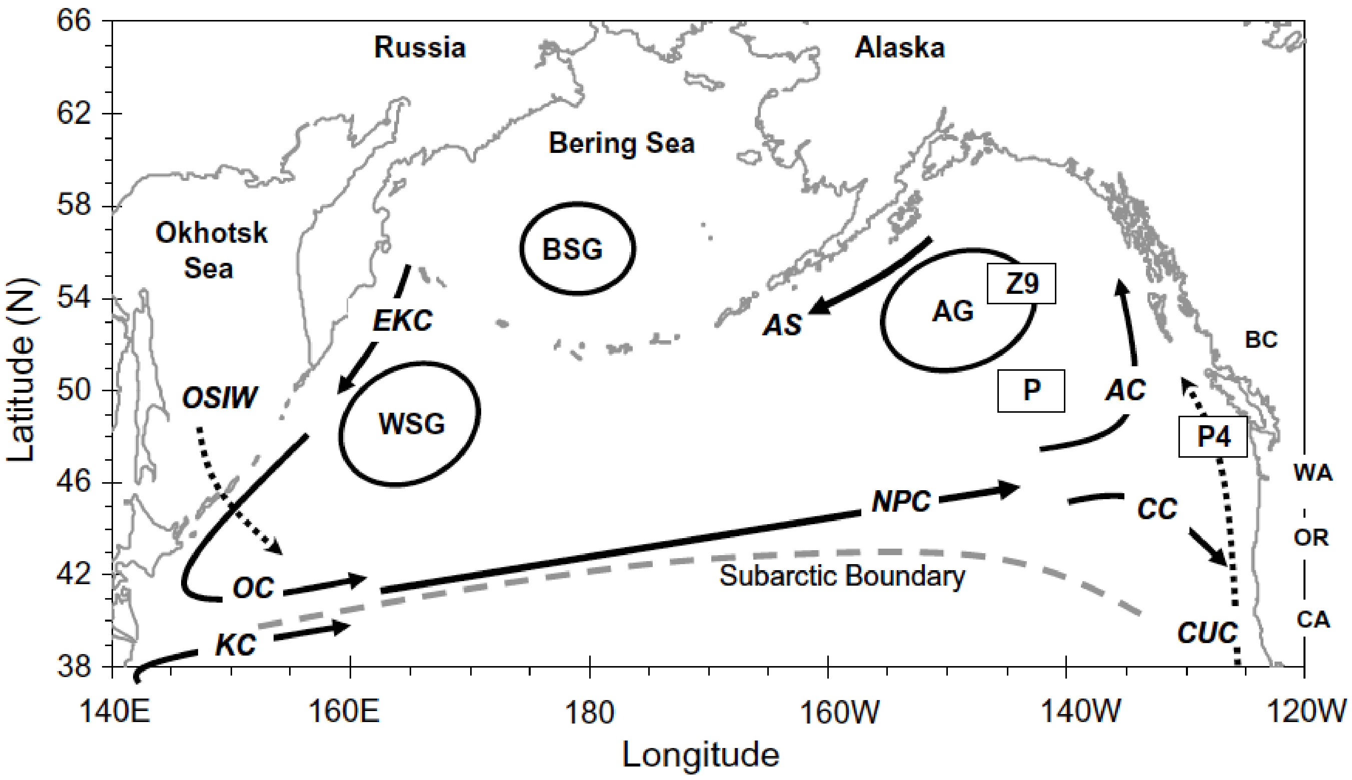
Thomson & Krassovski (2010 JGR)
Poleward reach of the California Undercurrent extension



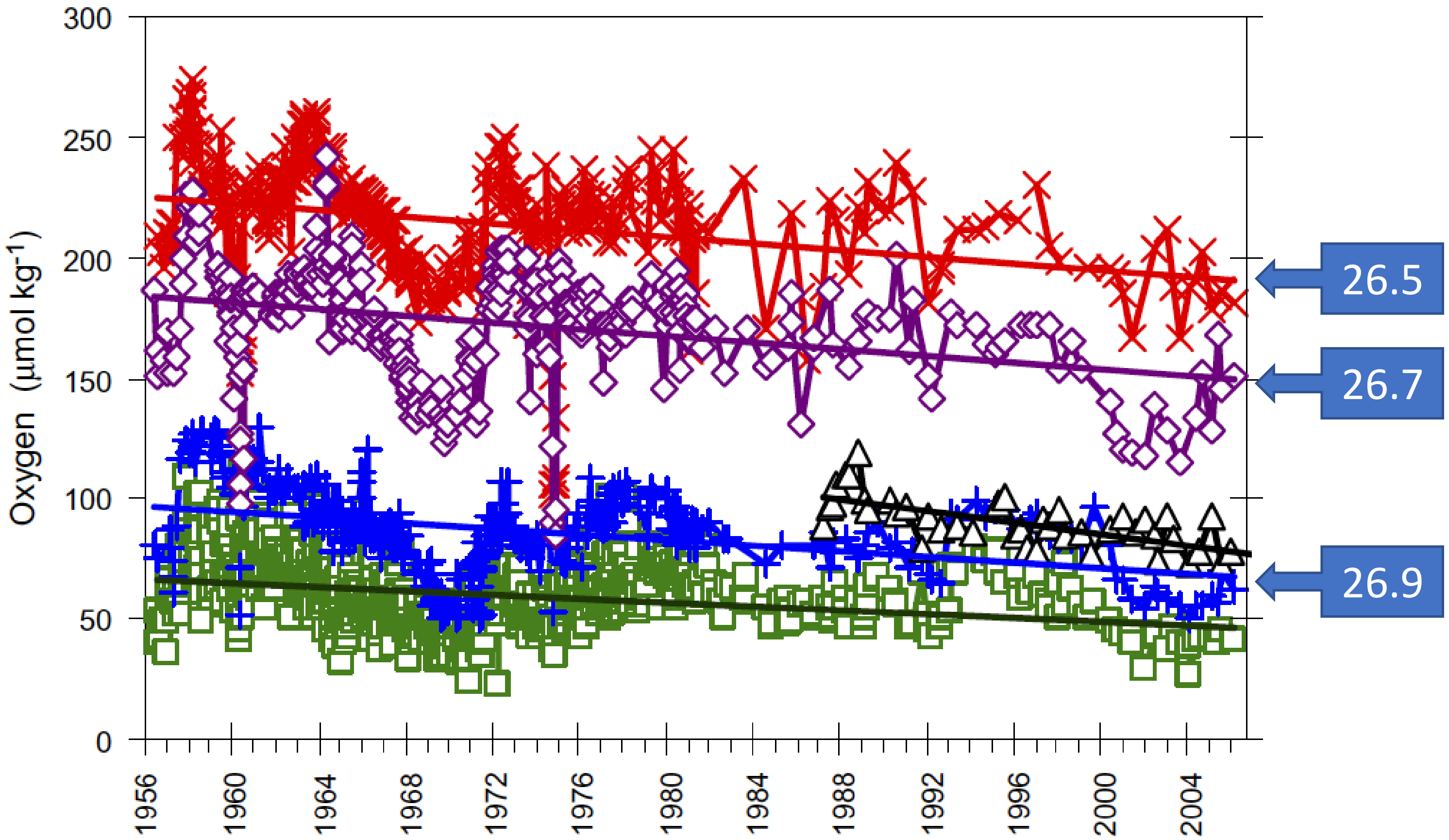
Source of the Pacific Subarctic Upper Water (PSUW)

Whitney et al. (2007, Progress in Oceanography) Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific

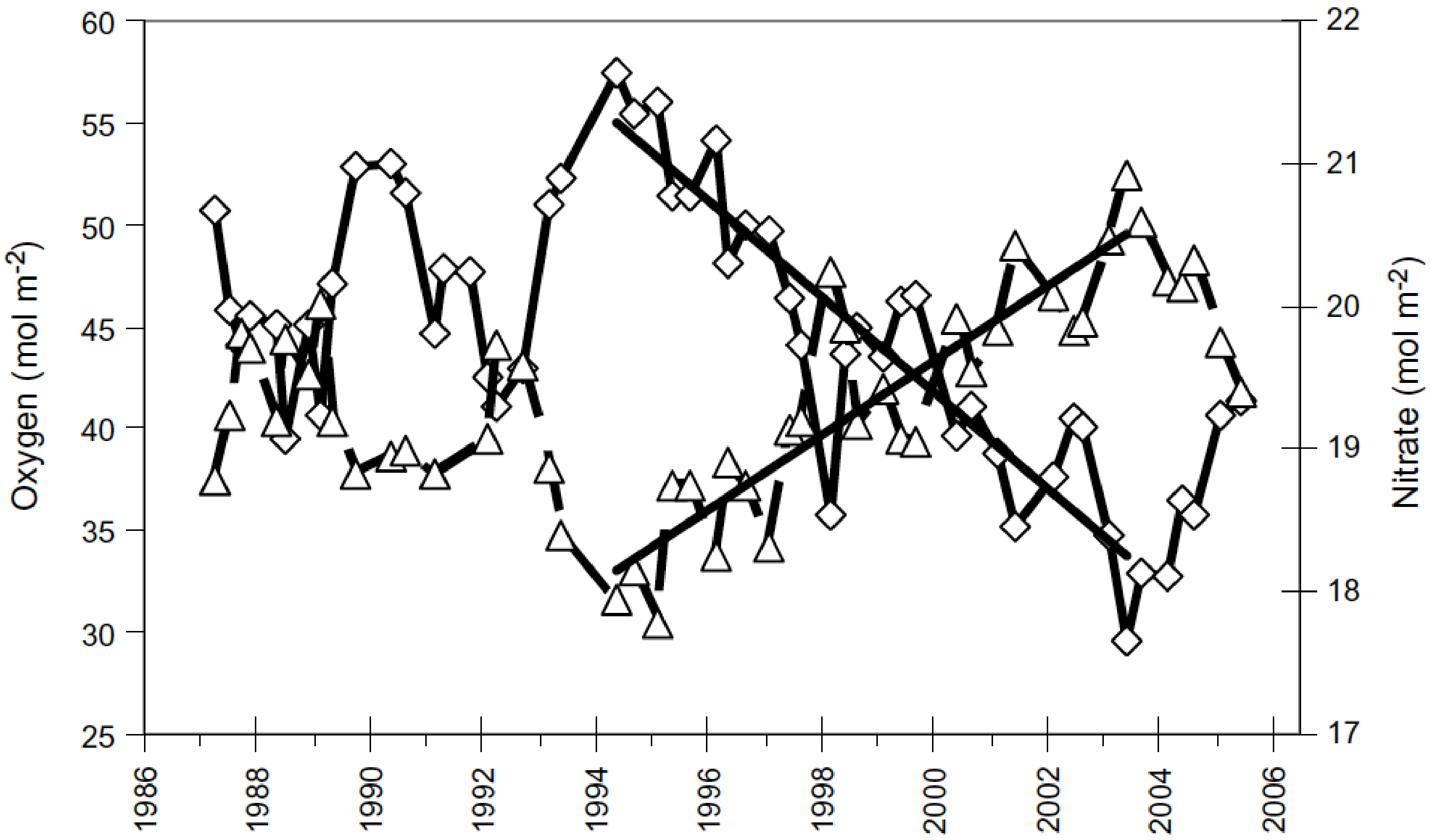
- Increased stratification in the western subarctic gyre decreases ventilation of the PSUW
- PSUW takes about 7 years to cross the Pacific
- If it goes slower it loses more oxygen



Whitney et al. (2007) Oxygen trends over 50 years at Ocean Station Papa



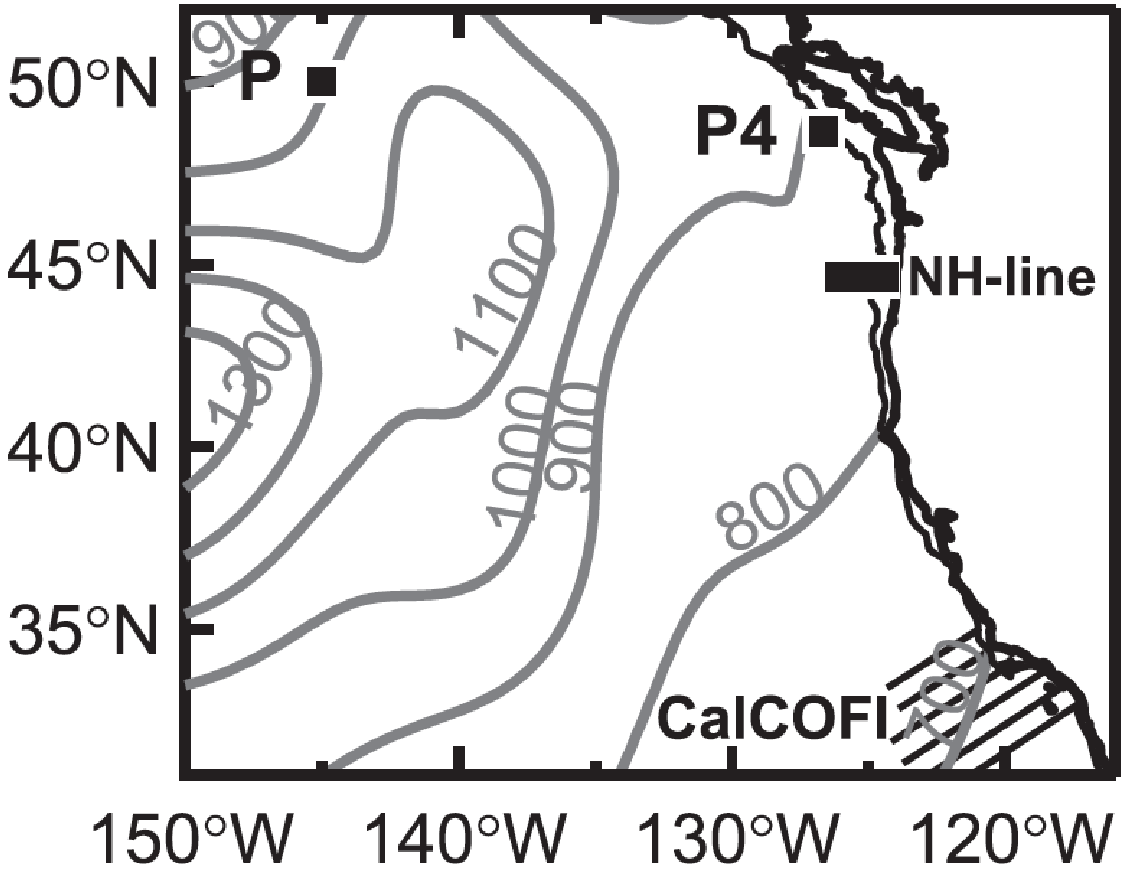
Whitney et al. (2007) DO and Nitrate integrated over 100–600 m at OSP

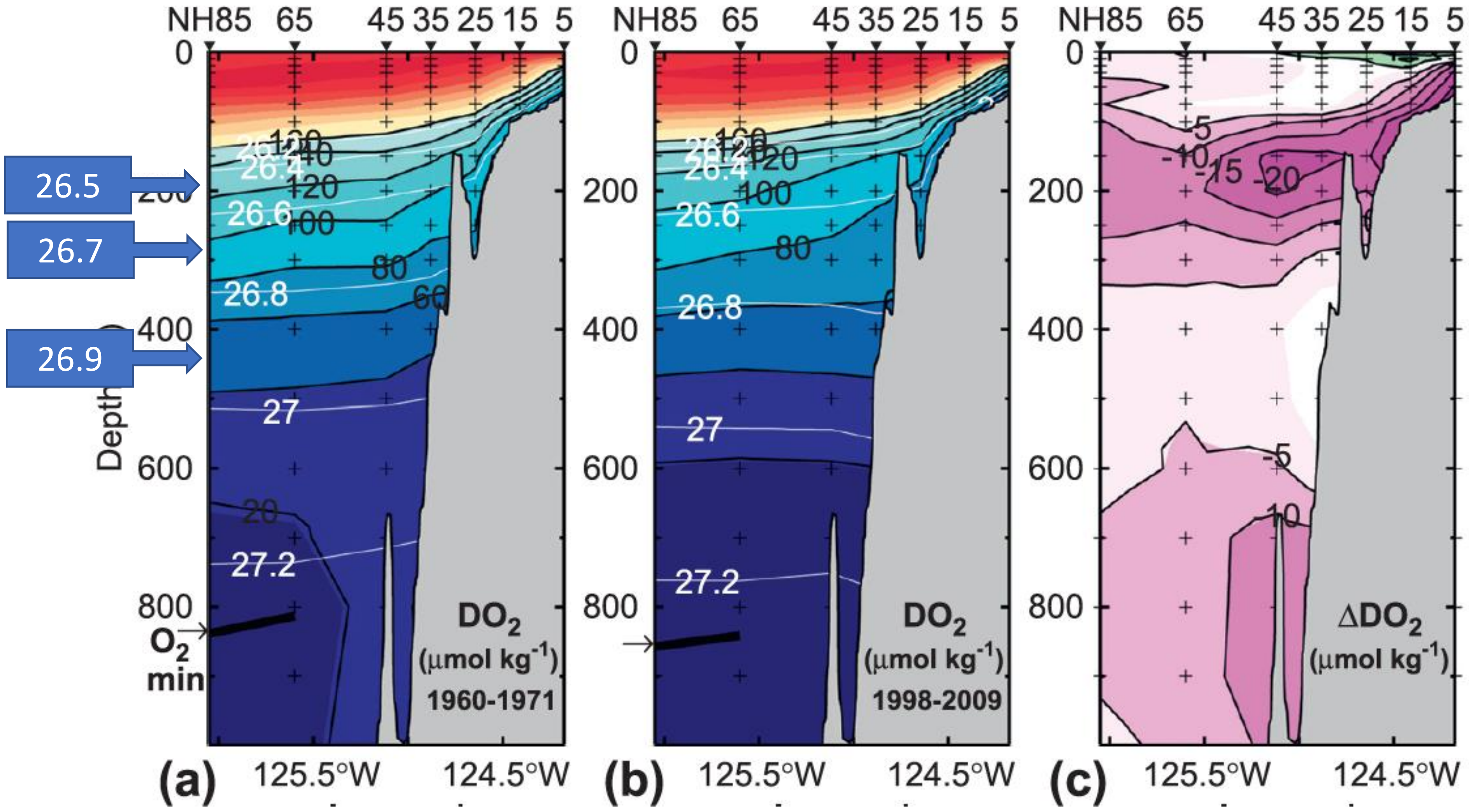


10 mols of DO <u>decrease</u> is equivalent to about 1 mol Nitrate <u>increase</u> due to remineralization of organic particles

Pierce et al. (2012 JPO) Declining Oxygen in the Northeast Pacific

Contours of the oxygen minimum depth from World Ocean Atlas 2009





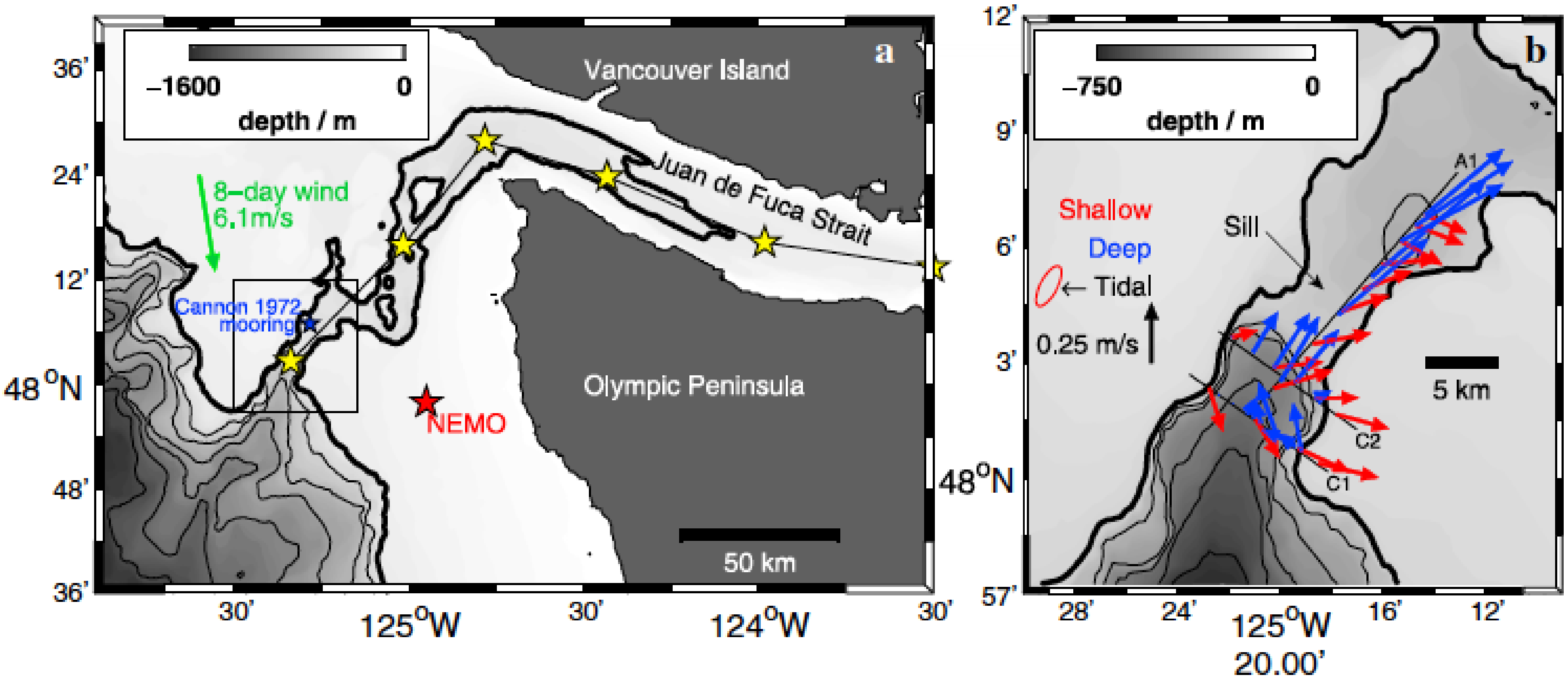
DO decreased by about 20% at the depth of the shelf break, over 40 years.

Pierce et al. (2012) "In the subpolar gyre, a major factor in oxygen decline may be a reduction in outcropping of density in the vicinity of sigma-theta = 26.6 due to increased stratification in the northwest corner of the Pacific (Emerson et al. 2004; Deutsch et al. 2006)."

Hickey & Banas (2008):
Juan de Fuca Canyon may be an important pathway for deepest water from beyond the shelf break

Observations at the seaward end of the canyon:

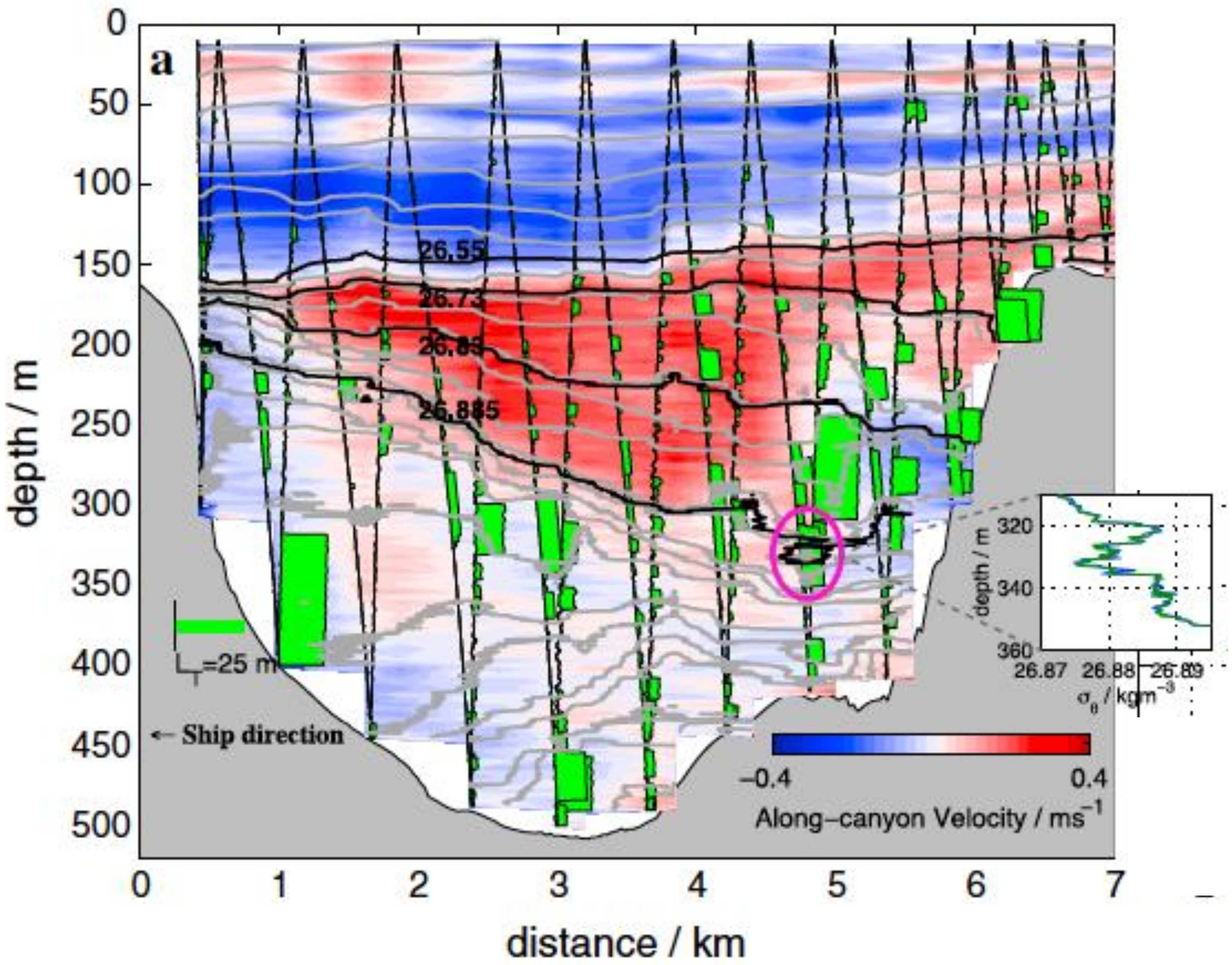
Alford, M. H., and P. MacCready (2014), Flow and mixing in Juan de Fuca Canyon, Washington. *Geophys. Res. Lett.*, 41



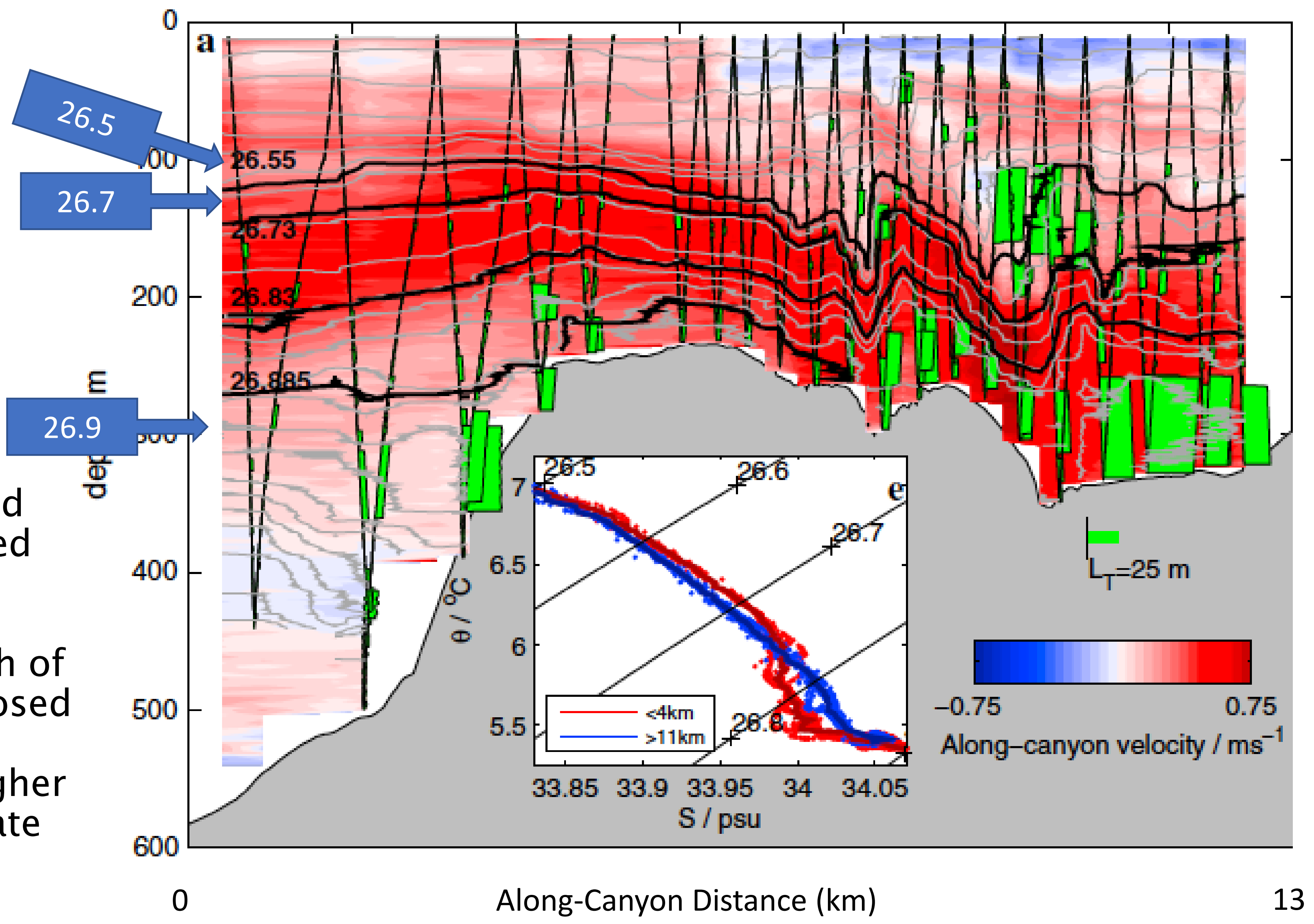
Cross-Canyon Section:

strong inflow of deep water during upwelling winds

(reverses during downwelling winds)



Along-Canyon Section:

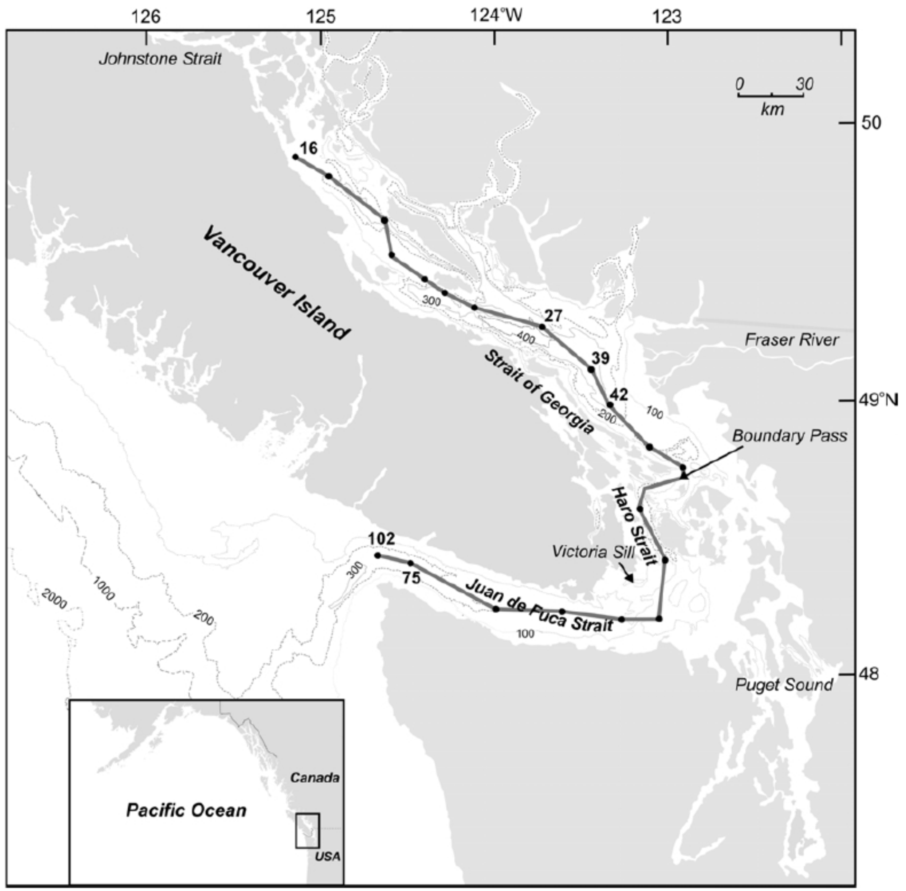


Large lee waves and mixing are observed

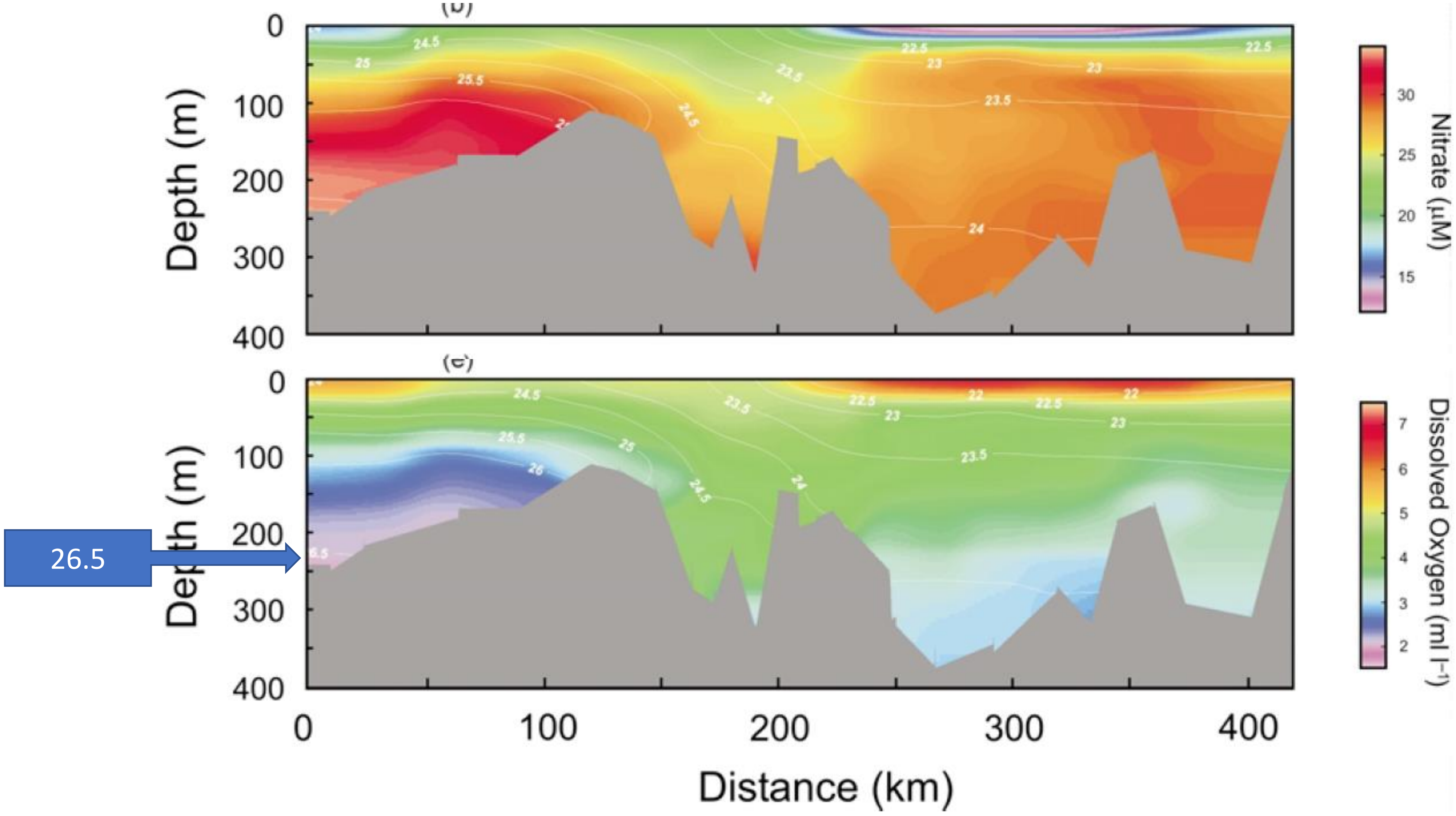
RESULT: water reaching the mouth of JdF is partly composed of shallower water types, meaning higher DO and lower Nitrate

Observed Nitrate and Oxygen Sections

- Masson (2006 Ocn-Atm) Seasonal Water Mass Analysis for the Straits of Juan de Fuca and Georgia
- 19 surveys 1999-2003



Masson (2006) Sections



Masson (2006) Water mass analysis:
SW_2 is deep inflow from the mouth of JdF

Spring	Summer
Winter	Fall

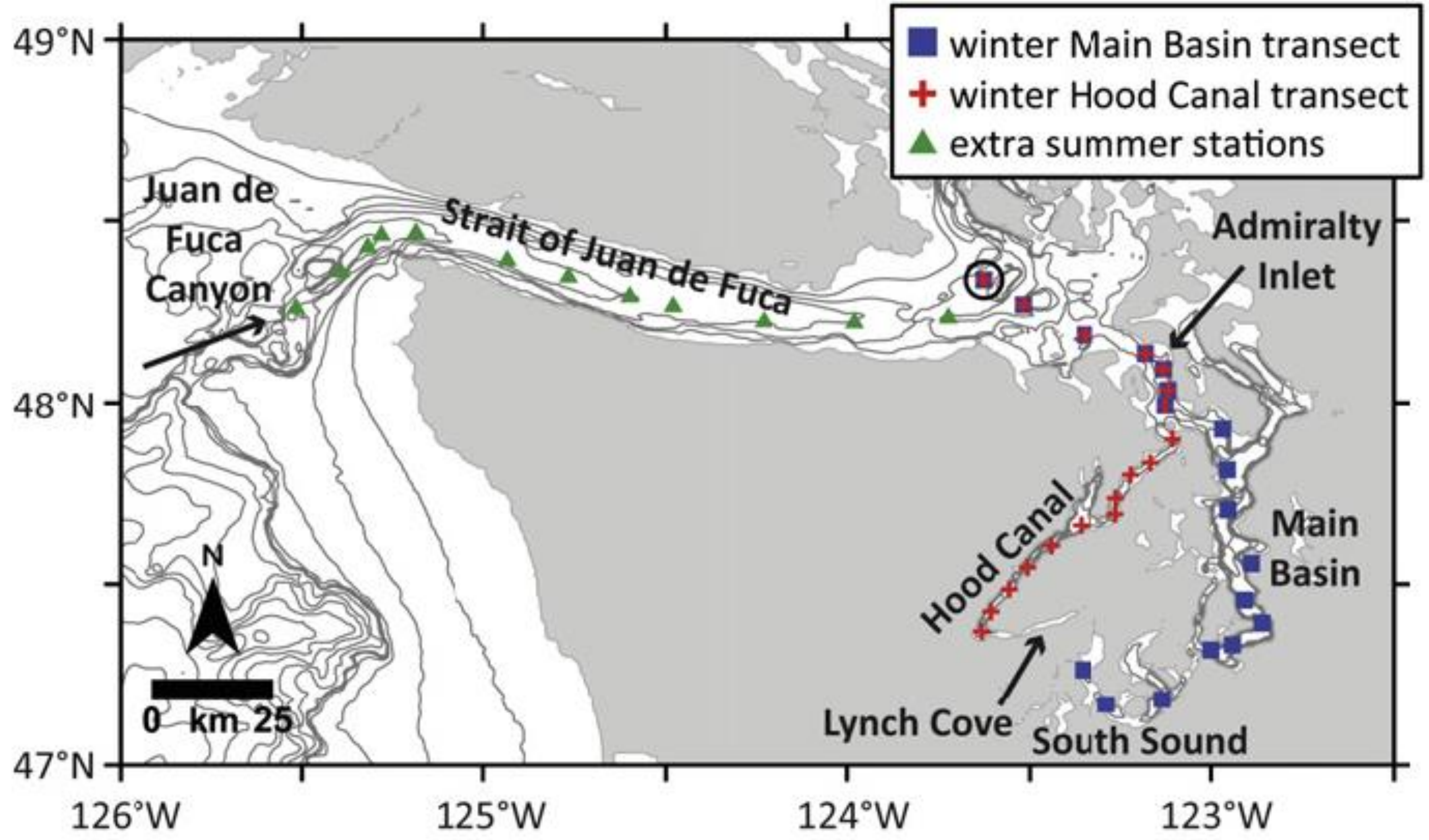
TABLE 1 Property values for each of the source water types for the four seasons given clockwise from the top left corner as spring, summer, fall, winter.

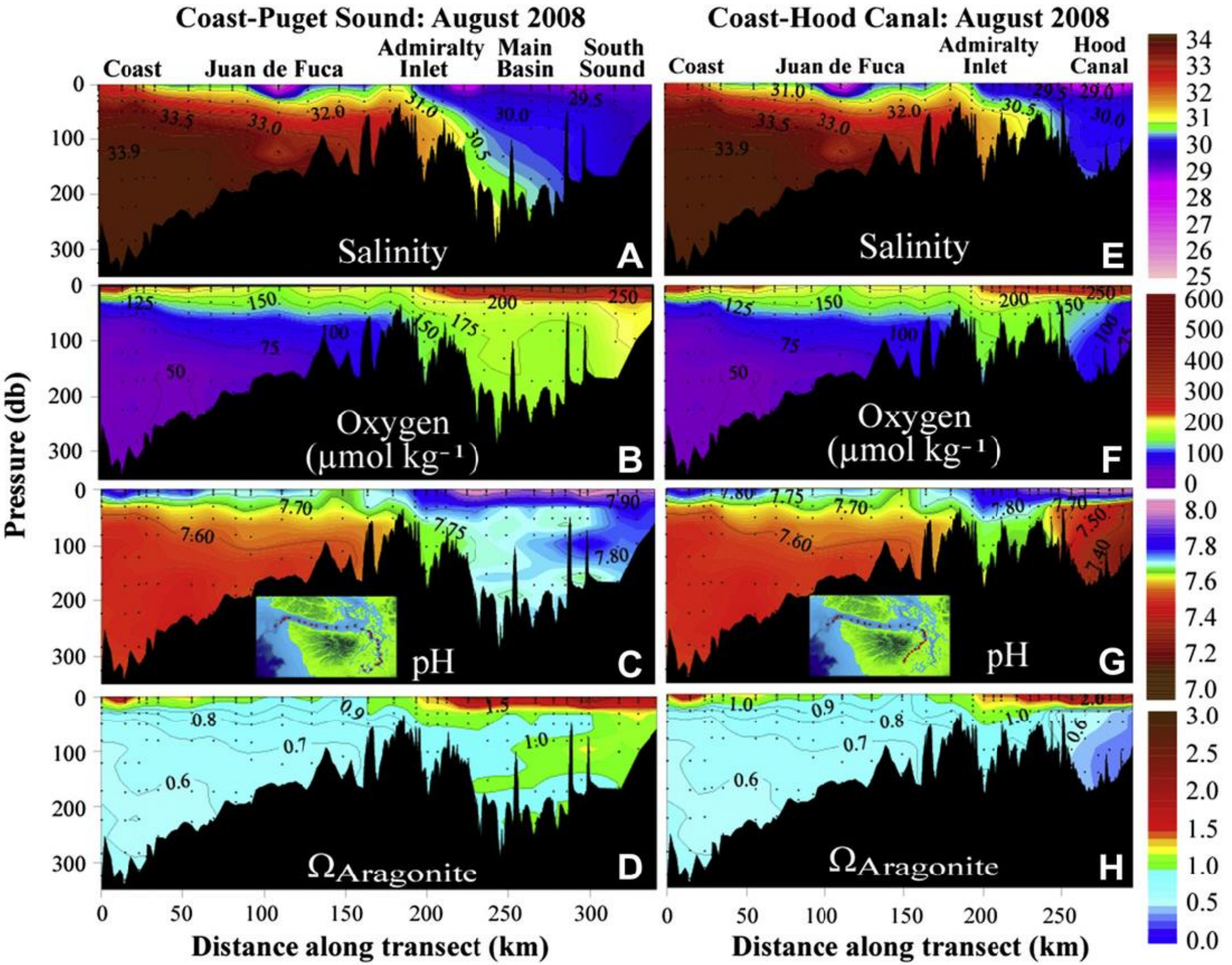
Source water type	Temp (°C)		Salinity		Oxygen (mL/L)		Nitrate (µM)		Phosphate (µM)		Silicate (µM)	
SW_1: river	9.1	12.5	27.3	25.1	7.5	6.1	10.1	11.1	1.1	1.2	25.0	33.3
	8.1	13.9	27.5	26.2	6.1	6.0	26.3	6.8	2.3	0.9	53.5	30.0
SW_2: deep south	6.8	6.4	33.9	33.9	2.1	1.8	33.4	35.5	2.6	2.7	51.5	57.3
	8.0	6.8	33.2	33.9	3.1	1.6	28.1	34.8	2.4	2.7	43.3	56.1
SW_3: pre-season	9.4	9.1	31.2	31.0	2.9	3.0	28.8	29.4	2.8	2.8	58.1	61.4
	9.2	8.9	31.1	30.9	3.2	3.5	28.4	28.1	2.6	2.6	54.0	56.1
SW_4: surface south	9.7		30.3		6.5		7.3		1.0		17.8	
SW_5 : deep north	8.9	8.7	30.4	30.5	3.9	3.7	28.4	29.2	2.6	2.7	56.8	59.8
	9.0	9.4	30.3	30.3	3.7	3.5	28.4	26.0	2.6	2.6	56.2	54.8

Summer and Fall have the lowest incoming DO and the highest Nitrate

More Observed Property Sections

Feely et al. (2010 ECSS) The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary

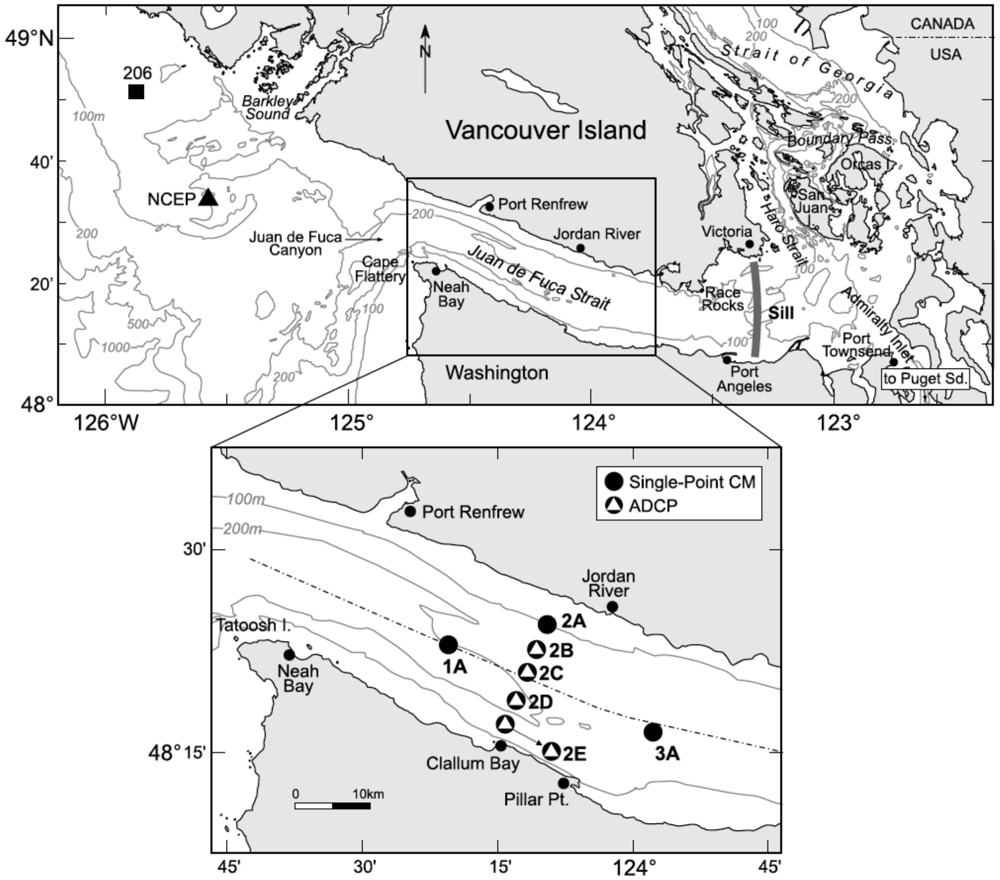


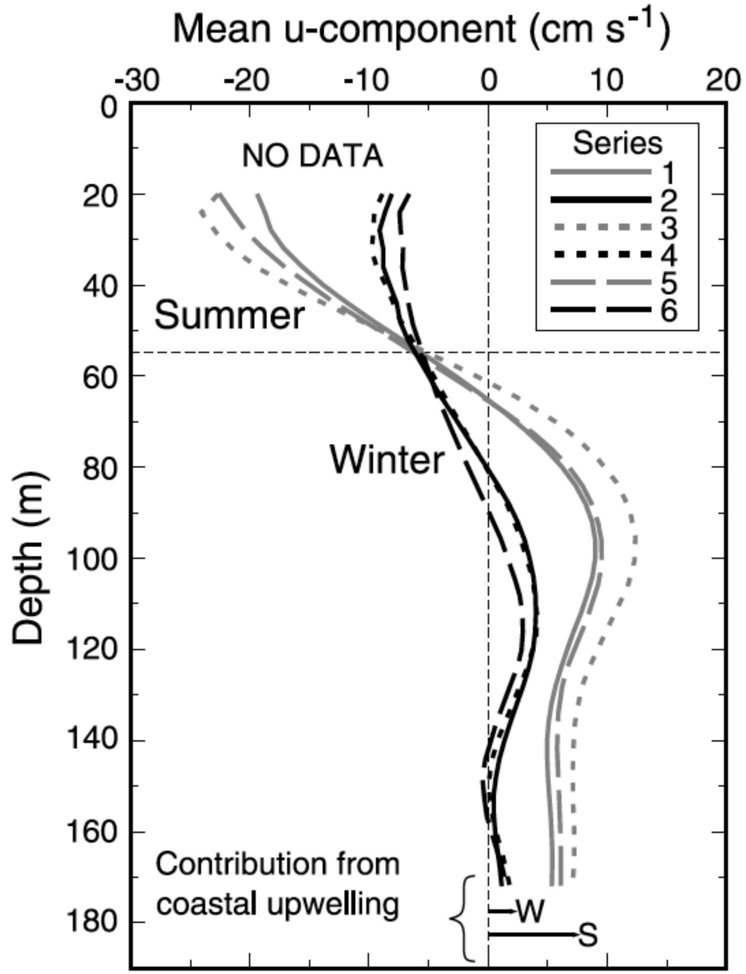


Summer sections:

Low DO inflow also has low Ph and low Aragonite Saturation State

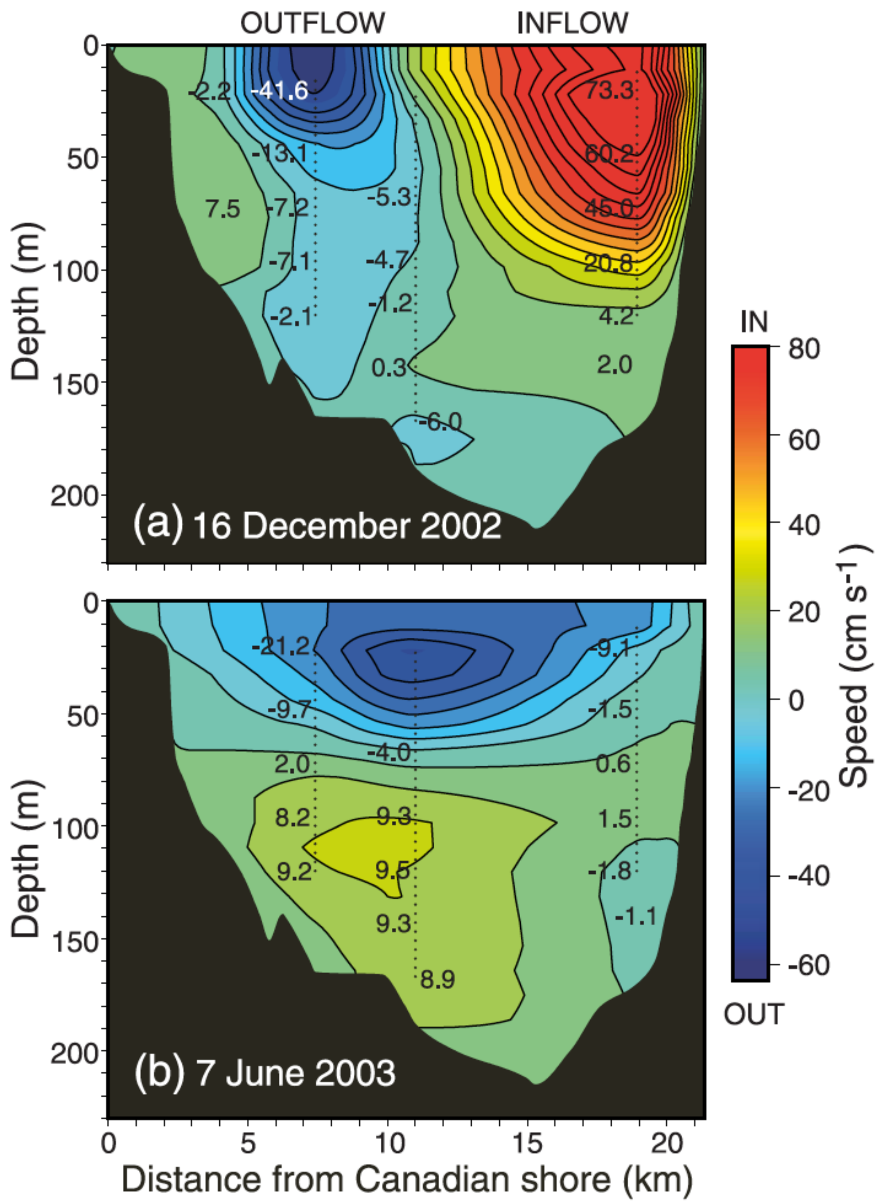
The Strait of Juan de Fuca has a persistent estuarine exchange flow, pulling in about 140×10^3 m^3/s of water from the Canyon (like 20 times all the river flow in the Salish Sea!)

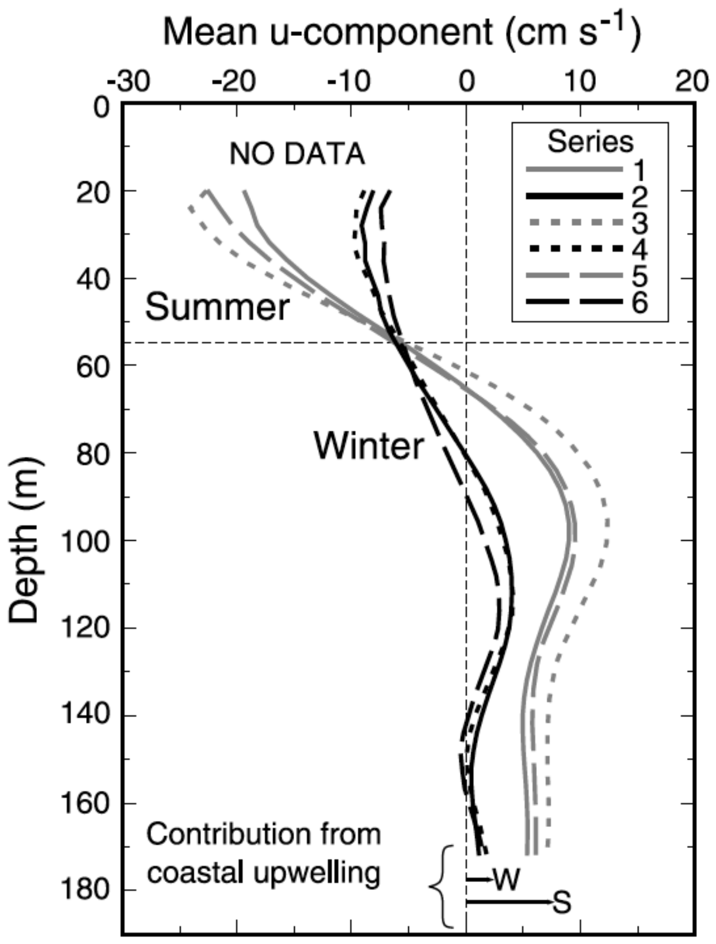




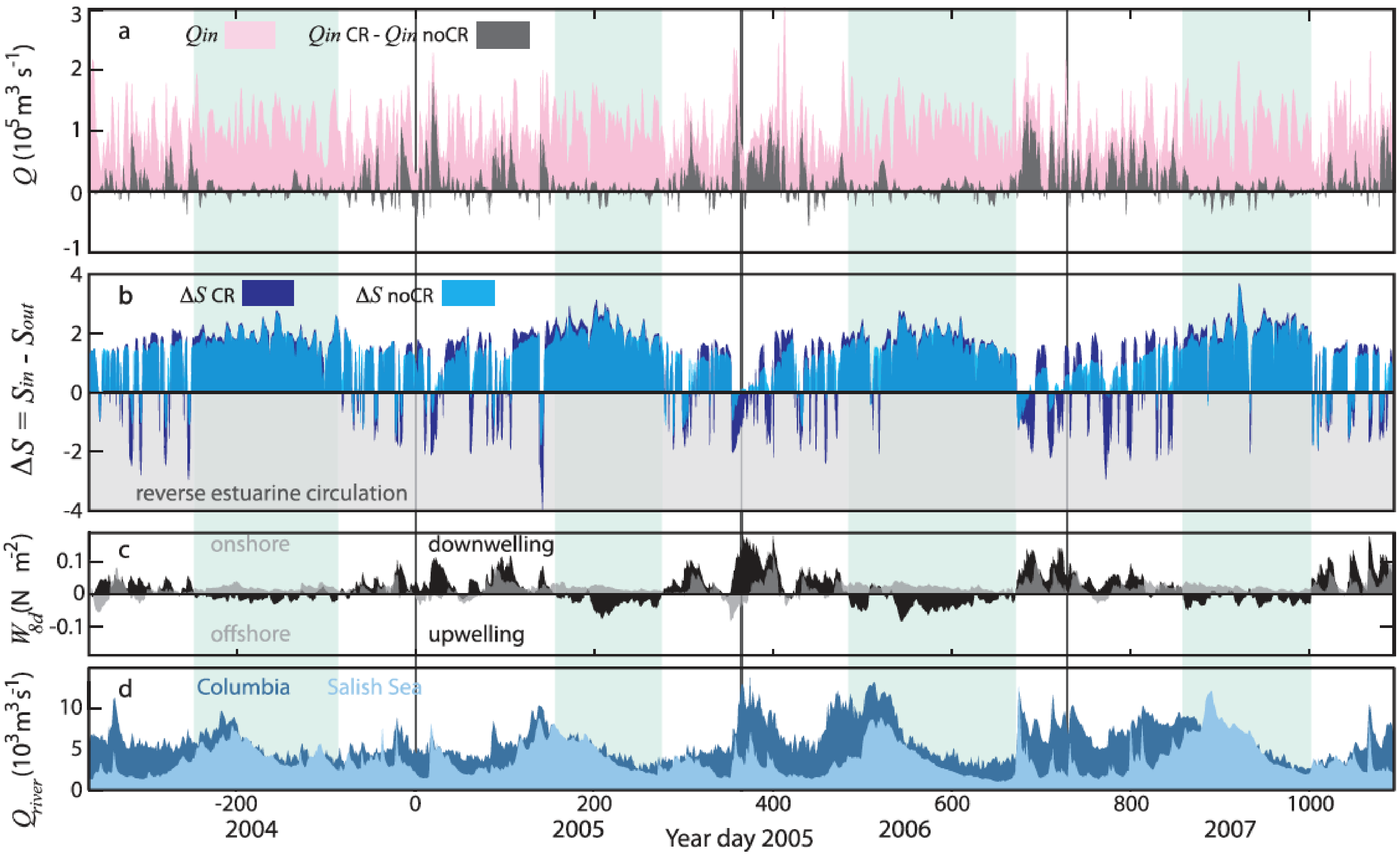
Thomson, R. E., S. F. Miha´ly, and E. A. Kulikov (2007), Estuarine versus transient flow regimes in Juan de Fuca Strait, J. Geophys. Res., 112, C09022, doi:10.1029/2006JC003925.

The JdF exchange flow also has many “reversals” especially during Winter, when Columbia River water flows in at the surface.





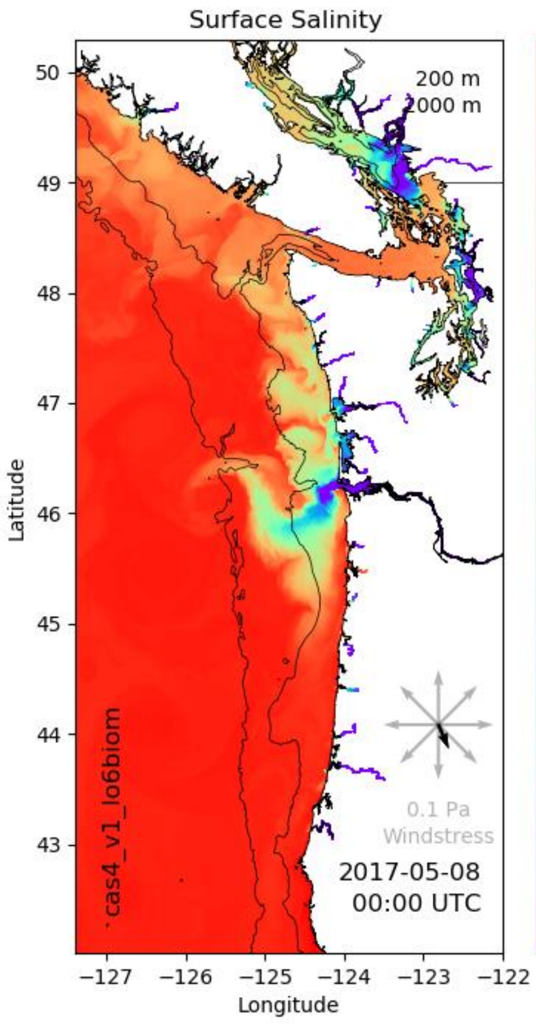
Model simulation of JdF Exchange Flow

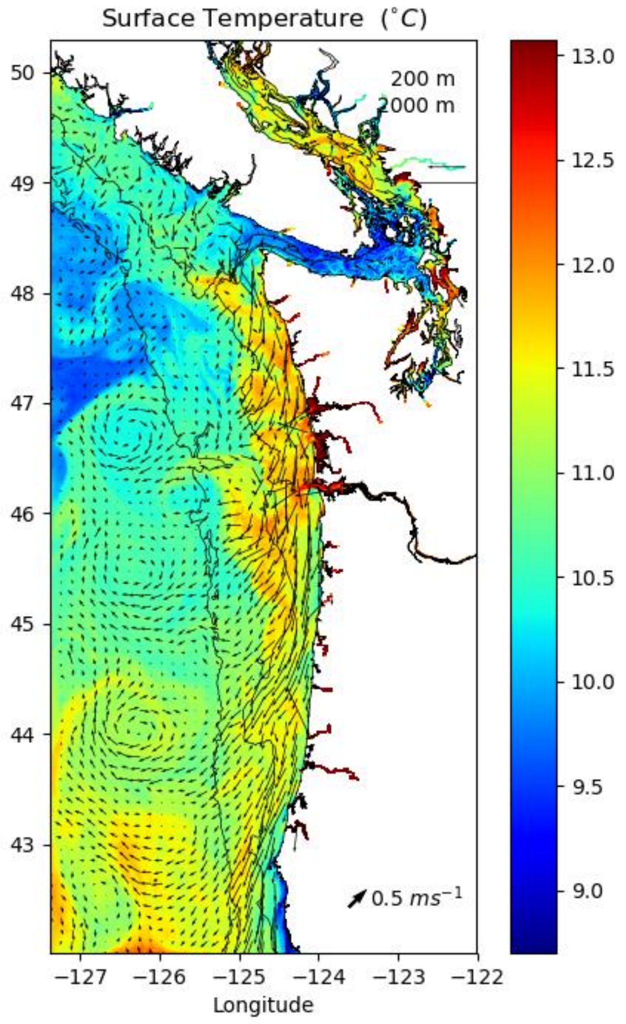


Giddings, S. N., & MacCready, P. (2017). Reverse estuarine circulation due to local and remote wind forcing, enhanced by the presence of along-coast estuaries. Journal of Geophysical Research: Oceans, 122, 10,184–10,205. https://doi.org/10.1002/2016JC012479

More model results

LiveOcean
A daily forecast model of currents and water properties for the Pacific Northwest coast and Salish Sea

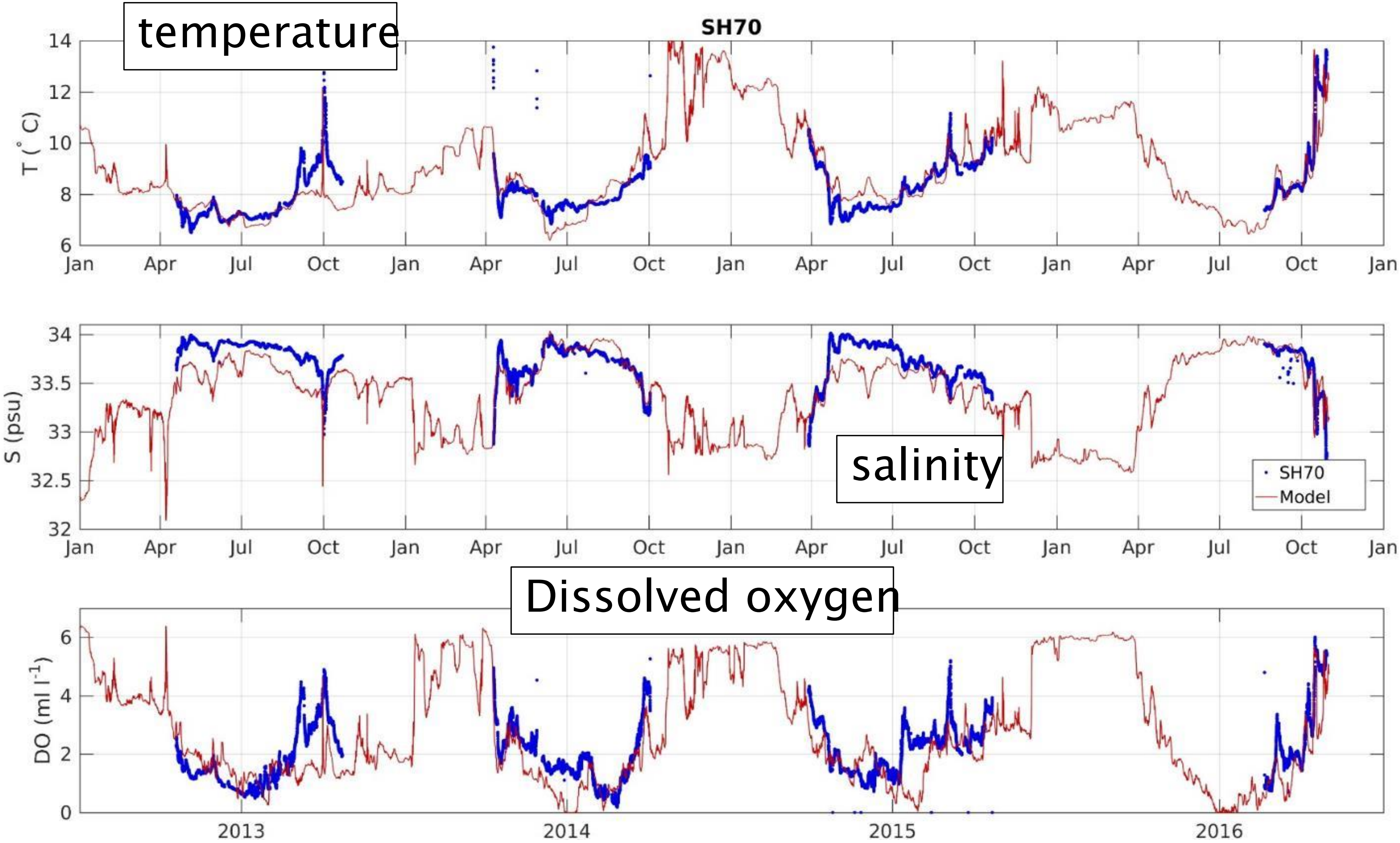


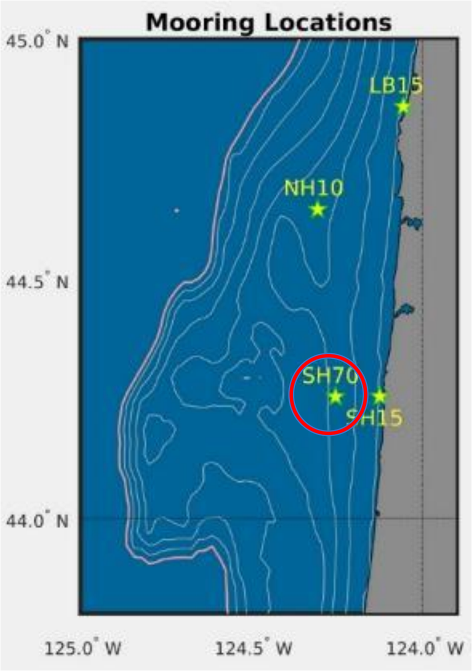


UW Coastal Modeling Group

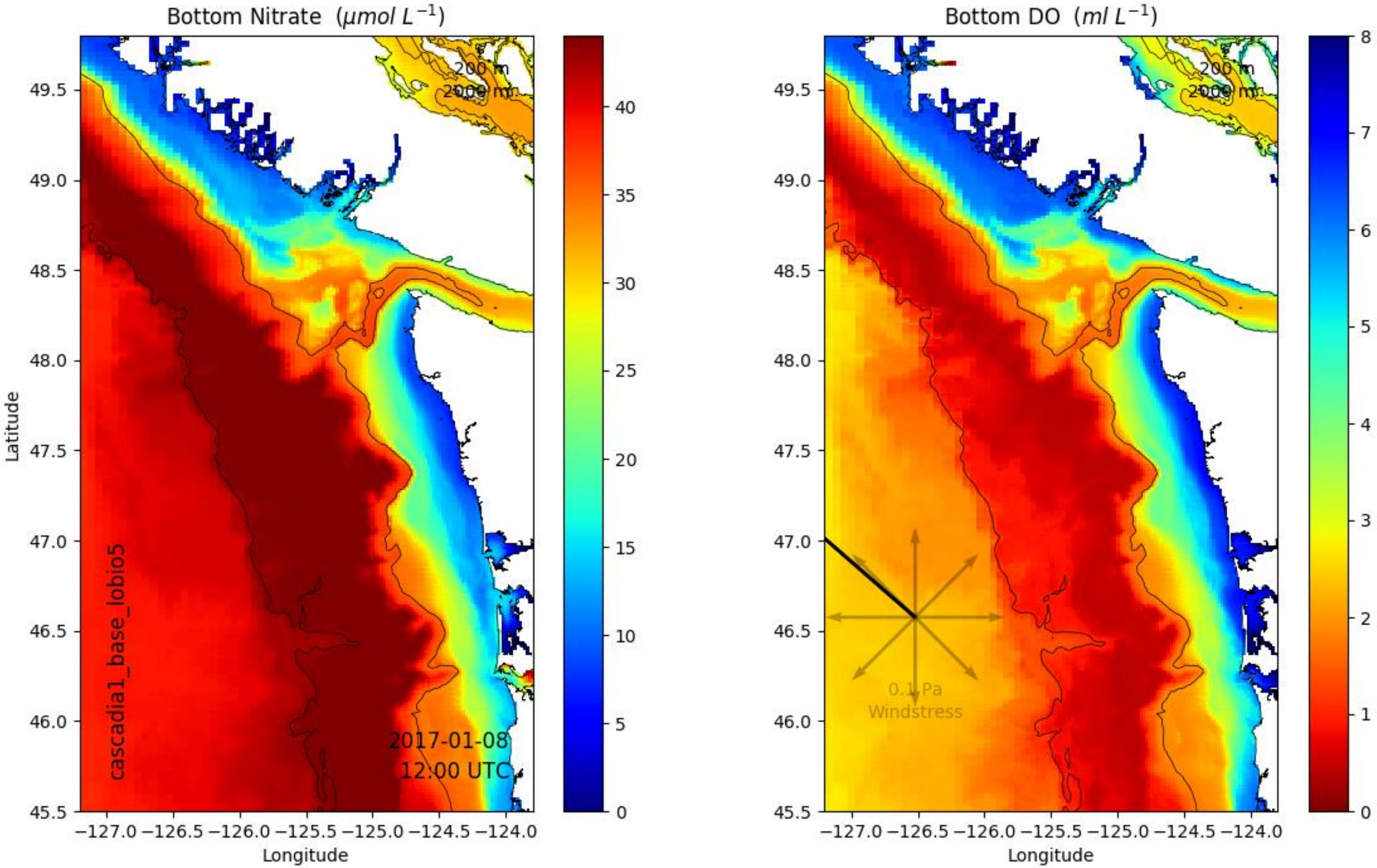
- Parker MacCready
- Samantha Siedlecki
- Ryan McCabe
- Neil Banas
- Hally Stone
- Elizabeth Brasseale
- Bridget Ovall
- David Darr

VALIDATION: 4 Years of Mooring Records: Oregon Shelf (Barth, Durski OSU)

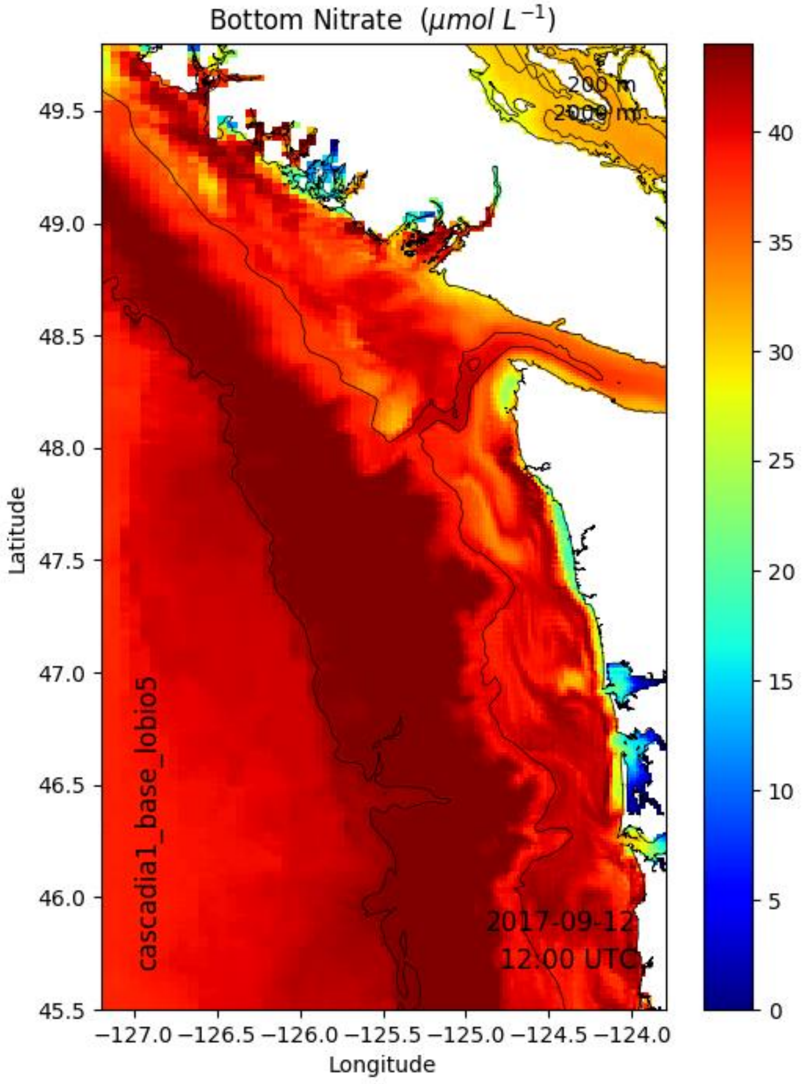


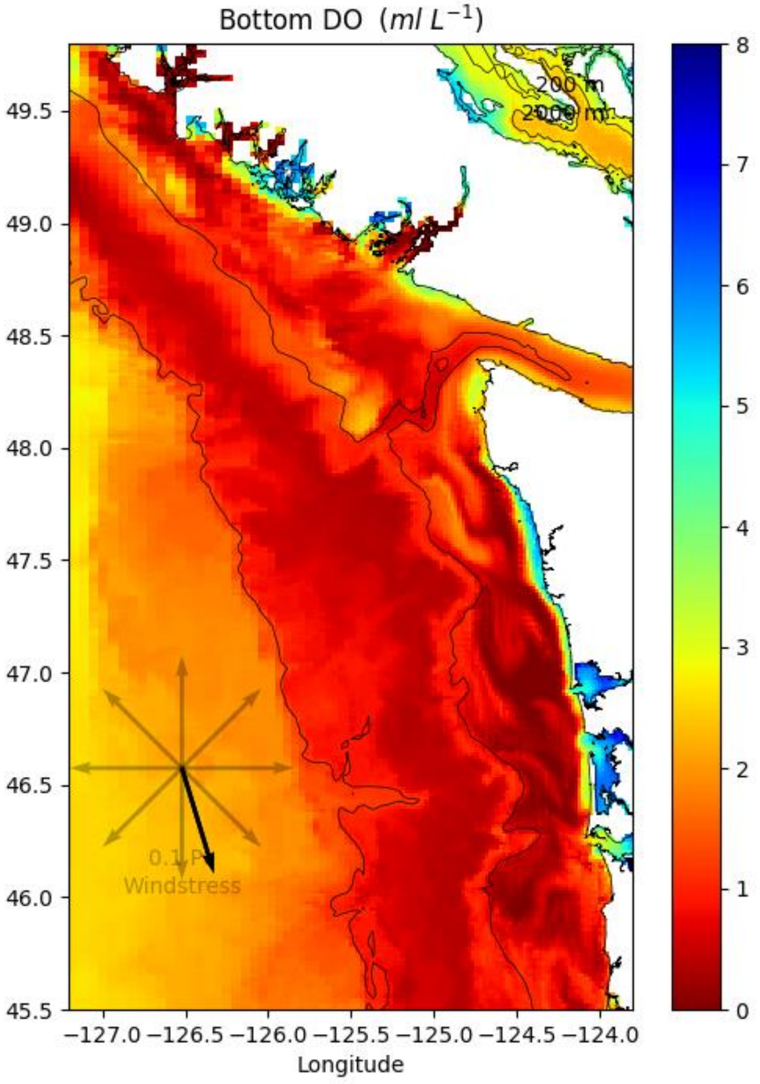


Winter Bottom Nitrate and DO



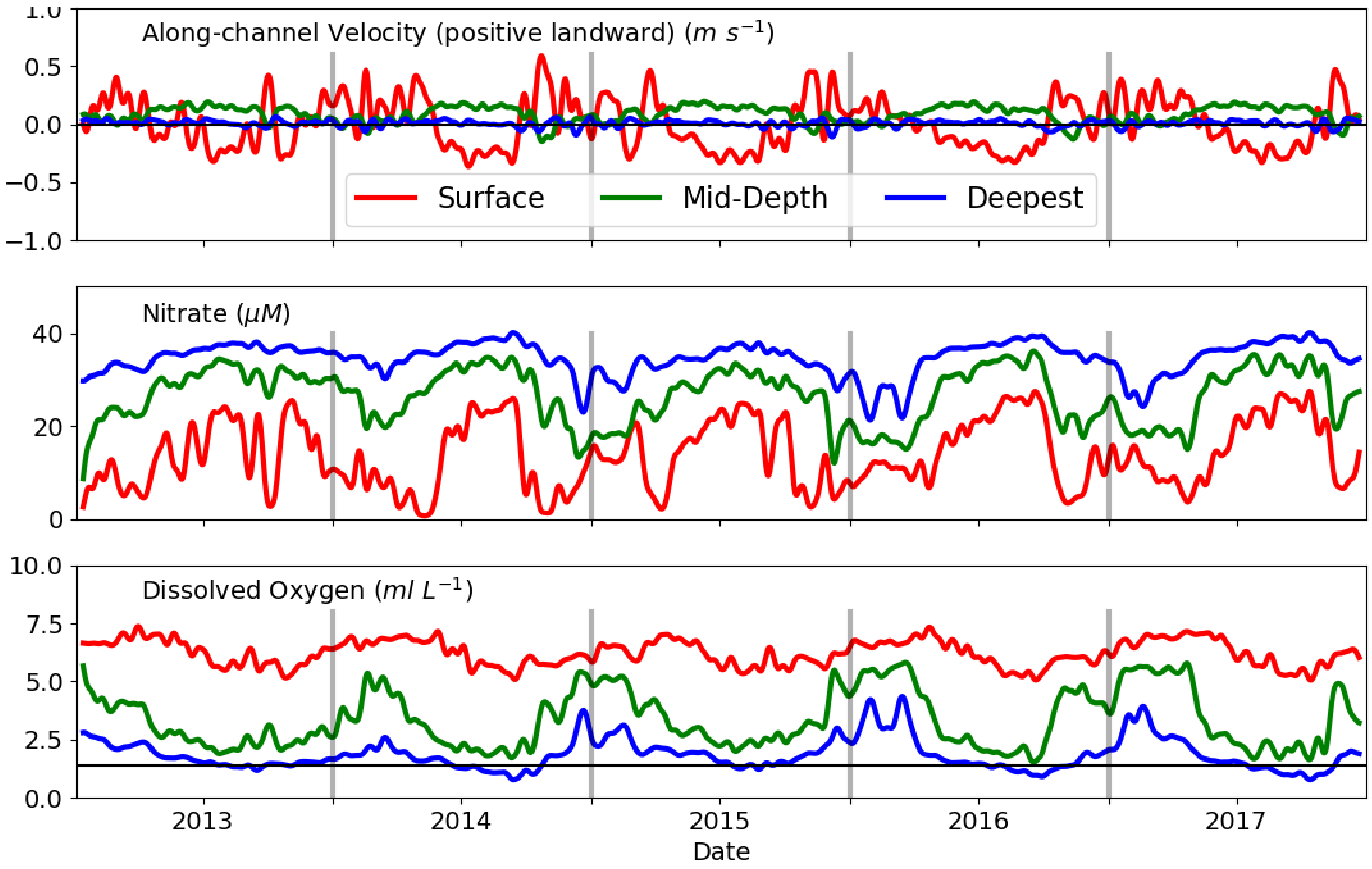
Late Summer Bottom Nitrate and DO





LiveOcean 5-year time series from a virtual mooring at the mouth of JdF

Again, DO is lowest, Nitrate is highest, and the exchange flow strongest in the summer



Summary

- We know that the DO of source waters has declined by 20% (20 uM) in the last 40 years.
- It is likely that Nitrate has increased by about 2 uM (6%) over that same time.
- The Juan de Fuca Canyon and Strait are effective conduits – during upwelling winds – for pulling in Pacific water from as deep as 300 m. This then feeds the estuarine inflow of the Salish Sea, which is strongest during summer in part because the Fraser River flow is larger then.
- Will the depth of isopycnals change in the future? This matters because of the strong vertical gradients of Nitrate and DO.