

SEASONAL HYDROGRAPHY AND HYPOXIA OF COOS BAY, OREGON

by

MOLLY ANNE O'NEILL

A THESIS

Presented to the Department of Geological Sciences
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Master of Science

September 2014

THESIS APPROVAL PAGE

Student: Molly Anne O'Neill

Title: Seasonal Hydrography and Hypoxia of Coos Bay, Oregon

This thesis has been accepted and approved in partial fulfillment of the requirements for the Master of Science degree in the Department of Geological Sciences by:

Josh Roering	Chairperson
David Sutherland	Advisor
Alan Shanks	Member

and

J. Andrew Berglund	Dean of the Graduate School
--------------------	-----------------------------

Original approval signatures are on file with the University of Oregon Graduate School.

Degree awarded September 2014

© 2014 Molly Anne O'Neill

THESIS ABSTRACT

Molly Anne O'Neill

Master of Science

Department of Geological Sciences

September 2014

Title: Seasonal Hydrography and Hypoxia of Coos Bay, Oregon

The recent rise of inner shelf hypoxia in the California Current System has caused concern within the scientific community, sparking a surge in studies addressing the issue. While regional studies of hypoxia abound, relatively little attention has been focused on the smaller coastal estuarine systems in the Pacific Northwest. Here, we present results from Coos Bay, a small, highly seasonal estuary on the southern Oregon coast. Due to wide fluctuations in freshwater input, Coos Bay exhibits characteristics of a salt-wedge type estuary in the winter, a well-mixed estuary in the summer, and a partially-mixed estuary during times of moderate discharge. Despite a strong coupling with coastal waters, we did not find evidence for pervasive hypoxia in Coos Bay. The primary drivers of variability in dissolved oxygen levels in the estuary are upwelling wind stress, residence time, and *in-situ* biologic processes.

CURRICULUM VITAE

NAME OF AUTHOR: Molly Anne O'Neill

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene, OR
Lehigh University, Bethlehem, PA

DEGREES AWARDED:

Master of Science, Geological Science, 2014, University of Oregon
Master of Education, Secondary Education, 2012, Lehigh University
Bachelor of Science, Earth and Environmental Science, 2011, Lehigh University

AREAS OF SPECIAL INTEREST:

Coastal oceanography
Education
Environmental Science

GRANTS, AWARDS, AND HONORS:

Graduate Teaching Fellowship, University of Oregon, 2012-2014
2013 Heceta Head Coastal Conference Student Poster Award, October 2013

ACKNOWLEDGMENTS

I would like to thank my primary thesis advisor, Dave Sutherland, for his unwavering and patient guidance in the completion of this work. I would also like to thank my committee members, Alan Shanks and Josh Roering. Alan provided both expert knowledge and intuition regarding Coos Bay and the larger oceanographic setting. Josh added big-picture feedback and insightful comments about the data and interpretations.

I thank my officemates and friends, George Roth and Dustin Carroll, for being there with me through the “highs” and “lows” of grad school. I would especially like to thank Dustin for his mentorship, encouragement, and guidance in school, research, and life. I would like to thank Kelly Sutherland and her students, Keats Conley and Sam Zeman, for providing research assistance and good company.

My fieldwork in Coos Bay could not have been completed without the support from the Oregon Institute of Marine Biology (OIMB), specifically Larry Draper, the boat captain who is the backbone of operations at OIMB. Barb Butler, the librarian at OIMB, went above and beyond helping me in my endless search for literature and data. I extend my thanks to them, and to the entire OIMB community for supporting me in my work. Field assistance was crucial to this project and I would like to thank Ben Shapiro, Kirstin Meyer, Cate Pritchard, Leif Rasmusson, and Shandy Buckley, in addition to George, Dustin, and Sam, for their help on the water.

I would like to thank the University of Oregon Department of Geological Sciences for the opportunity to study, work, and teach here in Eugene. The community here has diverse scientific interests, and collectively fosters great work and great people.

The larger oceanographic community at Oregon State University welcomed our budding UO oceanography research group into their own community through instruction, support, and friendship. I would like to thank Jack Barth, Francis Chan, Mike Kosro, Murray Levine, Jim Lerczak, Kipp Sherman, and Angel White for their time and the opportunities they extended to me. I would like to thank my colleagues, Ale Sanchez and Atul Dhage, for their friendship and support.

Lastly, I would like to thank my friends and family. Thanks to Angie Seligman, Dana Drew, Mindy Homan, and Anna Moore for being my friends and my “home away from home”. Thanks to my family for all their love and support through the years. And I would like to thank Joe Mulhern, for his loving support, friendship, and trust.

TABLE OF CONTENTS

Chapter	Page
I. INTRODUCTION	1
1.1. Research Objectives	1
1.2. Thesis Overview	2
II. BACKGROUND ON COOS BAY AND ESTUARINE DYNAMICS	4
2.1. Coos Bay	4
2.2. Regional Oceanography in the California Current System.....	7
2.3. Hypoxia in the California Current System.....	10
2.4. Coos Bay as an Oregon Estuary.....	14
2.5. Estuarine Classification Theory	15
III. METHODS AND DATA SOURCES	20
3.1. Monthly CTD Surveys.....	20
3.2. Physical Environmental Conditions.....	22
3.3. Complementary Time Series Data	26
3.4. Historic Dissolved Oxygen Data	29
IV. SEASONAL HYDROGRAPHY OF COOS BAY	31
4.1. Results.....	31
4.1.1. Estuary Classification	31
4.1.2. River Discharge and Freshwater Flow Velocities	46
4.1.3. Oceanic and Atmospheric Forcings	50
4.1.4. Estuarine Circulation and Residence Time.....	54
4.1.5. Box Model	60

Chapter	Page
4.2. Discussion	64
4.2.1. Seasonal Forcing on Coos Bay Estuarine Circulation	64
4.2.2. Strain-Induced Periodic Stratification.....	67
4.2.3. Lateral Circulation	68
4.2.4. Residence Time.....	69
V. COMPARISON BETWEEN YEARS 2012 AND 2013	71
5.1. Results.....	71
5.2. Discussion	80
VI. HYPOXIA IN COOS BAY	83
6.1. Results.....	83
6.1.1. Spatiotemporal Variability in Dissolved Oxygen Levels	83
6.1.2. Historic Occurrence of Hypoxia	90
6.2. Discussion	92
VII. CONCLUSIONS AND IMPLICATIONS	95
7.1. Conclusions.....	95
7.2. Implications	97
APPENDICES	101
A. COOS BAY SPECIFICATIONS.....	101
B. CTD DATA.....	103
REFERENCES CITED.....	131

LIST OF FIGURES

Figure	Page
1. Map of the Coos Bay estuary and the instrumentation used in the study. (Inset) Map of Oregon estuaries, Coos Bay starred.....	5
2. Map of currents in the CCS, adapted from Checkley & Barth (2009)	9
3. Geyer & MacCready (2014) estuarine parameter space	18
4. Map showing the two different CTD sampling strategies.	22
5. Map of the Coos Watershed, modified from the CWA	24
6. Locations of instrumentation providing oceanic and atmospheric data.....	26
7. Sontek ADCP mooring deployed by SSNERR	28
8. CTD transect data plotted in temperature-salinity (TS) space.....	32
9. A CTD transect collected on February 22, 2014.	34
10. A CTD transect collected on April 27, 2013	35
11. A CTD transect collected on September 17, 2013	36
12. Schematic of the along-estuary and vertical gradients in salinity.....	37
13. Locations of the target endpoints in calculating the along-estuary gradient, $\partial s / \partial x$, and the CTD casts for each month that fell the closest to them	38
14. Depth-averaged horizontal salinity gradients from the CTD transects.....	39
15. The along-estuary gradients from the CTD transects plotted against the mean discharge the week leading up to, and including, the day of each CTD transect.	40
16. Mean stratification (psu/m) of all the CTD casts for each sampling trip.....	41

17. Mean discharge over the seven days leading up to, and including, the day of sampling plotted versus the mean stratification of all the casts taken that day.....	41
18. Coos Bay plotted on the Geyer & MacCready (2014) estuarine parameter space.....	45
19. Discharge scaled to the entire watershed area using CWA gage data from 2002-2013	47
20. Linear regression between the Siuslaw River discharge and the scaled CWA discharge	48
21. (Top) Comparison of Siuslaw discharge to Coos discharge over the period 2002-2013. (Bottom) The residuals of the two datasets.	49
22. A month of tidal data for Coos Bay, measured in the Charleston boat basin	50
23. Daily and mean precipitation at the North Bend Airport for the years 2000-2013	51
24. Cumulative precipitation for each water year from 2000-2013	52
25. Hourly alongshore wind stress, measured by NOAA buoy 46015 from 2003-2013	53
26. Temperature, salinity, and density data from the NEP-GLOBEC program's Coos Bay mooring, maintained from 2000-2004	54
27. Data from November 25, 2013 to May 27, 2014 showing the seasonal and synoptic forcing on flows in Coos Bay	55

Figure	Page
28. Depth-averaged, along-estuary rotated velocities (top). Rotated and tidally-averaged lateral (center) and along-estuary (bottom) velocities.....	57
29. Boxplots of estimated filling and transit times	59
30. Figure 27 plotted with corresponding transit and fill times (bottom panel)	60
31. Schematic of box model, notation, and transports.....	61
32. Map of the boxes used for Coos Bay in the box model residence time calculation	62
33. Transports calculated from the box model for March	64
34. Temperature and salinity diagrams for the 2012 (top) and 2013 (bottom) water years at the BLM boat dock	72
35. Cumulative precipitation (top) and scaled discharge (bottom) for the 2011-2013 water years.....	73
36. Daily alongshore wind stress and scaled discharge for Coos Bay, OR	74
37. Magnitude of the residual flow for Coos Bay, calculated using the tidally-averaged logger data from 2012 and 2013.....	76
38. Histograms showing the distributions of DO measurements at the BLM boat dock logger, Empire Boat dock logger, and the Charleston Bridge logger	77
39. PFEL monthly upwelling anomalies for the 2012 and 2013 water years at 42N 125W and 45N 125W	78
40. Cumulative northward wind stress during the 2012 and 2013 upwelling seasons from http://damp.coas.oregonstate.edu/windstress/index.html	79

Figure	Page
41. Minimum DO values from CTD data versus their location measured by along-estuary distance.....	84
42. Upwelling event in April 2013	85
43. Number of DO measurements <6.5 mg/L by hour of day	86
44. Instances when N/S component of wind speed >2 m/s, by hour of day	86
45. DO measurements <6.5 mg/L from the CTCLUSI and SSNERR water quality loggers, by month of year	87
46. Percentages of DO measurements < 6.5 mg/L, < 4.6 mg/L, and < 2.0 mg/L at the Charleston Bridge logger	88
47. Logger data from SSNERR, CTCLUSI, and CIT showing DO data from 2011 to 2014	89
48. Historic DO measurements in Coos Bay from the DEQ plotted versus time	90
49. Total number of DO measurements per year in Coos Bay, with values <6.5 mg/L. (Inset) Map showing location of measurements within and outside the main stem of Coos Bay.....	91
50. SSNERR Charleston Bridge DO data plotted versus time	91
51. CTD transect profiles from November 3, 2012	103
52. CTD transect profiles from January 19, 2013.....	104
53. CTD transect profiles from February 21, 2013.....	105
54. CTD transect profiles from March 12, 2013.....	106
55. CTD transect profiles from March 26, 2013.....	107

Figure	Page
56. CTD transect profiles from April 27, 2013.....	108
57. CTD transect profiles from May 19, 2013.....	109
58. CTD transect profiles from July 11, 2013	110
59. CTD transect profiles from August 16, 2013.....	111
60. CTD transect profiles from September 7, 2013	112
61. CTD transect profiles from September 17, 2013	113
62. CTD transect profiles from September 21, 2013	114
63. CTD transect profiles from October 16, 2013	115
64. CTD transect profiles from October 20, 2013	116
65. CTD transect profiles from November 30, 2013	117
66. CTD transect profiles from January 25, 2014.....	118
67. CTD transect profiles from February 22, 2014.....	119
68. CTD transect profiles from March 18, 2014.....	120
69. CTD transect profiles from April 6, 2014.....	121
70. CTD transect profiles from May 13, 2014.....	122
71. CTD transect profiles from June 17, 2014.....	123
72. CTD transect profiles from July 24, 2014	124
73. Map of October 10, 2013 cross-estuary transect near Buoy 10	125
74. October 10, 2013 CTD cross-estuary transect profiles near Buoy 10	126
75. Map of October 10, 2013 cross-estuary transect near the North Bend Airport.....	127

Figure	Page
76. October 10, 2013 CTD cross-estuary transect profiles near the North Bend Airport.....	128
77. Map of October 10, 2013 cross-estuary transect near the confluence of the Coos River and Isthmus Slough.....	129
78. October 10, 2013 CTD cross-estuary transect profiles near the confluence of the Coos River and Isthmus Slough	130

LIST OF TABLES

Table	Page
1. The water properties of the three main water masses that feed the CCS.....	7
2. Dates, conditions, and sampling details of the 23 CTD transects.....	20
3. Parameter values used for the nondimensional parameterizations of Coos Bay	43
4. Estuarine parameters for Coos Bay.....	46
5. Specifications for the Coos Bay estuary, listed with their sources	101

CHAPTER I

INTRODUCTION

In the past decade, scientists have observed an unprecedented increase of hypoxic, or low oxygen, waters on the shelf in the California Current System (CCS) during the dry season (Chan et al. 2008; Grantham et al. 2004; Bograd et al. 2008; Connolly et al. 2010). These low oxygen conditions are lethal to many fish populations (Vaquer-Sunyer and Duarte, 2008; Rabalais et al. 2010), and have been known to cause major die-offs on the shelf (Chan et al. 2008; Grantham et al. 2004). However, the extent to which these hypoxic waters are affecting smaller estuarine systems in the Pacific Northwest is largely unknown (NOAA, 1998). This study examines Coos Bay, the second largest estuary in Oregon (Arneson, 1976) with significant ecologic and economic value. Here, we describe the hydrography and circulation in Coos Bay that are important physical controls on the occurrence of hypoxia within an estuary (Gray et al., 2002; Scully, 2013).

1.1. Research Objectives

The three primary research questions that this study seeks to address are:

- **How do ocean properties and the seasonal change in forcing mechanisms affect estuarine circulation in the Coos Bay estuary?**

The Pacific Northwest (PNW) has a distinctive seasonal cycle driven by large-scale atmospheric and oceanographic conditions (Huyer, 1983; Hickey & Banas, 2003). The seasonal cycle is evident in the circulation patterns of PNW estuaries. For Coos Bay, past studies show it is a well-mixed system that shifts to partially-mixed during periods of high freshwater input, usually in the winter and spring (Burt & McAlister, 1959; Blanton, 1969; Arneson, 1976; Baptista, 1989; NOAA, 1998; Rumrill, 2006; Lee & Brown, 2009).

We test this description by quantifying and parameterizing the hydrography in Coos Bay. We describe the average flow structure and seasonal variability in response to the changing atmospheric and oceanographic conditions.

- **Is there a record of hypoxia in Coos Bay either historically or currently?**

Certain years have exhibited more persistent and severe hypoxic events on the PNW shelf (Grantham et al., 2004; Chan et al., 2008). Whether these hypoxic shelf waters are communicated into, and to what extent, in Coos Bay is the second objective of this research project. This component looks at past records of dissolved oxygen levels in Coos Bay to determine the historical extent, if any, of hypoxia in the estuary. Data from the past decade, when anomalous shelf hypoxia was observed, will be examined more closely to understand if, and how far into, the hypoxic shelf signature propagates into Coos Bay.

- **What influences the spatial and temporal variability in observed DO levels?**

We focus our study primarily on the physical controls on DO variability. Spatially dense CTD data are used to describe the along-estuary variability in DO while temporally dense time series data will allow us to make correlations with atmospheric and offshore oceanic conditions.

1.2. Thesis Overview

To address these research questions, we begin in Chapter II by providing background information on the study site and the larger oceanographic setting. We define hypoxia and discuss its occurrence in coastal waters. Lastly, here, we relate Coos Bay to

other Oregon estuaries, and describe classic and novel approaches to estuarine classification.

Chapter III details the data collection and sampling we carried out. We also describe external datasets that were accessed and analyzed in the study.

Chapter IV classifies Coos Bay, and elaborates on its highly seasonal hydrography, and the forces driving it. Interannual variability in the estuary is explored in Chapter V. In Chapter VI, we examine dissolved oxygen levels in the estuary on multiple timescales. Chapter VII concludes the study by summarizing key findings and describing possible implications of the work.

CHAPTER II

BACKGROUND ON COOS BAY AND ESTUARINE DYNAMICS

2.1. Coos Bay

Coos Bay is the second largest estuary in Oregon, and the largest entirely within state borders (Hickey & Banas, 2003; Arneson, 1976). Only the Columbia River Estuary exceeds it by volume. It is located on the southern Oregon coast and is home to the most populated coastal Oregon city—Coos Bay (Figure 1). It is a drowned river valley estuary, formed when seas rose at the end of the last glaciation, during the late Pleistocene (Blanton, 1969). High sedimentation rates and tidal fluctuations result in vast intertidal areas that make up approximately half of the estuary's 54 km² surface area (Percy, 1974; Rumrill, 2006). The estuary has one opening to the Pacific Ocean at its southern end, near the town of Charleston. The main channel extends north, almost parallel to the coast, before turning sharply to the southeast in the town of North Bend. The estuary ends in the town of Coos Bay, 21 kilometers from the mouth (Figure 1).

The Coos Bay estuary is a vital resource for the area. The Port of Coos Bay serves as a hub for timber and other goods. The US Army Corps of Engineers (USACE) routinely dredges the channel to maintain accessibility for the large vessels that transit through the estuary. In March 2014, the Department of Energy approved the Jordan Cove Energy Project to construct a liquid natural gas (LNG) terminal on the North Spit of Coos Bay that would export approximately 6 million metric tons of LNG per year (<http://www.jordancoveenergy.com/project.htm>). In addition to its shipping capacities, Coos Bay boasts productive fisheries and promotes recreational commerce. Such significant industrial and recreational capital warrants an in-depth understanding of the

Coos Bay estuary's biophysical dynamics. Quantifying spatiotemporal variability in circulation within the estuary is important for fishermen, seamen, landowners and engineers. In addition, monitoring the estuary's health is crucial to the estuary ecosystem.

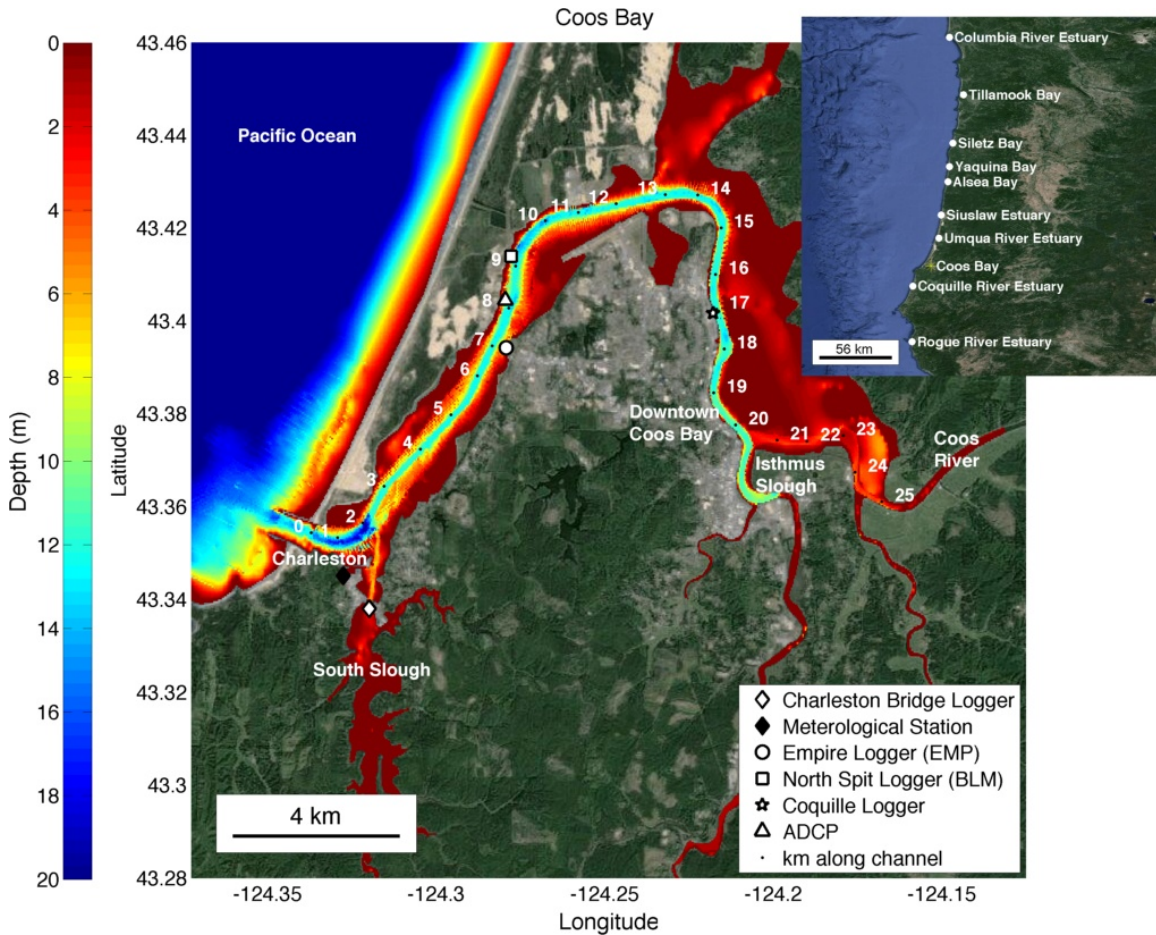


Figure 1. Map of the Coos Bay estuary and the instrumentation used in the study. (Inset) Map of Oregon estuaries, Coos Bay starred.

Coos Bay is currently the largest city on the Oregon coast and its establishment can largely be attributed to its maritime ties (Robbins, 1984). The growth of the fishing industry in Coos Bay followed the coal and lumber industries. The combination of an accessible shipping port and abundant natural resources kept the otherwise isolated Coos

Bay a viable economic center in the late 19th and 20th centuries. The thriving industries of the port city justified the allocation of funds for modifications and upkeep of the port, beginning in 1880 and continuing today. The USACE started work on Coos Bay with the construction of jetties and dunes at the bay entrance (ACOE, 1993). Dredging projects began in 1894 to ensure the safe passage of large shipping vessels into and out of the bay. In the late 1950s, increasing pressure from the growing numbers of fisherman helped secure a bond for the construction of the Charleston Boat Basin (Adams, 1982). Yearly projects and improvements to the harbor are a permanent feature of Coos Bay.

Governmental monitoring and oversight of the estuary's health began in the 1970's, with NOAA selecting the South Slough of Coos Bay as the first site for a National Estuarine Research Reserve (SSNERR). South Slough is a sub-basin of Coos Bay, with its entrance near the mouth extending south, opposite the direction of the main estuary channel (Figure 1). In addition to SSNERR data-gathering, resident and visiting scientists have been collecting biological data and conducting studies at the Oregon Institute of Marine Biology (OIMB), established as a year-round marine lab in 1966.

Despite the establishment of these research centers there is only limited knowledge of the estuarine circulation and water property variations throughout Coos Bay (Juza, 1995; Roegner and Shanks, 2001). Most of the existing research literature deals with biota and biological systems, the primary focus of OIMB. The SSNERR publishes research encompassing a greater breadth of subjects. These data and findings are mostly limited, though, to the South Slough of Coos Bay (Rumrill, 2006).

2.2. Regional Oceanography in the California Current System

In the Pacific Northwest, the California Current System (CCS) controls the nearshore water properties. The CCS is the eastern boundary current system of the North Pacific Gyre that extends from southern British Columbia to southern Baja California (Lynn & Simpson, 1987). The CCS merges three main water masses (Table 1) to form the waters off the Oregon coast: Pacific Subarctic, North Pacific Central, and Southern/Equatorial (Hickey & Banas, 2003). The low salinity and low temperature, high oxygen and nutrient-rich Pacific Subarctic waters enter the CCS from the north; the high salinity and high temperature, low nutrient and oxygen-poor North Pacific Central waters enter the CCS from the west; and the high salinity, high temperature, and nutrient-rich, and low oxygen-Southern/Equatorial waters enter the CCS from the south (Hickey & Banas, 2003).

Table 1. The water properties of the three main water masses that feed the CCS.

Properties of Water Masses in the CCS				
Water Mass	Salinity	Temperature	Oxygen	Nutrients
Pacific Subarctic	Low	Low	High	High
North Pacific Central	High	High	Low	Low
Southern/Equatorial	High	High	Low	High

The CCS controls the flow of these different water masses and is comprised of four major currents and many smaller shelf and slope currents (Figure 2). The California Current flows southward year-round just off the shelf break, extending over the upper 500 m of the water column, with a summertime peak in speed. This current carries the Pacific Subarctic water southward, and at a mean current speed of ~ 10 cm/s. The narrower California Undercurrent flows northward over the continental slope at depths of 100-400 m, transporting warm, salty Southern/Equatorial waters (Chelton, 1984; Lynn &

Simpson, 1987; Hickey, 1988). It is the source of much of the nutrient-laden Southern/Equatorial water transported to the shelf during upwelling (Hickey and Banas, 2003). The Davidson Current, strongest at the surface, flows over the continental shelf and slope northward in the fall and winter. Also in the winter, the Washington Undercurrent flows southward over the continental slope at depths of 300-500 m. The strength and existence of both the California Undercurrent and the Washington Undercurrent depends on the co-occurrence of opposing wind stress and alongshore pressure gradient forces (Hickey and Banas, 2003).

Within the general framework of currents in the CCS, a seasonal variation in oceanographic circulation arises from shifts in atmospheric pressure systems. In the winter, the Aleutian Low sits over the North Pacific and causes strong northward winds along the PNW coast (Huyer, 1983). Wintertime poleward winds push warmer, fresher, nutrient-depleted surface waters inshore and cause coastal downwelling. The shift from these wintertime conditions, termed the Spring Transition, varies interannually, but usually occurs within a week during a strong southward wind event in late April or May (Huyer et al., 1979). These winds are the result of the Aleutian Low weakening and the northward migration of the North Pacific High to off the coast of northern California. This high-pressure system's winds blow equatorward along the west coast of the US. Equatorward winds cause surface waters to be blown away from shore, facilitating the upwelling of deep, cold, oxygen-poor, nutrient-rich water near the coast (Huyer, 1983). The return to wintertime conditions, the Fall Transition, is generally more gradual (Strub & James, 1988).

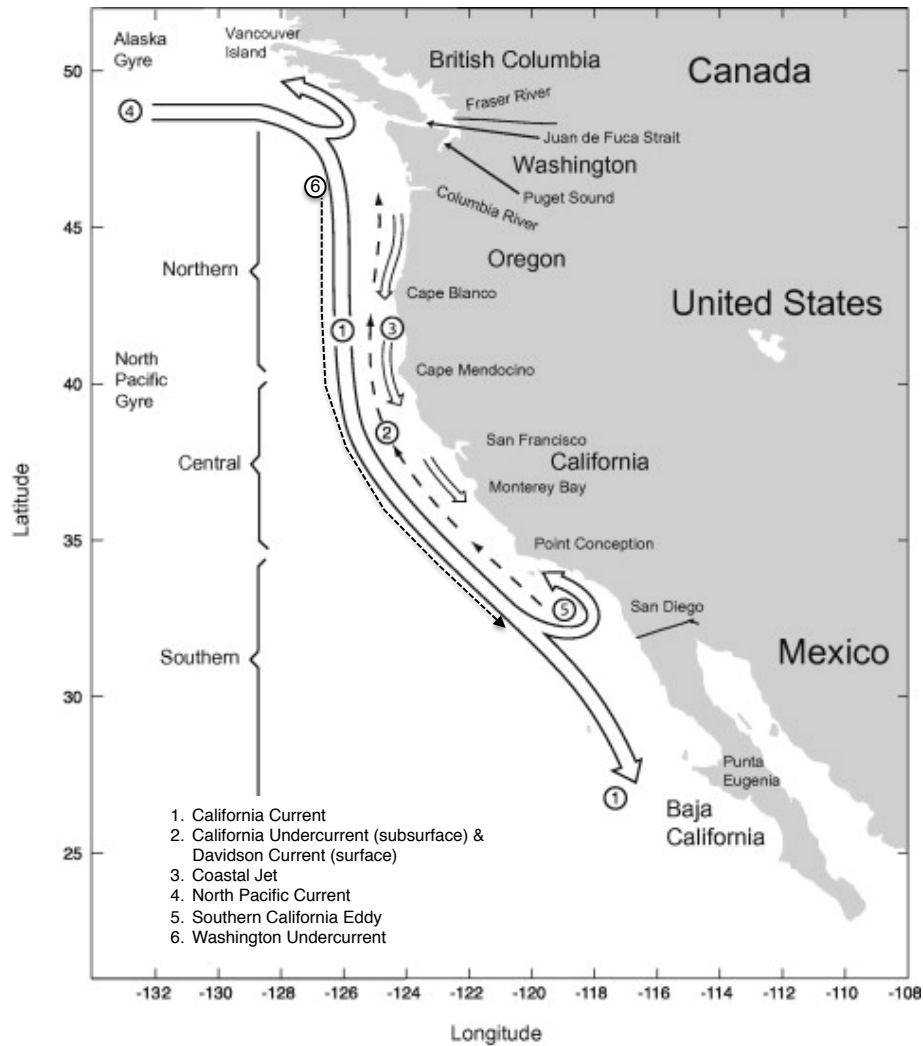


Figure 2. Map showing the major currents, jets, gyres, and eddies within the CCS. Adapted from Checkley & Barth (2009), and reprinted with permissions from Elsevier.

The seasonal shift in circulation regimes drives a productive coastal ecosystem on the west coast of the United States. The summertime cool, nutrient-rich water upwelled from depth stimulates phytoplankton growth (Hickey & Banas, 2003). Phytoplankton blooms, in turn, enhance secondary productivity and generate productive fisheries (Chan et al., 2008; Emmett et al., 2000; Checkley & Barth, 2009).

2.3. Hypoxia in the California Current System

During the summer, it is normal for dissolved oxygen levels on the shelf in the CCS to be lower due to upwelling. However, hypoxia, a condition where DO is diminished to levels that are lethal or stressful to biota, occurs when physical and biological processes are coupled in the upwelling season (Connolly et al., 2010; Monteiro et al., 2006). Upwelling brings low DO, nutrient-rich waters up from depth, and the resulting blooms cause an organic matter (OM) flux on the shelf. The breakdown and decomposition of this organic matter via microbial respiration can cause the waters to become hypoxic or even anoxic—devoid of oxygen.

In the literature, definitions for biological hypoxia vary (Vaquer-Sunyer & Duarte, 2008; Rabalais et al. 2010). The Environmental Protection Agency (EPA) states that most plants and animals can grow and reproduce unimpaired when dissolved oxygen (DO) levels exceed 5 mg/L. When levels drop to 3-5 mg/L, organisms exhibit signs of stress. The EPA categorizes the hypoxic threshold as when the DO levels fall below 3 mg/L; anoxic conditions, occurring when DO levels less than 0.5 mg/L, result in the death of any organism requiring oxygen to survive (EPA, 2006). Gray et al. (2002) found DO levels below 6 mg/L stunted growth, levels below 4 mg/L negatively affected other aspects of metabolism, and levels between 2.0 and 0.5 mg/L to be lethal. To support the salmonoid population, the official criterion in Oregon for estuarine waters is 6.5 mg/L (Riparian Research Group, 2002). Vaquer-Sunyer (2008) reviewed the literature on hypoxic thresholds and calculated the mean and standard deviations of thresholds proposed to be 2.05 +/- 0.09 mg/L. This average reflects a range of thresholds cited, with over half of the reports referring to a value of 2 mg/L or lower (Vaquer-Sunyer & Duarte,

2008). Practically speaking, vulnerabilities of different taxa to hypoxia vary; therefore, the establishment of one threshold for hypoxic conditions may be misguided. Different organisms experience adverse effects at a range of DO levels.

DO concentration can be increased in two ways: reaeration and photosynthesis. Reaeration occurs at the air-water interface, where oxygen can either enter the water, or exit, depending on the partial pressure of oxygen in addition to the temperature and salinity of the water. Solubility of oxygen in water is inversely proportional to the temperature and salinity (Truesdale et al., 1955). Green plants, such as phytoplankton, can produce oxygen through photosynthesis when are within the photic zone. Both these processes—reaeration and photosynthesis—happen at, or near the surface. The dissolved oxygen then diffuses or is advected from the surface layer to depth. Respiration and decomposition of OM in the water column reduces DO concentration. Eutrophication, a process resulting from excessive nutrient loading to a system, accelerates the influx of OM. Decomposition of this sudden flood of OM consumes DO, leading to hypoxic or anoxic conditions. Eutrophication and hypoxia are paired processes, well recognized in places such as the Gulf of Mexico where the OM influx from the Mississippi River has tripled since the 1950s due, in large part, to fertilizer runoff (Rabalais et al., 2010). This OM runoff causes widespread hypoxia in the Gulf every summer, commonly called the “dead zone”. In the PNW, the high influx of OM is not from local runoff, but from upwelled nutrients from the deep (Grantham et al., 2004; Diaz & Rosenberg, 2008).

Low levels of DO are natural in certain places and at depth in the ocean. Oxygen minimum zones (OMZs) typically occur between 100 m and 1500 m where oxygen levels are less than 10% of surface values (Helly & Levin, 2004). They typically occur in deep

basins, eastern boundary upwelling systems, and fjords (Rabalais et al., 2010). Their formation is due to the decomposition of sinking OM from surface waters. The OM is broken down above the pycnocline by respiring microbes that draw the oxygen levels down. OMZ boundaries result from features and processes such as surface productivity, water mass age, and circulation (Helly & Levin, 2004). Intensity, vertical position, and thickness of the OMZ vary with latitude in the eastern Pacific Ocean (Helly & Levin, 2004). Off the coast of Oregon, the OMZ lies at greater than 600 m depth (Chan et al., 2008).

Recent studies have shown the OMZ is shoaling in the eastern Pacific (Whitney et al., 2007; Chan et al., 2008; Bograd et al., 2008; Stramma et al., 2008). This pattern, in conjunction with observations of declining DO levels in shelf and estuarine waters in the California Current System have recently prompted concern in the scientific community (Bograd et al., 2008; Whitney et al., 2007; Chan et al., 2008; Stramma et al., 2008; Vaquer-Sunyer & Duarte, 2008). Chan et al. (2008) report that in the past decade, scientists have observed areas of severe hypoxia on the shelf that have never been seen there before. Basin-scale fluctuations in ocean-atmosphere processes are thought to be causing these events by altering the oxygen content of upwelled water, the intensity of upwelling wind stress, and the productivity-driven increases in coastal respiration (Chan et al., 2008).

Some studies suggest that the effects of climate change will aggravate hypoxia by increasing its frequency, duration, and intensity (Rabalais et al., 2010; Bakun, 1990; Whitney, 2007). Strengthened stratification of the water column by increased solar heating of surface waters could further isolate oxygen-depleted waters from reaeration.

Detrimental human activities such as the overuse of fertilizers, the burning of fossil fuels, urbanization, and wastewater generation exacerbate the system further. Nutrient loading in rivers from these processes paired with increases in precipitation intensity will likely worsen eutrophication and subsequent hypoxia. Changes in the wind fields could expand OMZ's onto continental shelf areas (Rabalais et al., 2010; Bakun, 1990). These effects are spatially dependent, however. Some areas might see contrasting effects if sea surface temperatures decrease with shifting current patterns. An increase in storm frequency and severity can disrupt hypoxia by mixing surface waters.

It is also unclear what the effect of lower DO levels on the shelf will mean for Pacific Northwest coastal estuaries. While eutrophication-induced hypoxia has been well documented and studied (Rabalais et al., 2002; Diaz & Rosenberg, 2008; Breitburg, 2002; Sculley, 2013; Wenner et al., 2004), studies on the effects of upwelling-induced hypoxia are limited, especially for the smaller estuaries of the Pacific Northwest (NOAA, 1998). In the CCS, upwelling pulls water from the California Undercurrent onto the continental shelf (Hickey & Banas, 2003). These low DO, nutrient-rich waters then are in prime position for advection into coastal estuaries. In the Pacific Northwest, upwelling-induced low DO events have been documented in the Columbia River estuary (Roegner et al., 2011), in the Yaquina estuary (Brown & Power, 2011), in Willapa Bay (Pearson & Holt, 1960), and in Hood Canal (Newton et al., 2007). The advection of upwelled waters into Coos Bay has been observed (Roegner & Shanks, 2001), however the presence or absence of hypoxia in the estuary has yet to be determined.

2.4. Coos Bay as an Oregon Estuary

Coos Bay is mesotidal with mixed semidiurnal tides ranging from 2.3 m at the mouth to 2.2 m at the city of Coos Bay (Rumrill, 2006). Low tide exposes vast tidal flats that make up approximately half of the estuary's surface area (Percy, 1974). These extensive flats, in conjunction with a deep channel, produce an ebb-dominant system where flood tides are dampened by friction with the flats and ebb tides rush out the channel (Hyde, 2007). Coos Bay has a tidal prism of $7.65 \times 10^8 \text{ m}^3$ (Rumrill, 2006; $1.89 \times 10^9 \text{ ft}^3$, Johnson, 1972), smaller only than the Columbia and Tillamook estuaries in Oregon. The tidal currents average 1 m/s, with maximum-recorded currents at 1.7 m/s (Baptista, 1989).

Coos Bay, like most estuaries, has an along-estuary salinity gradient from its mouth to its head that induces an along-estuary density gradient that drives the gravitational circulation (e.g., Hansen & Rattray, 1965; Stacey et al., 2001; Geyer & MacCready, 2014). The saltier oceanic water enters the estuary at the mouth, and proceeds landward at depth. Freshwater input from the rivers flows seaward, buoyantly riding over the salty seawater. This circulation is considered secondary, or the residual, to the tidal circulation, and depends on the freshwater input, geometry, and tidal strength (Geyer & MacCready, 2014).

In the PNW, most estuaries are small in size and have relatively low freshwater discharge (Emmett et al., 2000). The Columbia River is an exception, as it supplies enormous an freshwater input to the coastal system, accounting for 77% of the drainage along the U.S. west coast north of San Francisco (Barnes et al., 1972). Estuaries and their associated rivers play a role in coastal circulation by injecting nutrients, freshwater and

energy (Whitney et al., 2005), and by modifying stratification and turbidity. However, aside from the Columbia, river plumes on the U.S. west coast are small and their effects are limited to one or two tidal excursions of the mouth of the river or estuary (Hickey & Banas, 2003). Seasonal variability in river discharge and stratification, vast tidal flats, and large tidal prisms are properties common to Pacific Northwest estuaries that make tidal stirring an important component of flushing (Hickey & Banas, 2003). In the dry season as river inputs dramatically decrease, the water properties of these small estuaries are controlled more by mesoscale coastal ocean processes than by *in-situ* processes (Hickey et al., 2002, Hickey & Banas, 2003).

2.5. Estuarine Classification Theory

Despite the minimal hydrographic research on small PNW estuaries, we can leverage the broader literature on estuarine dynamics to provide context for the Coos Bay system.

The long-standing definition of an estuary is “a semi-enclosed coastal body of seawater which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage” (Pritchard, 1967). Estuaries can be further delineated according to mixing properties and circulation patterns arising from density differences caused by salinity distribution (Dyer, 1973). Salt-wedge estuaries occur where the influence of river flow is much greater than the tides, such that vertical stratification is strong and pronounced. Moderate stratification develops when tidal action is the dominant force mixing salt and fresh water. This produces a partially mixed estuary characterized by mixing at all depths, but with lower

waters remaining saltier than overlying waters. The third type of estuary is a well-mixed estuary. Vertical homogeneity results from strong tidal currents breaking down any layering in the water column and eliminating vertical stratification. When salinity is vertically averaged in the water column, all estuary types are saltiest where the estuary meets the ocean and freshest at the river mouths.

Hansen and Rattray (1966) were among the first to provide a method for quantifying estuarine classification via stratification. They crafted a two-dimensional scheme based off a theoretical examination of estuarine dynamics. They compared an estuary's strength of stratification (defined as the ratio between vertical salinity difference to the mean salinity: $\frac{\partial s}{s_0}$) to its strength of circulation (defined as the ratio of near surface velocity to freshwater flow: $\frac{u_s}{u_f}$). Where an estuary falls in this 2-D parameter space characterizes its classification.

Following Hansen and Rattray's analysis, Fischer (1972) developed an estuarine Richardson number, Ri_e , that compares the potential energy input from river inflow to the work done by bottom stress: $Ri_e = \frac{\beta g s_0 h_0 u_f}{u_t^3} = \frac{u_d^2 u_f}{u_t^3}$. The terms in the equation are the freshwater discharge rate per unit cross-sectional area of the estuary, the freshwater flow: $u_f = \frac{Q_f}{A}$; a representative value for tidal velocity: u_t ; and the densimetric velocity: $u_d = \sqrt{\beta g s_{ocean} h_0}$, where $\beta = 7.7 \times 10^{-4} \text{ psu}^{-1}$, g is the acceleration of gravity, s_0 is the oceanic salinity, and h_0 is the water depth. The transition from well-mixed to highly stratified conditions occurs over $0.08 < Ri_e < 0.8$ (Fischer, 1976). Smaller Ri_e imply the water column is less stratified and turbulence has a larger role due to increased current shear.

Stacey et al. (2001) built on Fischer's approach by adding in a term that takes into account an estuary's aspect ratio. This new parameterization, originally termed the horizontal Richardson number, is now called the Simpson number (Geyer & Ralston, 2011): $Si = \frac{\beta g \frac{\partial s}{\partial x} h_0^2}{C_D u_t^2}$. The terms $\partial s / \partial x$ and C_D represent the depth-averaged, along-estuary salinity gradient and the bottom drag coefficient, respectively. $Si < 1$ indicate that tidal flows are strong enough to overcome the effects of baroclinic flow and destratify the water column (Stacey et al., 2001).

The Hansen-Rattray classification has dominated estuarine parameterization since its inception. However, it neglects temporal variability in estuarine stratification and circulation. A more recent approach (Geyer & MacCready, 2014), resolves this issue by creating a parameter space (Figure 3) based on the freshwater Froude number $Fr_f =$

$$\frac{u_f}{\sqrt{\beta g_{\text{ocean}} h_0}} \text{ and mixing parameter } M = \sqrt{\frac{C_D u_t^2}{\omega N_0 h_0^2}}. Fr_f \text{ characterizes estuarine circulation}$$

as a ratio of the river flow velocity to the densimetric velocity, u_d , which is the maximum possible velocity driven by the density gradient. The mixing parameter M better represents stratification within an estuary because it relates the tidal timescale to the vertical mixing timescale. High, intermediate, and low M values indicate strong tidal nonlinearity, strain-induced periodic stratification (SIPS; Simpson et al., 1990), and conventional estuarine dynamics, respectively (Geyer & MacCready, 2014). Because tidal velocities u_t , river flow u_f , and depth h_0 can vary through time significantly within an estuary, each is displayed in the parameter space as a rectangle, not a single point (Figure 3).

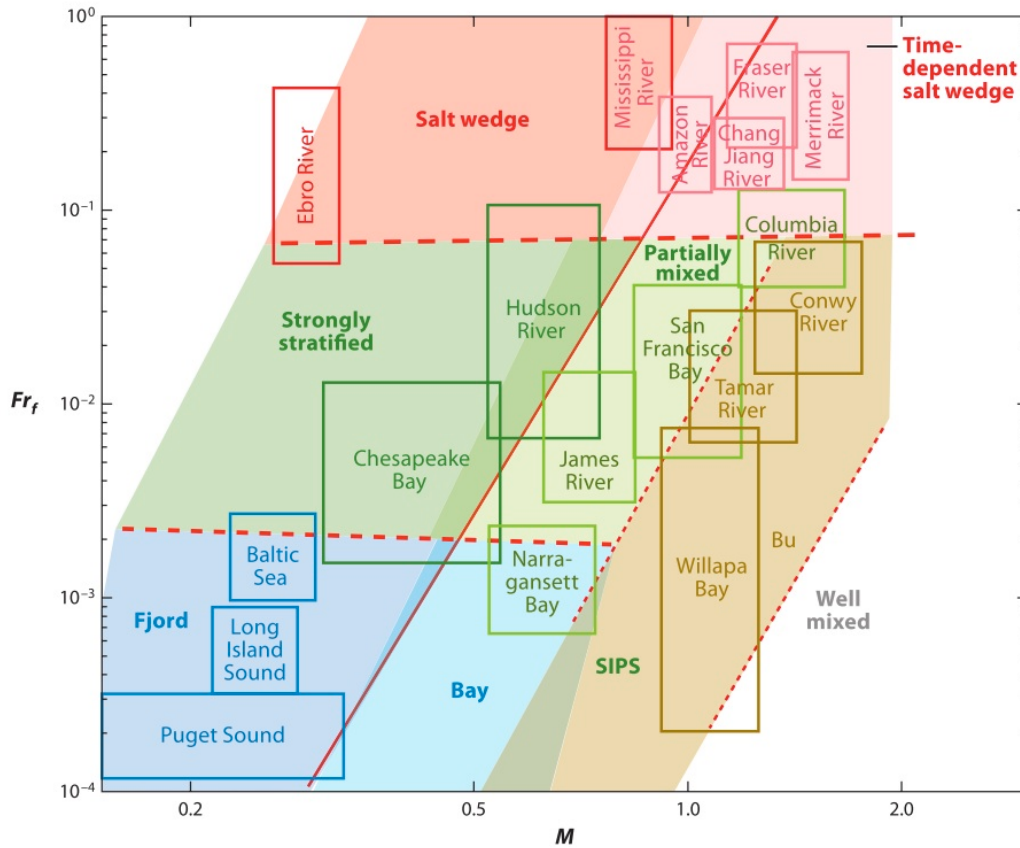


Figure 3. Geyer & MacCready's (2014) estuarine parameter space; systems are classified by their freshwater Froude numbers, Fr_f , and a ratio of tidal stirring to stratification, M . The bold, diagonal red line represents where the tidal boundary layer can reach the surface, based on M .

Estuaries can, and often do, shift from one classification to another throughout the year as currents and salinity distributions change with variations in river flow, width, depth, and tidal range, among other factors (Burt & McAlister, 1959). The literature cites Coos Bay as a well-mixed estuary, occasionally becoming partially mixed during winter months of high freshwater inflow (Burt & McAlister, 1959; Blanton, 1969; Arneson, 1976; Baptista, 1989; Rumrill, 2006). Shallow depths (mean depths: 2 m below mean low low water; Rumrill, 2006) throughout much of the estuary facilitate complete mixing of the fresh and saltwater, with the notable exception being the deep, dredged navigation

channel (Rumrill, 2006). Despite these previous studies, a detailed seasonal characterization of Coos Bay had yet to be completed until now.

CHAPTER III

METHODS AND DATA SOURCES

3.1. Monthly CTD surveys

The primary sampling program for this study involved monthly along-channel sections of CTD (conductivity, temperature, depth) profiles. These CTD sections were collected from a 20-foot aluminum (Woolridge) boat with a 130-horsepower outboard motor, maintained by OIMB. Data used in this study span sampling cruises starting in November 2012 and continuing through July 2014. Table 2 lists information about each of the sampling cruises presented in this study.

Table 2. Dates, conditions, and sampling details of the 23 CTD transects taken from November 2012- July 2014.

Count	Date	Instrument	Tidal Stage	Casts Taken	Oxygen	Lunar Tides
1	11-3-12	RBR XR-620	flood	22	Y	spring
2	1-19-13	RBR XR-620	flood	33	Y	neap
3	2-21-13	RBR XR-620	high slack	9	Y	spring
4	3-12-13	RBR XR-620	ebb	11	Y	spring
5	3-26-13	RBR XR-620	high slack	32	Y	spring
6	4-27-13	RBR XR-620	flood	32	Y	spring
7	5-19-13	RBR XR-620	ebb	19	Y	neap
8	7-11-13	SBE 19plus V2 SeaCAT Profiler	flood	16	N	spring
9	8-16-13	CastAway CTD	low slack	17	N	spring
10	9-7-13	CastAway CTD	flood	16	N	spring
11	9-17-13	RBR XR-620	flood	11	Y	spring
12	9-21-13	RBR XR-620	flood	13	Y	spring
13	10-10-13	RBR XR-620	flood	27	Y	neap
14	10-16-13	SBE 19plus V2 SeaCAT Profiler	high slack	8	N	spring
15	10-20-13	RBR XR-620	high slack	14	Y	spring
16	11-30-13	RBR Concerto	high slack	14	Y	spring
17	1-25-14	RBR Concerto	low slack	26	Y	neap
18	2-22-14	RBR XR-620	low slack	21	Y	neap

19	3-18-14	RBR XR-620	flood	11	2-11	spring
20	4-6-14	RBR XR-620	low slack	22	Y	neap
21	5-13-14	RBR Concerto	flood	19	1-4	spring
22	6-17-14	RBR Concerto	low slack	13	Y	spring
23	7-24-14	RBR Concerto	high slack	17	Y	spring

The CTD most often used was a RBR Titanium XR-620 Profiling CTD with three cable-mounted sensors (Rinko DO, Seapoint Turbidity and Seapoint Fluorometer). This CTD can be set to thresholding or constant logging settings to maximize either data collection or battery life. The sample rate is set at 6Hz. Other instruments that were used include a SeaBird CTD, a Castaway CTD, and a RBR Concerto CTD. The SeaBird and Castaway lack DO sensors, thus, for some months, DO data was not collected along estuary.

Sampling along the estuary typically began near the mouth, proceeded up-estuary, and was confined to the main channel. The CTD was lowered on a line off the side of the boat by hand at a controlled pace. When the line went slack, indicating the CTD had reached the bottom, it was brought back to the surface. The latitude, longitude, bottom depth, and time were all logged. At the end of the cruise, the data were downloaded using the RBR Ruskin software. The data were quality controlled and processed in Mathwork's MATLAB software. Predominantly, analysis of the CTD data was restricted to the downcast, because it recorded an undisturbed water column and had a more constant descent rate.

From November 2012 to January 2014, sampling followed the channel from the mouth past downtown Coos Bay, towards Isthmus Slough (Figure 4). Beginning in February 2014, the transect was modified to go up the Coos River instead of heading

towards Isthmus Slough. The intention was to capture more of the freshwater signal and inputs to Coos Bay. Another nonconventional sampling trip was October 10, 2013, when three cross-estuary transects were taken (See Appendix B).

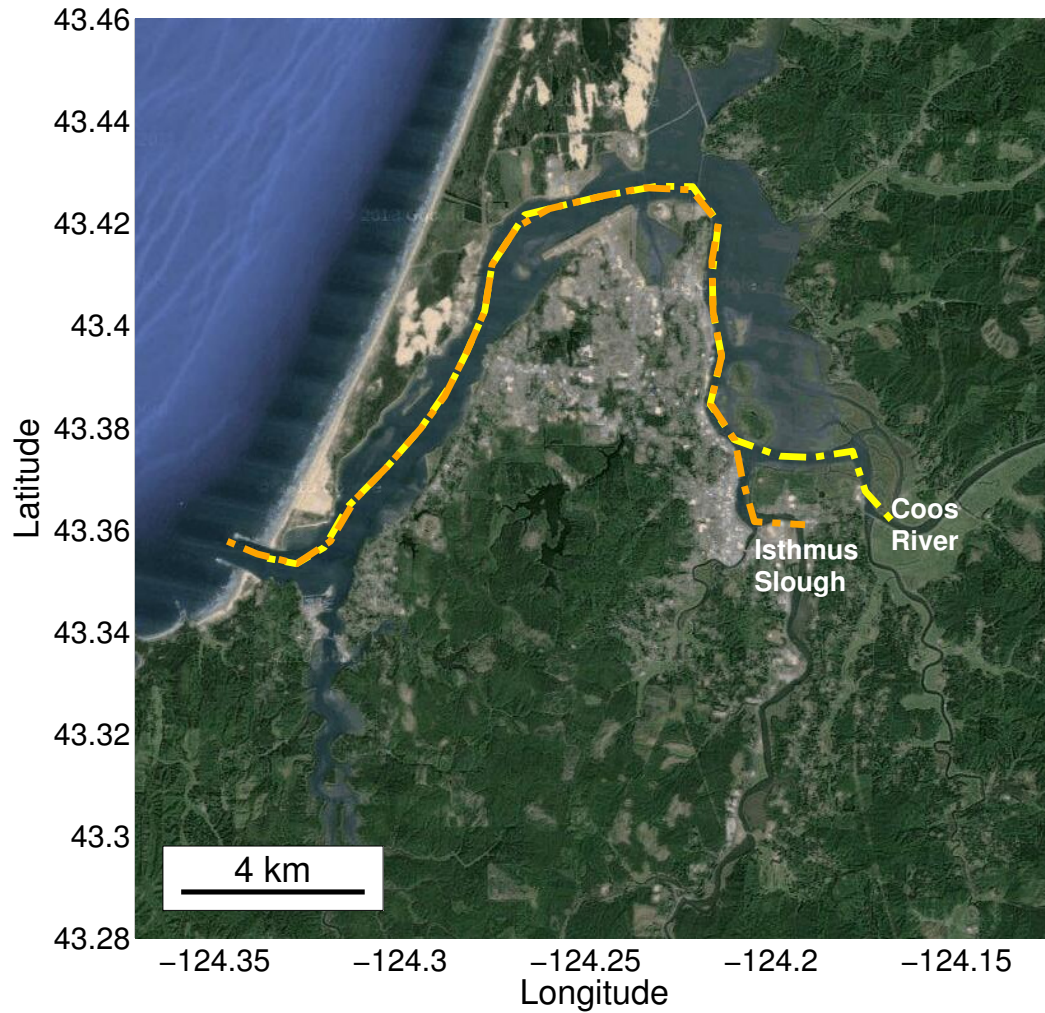


Figure 4. Map showing the two different CTD sampling strategies. The orange line is the transect route up until February 2014, where sampling proceeds up Isthmus Slough. Starting in February 2014, sampling targeted the Coos River, where more of the freshwater enters the estuary.

3.2. Physical Environmental Conditions

Before describing the observed hydrography, we present data on oceanic, atmospheric, and terrestrial conditions that dictate the physical environment of Coos Bay.

The Coos watershed includes all forks and tributaries of the Coos and Millicoma Rivers, and all of the sloughs and creeks that drain into the estuary. A local non-profit organization, the Coos Watershed Association (CWA), maintains and operates thirteen stream gaging stations and three weather stations through a variety of grants and funding sources. The gaging data were archived for each water year; data begins in 2003 and continues yearly. Data can be accessed at <http://www.cooswatershed.org/home.html>. Some of the earlier years have substantial gaps in data due to instrumentation complications. The CWA fills these gaps using Kister's Wiski software, the industry standard for management and analysis of stream discharge data (F. Reasor, CWA, personal communication, March 2014). Recent records (2009 - present) are more complete.

Only some of the gaging stations have data available, but the operational gaging stations include the South Fork of the Coos River and the East and West Forks of the Millicoma River (Figure 5)—the largest contributors to the freshwater inflow into Coos Bay (Rumrill, 2006). Discharge data from the CWA was used to estimate freshwater inflow to the estuary. Total freshwater inflow to Coos Bay was estimated by extrapolating discharge data and drainage areas from the major instrumented tributaries to the total drainage area of the Coos watershed.

The CWA only updates their gage data yearly, so discharge data were obtained from the nearby Siuslaw River to investigate if there was a relationship between it and the major tributaries of Coos Bay. Siuslaw River discharge data is made available by the U.S. Geological Survey (USGS). Data is updated in real-time on <http://waterdata.usgs.gov/nwis>.

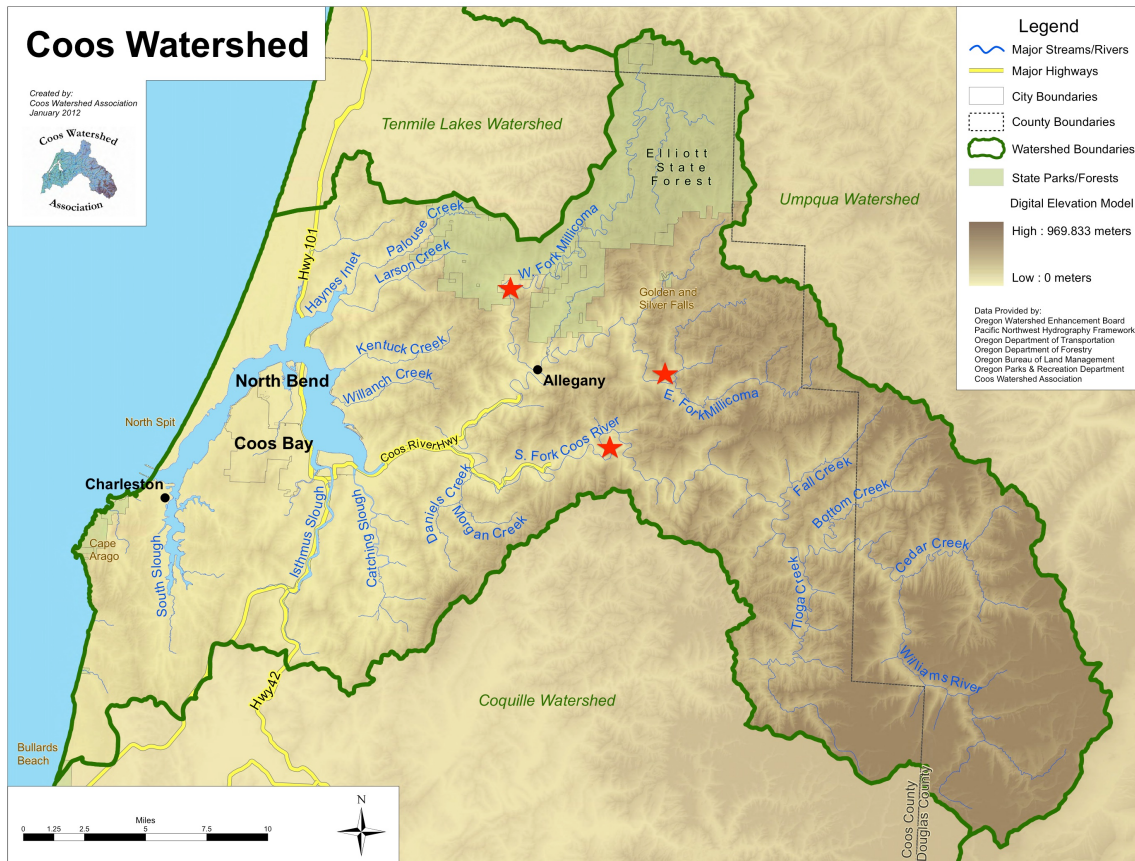


Figure 5. Map of the Coos watershed, created by the CWA. Modified to show the three major contributors to freshwater inflow (denoted by red stars): the South Fork of the Coos River, the West Fork of the Millicoma, the East Fork of the Millicoma.

Measurements of wind speed and direction, and air and water temperature were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (<http://www.ndbc.noaa.gov/>). Buoy 46015, located 15 nautical miles west of Port Orford and approximately 75 km southwest of Coos Bay (Figure 6), was selected for this study due to its proximity and robust (10+ years) dataset of wind speed and direction. These data were used to calculate daily alongshore wind stress, following the methods of Large and Pond (1981). Water temperature data from Buoy 46229 are also used for comparison. This buoy is approximately 48 km northwest of the mouth of

Coos Bay (Figure 6). It lacks wind data, but because mean spring and summer shelf currents are southward, the water temperatures from it are more indicative of the shelf waters entering Coos Bay in the dry season. Local wind data came from the SSNERR meteorological station, located on the OIMB campus in Charleston (Figure 1).

Precipitation data for this study came from NOAA's National Climatic Data Center (NCDC; <http://www.ncdc.noaa.gov/>). Daily precipitation data from the North Bend Airport (Figure 6) were used to understand the periodicity and intensity of storm events affecting the near Coos Bay.

Not much data exists for the shallow shelf off Coos Bay, except for a dataset from the GLOBEC-NEP program (Batchedler et al., 2002) that maintained a mooring about 16 km southwest of the mouth Coos Bay (Figure 6). The mooring gathered temperature, salinity, and velocity data from late in April 2000 to early September 2004. While the data do not coincide with the CTD transects, they do overlap with the SSNERR water quality logger data. The mooring dataset provided context for the background shelf conditions near Coos Bay. The data were accessible via an online data repository set up by the University of Washington (<http://coast.ocean.washington.edu/coastdata/GLOBEC/GLOBECPCB.htm>).

Water level data from the Charleston tidal gage were used to examine tidal variability in Coos Bay (available at: <http://tidesandcurrents.noaa.gov/>). The gage is located in the Charleston Boat Basin. The average lag between high tide at the entrance to Coos Bay and downtown Coos Bay (Figure 1) is 38.5 minutes (Arneson, 1976).

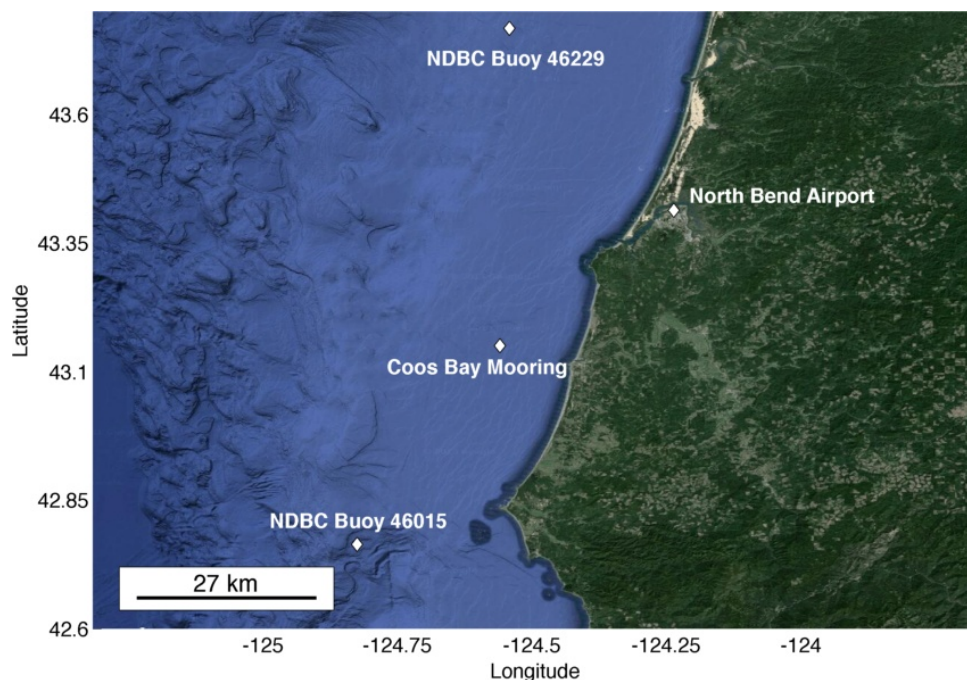


Figure 6. Locations of instrumentation providing oceanic and atmospheric data. NDBC buoys 46229 and 46015 on the shelf northwest and southwest of Coos Bay were used along with precipitation data from the North Bend Airport, and mooring data from the Coos Bay mooring (2000-2004).

3.3. Complementary Time Series Data

Data from several monitoring organizations were used in this study to investigate temporal trends in hydrography and DO levels, providing valuable context for the monthly CTD transects and the seasonal cycle in Coos Bay.

The SSNERR data is available online (<http://cdmo.baruch.sc.edu/>) from the Centralized Data Management Office (CDMO), an accessible database of all estuaries in the National Estuarine Research Reserve System. Meteorological, water quality, and nutrient data is available from 1995-present. This high-resolution data was analyzed to investigate longer-term trends in water quality and to relate the South Slough to the larger Coos estuary.

There are five Yellow Spring Instrument (YSI) dataloggers that have been operational for a decade or longer at the following sites: Winchester Arm, Sengstacken Arm, Valino Island, Elliot Creek, and Charleston Bridge. These sites use 6600 V2 sondes deployed approximately 0.5 m off the bottom inside protective tubes (<http://www.partnershipforcoastalwatersheds.org/coos-bay-water-quality-monitoring-network/>), collecting data every 15 minutes. Here, we primarily used the logger at the Charleston Bridge station (Figure 1) due to its proximity to the main estuary, and the depth of the water it is positioned in.

In late November 2013, the SSNERR deployed a suite of instrumentation throughout Coos Bay to aid in the development of the hydrodynamic model being developed by Dr. David Sutherland at the University of Oregon. Temperature and salinity loggers were positioned throughout the estuary and in some sloughs; the data from these loggers, however, is not presented here. In addition SSNERR deployed a Sontek Argonaut Acoustic Doppler Current Profiler (ADCP) about 8 km from the mouth, up-estuary, slightly out of the channel (Figure 1). The ADCP is moored to the bottom at 9 m depth, is upward-facing, and samples at 1500 kHz (Figure 7). The data were binned into ten, 1 m bins. Data from November 25, 2013 to May 27, 2014 were used in this study.



Figure 7. Sontek ADCP deployed by SSNERR 8 km up-estuary. Moored at 9 m depth.

Finally, two non-federal entities also monitored water quality in Coos Bay. The Confederated Tribes of the Coos, Lower Umpqua & Siuslaw (CTCLUSI) instituted a monitoring program in 2004 to manage and improve water quality in the watersheds of the southern Oregon coast. Since 2007, their program includes a YSI data logger located on the Bureau of Land Management (BLM) boat ramp on the North Spit of Coos Bay (Figure 1). The logger is approximately 8.4 km from the mouth of Coos Bay and it records temperature, salinity, DO, turbidity, pH, and water bacteria, taking readings every 15 minutes during the 2012 and 2013 water years. A second YSI logger at the Empire Docks (EMP), approximately 6.9 km from the mouth, took the same suite of measurements as previously described. These data were made available via a personal correspondence with Margaret Corvi, the environmental monitoring specialist for the CTCLUSI.

Additionally, the Coquille Indian Tribe's Water Quality Monitoring Program also operates a water quality logger. The logger is located near the Mill Casino in North Bend around 17 km up estuary (Figure 1). Exact coordinates of this logger are 43.4016 N, 124.219 W. The logger is moored at approximately 9 m. It records pH, total dissolved solids, salinity, temperature, dissolved oxygen, oxygen saturation, turbidity, and time. Bryan Duggan (Water and Environmental Specialist, Coquille Indian Tribe) provided logger data from September 2013- June 2014 for this study.

3.4. Historic Dissolved Oxygen Data

The Oregon Department of Environmental Quality LASAR database houses a long-term dataset of temperature, salinity, and oxygen in Coos Bay from 1957-2007 (C. Brown, personal communication). Previous publications have explored this data (Brown & Power, 2011; Lee & Brown, 2009); yet, they do not specifically focus on the mechanisms facilitating, nor conditions surrounding, the presence of hypoxic waters in Coos Bay.

The fifty-year DEQ dataset, while temporally robust, lacked proper documentation about sampling methods and data quality. It is likely that the temperature and salinity measurements preceding 1989 were made using an analog SCT meter and DO was measured through Winkler titrations (Larry Caton, DEQ, personal communication). After 1989, analog SCT meters were gradually phased out in favor of digital SCT meters and rapid-pulse polarographic oxygen sensors. Until 1999, the DEQ's salinity and temperature data was collected in conjunction with fecal bacteria monitoring in shellfish growing waters. After 1999, the DEQ partnered with the EPA's National

Coastal Assessment western pilot project and continued randomized sampling of water quality, fish tissue, and sediments (Larry Caton, DEQ, personal communication).

One major drawback of the DEQ dataset is that the depths of the sample measurements are not recorded. Latitude, longitude, station, date, time, and sampling matrix (surface water or bay/estuary/ocean) are recorded along with DO, salinity, temperature, and percent saturation DO.

CHAPTER IV

SEASONAL HYDROGRAPHY OF COOS BAY

This chapter addresses the first research objective of this study, “How do ocean properties and the seasonal change in forcing mechanisms affect estuarine circulation in the Coos Bay estuary?” This chapter shows that the seasonal cycle in oceanic, atmospheric, and terrestrial conditions can explain most of the observed hydrographic variability in Coos Bay. An overview of the hydrography will be presented first, followed by the terrestrial, atmospheric, and oceanic conditions that force the estuary system. Lastly, the estuarine circulation is presented with estimations of residence times for Coos Bay.

4.1. Results

4.1.1. Estuary Classification

The monthly CTD transects provided a diagnostic tool for observing how Coos Bay’s hydrography evolved through time. Temperature and salinity data from the CTD transects were visualized using a simple T-S (temperature-salinity) diagram. The data show how dynamic the system is (Figure 8). In the winter months sampled – late November, January, February, March—the waters were all relatively cold (5.5-12°C), and had a large range in salinity (0-33 psu). Large ranges in salinity indicated the elevated presence of freshwater in the estuary. The summer months of June, July, August, and September were warmer (10-21.5°C) and had a much narrower range in salinity (15-34 psu). Salinities were high because salt water was dominating the estuary. High solar insolation and relatively shallow estuarine depths facilitated high temperatures, especially

in the upper estuary. The spring and fall months showed the transition from the cold, mixed winter waters to the warmer, saltier summer waters in Coos Bay.

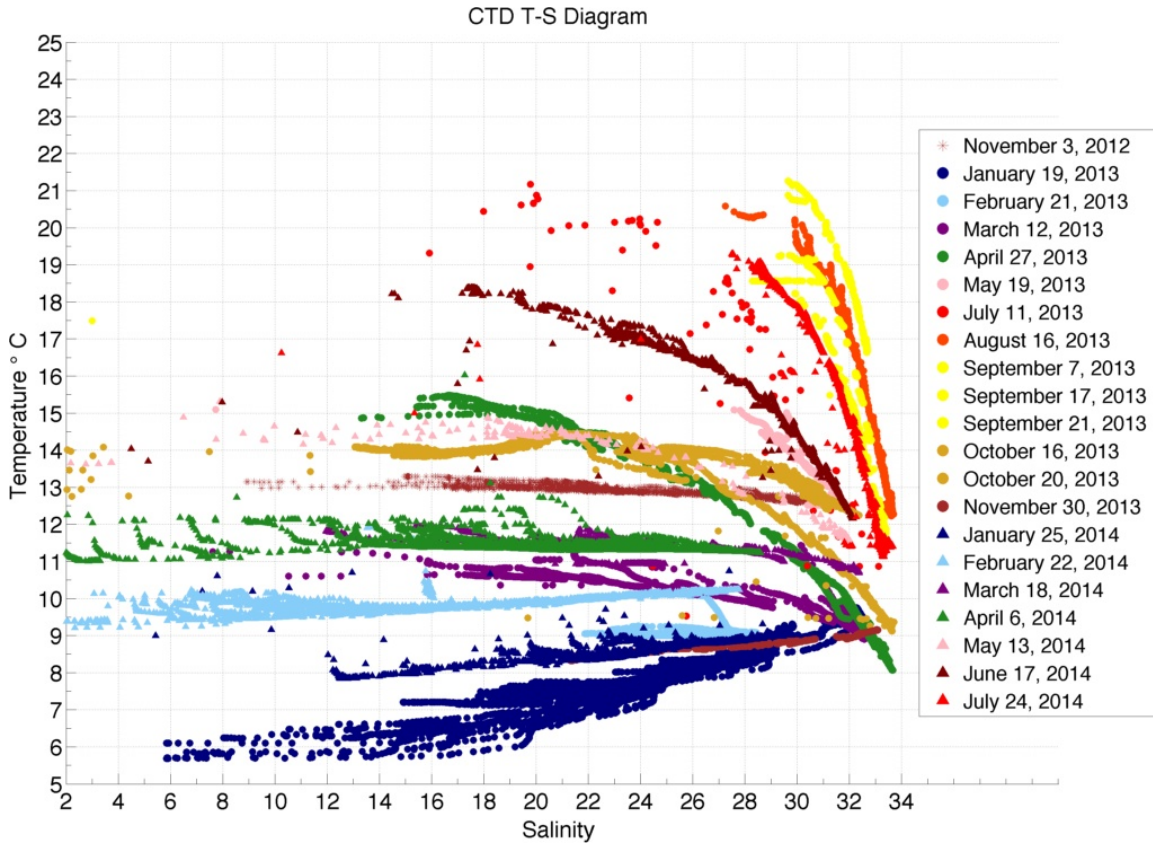


Figure 8. CTD transect data plotted in temperature-salinity (TS) space. Each color is representative of the month the transect was taken. Starred points (*) indicate data from 2012, circled points indicate data from 2013, triangular points represent data from 2014.

The CTD T-S diagram also revealed spatial variability in water properties along the estuary. River waters, which are the left-most points on the T-S plot, have a larger range in temperature (5.5-21.5°C), but are fresh, originating at the $S = 0$ intercept. Ocean waters, which are the lower right endpoints of each month on the plot, have a smaller range in temperature (8-12°C) and are salty (>30 psu). As each month's data trended away from the ocean end-member, movement up-estuary is implied.

From the CTD data, we created vertical sections of along-estuary water properties. The monthly CTD data suffer from tidal aliasing since the sampling transects usually took about 2-4 hours to complete, and were not done on a consistent tidal stage. Nonetheless, they served as useful tools in understanding hydrographic variation on longer timescales.

The vertical sections (Figures 9 -12, below) show contours of different water properties versus depth and distance. Distance is measured from the estuary mouth at $x = 0$ km (Figure 1), proceeding up-estuary along the deepest part of the main channel. Data are linearly interpolated in the vertical and horizontal to provide a continuous profile.

Figure 9 shows a CTD section from February 2014. In February, low river-end surface salinities indicated high river discharge. Isohalines were tilted horizontally, and stratification was distinct. Temperatures were low ($\sim 10^{\circ}\text{C}$) throughout the estuary and dissolved oxygen levels were high (> 9 mg/L).

The April CTD transect (Figure 10) showed a strong, along-estuary gradient in water properties. A plug of low temperature, high salinity water was apparent at depth near the mouth of the estuary. This water was also had relatively lower dissolved oxygen (Figure 10, bottom), presumably coming from depth off the shelf. Up-estuary of $x = 4$ km, isohalines were nearly vertical, indicating more well-mixed conditions away from the mouth.

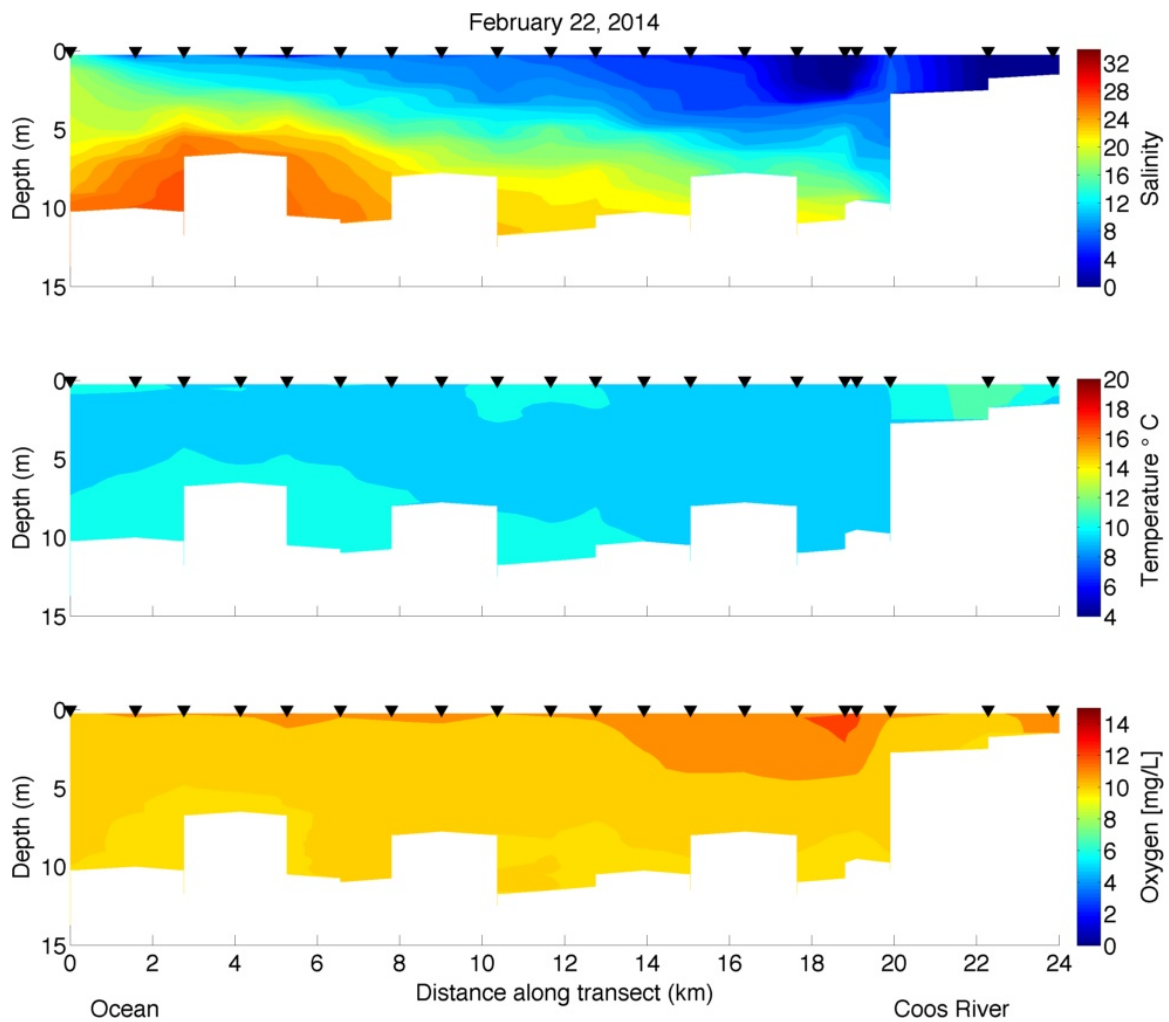


Figure 9. A CTD transect collected on February 22, 2014. The distance is measured from a point near the mouth of the estuary, and continues up-estuary in the channel to the Coos River. Salinity (top), temperature (center), and oxygen (bottom) are contoured and plotted versus distance and depth.

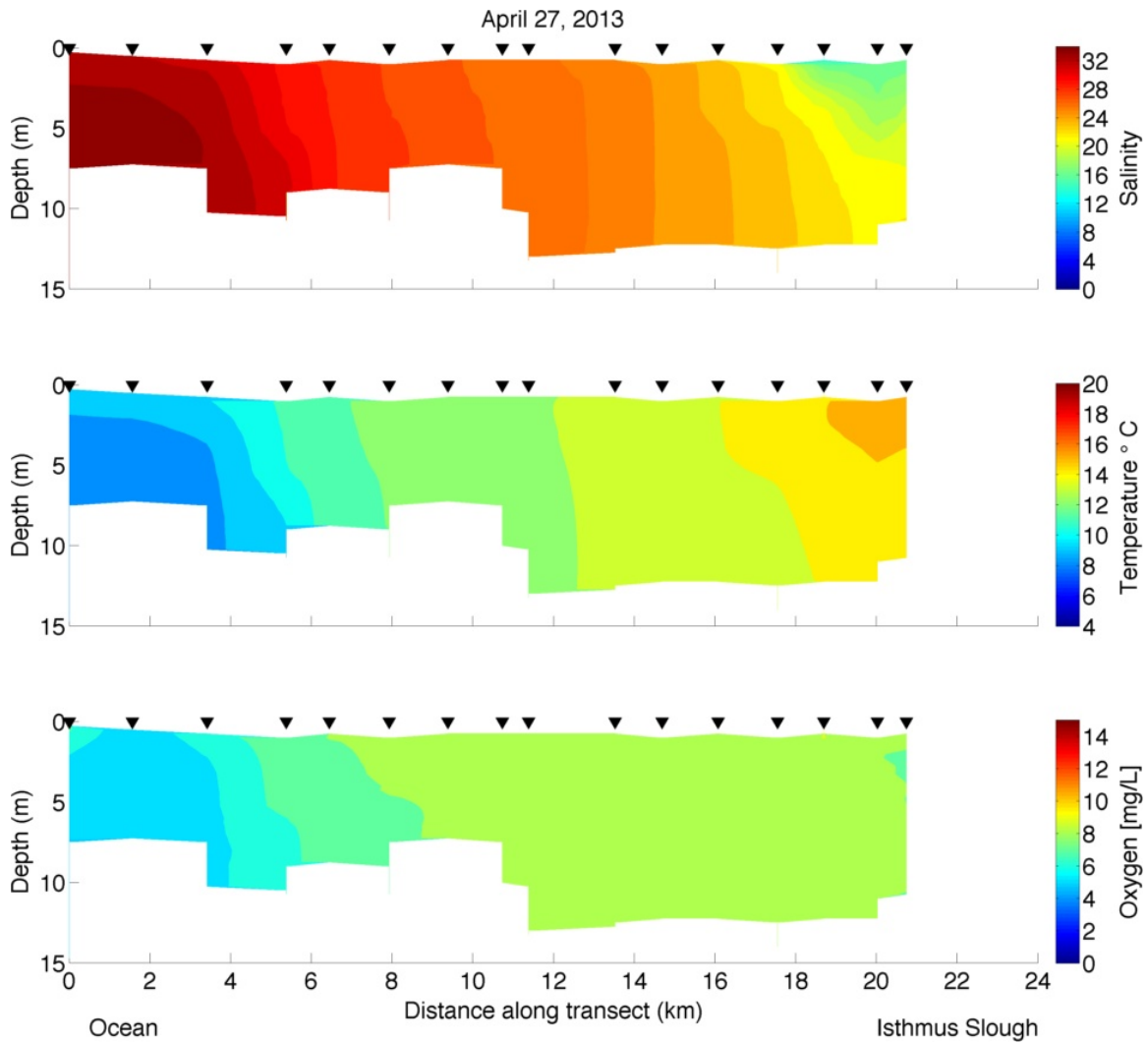


Figure 10. A CTD transect collected on April 27, 2013. The distance is measured from a point near the mouth of the estuary, and continues up-estuary in the channel to Isthmus Slough. Salinity (top), temperature (center), and oxygen (bottom) are contoured and plotted versus distance and depth.

In September (Figure 11), the estuary was completely inundated with high-salinity seawater. There was little river discharge mixing with the seawater, as evidenced by the presence of high salinity water in the upper estuary. Isohalines were vertical throughout the estuary, indicating well-mixed conditions. Water temperatures were lower at the mouth of the estuary. Dissolved oxygen levels were low, but still above the threshold of hypoxia.

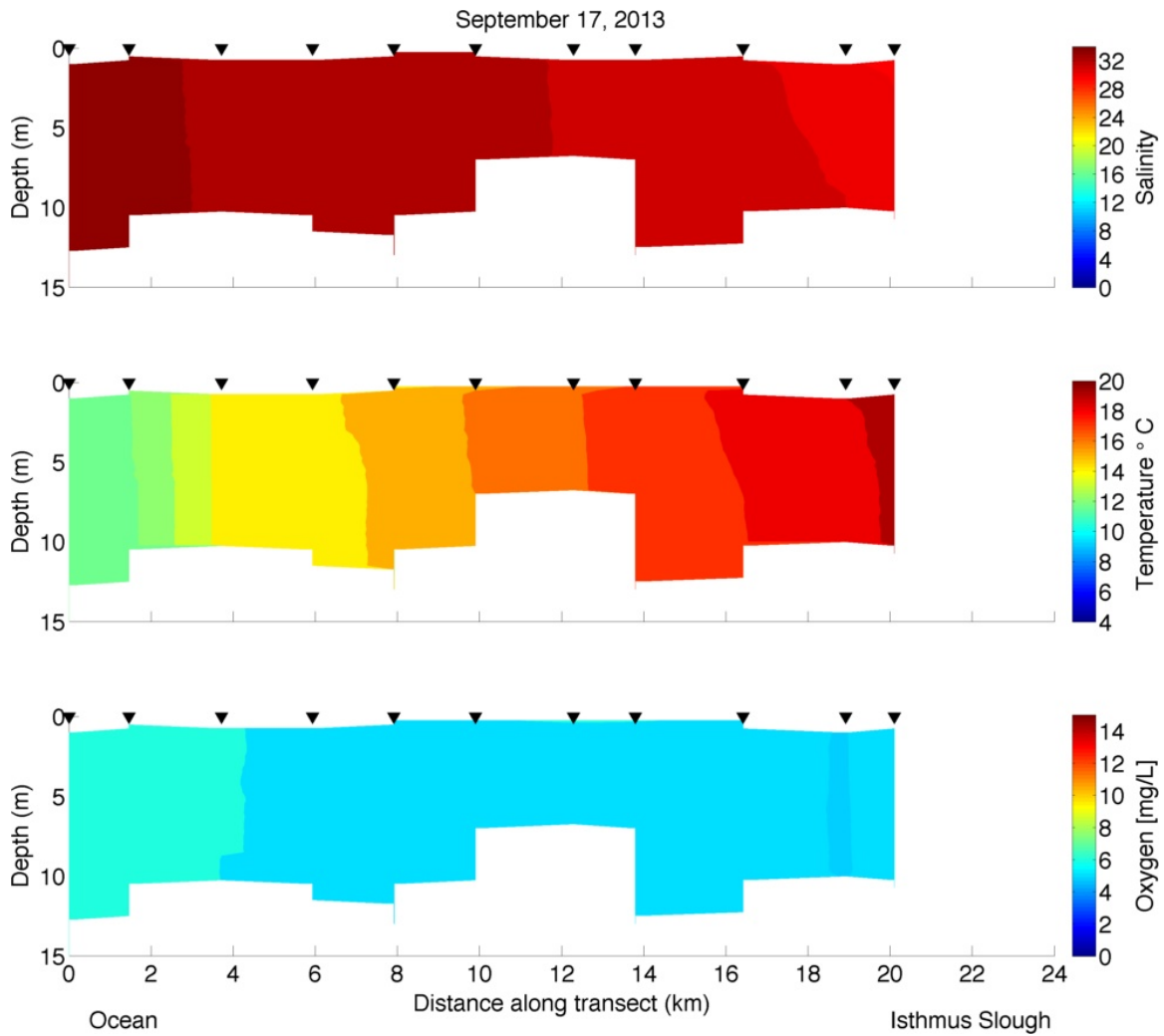


Figure 11. A CTD transect collected on September 17, 2013. The distance is measured from a point near the mouth of the estuary, and continues up-estuary in the channel to Isthmus Slough. Salinity (top), temperature (center), and oxygen (bottom) are contoured and plotted versus distance and depth.

The salinity profiles from the monthly CTD transect data can be repurposed to calculate along estuary salinity gradients. The along-estuary salinity gradient (Figure 12), $\partial s / \partial x$, is a useful parameter in estuary classification. Because salinity changes so much along the lengths of estuaries (Figures 8-11), it dominates seawater density. So the along-

estuary salinity gradient is a simpler way to look at the along-estuary density gradient, which in turn is a proxy for the baroclinic pressure gradient driving the estuarine circulation.

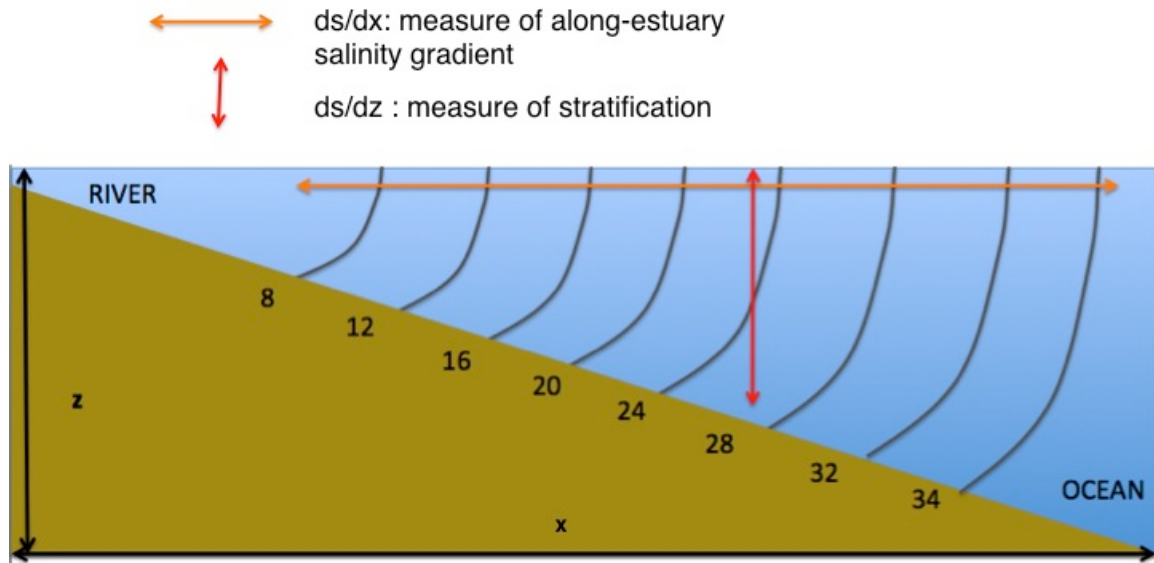


Figure 12. Schematic of the along-estuary and vertical gradients in salinity. Black numbered lines represent different isohalines throughout an estuary.

Since the monthly transects did not always follow the same route (i.e. Isthmus Slough vs. Coos River, Figure 4), for each month a station near the mouth was selected in addition to a station near the confluence of the Coos River with the main estuary (Figure 13). The monthly stations selected were all within a kilometer of their target points. To obtain ∂s , the depth-averaged salinity of the ocean end-member cast was subtracted from the depth-averaged salinity of the riverine end-member cast. The seawater distance between the two cast stations was ∂x (mean 9.80 km). Figure 14 shows how $\partial s / \partial x$ varied between each of our sampling trips. The along-estuary gradient varied by an order of magnitude, going from a minimum of 0.20 psu/km in the dry season to a maximum of 1.84 psu/km in the wet season.

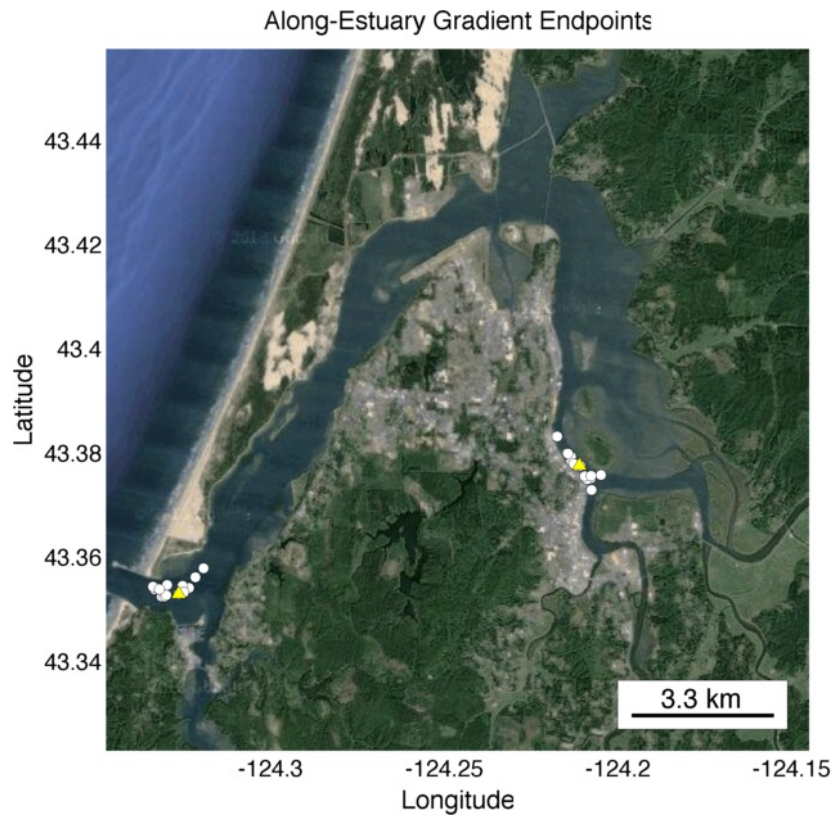


Figure 13. Locations of the target endpoints (yellow stars) in calculating the along-estuary gradient, $\partial s / \partial x$. White points represent the CTD casts for each month that fell the closest to the target endpoints.

It is worth noting $\partial s / \partial x$ varied with conditions that were not controlled for during our sampling trips. Tidal stage, spring/neap cycles, wind and discharge conditions can all influence $\partial s / \partial x$. We expect, however, the main control on $\partial s / \partial x$ in Coos Bay to be discharge, which varies more slowly than winds or tides. High discharge freshens the river end-member stations, increasing the gradient. Discharge and the along-estuary salinity gradient appear to have a logarithmic relationship.

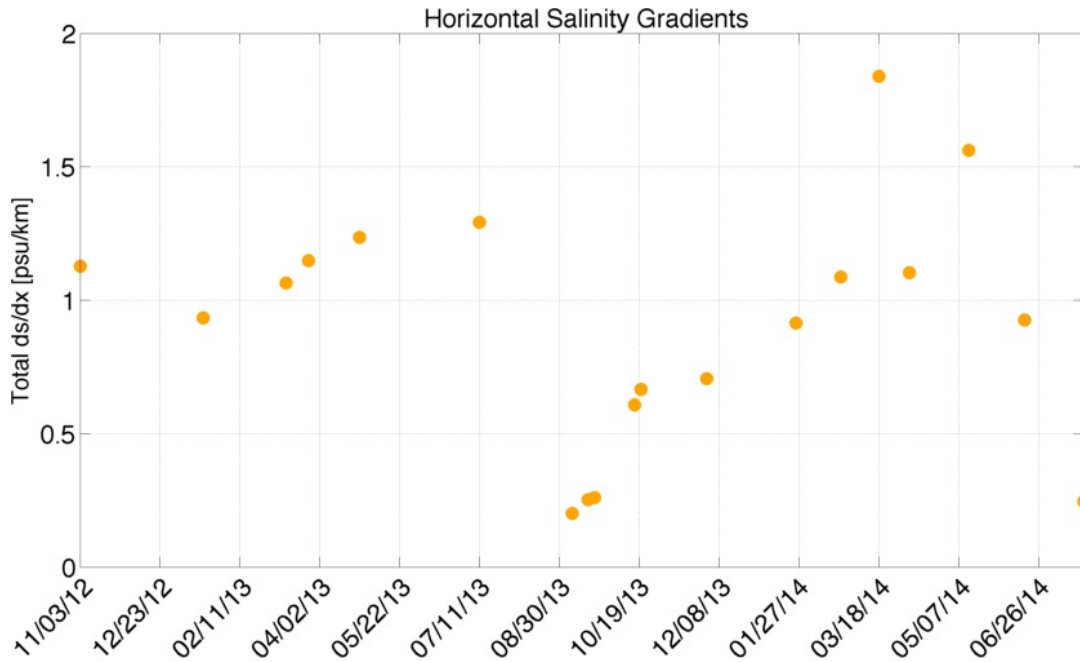


Figure 14. Depth-averaged horizontal salinity gradients from the CTD transects. These $\partial s/\partial x$ are not tidally averaged.

Figure 15 shows the along-estuary salinity gradient plotted against the mean discharge over the week leading up to and including the sampling date. For sampling dates prior to the start of the 2014 water year, discharge was calculated using the sum of the CWA gaging stations multiplied by the scaling factor (see section 4.1.2). After the start of the 2014 water year (10/01/2013), discharge was extrapolated from the Siuslaw River gage data. When discharge is less than $150 \text{ m}^3 \text{ s}^{-1}$, there is a linear relationship with $\partial s/\partial x$. However, at discharges greater than $150 \text{ m}^3 \text{ s}^{-1}$ this relationship appears to break down. It is likely that such strong discharge events push the saline ocean water further out of the estuary, freshening the middle and upper reaches considerably and driving down the gradient.

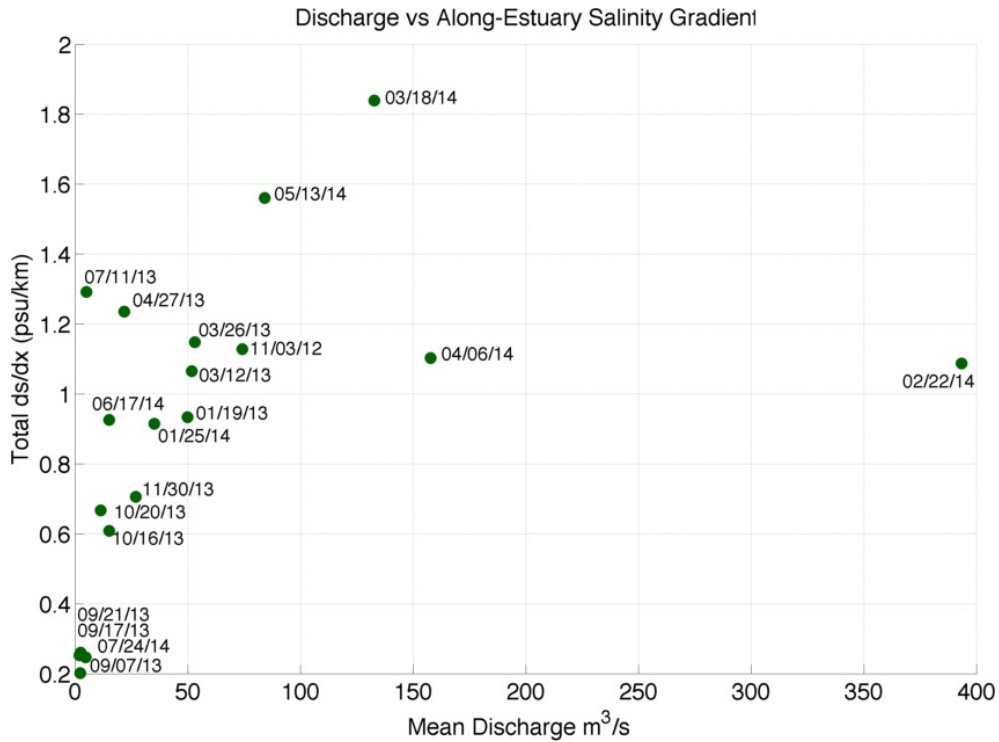


Figure 15. The along-estuary gradients from the CTD transects plotted against the mean discharge the week leading up to, and including, the day of each CTD transect. Labeled dates are the days of the CTD transects.

As mentioned previously, salinity is the primary control on density in an estuary. Thus, water column stratification can be estimated from $\partial s / \partial z$ alone. Using the monthly CTD data, we quantified $\partial s / \partial z$ for each of the sampling trips. The mean salinity of the upper 2 m of the water column was subtracted from the mean salinity of the lowermost 2 m of the water column to obtain ∂s . The difference between corresponding depths of those salinity measurements was ∂z . Since a $\partial s / \partial z$ could be determined for each CTD cast, the mean over the entire sampling trip was taken to represent that month's stratification. Figure 16 shows the stratification for each trip. Vertical differences in salinity are almost nonexistent in the dry season, but high discharge drives greater stratification in the wet season.

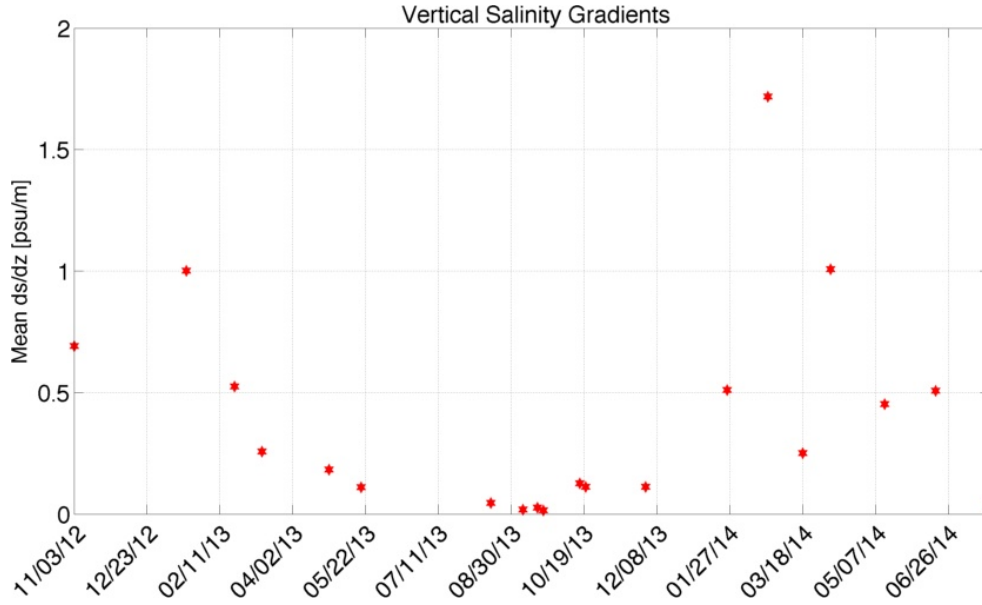


Figure 16. Mean stratification (psu/m) of all the CTD casts for each sampling trip.

Figure 17 shows the mean discharge for the seven days leading up to, and including, the sampling day, plotted against stratification. Stratification was linearly correlated to discharge, with an $R^2 = 0.71$.

Using these data, we employed dimensionless estuarine parameters to classify Coos Bay. The estuarine Richardson (Ri_e) number is a dimensionless ratio of the energy input from river flow to the work done by bottom stress. This formulation was discussed in Chapter III ($Ri_e = \frac{\beta g s_0 h_0 u_f}{u_t^3} = \frac{u_d^2 u_f}{u_t^3}$), and we use it to classify Coos Bay and to show why high discharge causes high stratification in the estuary.

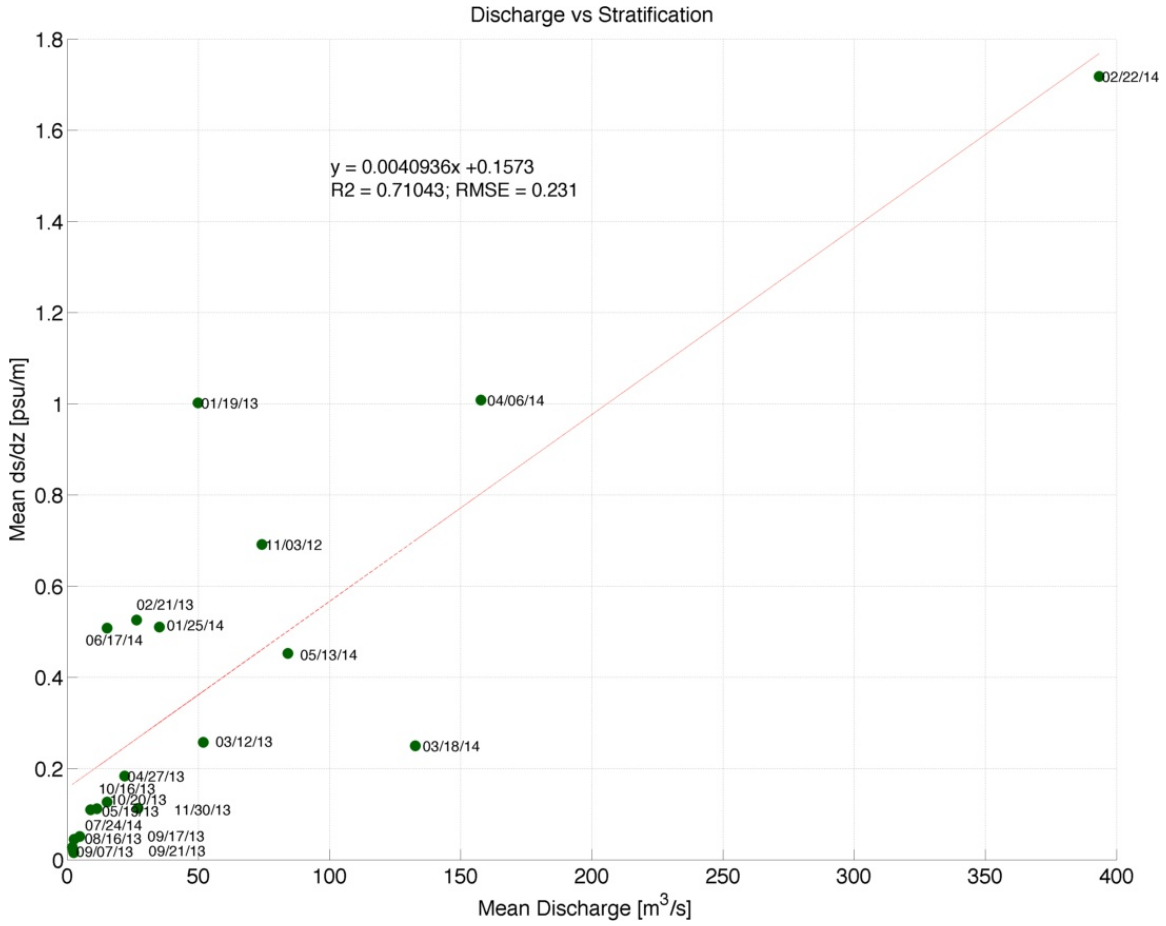


Figure 17. Mean discharge over the seven days leading up to, and including, the day of sampling plotted versus the mean stratification of all the casts taken that day. The red line indicates the linear regression of stratification and discharge.

We calculated Ri_e using the values from Table 3. We employed freshwater flow velocities from the CWA from 2003-2013 for u_f . The oceanic salinity and the freshwater flow velocities varied in time, otherwise all parameters were constant. In reality, the depth (h_0) and tidal velocities (u_t) would vary also, however, the CTD data did not resolve the variability in these parameters well. With these values, the mean and standard deviation Ri_e is 0.07 ± 0.065 ; the median Ri_e is 0.06. From May- October, $Ri_e < 0.08$, indicating that the stratification in Coos Bay can be mixed away by bottom

generated tidal mixing and it is a well-mixed estuary (Table 4). Under higher discharges from November – April, $0.08 < Ri_e < 0.8$, and Coos Bay is partially mixed (Table 4).

Table 3. Parameter values used for the nondimensional parameterizations of Coos Bay.

Parameter	Value
β : coefficient of expansivity for salinity	$7.7 \times 10^{-4} \text{ psu}^{-1}$
g : gravitational force	9.8 m s^{-2}
a_0 : numerical constant	0.028
ω : tidal frequency	$2 \pi/T$
T : tidal period	44712 s (12.42 hr)
η : tidal amplitude	2.2 m
s_{ocean} : salinity of oceanic water	33-35 psu
H : depth	8 m – 15 m
w : width	1000 – 3000 m
Q_f : river discharge	$0 - 2200 \text{ m}^3 \text{ s}^{-1}$
u_f : freshwater flow velocity	$0 - 0.89 \text{ ms}^{-1}$
A : estuary cross sectional area	$2500 \text{ m}^2 - 3500 \text{ m}^2$
C_D : bottom drag coefficient	2×10^{-3}
$\partial s / \partial x$: along-estuary salinity gradient	$0.15 \times 10^{-3} - 0.95 \times 10^{-3} \text{ psu m}^{-1}$

The Simpson number ($Si = \frac{\beta g \frac{\partial s}{\partial x} h_0^2}{C_D u_t^2}$), also discussed in Chapter III, compares the strength of tidal mixing to the estuarine circulation (Stacey et al., 2001). Using CTD observations from Coos Bay (Table 3), $Si < 1$ in all instances. When the Si number is between 0.1-0.3 there is tidal variation in stratification, such that during flood tides the water column completely destratifies, then at least partially restratifies during ebbs (Geyer & MacCready, 2014). This phenomenon is called strain-induced periodic stratification, or SIPS (Simpson, 1990). According to the Si calculation, Coos Bay was in the SIPS regime during the September and October 2013 sampling cruises, the cruise in late November 2013, and the cruise in July 2014. CTD data from these transects yield $Si = 0.1 - 0.3$. Every other sampling cruise resulted in a Simpson number greater than 0.3,

implying the energy from the estuarine circulation was greater than that of tidal mixing, allowing the water column to remain partially stratified throughout the tidal cycle.

To compare Coos Bay against other estuarine systems, we followed the general approach of Geyer & MacCready (2014), using the freshwater Froude number $Fr_f =$

$\frac{u_f}{\sqrt{\beta g_{\text{ocean}} h_0}}$ against a mixing parameter, $M = \sqrt{\frac{C_D u_t^2}{\omega N_0 h_0^2}}$ (see Chapter III for theory). Using

values from Table 3, Fr_f 's were calculated to reflect the range of discharge conditions that Coos Bay experiences over a year. For these calculations, depth, h_0 , is approximated with endpoints of 8 m and 15 m, discharge values, Q_R , are from the scaled CWA discharges, and cross-sectional areas of 2500 m² and 3500 m² are used to approximate the area where the Coos River enters the main estuary. With these values, Fr_f for Coos Bay was on the order of $\sim 10^{-3}$ to $\sim 10^{-2}$ for months that experience low to moderate discharge. Winter and spring months had Fr_f 's on the order $\sim 10^{-1}$.

The mixing parameter, M , was calculated using the equation, $M = \sqrt{\frac{C_D u_t^2}{\omega N_0 h_0^2}}$. Tidal velocities, u_t , are found from, $u_t = \frac{1}{2} \frac{\eta}{H} \sqrt{g h_0}$, and the buoyancy frequency, $N_0 = \sqrt{\frac{\beta g_{\text{ocean}}}{h_0}}$. The values listed in Table 3 used in these equations yielded mixing parameters for Coos Bay of 0.55 – 1.6.

The values used to find the mixing parameter vary little on seasonal timescales. However, the tidal velocities will vary over a tidal cycle, in addition to spring/neap cycles. Depth bounds of 8 m and 15 m were used to simulate the behavior of estuarine circulation in the deep, dredged channel. Note, however, the mean depth of Coos Bay is 2 m (below MLLW; Rumill, 2006) due to the vast tidal flats. Using a smaller H would

result in higher values of M , putting Coos Bay further into the well-mixed regime. The tidal flats are likely more well-mixed all the time.

In the M vs. Fr_f parameter space, Coos Bay spanned several classification regimes (Figure 18). During low to medium discharge, when Fr_f values are small, and the tidal velocities are strong (causing higher M), Coos Bay falls in the SIPS space. Otherwise, with weaker tidal flows, Coos Bay is partially mixed. If discharge is high, then Fr_f values are high, and Coos Bay falls in the salt wedge classification. Using this classification scheme, Coos Bay notably never is in the well-mixed regime—a result that disagrees with our dry season CTD observations and calculated Ri_e values.

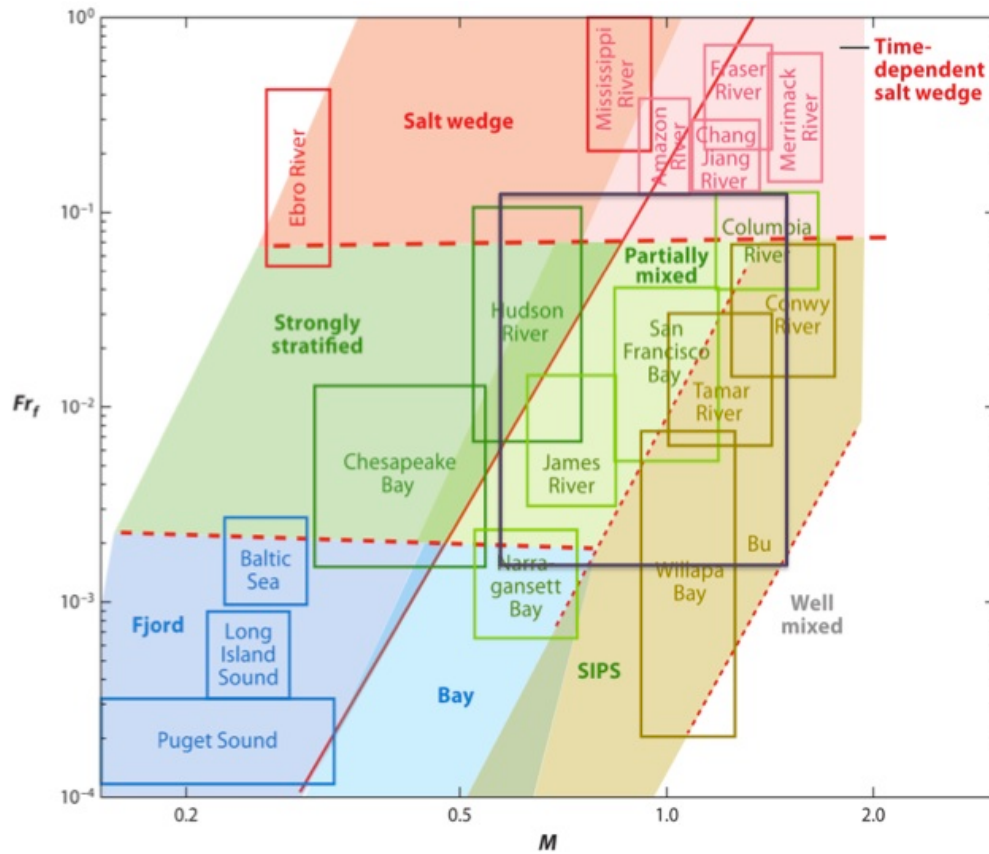


Figure 18. Coos Bay plotted in Geyer & MacCready’s estuarine parameter space (2014). Each estuary system is classified by its freshwater Froude numbers, Fr_f , and a ratio of tidal stirring to stratification, M . The bold, diagonal red line represents where the tidal boundary layer can reach the surface, based on M .

Table 4 gives a summary of the estuarine parameters used in defining the different regimes Coos Bay occupies over the course of a year. CTD observations and river inputs show that Coos Bay is well-mixed at times of low discharge, partially mixed at moderate discharges, and it becomes a salt-wedge type estuary at high discharges. Si numbers reveal Coos Bay can experience SIPS, however, to date there is no observational confirmation of this result.

Table 4. Estuarine parameters for Coos Bay. Si is the Simpson, or horizontal Richardson number. Ri_e is the estuarine Richardson number, Fr_f is the freshwater Froude number, and M is a mixing parameter.

Estuarine Parameters												
Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Si	0.36	0.43	0.53	0.46	0.61	0.36	0.30	NaN	0.09	0.25	0.36	NaN
Ri_e	0.17	0.10	0.16	0.09	0.04	0.03	0.01	0.00	0.01	0.01	0.08	0.17
Fr_f	0.40	0.24	0.38	0.22	0.09	0.06	0.02	0.01	0.02	0.02	0.20	0.40
M	0.5 - 1.6											

4.1.2. River Discharge and Freshwater Flow Velocities

To calculate many of the estuarine parameters, freshwater input to the system was quantified. Since only a fraction of the freshwater tributaries to Coos Bay are gaged, a scaling factor was calculated for the gaged watershed and the total watershed to obtain an estimate of freshwater inflow. A mean total watershed area (1542 km²), averaged using values found in the literature (NOAA, 1985; Percy, 1974; Arneson, 1976; Rumrill, 2006; Coos Bay EIS Supplement, 1975; Lee & Brown, 2009) was divided by the sum of the drainage areas given by the Coos Watershed Association (852 km²). Only stations with records dating back to 2003 were selected – the South Fork of the Coos River (SFCR), the East Fork of the Millicoma River (EFM), the West Fork of the Millicoma River (WFM), and Marlow Creek (MC). Dividing a mean total drainage area of 1542 km²

by the combined drainages 852 km², a scaling factor of 1.81 was obtained. Thus an approximation of the total freshwater inflow to the estuary was acquired by multiplying the sum of the discharges from these four gaged stations by the scaling factor. Figure 19 shows the scaled discharge for Coos Bay from 2002-2013.

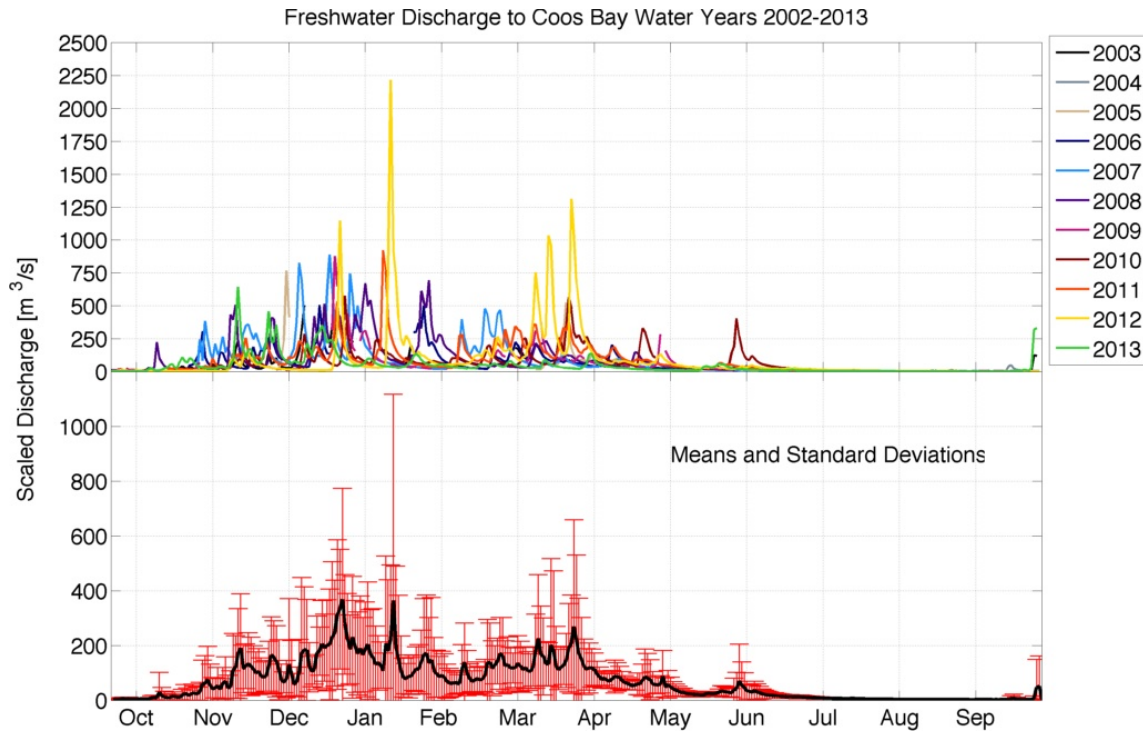


Figure 19. Discharge scaled to the entire watershed area using CWA gage data from 2002-2013. (Top) Each year represented with a different color line. (Bottom) Means and standard deviations over the 11-year record.

A seasonal cycle was apparent in the 11-year record of scaled discharge (Figure 19). Discharge was very low from May through October. From November through April, discharge was higher and punctuated by intense, synoptic events. High discharge events usually peaked over the timescale of a week.

Because the CWA only updates the gage data on its website annually, it was useful to have gage data from a major instrumented river that updated continuously. The

Siuslaw River is about 60 km north of Coos Bay and it is monitored by the USGS in real-time. The relationship between the Siuslaw gage data and the scaled Coos River gage data was determined by performing a linear regression on the datasets (Figure 20). Overlapping daily discharge data for the two rivers from October 1, 2002 to September 30, 2013 were plotted against one another in m^3/s . Days where data were missing from one or both rivers were eliminated from the analysis. With an $n = 3007$, the linear fit between the datasets had an $r^2 = 0.87$ and a root mean square error of 42.5. From this relationship, daily estimates of the freshwater contribution to Coos Bay were generated beyond the end of the 2013 water year.

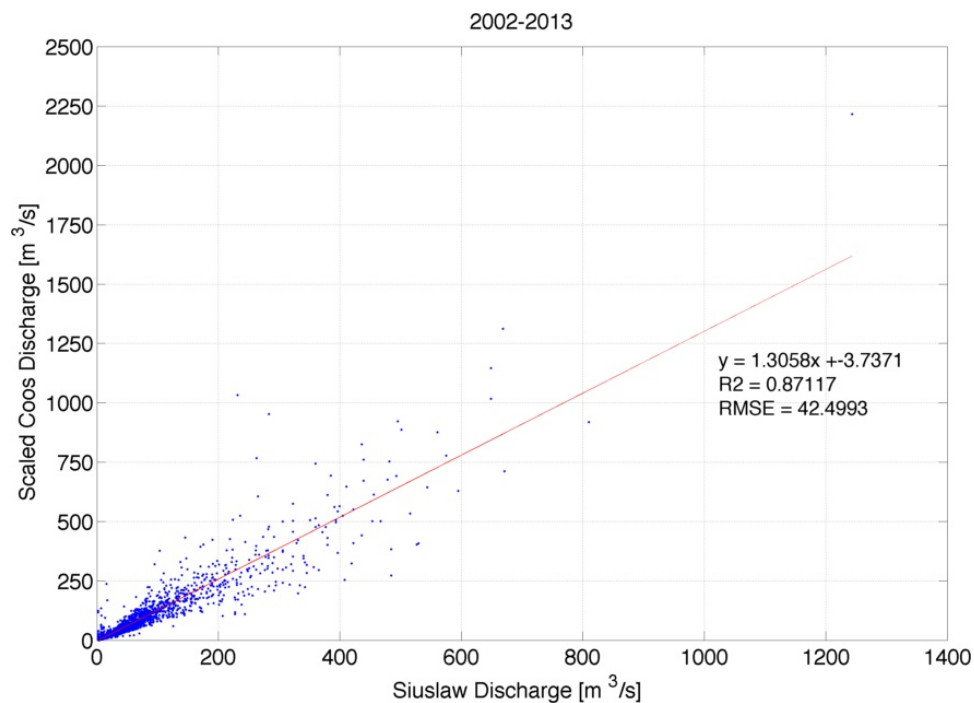


Figure 20. Linear regression between the Siuslaw River discharge and the scaled Coos discharge. Data from Oct. 1, 2002 to Sept. 31, 2013 were compared in the analysis.

To check the robustness of this method, the extrapolated Coos discharge using the linear regression fit from the Siuslaw was back-forecasted and plotted against the scaled

Coos discharge (Figure 21). The results matched the observed discharges fairly well. The mean +/- the standard deviation of the residuals were $\ll 1$ +/- 42.5. The median residual was -0.3698. There were some events when the residual was very large, likely due to delays in storm arrival between the two watersheds or instrumentation error. Overall, the fit was a good approximation of the discharge to Coos Bay.

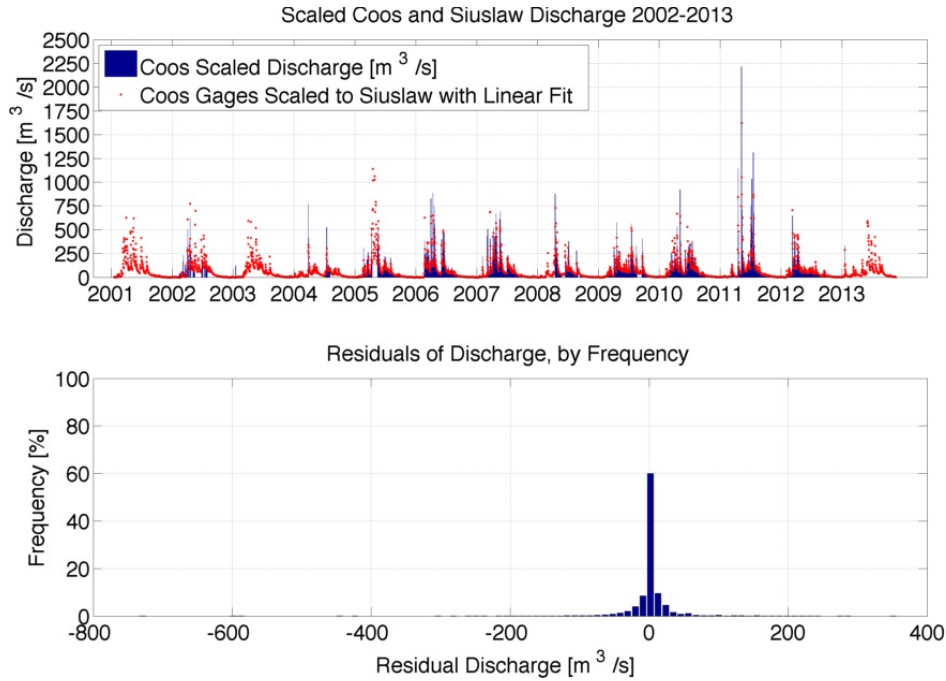


Figure 21. (Top) Comparison of Siuslaw discharge to Coos discharge over the period 2002-2013. Using the linear regression fit, the Siuslaw is modified and back-calculated (red dots) to match the measured CWA discharges (blue bars). (Bottom) The residuals of the two datasets. Negative residuals occur when the CWA gage discharge is larger than the Siuslaw fit discharge, and vice versa.

With these different means of approximating discharge to Coos Bay, we were able to calculate freshwater velocities, u_f . Assuming the estuary's deepest point is in the channel and shoals equally towards each shore (i.e., $A = \frac{1}{2} \cdot b \cdot h$), we approximated the cross sectional area of where the Coos River enters Coos Bay. Using the cross-sectional area with the scaled discharge data, we could find $u_f = \frac{Q_f}{A}$. The mean and standard

deviation of u_f calculated from the scaled discharges from October 2002 to September 2013 ($n=3007$) was $0.0265 \pm 0.047 \text{ ms}^{-1}$. The median u_f was 0.01 ms^{-1} , and the maximum u_f was 0.887 ms^{-1} .

4.1.3. Oceanic and Atmospheric Forcings

Now that we have established what type of estuary Coos Bay is, and quantified the freshwater inputs, we discuss the oceanic and atmospheric conditions that influence the hydrography and water properties of the estuary.

In Coos Bay the tides are mixed-semi diurnal, so there are two highs and two lows each day. There is also monthly variation in the tides due to the spring/neap cycle. Figure 20 shows a month of tidal data from the Charleston tide gage station, downloaded from <http://tidesandcurrents.noaa.gov/>.

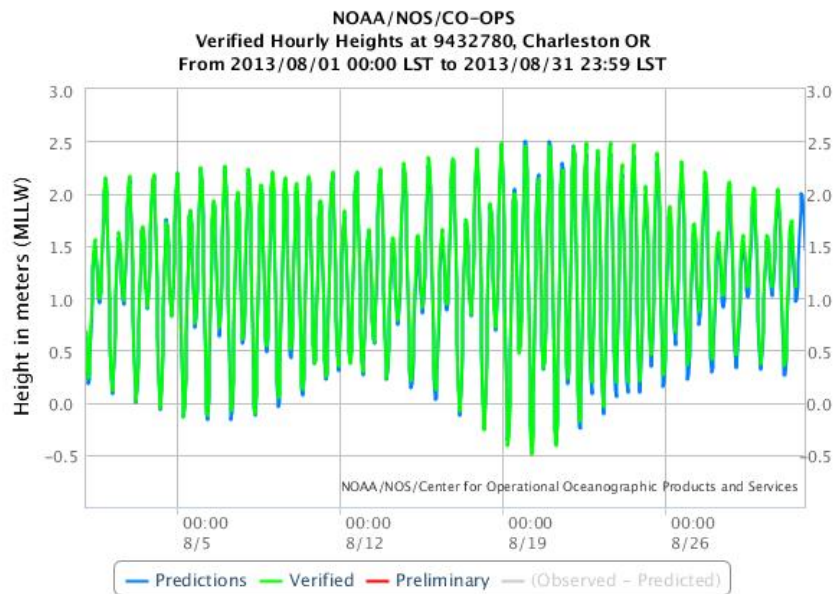


Figure 22. Plot from <http://tidesandcurrents.noaa.gov/> showing a month of tidal data for Coos Bay, measured in the Charleston boat basin. Spring/neap cycle is evident in the fluctuating range of water levels.

Precipitation in Coos Bay follows the seasonal pattern arising from shifts in the atmospheric pressure systems sitting over the Pacific Northwest. There is a distinct wet and dry season, as evidenced by rain gage data from the North Bend Airport.

Precipitation is high in the wet season (November – April), then diminishes and is sparse in the dry season (May-October) (Figure 23). Looking at the cumulative precipitation (Figure 24) throughout the water years, it is apparent that internannual variability is present, in addition to the seasonal variability. Some years see significantly more precipitation than others (2003, 2004, 2006 vs. 2001, 2009, 2012).

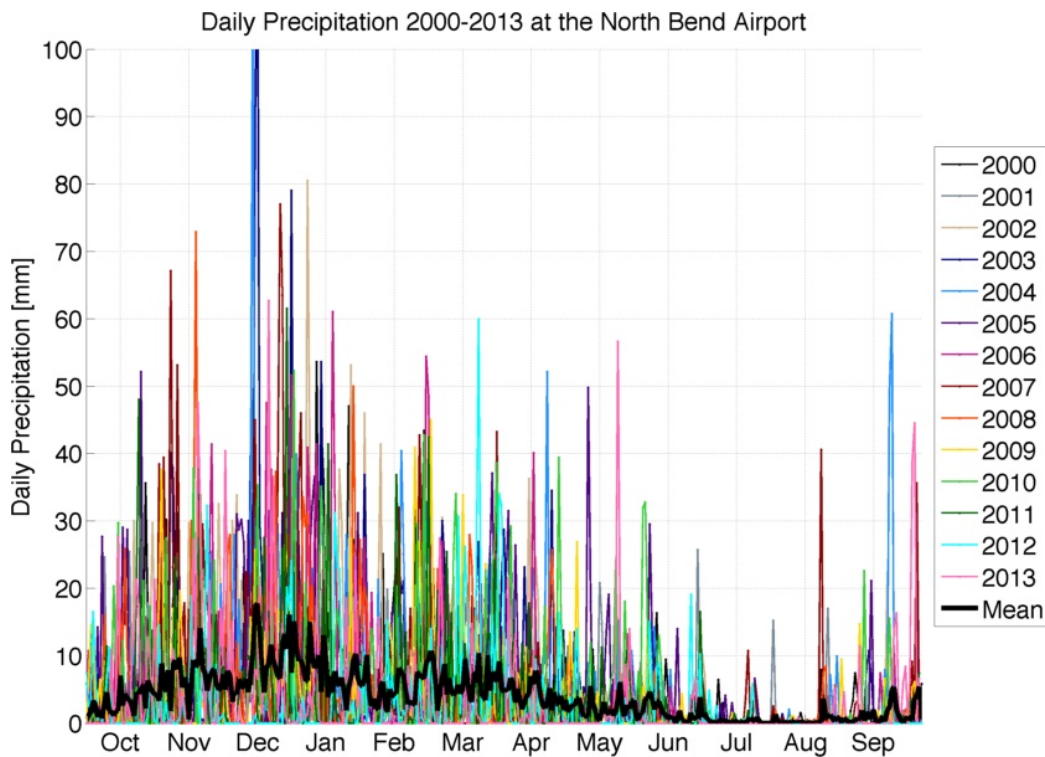


Figure 23. Daily precipitation at the North Bend Airport for the years 2000- 2013. Precipitation is measured in millimeters and the data is plotted versus day of year. The mean of all 14 years is shown in the bold black line. Precipitation is high in the winter, and low in the summer.

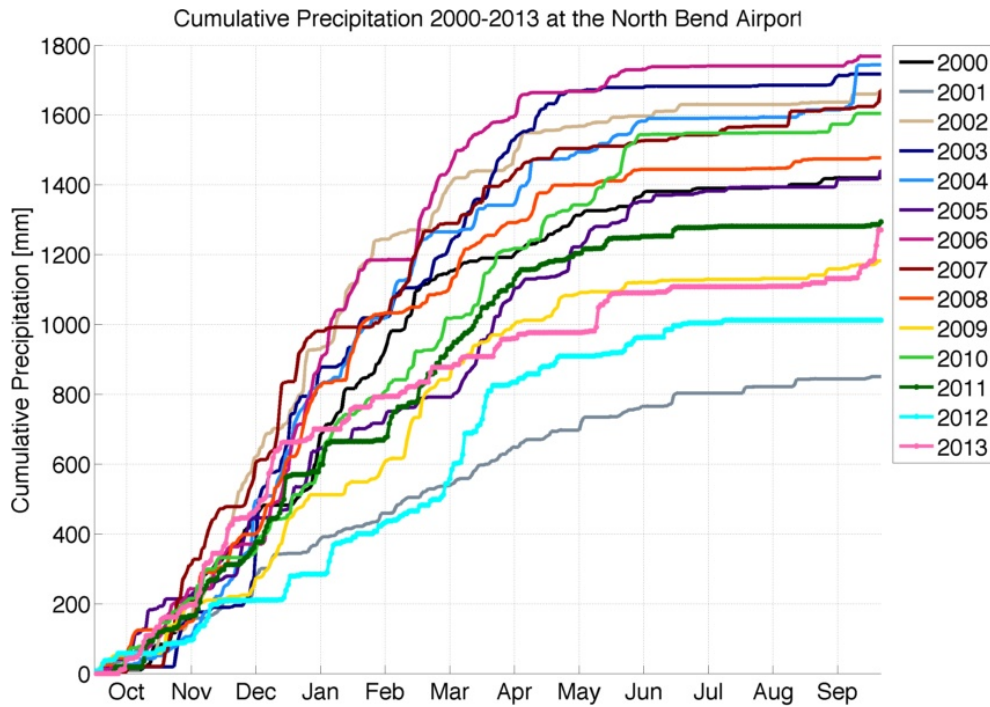


Figure 24. Cumulative precipitation (mm) for each water year from 2000-2013. There is up to 1000 mm range in cumulative precipitation between years.

Precipitation is high in the winter as the Aleutian Low sits over the North Pacific, driving storms and wind northward along the coast. Summertime experiences much less precipitation as the North Pacific High migrates to off the coast of California, bringing southward winds and predominantly dry conditions. Although winds are highly variable on an hourly timescale, this idealized two-system regime is apparent in shelf buoy wind data (Figure 25). Interannual differences exist here too, in the timing of the Spring and Fall transitions (the times of seasonal wind reversals). The Spring transition usually falls in mid-to-late April or May, while the Fall transition tends to occur in late October or November (Huyer et al., 1979; Strub et al., 1987).

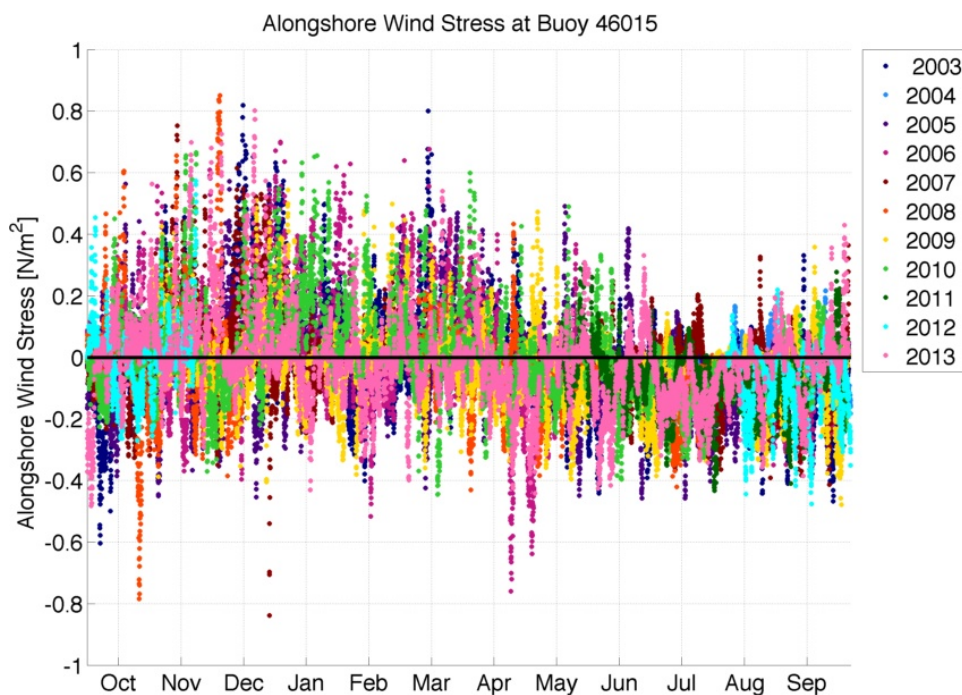


Figure 25. Hourly alongshore wind stress, measured by NOAA buoy 46015 from 2003-2013. Solid black line indicates the point above which wind stress is positive and to the north, below which, wind stress is negative and to the south.

Oceanic water properties respond to shifting winds and precipitation arising from the atmospheric changes in the CCS throughout the year. Time series data from the GLOBEC Coos Bay mooring (Figure 6) showed that waters on the shelf are warmer and fresher in the winter, and colder and saltier in the summer (Figure 26). Salinities during the dry season ranged from 32.5 to 34 psu between 21 and 95 meters depth. Temperatures were generally between 7.5 and 9.5 degrees Celsius at these depths on the shelf.

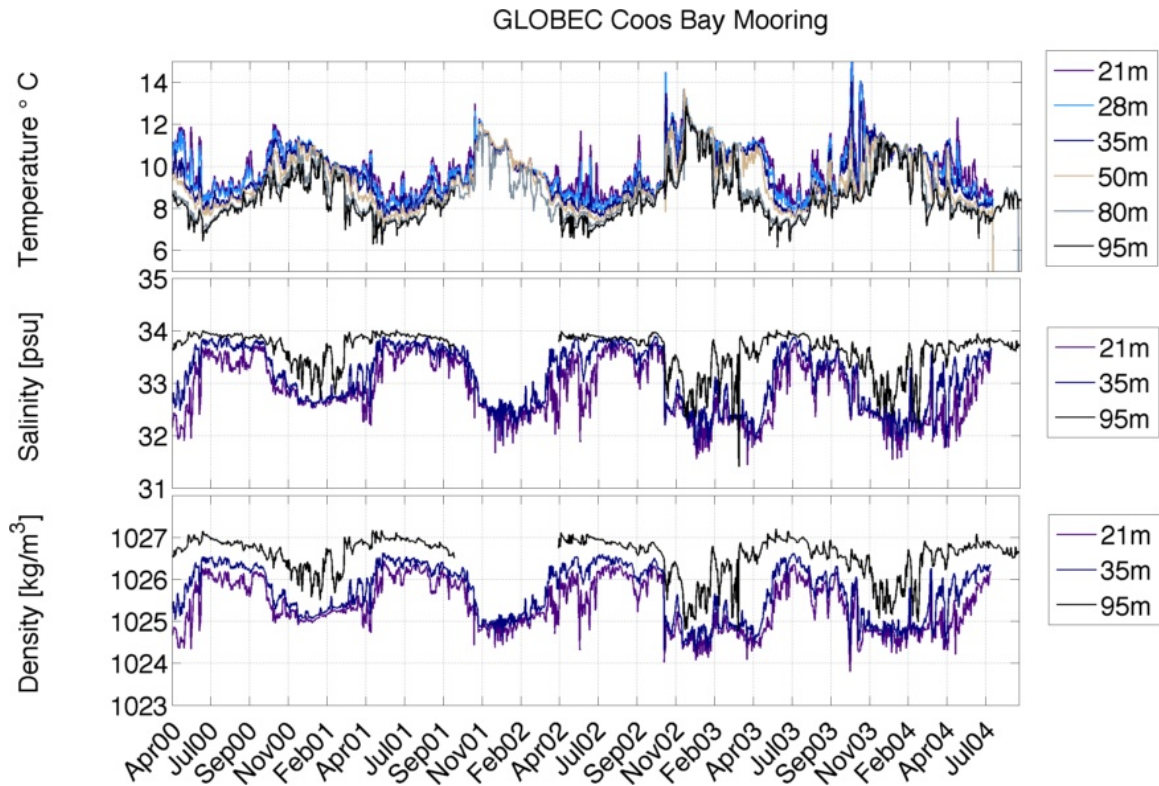


Figure 26. Temperature, salinity, and density data from the NEP-GLOBEC program's Coos Bay mooring, located 16 km southwest of the mouth of Coos Bay and maintained from 2000-2004. Data accessible at <http://coast.ocean.washington.edu/coastdata/GLOBEC/GLOBECPCB.htm>.

4.1.4. Estuarine Circulation and Residence Time

We used the conditions presented above to explain the variability in the resulting estuarine circulation in Coos Bay. The estuarine circulation is the tidally-averaged, along-channel velocity that, although an order of magnitude smaller than tidal flows, is of disproportionate importance due to its role in sediment accumulation, nutrient recycling, acidification, and the formation of hypoxia (Geyer & MacCready, 2014).

The most direct way to quantify the estuarine circulation is using ADCP data. While the ADCP deployment did not overlap with all of our CTD transects or the water quality logger deployments, the time series was long enough to reflect the seasonal

differences. Figure 27 shows the discharge, wind conditions, depth-averaged along-estuary velocities, and the tidally-averaged along-estuary velocities from the ADCP data deployment.

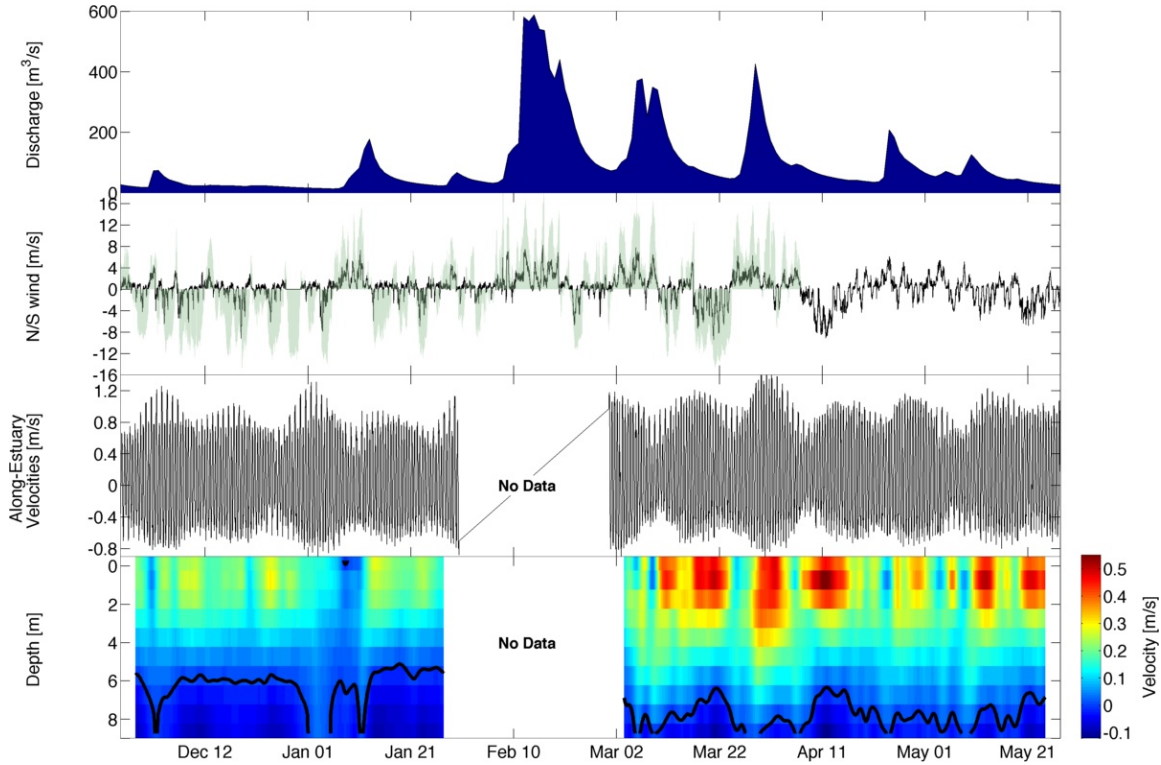


Figure 27. Data from November 25, 2013 to May 27, 2014 showing the seasonal and synoptic forcing on flows in Coos Bay. (Top) Discharge extrapolated from the Siuslaw to represent the inflows to Coos Bay during this time. (Top, center) Alongshore wind velocities available from NOAA buoy 46015 (shaded green) and the SSNERR meteorological station (black line). Positive velocities indicate northward (poleward) winds, negative velocities indicate southward (equatorward) winds. (Center, bottom) Rotated, along-channel, depth-averaged current velocities. Negative velocities are up-estuary; positive velocities are down-estuary. (Bottom) Rotated, along-channel, tidally-averaged current velocities. The solid black line indicates 0 m/s current flow. Cooler colors (negative) indicate current flow up-estuary, warmer colors (positive) indicate current flow out-estuary.

While the ADCP dataset fails to encompass the full range of seasons, it does capture currents from late November 2013 to late May 2014—fall, winter, and spring of the 2014 water year. The data show tidal currents on the order of ~ 1 m/s (Figure 27,

center bottom) and residual currents on the order of ~ 0.1 m/s (Figure 27, bottom). The dominant variability in the along-estuary currents is due to the tides. A strong spring/neap cycle is apparent in the data (Figure 27, center bottom, and bottom). The residual, or estuarine, circulation is seasonally variable. In the late fall and winter months during the ADCP deployment, residual flows are weak (Figure 27, bottom), corresponding to the low discharge to the estuary from November- February (Figure 27, top). In spring months, the residual flow strengthens with the arrival of large discharge events in mid February- May.

Although the along-estuary residual flow is the dominant component in many estuarine processes, lateral flows add complexity and cannot be completely ignored as we discuss circulation in Coos Bay. The ADCP data reveals tidally-averaged lateral flows about an order of magnitude weaker than the along-estuary flows (Figure 28). Lateral velocities were typically order 10^{-2} ms^{-1} , while along-estuary velocities were order 10^{-1} ms^{-1} .

We used the ADCP data to approximate residence times for Coos Bay. There are numerous definitions of residence time in the estuarine literature. Here, we use two of the more common, and easily estimated, definitions: 1) the transit time and 2) the filling time. The transit time quantifies the time a particle takes to exit the estuary from a particular point of input (Vallino & Hopkinson, 1998; Sheldon & Alber, 2002). The filling time is the time it would take to fill the volume of the estuary, given a specified volume transport (Sutherland et al., 2011).

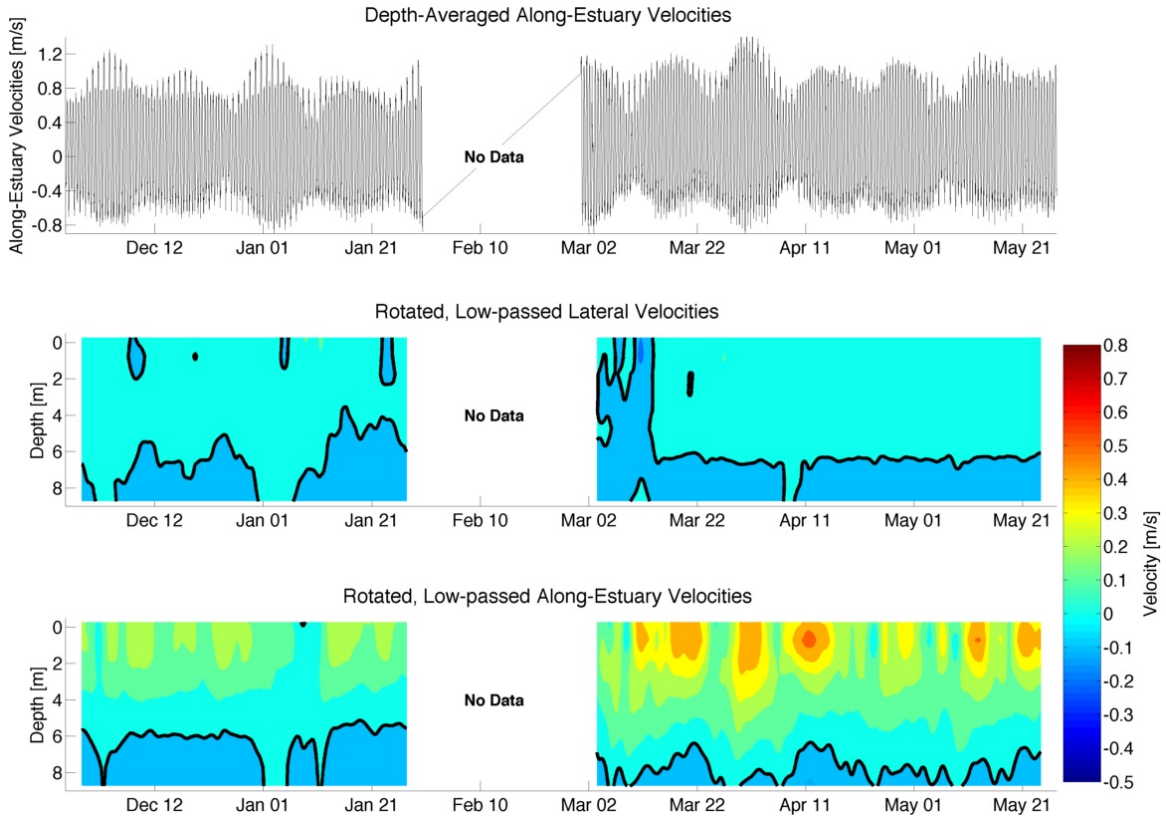


Figure 28. Depth-averaged along-estuary rotated velocities (top). Rotated and tidally-averaged lateral (center) and along-estuary (bottom) velocities. System is aligned such that positive velocities indicate movement to the left (west) and out-estuary (south).

To calculate transit and filling times, velocity vector components measured from the ADCP were rotated to align with the channel. The data were then low-pass filtered with a 24-24-25 hr Godin filter to remove tidal variability (Figure 27, bottom). These residual flow velocities, u_e , were then used to calculate transit and filling times. There are several assumptions to this approximation that can cause it to break down. First, the approximation assumes cross-estuary advection is negligible. Second, it discounts the influence of tidal motions on residence times. Third, it assumes the along-estuary velocities measured at the ADCP are constant along the estuary. And fourth, it assumes the ADCP captures the full water column velocity structure.

For transit times, at each time step, the mean velocities for the upper and lower layers of the estuary were calculated. The coordinate system is aligned such that $u_e < 0$ indicates movement up-estuary, $u_e > 0$, down-estuary. A transit time from the mouth to the head of the estuary was calculated by dividing the distance (21 km) by the lower layer velocity. A total transit time was then found by adding the up-estuary transit time to the down-estuary transit time (distance the water travels to leave the estuary (21 km) divided by the mean upper-layer velocity). This approximation was done for every time step of the ADCP record to see how transit time changes seasonally.

For the ADCP time series from late November to late May, transit times are on the order of one to two weeks (Figure 29). The median transit time is 8.92 days, the mode is 4.20 days, and the mean and standard deviation are 22.25 +/- 120.10 days. The breakdown in this approximation occurs when flows are weak and the water column measured by the ADCP is entirely moving either up or down estuary (Figure 30). Since the ADCP does not capture the full depth of the water column, the landward flow at depth is not resolved. When the line of zero velocity approaches the extent of the ADCP profile (Figure 30, center, bottom; black bold line), it causes our assumptions to be violated, and unreasonable residence times result.

The second measure used to approximate residence times in Coos Bay is a filling time, or the amount of time it would take to fill a certain volume of the estuary. In this case, the volume used was calculated as the volume of the estuary up-estuary of the ADCP using a bathymetric dataset of Coos Bay, which includes a digital elevation model from NOAA and bathymetry from the USACE. Zero crossings in the ADCP along-estuary current profiles were identified for every time step. Using those zero crossings,

cross sectional areas for the bottom and top layers were calculated. Transports were then found by multiplying the cross sectional areas by the mean velocities in the upper and lower layers. Dividing the total up-estuary volume by the lower layer transport resulting in a filling time for each time step of the ADCP dataset.

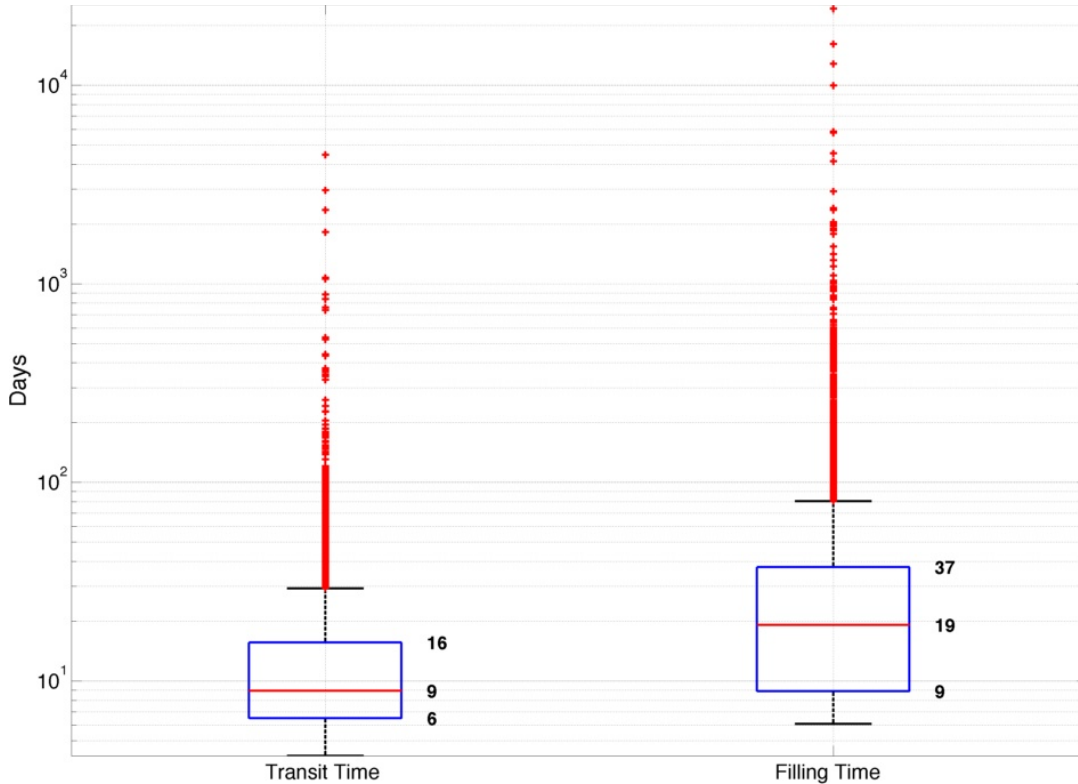


Figure 29. Boxplot of transit and filling times for Coos Bay, calculated using ADCP data and bathymetric data from the USACE. The median values are denoted by the central line, the box edges in blue are the 25th and 75th percentiles, red crosses indicate outliers.

The results of this approximation give a median filling time of 19.16 days, a mode of 6.08 days, and mean and standard deviation of 83.39 +/- 644.34 days (Figure 29). Like the transit times, this approximation breaks down during periods where the along-estuary components of the velocities are going in the same direction at all depths measured by the ADCP. The filling times are longer than the transit times, but follow the same pattern.

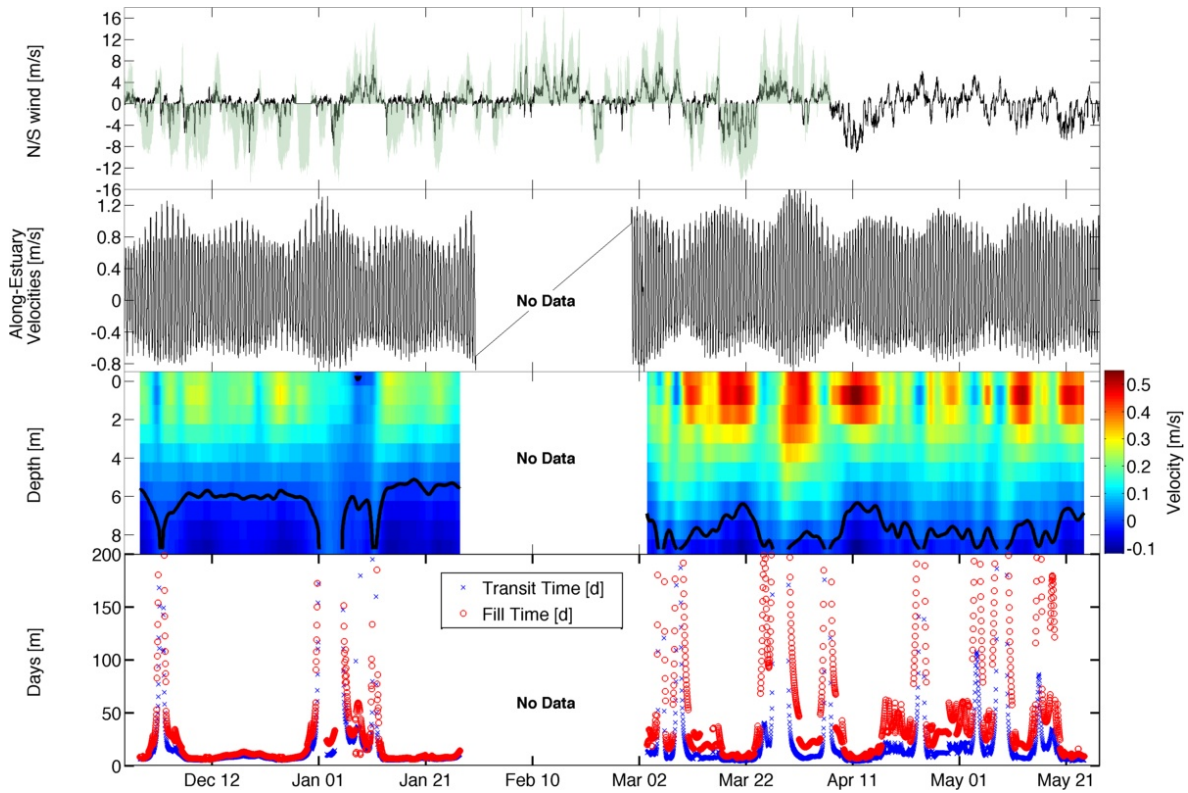


Figure 30. Figure 27 plotted with corresponding transit and fill times (bottom panel). Transit times are denoted by blue crosses, fill times by red circles. Transit and fill times are amplified to unreasonable amounts when winds cause breakdown in the two-layer estuarine circulation.

4.1.5. Box Model

A more precise approximation of residence time in Coos Bay was attempted in this study by applying the box model approach presented by Hagy et al. (2000). Using conservation of salt, Hagy is able to estimate transports through a series of linear equations. The estuary is first divided into upper and lower layers, and then into zones, or boxes (Figure 31). For each box, four transports—seaward advection, landward advection, vertical advection, and non-advective vertical exchange—are quantified using salt balance equations. This approach assumes horizontal non-advective exchange is negligible and that box volumes are constant through time (Hagy, 2000). The one place

where horizontal non-advective exchange needs to be defined is at the interface between the first and second boxes. Because the first box is restricted to only an upper layer to simulate the freshwater inflow, any salinity found in it must be attributed to dispersion, rather than the gravitational circulation that exists in the other boxes' two-layer system. Four types of data are needed to solve these equations—box volumes, freshwater inputs, salinity distributions, and rates of salinity change.

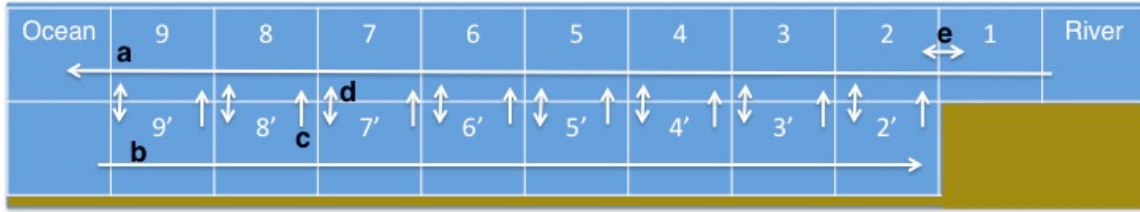


Figure 31. Schematic of the box model, notation, and transports. The transports are (a) seaward advection, (b) landward advection, (c) vertical advective exchange, (d) non-advective vertical exchange, and (e) non-advective horizontal exchange.

Coos Bay was divided into 9 boxes, 8 of which had an upper and lower layer (Figure 31, 32). Box 1 encompasses the Coos River at the head of the estuary, and only had one layer. Freshwater input to Coos Bay was limited to Box 1—a simplification from Hagy's approach.

The four main transport equations,

1. Seaward Advection:
$$Q_m = \frac{(s'_{m+1}[\sum_{j=1}^m Q_{fj} + Q_r] + [\sum_{j=1}^m V_j \frac{\partial s_j}{\partial t} + \sum_{j=2}^m V'_j \frac{\partial s'_j}{\partial t}])}{s'_{m+1} - s_m}$$
2. Landward Advection:
$$Q'_{m+1} = Q_m - \sum_{j=1}^m Q_{fj} + Q_r$$
3. Vertical Advective Exchange:
$$Q_{vm} = Q'_{m+1} - Q'_m$$
4. Vertical Non-advective Exchange:
$$E_{vm} = \left(\frac{V_m \frac{\partial s_m}{\partial t} + Q_m s_m - Q_{m-1} s_{m-1} - Q_{vm} s'_m}{s'_m - s_m} \right),$$

and the fifth transport equation for the salt balance in box 1,

5. Horizontal Non-advective Exchange:
$$E_{12} = \frac{V \frac{\partial s_1}{\partial t} + Q_1 s_1}{(s_2 - s_1)}$$

were solved using salinity data from the monthly CTD transects and gage data from the CWA. The equations listed above use notation where s is the salinity, subscript m is the box of interest, subscript $m+1$ is the down-estuary box, subscript $m-1$ is the up-estuary box, and primes notate lower boxes. River and freshwater inputs are represented with Q_r and Q_f , respectively.

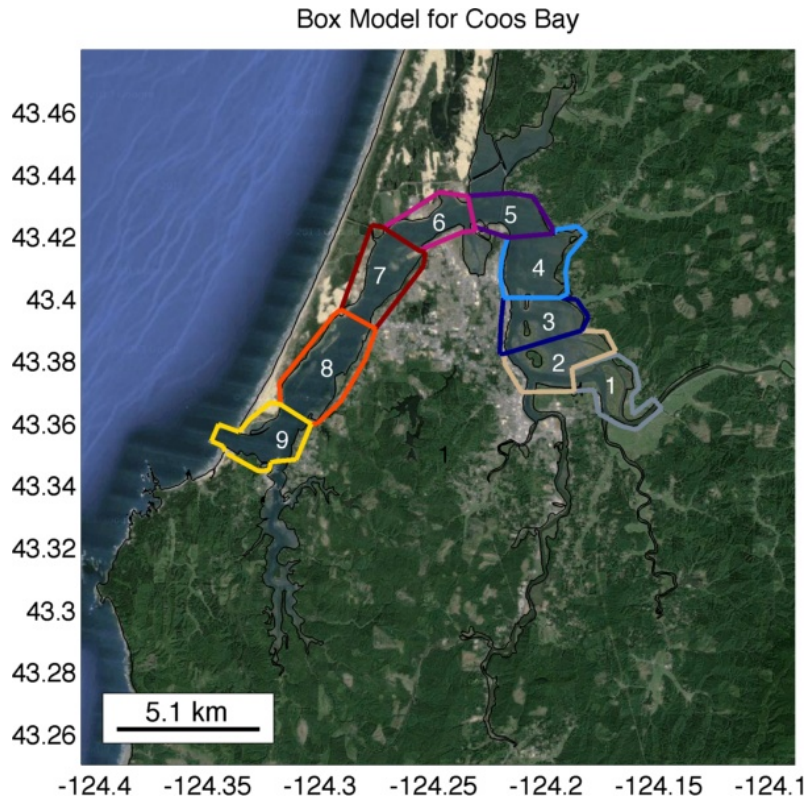


Figure 32. Map of the boxes used for Coos Bay in the box model residence time calculation.

The monthly CTD data was first sorted into the 9 boxes, such that every cast taken over the ~1.5 years of sampling was assigned a box from its corresponding latitude,

longitude coordinates. For each month and each box, a mean salinity for every sampled depth was calculated from all the CTD casts included. To ease the computational process, the mean salinities were calculated from linearly interpolated uniformly-spaced depth grids. Then within each box and each month, the depth closest to the mean salinity was found to separate each box into upper and lower layers. For months where there was not enough data (December, June, July), salinities were interpolated from surrounding months' data. The ocean salinities that influence box 9 were calculated by extending the salinity gradient between boxes 8 to 9 beyond box 9. The salinity of the freshwater input was zero. Rates of salinity change could then be found from the monthly upper and lower boxes' mean salinities.

Freshwater input to the box model was taken from the CWA data. Monthly means of the East and West Forks of the Millicoma, and the South Fork of the Coos River were summed to approximate the freshwater input through the Coos River. These are the largest of the tributaries to Coos Bay; others were ignored to simplify the calculation.

Lastly, volumes were derived from a bathymetric dataset that combines a base digital elevation model (DEM) from NOAA with USACE bathymetric maps. Using the same depths as were utilized in finding the monthly salinities, volumes could be found for the upper and lower layers for each month and each box.

Solving the five transports for each month highlighted a flaw in our model. Because our CTD sampling strategy rarely, if ever, went far enough up-estuary to capture the 0 isohaline of the river, the fifth transport equation, the horizontal non-advective exchange between boxes 1 and 2 was completely unreasonable (Figure 33). Over the 12

months, it was consistently on the order of, and sometimes even larger than, the advective transports and the river flow.

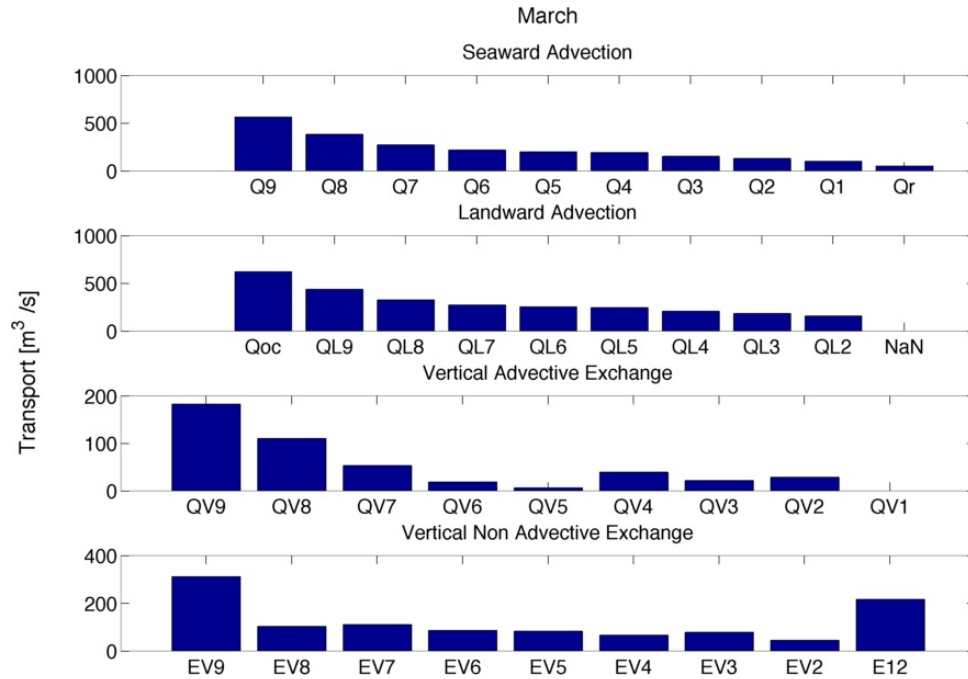


Figure 33. Transports calculated from the box model for March. The horizontal non-advective (E_{12}) transport is larger than the river discharge (Q_r).

Unfortunately, this study was not able to resolve the flaw in the model for Coos Bay. More data will need to be collected further up the Coos River to capture the fresh water. It is likely that the box model will then need more boxes, and more bathymetry for an undefined and variable length up the Coos River.

4.2. Discussion

4.2.1. Seasonal Forcing on Coos Bay Estuarine Circulation

One of the primary objectives of this study is to understand how ocean properties and the seasonal change in forcing mechanisms affect estuarine circulation in Coos Bay.

The atmospheric data – winds and precipitation – show a clear two-season regime that also manifests in the discharge and ocean property data (Figures 19, 23-26). Coos Bay experiences the same large-scale seasonal shift as other, more well-studied estuaries in the California Current System—San Francisco Bay, the Columbia River Estuary, and Puget Sound (Hickey & Banas, 2003; Huyer, 1983; Emmett et al, 2000). What makes it an interesting system is that it is much smaller than these estuaries, has a smaller drainage basin, and its discharge is nearly nonexistent in the dry season.

Because Coos Bay is such a relatively narrow estuary (1-2 km), the baroclinic Rossby radius is much greater than the width of the estuary and rotational effects are not as important as buoyancy-driven flows. The buoyancy forcing is highly variable over the course of a year due to the variable freshwater inflow. Therefore, changes in river flow have a large effect on the estuary. With less freshwater input, the stratification weakens (Figure 17) and estuarine circulation diminishes (Figure 27), but it reaches over a longer stretch of the estuary and the salinity intrusion increases (Figures 8-11) (Festa & Hansen, 1975).

The seasonal shift is apparent when looking at Coos Bay in parameter space. The estuarine Richardson number reveals that higher discharge can force the estuary into the partially stratified regime, but more often Coos Bay is well-mixed (Table 4). The Simpson numbers calculated corroborate this conclusion.

In the broader estuarine parameter space, Coos Bay falls into different regimes dependent mainly on the discharge (Figure 18), which is time varying and dominates the freshwater Froude number (Geyer & MacCready, 2014). The mixing parameter shifts over the tidal cycle and between spring/neap cycles as the strength of tidal flows wax and

wane. Stronger tides produce a more well-mixed system, while weaker tidal flows are less likely to breakdown the stratification. In addition, shallower parts of the estuary are likely more mixed than the deeper channel. As depth decreases, the denominator in the mixing term gets smaller, making for a more well-mixed water column.

For low discharges ($0-30 \text{ m}^3\text{s}^{-1}$), common in the dry season, Coos Bay falls in the SIPS and partially mixed regimes; the freshwater Froude number is order 10^{-3} to 10^{-2} . For medium discharges ($30-150 \text{ m}^3\text{s}^{-1}$), common in the wet season, the circulation is either SIPS, partially mixed, salt wedge, or time-dependent salt-wedge; the Fr_f is order 10^{-1} . At high discharges ($>150 \text{ m}^3\text{s}^{-1}$), which only occur during severe winter storms, $Fr_f \sim 1$, which puts it clearly in the salt wedge/ time-dependent salt-wedge space. These results reveal a deeper complexity to Coos Bay's circulation than was previously found. The majority of the year, partially stratified and SIPS conditions dominate. On rare occasions of high discharge, it becomes a salt wedge-type estuary. The variability and range in conditions is larger than any of the other estuaries in Geyer and MacCready's parameter space. This parameterization also inaccurately predicts that Coos Bay is not in the well-mixed regime, which contradicts our CTD data, Si , and Ri_e numbers.

Coos Bay's large range in parameter space presumably could be attributed to highly variable discharge entering an extremely modified system. Prior to dredging in 1880, the main channel was a mere 3.35 m (11 feet; ACOE, 1975) from the mouth to the turn at North Bend. Above North Bend, the channel narrowed and shoaled to a depth of only 6 feet (1.83 m) at the town of Marshfield. The depth was not consistent, with many shoals along the length of the estuary. Now the main channel is 45 feet (13.72 m) deep, and two jetties extend from the mouth of the Bay to accommodate large shipping vessels.

In addition, many of the salt marshes around Coos Bay were filled with dredge spoils, altering local hydrology and biotic communities (ACOE, 1975; Taylor, 1983). Increasing the depth of an estuary has been shown to increase gravitational circulation and salt intrusion, and decrease stratification (Festa & Hansen, 1976). So M decreases and Fr_f likely increases due to more runoff (less salt marshes, more sedimentation).

4.2.2. Strain-Induced Periodic Stratification

The Geyer & MacCready parameterization (2014) shows that at times Coos Bay has strain-induced periodic stratification (SIPS). This implies that over the tidal cycle the stratification in Coos Bay varies due to the interaction of the tidal currents with the horizontal density gradient. On ebb tides, the horizontal density gradient compounds the vertical shear in the tidal current and enhances stratification (Simpson, 1990). This phenomenon is reversed on the flood tide, diminishing stratification.

While the Simpson number and the parameter space show that the estuarine circulation in Coos Bay experiences SIPS, observational data in this study cannot validate this finding. The temporal resolution of the CTD data is too coarse to resolve variations in stratification over the tidal cycle. And the loggers deployed in the estuary only capture horizontal variation, not vertical. Future efforts should seek to quantify the tidal variation in stratification, both over the tidal cycle and over the spring/neap cycle. One possibility might be an instrumented mooring that could provide a robust temporal record of stratification. Observational validation of SIPS in Coos Bay would aid in the development of the hydrodynamic model. The effects of tidal straining will need to be taken into account in order to accurately reconstruct the influence of turbulent mixing on

the estuarine circulation. Modelers should consider the occurrence of SIPS in Coos Bay when selecting a turbulence closure scheme.

4.2.3. Lateral Circulation

This study focused on the along-estuary hydrography and circulation of Coos Bay. Future work will be needed to resolve variability in lateral flow structure and magnitude. The limited time series from the ADCP data show that the subtidal lateral flows are an order of magnitude weaker than subtidal along-estuary flows (Figure 28). Granted, the ADCP data only shows one location along the estuary, but it highlights the fact that lateral circulation is likely non-negligible.

More evidence for the importance of lateral circulation in advective flows in Coos Bay comes from observations of floating material and foam snaking along the channel during the flood tides. These observations were made during CTD sampling multiple times. Such surface expressions are a signature of tidally-induced lateral circulation (Nunes & Simpson, 1985; Geyer & MacCready, 2014). This phenomenon occurs due to cross-estuary depth variations producing stronger currents in the channel. On the flood tide, this lateral velocity shear generates a cross-estuary density gradient, which draws surface waters towards the channel (Geyer & MacCready, 2014). This circulation manifests itself in the form of axial convergence fronts of debris and foam. Nunes & Simpson (1985) found velocities from this circulation to be 20% of the along-estuary flow velocities. In Coos Bay, the surface expressions of this lateral circulation on the flood tide were frequently observed along most of the length of the estuary, from the mouth about 15-20 km up estuary. These observations reveal that despite their relative

weakness, lateral flows are non-negligible in this system. They likely play an important role in the transport of debris, OM, and organisms in the estuary. Further investigation using drifters or a hydrodynamic model will aid in the understanding of circulation in Coos Bay.

4.2.4. Residence Time

The median filling and transit times approximated from the ADCP velocity data are close to the range of residence times cited in the literature for Coos Bay. Arneson (1976) and Choi (1975) calculated residence times using the modified tidal prism and fraction of freshwater methods. They found residence times of 2-16 days and 11-48 days for the wet and dry seasons, respectively (see Appendix A). The unreasonable outliers that arose due to the limited extent of the ADCP profile caused the statistics of the transit time and filling time approximations to be skewed higher than the literature values.

Having more accurate approximations for residence times would be very informative for the study of Coos Bay. The approximations would allow for better insight into the fate of sediments, salt, oxygen, and organic matter in the estuary. Low residence times cause high dispersal of sediments and OM, and high productivity. Higher residence times facilitate more sediment accumulation, and increase the likelihood of hypoxia and acidification (Geyer & MacCready, 2014). There are several approaches to attain more accurate estimations. Resolving the freshwater inflow in the CTD sampling would correct the flaw in the box model approach. Longer ADCP time series, especially in the dry season, would show how drastically residence times are inflated when river flow is low.

And perhaps the best chance of resolving residence times in Coos Bay will come from the development of the hydrodynamic model.

Banas and Hickey (2005) modeled the residence times of an estuary similar to Coos Bay using a numerical model, GETM. Willapa Bay, located on the southern Washington coast, is larger than Coos Bay, but has a comparable mean depth (3.2 m WB; 4 m CB), tidal range (1.9 m WB; 1.7 m CB), and intertidal area (55% WB; 47% CB) (Hickey & Banas, 2003). The model showed that, like Coos Bay, Willapa Bay has significant lateral circulation and experiences SIPS. This model also showed substantial along-estuary gradients in water age, a proxy for residence time, in addition to cross-estuary gradients, especially during the dry season. During the dry season, tides were the dominant driver in setting the residence time of the estuary. Throughout the year, however, there exists a mid-estuary minimum in diffusivity. Beyond this point the age gradient is sharp, while below it, water is flushed relatively rapidly out of the estuary.

It is likely that such a gradient in water age exists in Coos Bay. Anecdotal evidence from Willapa Bay of oyster larvae spawning south (up-estuary) of the diffusivity minimum (Banas and Hickey, 2005) matches similar evidence from Coos Bay where oyster larvae are also only found in the upper reaches of the estuary (Pritchard, 2013). These organisms require long retention times in the estuary to survive; to accomplish this, they spawn where it is likely they will not be swept out to sea. Differential residence times along the estuary will have implications for dissolved oxygen levels; this will be discussed further in chapters V and VI.

CHAPTER V

COMPARISON BETWEEN YEARS 2012 AND 2013

The CTD sampling surveys, in addition to robust logger time series, allowed for a more thorough examination of hydrography and hypoxia in the 2012 and 2013 water years. Pronounced differences in the two years show how sensitive the system is to freshwater inputs.

5.1. Results

Time series from the water quality loggers showed distinct differences in the water properties throughout Coos Bay between 2012 and 2013. During the 2012 water year, there was a wide range (2- 34 psu) in salinities during the winter and spring months (Figure 34) at the BLM boat dock. Very cold and salty water was present during July and August. In contrast, the 2013 water year T-S diagram from the same location showed less of a range in salinity (14-34 psu). The coldest, saltiest water present in 2012 is absent in 2013. In 2013, the temperatures during the summer months are higher than in 2012, reaching above 17 °C during June, July, August, and September.

To investigate the pronounced difference in water salinity in Coos Bay between 2012 and 2013, we analyzed precipitation and discharge data from the water years 2011, 2012, and 2013 (Figure 35). Cumulative precipitation is highest in 2011 (1294 mm), and 2013 (1271 mm) has more overall precipitation than 2012 (1013 mm).

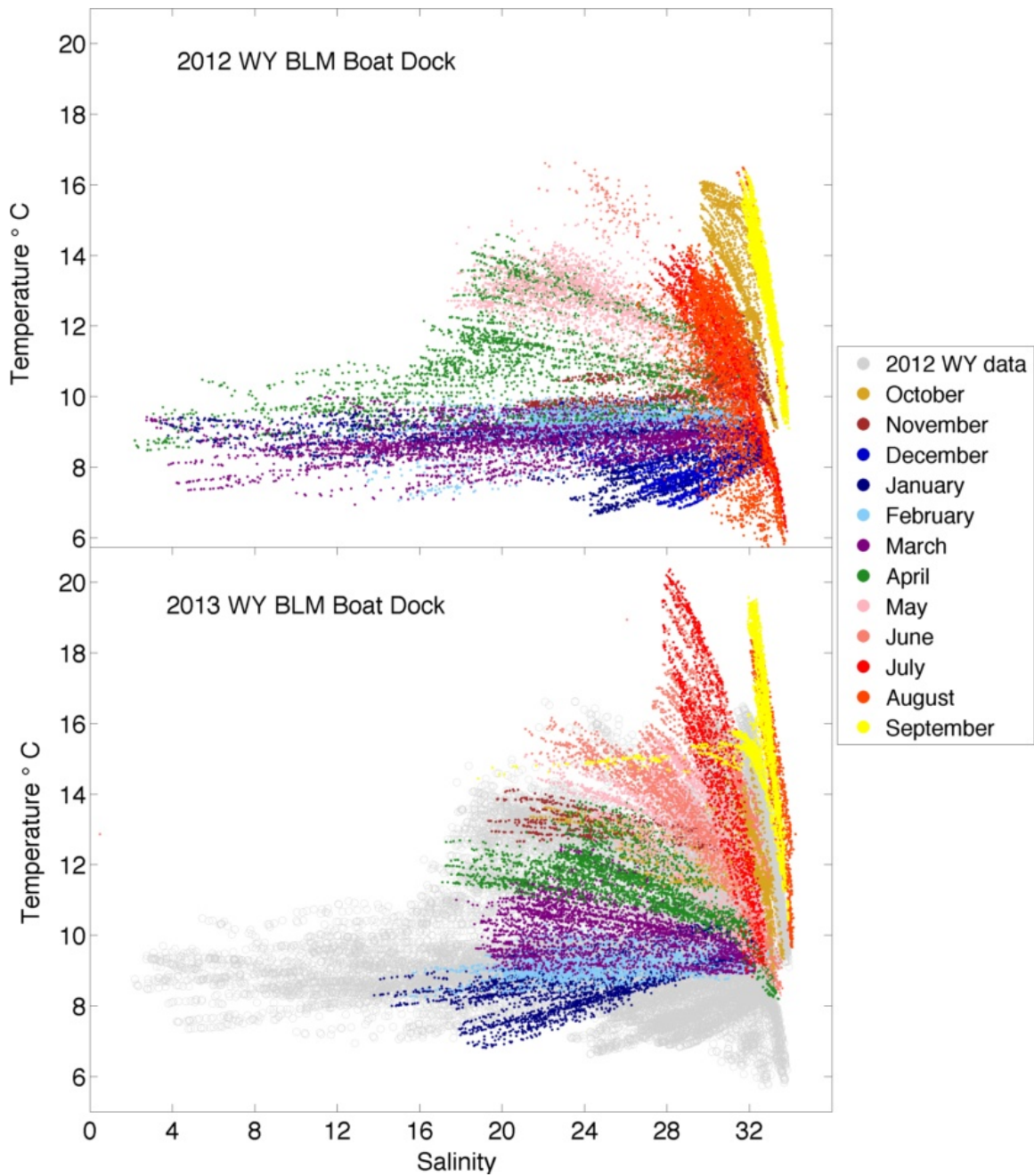


Figure 34. Temperature and salinity diagrams for the 2012 (top) and 2013 (bottom) water years at the BLM boat dock. Each month is shown using a different color. (Bottom) 2012 data in grey is overlaid with 2013 data to show the pronounced difference between the years.

Precipitation was greater earlier in the season in 2013, indicated by the steep slope of the cumulative precipitation. The slope leveled off in January. In 2012, precipitation was markedly lower from late November- early March, finally increasing in late March.

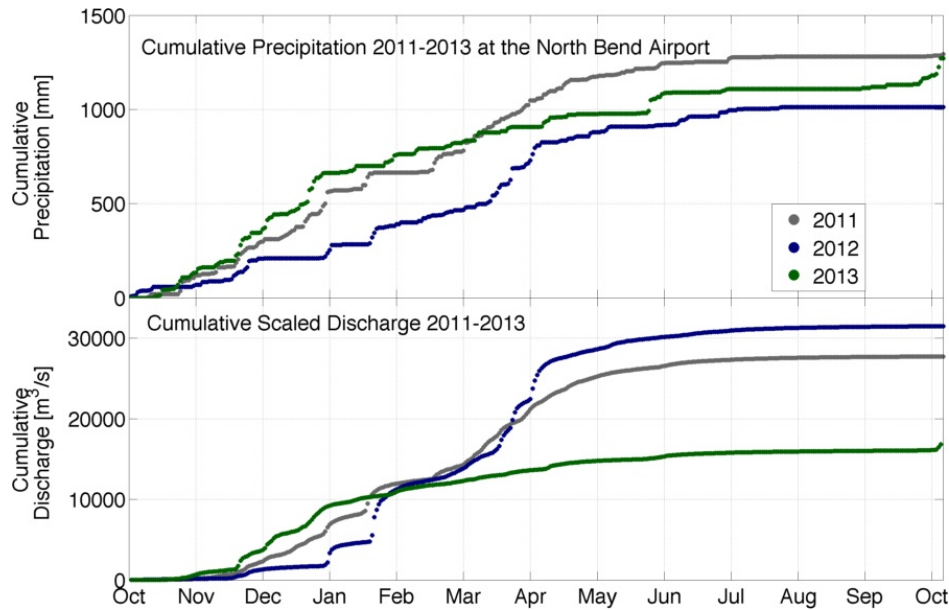


Figure 35. Cumulative precipitation (top) and scaled discharge (bottom) for the 2011-2013 water years. Precipitation data is from the North Bend Airport, discharge data is the scaled CWA gage data.

Scaled discharge from the CWA for 2012 is higher than 2013 (Figure 35). The mean +/- the standard deviation for scaled daily discharge for 2012 is $86.04 \pm 202.19 \text{ m}^3\text{s}^{-1}$; the median is $25.32 \text{ m}^3\text{s}^{-1}$. The large standard deviation reflects how much daily variation there is, in addition to the seasonal disparity in freshwater flow. The mean +/- the standard deviation for scaled daily discharge for 2013 is $46.07 \pm 73.20 \text{ m}^3\text{s}^{-1}$; the median daily discharge is $25.34 \text{ m}^3\text{s}^{-1}$. While the median flows for the two years are very similar, 2012 had some much larger events (Figure 36), which made the total for the year much greater than 2013 ($31,490 \text{ m}^3\text{s}^{-1}$ vs. $16,810 \text{ m}^3\text{s}^{-1}$).

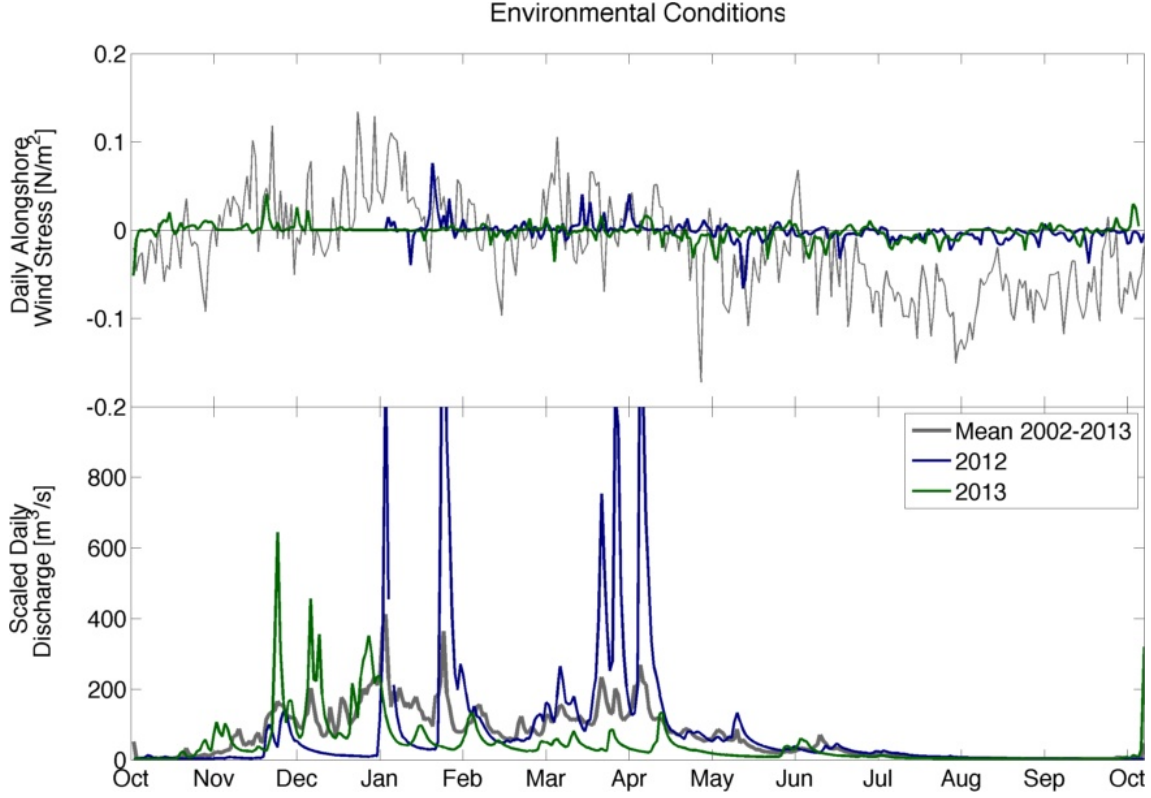


Figure 36. Daily alongshore wind stress and scaled discharge for Coos Bay, OR. (Top) Positive values indicate poleward winds, negative, equatorward. The gray line is the average daily along shore wind stress measured at NOAA buoy 46015 from 2002-2013. The colored lines are 2012 (blue) and 2013 (green) data from the SSNERR meteorological station. (Bottom) Mean scaled daily discharge from CWA data 2002-2013 in gray. Data from 2012 in blue and 2013 in green.

As discussed in Chapter IV, the estuarine circulation responds linearly to the along-estuary salinity gradient induced by the buoyancy forcing from the freshwater.

Since the ADCP data do not resolve these years, we can approximate the estuarine

circulation (also called exchange or residual flow) using the equation, $u_e = \frac{g \beta \frac{\partial s}{\partial x} H^3}{48 K_M}$,

with the vertical eddy viscosity, $K_M = a_0 C_D U_T H$ (MacCready & Geyer, 2010). Values for constants in these equations can be found in Table 3.

Because CTD sampling did not begin until November of 2012, we could not use those $\partial s / \partial x$ for this comparison. The only datasets that encompassed both water years were the water quality loggers. Because the loggers are positioned at a fixed depth, the gradient obtained from them is not depth-averaged. Their sampling intervals of 15 min, however, allow for the tidal averaging needed to obtain an accurate estimate of u_e .

A running filter of 24, 24, 25 hours was applied to filter out the tides from the salinity data over the time period Oct. 1, 2011 to Sept. 31, 2013. To get ∂s , we then took the difference in tidally-averaged salinity between the SSNERR Charleston logger and the CTCLUSI BLM logger. The distance between the two is about 9 km, which we use for ∂x . Anytime data was missing from one or both of the loggers, $\partial s / \partial x$ could not be calculated. Thus, with an approximation of the tidally-averaged, along-estuary salinity gradient, the magnitudes of the residual flow, u_e , were calculated. Figure 37 shows the results of this computation.

The magnitude of residual flows is greater in 2012 than in 2013 (Figure 37). Although data gaps prevent a full picture of the two years, for the record available, it is clear there are several instances where the exchange flow exceeds 0.15 ms^{-1} in 2012, whereas, in 2013, the exchange flow is almost always less than 0.15 ms^{-1} .

In estuaries, diminished residual flows increase the likelihood that hypoxia will develop. While the loggers did not record the presence of hypoxic waters ($< 2 \text{ mg/L DO}$), they did show differences between the DO levels during the 2012 and 2013 water years (Figure 38).

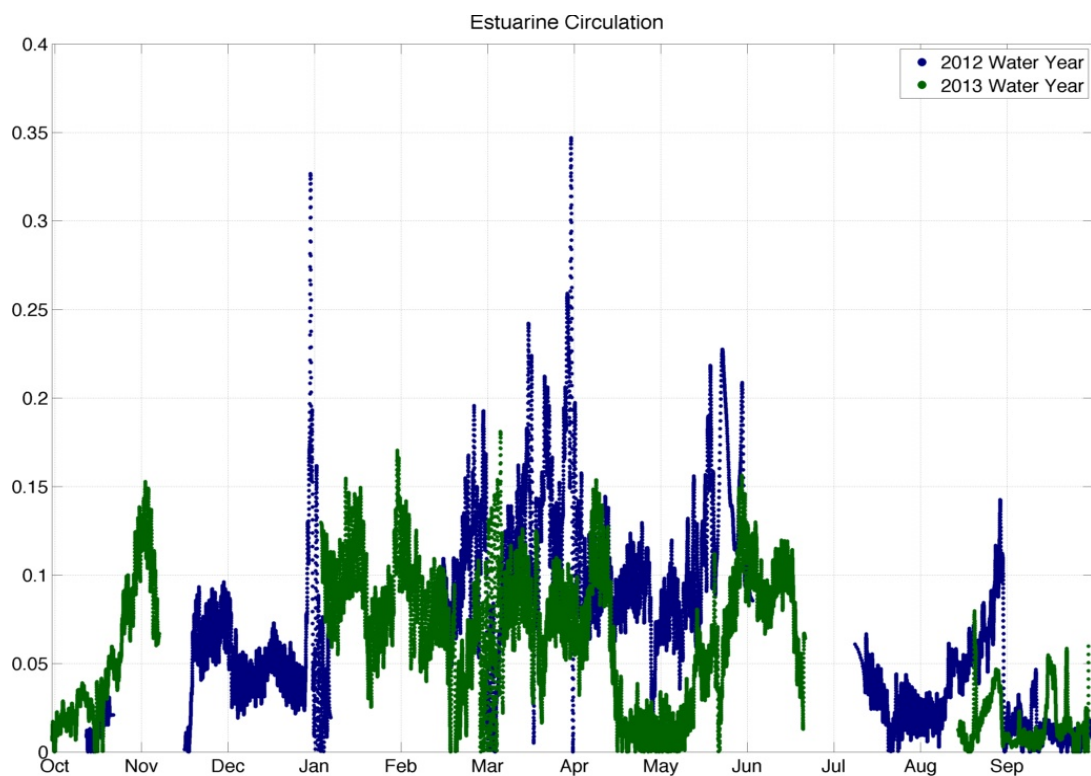


Figure 37. Magnitude of the residual, or estuarine exchange, flow for Coos Bay, calculated using the tidally-averaged salinity gradient between the CTCLUSI BLM logger and the SSNERR Charleston Bridge logger. Data from the 2012 water year in blue, data from the 2013 water year in green.

In 2012, DO levels at the BLM boat dock only fell below 6.5 mg/L less than 1% of the time ($n = 29512$). In 2013, the number of measurements below 6.5 mg/L increased to 2.23% ($n = 35030$). Performing the Student's t-test shows that there is a significant difference between the two years ($p < 0.01$). A similar pattern emerged at the Empire boat dock where values dipped below 6.5 mg/L approximately 2.19% of the time in 2012 ($n = 22874$) and 10.34% in 2013 ($n = 35032$), again exhibiting significant difference between the years ($p < 0.01$). The Charleston Bridge logger showed a smaller, but still significant difference between the two years ($p < 0.01$). But here, 2013 actually saw fewer instances of DO less than 6.5 mg/L (2.82%, $n = 7895$ vs. 3.07%, $n = 7207$ in 2012).

While hypoxia is more likely to develop in estuaries with low residual flows and long residence times, the conditions on the shelf during the dry season strongly dictate whether or not it will occur. More upwelling onto the shelf puts a greater volume of low DO water in place to be advected into coastal estuaries. Here we used wind data and upwelling indices to compare the amount of upwelling between 2012 and 2013.

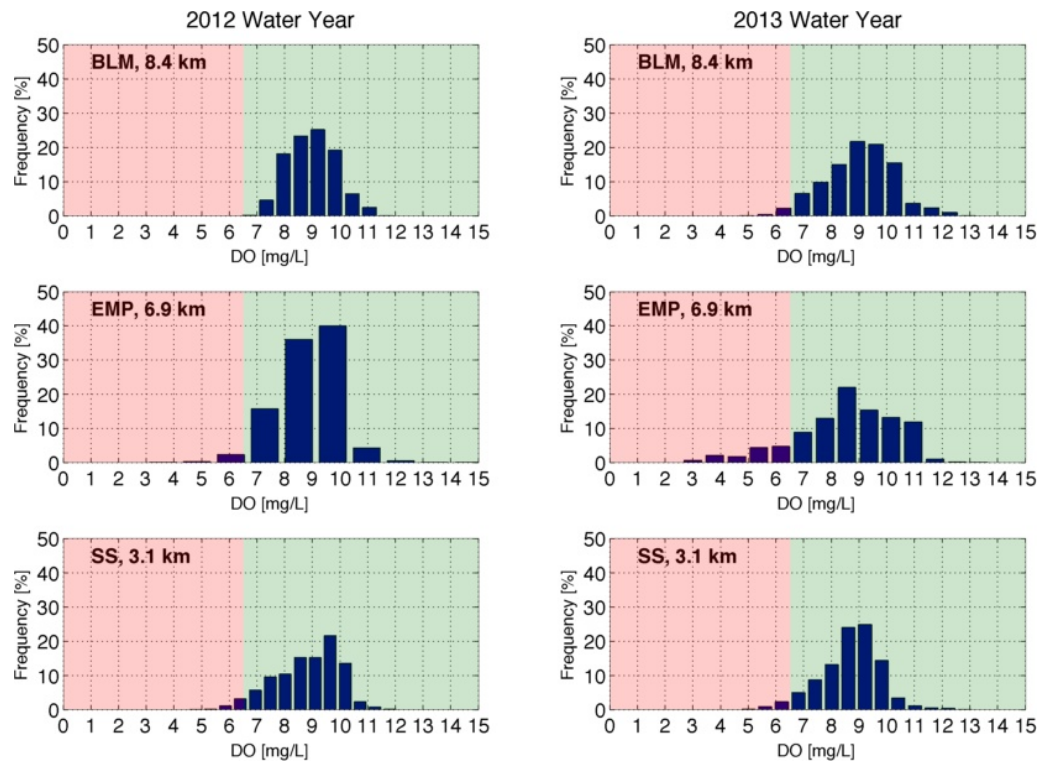


Figure 38. Histograms showing the distributions of DO measurements at the BLM boat dock logger, Empire Boat dock (EMP) logger, and the Charleston Bridge logger (SS). DO levels <6.5 are shaded pink, DO levels >6.5 are shaded green.

The coastal upwelling for the two years can be estimated using existing upwelling indices. Upwelling indices are a measure of Ekman transport towards the coast, which varies with the strength and direction of surface wind stress on surface waters (Bakun, 1973). Poleward winds cause surface transport onshore, driving downwelling, whereas

equatorward winds cause surface transport offshore, and subsequently, upwelling. Here we use the Pacific Fisheries Environmental Laboratory's (PFEL) upwelling indices. Six-hourly, daily, and monthly indices and anomalies for fifteen sites in the Northern Hemisphere are available from 1967- present. The data can be accessed online at <http://pfeg.noaa.gov/products/PFEL/modeled/indices/PFELindices.html>.

Figure 39 shows the anomalies from the monthly average upwelling indices for 2012 and 2013 for two of the fifteen Northern Hemisphere sites. The upwelling indices reflect conditions north (45N latitude) and south (42N latitude) of Coos Bay, which lies between the two. The data show that except for July, upwelling was weaker than average in the summer of 2013. During the summer of 2012, upwelling was generally stronger than average at the southern site, and near normal levels at the northern site.

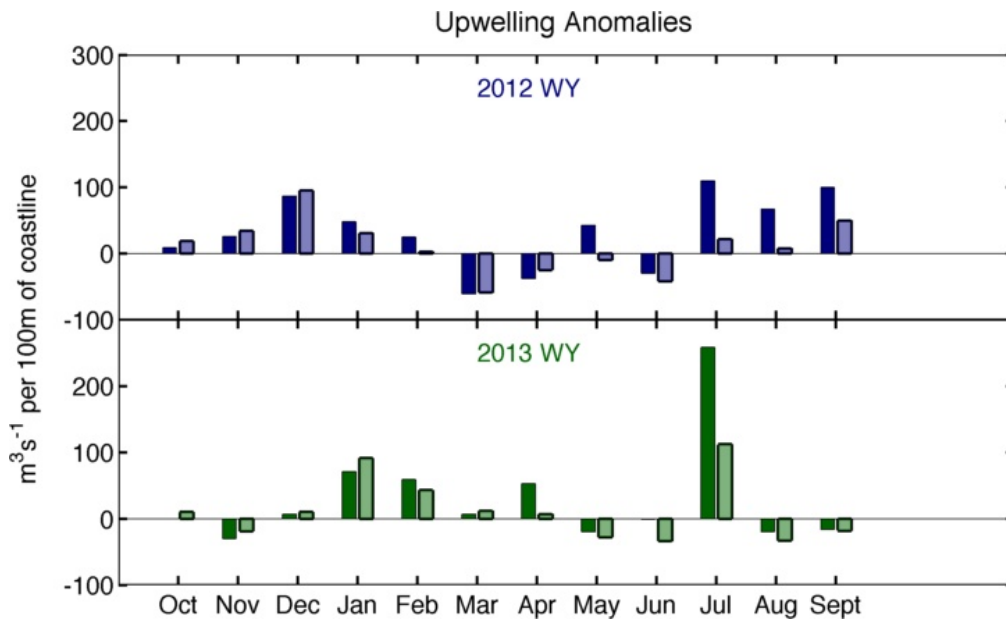


Figure 39. PFEL monthly upwelling anomalies for the 2012 and 2013 water years at 42N 125W and 45N 125W (bolded border). Upwelling indices are estimates of the Ekman mass transport on/offshore due to wind stress. Negative values imply onshore surface transport and downwelling, positive values, offshore surface transport and upwelling.

Another metric for upwelling strength is cumulative wind stress. Steve Pierce and Jack Barth of Oregon State University maintain a data repository that includes the timing of the spring transition and cumulative wind stress for the Oregon coast at <http://damp.coas.oregonstate.edu/windstress/index.html>. Using the alongshore wind stress from Newport, Oregon, they estimate spring and fall transition dates, and provide the cumulative upwelling-favorable wind stress over that period. Data is available from 1985-present; data from 2012 and 2013 is presented here. Figure 40 shows the timing of the spring transition and the cumulative northward wind stress over the course of the two upwelling seasons. The 2013 upwelling season starts and ends (days 97- 234) earlier than the 2012 upwelling season (days 125-281). In addition to being shorter, there are two major relaxation events in 2013.

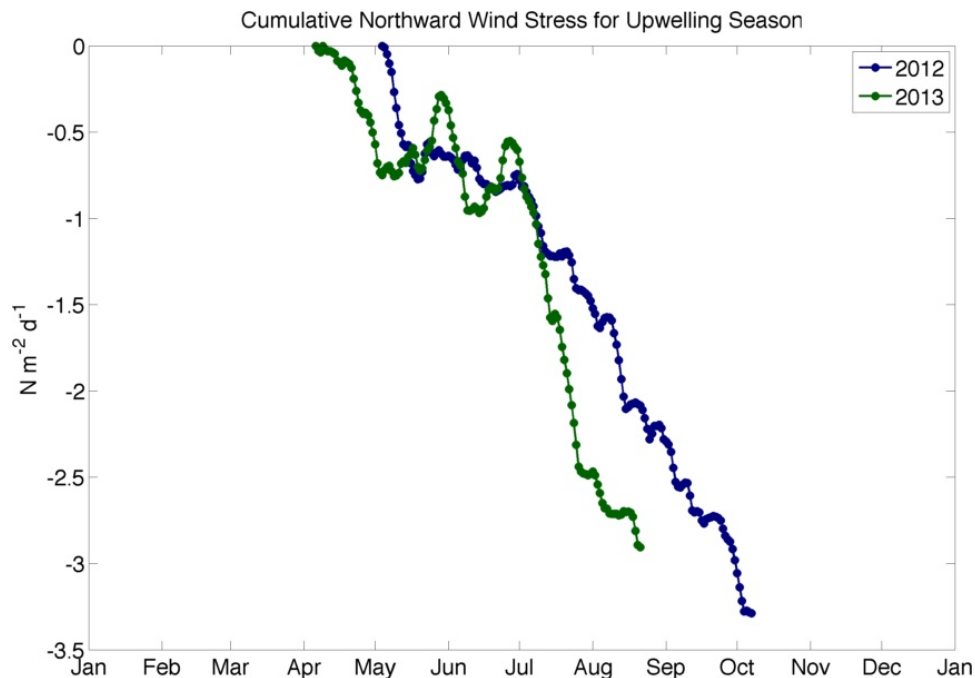


Figure 40. Cumulative northward wind stress from 2012 and 2013 upwelling seasons for the Oregon coast (data from Pierce & Barth, <http://damp.coas.oregonstate.edu/windstress/index.html>).

5.2. Discussion

The primary driving force behind the 2012/2013 disparity in T-S space is the freshwater discharge to the estuary. Discharge is higher in 2012, resulting in a wider range in salinity space. Incongruously, the cumulative precipitation for 2012 was lower than in 2013. Intuitively it would seem as if this would cause discharge to be lower as well. However, this is not what the data show for Coos Bay. It is possible that the rain gage at the North Bend airport is not representative of precipitation feeding the watershed. The gage is located at sea level, whereas the tributaries that feed Coos Bay originate in the steep, forested catchments of the Oregon Coast Range. The discrepancy between the precipitation and discharge data could also be the result of the timing and intensity of precipitation events during the two years.

Sayama et al. (2011) studied the storage patterns of two small watersheds in Northern California, less than 200 km south of Coos Bay. While the watersheds are an order of magnitude smaller than the Coos Bay watershed ($\sim 100 \text{ km}^2$ vs. $\sim 1500 \text{ km}^2$), they share the same distinct wet and dry seasonality of the Pacific Northwest, as well as the same geologic setting. What the study revealed is that each watershed has a unique storage limit. Before the limit is reached, rainfall generates little corresponding runoff. After this limit is exceeded, the watershed will release considerably more water. Precipitation is preferentially stored at the beginning of wet season before the watershed reaches its threshold, then rainfall actively generates storm runoff (Sayama et al., 2011). The second finding from their study was that steeper catchments store more water, requiring more rainfall to activate the rapid rainfall-release response.

This study is informative for the Coos Bay watershed and the differences seen in the estuarine hydrography between 2012 and 2013. In 2012, precipitation events were relatively constant throughout the winter and into the spring months (Figure 36). Cumulative discharge was lower than 2011 and 2013 until February, where it proceeded to surpass both late in the spring (Figure 35). It is likely that in the late fall and winter months, a large portion of rainfall was going into storage. After the storage threshold was surpassed in the early spring, the discharge response to rainfall events was greater. In 2013, more precipitation fell early in the wet season, with very few events in the spring (Figure 36). It is possible that the early season rain preferentially went into storage, and the weak late season rainfall never surpassed the threshold needed for the rapid rainfall-release response.

The T-S plots corroborate this hypothesis. Figure 34 shows that in January-April of 2013 the waters are much saltier than the previous year. The exchange circulation is more diminished during these months in 2013 as well (Figure 37). This diminished estuarine circulation could explain the absence of the coldest and saltiest water in the estuary later in the season (Figure 34). With less buoyancy forcing the salinity gradient weakens, causing estuarine circulation to weaken, and stratification to break down. This induces increased mixing of the incoming salty shelf waters with the overlying brackish outflowing waters. This provides one explanation for the absence of the coldest, saltiest waters from the estuary in the summer of 2013.

The upwelling intensity and duration in 2013 may be another factor in the absence of the cold, salty water in 2013 that was present in July and August of 2012. The PFEL upwelling indices (Figure 39) show that for most of the summer of 2013, upwelling is

less than normal at both the 42N site and the 45N site. The upwelling season starts earlier in 2013 (Figure 40), but two major relaxation events in late May and mid-June likely ‘reset’ shelf water properties. Deep, cold waters would have been advected back offshore, and warmer surface waters would have been pushed back onshore. The 2013 upwelling season also ends more than a month earlier than the 2012 season.

Despite the coldest, saltiest shelf waters never reaching Coos Bay during the summer of 2013, the dissolved oxygen levels were lower than in 2012. Presumably, this could be attributed to diminished estuarine circulation facilitating longer residence times, stagnating waters in the estuary, and allowing for more biologic drawdown of DO. Recorded temperatures were also higher in 2013, which would cause an increase in biological oxygen demand and a decrease in oxygen solubility across the air-water interface. Regardless, DO never reaches hypoxic levels in either year—which is an important result that will be covered in depth in Chapter VI of this study.

The pronounced difference between 2012 and 2013 offers a glimpse of how climate change could alter the hydrography of Coos Bay. An analysis of climate models from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) showed the Pacific Northwest experiencing little change in mean precipitation in the coming century, however, the winters are projected to be wetter and the summers, drier (Mote & Salathé, 2010). Less precipitation later in the wet season and into the dry season could alter the estuarine circulation by reducing the along-estuary salinity gradient. This could cause longer residence times, and more vertical mixing within the estuary during the summer.

CHAPTER VI

HYPOXIA IN COOS BAY

The previous two chapters have focused primarily on the hydrography and circulation in Coos Bay—what drives it, how it changes seasonally and interannually, and how it compares to other systems. This chapter will address the second and third objectives of this study—determining whether or not there is a history of hypoxia in Coos Bay, and what drives spatiotemporal variability in dissolved oxygen in the estuary.

6.1. Results

6.1.1. Spatiotemporal Variability in Dissolved Oxygen Levels

The monthly CTD transects revealed along-estuary variability in dissolved oxygen levels in Coos Bay. We have a total of 15 (Nov. 2012 – Jul. 2014) monthly DO datasets. Figure 41 shows the minimum DO measurements for each cast along the estuary. March and April of 2013 and 2014 indicate a positive gradient of DO with distance along-estuary. In contrast, data from June 2014, July 2014, September 2013, and October 2013 show declining DO from the mouth to the estuary head. Minimum DO levels from CTD transects during November, January and February are nearly uniform along the length of the estuary.

April 2013 showed the most pronounced along-estuary gradient in DO. Further investigation of water properties and wind conditions show a strong upwelling event occurred just prior to the sampling trip (Figure 42). Simultaneous buoy and logger time series data show that salinity increased, while temperature and DO levels decreased as a strong upwelling-favorable wind event occurred on the shelf.

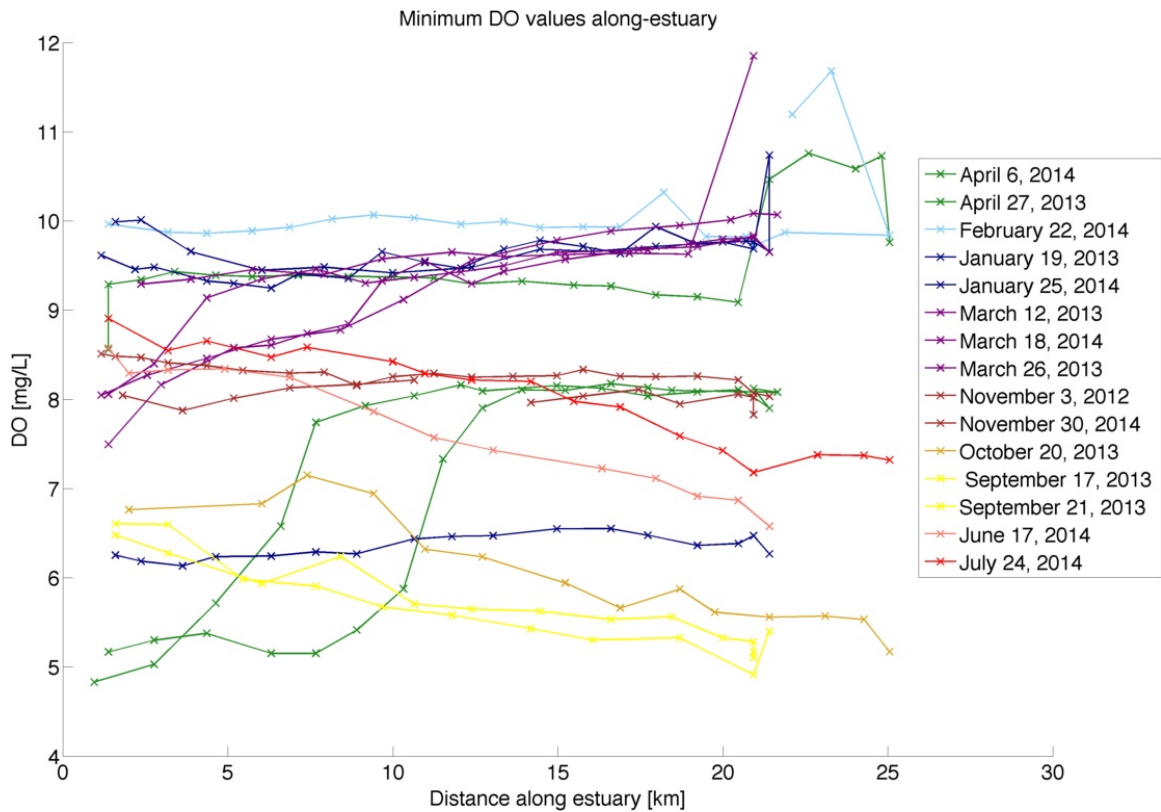


Figure 41. Minimum DO values from CTD data versus their location measured by along-estuary distance.

The loggers from the SSNERR and the CTCLUSI provide higher temporal resolution of DO variability. Because these loggers collected measurements every fifteen minutes, the datasets resolve the tidal, diurnal, and seasonal cycles. Figure 43 shows data from the CTCLUSI's BLM and Empire (EMP) boat dock loggers along with the SSNERR Charleston Bridge logger.

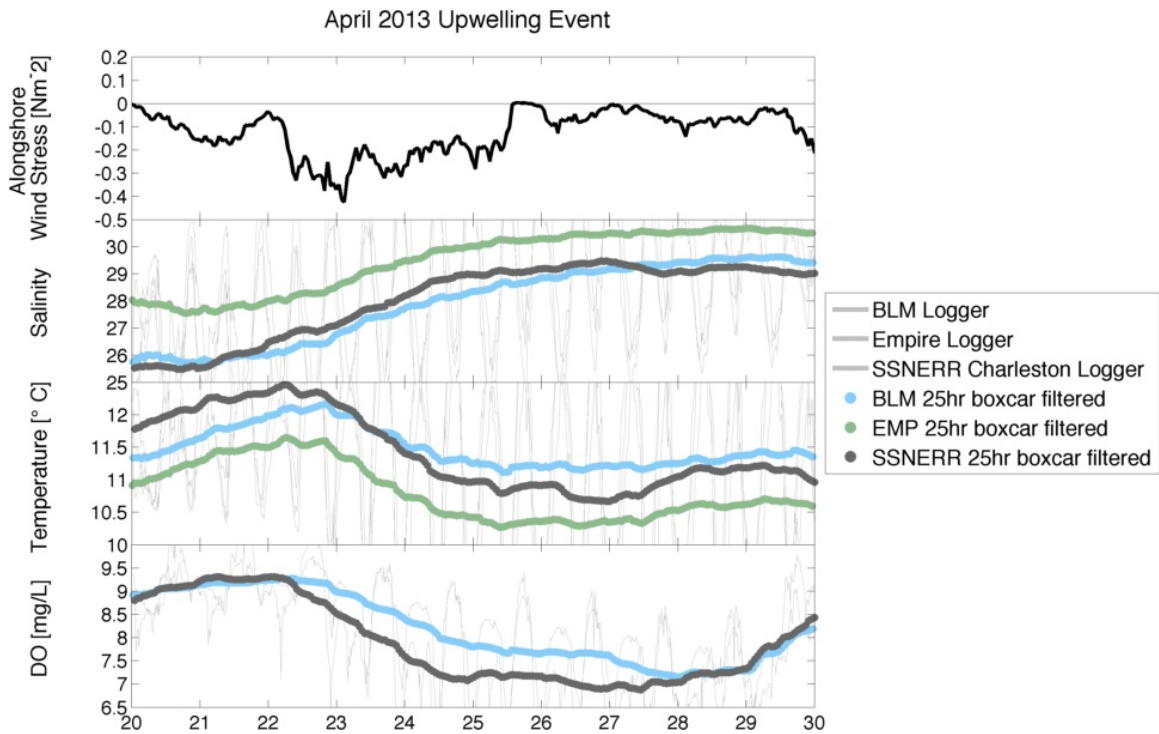


Figure 42. An upwelling event observed during the period April 20-30, 2013. (Top) alongshore wind stress calculated from NOAA buoy 46015 wind measurements, negative is upwelling favorable, equatorward wind stress. (Center and bottom) 25-hr boxcar filtered salinity, temperature, and DO measurements from the BLM boat dock logger (blue), the Empire boat dock logger (green) and the Charleston Bridge logger (dark grey). Light grey lines in the background show unfiltered data with tidal variability.

The data show the diurnal cycle in dissolved oxygen levels due to photosynthesis and respiration. DO is lower at night (more instances where $DO < 6.5$ mg/L) due to the cessation of photosynthesis and the continued demand of respiration. During the day, DO increases as photosynthesis adds oxygen back into the system. In addition, wind data from the SSNERR meteorological station show a strong diurnal pattern in the local winds, with strong winds more likely to occur in the afternoon and early evening (Figure 44). Strong winds induce more mixing and reaeration of the water column, further buffering the system from hypoxia.

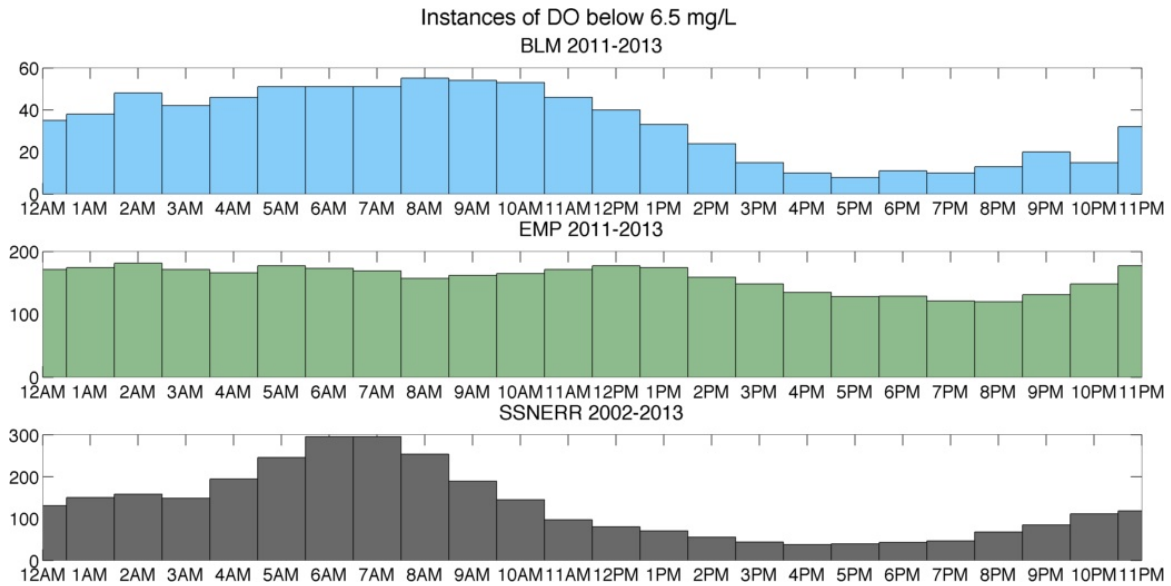


Figure 43. Number of DO measurements <6.5 mg/L from the CTCLUSI and SSNERR water quality loggers, by hour of day. The CTCLUSI logger data span 2011-2013, and the SSNERR logger spans 2002-2013. All loggers show fewer instances of low DO during the daytime.

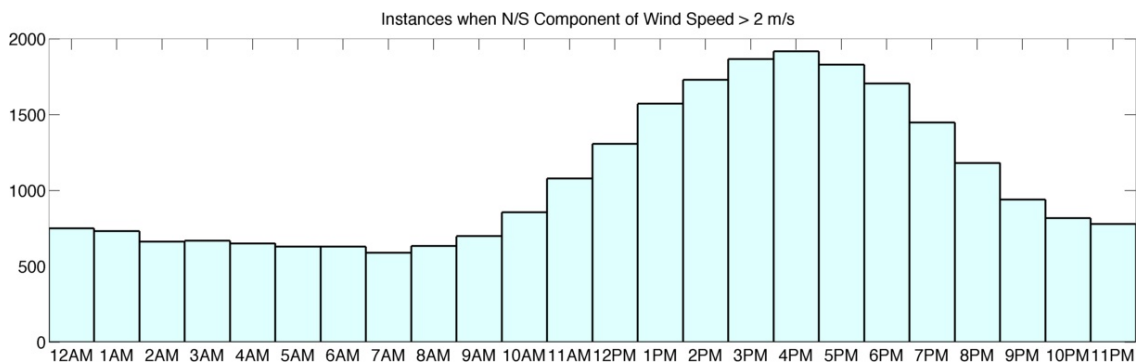


Figure 44. Instances when the N/S component of wind speed is greater than 2 m/s, by hour of day. Wind data comes from the SSNERR meteorological station between Jan. 1, 2012 and May 31, 2014. Winds are stronger in the afternoon in Coos Bay.

In addition to the diurnal variability, DO levels are also highly seasonal. The wet season experiences very few instances of DO levels < 6.5 mg/L. However, with the switch to upwelling conditions, progressively less oxygenated waters are observed

throughout the estuary (Figure 45). Observations of low DO levels increase from April through to September and October, before dropping off again.

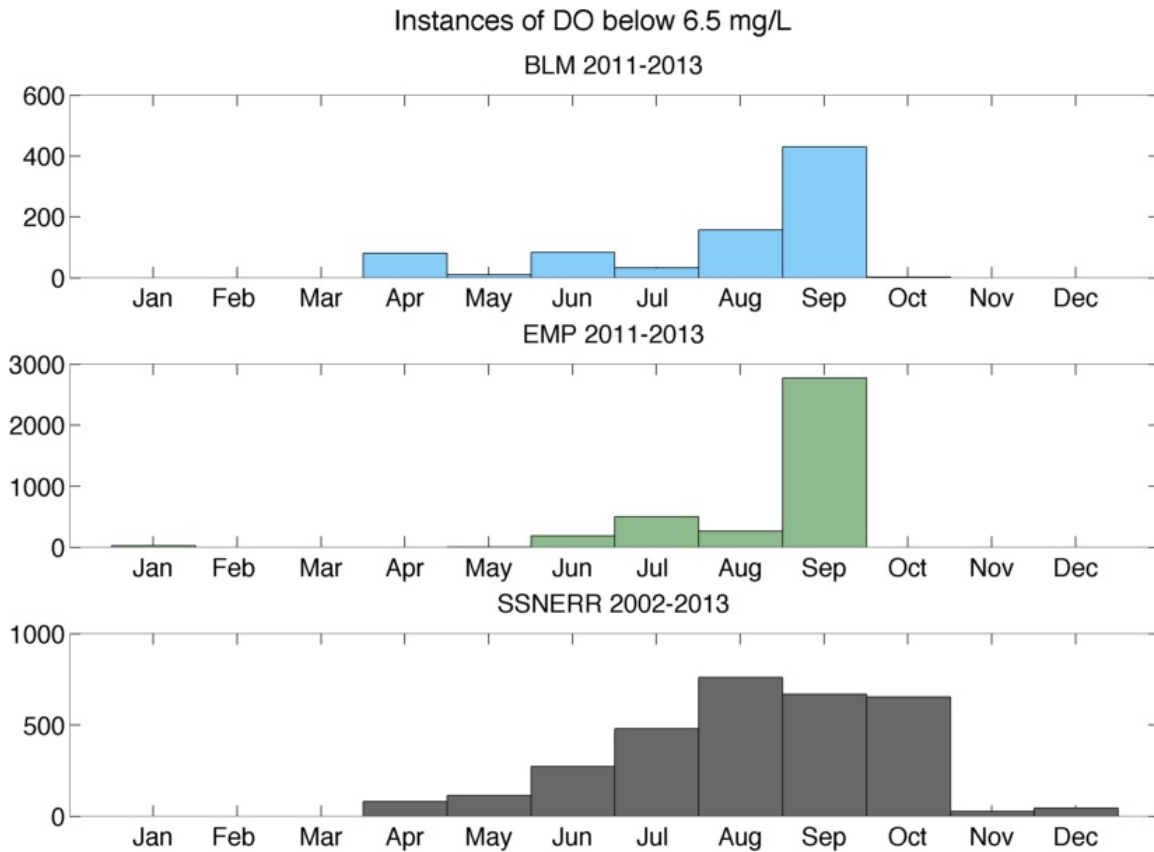


Figure 45. DO measurements <6.5 mg/L from the CTCLUSI and SSNERR water quality loggers, by month of year. The CTCLUSI logger data span 2011-2013, and the SSNERR logger spans 2002-2013. Measurements of DO <6.5 mg/L increase as the dry season progresses.

Using the SSNERR dataset, it was possible to look at interannual differences in DO levels (Figure 46). 2006 stands out as a year of significantly more low-oxygen waters reaching Coos Bay. 2002 had the next highest occurrence of DO levels < 6.5 mg/L, followed by 2008; all the other recorded years had DO >6.5 mg/L 95% of the time. This data gives further evidence for strong interannual variability (explored in Chapter V) in Coos Bay.

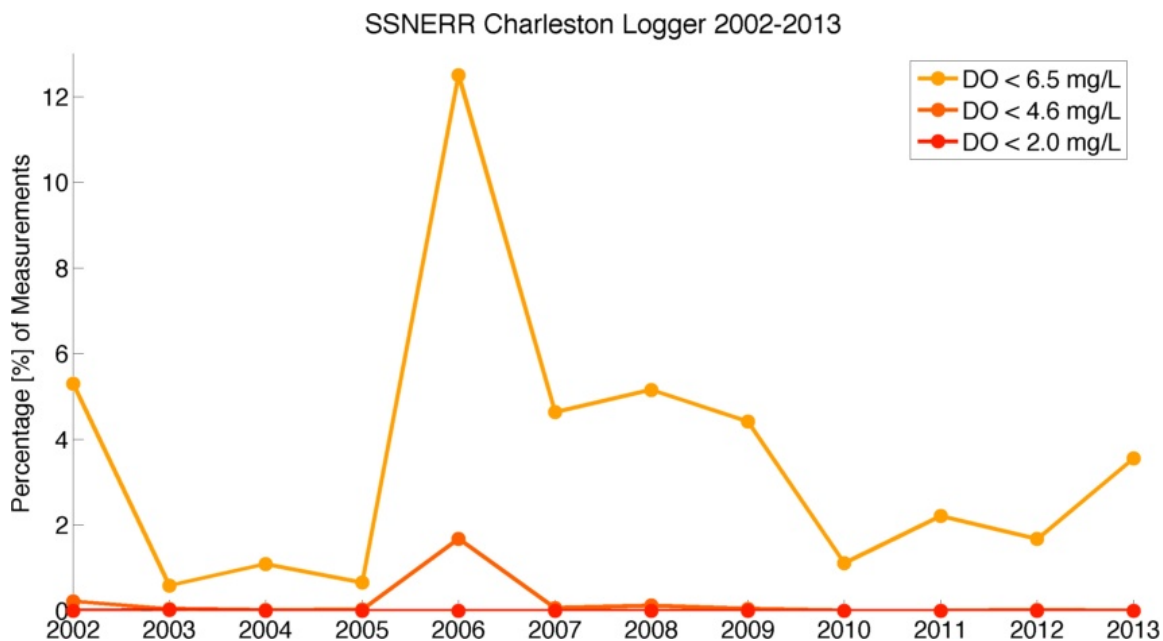


Figure 46. Percentages of DO measurements < 6.5 mg/L (yellow), < 4.6 mg/L (orange), < 2.0 mg/L (red) at the Charleston Bridge logger maintained by SSNERR. Data spans Apr. 2002- Dec. 2013.

It is clear from the logger data that hypoxia is not currently a problem in Coos Bay. The highest threshold of 6.5 mg/L, which is the official state of Oregon threshold for estuarine hypoxia based on salmon success (6.5 mg/L; US EPA, 2003; Brown & Power, 2011), was breached 12.5% of the time in 2006, and much less frequently in other years. Even in 2006, the year that had the most instances of low DO at the Charleston Bridge station, only experienced < 2% of measurements < 4.6 mg/L—the threshold found to maintain most species, except the most sensitive 10% (Vaquer-Sunyer & Duarte 2008). And DO never fell below the hypoxic threshold of 2 mg/L that year.

From the twelve-year record there was only one measurement of DO < 2 mg/L at the Charleston Bridge location. Measurements from this logger are taken every 15

minutes, so that is the maximum duration that hypoxia could have persisted during this one, isolated occurrence in 2003.

Because this logger only takes measurements at one place in the estuary, it alone cannot rule out hypoxia in other parts of the estuary. However, the two full years of data from the BLM and EMP loggers and the recent data from the Coquille Indian Tribe (CIT), in conjunction with the longer-term SSNERR dataset, show that hypoxic waters were rarely observed throughout the estuary during 2012, 2013, and into the beginning of 2014 (Figure 47). Most of the time, DO levels are above 6.5 mg/L, and not once was DO < 2mg/L. Fluctuations in DO levels are greater during the dry season, while in the wet season, DO levels are higher and more constant.

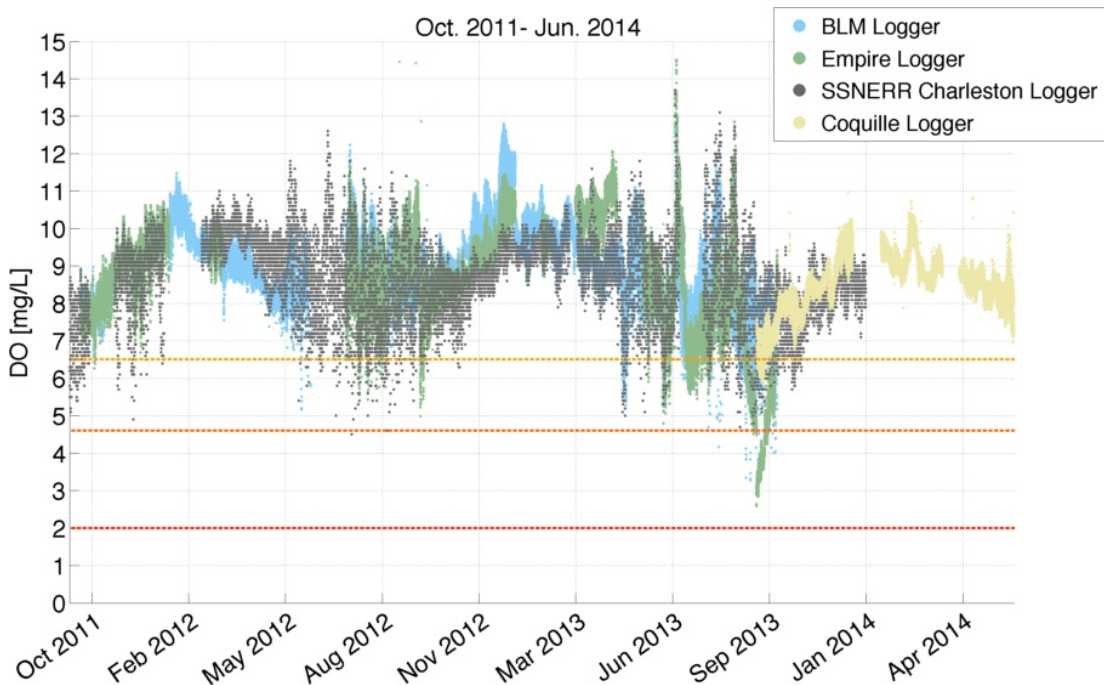


Figure 47. Logger data from SSNERR, CTCLUSI, and CIT showing DO data from October 2011 to June 2014. The yellow, orange, and red horizontal lines indicate thresholds for 6.5 mg/L, 4.6 mg/L, and 2.0 mg/L, respectively. No instances of DO < 2 mg/L were recorded at these stations.

6.1.2. Historic Occurrence of Hypoxia

The fifty-year DEQ dataset of DO measurements in Coos Bay only includes one measurement of hypoxia in the main estuary (Figure 48) and shows there to be no trend of declining DO levels over time. The SSNERR Charleston Bridge logger 12-year dataset also shows no trend over time (Figure 50).

While these datasets show hypoxia is rare in the main estuary of Coos Bay, it is difficult to say conclusively if there is no historic pattern of low DO in the estuary. The DEQ dataset contains some years with very few measurements, while others have orders of magnitude more (Figure 49). Another issue is that no depths were documented with these measurements, severely limiting our conclusions drawn from them.

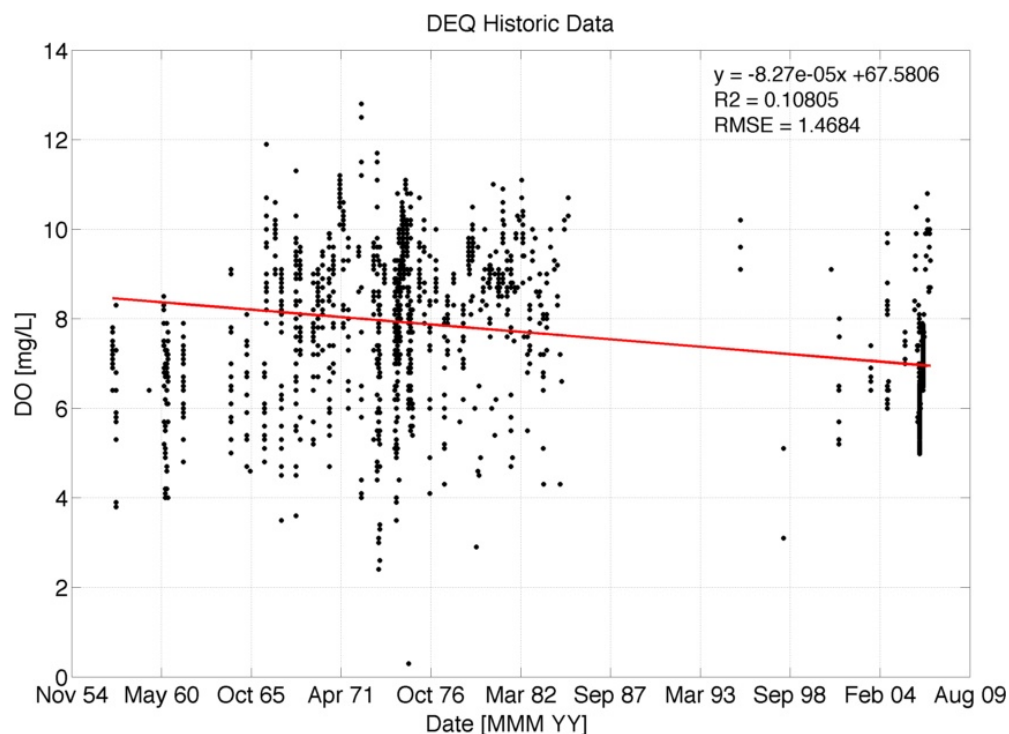


Figure 48. Historic DO measurements in Coos Bay from the DEQ plotted versus time. Linear regression shows no significant trend over time ($r^2 = 0.108$).

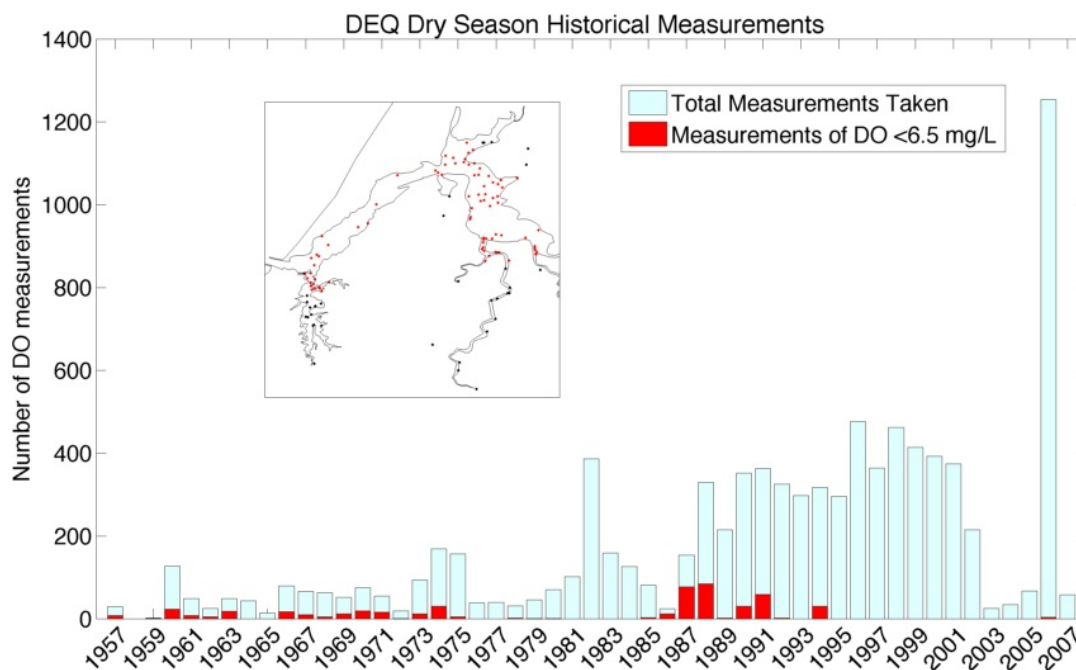


Figure 49. Number of DO measurements per year in Coos Bay. Data from the DEQ; some years are sampled much more thoroughly than others. Red portion of the bars signify DO values <6.5 mg/L. (Inset) Map shows the location of measurements considered in this study (red dots) and the measurements considered to be outside the main stem of Coos Bay (black dots).

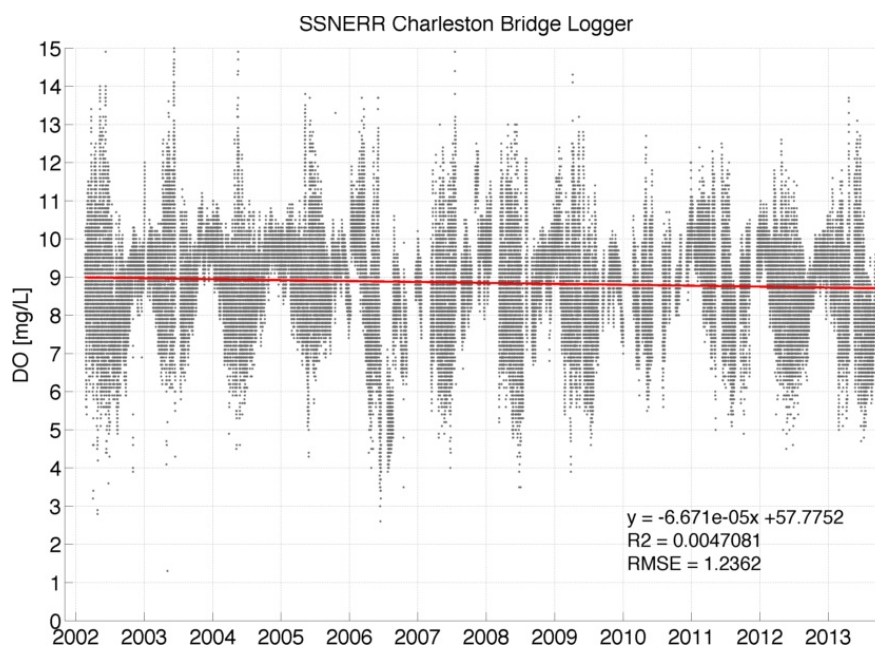


Figure 50. SSNERR Charleston Bridge DO data plotted versus time. Linear regression shows no significant trend over time ($r^2 = 0.0047$).

6.2. Discussion

The datasets in this analysis show that hypoxia is not pervasive in the main channel of Coos Bay, and has not been for the past decade, and possibly longer. The historic dataset from the DEQ is not well-documented, therefore it is not possible to draw conclusions about longer-term trends in Coos Bay, at present.

There is daily, seasonal, and interannual variability in the estuary's DO levels. Daily variability is primarily due to biotic processes and local wind events. Seasonal variability is attributed to upwelling/downwelling dynamics on the shelf. Greater variability is observed in DO levels during the dry season, as upwelling brings low DO waters onto the shelf, but relaxation events bring oxygenated surface waters shoreward. As the dry season progresses, the occurrence of lower DO waters in the estuary increases (Figure 45), likely due to longer residence times, and lower DO shelf waters. When the downwelling regime and the rains return in the wet season, DO levels increase and stay high throughout the winter. Interannual variability in DO in Coos Bay is observed for the 2012 and 2013 water years. Our two-year dataset limits our ability to specifically link interannual variability to certain conditions. However, it is likely that differences in the shelf DO levels due to upwelling conditions, and residence times within the estuary play a large role in interannual variability.

In addition to temporal variability, we also observed spatial variability in DO levels throughout the estuary (Figure 41). The CTD transects showed along-estuary variability in DO, especially during the spring and summer months. DO levels were nearly uniform along the estuary during the winter. In March and April, DO increases with distance along the estuary. It is likely that river input is still relatively high at the

head of the estuary, while our sampling transects occurred as upwelling had set in, causing lower DO levels at the mouth. The months of September and October, while having the highest frequency of lower DO water throughout the estuary, saw slightly increasing DO with distance up-estuary. This can be likely be attributed to extremely low freshwater inputs coupled with long residence times in the summer. The depleted shelf waters are advected into the estuary, but then spend weeks before circulating back out. High biologic activity in the estuary could draw the DO down further.

The contribution of biology to the DO levels in Coos Bay is an important component that was outside the scope of this study. During the summer, when residence times are long, biologic activity is high, and DO levels are naturally more variable and lower, *in-situ* biologic activity could either accelerate or buffer the onset of hypoxia. To fully understand DO dynamics in Coos Bay, quantifying variability in net ecosystem metabolism (NEM) of the estuary is crucial. NEM is a measure of the difference between net primary production and total system respiration (Caffrey et al., 1998). An autotrophic system has positive NEM, with production outpacing respiration, adding oxygen to the system. A heterotrophic system has negative NEM, thus respiration is greater than production and oxygen levels are reduced. A study by Caffrey (2004) found certain sites in the South Slough of Coos Bay to be net heterotrophic. However, NEM varies on multiple temporal and spatial scales, and an in-depth study constraining NEM on these scales is needed to understand the biologic contribution to DO levels in the estuary.

The absence of hypoxia currently in Coos Bay is a conclusion that warrants further examination. Our study focused on the main channel of Coos Bay in order to determine the oceanic contribution to DO levels. Because no persistent hypoxia was

observed along the channel, it is likely that the shelf waters entering Coos Bay are not hypoxic. A recently published study proposed that regions in the CCS that have a narrow shelf are less likely to experience hypoxia than regions with wide shelves (Peterson et al., 2013). Wide shelf regions experience longer retention of water masses, allowing for further reduction of DO as biology acts on the already low-DO, upwelled water. Coos Bay is located in a region where the Oregon shelf is very narrow, thus substantiating this hypothesis. To give further support this hypothesis, however, more DO measurements from the shelf region off Coos Bay are needed.

In focusing our study on the main channel of the estuary, we neglected the search for hypoxic waters in other reaches of the estuary—in its sloughs, and shallow tideflats. Hypoxic waters in these parts of the estuary would not be a result of shelf hypoxia; rather they mostly result due to stagnation, high temperatures, OM, and high biological oxygen demand.

This study should be informative for future monitoring of the estuary's health. If the effects of climate change—high surface ocean temperatures and stratification, more upwelling-favorable winds, more productivity-generated respiration, and lower DO source waters—continue to worsen, it is likely that hypoxic and anoxic conditions will persist and worsen on the Oregon shelf. This study can serve as reference point for a time when the ecosystem was relatively healthy and hypoxia was not yet a pressing issue for the estuary.

CHAPTER VII

CONCLUSIONS AND IMPLICATIONS

7.1. Conclusions

- **How do ocean properties and the seasonal change in forcing mechanisms affect estuarine circulation in the Coos Bay estuary?**

Classifying Coos Bay using nondimensional hydrodynamic parameters revealed a highly variable system that, over the course of a year, falls in several different estuarine regimes. Most of the variability is attributed to the highly seasonal buoyancy input of the riverflow, which varies by three orders of magnitude over a year. During the dry season (May – October) when discharge is low ($0\text{--}30\text{ m}^3\text{s}^{-1}$), Coos Bay is well-mixed, and can experience SIPS conditions. As riverflow increases ($30\text{--}150\text{ m}^3\text{s}^{-1}$), thus driving up Fr_f , Coos Bay becomes partially mixed. During times of high flows when discharge $>150\text{ m}^3\text{s}^{-1}$, (i.e. Jan. 19, 2013, Feb. 22, 2014, see Appendix B), Coos Bay becomes a salt wedge/ time-dependent salt-wedge- type estuary.

As riverflow increases up to $150\text{ m}^3\text{s}^{-1}$, $\partial s/\partial x$ follows linearly (Figure 15). Increased along-estuary gradients drive stronger residual circulation (Figure 37), which decreases residence times in the estuary (Figure 30). Riverflow exceeding $150\text{ m}^3\text{s}^{-1}$ appears to push the salt intrusion further down-estuary, and the linear relationship with $\partial s/\partial x$ degrades (Figure 15). Diminished river inputs stagnate the residual, estuarine circulation, and cause residence times to increase (Figure 30). In Coos Bay, there is likely a gradient in residence time with distance up-estuary, as in Willapa Bay, WA (Banas & Hickey, 2005). The declines in minimum dry season DO with distance in Coos

Bay (Figure 41) imply the waters up-estuary have been subjected to *in-situ* biologic processes that draw down DO for a longer time than waters near the mouth. This gradient in residence times with distance up-estuary in Coos Bay has been posited to explain observations of large oyster larvae populations in the upper reaches of the estuary where long retention times allow for optimal growth conditions (Pritchard, 2013).

In the dry season, freshwater inputs are low, so other forcings dominate the hydrography in Coos Bay. The estuary becomes inundated with salty ocean water, residual flows diminish, and stratification weakens. The nondimensional parameterization of Coos Bay shows that strong tidal currents during the dry season can cause SIPs conditions. Future work should target this phenomenon as it likely plays an interesting role in the mixing dynamics of the estuary.

Interannual variability in the hydrography of Coos Bay is linked to both freshwater inputs and shelf water conditions. We observed distinct differences in the T-S properties, DO levels, and residual circulation between 2012 and 2013. Lower discharge in 2013 caused decreased residual flows (Figure 37), increased residence times, and led to lower overall DO levels in the estuary (Figure 38). Higher residual flows driven by greater discharge in 2012 led to a wide range in T-S space (Figures 37 & 34). A longer, more consistent upwelling season in 2012 meant colder, saltier water from the shelf could reach the estuary during the dry season (Figure 34).

- **Is there a record of hypoxia in Coos Bay either historically or currently?**

Despite the presence of upwelled water in Coos Bay (Figure 42), our data show hypoxia is not currently a problem for the estuary (Figures 45, 46, 47), and there is little evidence to show it has been a problem in the past (Figure 49). Longer-term datasets

from the SSNERR and the DEQ show DO levels neither increasing nor decreasing with time (Figures 48 & 50). However, due to limited spatial coverage (SSNERR) and poor data records (DEQ), understanding of the historical extent of hypoxia in Coos Bay is limited.

- **What influences the spatial and temporal variability in observed DO levels?**

While there is no hypoxia in Coos Bay currently, there is significant spatiotemporal variability in DO levels. Lower DO at night and higher DO in the late afternoon can be linked to biologic processes (photosynthesis, respiration) and physical processes (wind-driven mixing; Figure 44). High DO from river water, downwelling, and winter wind-driven mixing keep DO levels high during the wet season. As riverflow diminishes and conditions switch to upwelling-favorable on the shelf, ambient DO levels in Coos Bay drop. As the dry season progresses, there are more instances of lower-DO water in the estuary (Figure 45). It is likely that longer residence times, especially in the upper reaches of Coos Bay, in conjunction with higher biologic oxygen demand facilitated by high water temperatures, cause DO to be lower up-estuary (Figure 41). Shelf waters set ambient DO conditions during the dry season when riverflow is nearly nonexistent. Therefore, upwelling conditions on the shelf dictate the level of DO in waters reaching the estuary. However, residence times and the biological oxygen demand of the estuary determine the level of DO degradation of waters within Coos Bay.

7.2. Implications

Our data show that the water entering Coos Bay from the shelf is not hypoxic. This result could aid researchers studying the regional occurrence of hypoxia on the

Oregon coast, and in the larger CCS system. It has been established that there is along-shelf variability in the occurrence of inner-shelf hypoxia (Peterson et al. 2011). This latitudinal variability has been attributed, at least partially, to shelf width (Peterson et al. 2011; Send & Nam 2012). Regions in the CCS with narrow continental shelves experience less hypoxia than areas with wider shelves (Peterson et al. 2011). On a wide shelf, upwelled water does not reach as shallow depths as it would on a narrow shelf. Because of this, biologic processes can further reduce DO concentrations; then, when relaxation from upwelling occurs, that same water is pushed back off the shelf to depth where it is further isolated from DO-enriching processes (Send & Nam 2012). On a narrow shelf, like that bordering Coos Bay, upwelled water reaches shallower depths under the same conditions. But here, the water parcel would be shallow enough to benefit from photosynthetic organisms and wind-driven mixing processes. Our finding that hypoxic waters are not entering Coos Bay may be of use to biogeochemical modelers in initializing and testing regional models of hypoxia.

While hypoxia is not currently a problem in Coos Bay, monitoring should continue as the effects of climate change advance, and likely, beget conditions ripe for hypoxic waters on the inner shelf in the CCS. Increasing surface-ocean temperatures (Rhein et al., 2013) enhance stratification, decrease mixing, and decrease the solubility of oxygen across the air-water interface. Increasing air temperatures warm riverine waters, also decreasing the solubility of oxygen in estuary-bound waters. Warmer oceanic, riverine, and estuarine water temperatures drive higher respiration and decomposition oxygen demands. In addition to warming temperatures, upwelling winds in the CCS are intensifying, causing a greater volume of upwelled water onto the shelf (Bakun, 1990).

The DO content of these waters is decreasing as the OMZ shoals in the CCS (Bograd et al. 2008; Pierce et al. 2012). Coos Bay is ocean-dominated in the summers, so it will be vulnerable to the degrading conditions for DO occurring on the shelf.

In tandem with the coastal effects of climate change on hypoxia, alterations to Coos Bay's hydrography should be expected under climate change scenarios. An analysis of climate models from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) showed the Pacific Northwest experiencing little change in mean precipitation in the coming century, however, the winters are projected to be wetter and the summers, drier (Mote & Salathé, 2010). Less precipitation later in the wet season and into the dry season could alter the estuarine circulation by further reducing the along-estuary salinity gradient. This will cause longer residence times, and more susceptibility to biologically-driven hypoxia.

The estuarine circulation in Coos Bay will be further altered in the coming years as conditional approval for a liquid natural gas (LNG) terminal was issued in March, 2014. Approximately 5.6 million cubic yards of the north spit of Coos Bay will be dredged to accommodate LNG shipping vessels, and there are proposals to widen (300 ft to 600 ft) and deepen (37 ft to 51 ft below MLLW) the main channel of Coos Bay (United States Department of Energy, Federal Energy Regulatory Commission, 2009). These dredging projects will increase the reach of oceanic waters, especially in the dry season. Gravitational circulation will be increased, which could lower residence times in the estuary and decrease stratification.

It is our hope that this work will serve as a reference for future study of Coos Bay. Increased monitoring efforts by SSNERR, and other local agencies, in addition to the

development of a hydrodynamic model for the estuary, will undeniably increase our understanding of this system, and inform future management of this ecologically and economically valuable natural resource.

APPENDIX A

COOS BAY SPECIFICATIONS

Table 5. Specifications for the Coos Bay estuary, listed with their sources.

Parameter	Value	Source
Mean Width	365 m (low tide)	Coos Bay EIS Supplement, 1975
Mouth Width	620 m	Lee & Brown, 2009
Length	21 km	Coos Bay EIS Supplement, 1975
Mean Depth	4 m	Hickey & Banas, 2003
	1.5 m	Percy, 1974
	2 m below MLLW	Rumrill, 2006
Volume below MSL	0.14 km ³	Hickey & Banas, 2003
Estuarine Volume	2.1 x 10 ⁸ m ³	Lee & Reusser, 2006
Area	54.9 km ²	Lee & Brown, 2009
	34 km ² at MSL	Hickey & Banas, 2003
	44.4 km ² at HW (10,973 acres)	Percy, 1974
	38.6 km ² average (9543 acres)	
	54 km ²	Rumrill, 2006
Coos Bay Watershed Drainage Area	1500 km ²	NOAA, 1985
	1567 km ² (605 sq. miles)	Percy, 1974
	1502 km ²	Arneson, 1976
	1575 km ² (608 sq. miles)	Rumrill, 2006
		Lee & Brown, 2009
	1567 km ²	Coos Bay EIS Supplement, 1975
Monthly Mean River Flow	Lowest: 2.8 m ³ s ⁻¹ Highest: 190 m ³ s ⁻¹	Hickey & Banas, 2003
Intertidal Area	47% at MHW	Hickey & Banas, 2003
	48% ; 18.49 km ²	Percy, 1974
	55%	Lee & Brown, 2009
Tidal Prism	7.65 x 10 ⁸ m ³	Johnson, 1972
	5.27 x 10 ⁷ m ³	Percy, 1974
Dominant Tidal Period	12.42 h (M2)	U.S. Coast and Geodetic Survey, 1942 (Blanton, 1969)
Average Tidal Current Speed	1 ms ⁻¹	Baptista, 1989 (Rumrill, 2006)

Mean Tidal Range	1.7 m (at mouth)	Hickey & Banas, 2003
	2.3 m (mouth)	Rumrill, 2006
	2.2 m (Coos Bay)	
Ratio of Estuarine Volume to Tidal Prism	3.9	Lee & Brown, 2009
Residence Time	<i>Wet Season:</i> 7-13 days (modified tidal prism); 2-10 days (fraction of freshwater) <i>Dry Season:</i> 11-16 days (modified tidal prism); 34 days (fraction of freshwater)	Choi, 1975 Choi, 1975
	<i>Wet Season:</i> 13-16 days (modified tidal prism); 3-11 days (fraction of freshwater) <i>Dry Season:</i> 40-48 days (modified tidal prism); 19-31 days (fraction of freshwater)	Arneson, 1976
Flushing Time	3 d	Wilson, 2003 (Rumrill, 2006)
River Gaging Stations Drainage Areas South Fork Coos River East Fork Millicoma West Fork Millicoma Marlow Creek	543.898 km ² (210 mi ²) 169.6442 ² (65.5 mi ²) 120.952 ² (46.7 mi ²) 17.50832 ² (6.76 mi ²)	Coos Watershed Association http://www.cooswatershed.org/

APPENDIX B

CTD DATA

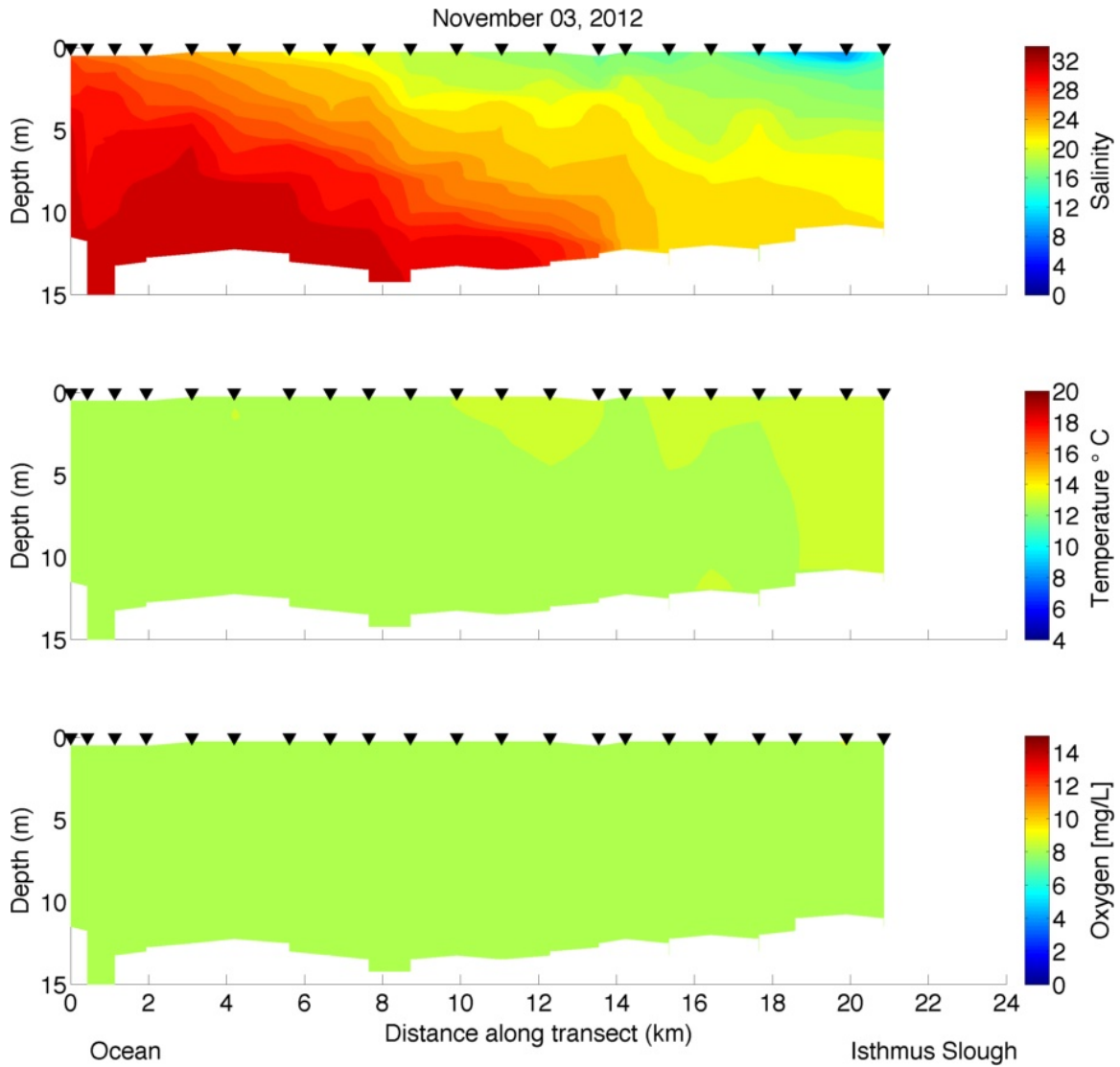


Figure 51. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from November 3, 2012.

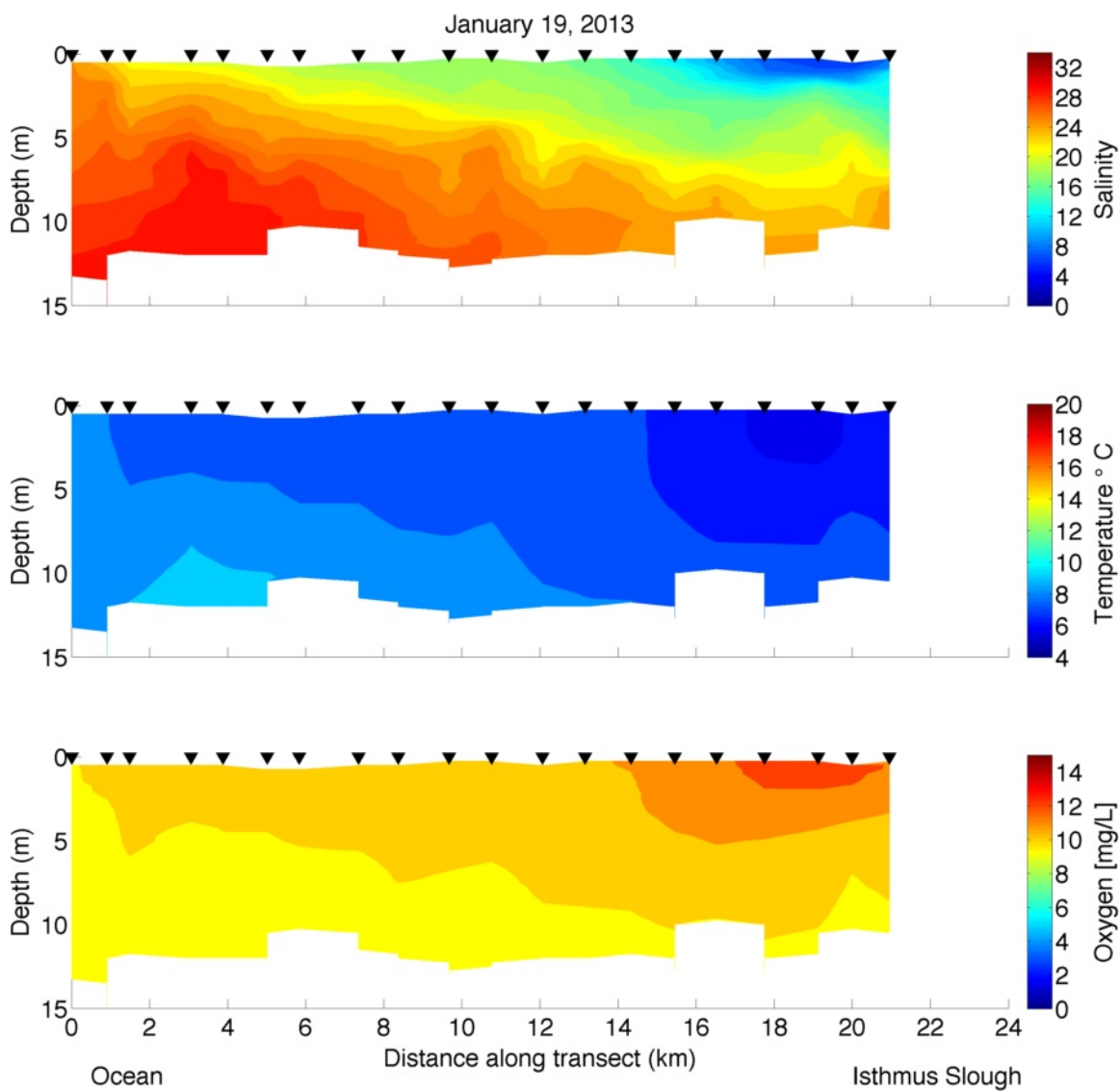


Figure 52. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from January 19, 2013.

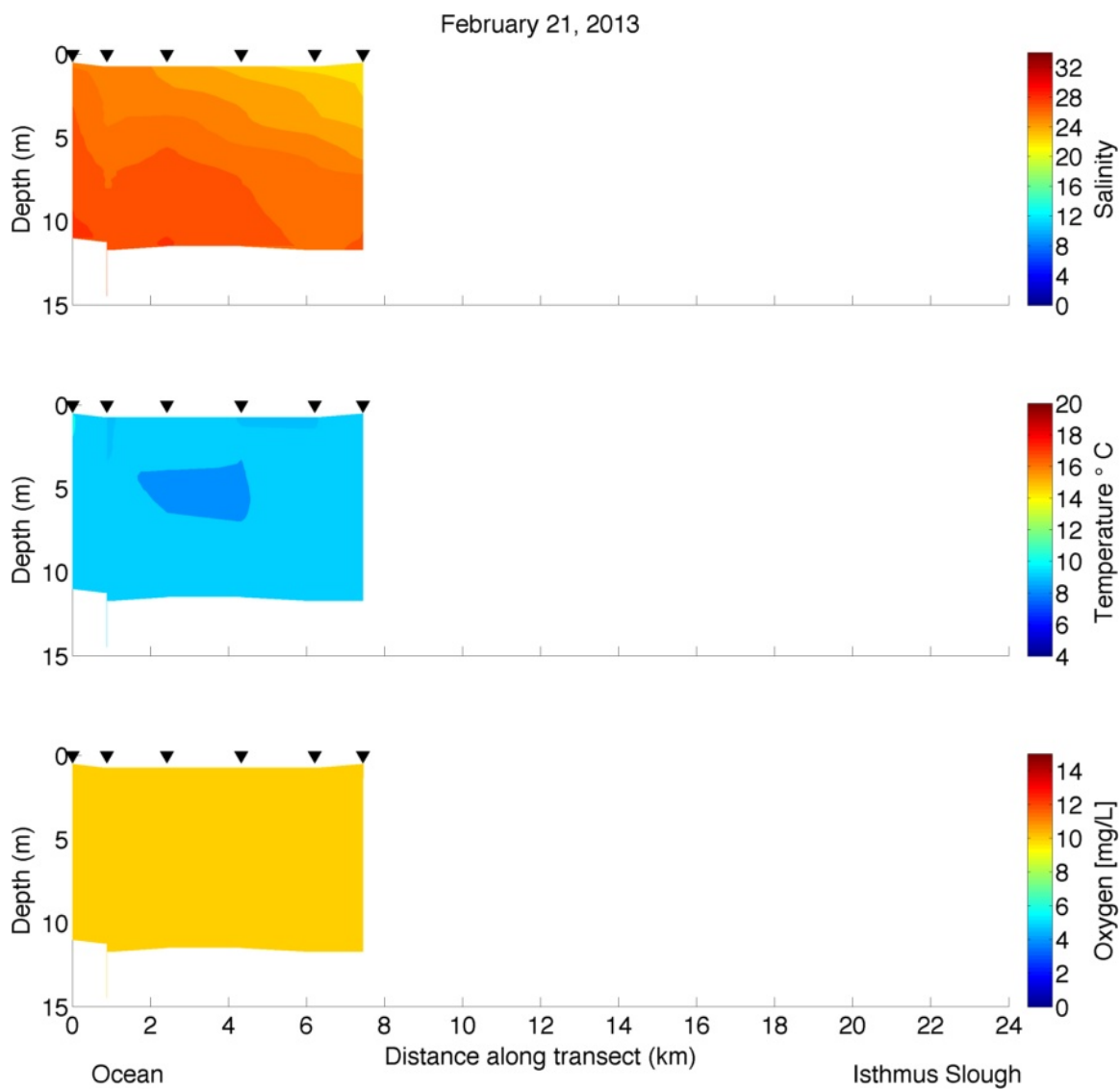


Figure 53. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from February 21, 2013. This was an abbreviated transect, with only 6 casts taken.

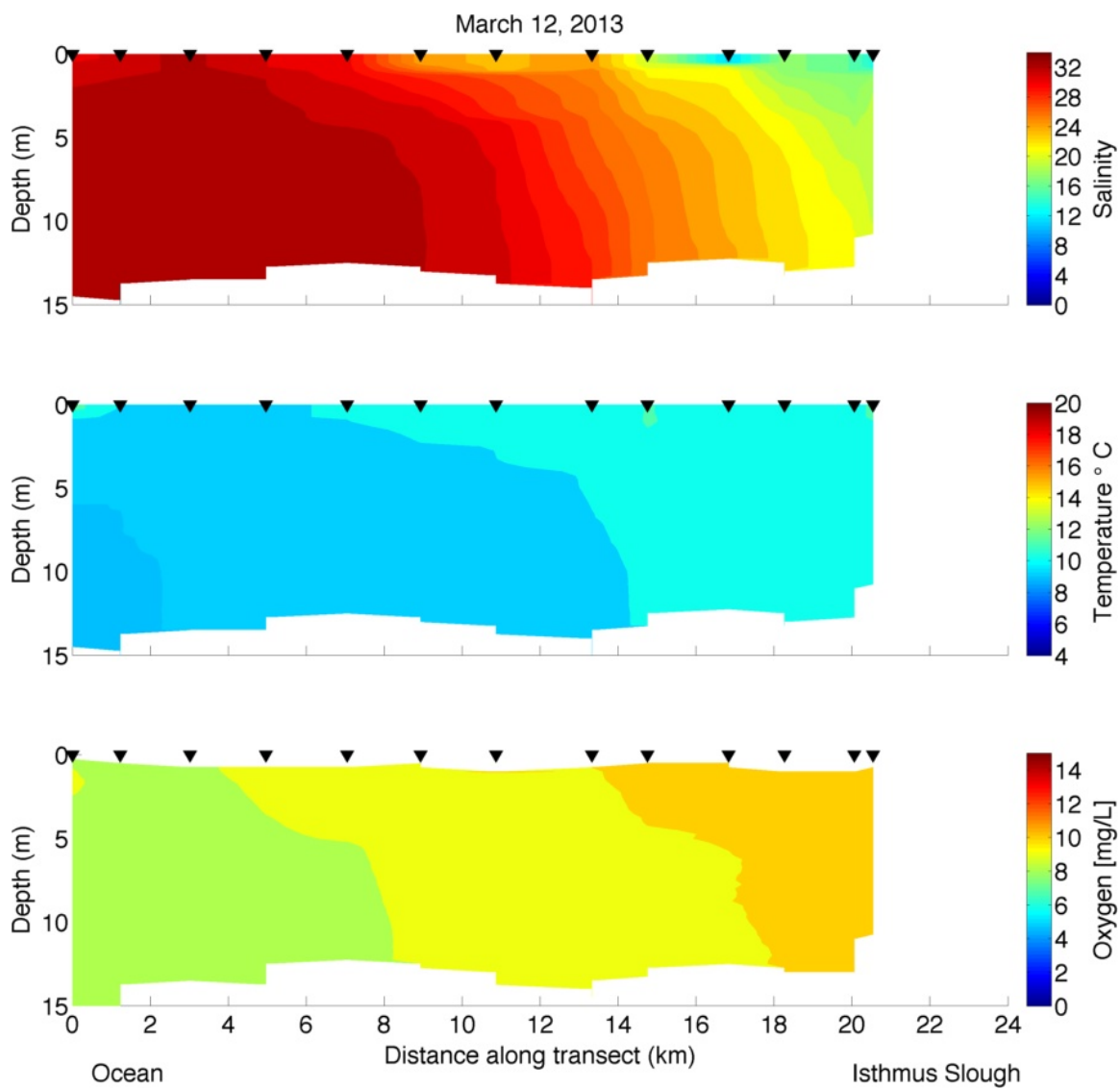


Figure 54. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from March 12, 2013.

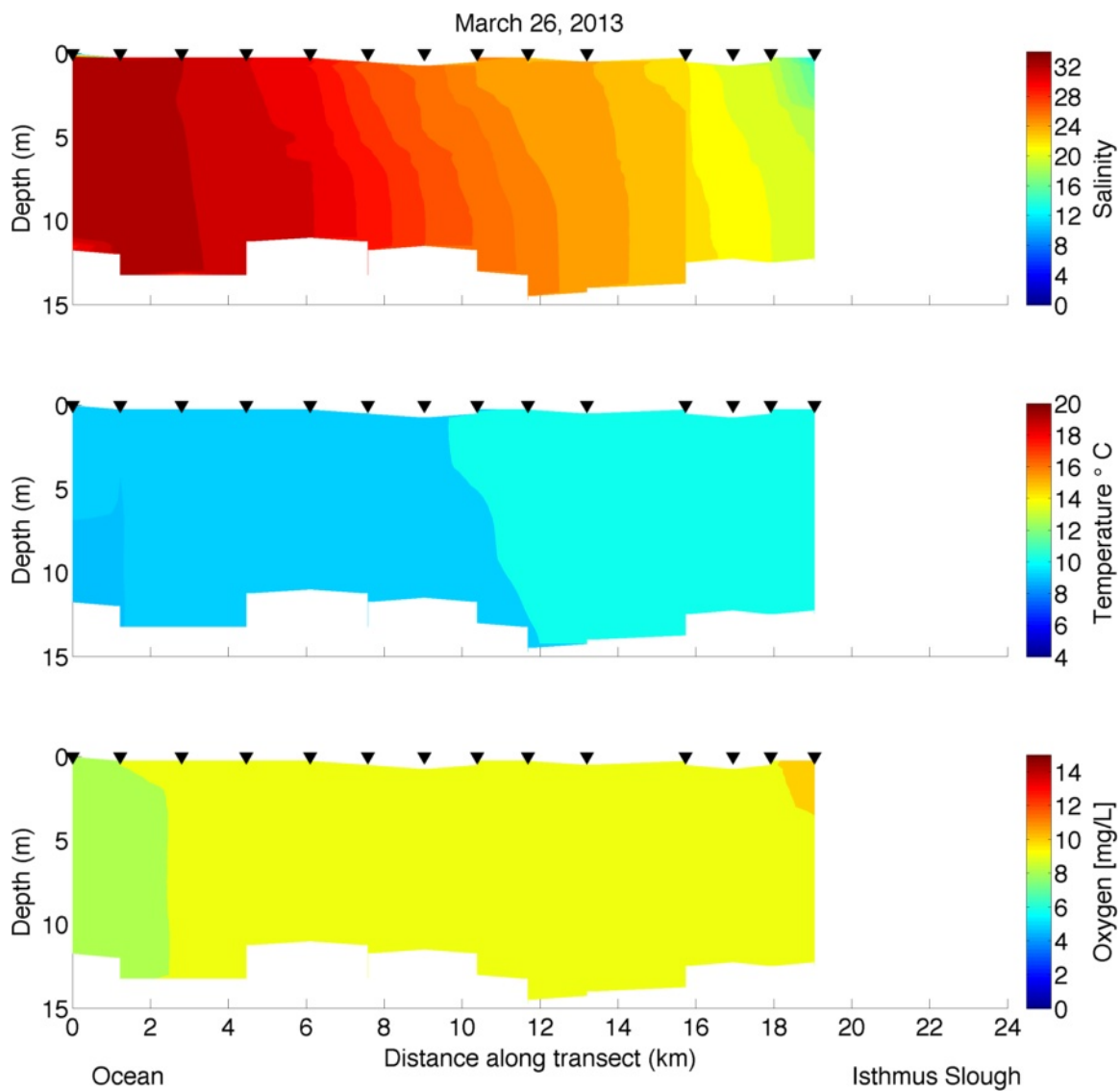


Figure 55. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from March 26, 2013.

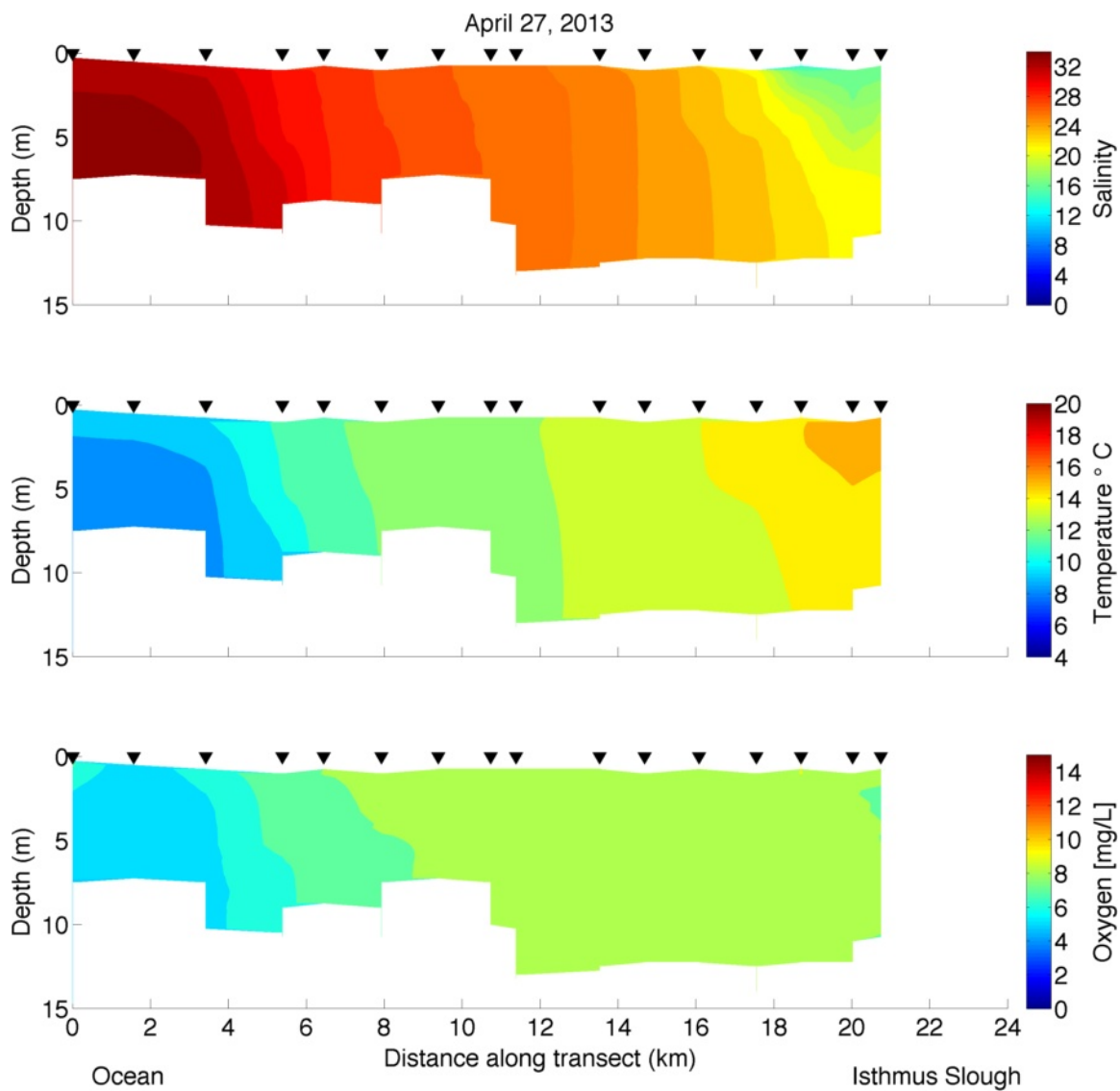


Figure 56. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from April 27, 2013.

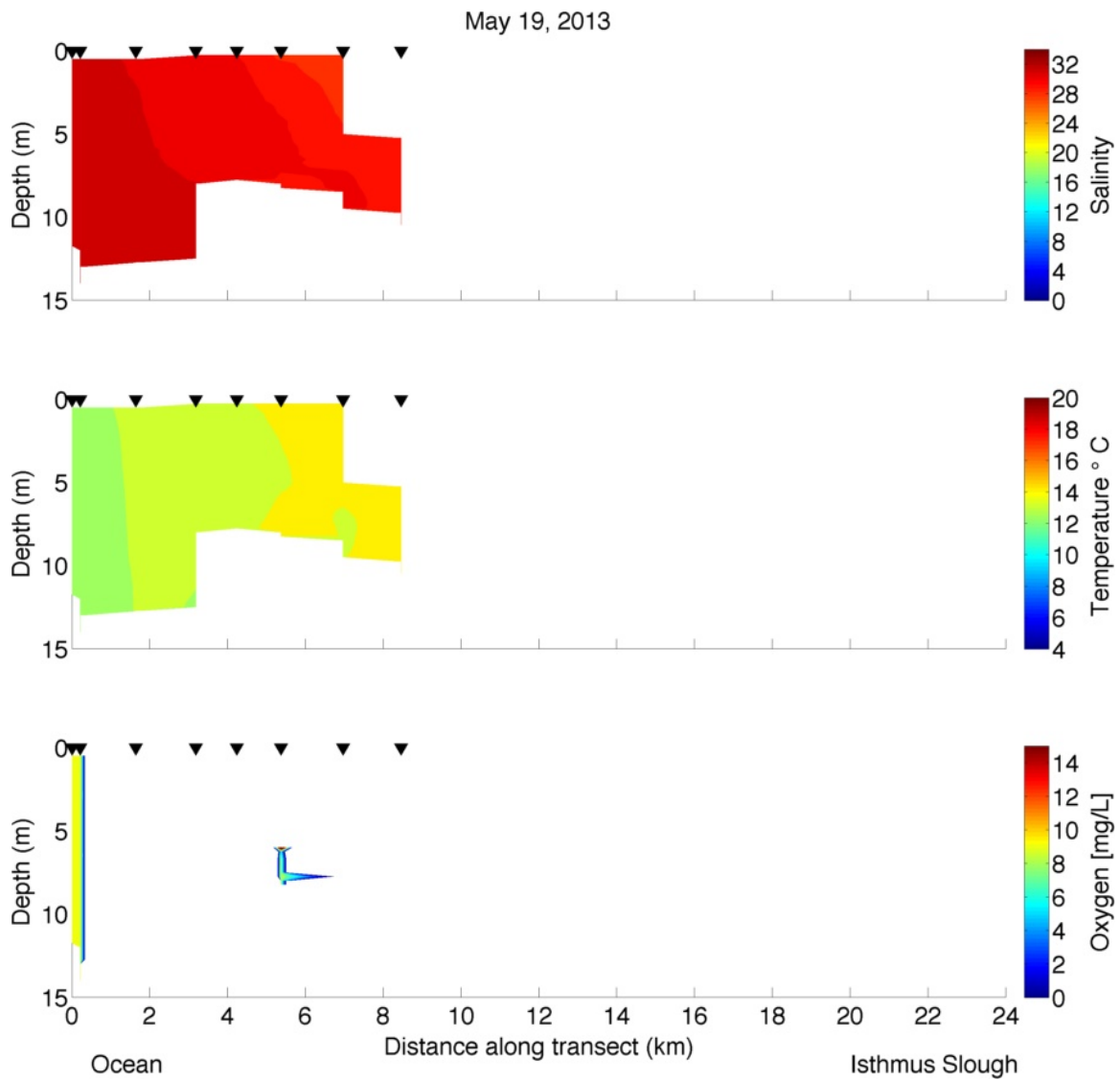


Figure 57. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from May 19, 2013. The CTD malfunctioned for unknown reasons during this sampling trip. It was then sent for recalibration.

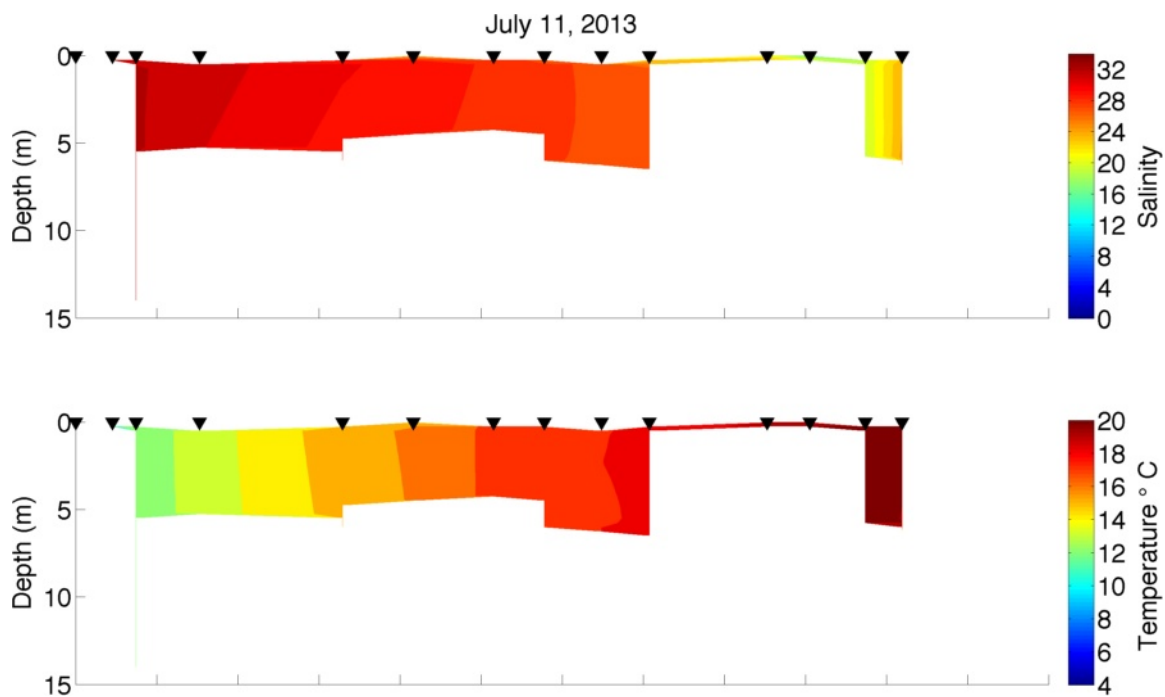


Figure 58. Salinity (top) and temperature (bottom) profiles from the CTD transect from July 11, 2013. A slow sampling rate from this CTD (SBE 19plus V2 SeaCAT Profiler), returned shorter casts.

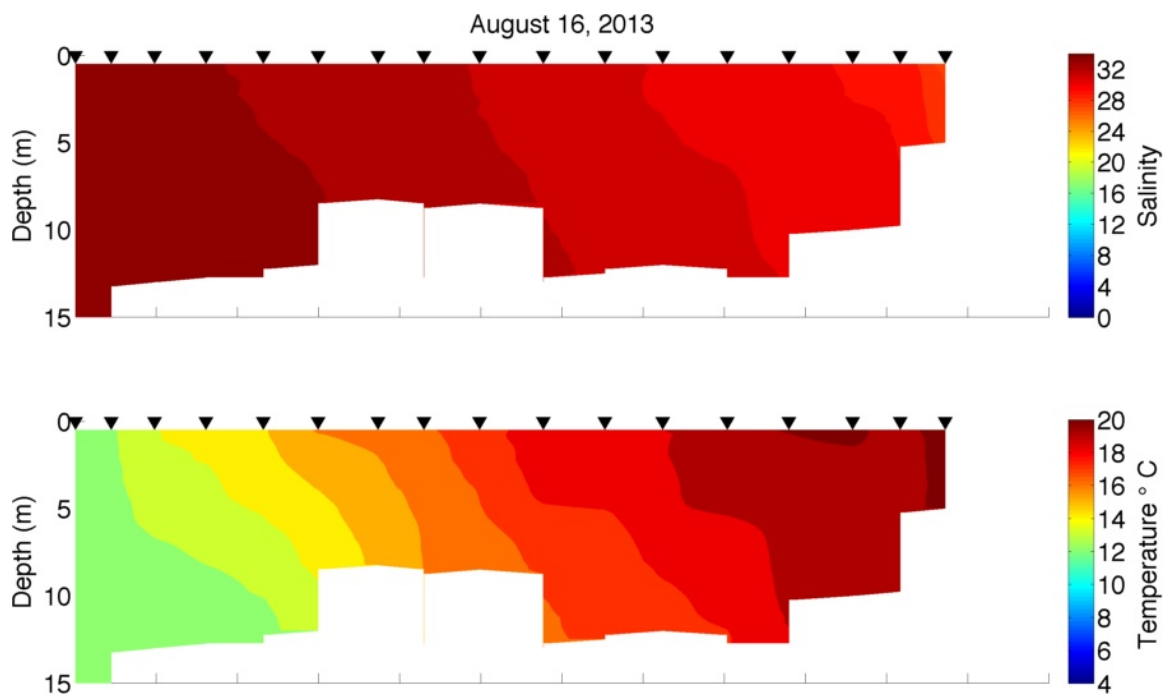


Figure 59. Salinity (top) and temperature (bottom) profiles from the CTD transect from August 16, 2013.

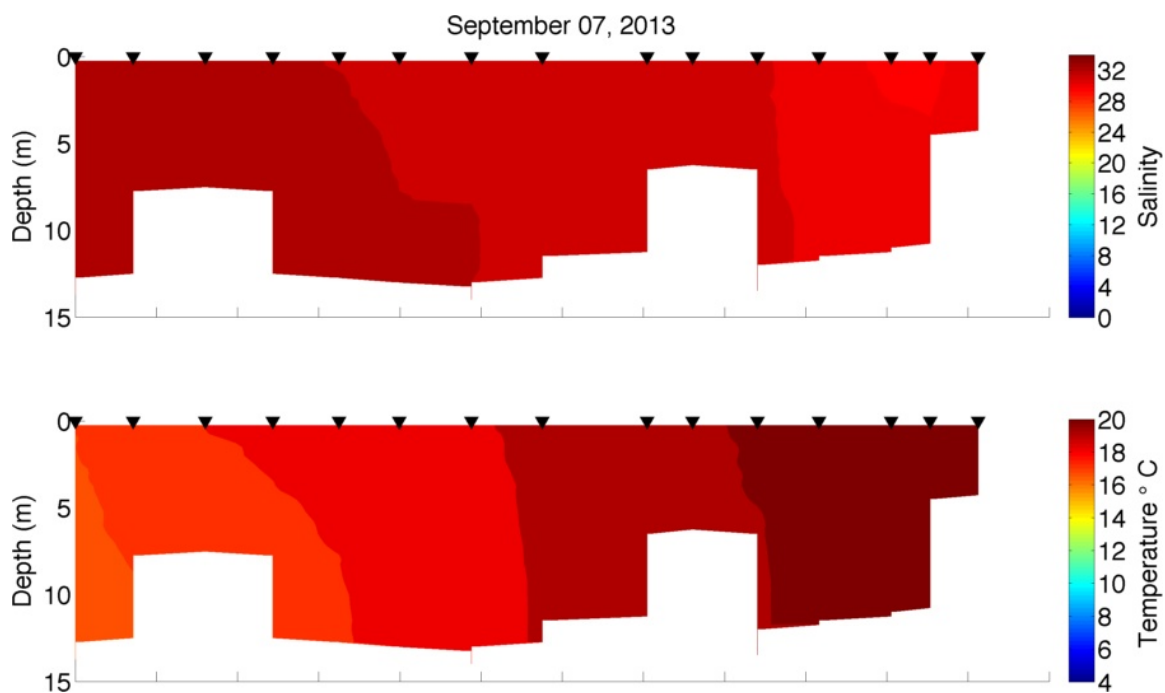


Figure 60. Salinity (top) and temperature (bottom) profiles from the CTD transect from September 7, 2013.

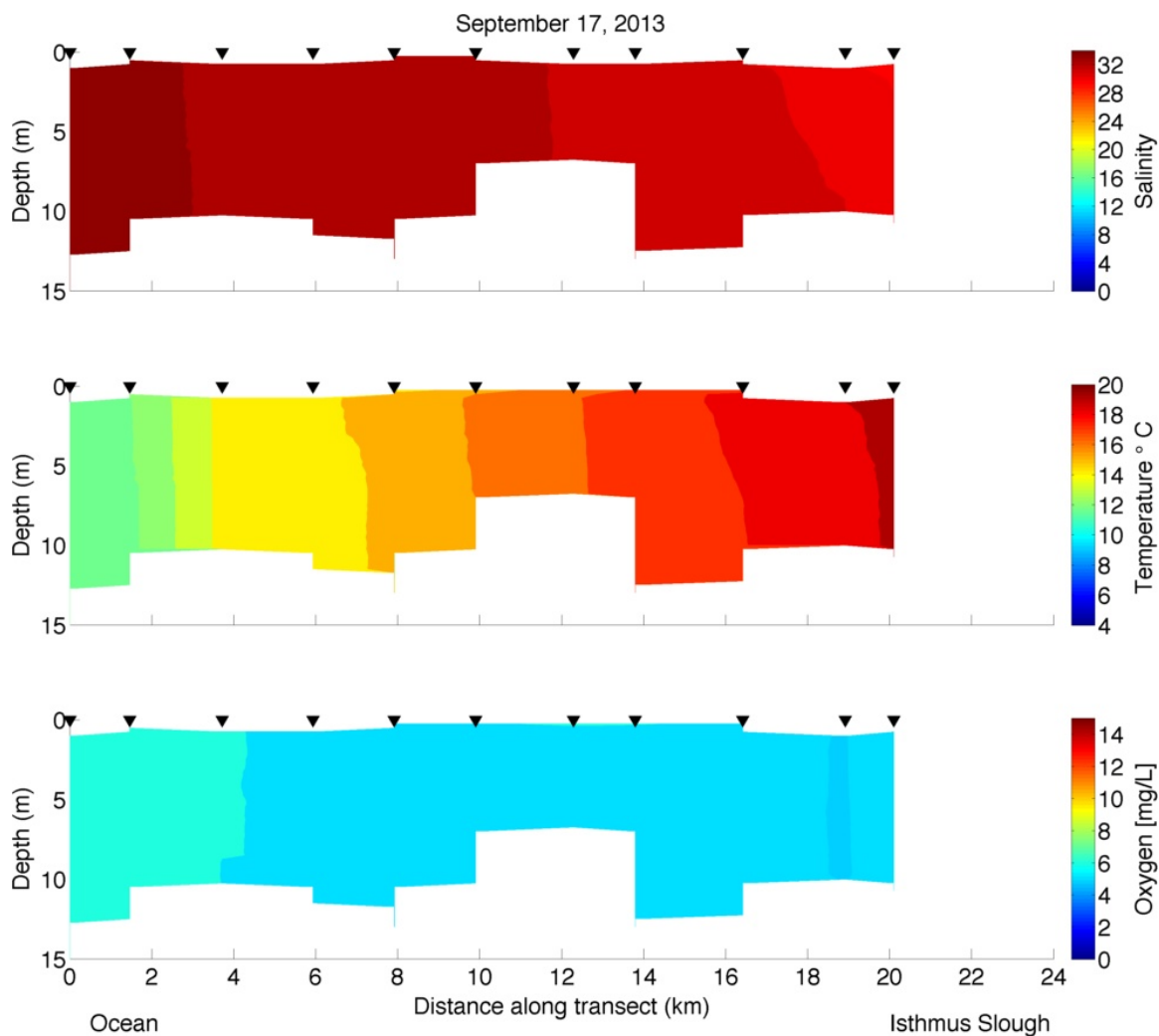


Figure 61. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from September 17, 2013.

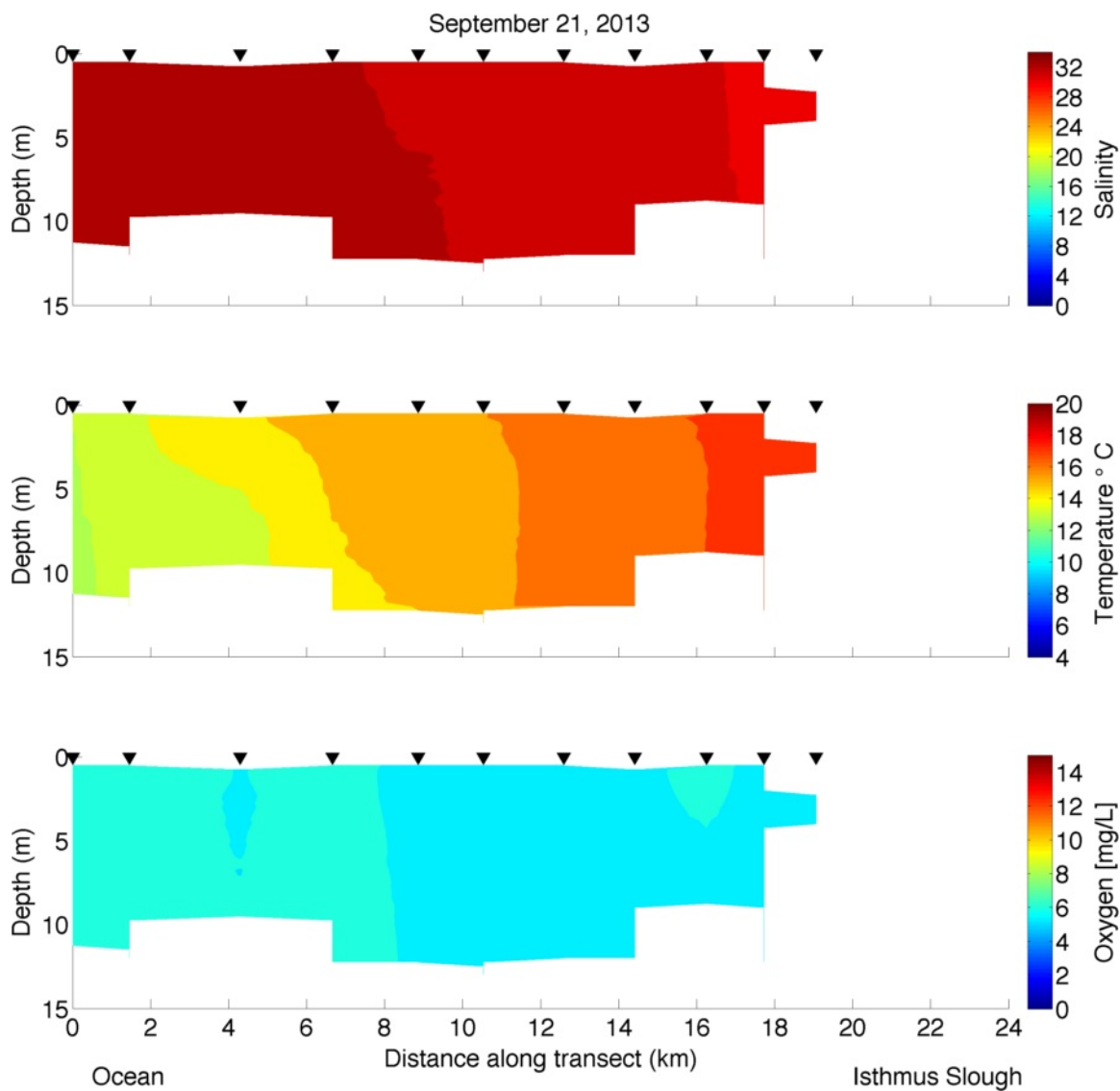


Figure 62. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from September 21, 2013.

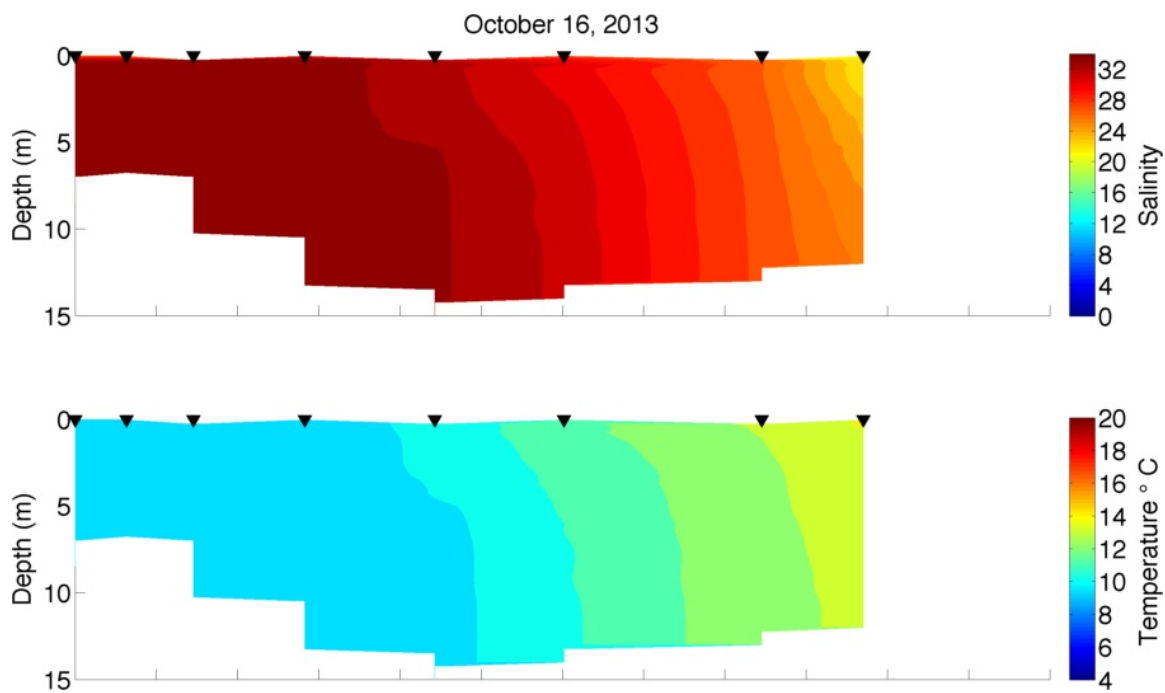


Figure 63. Salinity (top) and temperature (bottom) profiles from the CTD transect from October 16, 2013.

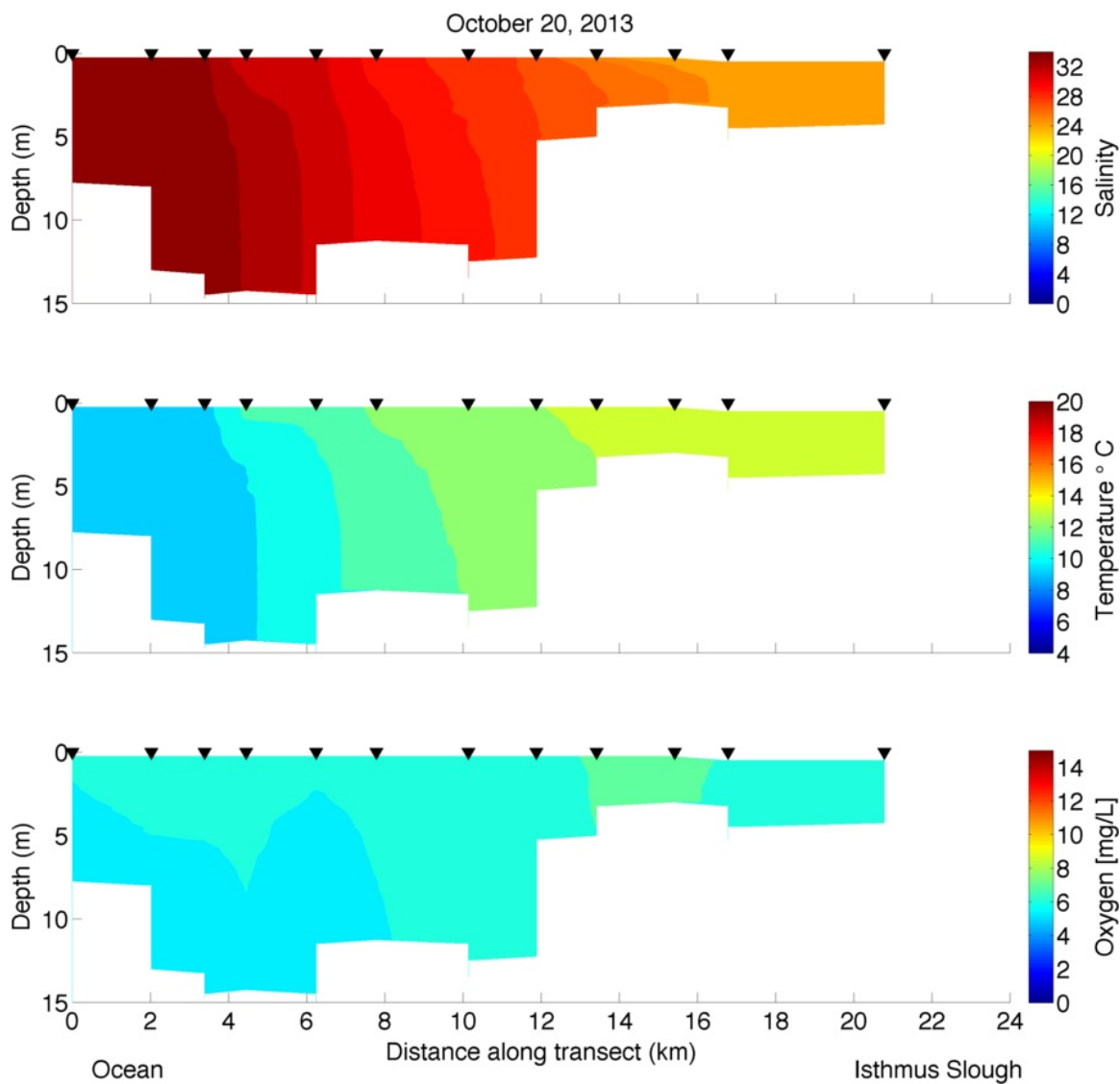


Figure 64. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from October 20, 2013.

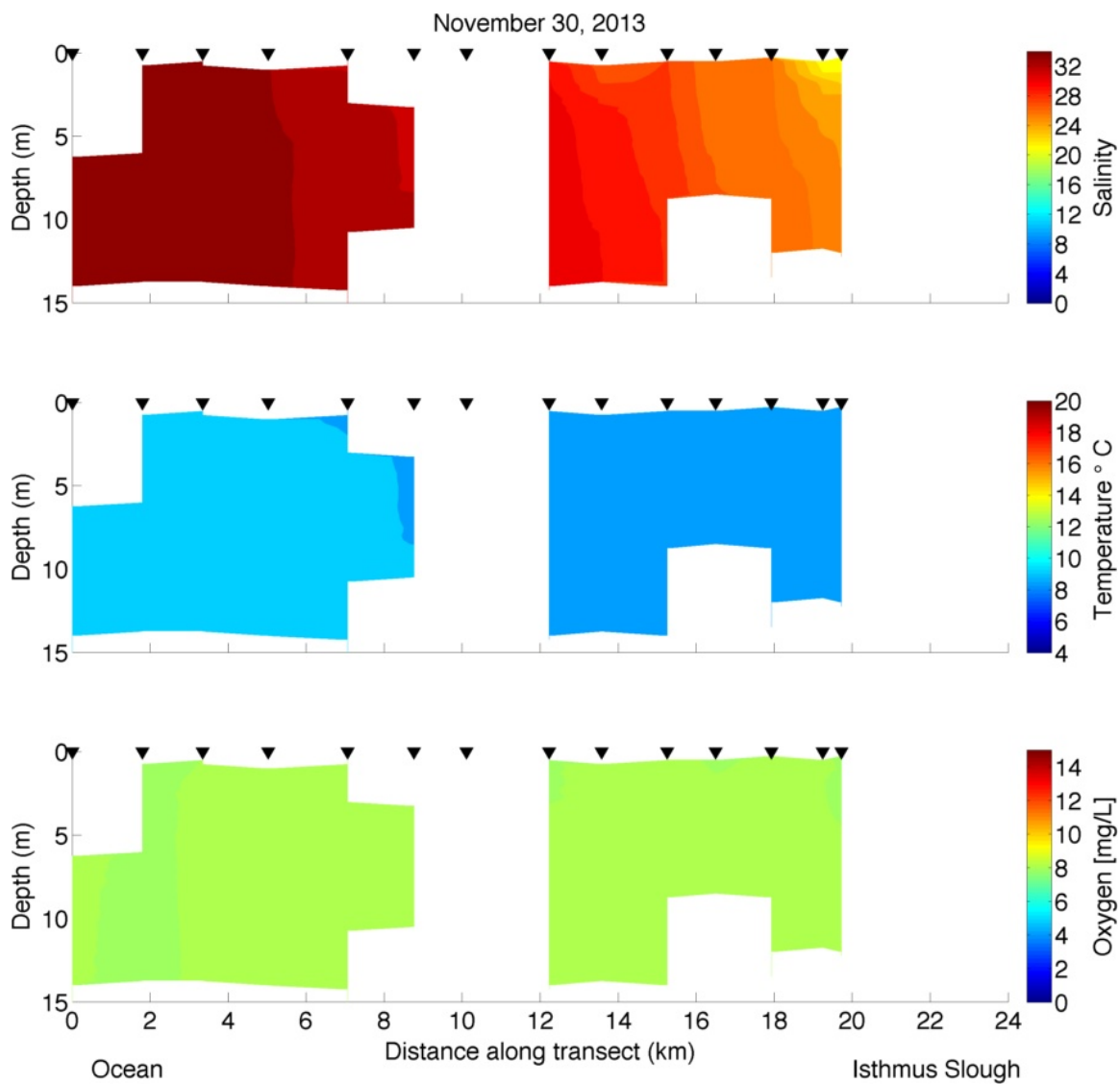


Figure 65. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from November 30, 2013.

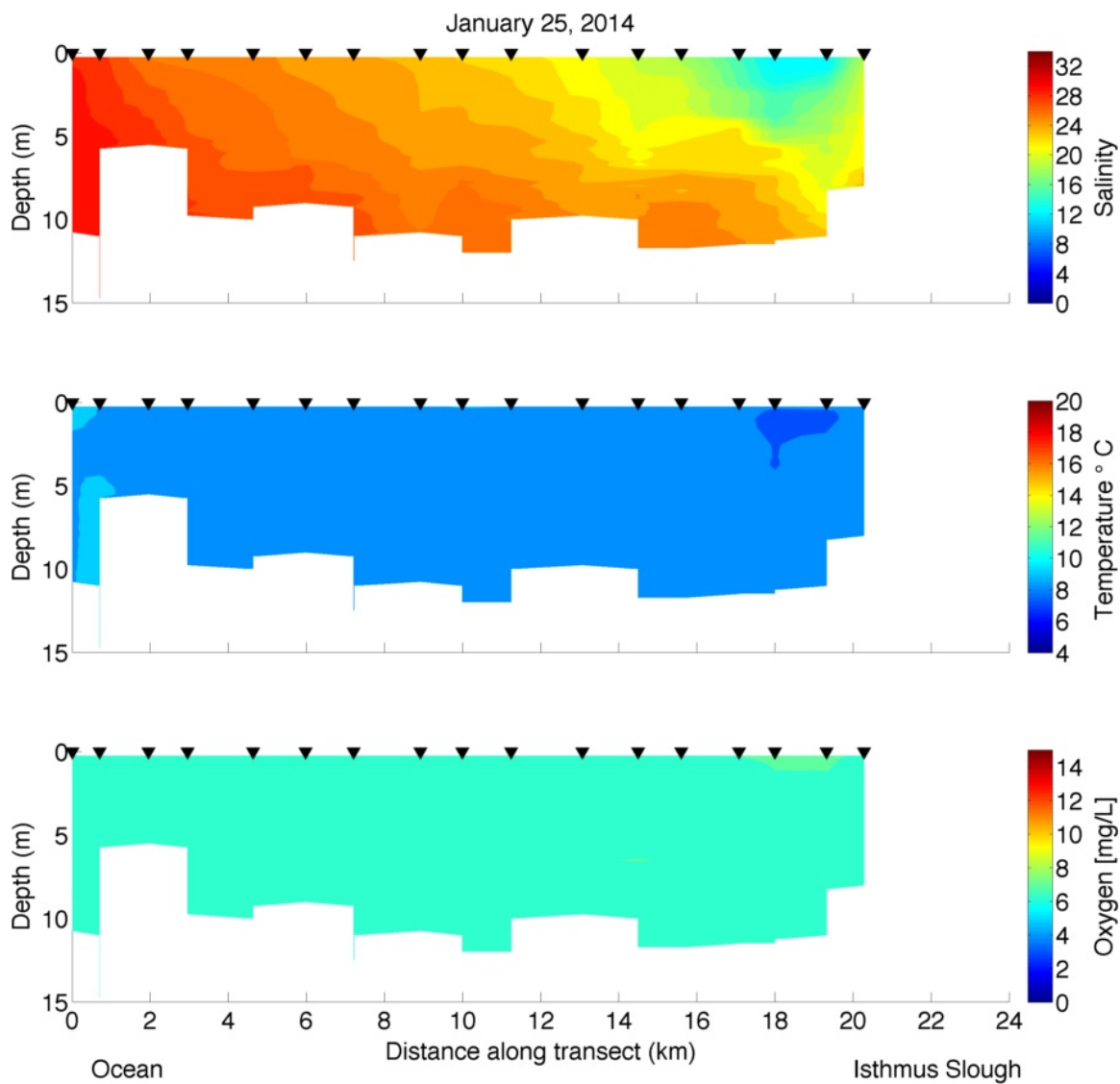


Figure 66. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from January 25, 2014.

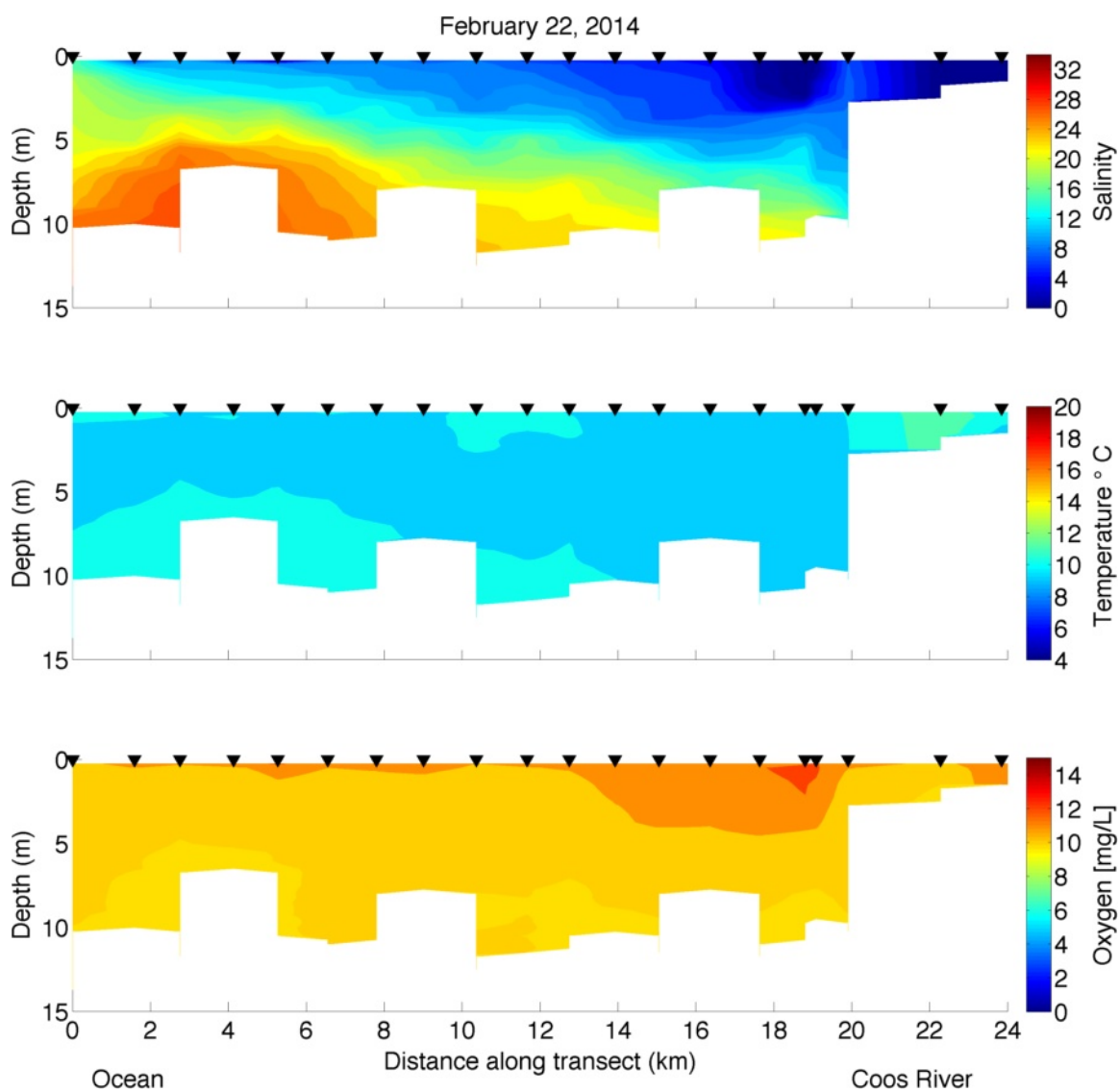


Figure 67. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from February 22, 2014.

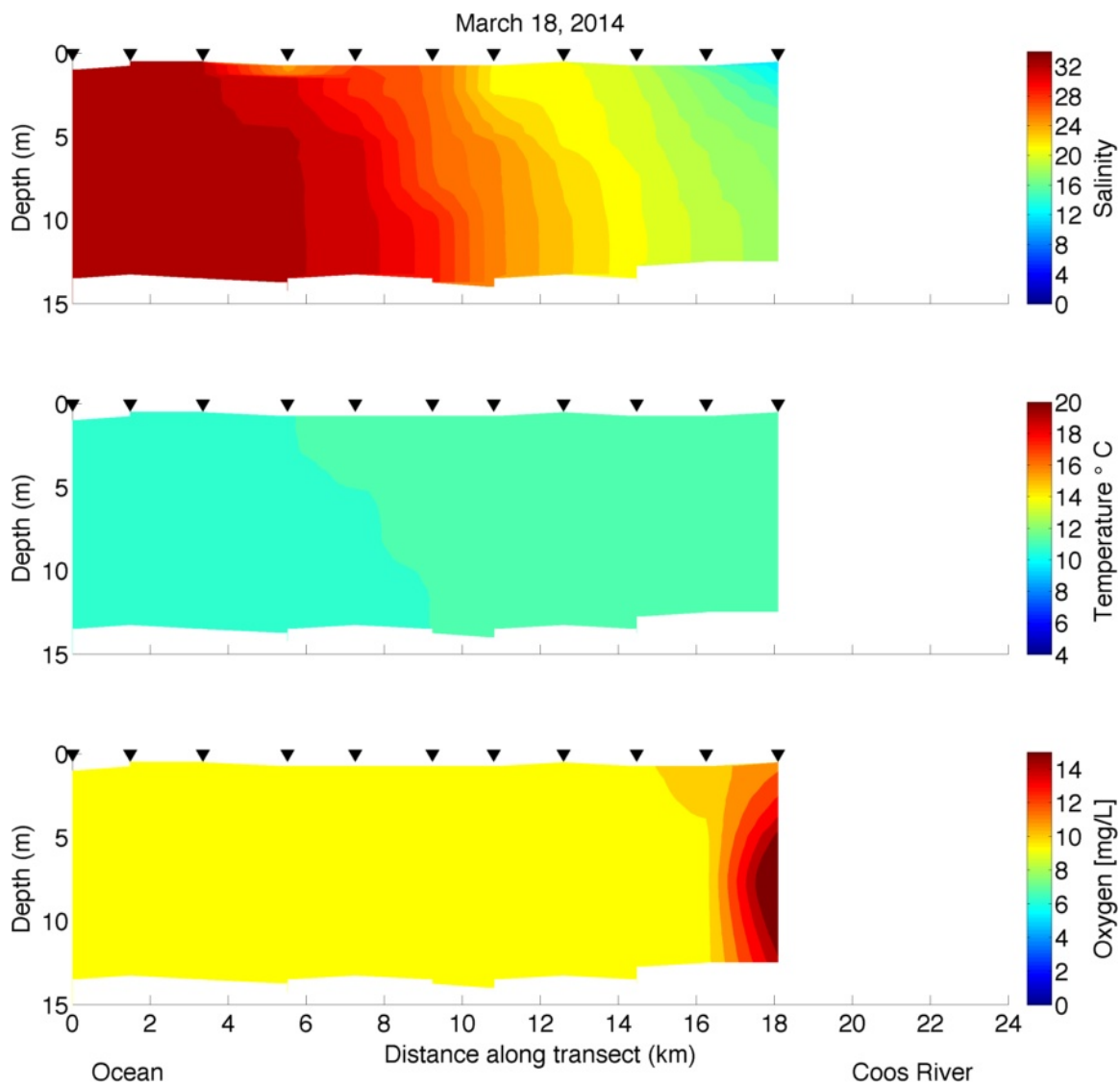


Figure 68. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from March 18, 2014. The DO sensor was capped during the cast at 18 km, resulting in bad data at that station.

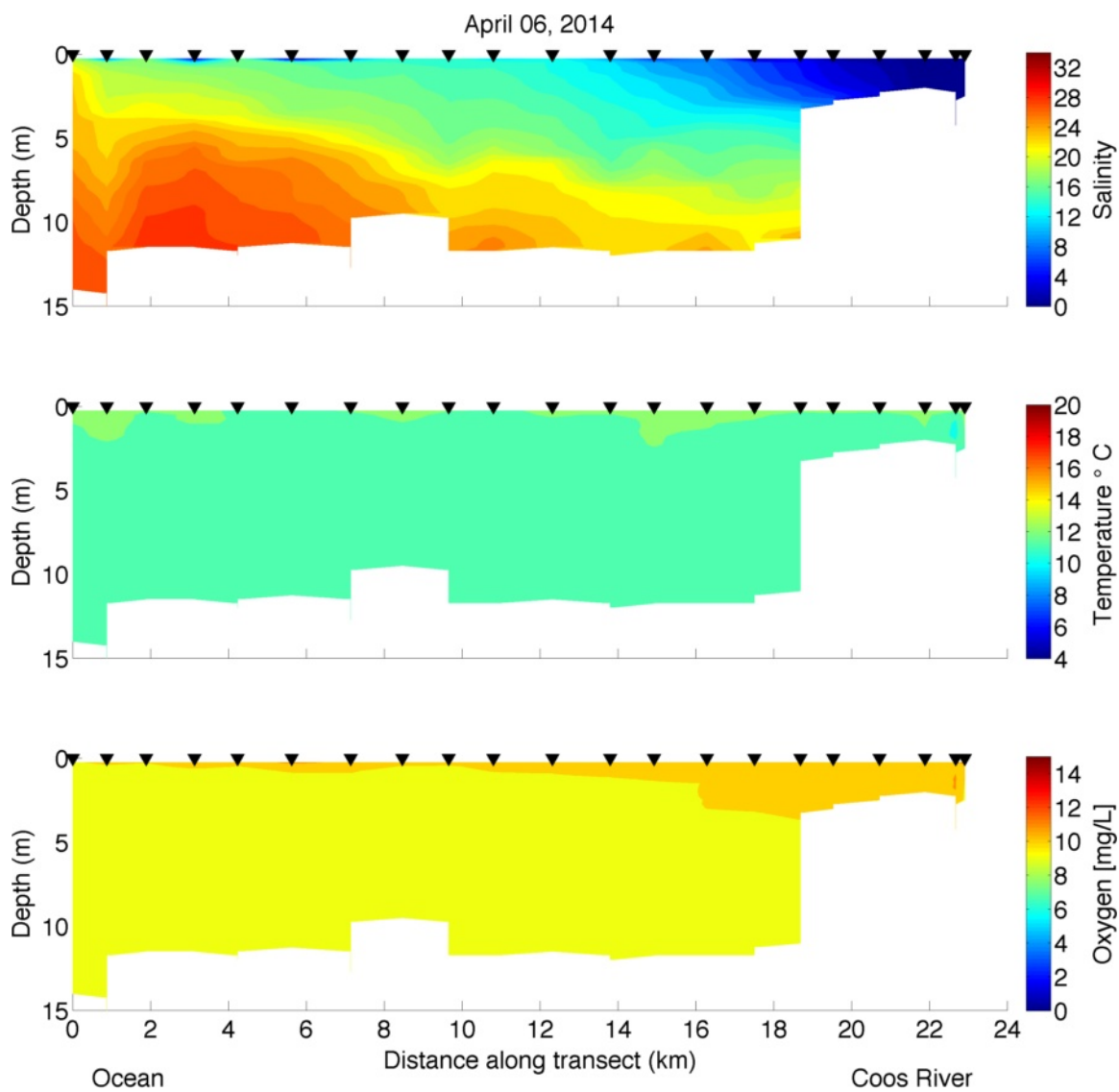


Figure 69. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from April 6, 2014.

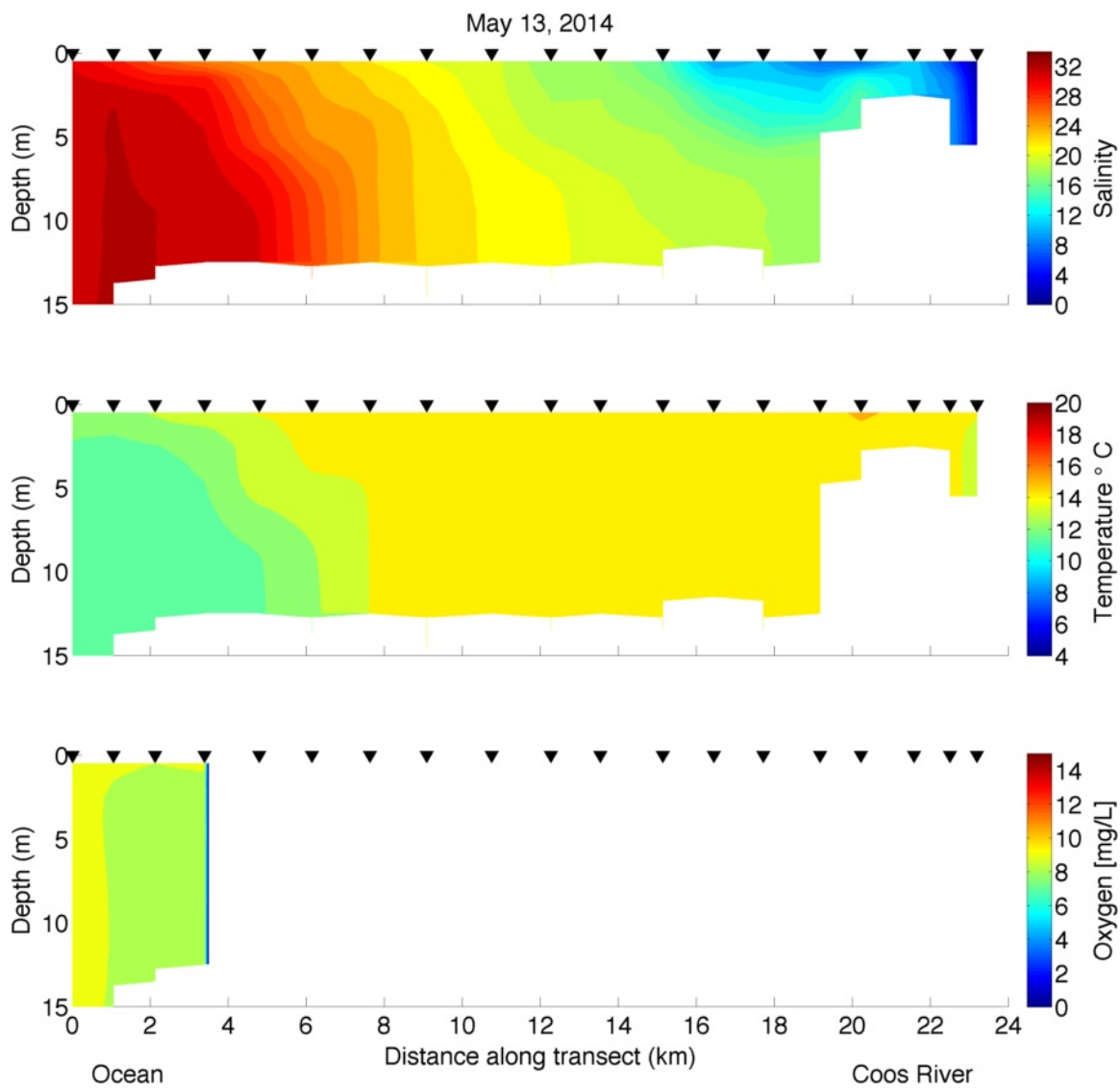


Figure 70. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from May 13, 2014. Oxygen data missing for casts beyond 4 km due to the sensor being capped.

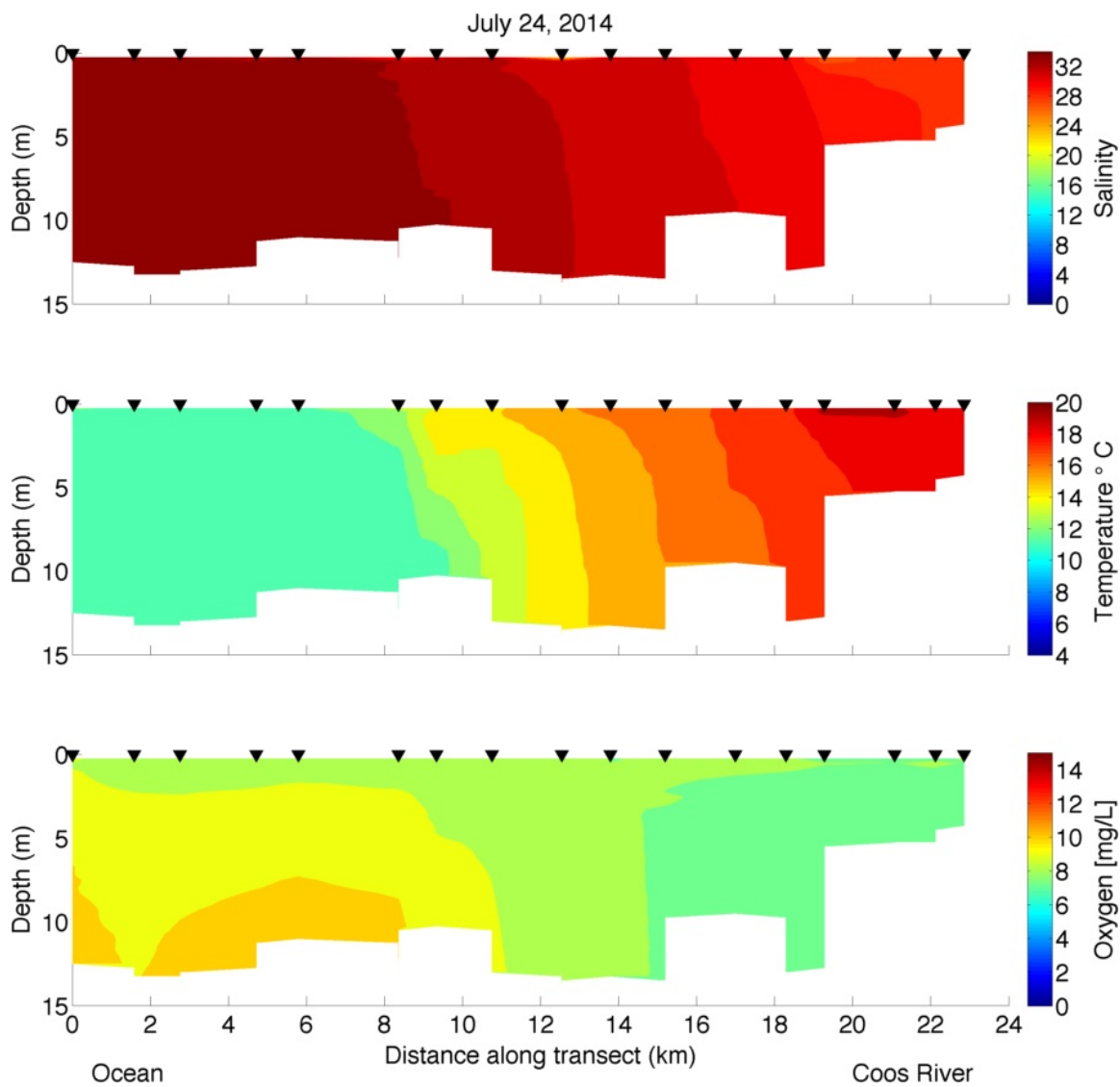


Figure 72. Salinity (top), temperature (center), dissolved oxygen (bottom) profiles from the CTD transect from July 24, 2014.

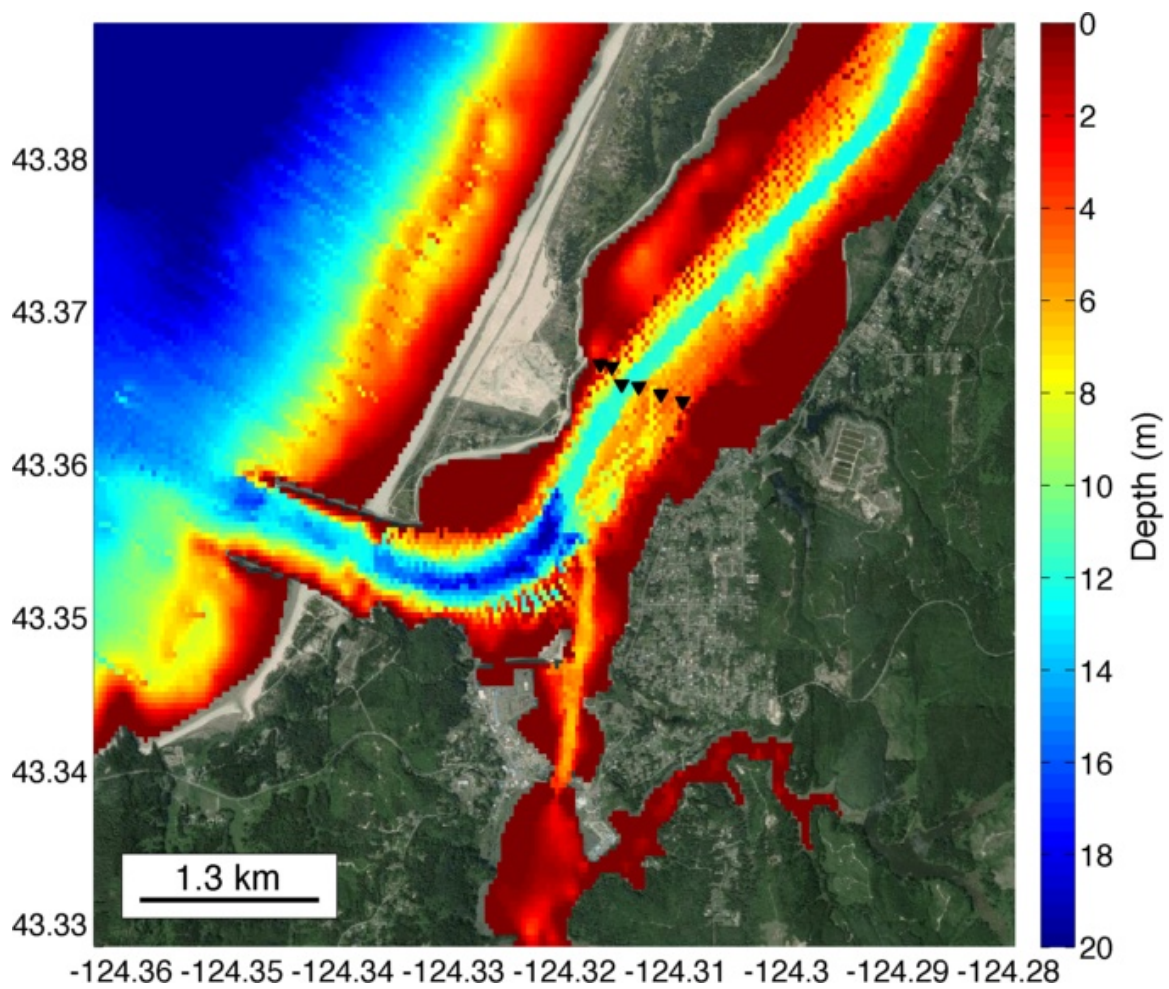


Figure 73. Map of cross estuary CTD transect taken on October 10, 2013 at near Buoy #10.

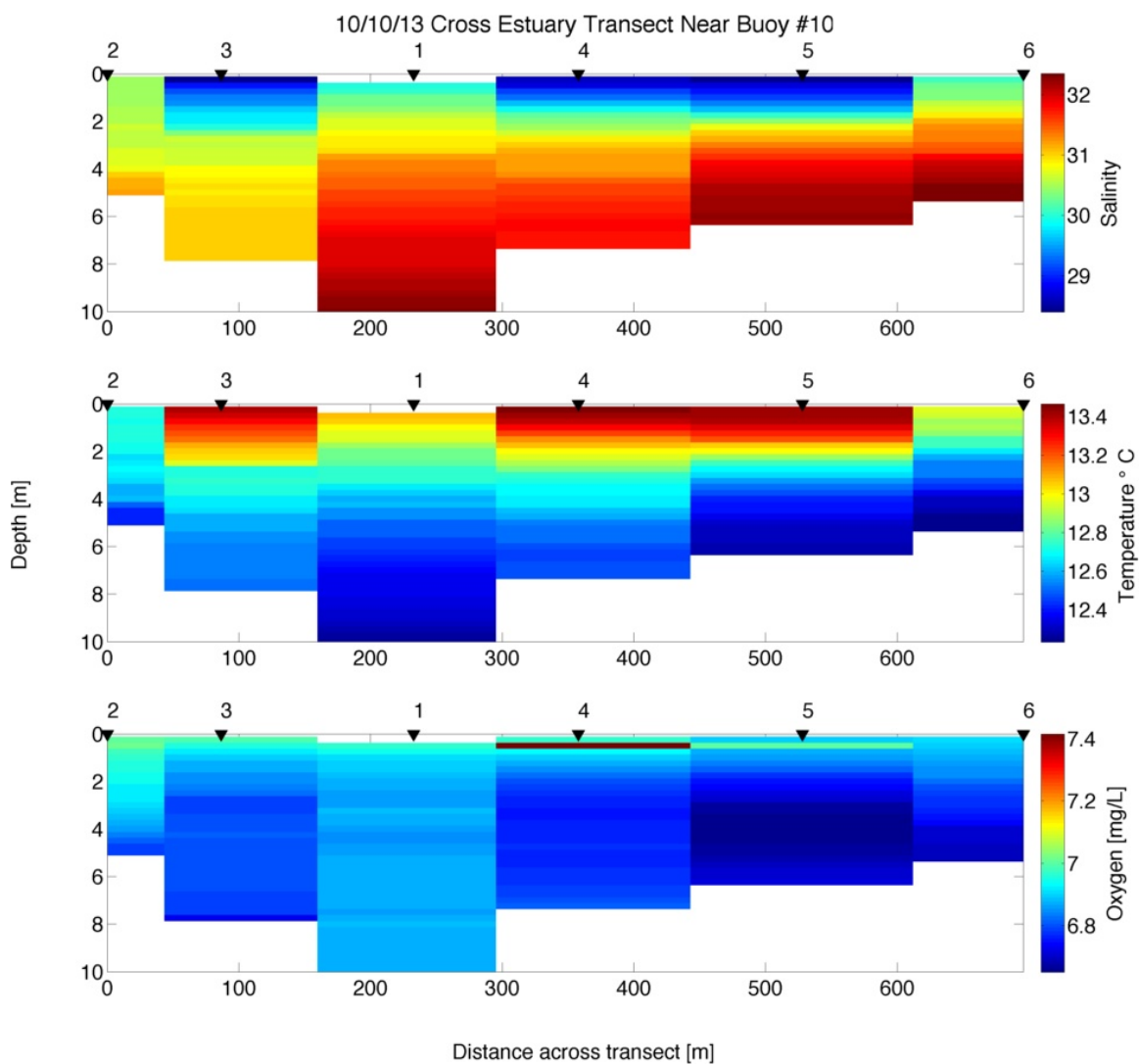


Figure 74. Results of the cross-estuary transect: salinity (top), temperature (center) and oxygen (bottom). Numbers at the top of each profile denote the order in which the casts were taken.

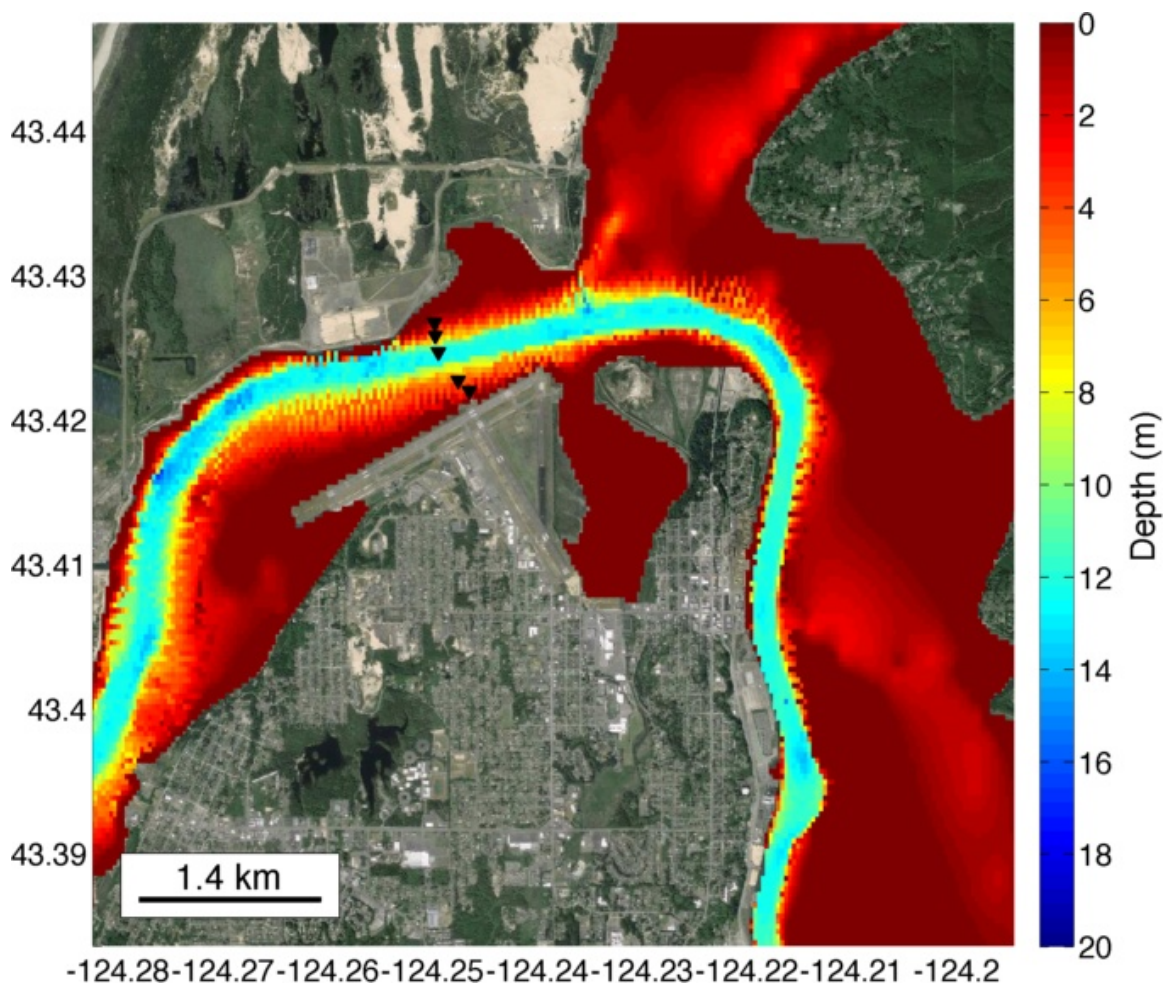


Figure 75. Map of cross estuary CTD transect taken on October 10, 2013 at near the North Bend Airport.

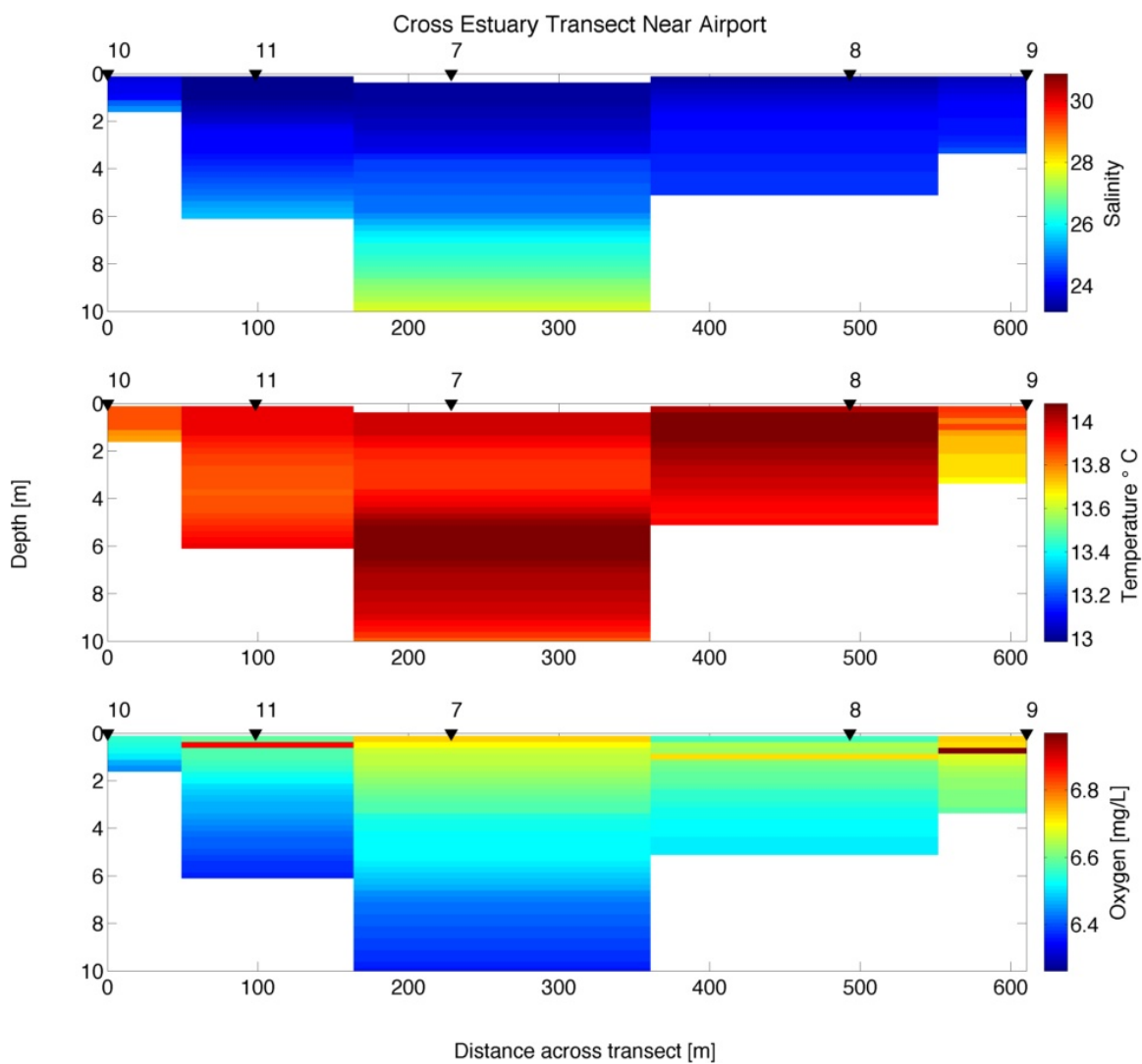


Figure 76. Results of the cross-estuary transect: salinity (top), temperature (center) and oxygen (bottom). Numbers at the top of each profile denote the order in which the casts were taken.

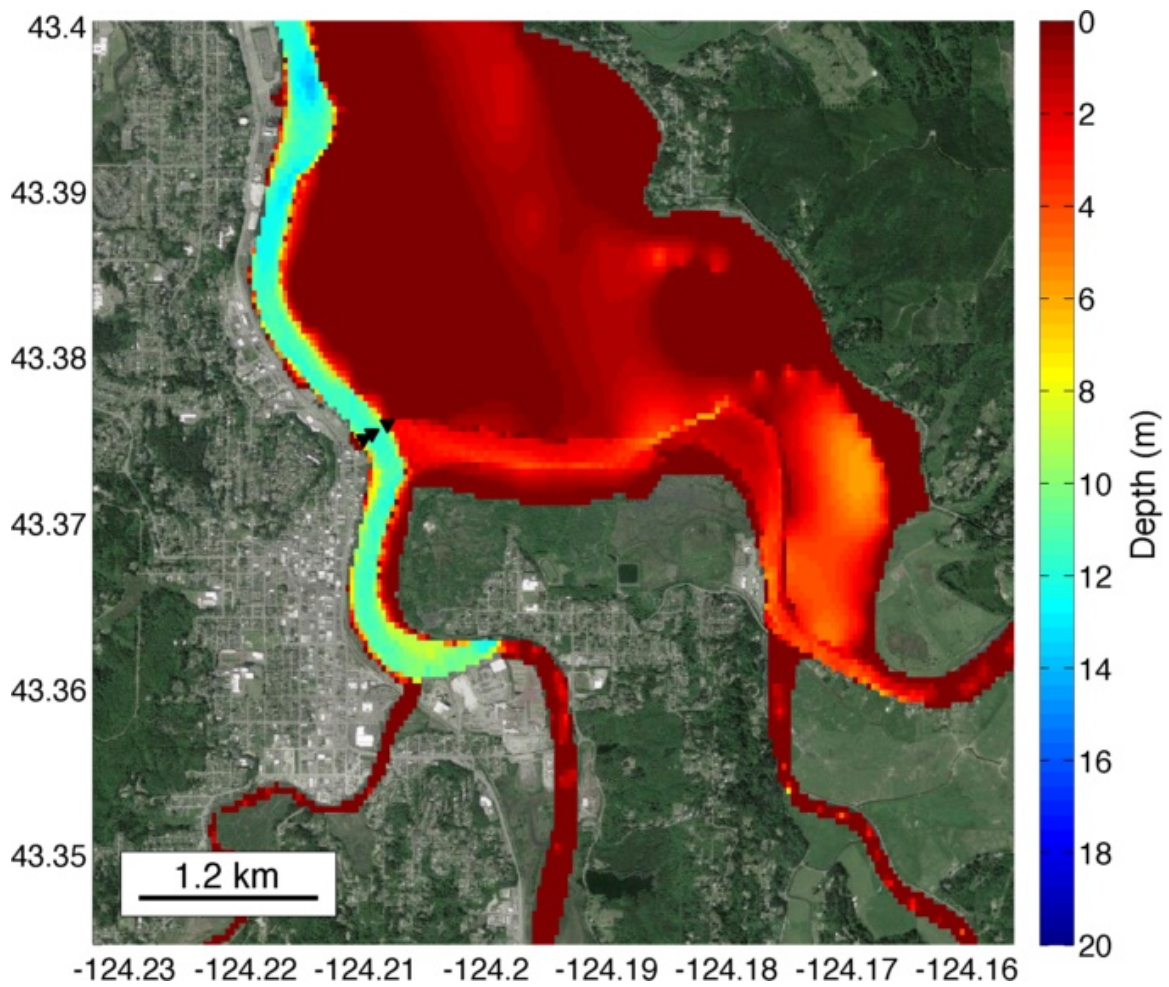


Figure 77. Map of cross-estuary transect taken on October 10, 2013 near the confluence of the Coos River and Isthmus Slough.

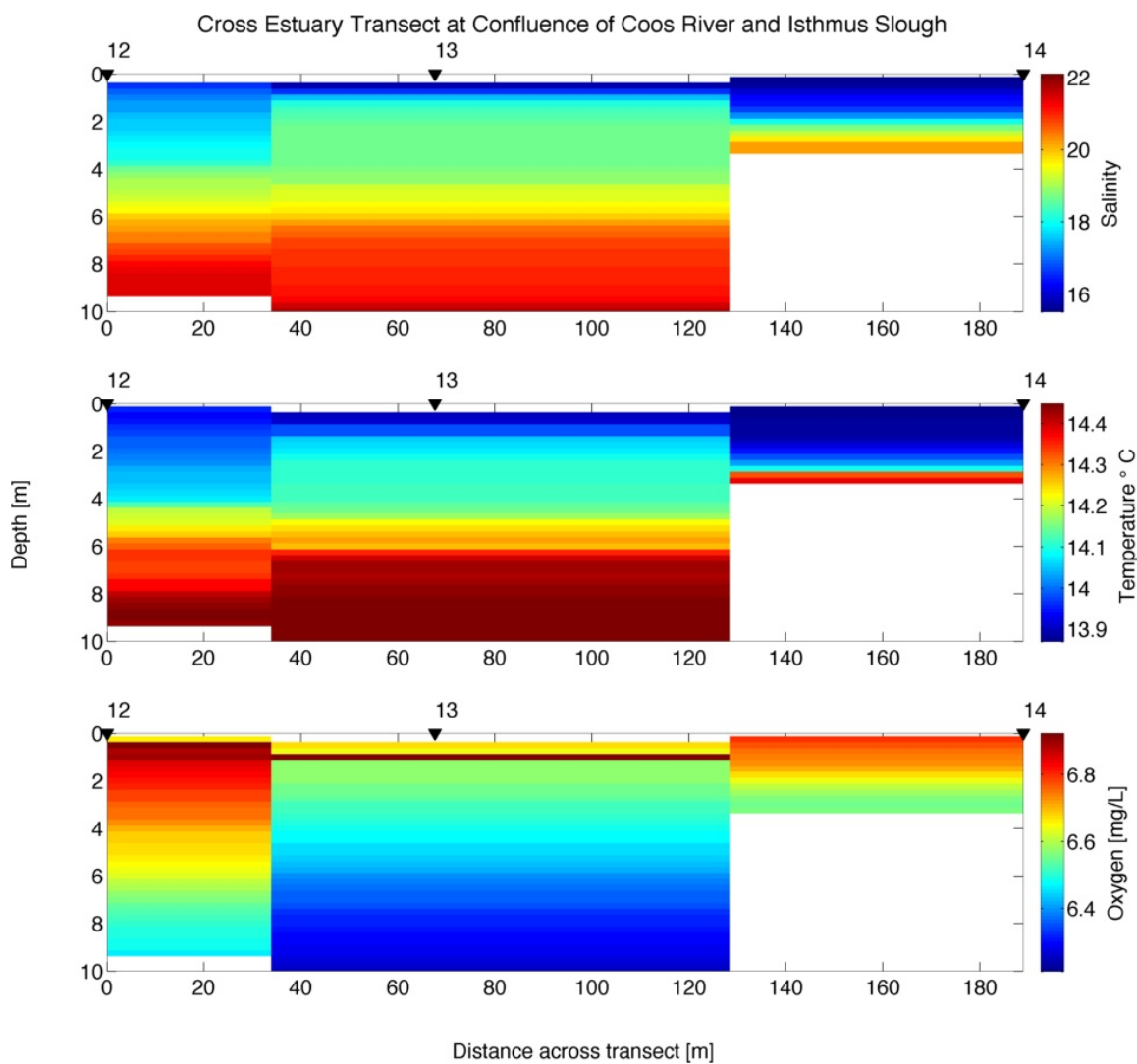


Figure 78. Results of the cross-estuary transect: salinity (top), temperature (center) and oxygen (bottom). Numbers at the top of each profile denote the order in which the casts were taken.

REFERENCES CITED

- ACOE. (1975). Coos Bay, Oregon. Deep draft navigation project, Environmental Impact Statement. U.S. Army Corps of Engineers, Portland, OR.
- ACOE. (1993). Feasibility report on navigation improvements with Environmental Impact Statement. Vol. I. U.S. Army Corps of Engineers, Portland, OR. 81 pp.
- Adams, K. A., Barth, J.A., & Chan, F. (2013) Temporal variability of near-bottom dissolved oxygen during upwelling off central Oregon. *Journal of Geophysical Research: Oceans*, 118 (10), 4839-4854.
- Adams, R. P. (1982). *The-Landscape Of Commercial Fishing In Coos Bay, Oregon* (Doctoral dissertation, University of Oregon).
- Arneson, R. J. (1976). *Seasonal Variations in Tidal Dynamics, Water Quality, and Sediments in the Coos Bay Estuary* (Master's Thesis). Retrieved from OSU Scholars Archive.
- Bakun, A. (1973). *Coastal upwelling indices, west coast of North America, 1946-71*. US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service.
- Bakun A. (1990). Global climate change and intensification of coastal ocean upwelling. *Science*, 247:198-201.
- Banas, N. S., & Hickey, B. M. (2005). Mapping exchange and residence time in a model of Willapa Bay, Washington, a branching, macrotidal estuary. *Journal of Geophysical Research: Oceans* (1978–2012), 110(C11).
- Baptista, A.M. (1989). Salinity in Coos Bay, Oregon: review of historical data (1930-1989). Report ESE-89- 001, U.S. Army Corps of Engineers, Portland, OR. 40 pp.
- Barnes, C. A., Duxbury, A. C., & Morse, B. (1970). *The Circulation And Selected Properties Of The Columbia River Effluent At Sea* (No. RLO--1725-179). Washington Univ., Seattle. Dept. of Oceanography.
- Barth, J. A., Menge, B. A., Lubchenco, J., Chan, F., Bane, J. M., Kirincich, A. R., ... & Washburn, L. (2007). Delayed upwelling alters nearshore coastal ocean ecosystems in the northern California current. *Proceedings of the National Academy of Sciences*, 104(10), 3719-3724
- Batchelder, H. P., Barth, J. A., Kosro, P. M., Strub, P. T., Brodeur, R. D., Peterson, W. T., ... & Ramp, S. R. (2002). The GLOBEC Northeast Pacific California Current System Program. *Oceanography*. Washington DC. Oceanography Society, 15(2), 36-47.

- Blanton, J. (1969). Energy dissipation in a tidal estuary. *Journal of Geophysical Research*, 74(23), 5460-5466.
- Bograd, S. J., Castro, C. G., Di Lorenzo, E., Palacios, D. M., Bailey, H., Gilly, W., & Chavez, F. P. (2008). Oxygen declines and the shoaling of the hypoxic boundary in the California Current. *Geophysical Research Letters*, 35(12), L12607. doi:10.1029/2008GL034185.
- Bograd, S. J., Schroeder, I., Sarkar, N., Qiu, X., Sydeman, W. J., & Schwing, F. B. (2009). Phenology of coastal upwelling in the California Current. *Geophysical Research Letters*, 36(1).
- Booth, J. A. T., McPhee-Shaw, E. E., Chua, P., Kingsley, E., Denny, M., Phillips, R., Bograd, S., Zeidberg, L.D., Gilly, W. F. (2012). Natural intrusions of hypoxic, low pH water into nearshore marine environments on the California coast. *Continental Shelf Research*, 45, 108–115. doi:10.1016/j.csr.2012.06.009
- Breitburg, D. (2002). Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries*, 25(4), 767–781. doi:10.1007/BF02804904.
- Brown, C. A., & Power, J. H. (2011). Historic and recent patterns of dissolved oxygen in the Yaquina Estuary (Oregon, USA): Importance of anthropogenic activities and oceanic conditions. *Estuarine, Coastal and Shelf Science*, 92(3), 446–455. doi:10.1016/j.ecss.2011.01.018.
- Burchard, H., & Bolding, K. (2002). *GETM: A General Estuarine Transport Model; Scientific Documentation*. European Commission, Joint Research Centre, Institute for Environment and Sustainability.
- Caffrey, J. M., Cloern, J. E., & Grenz, C. (1998). Changes in production and respiration during a spring phytoplankton bloom in San Francisco Bay, California, USA: implications for net ecosystem metabolism. *Marine Ecology-Progress Series*, 172, 1-12.
- Caffrey, J. M. (2004). Factors controlling net ecosystem metabolism in U.S. estuaries. *Estuaries*, 27: 90-101.
- Chan, F., Barth, J. A., Lubchenco, J., Kirincich, A., Weeks, H., Peterson, W. T., & Menge, B. A. (2008). Emergence of anoxia in the California current large marine ecosystem. *Science*, 319 (5865), 920. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/18276882>.
- Checkley Jr, D. M., & Barth, J. A. (2009). Patterns and processes in the California Current System. *Progress in Oceanography*, 83(1), 49-64.

- Chelton, D. B. (1984). Seasonal variability of alongshore geostrophic velocity off central California. *Journal of Geophysical Research: Oceans (1978–2012)*, 89(C3), 3473–3486.
- Choi, B. (1975). *Pollution and tidal flushing predictions for Oregon's estuaries*. M.S. Thesis, Oregon State University, Corvallis, OR. 163 p.
- Connolly, T. P., Hickey, B. M., Geier, S. L., & Cochlan, W. P. (2010). Processes influencing seasonal hypoxia in the northern California Current System. *Journal of Geophysical Research: Oceans (1978–2012)*, 115(C3).
- Diaz, R. J., & Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *Science (New York, N.Y.)*, 321 (5891), 926–9. doi:10.1126/science.1156401.
- Dyer, K. R. (1973). *Estuaries: A physical introduction*. Wiley.
- Emmett, R., Llanso, R., Newton, J., Thom, R., Hornberger, M., Morgan, C., Levings, C., Copping, A., & Fishman, P. (2000). Geographic signatures of North American west coast estuaries. *Estuaries*, 23(6), 765–792.
- EPA. (2006). Chapter 9: Dissolved Oxygen and Biochemical Oxygen Demand. Voluntary Estuary Monitoring Manual, A Methods Manual, 2nd ed.
- Festa, J. F., & Hansen, D. V. (1976). A two-dimensional numerical model of estuarine circulation: The effects of altering depth and river discharge. *Estuarine and coastal marine science*, 4 (3), 309–323.
- Fischer, H. B. (1972). Mass transport mechanisms in partially stratified estuaries. *J. Fluid Mech*, 53 (4), 671–687.
- Fischer, H. B. (1976). Mixing and dispersion in estuaries. *Annual Review of Fluid Mechanics*, 8 (1), 107–133.
- Geyer, W. R., & MacCready, P. (2014). The estuarine circulation. *Annual Review of Fluid Mechanics*, 46 (1), 175.
- Geyer, W. R., & Ralston, D. K. (2011). The Dynamics of Strongly Stratified Estuaries. *Treatise on Estuarine and Coastal Science* (Vol. 2, pp. 37–52). Elsevier Inc. doi:10.1016/B978-0-12-374711-2.00206-0.
- Grantham, B. A., Chan, F., Nielsen, K. J., Fox, D. S., Barth, J. A., Huyer, A., ... & Menge, B. A. (2004). Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature*, 429(6993), 749–754.
- Gray, J. S., Wu, R. S., & Or, Y. Y. (2002). Effects of hypoxia and organic enrichment on the coastal marine environment. *Marine Ecology Progress Series*, 238, 249–279.

- Hansen, D.V., Rattray, M., Jr., (1966). New dimensions in estuary classification. *Limnology and Oceanography*, 11, 319–326.
- Helly, J. J., & Levin, L. A. (2004). Global distribution of naturally occurring marine hypoxia on continental margins. *Deep Sea Research Part I: Oceanographic Research Papers*, 51 (9), 1159–1168. doi:10.1016/j.dsr.2004.03.009
- Hickey, B. M. (1998). Coastal oceanography of western North America from the tip of Baja California to Vancouver Island. *The sea*, 11 (12), 345-393.
- Hickey, B., & Banas, N. S. (2003). Oceanography of the U.S. Pacific Northwest coastal ocean and estuaries with application to coastal ecology. *Estuaries*, 26 (4), 1010–1031. Retrieved from <http://www.springerlink.com/index/10.1007/BF02803360>.
- Hickey, B., Geier, S., Kachel, N., & MacFadyen, A. (2005). A bi-directional river plume: The Columbia in summer. *Continental Shelf Research*, 25 (14), 1631-1656.
- Hickey, B., et al. (2010). River Influences on Shelf Ecosystems: Introduction and synthesis, *J. Geophys. Res.*, 115, C00B17, doi:10.1029/2009JC005452.
- Huyer, A. (1983). Coastal upwelling in the California Current system. *Progress in Oceanography*, 12: 259–284.
- Huyer, A., Sobey, E. J. C., & Smith, R. L. (1979). The spring transition in currents over the Oregon continental shelf. *Journal of Geophysical Research: Oceans (1978–2012)*, 84 (C11), 6995-7011.
- Johnson, J.W. (1972). Tidal inlets on the California, Oregon and Washington coasts. Hydraulic Engineering Laboratory Tech. Report HEL-24-12. University of California, Berkeley, CA. 145 pp.
- Large, W. G., & Pond, S. (1981). Open ocean momentum flux measurements in moderate to strong winds. *Journal of physical oceanography*, 11(3), 324-336.
- Lee, H. (2009). *Classification of regional patterns of environmental drivers and benthic habitats in Pacific Northwest Estuaries*. C. A. Brown (Ed.). National Health and Environmental Effects Research Laboratory, Office of Research and Development, US Environmental Protection Agency.
- Lee II, H. and D.A. Reusser, with contributions from K. Welch, R. Fairey, and L. Hillmann. (2006). Pacific Coast Ecosystem Information System (PCEIS) V. 1.0. United States Environmental Protection Agency and United States Geological Survey (Microsoft Access 2003 database).
- Lellis-Dibble, K. A., K. E. McGlynn, and T. E. Bigford. (2008). Estuarine Fish and Shellfish Species in U.S. Commercial and Recreational Fisheries: Economic Value as an

Incentive to Protect and Restore Estuarine Habitat. U.S. Dep. Commerce, NOAA Tech. Memo. NMFS- F/SPO-90, 94 p.

Lerczak, J. A., & Rockwell Geyer, W. (2004). Modeling the Lateral Circulation in Straight, Stratified Estuaries*. *Journal of Physical Oceanography*, 34 (6), 1410-1428.

Leung, L. R., Qian, Y., Bian, X., Washington, W. M., Han, J., & Roads, J. O. (2004). Mid-century ensemble regional climate change scenarios for the western United States. *Climatic Change*, 62 (1-3), 75-113.

Lynn, R. J., & Simpson, J. J. (1987). The California Current System: The seasonal variability of its physical characteristics. *Journal of Geophysical Research: Oceans* (1978–2012), 92(C12), 12947-12966.

MacCready, P., & Geyer, W. R. (2010). Advances in estuarine physics. *Annual Review of Marine Science*, 2, 35-58.

McAlister, W. B. & Blanton, J. O. (1963). Temperature, salinity, and current measurements for Coos Bay, Oregon. Oregon State University, Dept. of Oceanography, Data Report No. 10, Corvallis, Oregon.

Monteiro, P. M. S., Van der Plas, A., Mohrholz, V., Mabilhe, E., Pascall, A., & Joubert, W. (2006). Variability of natural hypoxia and methane in a coastal upwelling system: Oceanic physics or shelf biology? *Geophysical Research Letters*, 33 (16).

Montgomery, D. R., & Dietrich, W. E. (2002). Runoff generation in a steep, soil-mantled landscape. *Water Resources Research*, 38 (9), 7-1.

Mote, P. W., & Salathe Jr, E. P. (2010). Future climate in the Pacific Northwest. *Climatic Change*, 102 (1-2), 29-50.

National Oceanic and Atmospheric Administration (NOAA). (1985). National Estuarine Inventory Data Atlas. Strategic Assessment Branch, Ocean Assessments Division, Office of Oceanography and Marine Assessment, National Ocean Service, Rockville, Maryland.

National Oceanic and Atmospheric Administration. (1998). NOAA's Estuarine Eutrophication Survey; Volume 5: Pacific Coast Region. Office of Ocean Resources Conservation and Assessment, Silver Springs, Maryland.

National Oceanic and Atmospheric Administration, Office of Ocean and Coastal Resource Management, National Estuarine Research Reserve System-wide Monitoring Program. (2004). Centralized Data Management Office, Baruch Marine Field Lab, University of South Carolina <http://cdmo.baruch.sc.edu>.

- Newton, J., Bassin, C., Devol, A., Kawase, M., Ruef, W., Warner, M., ... & Rose, R. (2007). Hypoxia in Hood Canal: An overview of status and contributing factors. In *2007 Georgia Basin Puget Sound Research Conference*, Vancouver, British Columbia.
- Nunes, R. A., & Simpson, J. H. (1985). Axial convergence in a well-mixed estuary. *Estuarine, Coastal and Shelf Science*, 20 (5), 637-649.
- O'Higgins, T. & Rumrill, S. (2007). Tidal and watershed forcing of nutrients and dissolved oxygen stress within four pacific coast estuaries: Analysis of time-series data collected by the National Estuarine Research Reserve System-Wide Monitoring Program (2000–2006) within Padilla Bay (WA), South Slough (OR), Elkhorn Slough (CA) and the Tijuana River estuary (CA). Report for the NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET), 58.
- Pearson EA, Holt GA (1960) Water quality and upwelling at Grays Harbor entrance. *Limnol. Oceanogr.*, 5: 48–56.
- Peterson, J. O., Morgan, C. A., Peterson, W. T., & Di Lorenzo, E. (2013). Seasonal and interannual variation in the extent of hypoxia in the northern California Current from 1998-2012. *Limnol. Oceanogr.*, 58 (6), 2279-2292.
- Percy, K. L. (1974). Descriptions and information sources for Oregon estuaries.
- Pierce, S. D., Barth, J. A., Shearman, R. K., & Erofeev, A. Y. (2012). Declining Oxygen in the Northeast Pacific*. *Journal of Physical Oceanography*, 42(3), 495-501.
- Pritchard, Cate. (2013). *Distribution of Larval Bivalves in the Coos Bay Estuary, Oregon* (Master's Thesis). Oregon Institute of Marine Biology, University of Oregon, Charleston, Oregon.
- Pritchard, D. W. (1967). What is an estuary: physical viewpoint. *Estuaries*, 83, 3-5.
- Rabalais, N. N., Díaz, R. J., Levin, L. A., Turner, R. E., Gilbert, D., & Zhang, J. (2010). Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences*, 7(2), 585–619. doi:10.5194/bg-7-585-2010.
- Rabalais, N. N., Turner, R. E., & Wiseman, W. J. (2002). Gulf of Mexico Hypoxia, a.k.a. "The Dead Zone." *Annual Review of Ecology and Systematics*, 33(1), 235–263. doi:10.1146/annurev.ecolsys.33.010802.150513.
- Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley and F. Wang. (2013). *Observations: Ocean. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, T.F., D. Qin, G.-K. Plattner, M.

Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Riparian Research Group. (2002). Appendix B: Oregon's Water Quality Standards And Criteria Related To Riparian Corridors. Oregon State Programs for Managing Riparian Resources.

Robbins, W. G. (1984). Timber Town: Market Economics in Coos Bay, Oregon, 1850 to the Present. *The Pacific Northwest Quarterly*, 146-155.

Roegner, G. C., Hickey, B. M., Newton, J. A., Shanks, A. L., & Armstrong, D. A. (2002). Wind-induced plume and bloom intrusions into Willapa Bay, Washington. *Limnology and Oceanography*, 47 (4), 1033-1042.

Roegner, G. C., Needoba, J. A., & Baptista, A. M. (2011). Coastal upwelling supplies oxygen-depleted water to the Columbia River estuary. *PloS one*, 6 (4), e18672. doi:10.1371/journal.pone.0018672.

Rumrill, S. (2006). The Ecology of the South Slough Estuary : Site Profile of the South Slough National Estuarine Research Reserve. NOAA / Oregon Department of State Lands, pp. 1-238.

Sayama, T., McDonnell, J. J., Dhakal, A., & Sullivan, K. (2011). How much water can a watershed store? *Hydrological Processes*, 25 (25), 3899-3908.

Scully, M. E. (2013). Physical controls on hypoxia in Chesapeake Bay: A numerical modeling study. *Journal of Geophysical Research: Oceans*, 118 (3), 1239–1256. doi:10.1002/jgrc.20138

Simmons, H. B. (1955). Some effects of upland discharge on estuarine hydraulics. *Proceedings of the American Society of Civil Engineers*, 81 (792), 1-20.

Simpson, J. H., Brown, J., Matthews, J., & Allen, G. (1990). Tidal straining, density currents, and stirring in the control of estuarine stratification. *Estuaries*, 13 (2), 125-132.

Sheldon, J. E., & Alber, M. (2002). A comparison of residence time calculations using simple compartment models of the Altamaha River Estuary, Georgia. *Estuaries*, 25(6), 1304-1317.

Snyder, M. A., Sloan, L. C., Diffenbaugh, N. S., & Bell, J. L. (2003). Future climate change and upwelling in the California Current. *Geophysical Research Letters*, 30 (15).

Stacey, M.T., Burau, J.R., Monismith, S.G. (2001). Creation of residual flows in a partially stratified estuary. *Journal of Geophysical Research* 106, 17013–17037.

- Stramma, L., Schmidtko, S., Levin, L. A., & Johnson, G. C. (2010). Ocean oxygen minima expansions and their biological impacts. *Deep Sea Research Part I: Oceanographic Research Papers*, 57 (4), 587–595. doi:10.1016/j.dsr.2010.01.005
- Strub, P. T., Allen, J. S., Huyer, A., & Smith, R. L. (1987). Large-scale structure of the spring transition in the coastal ocean off western North America. *Journal of Geophysical Research: Oceans* (1978–2012), 92 (C2), 1527-1544.
- Strub, P. T., & James, C. (1988). Atmospheric conditions during the spring and fall transitions in the coastal ocean off western United States. *Journal of Geophysical Research: Oceans* (1978–2012), 93 (C12), 15561-15584.
- Sutherland, D. A., MacCready, P., Banas, N. S., & Smedstad, L. F. (2011). A Model Study of the Salish Sea Estuarine Circulation*. *Journal of Physical Oceanography*, 41 (6), 1125-1143.
- Taylor, A. H. (1983). Plant Communities and Elevation in a Diked Intertidal Marsh in the Coos Bay Estuary, Oregon. *Northwest Science*, 57 (2).
- Thomas, A. C., Strub, P. T., & Brickley, P. (2003). Anomalous satellite-measured chlorophyll concentrations in the northern California Current in 2001–2002. *Geophysical Research Letters*, 30 (15).
- Truesdale, G. A., Downing, A. L., & Lowden, G. F. (1955). The solubility of oxygen in pure water and sea-water. *Journal of Applied Chemistry*, 5 (2), 53-62.
- United States Army Corps of Engineers. *Coos Bay final EIS supplement*. (1975). Portland District. Print.
- U.S. Coast and Geodetic Survey. (1942). Tidal Harmonic Constants, Pacific and Indian Oceans. p. 12, Washington, D.C.
- United States Department of Energy, Federal Energy Regulatory Commission. (2009). *Final Environmental Impact Statement: Jordan Cove Energy and Pacific Connector Gas Pipeline Project (Volume I –Executive Summary, Sections 1, 2, 3 and 4.0 - 4.4)*. Washington, DC. Retrieved from: <http://www.jordancoveenergy.com/pdf/FEIS%20-%20Volume%201.pdf>.
- Vallino, J. J., & Hopkinson Jr, C. S. (1998). Estimation of dispersion and characteristic mixing times in Plum Island Sound estuary. *Estuarine, Coastal and Shelf Science*, 46 (3), 333-350.
- Vaquer-Sunyer, R., & Duarte, C. M. (2008). Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Sciences of the United States of America*, 105(40), 15452–7. doi:10.1073/pnas.0803833105

Voluntary Estuary Monitoring Manual. (2006). Chapter 9: Dissolved Oxygen and Biochemical Oxygen Demand. EPA.

Wenner, E., Sanger, D., Arendt, M., Holland, A. F., & Chen, Y. (2004). Variability in dissolved oxygen and other water-quality variables within the National Estuarine Research Reserve System. *Journal of Coastal Research*, 17-38.

Whitney, F. A., Crawford, W. R., & Harrison, P. J. (2005). Physical processes that enhance nutrient transport and primary productivity in the coastal and open ocean of the subarctic NE Pacific. *Deep Sea Research Part II: Topical Studies in Oceanography*, 52 (5), 681-706.

Whitney, F. A., Freeland, H. J., & Robert, M. (2007). Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific. *Progress in Oceanography*, 75 (2), 179–199. doi:10.1016/j.pocean.2007.08.

Wilson, C. (2003). Erosion and transport of fine sediments from watersheds tributary to NERR estuaries. Ph.D. thesis, Case-Western University. 156 pp.

Yang, Z., & Khangaonkar, T. (2009). Modeling tidal circulation and stratification in Skagit River estuary using an unstructured grid ocean model. *Ocean Modelling*, 28 (1), 34-49.