Prepared in cooperation with the Skagit River System Cooperative

Nearshore Circulation and Water-Column Properties in the Skagit River Delta, Northern Puget Sound, Washington

Juvenile Chinook Salmon Habitat Availability in the Swinomish Channel

Scientific Investigations Report 2007-5120

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DIRK KEMPHORNE, Secretary

U.S. Geological Survey
Mark Myers, Director

U.S. Geological Survey, Reston, Virginia 2007

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Grossman, EE, Stevens, A, Gelfenbaum, G and Curran, C. 2007, Nearshore circulation and water column properties in the Skagit River Delta, northern Puget Sound, Washington - Juvenile Chinook salmon habitat availability in the Swinomish Channel: U.S. Geological Survey Scientific Investigations Report 2007-5120, 97 p.

This report and any updates to it are available online at:
http:pubs.usgs.gov/sir/2007/5120/

Cover—The Swinomish Channel in La Conner, Washington. Inset shows U.S. Geological Survey instrument tripod used to measure circulation and water-column properties. (Photographs by E. Grossman and A. Stevens, U.S. Geological Survey.)

Contents

Figures

Tables

Nearshore Circulation and Water-Column Properties in the Skagit River Delta, Northern Puget Sound, Washington

Juvenile Chinook salmon habitat availability in the Swinomish Channel

By Eric E. Grossman, Andrew Stevens, Guy Gelfenbaum and Christopher Curran

Abstract

Time-series and spatial measurements of nearshore hydrodynamic processes and water properties were made in the Swinomish Channel to quantify the net direction and rates of surface water transport that influence habitat for juvenile Chinook salmon along their primary migratory corridor between the Skagit River and Padilla Bay in northern Puget Sound, Washington. During the spring outmigration of Skagit River Chinook between March and June 2006, currents measured with fixed acoustic doppler current profilers (ADCP) at the south and north end of the Swinomish Channel and with roving ADCP revealed that the currents are highly asymmetric with a dominant flow to the north (toward Padilla Bay). Maximum surface current velocities reached 1.5 m/s and were generally uniform across the channel near McGlinn Island Causeway. Transport times for surface water to travel the 11 km from the southern end of Swinomish Channel at McGlinn Island to Padilla Bay ranged from 2.1 hours to 5.5 days. The mean travel time was ~1 day, while 17 percent of the time, transport of water and passive particles occurred within 3.75 hours. Surface water in the Swinomish Channel during this time was generally very saline 20-27 psu, except south of the Rainbow Bridge in the town of La Conner where it ranged 0-15 psu depending on tide and Skagit River discharge. This salinity regime restricts suitable low salinity (<15-20 psu) surface waters for fry Chinook salmon to the southernmost 2 km of the channel. The mean change in salinity along the channel was 10-13 psu. The high northward current velocities have the capacity to transport Chinook fry into less suitable, high-salinity waters toward Padilla Bay within hours. The rapid transport times of 2.1 to 3.75 hours between McGlinn Island and Padilla Bay that occur 17 percent of the time, are considerably less than the time considered adequate for juvenile Chinook to acclimate and produce a temporal salinity gradient for pre-smolt salmon that can exceed 4 psu/hour during high northward current flow.

Introduction

The Swinomish Channel in Northeastern Puget Sound, Washington (figs. 1, 2), is considered a principal migratory corridor for juvenile and returning adult Skagit salmon that has lost connectivity and function due to human land use (Beamer and others, 2005.). Historically, the channel consisted of a network of shallow deltaic distributary channels (Collins, 2000) that connected the North Fork Skagit River to Swinomish Channel and Padilla Bay to the north. These connections provided a direct pathway for fish migration and an important supply of freshwater to maintain suitable salinity gradients for juvenile salmon smolts seeking important rearing habitat in Padilla Bay. Beginning in the 1890s, the channel was dredged and deepened to accommodate navigation and commercial transport, leading to increased tidal flow and surface salinities. In the 1930s, a causeway was constructed between La Connor and McGlinn Island to protect channel navigation from flood hazards and block sediment input to the channel from the river (fig. 3*A*). Beginning in 1938, a jetty was constructed from McGlinn Island out into Skagit Bay to further restrict sediment input from the river. A small fish passage retained near the landward edge of the jetty allows for fish passage only during high tide and/or high river flow (fig. 3*B*). It is hypothesized that Skagit Chinook experience high mortality due to osmotic stress as they circumvent the jetty and the high salinity waters (>15 to 20 practical salinity units (psu)) of Skagit Bay and the Swinomish Channel as they seek refuge and forage habitat in Padilla Bay. Pre-smolt chinook salmon are likely unable to survive immediate transfer to salinities greater than 15-20 psu and suitable time to acclimate may take days to weeks (Healey 1991). This may explain low presence of Chinook along traditionally important fish habitat along the Swinomish Channel (Beamer and others, 2005). Although the causeway and jetty have reduced sediment infilling of Swinomish Channel, it is periodically dredged by the U.S. Army Corps of Engineers to accommodate safe navigation. Diking, dredging, and causeway/jetty development along the Swinomish Channel has adversely impacted habitat function across much of northern Puget Sound by eliminating connectivity and altering estuarine mixing processes and they represent a principal focus for nearshore restoration efforts throughout Puget Sound today.

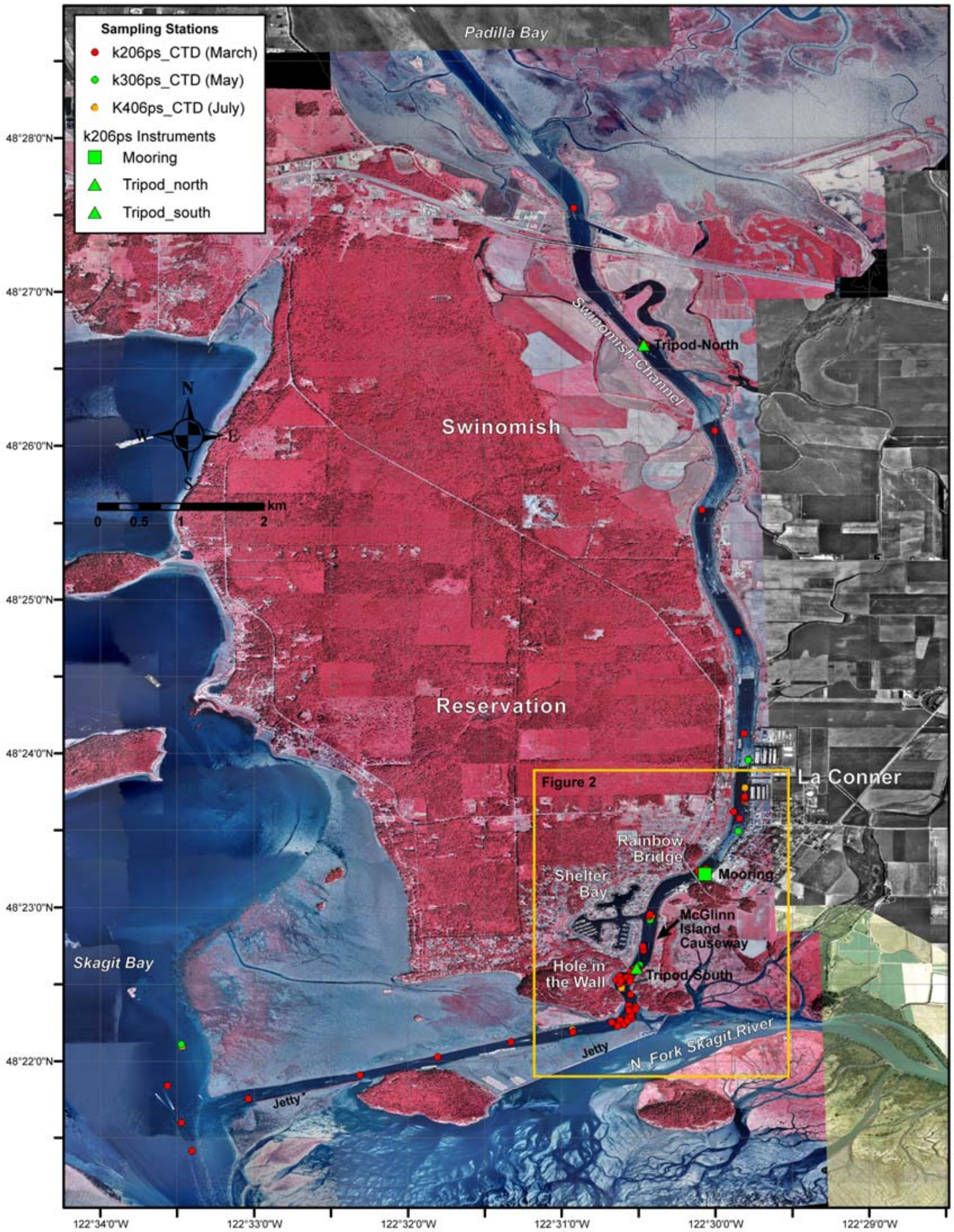


Figure 1. Map of study area showing the locations of Conductivity, Temperature, Depth surveys and instrument deployments (surface mooring, tripod-north and tripod-south) referred to in this report. Color infrared aerial photography over Swinomish Reservation (courtesy of Swinomish Tribe) shows false color with healthy vegetation (high reflection level of near-infrared wavelengths on color infrared film) appearing dark red. See later discussion for explanation of instruments and moorings. Inset shows area in figure 2.

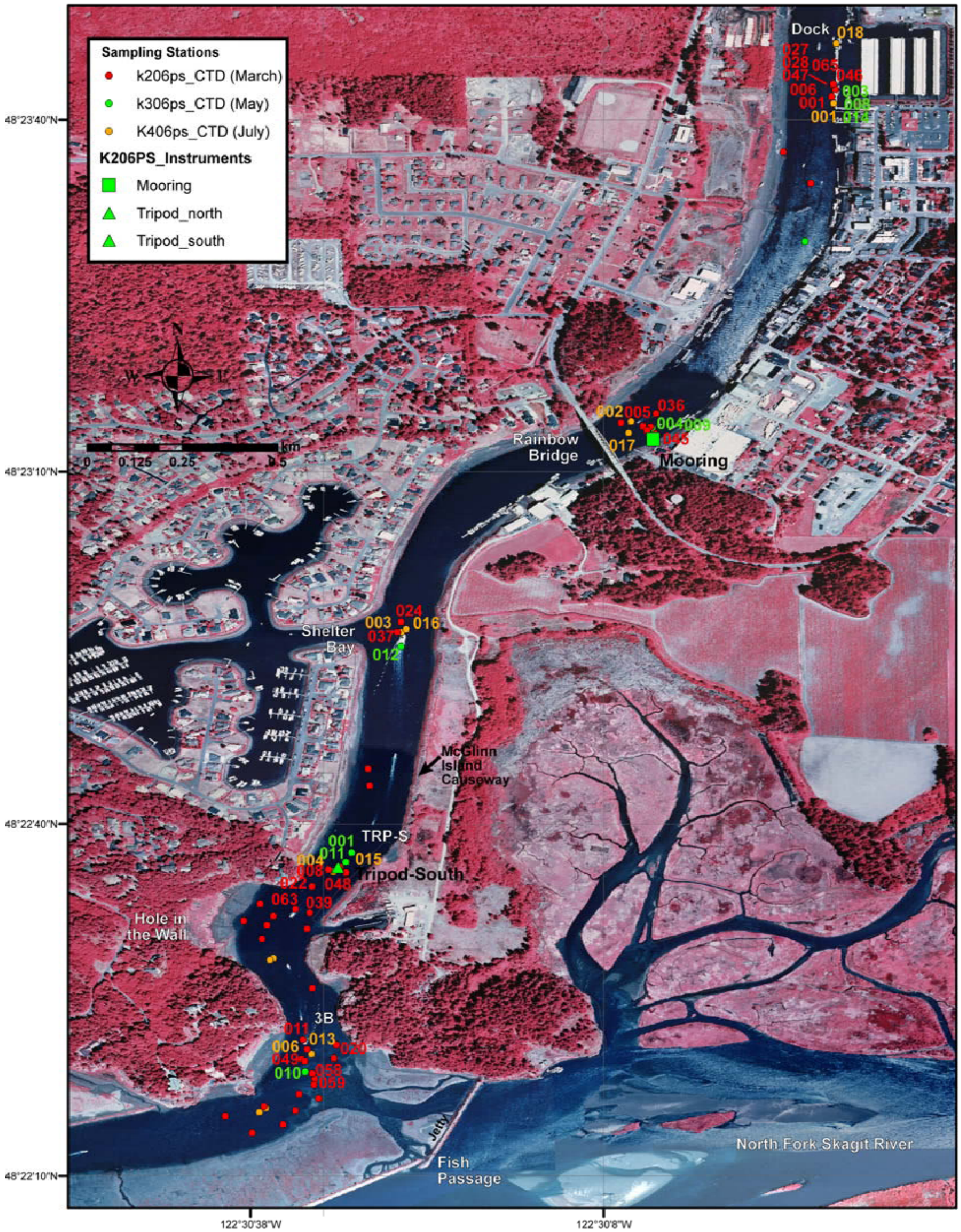


Figure 2. Detailed map of southern Swinomish Channel and study area showing the locations of Conductivity, Temperature, Depth surveys (numbers refer to casts) and instrument deployments (surface mooring and tripod-south) referred to in this report. See later discussion for explanation of instruments and moorings.

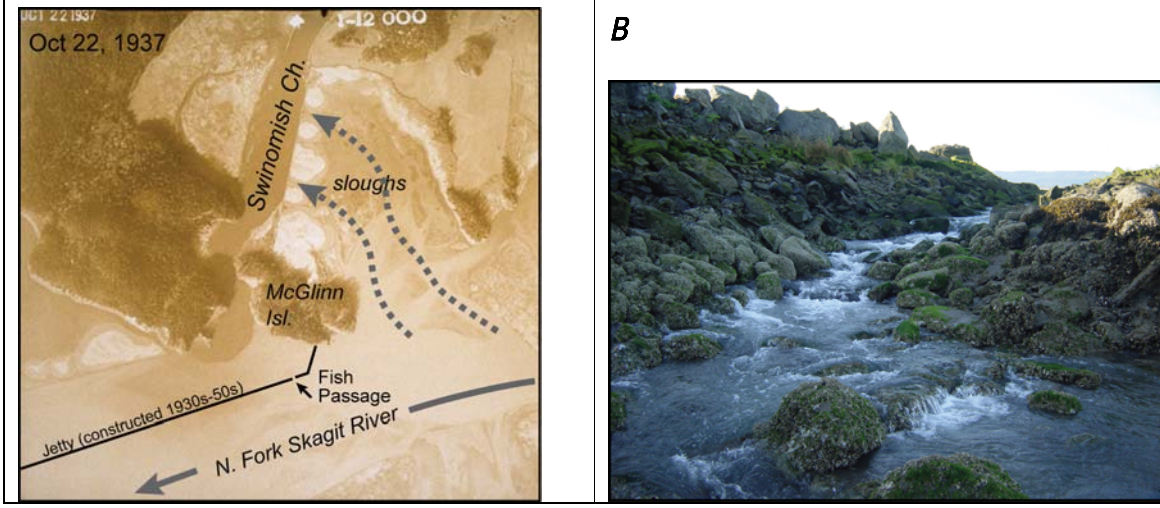


Figure 3. (*A*) Annotated 1937 aerial photograph showing sloughs that connected the N. Fork Skagit River to Swinomish Channel prior to infilling of McGlinn Island Causeway and construction of the Skagit Bay jetty. (*B*) The only fish passage for juvenile Skagit Chinook Salmon to Swinomish Channel is usable only at high tides.

This report presents data from hydrodynamic and water property measurements made in the Swinomish Channel and Skagit Bay during the Spring 2006 outmigration of Skagit Chinook salmon. This effort was made to quantify the nearshore circulation patterns, current velocities, and water properties that influence habitat availability for juvenile salmonids using the Swinomish Channel. These data enable calculations to be made of the volume of freshwater needed to sustain suitable salinity gradients for juvenile salmonids, particularly Chinook that require longer time to adjust to saline water, and to calculate transport times of water and juvenile/fry salmon through the channel. This information will help to evaluate possible restoration alternatives aimed to re-establish historical migratory connectivity between the Skagit River and essential rearing habitat in Padilla Bay and to design refuge habitats along the channel for fish to escape the high current velocities and adequately adjust to the increased salinities of northern Swinomish Channel and Padilla Bay.

Methods

Tripod and Mooring Setup

Two instrumented tripods equipped to measure currents and water properties were deployed on the north and south side of the Swinomish channel (figs. 1 and 2) for a 1.5 month period between March and May of 2006 (table 1). Each tripod was equipped with a Sontek 1500 kHz Acoustic Doppler Profiler (ADP). Water temperature was measured at the north tripod using a Brancker temperature sensor. At the South Site, a Seabird SB-37 Microcat recorded temperature, conductivity, and pressure. Each tripod had a retrieval system consisting of an Edgetech Cart acoustic release connected to a line and buoy. An acoustic pinger was placed on the tripod to aid in its recovery in the event that the release system failed. Figures 4 and 5 show photos of the two instrumented tripods immediately before deployment at the north and South Site, respectively.

Table 1. Deployment information for Swinomish Channel hydrodynamic studies.

	North Site	South Site	Surface Mooring
Deployment Date	3/28/2006	3/28/2006	3/29/2006
Deployment Latitude	48.4443 °N	48.3768 °N	48.38722 °N
Deployment Longitude	122.5078 °W	122.5086 °W	122.50125 °W
Recovery Date	5/16/2006	5/16/2006	5/16/2006

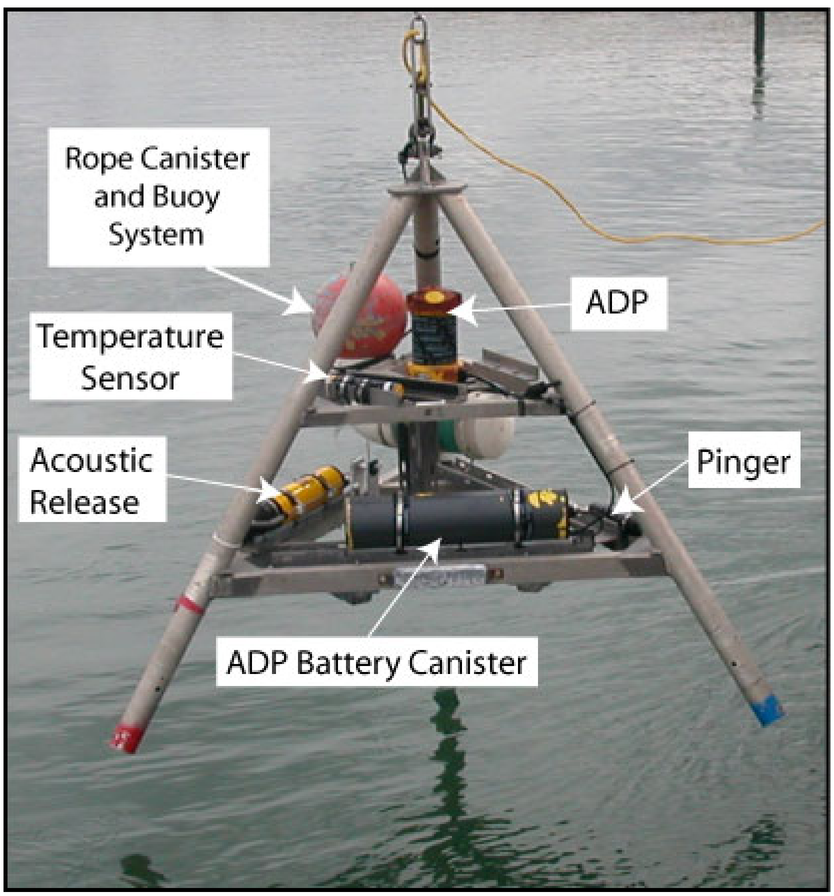


Figure 4. Photograph of the tripod deployed at the North Site, Swinomish Channel.

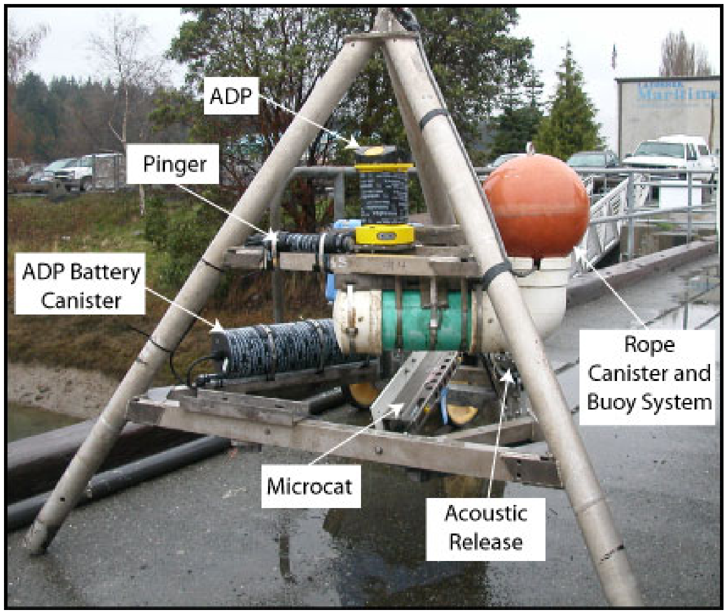


Figure 5. Photograph of the tripod deployed at the South Site, Swinomish Channel.

Continuous temperature and salinity measurements of the surface water were made with a Seabird SB-37 Microcat attached to a surface mooring (fig. 6). The mooring consisted of a Gilman 4CFR buoy with a Carmanah solar light attached to the top. The microcat was fixed to the mooring to measure temperature and salinity 50 cm below the surface. The mooring was deployed near the Rainbow Bridge between the two tripods to detect northward advection of freshwater from the N. Fork Skagit River. Table 2 reports the instruments deployed and their positions relative to the bottom of the tripod.

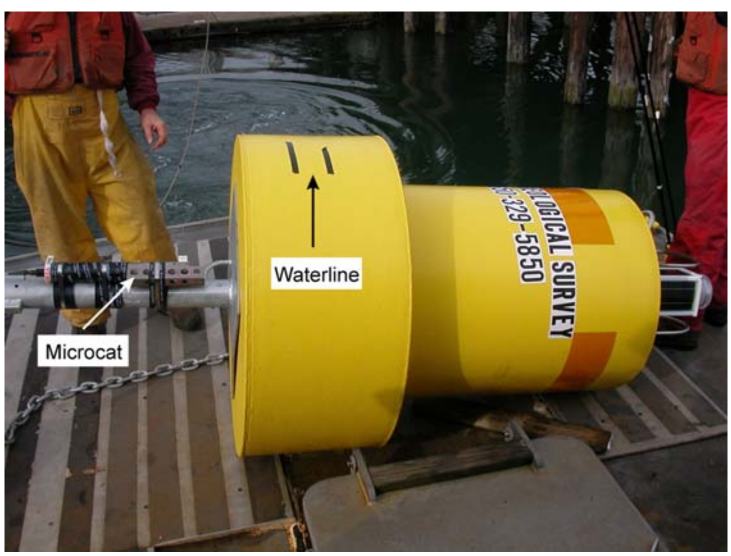


Figure 6. Photograph of the mooring deployed at Rainbow Bridge, Swinomish Channel.

Table 2. List of instruments and their relative positions on each platform.

Station	Instrument	Serial Number	Height (cmab)
North Site	ADP	C134	134.5
	Branker Temp. Sensor	6992	108.0
South Site	ADP	C132	135.0
	SB-37 Microcat	283	64.5
Surface Mooring	SB-37 Microcat	1700	35.0*

* The reported height of the SB-37 microcat attached to the surface mooring is cm below water surface.

SonTek acoustic Doppler profilers (ADPs) are designed to measure profiles of velocity throughout the water column. The sampling scheme for the current meters was designed in order to obtain accurate measurements in a region known to have relatively high current velocities and provide high resolution vertically in the water column. The current meters were set to average current measurements for a 5 min period to produce a current profile every 15 min. The start of each burst was set to begin 2.5 min before each quarter-hourly measurement. The vertical cell size was set to 0.25 m beginning 0.4 m from the transducer. Table 3 includes the sampling setup parameters for the two current profilers.

Table 3. Acoustic Doppler Profiler instrument setup information.

Parameters	North Site	South Site
ADP Serial Number	C134	C132
Frequency (kHz)	1500	1500
Cell size (m)	0.25	0.25
Blanking distance (m)	0.4	0.4
Number of cells	60	60
Ensemble interval (min)	15	15
Averaging interval (min)	5	5
Coordinate System	ENU	ENU
Time Zone	GMT	GMT
Magnetic Declination (degrees)	17.8	17.8

The ADPs also measured water temperature and pressure. An internal compass and two-axis tilt sensor measured heading, pitch and roll. Using the measurements of the compass (heading, tilt and roll), velocity measurements were transformed and stored in geographic components of velocity (east, north, up). Both tripods were recovered using an Edgetech Coastal Acoustic Release Transponder (CART) and buoy system. Upon recovery, both tripods had relatively little bio-fouling and all instruments appeared to be in good condition. The south tripod was estimated to have sunk into the sediment to a depth of 30-40 cm based on the complete lack of fouling on the lower legs of the tripod. On the north tripod, the depth of burial was unable to be determined because very little fouling occurred on the entire tripod.

Roving ADCP Measurements of Currents

Cross-channel variability in currents were measured with a boat-mounted 600 kHz Rio Grande Workhorse Acoustic Doppler Current Profiler (ADCP) and a Trimble Ag 132 DGPS that achieves sub-meter positional accuracy (fig. 7). The bottom-tracking ADCP was operated continuously with a ping rate of 5 Hz, vertical cell size of 0.5 m, and a 0.25 m blanking distance (distance from the transducer). The velocity, depth, temperature and position data were acquired and processed with WinRiver firmware version 10.14 ADCP software, averaging 3 pings per ensemble following Oberg and others, (2005). Boat speed ranged 3-6 kts, such that resulting processed current measurements span 1-2 m along track.

Figure 7. Photograph of the roving Acoustic Doppler Current Profiler and Differential Geographic Positioning System setup.

Spatial Measurements of Water Column Properties derived from Conductivity, Temperature and Depth Profiles

Water column properties including conductivity (converted to salinity), temperature, salinity, and depth (CTD) were measured at stations along the Swinomish Channel in March, May, and July 2006 (figs. 1 and 2) with a Seabird Electronics model 19+ Profiling CTD (fig. 7). The Seabird 19+ operates at 4 Hz and downcasts were conducted manually at an approximate rate of 1 m/10 sec to acquire at least 10 samples per 0.25 m. In addition to conductivity, temperature, and depth, turbidity, dissolved oxygen, photosynthetically active radiation, and chlorophyll were measured and average sound velocity was derived. Locations and times of CTD casts were obtained with a Garmin GPS.

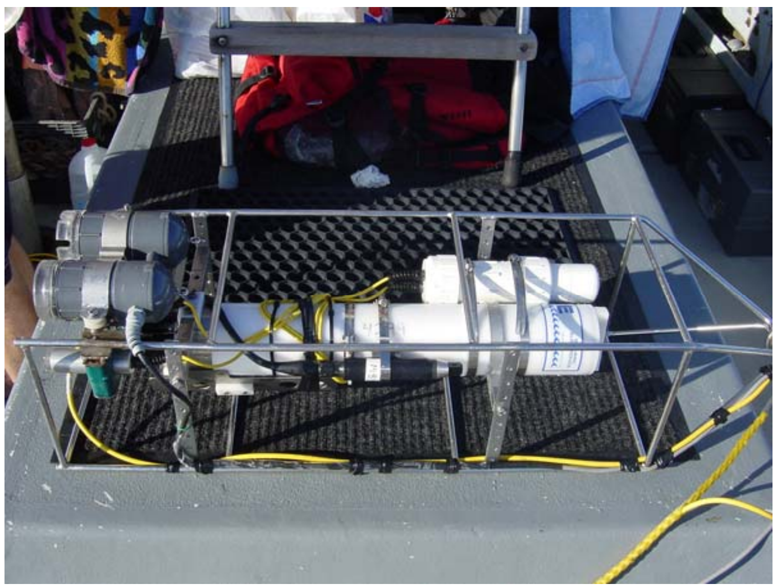


Figure 8. Photograph of Seabird 19+ profiling Conductivity, Temperature, and Depth sensor used for spatial measurements.

Environmental Setting

Atmospheric pressure, wind speed and direction, and air temperature during the Swinomish Channel deployment were obtained from the Whidbey Island Naval Air Station (USAF-WBAN_ID 690230 24255, http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~20027920). Wind direction was changed to the oceanographic convention whereby direction refers to the direction wind is flowing to. Skagit River discharge was obtained from the U.S. Geological Survey (USGS) Mount Vernon gauge station (Station 12200500, http://waterdata.usgs.gov/wa/nwis/uv/?site_no=12200500&amp).

Weather conditions during the deployment were characteristic of slow warming and rise in air pressure associated with the transition from early to late spring (fig. 9). Winds generally ranged 0-7 m/s and from the west and southeast (fig. 10) except for passing low pressure systems. Two significant low pressure systems during the middle of April and early May led to increases in wind velocities (10-15 m/s) originating from the east-southeast. Skagit River discharge ranged 1,000-2,000 cubic feet per second (cfs) during most of the deployment and began to rise toward spring flood levels near the end of our deployment.

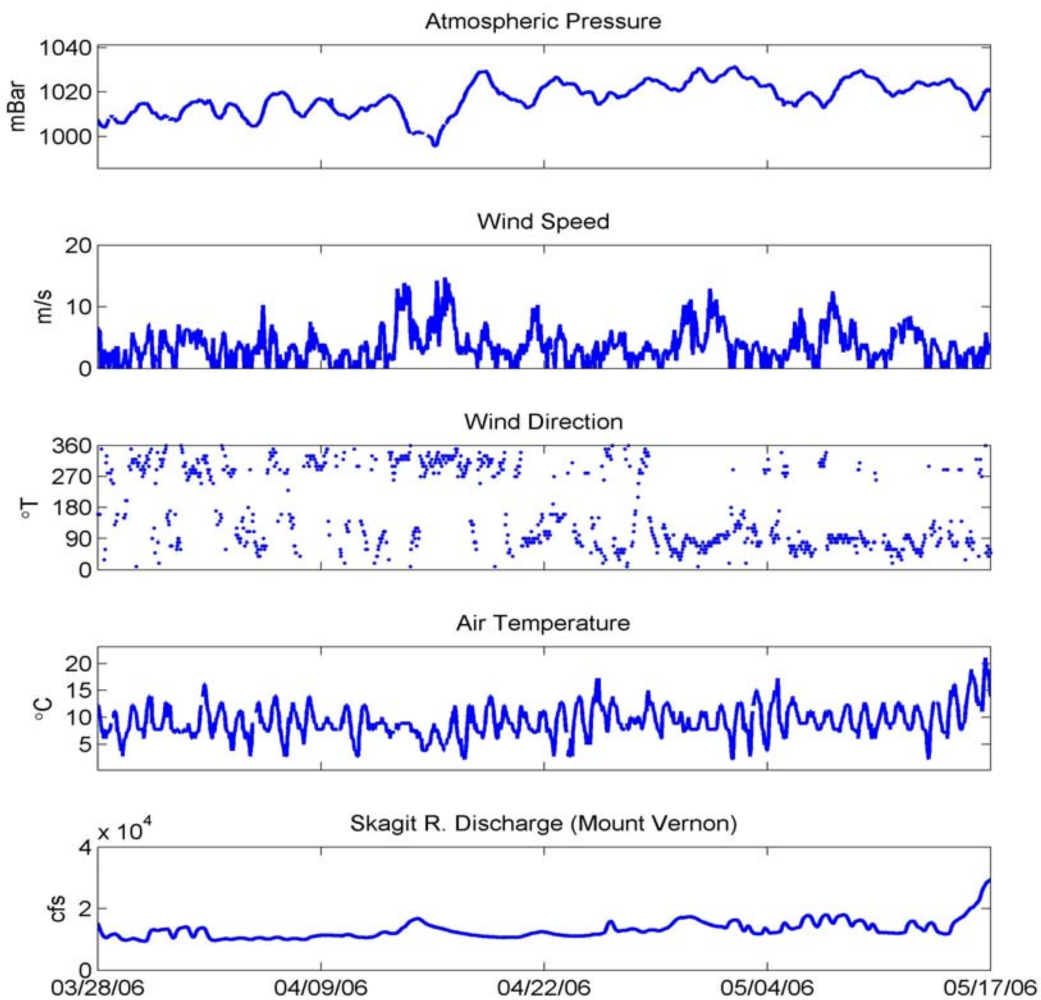


Figure 9. Time series of environmental data collected at the Whidbey Island meteorological station. Wind direction refers to the direction the wind is flowing to. River discharge is measured at the Mt. Vernon gauge (Station 12200500).

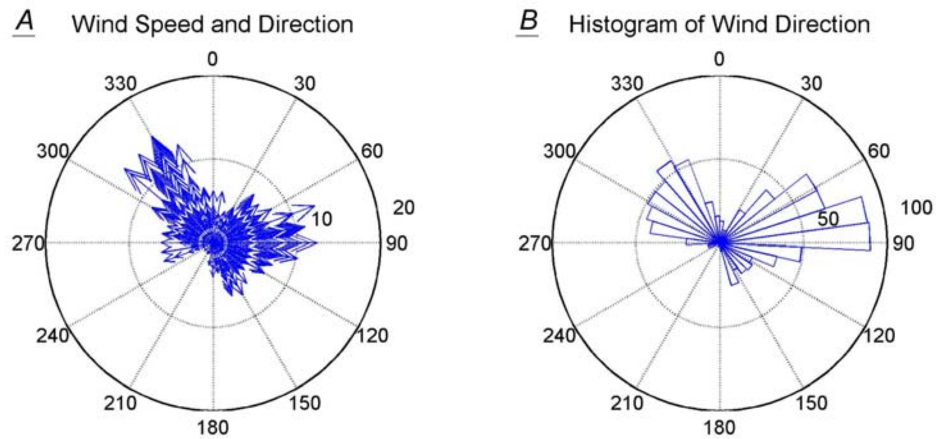


Figure 10. Plot of (*A*) wind speed (in m/s) and direction during the Swinomish Channel deployment. (*B*) Histogram of wind direction. Wind direction refers to the direction the wind is flowing to.

Data Processing

High quality data were recovered from all of the instruments deployed in this study. However, problems with the analog to digital converter (B. Macone, Sontek, oral commun.) resulted in bad pressure and temperature data recorded by ADP C132 at the South Site. Fortunately, the South Site tripod was also equipped with a SBE-37 microcat that made temperature and pressure measurements.

Data collected by the compass and 2-axis tilt sensor in the ADP suggest minor movement of both tripods within the first ~2 days of deployment as the tripod settles into the bed (figs. 11 and 12). Afterwhich, the heading, pitch and roll changed only gradually, suggesting that neither of the tripods were significantly disturbed during data collection.

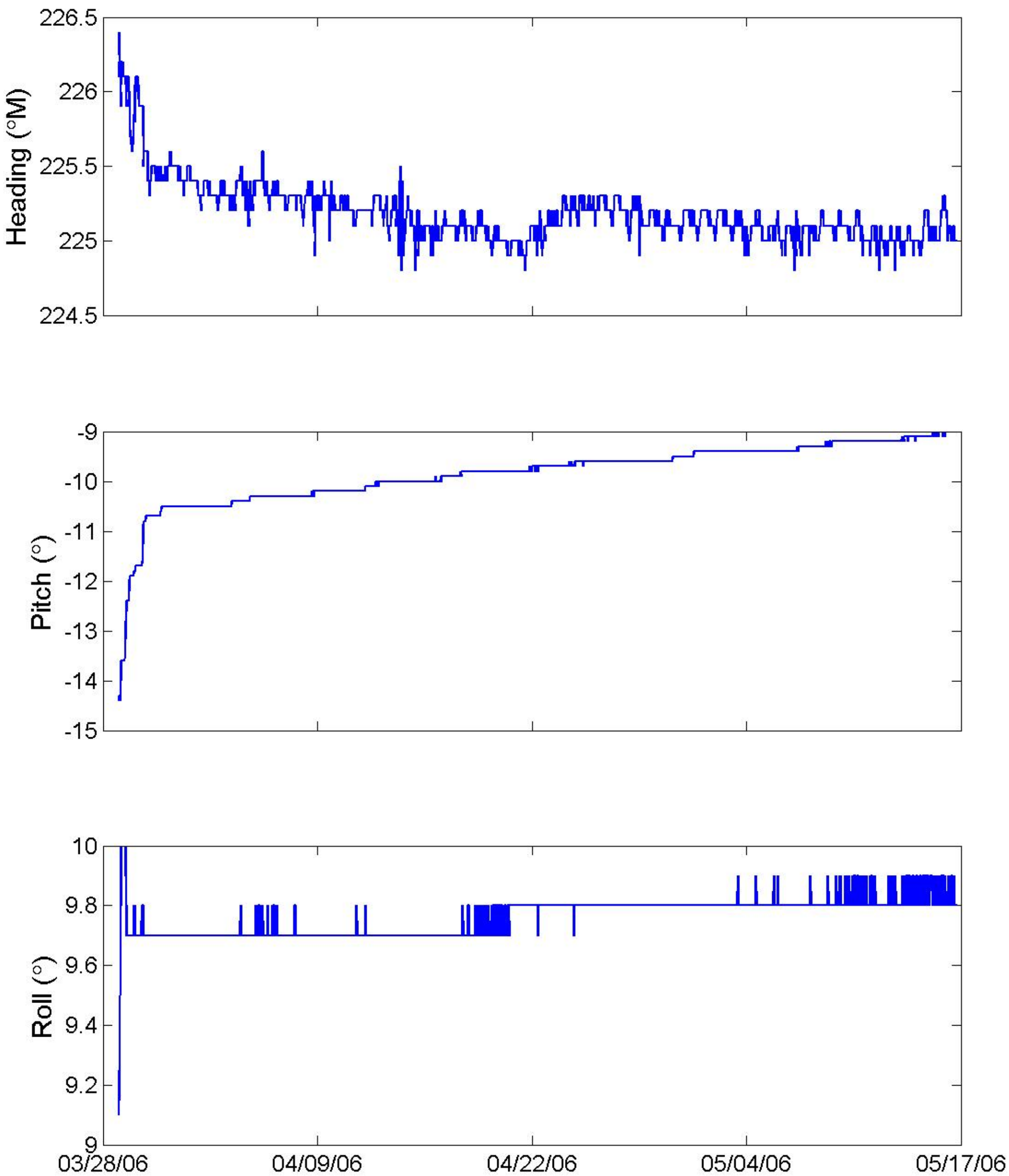


Figure 11. Time-series of heading, pitch and roll collected by the internal compass of the acoustic Doppler profiler (ADP) at the North Site. °M, degrees from magnetic north.

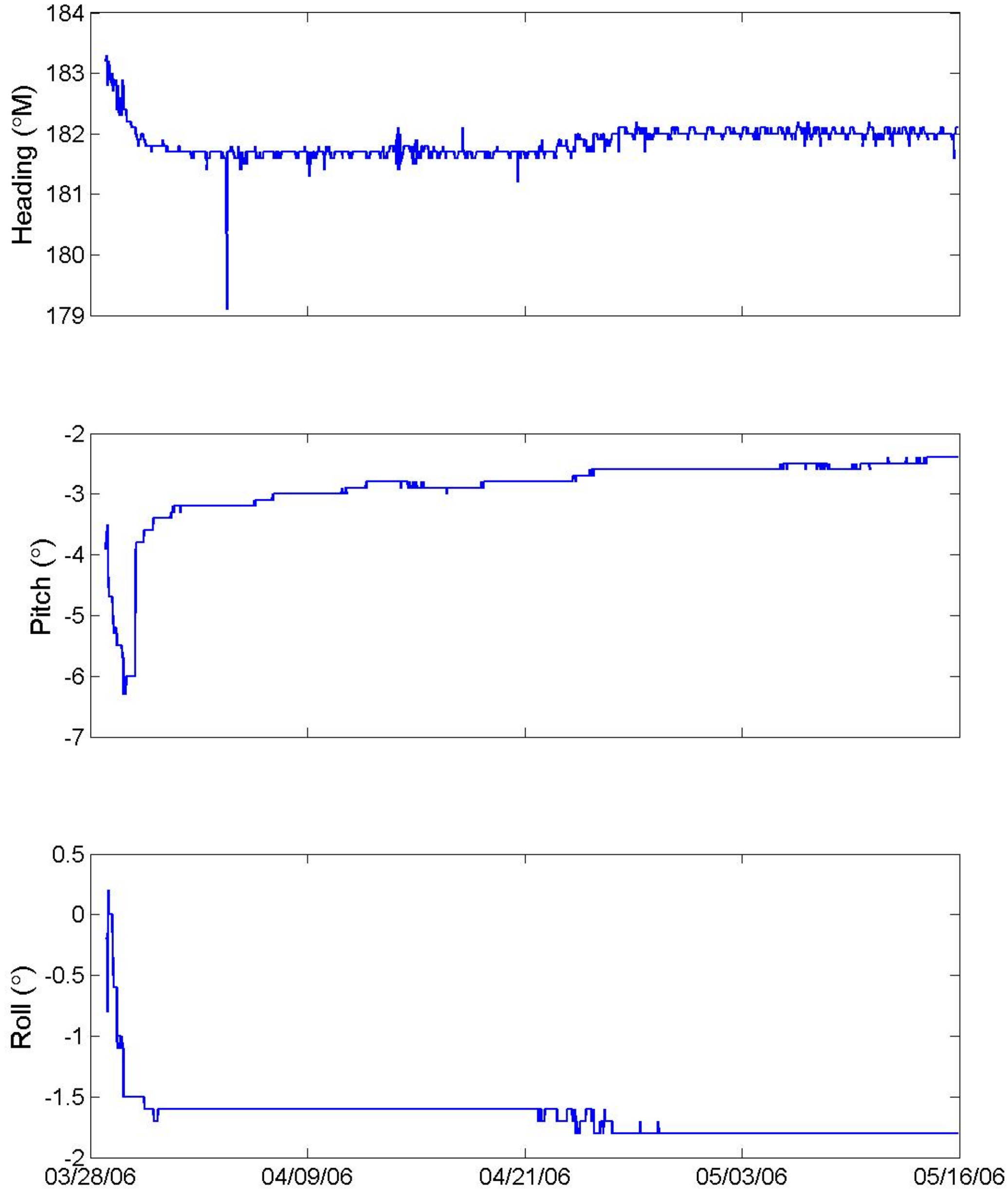


Figure 12. Time-series of heading, pitch and roll collected by the internal compass of the acoustic Doppler profiler (ADP) at the South Site. °M, degrees from magnetic north.

Time periods where valid data were collected were determined by visual inspection of the pressure as well as heading, pitch and roll time-series data. Data points recorded when the instruments were out of the water were removed from the record. Table 4 shows the periods when valid data were recorded for each instrument.

Table 4. Date, time and burst number of first and last valid data record for each instrument deployed during this experiment.

Station	Instrument	Sample	Start Date	Time	Sample	End Date	Time
North Site	ADP	1	3/28/2006	22:27:30	4688	5/16/2006	18:12:30
	Branker Temp. Sensor	678	3/28/2006	22:34:00	35840	5/16/2006	18:38:00
South Site	ADP	1	3/28/2006	20:57:30	4612	5/15/2006	21:42:30
	SB-37 Microcat	1235	3/28/2006	20:43:01	70435	5/15/2006	22:03:01
Surface Mooring	SB-37 Microcat	1449	3/29/2006	00:08:03	71612	5/16/2006	17:31:02

After nonvalid data points were removed, the raw data files were exported to ascii text files using Sontek's ViewAdp Pro software. The ascii files were read into a matlab data structure for further analysis. The east and north components of velocity were rotated to account for the site-specific variation in magnetic declination at the time of the deployment (17.8 °E).

A script in MATLAB was written to use the pressure sensor in the ADP to find and remove bins that were above the water surface. Water depth was determined by assuming that 1 dbar of pressure was equal to 1 m of water vertically in the water column. If the center of the bin did not fall below the defined surface, that bin and all bins above it were removed from the data record. In the case of the South Site ADP, where internal pressure data were bad, data from the microcat were used (after correcting for the vertical offset between the two instruments, 70.5 cm) to remove out-of-water bins.

In order to investigate net water movement in the channel, velocities in three layers were rotated into along- and across- channel components using principle component analysis (PCA). A standard (33-hr) low-pass filter was then applied to the rotated velocities to plot current patterns occurring at subtidal frequencies. Cumulative along-channel transport was calculated by taking the cumulative sum of the product of the along-channel velocity component and Δt (15 min or 900 s).

CTD measurements were processed with standard Seabird protocols using Seabird calibrations and correcting for surface soak and instrument priming. Measurements were averaged at 0.25 m depth intervals and merged with navigation, environmental data (tide stage, winds, river discharge), and current measurements. Analyses of CTD casts including cross-sections and surface maps were made using Matlab and ArcMap nearest neighbor grid algorithms. Plots of all casts are provided in appendices I-III.

Results

Time Series of Hydrodynamic Measurements

Tides

The tidal height at the north site was measured using the internal pressure sensor in the ADP. At the South Site, where pressure data were corrupt, pressure data from the microcat were used to estimate water levels. Water level at each site was estimated by assuming that each dbar of pressure represents one meter of water depth. Reported water level values (fig. 13) are relative to the mean water level at each site during the deployment (that is, the mean was removed from each time-series to compare water levels).

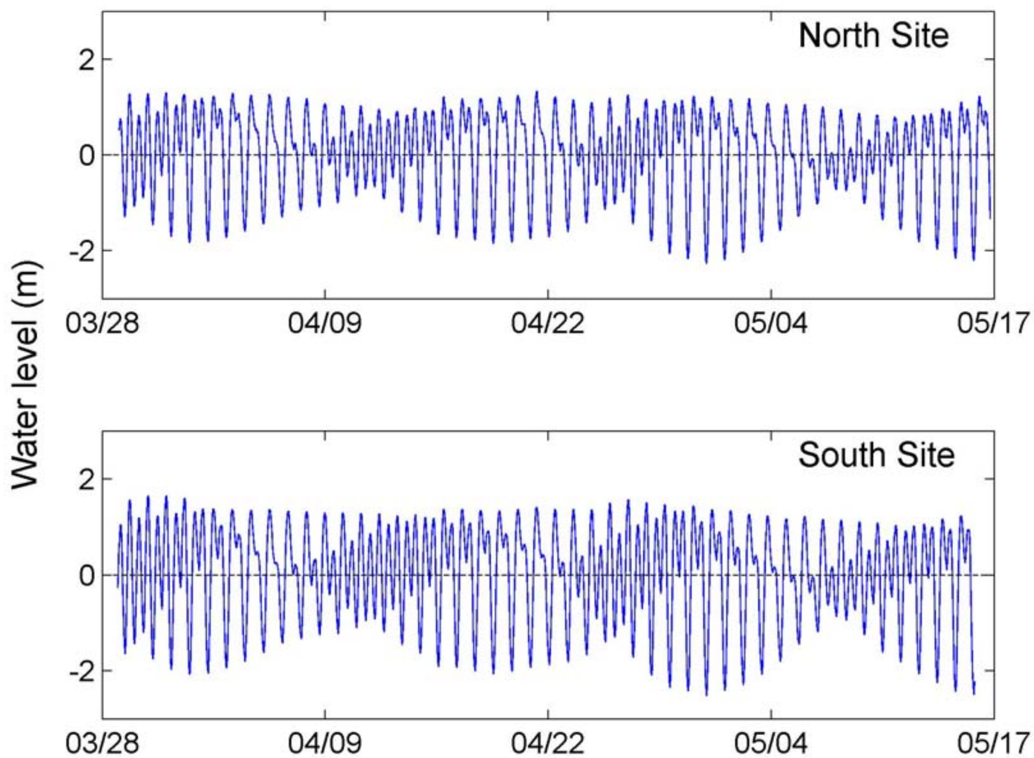


Figure 13. Water levels relative to the mean water height during the deployment for the north (top panel) and south (bottom panel) tripods.

Comparison of the water levels at the two sites (fig. 14) suggests that the amplitude of the tidal oscillations is larger at the South Site compared to the North Site. The instantaneous difference in tidal elevation is as high as 0.5 m at some times during the deployment (fig. 14, middle panel). Positive values indicate the water level was higher at the South Site relative to the North Site. Low-pass filtered differences in tidal elevation (fig. 14, bottom panel) show that the water level at the South Site is higher at subtidal frequencies throughout most of the data record.

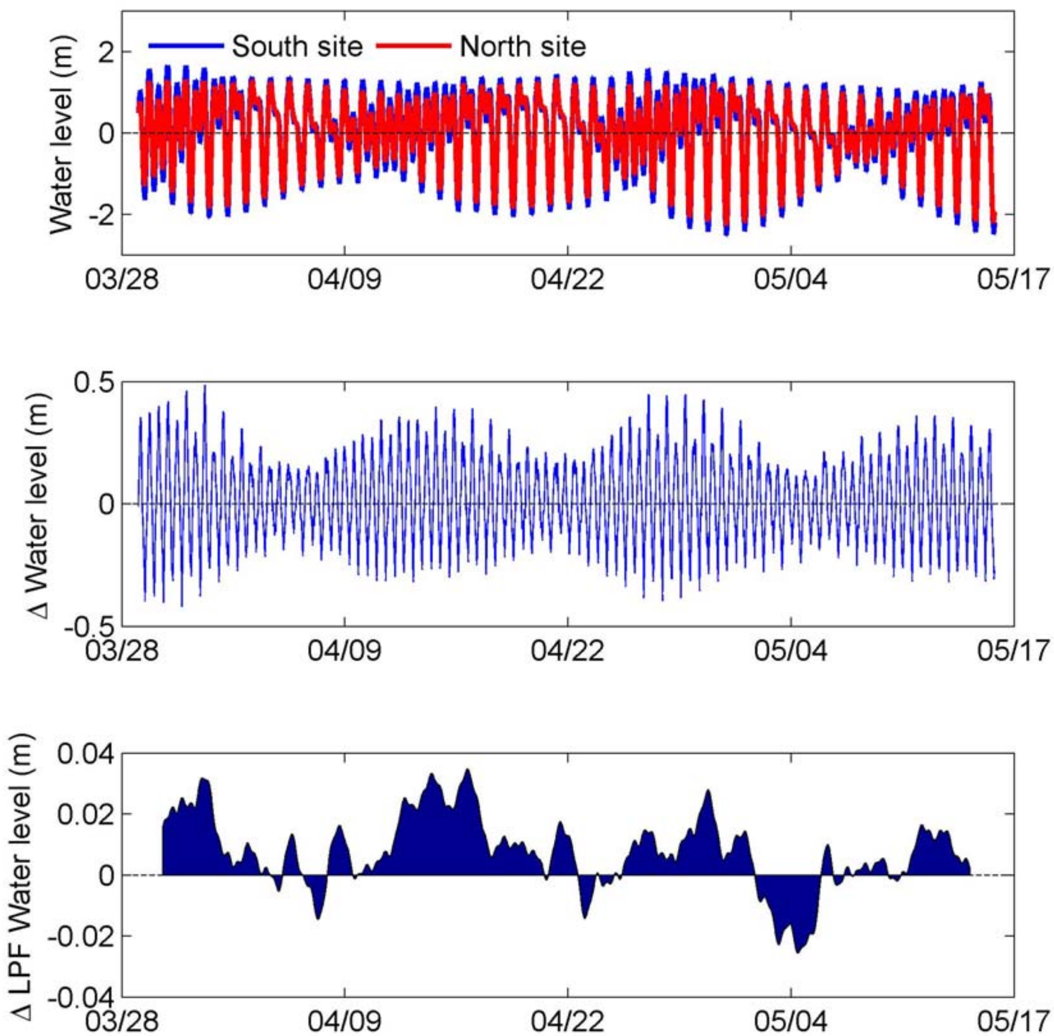


Figure 14. Comparison of water levels between the North and South Sites (top panel). The middle and bottom panel show the difference (South Site-North Site) and low-pass filtered (LPF) difference between the two sites, respectively.

Harmonic analysis on each of the water level time-series was carried out using the T_Tide analysis package for MATLAB (Pawlowicz and others, 2002). Comparison of the major harmonic constituents at each site (table 5) shows that the amplitude of the two biggest components, K1 and M2, are larger at the South Site than at the North Site. Also, there are differences in the phase of major tidal components between the two sites. For instance, a phase difference of 4.3 degrees for the M2 constituent equates to about a 9 min difference between the two sites.

Table 5. Comparison of the amplitude and phase of major harmonic tidal constituents at the north (NS) and south (SS) sites.

Constituent	Frequency [1/hr]	NS Amplitude [m]	SS Amplitude [m]	N-S Amplitude Diff. [m]	NS Phase [deg]	SS Phase [deg]	N-S Phase Diff [deg]
Q1	0.0372	0.076	0.073	0.003	231.7	231.9	-0.2
O1	0.0387	0.494	0.498	-0.004	254.7	253.3	1.4
K1	0.0418	0.800	0.823	-0.023	268.0	268.4	-0.4
J1	0.0433	0.037	0.036	0.001	319.0	323.3	-4.3
N2	0.0790	0.150	0.189	-0.039	336.6	337.5	-0.9
M2	0.0805	0.725	0.923	-0.198	15.7	19.9	-4.2
L2	0.0820	0.025	0.037	-0.012	77.1	97.9	-20.8
S2	0.0833	0.199	0.271	-0.072	31.8	35.4	-3.6
M3	0.1208	0.006	0.009	-0.003	235.5	213.9	21.6
M4	0.1610	0.007	0.012	-0.005	297.6	311.9	-14.3
S4	0.1667	0.001	0.002	-0.001	261.5	300.5	-39
2MK5	0.2028	0.012	0.017	-0.005	131.2	106.9	24.3
M6	0.2415	0.012	0.018	-0.006	215.9	146.8	69.1

Currents

North Site

Maximum horizontal velocities at the north site were 57.7 and 108.5 cm/s for the *u*- and *v*- components of velocity, respectively. Vertical velocities were always less than 10 cm/s and typically less than 5 cm/s. The maximum observed current speed at the surface was 115 cm/s (fig. 15), whereas the maximum depth-averaged current magnitude was 109 cm/s (fig. 16). The direction of the currents was primarily in the along-channel directions of 330° (toward Padilla Bay) and 150° (toward La Conner/ Skagit Bay).

Current speed and direction for each week of the deployment shows in detail the vertical structure of currents in the water column throughout the deployment (fig. 17*A*-*G*). Current speeds do not appear to closely match the range of a given tide, nor does the direction of the current switch exclusively at high and low tide. That is, slack water is not exclusively occurring at the crest and trough of the tidal cycle. Also, the current is asymmetric, typically flowing toward the northwest for a longer period than it does to the southeast.

The low-pass filtered, along-channel velocities (fig. 18) indeed show net transport to the northwest toward Padilla Bay, with only brief periods where net transport was directed to the southeast. Over the course of the 1.5 month deployment, net along-channel transport for the top 1-m was around 250 km. As would be expected in a confined channel, cross-channel net transport was negligible.

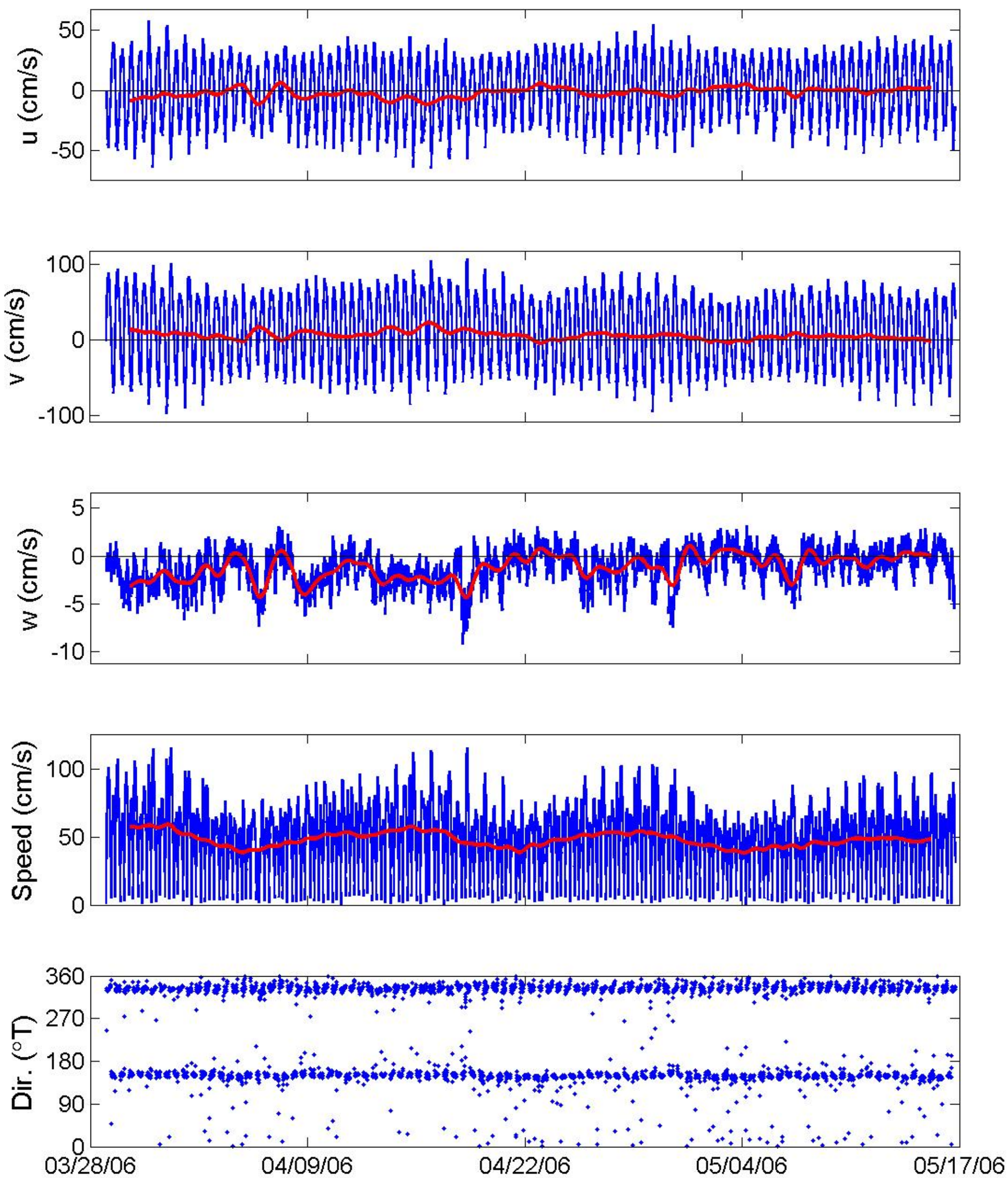


Figure 15. Time-series of *u* (positive eastward), *v* (positive northward), and *w* (positive up) velocity components, speed and direction for the top 1 m of the water column at the North Site. Low-pass filtered data (red lines) show the trends occurring at subtidal (> 33 hr) frequencies. °T, degrees from true north.

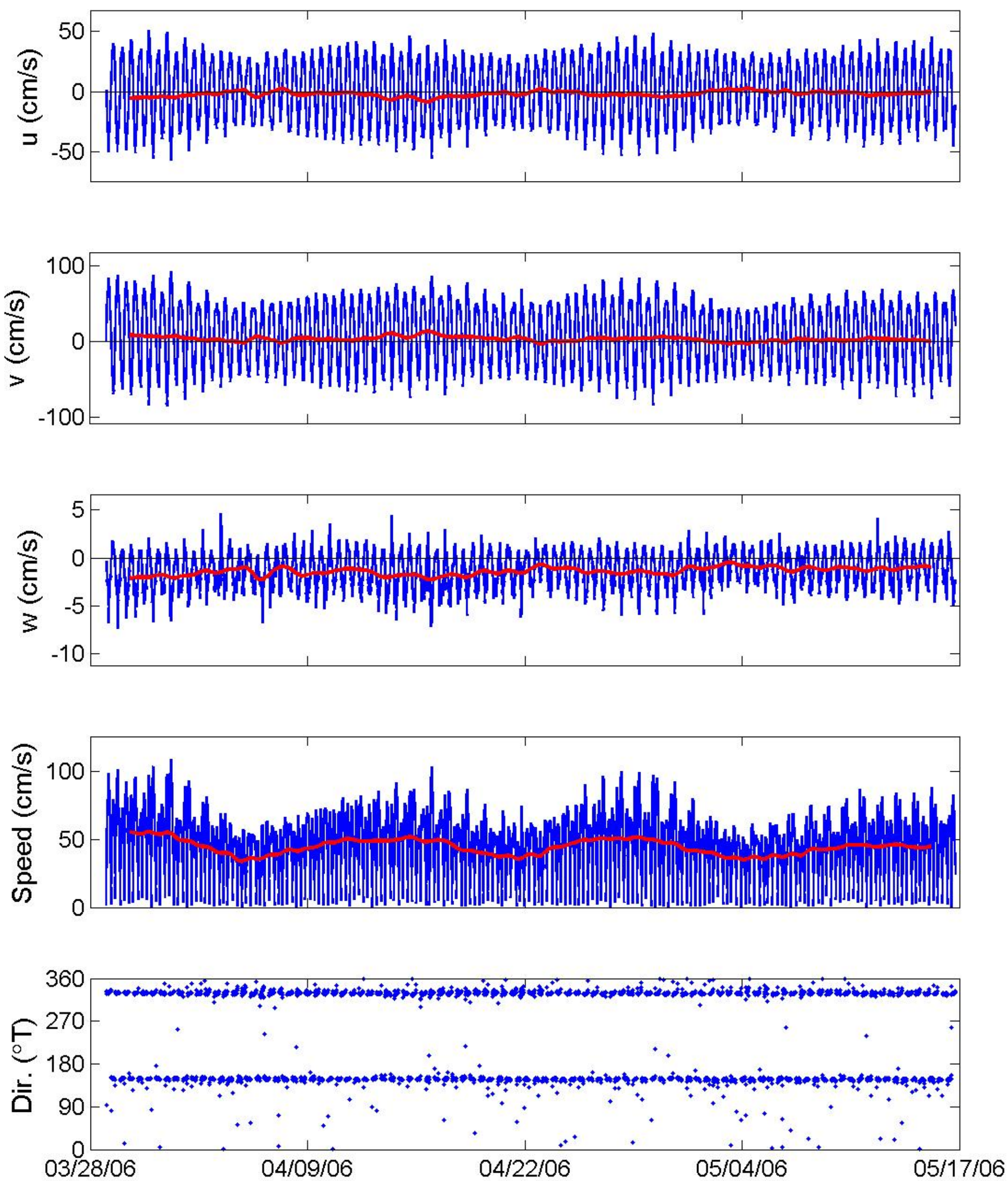


Figure 16. Time-series of *u* (positive eastward), *v* (positive northward), and *w* (positive up) velocity components, speed and direction averaged over the water column at he North Site. Low-pass filtered data (red lines) show the trends occurring at subtidal (> 33 hr) frequencies. °T, degrees from true north.

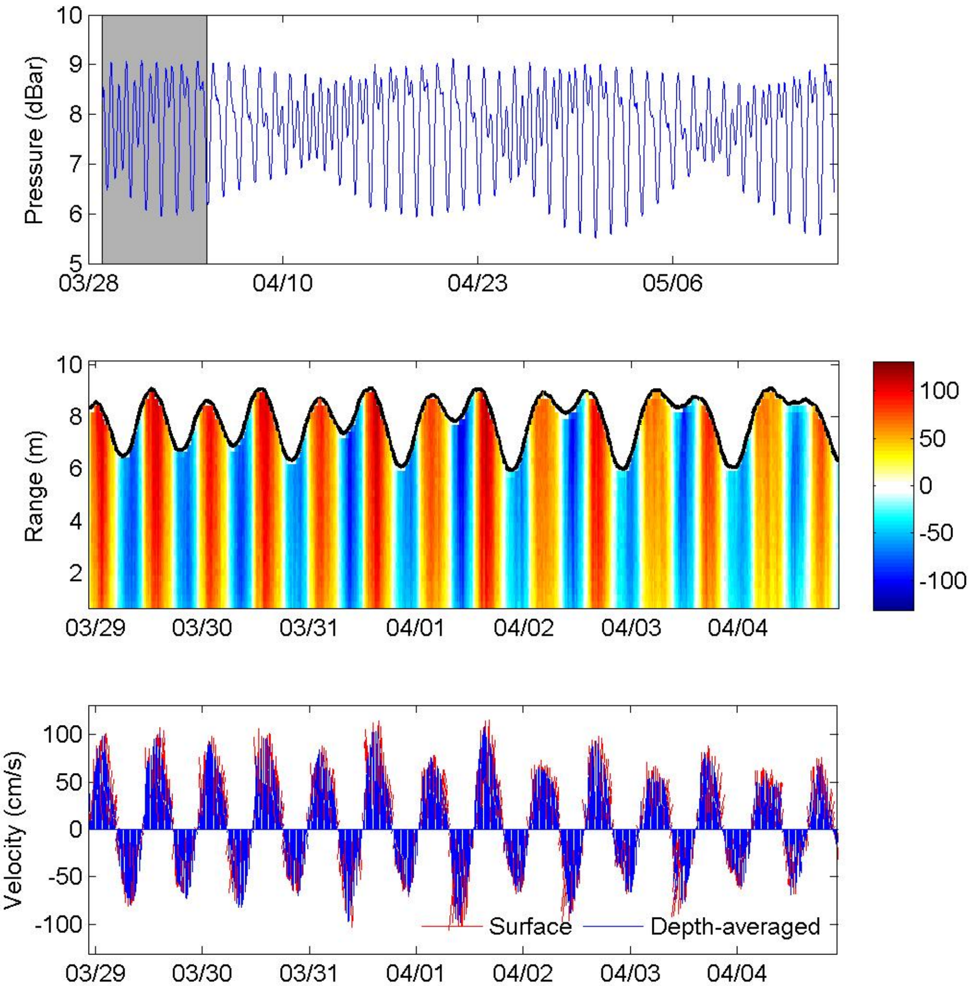


Figure 17*A*. Data from the North Site Acoustic Doppler Profiler during the week of 3/28 and 4/04 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

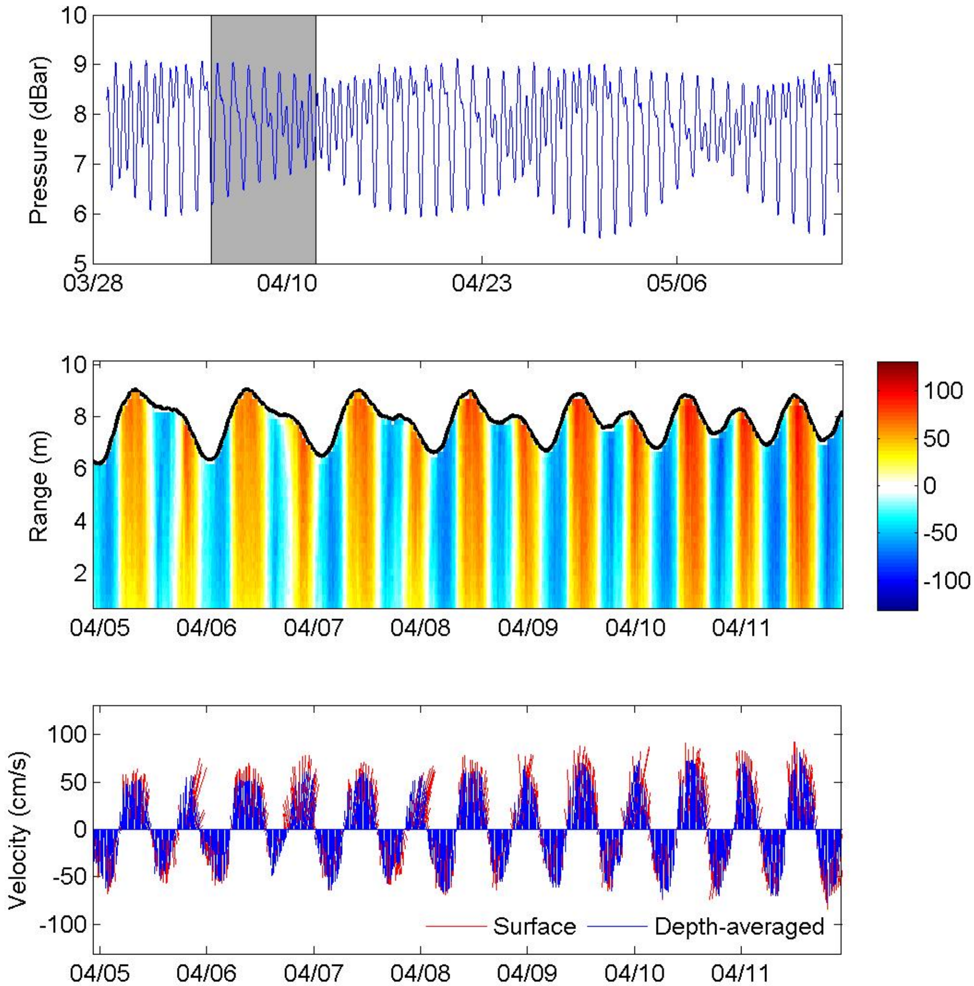


Figure 17*B*. Data from the North Site Acoustic Doppler Profiler during the week of 4/04 and 4/11 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

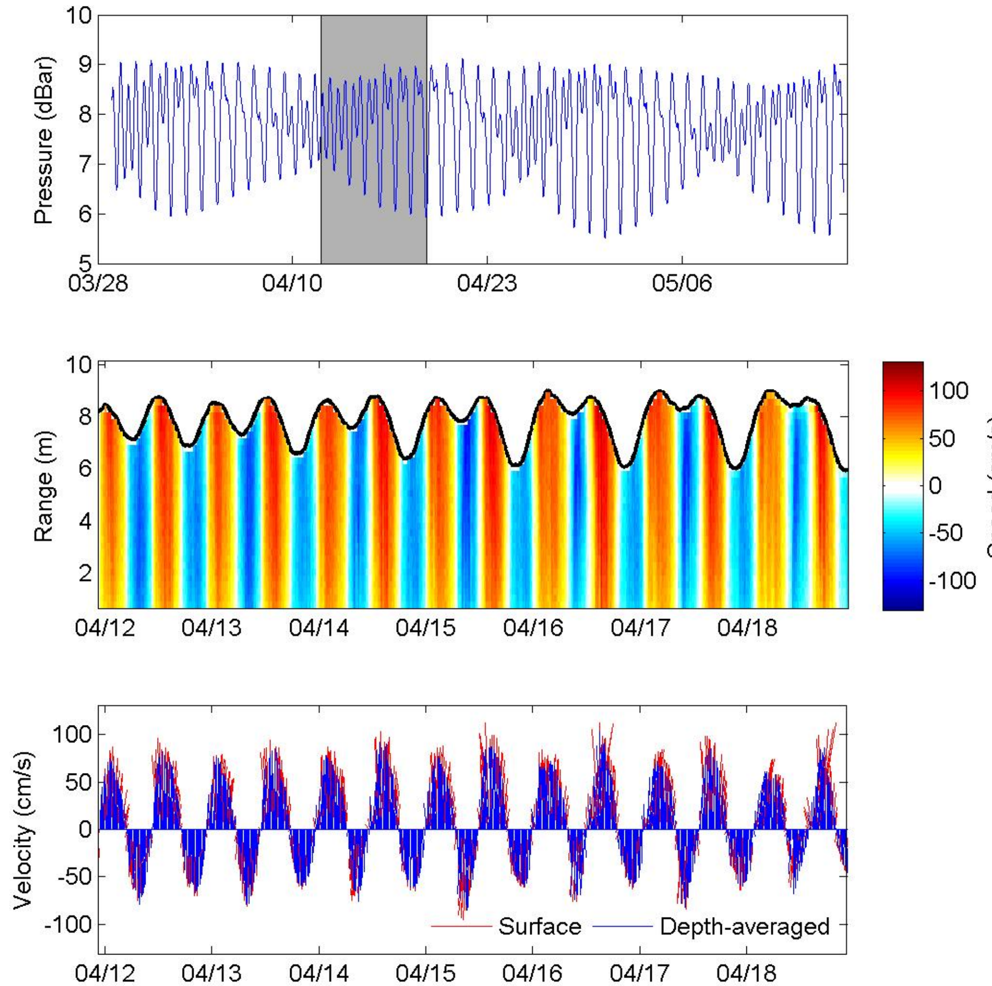


Figure 17*C*. Data from the North Site Acoustic Doppler Profiler during the week of 4/11 and 4/18 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

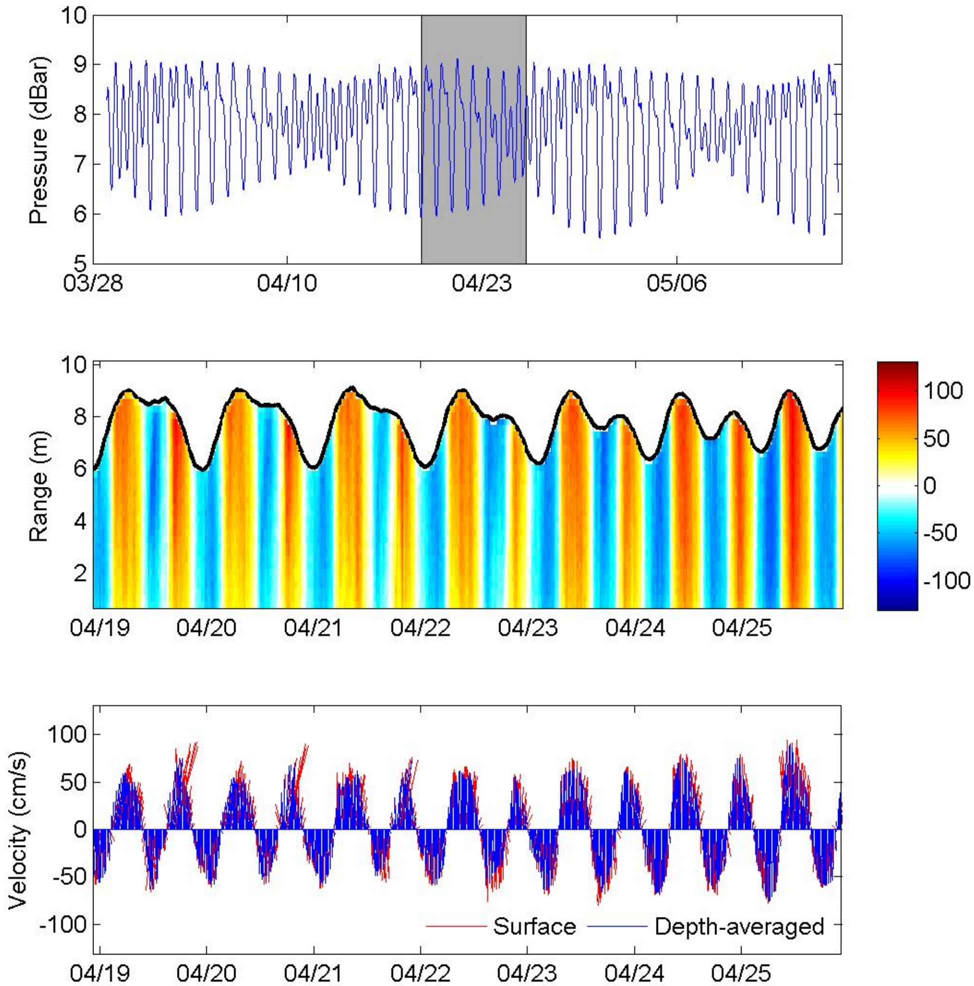


Figure 17*D*. Data from the North Site Acoustic Doppler Profiler during the week of 4/18 and 4/25 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

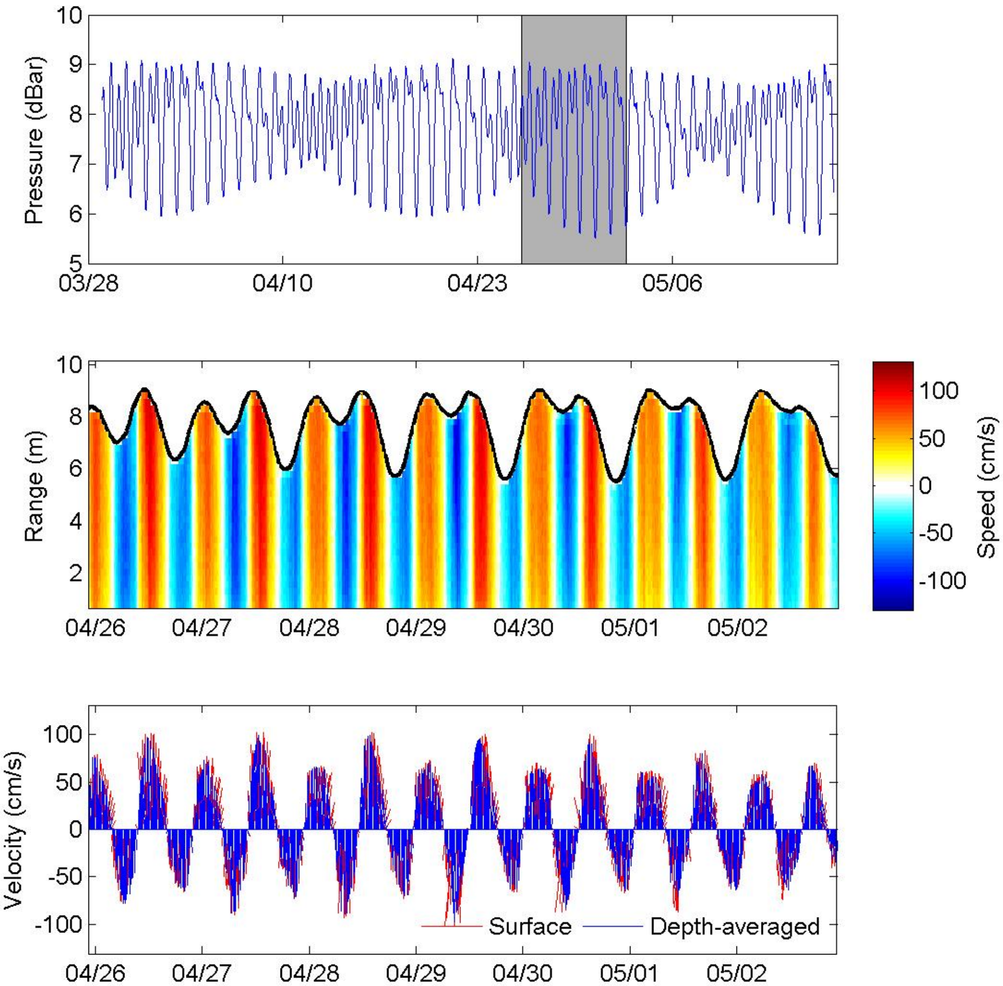


Figure 17*E*. Data from the North Site Acoustic Doppler Profiler during the week of 4/25 and 5/02 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

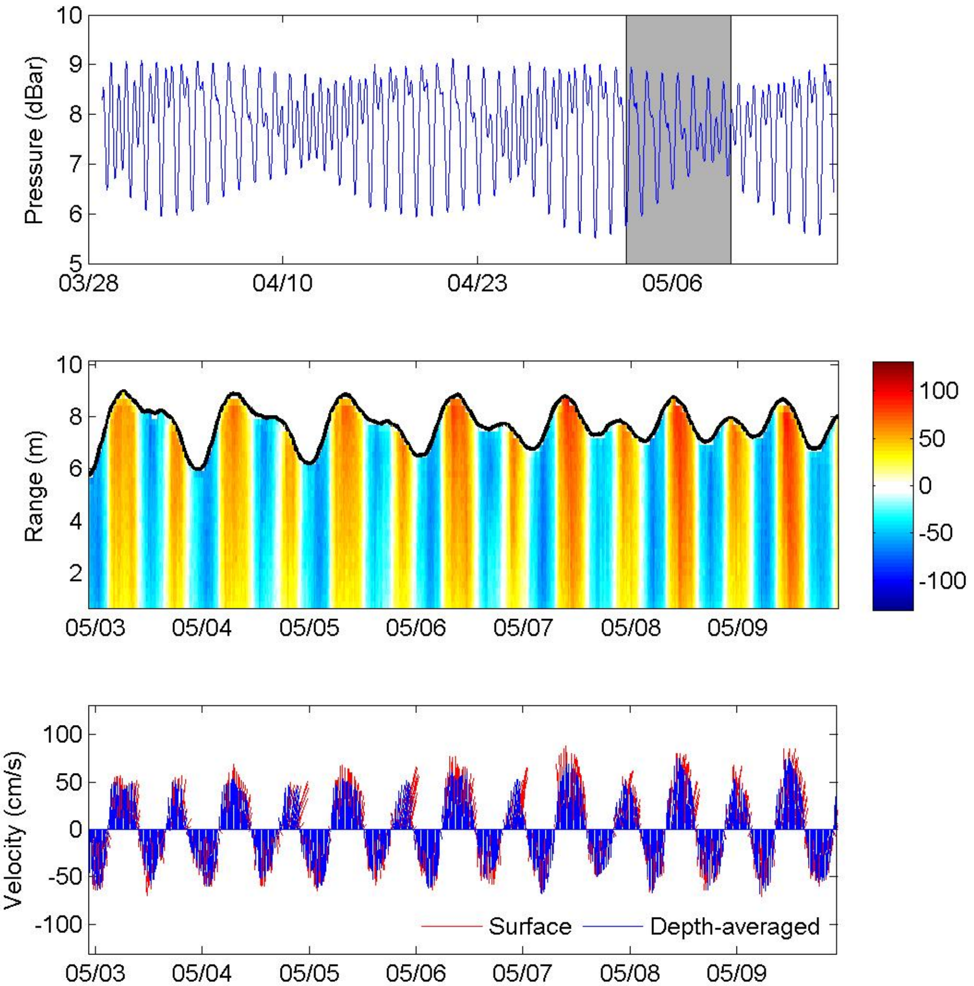


Figure 17*F*. Data from the North Site Acoustic Doppler Profiler during the week of 5/02 and 5/09 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

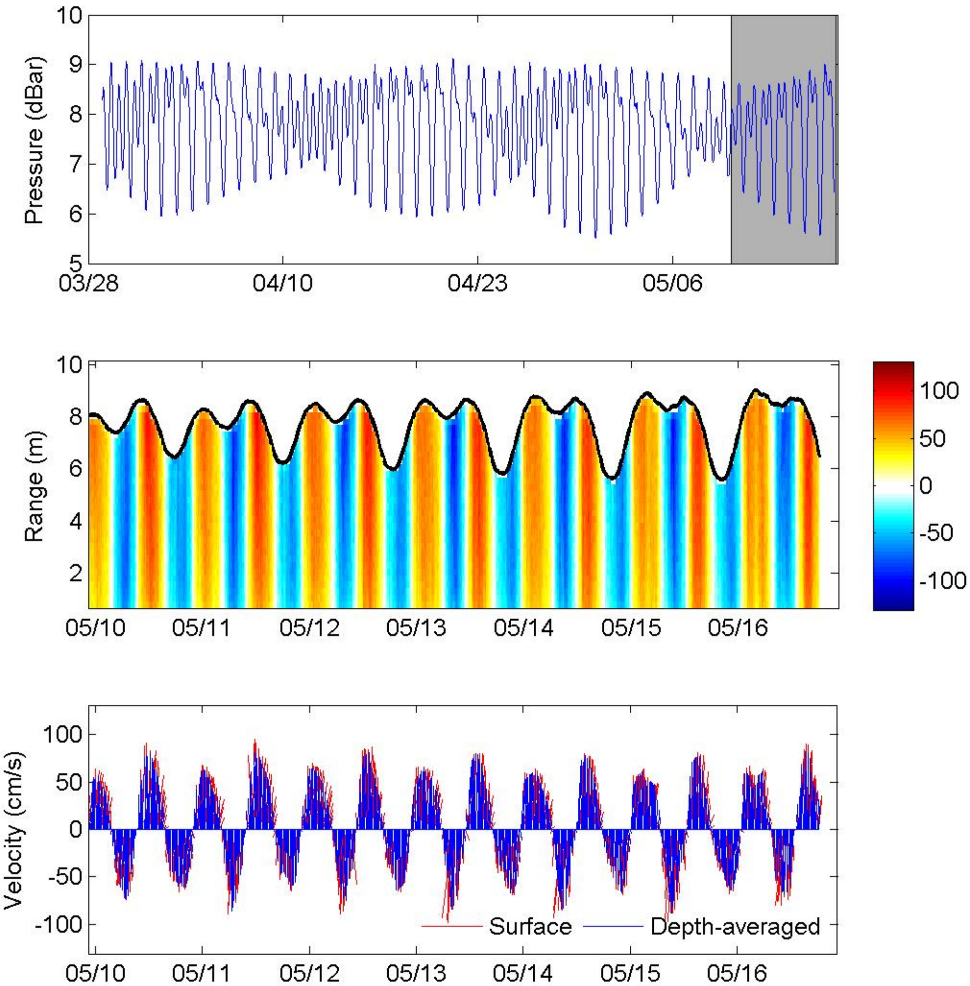


Figure 17*G*. Data from the North Site Acoustic Doppler Profiler during the week of 5/09 and 5/16 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

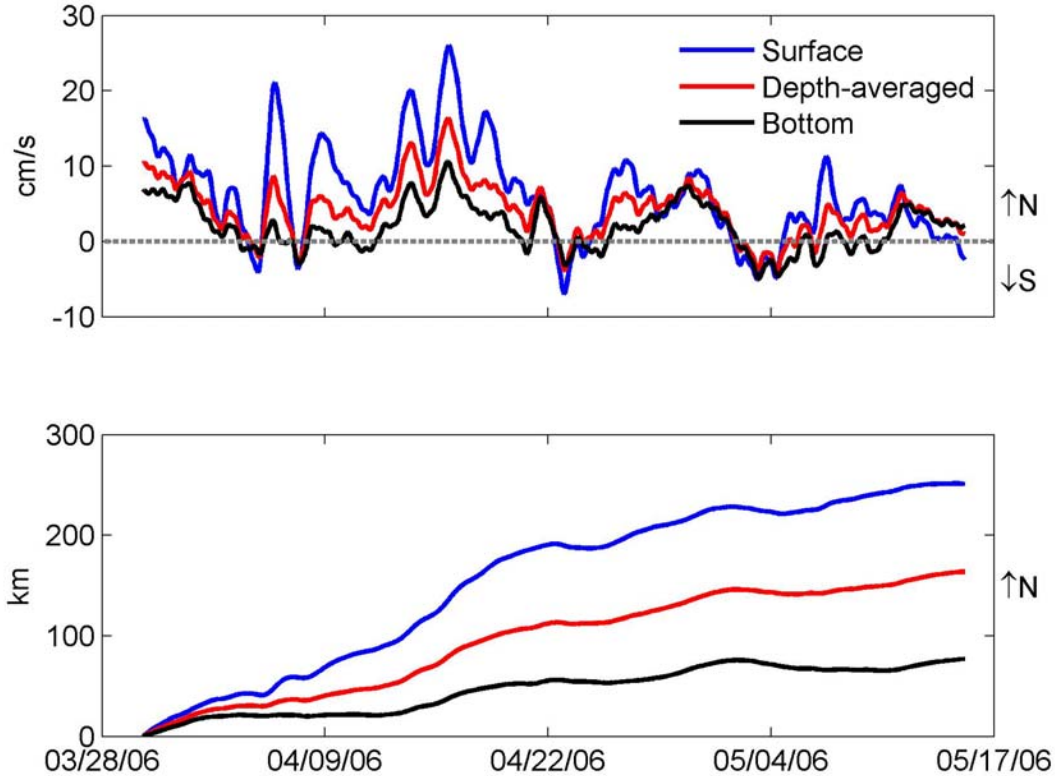


Figure 18. Time-series of low-pass filtered, along-channel velocity (top panel) for the surface (blue line), depth-averaged (red line) and bottom (black line) portion of the water column at the North Site. Positive values indicate northward transport (toward Padilla Bay) while negative values indicate net southward transport (toward Skagit Bay). The bottom panel shows the cumulative along-channel transport of water for the surface, depth-averaged and bottom. The surface values are representative of the top 1 m whereas the bottom represents the bottom 4 bins (1 m) measured by the Acoustic Doppler Profiler.

South Site

Maximum horizontal velocities at the South Site were 92.2 and 97.8 cm/s for the *u*- and *v*- components of velocity, respectively. Vertical velocities did not exceed 10 cm/s and were generally less than 5 cm/s. The maximum observed current speed at the surface was 133 cm/s (fig. 19) while the maximum depth-averaged current speed was 113 cm/s (fig. 20). The direction of the currents was primarily in the along-channel directions of 37° (toward Padilla Bay) and 215° (toward La Conner/ Skagit Bay).

Current speed and direction for each week of the deployment shows in detail the vertical structure of currents in the water column throughout the deployment (fig. 21*A*-*G*). Similarly to the north site, current speeds do not appear to closely match the range of a given tide, nor does the direction of the current switch exclusively at high and low tide. Also similar to the north site, the current at the South Site is asymmetric, flowing toward the northwest for a longer period than it does to the southeast.

The low-pass filtered, along-channel velocities at the South Site (fig. 22) show net transport to the northwest toward Padilla Bay, with only brief periods where net transport was directed to the southeast. Over the course of the 1.5-month deployment, net along-channel transport for the top 1-m was nearly 400 km. As would be expected in a confined channel, cross-channel net transport was negligible.

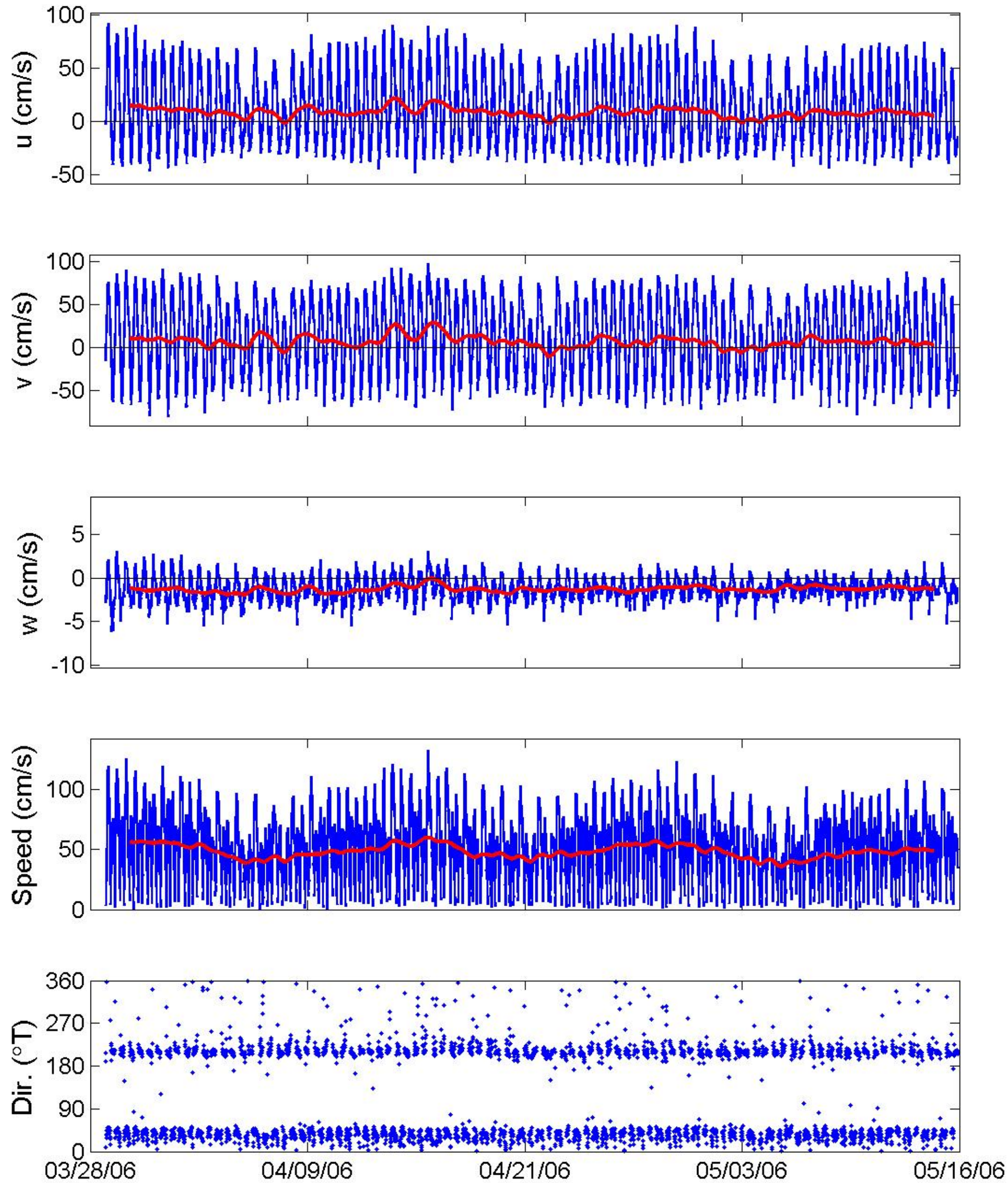


Figure 19. Time-series of *u* (positive eastward), *v* (positive northward), and *w* (positive up) velocity components, speed and direction for the top 1 m of the water column at the South Site. Low-pass filtered data (red lines) show the trends occurring at subtidal (> 33 hr) frequencies. °T, degrees from true north.

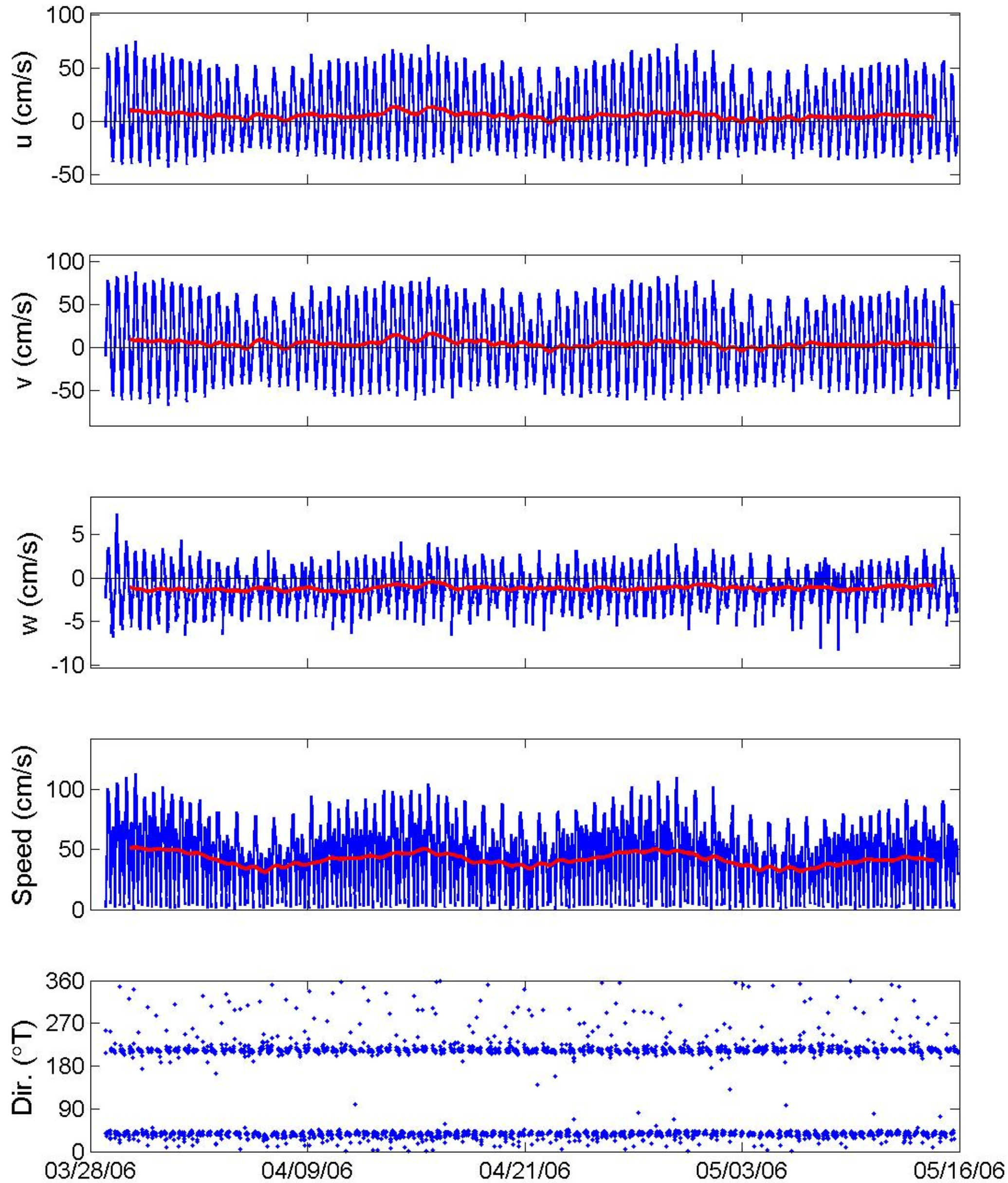


Figure 20. Time-series of *u* (positive eastward), *v* (positive northward), and *w* (positive up) velocity components, speed and direction averaged over the water column at the South Site. Low-pass filtered data (red lines) show the trends occurring at subtidal (> 33 hr) frequencies. °T, degrees from true north.

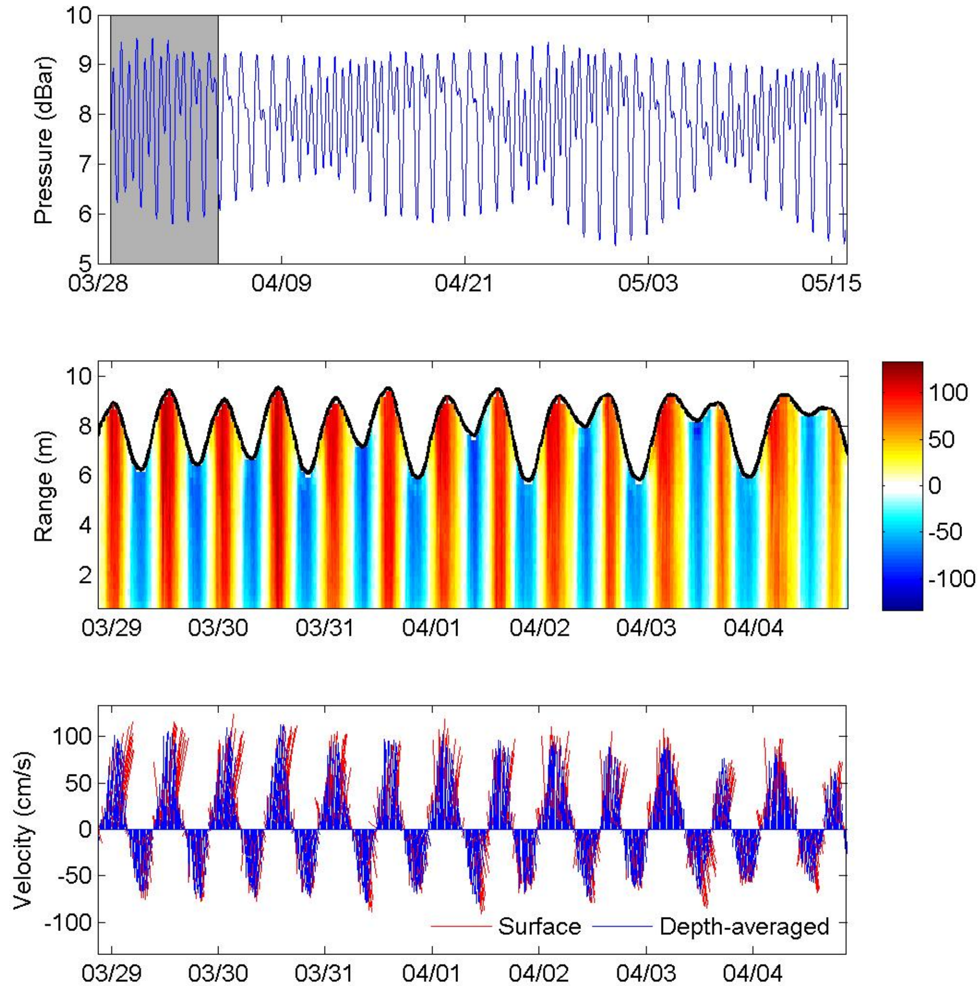


Figure 21*A*. Along-channel velocity from the Acoustic Doppler Profiler at the South Site during the week of 3/28 and 4/04. The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

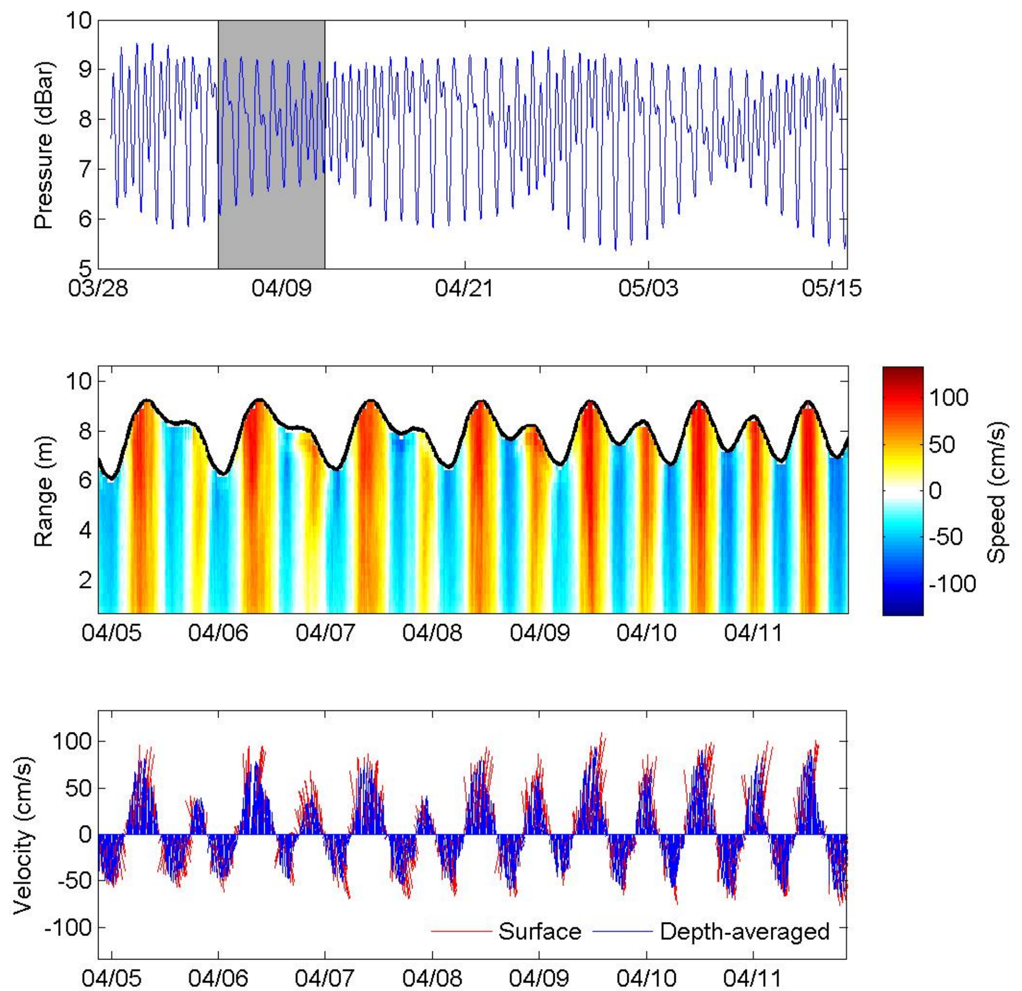


Figure 21*B*. Along-channel velocity from the Acoustic Doppler Profiler at the South Site during the week of 4/04 and 4/11 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

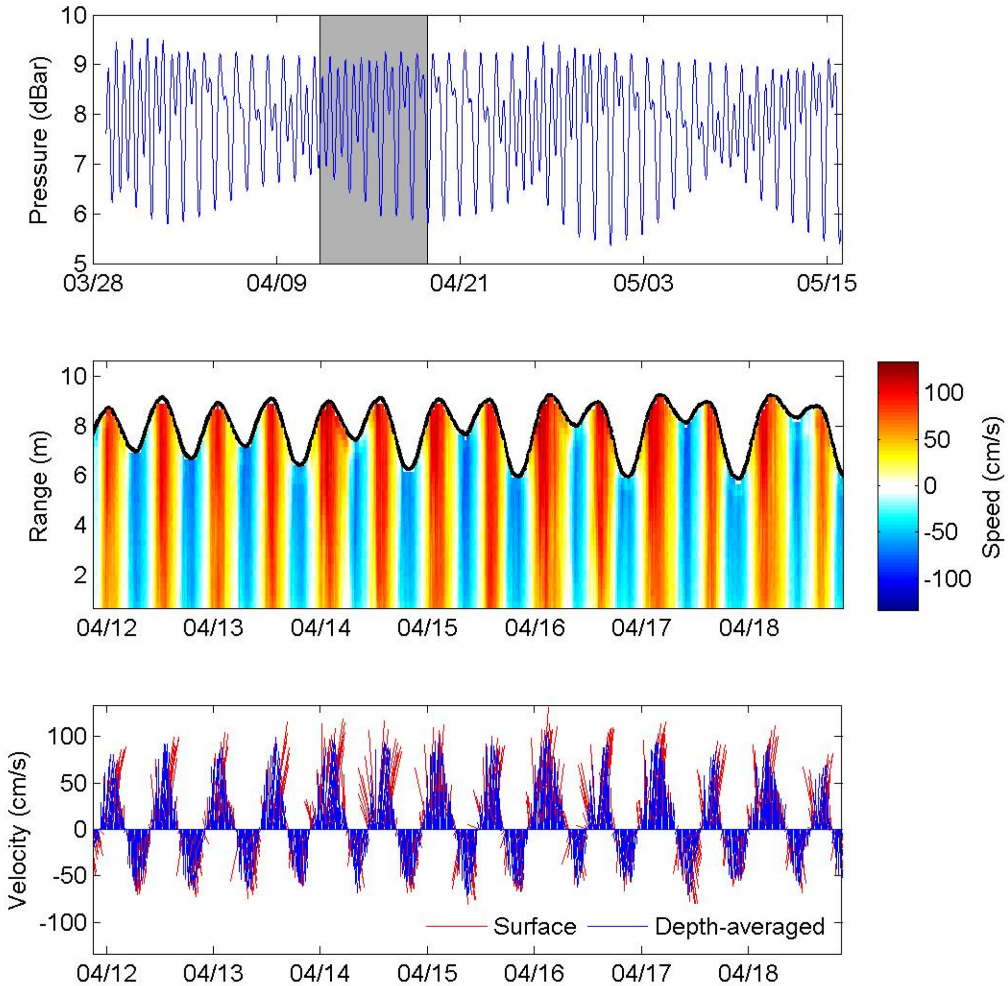


Figure 21*C*. Along-channel velocity from the Acoustic Doppler Profiler at the South Site during the week of 4/11 and 4/18 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

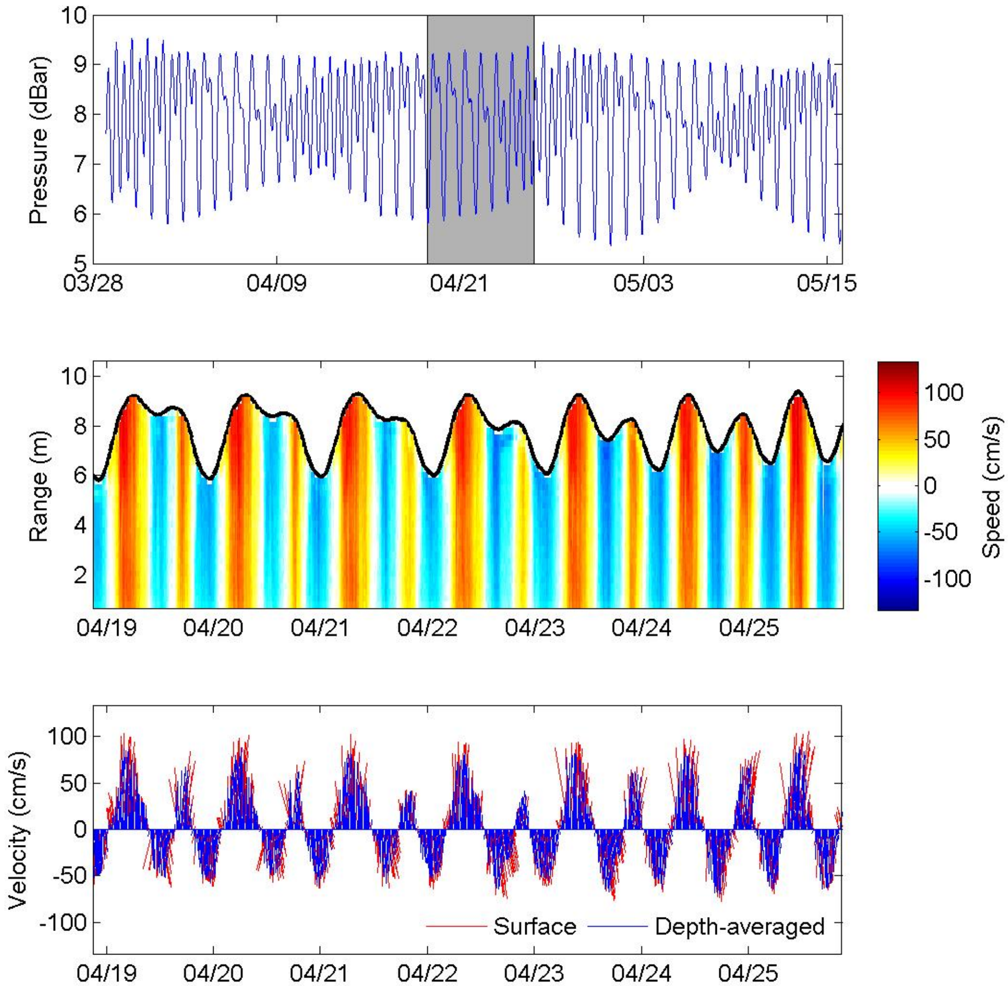


Figure 21*D*. Along-channel velocity from the Acoustic Doppler Profiler at the South Site during the week of 4/18 and 4/25 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

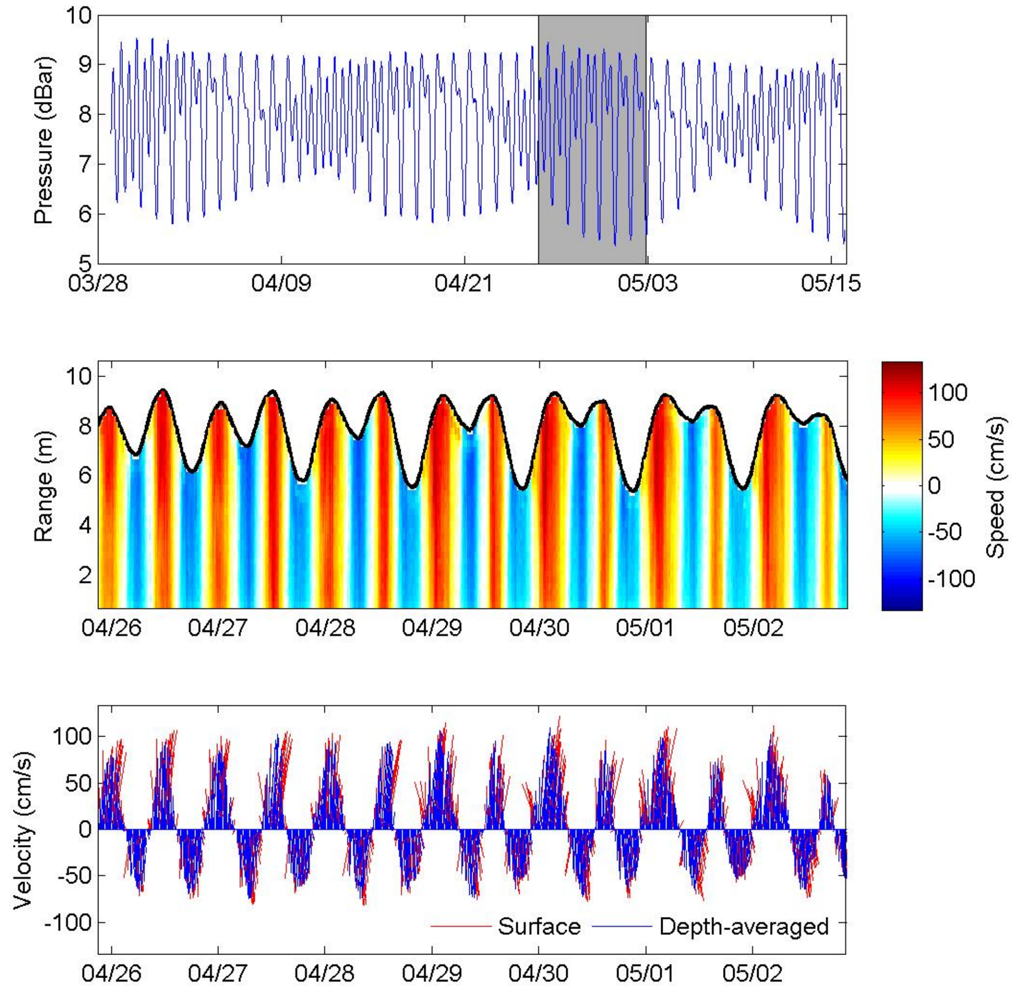


Figure 21*E*. Along-channel velocity from the Acoustic Doppler Profiler at the South Site during the week of 4/25 and 5/02 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

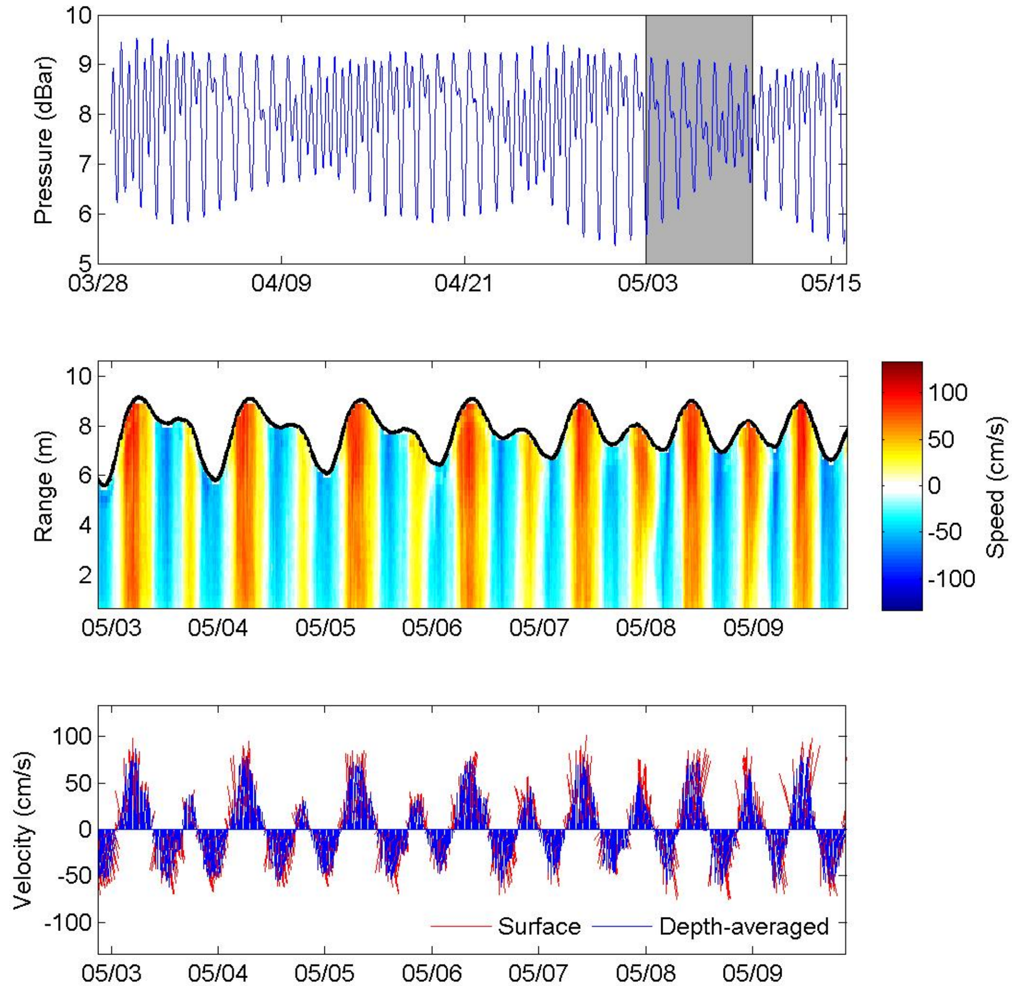


Figure 21*F*. Along-channel velocity from the Acoustic Doppler Profiler at the South Site during the week of 5/02 and 5/09 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

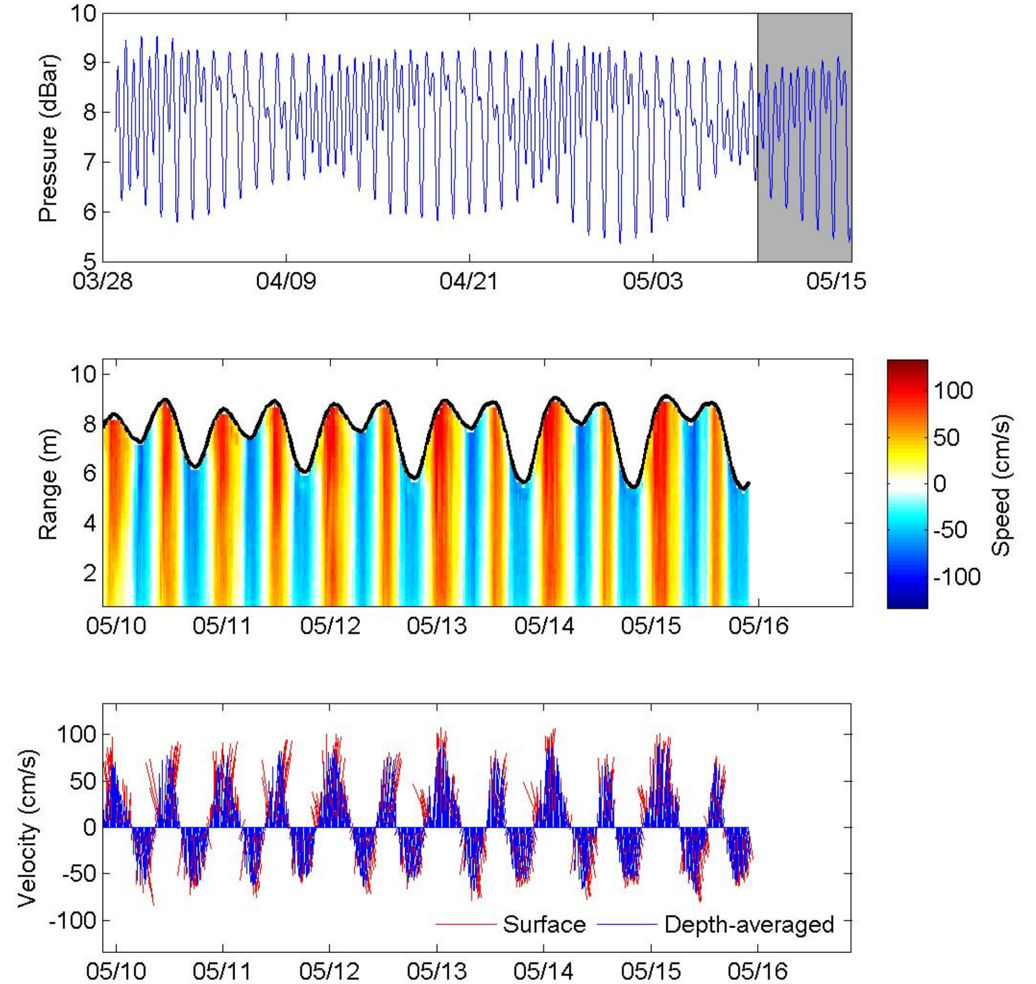


Figure 21*G*. Along-channel velocity from the Acoustic Doppler Profiler at the South Site during the week of 5/09 and 5/15 (gray box, top panel). The middle panel shows current speed in each 0.25-m bin throughout the water column. The bottom panel shows surface (red lines) and depth-averaged (blue lines) current vectors.

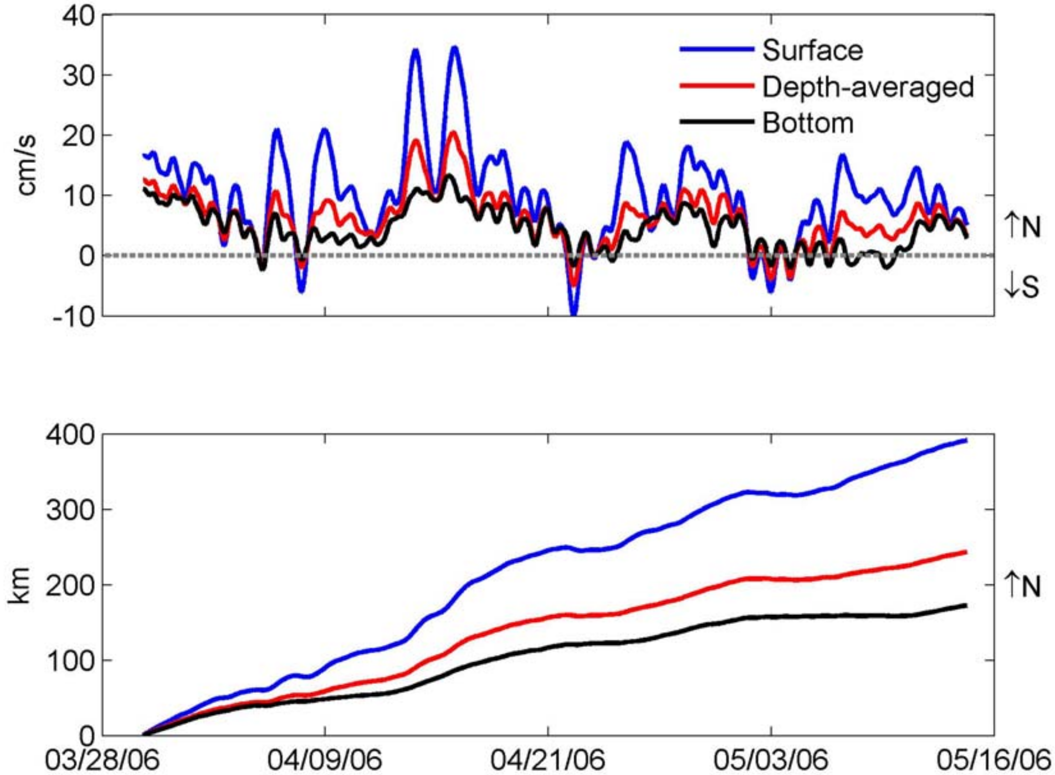


Figure 22. Time-series of low-pass filtered, along-channel velocity (top panel) for the surface (blue line), depth-averaged (red line) and bottom (black line) portion of the water column at the South Site. Positive values indicate northward transport (toward Padilla Bay) while negative values indicate net southward transport (toward Skagit Bay). The bottom panel shows the cumulative along-channel transport of water for the surface, depth-averaged and bottom. The surface values are representative of the top 1 m while the bottom represents the bottom 4 bins (1 m) measured by the Acoustic Doppler Profiler.

Cross-Channel Variability in Current Velocities—South Site

Peak current velocities measured across the channel with the roving ADCP agree well with currents measured at the south tripod site and show that current speed and directions are generally uniform across most of the channel. Figures 23*A-C* show that during flooding of a spring tide condition, surface current velocities range 1.3 to 1.5 m/s across most of the channel at the Hole in the Wall site, except for the west edge of the channel where shear occurs and eddys can form. These high current speeds also occur down 2-4 m across most of the channel and to the seafloor in the deepest section of the channel at the Hole in the Wall.

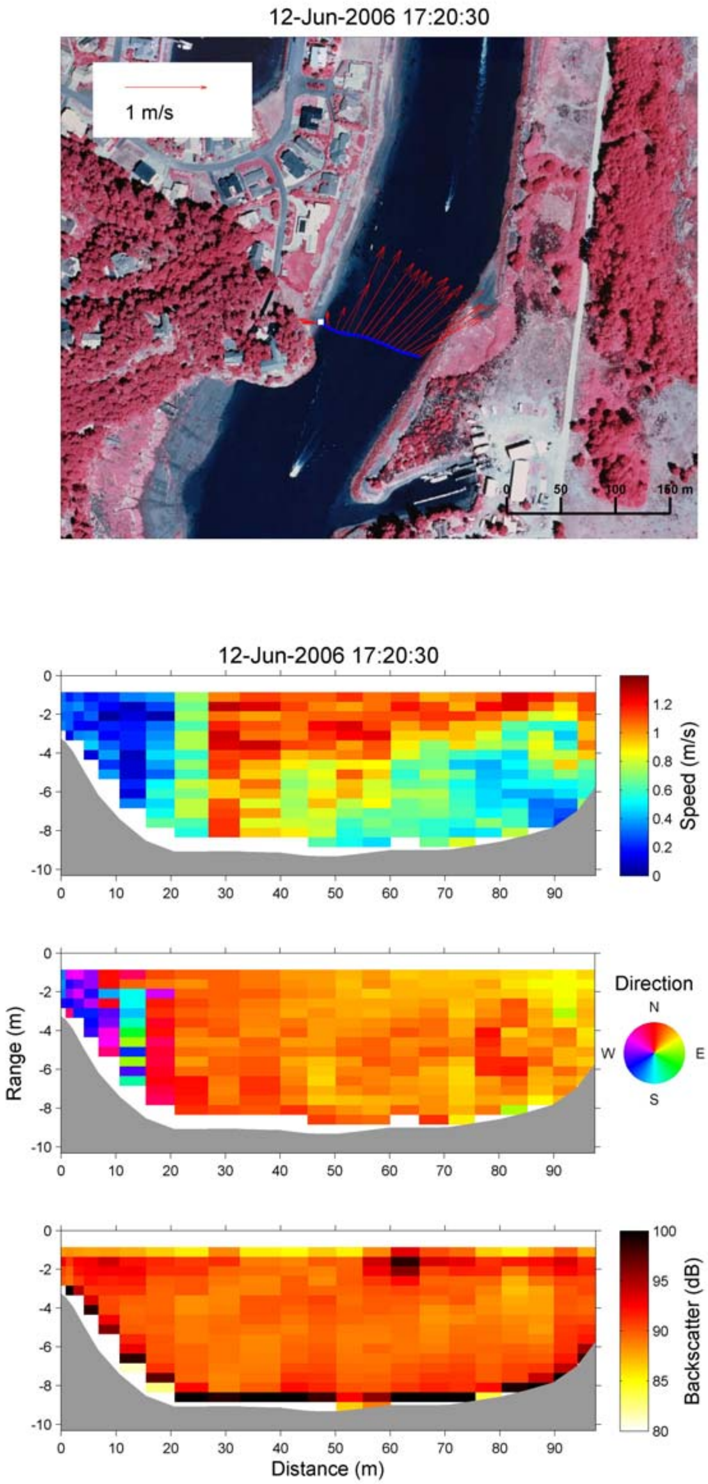


Figure 23*A*. (Top) Map of surface current velocity and direction across the South Site during flood of spring tide condition of June 12, 2006 (white box start of transect). (Bottom three plots) Cross-channel current velocity, direction, and backscatter with depth.

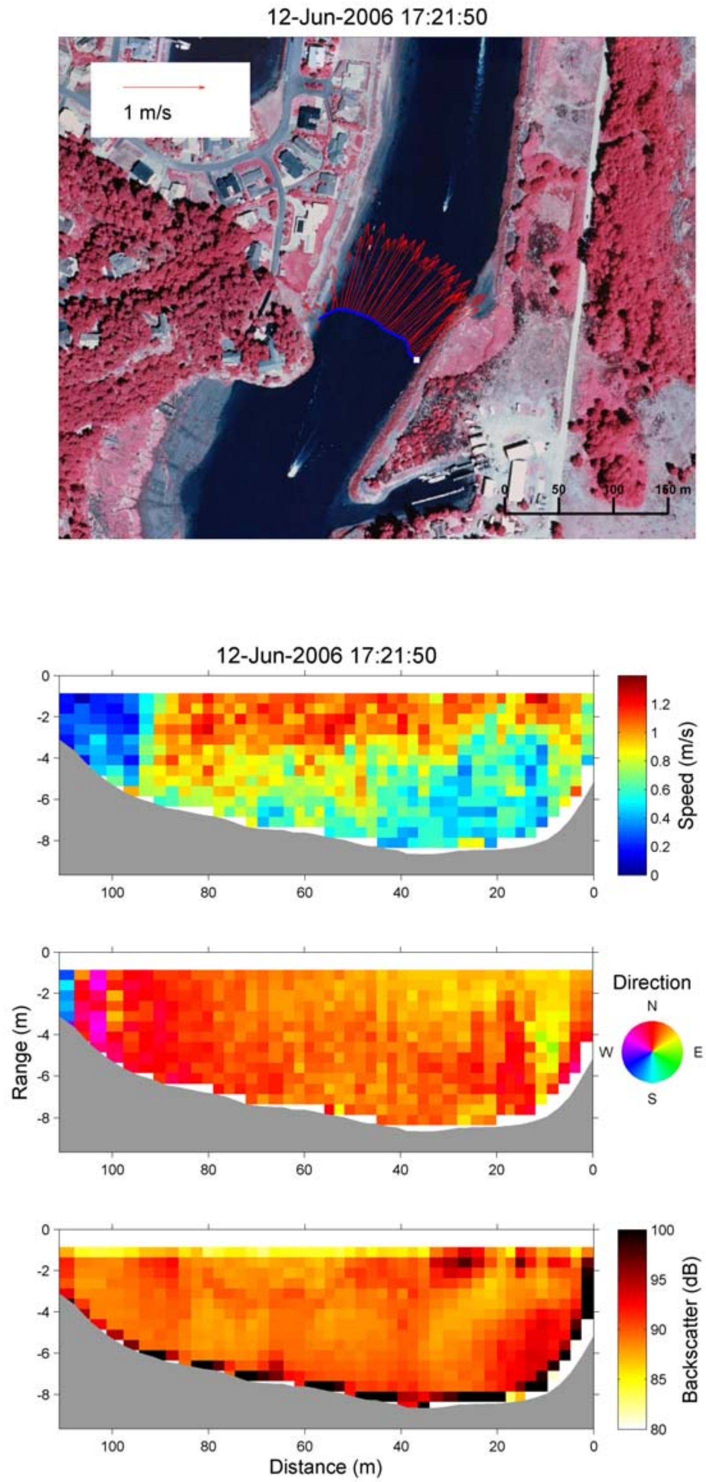


Figure 23*B*. (Top) Map of surface current velocity and direction across the South Site during flood of spring tide condition of June 12, 2006 (white box start of transect). (Bottom three plots) Cross-channel current velocity, direction, and backscatter with depth.

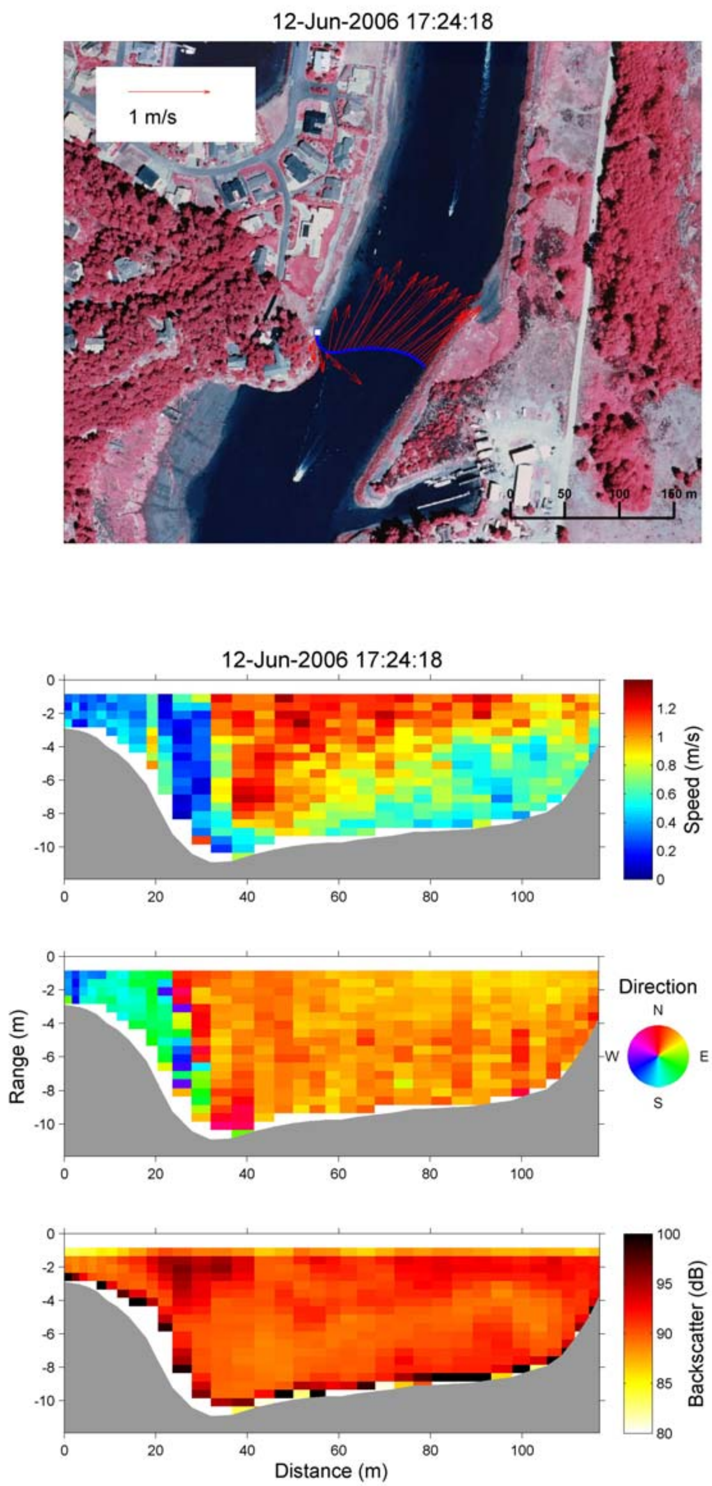


Figure 23*C*. (Top) Map of surface current velocity and direction across the South Site during flood of spring tide condition of June 12, 2006 (white box start of transect). (Bottom three plots) Cross-channel current velocity, direction and backscatter with depth.

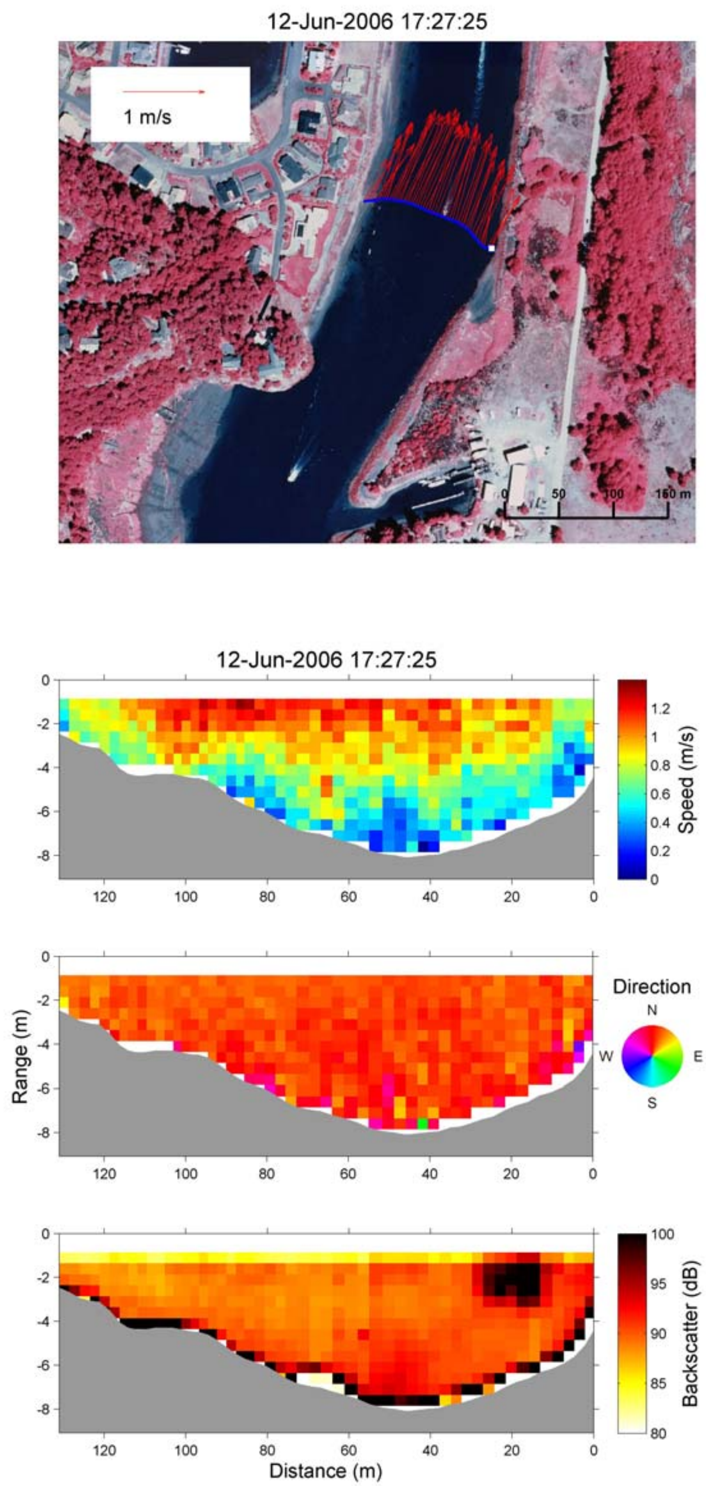


Figure 23*D*. (Top) Map of surface current velocity and direction 150 m north of the South Site during flood of spring tide condition of June 12, 2006 (white box start of transect). (Bottom three plots) Cross-channel current velocity, direction and backscatter with depth.

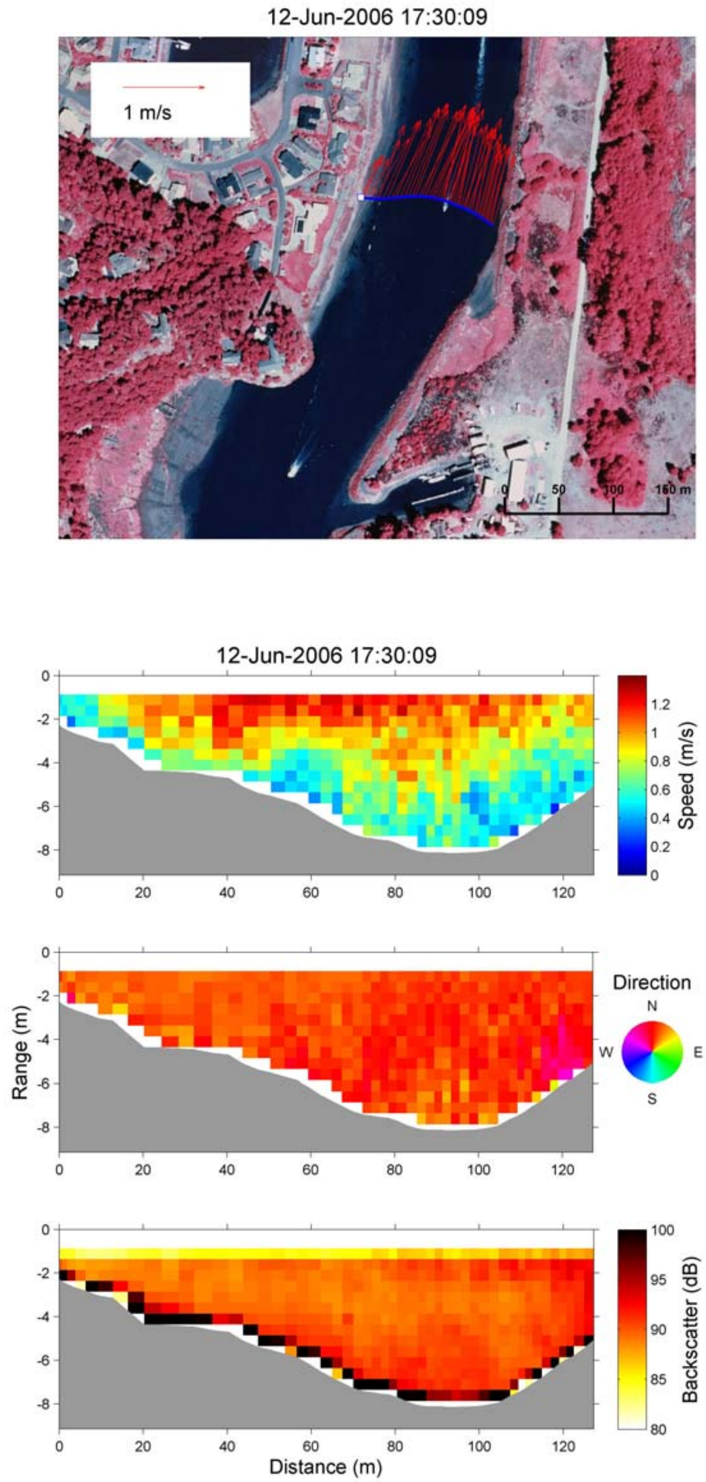


Figure 23*E*. (Top) Map of surface current velocity and direction 150 m north of the South Site during flood of spring tide condition of June 12, 2006 (white box start of transect). (Bottom three plots) Cross-channel current velocity, direction and backscatter with depth.

A second set of cross-channel profiles approximately 150 m north (figs. 23*D*-*E*) are characterized by slightly higher current velocities and more uniform directions. Backscatter intensity, reflecting suspended particle concentration in the water column, is high and relatively uniform across the channel under high current velocities. Figures 23*A*-*D* show isolated regions of higher backscatter between 1 and 3 m depth. It is unclear if these are transient features or persistent areas of high suspended particulate concentration.

Water Column Properties at the Mooring

The SBE-37 microcat attached to the surface mooring at roughly 35 cm below the surface recorded temperatures ranging from 7.3–13.9°C while temperatures on the bottom at the South Site varied between 7.4–13.2°C (fig. 24, top panel). Temperatures were typically slightly higher at the surface compared to the bottom (0.16°C on average) and were as much as 2°C higher at times. A general warming trend at both the surface and bottom was observed throughout the deployment.

Salinities measured at the surface mooring ranged from 9 to 26 practical salinity units (psu) with a mean of 20.9 psu (fig. 24, bottom panel). At the South Site, salinities measured at roughly 64.5 cm above the bed vary between 13 to 27 psu. The surface water salinity is typically lower than the near bottom salinities recorded at the South Site. Low frequency fluctuations in salinity at both sites are minor except during one time-period between April 12 and April 19 when salinity was fresher compared to the rest of the deployment.

In both the temperature and salinity records, high-frequency fluctuations were important in addition to longer term trends. The power spectral density of the temperature and salinity time-series were calculated using Welch's averaged modified periodogram method of spectral estimation. These spectra (fig. 25) indicate that the higher frequency fluctuations in both the temperature and salinity time-series are occurring at frequencies close to the major diurnal (K1, 23.9 hr) and semi-diurnal (M2, 12.4 hr) constituents. However, the temperature time-series is dominated by a diurnal signal, suggesting diurnal heating and cooling plays an important role. The salinity time-series shows a stronger influence of semi-diurnal (M2) and other shorter frequency fluctuations (M3, M4, 2MK5 and M6). During these tide variations, flood tides advect lower salinity water to the mooring site generally in the 15 to 20 psu range; occasionally spikes as low as 8-10 psu occur (fig. 24).

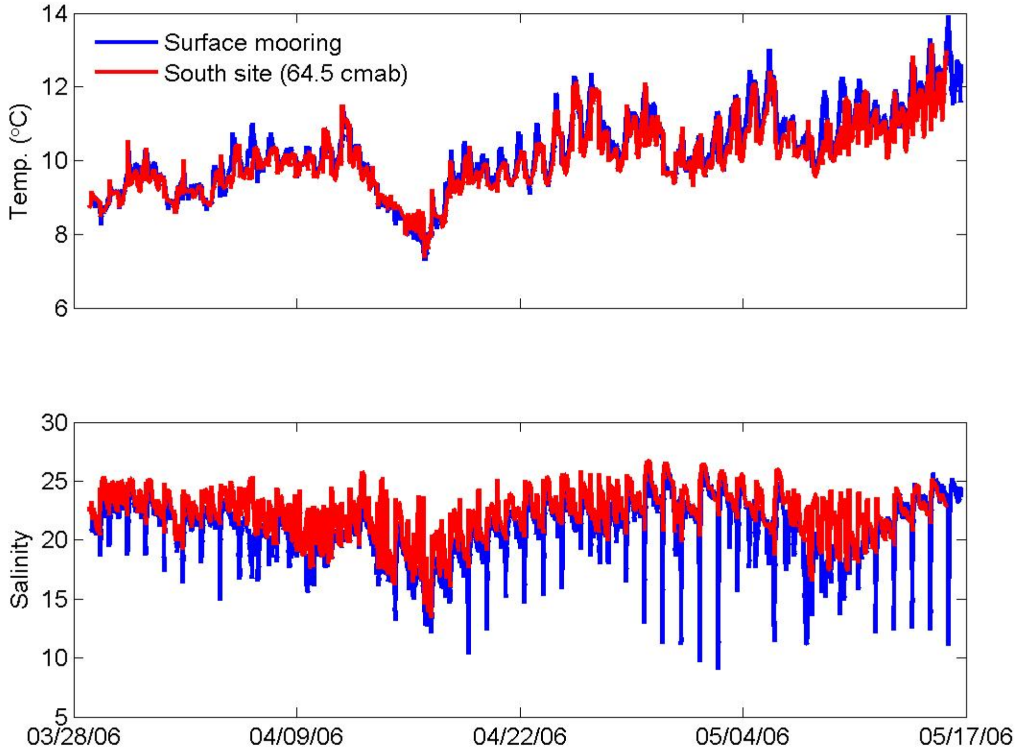


Figure 24. Time-series of temperature and salinity at the surface mooring (blue lines) and at the South Site (red lines).

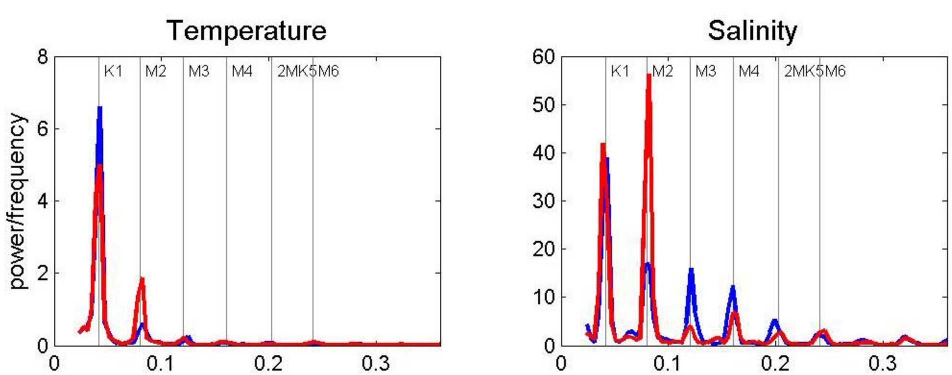


Figure 25. Power spectral density of temperature (left panel) and salinity (right panel) at the surface mooring (blue lines) and tripod (red lines).

A histogram shows that 66 percent of the time salinity ranged from 20 to 25 psu, whereas salinities lower than 15 were observed less than 3 percent of the data record. Thirty percent of the time surface salinity at the mooring site ranged from 15 to 20 psu.

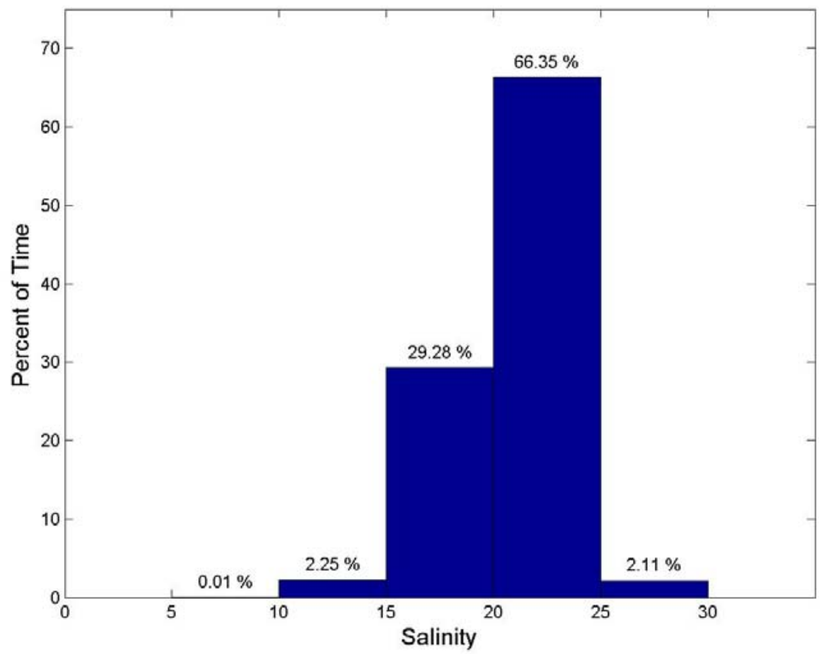


Figure 26. Normalized histogram of salinity at the mooring site.

Spatial Patterns in Water Properties

Repeat measurements water column profile of temperature and salinity throughout the area reveal that north of the Rainbow Bridge in La Conner, salinities between March and July were generally higher than 23 psu and water was relatively well mixed throughout the Swinomish Channel (fig. 27*A,B*; see figs. 1 and 2 for locations). Between Shelter Bay and the Rainbow Bridge, salinities were slightly lower 20-22 psu (figs. 27*C,D*), with an occasional thin (<1-3 m) fresher surface lens occurring only during peak flooding tides (K206PS_037, ~110 cm/sec) or high river flow (K306PS_009, 20,973 cfs; K306PS_012, 21,107 cfs; k406ps_003, 13,253 cfs) (see table 6 for environmental conditions at time of CTD profiling). Exceptions to this pattern exist with mixing of moderately saline (23 psu) water through the water column despite a modest flooding tide and river discharge (K206PS_024, 73 cm/sec flood tide currents, 11,250 cfs).

The only appreciable low salinity surface lenses occur between the Fish Passage near station 3B and the south tripod station (figs. 27*E,F*). At the south tripod station, salinities in the upper 3 m reached as low as 18 psu and showed a slightly fresher surface lens in 50 percent of the casts made. These conditions were generally associated with high river discharge (K306PS_011, 21,107 cfs) but also occur during only modest river discharge and during ebbing tides (fig. 27*E*) suggesting that lower salinity lenses (18-20 psu) may temporarily extend north of the south tripod site and are advected back to the south during reversal of flow. Only station 3B showed any appreciable low salinity surface water lens (fig. 27f). Salinity at station 3B typically ranged 12-25 psu and reached as low as 6 psu on one occasion during an ebb tide also suggesting that low salinity surface water is periodically advected southward during flow reversals away from the net northward regime. The low-salinity surface water lens was generally found to be only 1-2 m thick in this part of the Swinomish Channel.

Table 6. Environmental conditions during salinity measurements in Swinomish Channel.

Filename	Local Time	Tide (m)	Tide State*	River Flow (cfs)	Current (cm/s)	Direction (degrees)
TRP-N						
k206ps_004	3/28/2006 14:30	2.89	floodLH	11406	1.43	92.6
k206ps_030	3/29/2006 15:13	2.69	floodLH	10222	17.52	331.73
k306ps_005	5/15/2006 11:34	-0.24	ebbLL	16308	11.83	144.29
Dock						
k206ps_001	3/28/2006 8:30	1.29	ebbHL	14962	N/A	N/A
k206ps_006	3/29/2006 8:32	1.39	ebbLL	11629	3.13	346.65
k206ps_027	3/29/2006 11:47	0.58	floodLH	11162	69.89	212.99
k206ps_028	3/29/2006 14:11	1.95	floodLH	10460	11.62	39.91
k206ps_046	3/29/2006 17:51	3.24	ebbHL	9900	88.37	40.73
k206ps_047	3/30/2006 8:03	2.15	ebbLL	10286	27.76	37.34
k206ps_065	3/30/2006 10:33	0.16	ebbLL	10179	66.89	213.57
k306ps_003	5/15/2006 10:01	0.83	ebbLL	16086	27.9	216.24

k306ps_008	5/16/2006 9:30	1.72	ebbLL	20627	N/A	N/A
k306ps_014	5/16/2006 11:41	0.19	ebbLL	21241	N/A	N/A
k406ps_001	7/26/2006 5:51	2.6	ebbLL	13346	N/A	N/A
k406ps_018	7/26/2006 11:17	-0.42	turningLL	11295	N/A	N/A
Bridge						
k206ps_005	3/28/2006 16:15	3.23	ebbHL	10897	97.85	40.93
k206ps_036	3/29/2006 16:30	3.35	floodLH	10028	90.48	38.73
k206ps_045	3/29/2006 17:35	3.36	ebbHL	9900	94.57	40.65
k206ps_064	3/30/2006 10:20	0.16	ebbLL	10200	66.89	213.57
k306ps_004	5/15/2006 10:49	0.08	ebbLL	16160	48.31	211.65
k306ps_009	5/16/2006 10:41	0.95	ebbLL	20973	N/A	N/A
k406ps_002	7/26/2006 6:11	2.6	ebbLL	13253	N/A	N/A
k406ps_017	7/26/2006 10:58	-0.38	ebbLL	11406	N/A	N/A
Shelter Bay						
k206ps_024	3/29/2006 11:15	0.4	floodLH	11250	73.15	213.37
k206ps_037	3/29/2006 16:39	3.35	floodLH	9985	109.95	40.31
k306ps_012	5/16/2006 11:17	0.19	ebbLL	21107	N/A	N/A
k406ps_003	7/26/2006 6:21	2.36	ebbLL	13253	N/A	N/A
k406ps_016	7/26/2006 10:51	-0.38	ebbLL	11495	N/A	N/A
TRP-S						
k206ps_008	3/29/2006 9:01	1	ebbLL	11607	18.71	214.86
k206ps_022	3/29/2006 11:00	0.31	turningLL	11295	69.85	211.51
k206ps_039	3/29/2006 16:54	3.4	turningLH	9964	106.59	42.6
k206ps_048	3/30/2006 8:37	1.69	ebbLL	10222	6.04	22.12
k206ps_063	3/30/2006 10:08	0.44	ebbLL	10200	53.3	211.4
k306ps_001	5/14/2006 15:02	0.62	floodHH	11945	1.33	73.07
k306ps_011	5/16/2006 11:10	0.56	ebbLL	21107	N/A	N/A
k406ps_004	7/26/2006 6:28	2.36	ebbLL	13230	N/A	N/A
k406ps_015	7/26/2006 10:45	-0.38	ebbLL	11495	N/A	N/A
3B						
k206ps_011	3/29/2006 9:24	0.68	ebbLL	11540	50.89	215.71
k206ps_020	3/29/2006 10:45	0.31	turningLL	11361	68.42	212.45
k206ps_040	3/29/2006 17:00	3.4	turningLH	9964	106.59	42.6
k206ps_049	3/30/2006 8:45	1.24	ebbLL	10222	6.04	22.12
k206ps_058	3/30/2006 9:40	0.81	ebbLL	10200	42.95	214.02
k206ps_059	3/30/2006 9:44	0.81	ebbLL	10200	42.95	214.02
k306ps_010	5/16/2006 11:03	0.56	ebbLL	21000	N/A	N/A
k406ps_006	7/26/2006 6:39	2.36	ebbLL	13183	N/A	N/A
k406ps_013	7/26/2006 10:36	-0.25	ebbLL	11607	N/A	N/A

*Tide State: FloodLH= flooding from lowest semi-diurnal low tide to highest semi-diurnal high tide of the day.
ebbLL=ebbing from lowest semi-diurnal high tide to lowest semi-diurnal low tide of the day.
turningLL=turning from lowest semi-diurnal low tide of the day.
floodHH=flooding from highest semi-diurnal low tide to highest semi-diurnal high tide of the day.
turningLH=turning from lowest semi-diurnal high tide of the day.

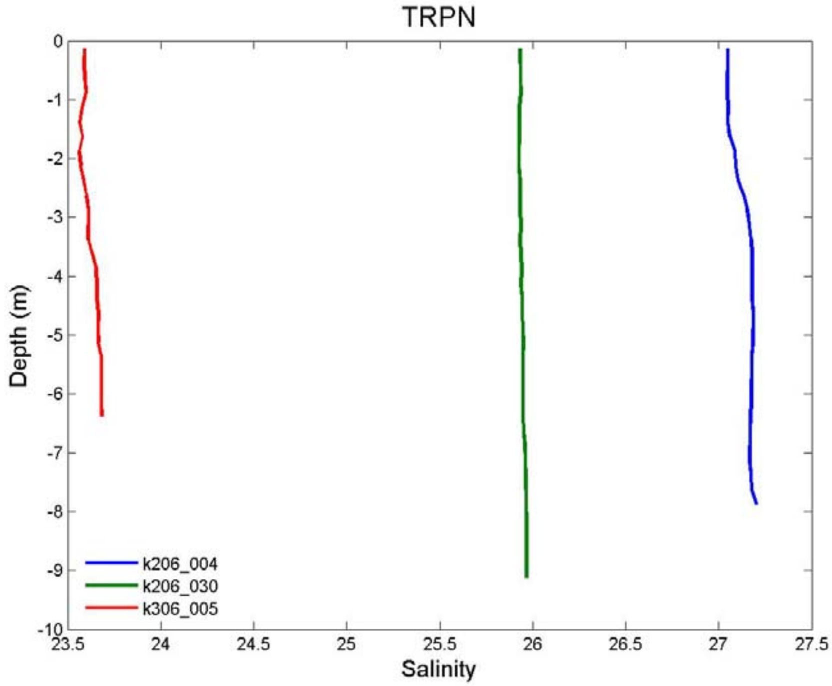


Figure 27*A*. Variability in salinity at station TRPN.

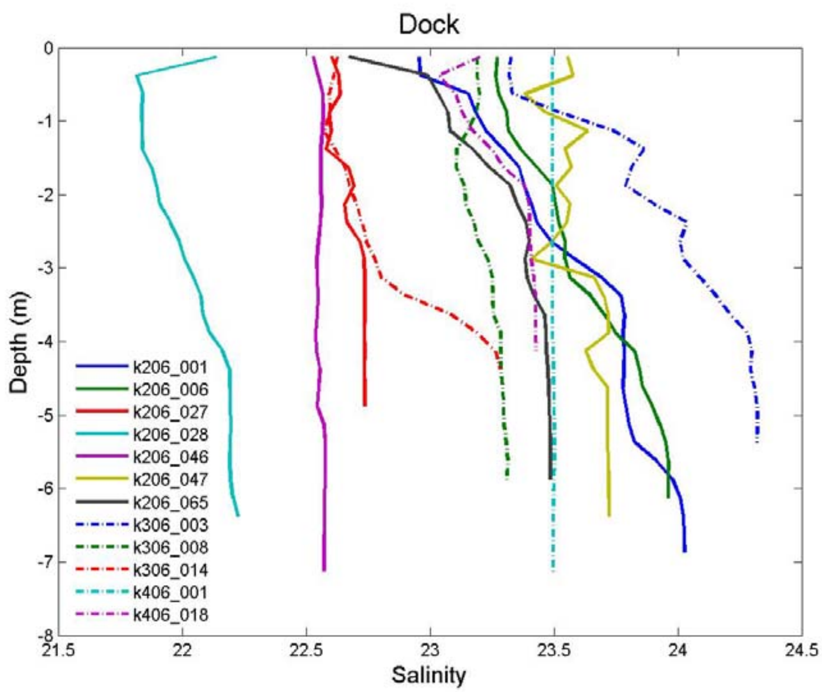


Figure 27*B*. Variability in salinity at station Dock.

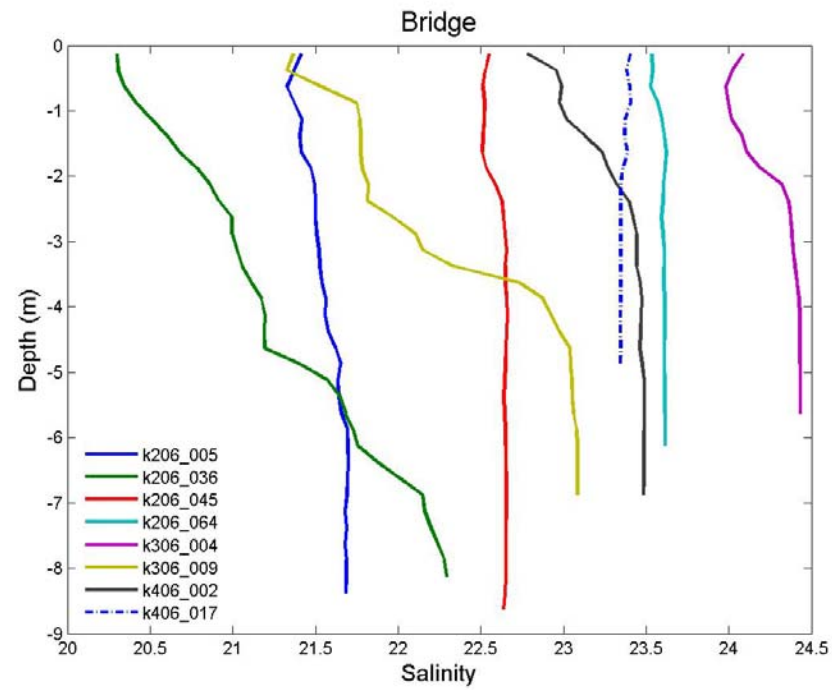


Figure 27*C*. Variability in salinity at station Bridge.

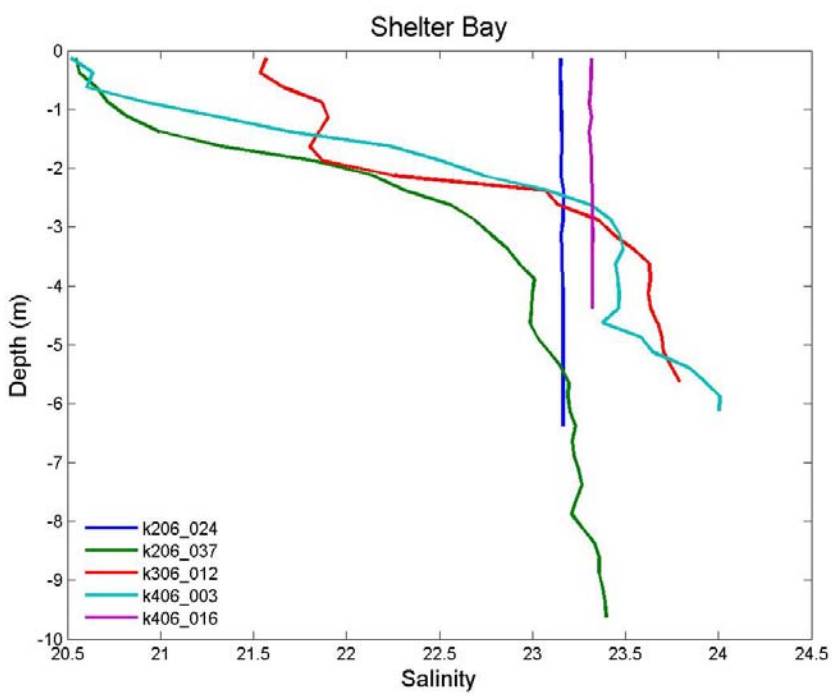


Figure 27*D*. Variability in salinity at station Shelter Bay.

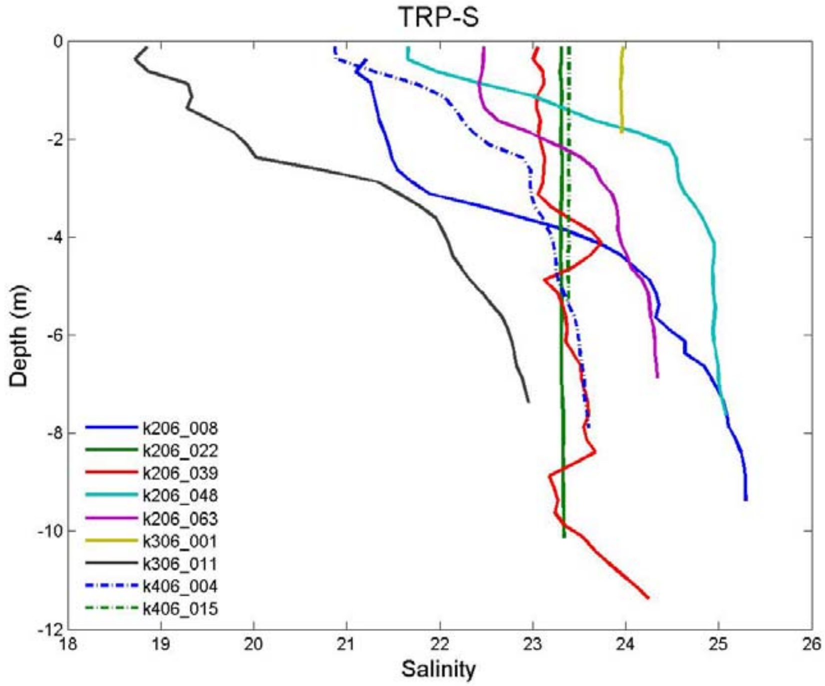


Figure 27*E*. Variability in salinity at station TRP-S.

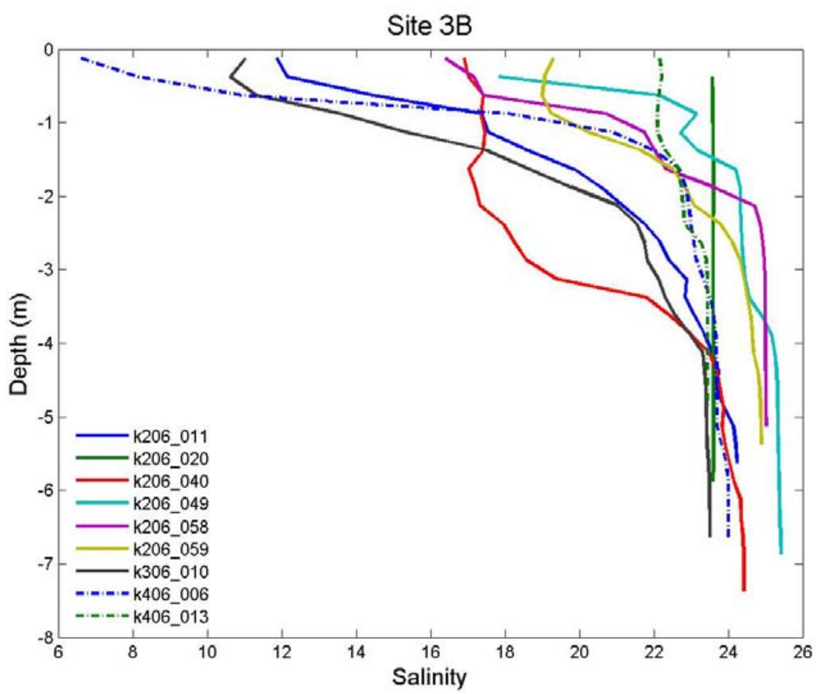


Figure 27*F*. Variability in salinity at station 3B.

A slight limitation of this data is the coverage of CTD profile data which span a greater range of ebb tide conditions than flood. It is likely that lower salinity surface water extends northward for greater duration of time than observed with these casts, but is limited to the area between the south tripod station and the bridge as indicated by the time-series data collected by the surface mooring. These results are consistent with those found by Yates (2001) who also observed low salinity zones restricted to the region near the jetty and Hole in the Wall.

Spatial Salinity Gradients

Spatial salinity gradients are difficult to depict as processes continuously modify them. Even so, mean conditions are useful to portray dominant patterns and examine temporal variability around the mean. The only suitable salinity gradients for juvenile Chinook during the study period were restricted to the southern Swinomish Channel as shown by the mooring and in two different CTD surveys in July during modest river discharge (13,253 cfs) and ebb tide conditions (fig. 28). In these two cases, the low salinity surface lens was restricted to the region south of the Hole in the Wall where salinities ranged between 8 and ~18 psu. During flood conditions this low salinity lens is advected northward along with saline water from Skagit Bay. Depending on river discharge level, current velocities and possibly local wind patterns, these water masses are largely mixed by the south tripod site and only during the highest river flows and flood currents do low salinity lenses extend to the Rainbow Bridge (fig. 24).

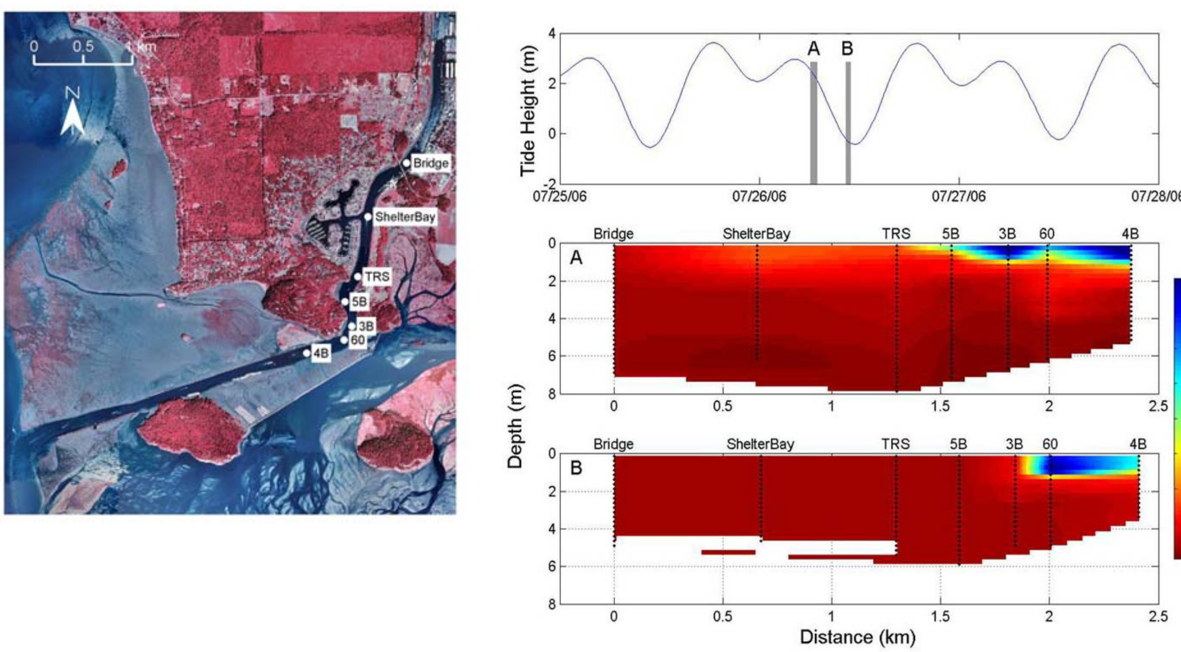


Figure 28. (*A*) Map of stations used to produce cross-section plots in (*B*). (*B*) Cross-section plots of salinity gradients between the Rainbow Bridge and station 4B (seaward of the Fish Passage) at two different tidal elevations. The grey lines indicate the length of time when the CTD transects were performed.

The average spatial salinity gradient that existed between McGlinn Island and Padilla Bay during the conditions characterizing our mooring deployment and CTD profiling surveys between March and July, 2006 was ~13 psu (fig. 29). Like figure 28 shows, the steepest gradient in salinity occurs in the southern portion of Swinomish Channel. North of the south tripod site the salinity averaged in excess of 20 psu.

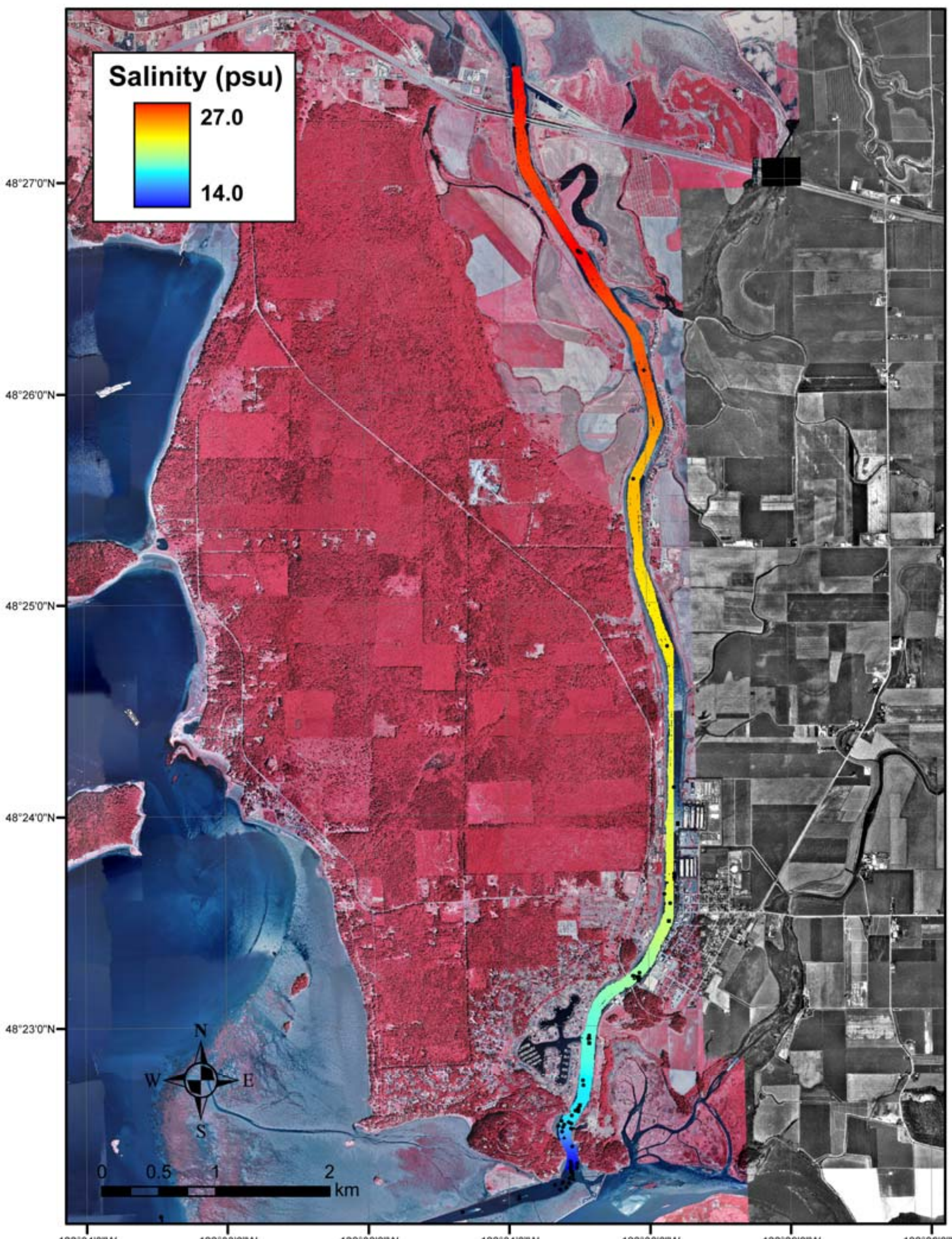


Figure 29. Map of the average spatial salinity gradient along Swinomish Channel based on mean surface water salinities measured at all stations in March, May, and July, 2006.

Surface Water Transport Times and Temporal Salinity Gradients

Of concern to juvenile Chinook use of the Swinomish Channel is the influence of the high current velocities on fresh water mixing, salinity gradients, and transport time to the high salinity water of Padilla Bay if and when entrained by the high current velocities as fry. Habitat restoration aimed at reconnecting the migratory fish pathways through McGlinn Island and a source of fresh water to maintain suitable salinity gradients for fry Chinook migration (figs. 2 and 3) will benefit from the net northward current flow in the Swinomish Channel. High northward current velocities will also impact the rate at which juvenile Chinook are transported to and through the high-salinity waters of Padilla Bay en route to important refuge and rearing habitat in the nearshore eelgrass meadows there. High northward current velocities will also influence the degree and extent of freshwater mixing beyond restored connections to the North Fork Skagit River.

Given the record of circulation during the deployment (fig. 30*A*), we calculated the total transport (fig. 30*B*) and travel time of surface water and passive particles over the 11-km distance between McGlinn Island and Padilla Bay (fig. 30*C*). These calculations are based on transport observed at the south tripod site. Variations likely exist along channel, however, similar transport at the north tripod site and across-channel (fig. 23) support these conclusions.

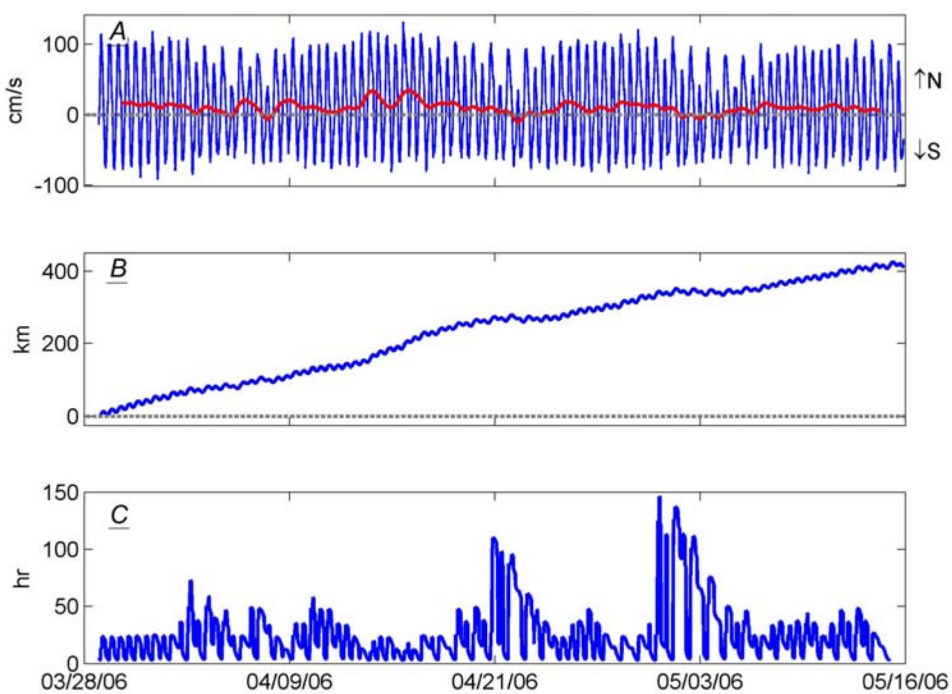


Figure 30. (*A*) Surface-water velocities during the deployment with positive current velocities to the north, negative velocities to the south. (*B*) Net transport based on instantaneous surface current velocities. (*C*) Surface-water travel between McGlinn Island and Padilla Bay (11 km).

Water, passive particles, and/or juvenile fish entrained by current velocities exceeding their swimming capacity, can be advected the length of the Swinomish Channel (11 km) in as little as 2.1 hours (fig. 30*C*); the maximum transit time was 6 days. Figure 31 shows a histogram of the percent of time that transport occurred along the 11-km distance from McGlinn Island to Padilla Bay in 6-hour intervals during our study. The mean transport time was ~1 day while the mode, the most frequent transport duration, was 3.75 hours. Transport within the mode time of 3.75 hours occurred 17 percent of the time. Critical to juvenile and fry Chinook survival are the salinity gradients encountered while smolting during outmigration. Although a mean spatial salinity gradient of 13 psu exists in surface waters between Padilla Bay and McGlinn Island (fig. 29), during strong northward transport this gradient varies significantly in time because of the large magnitude and variation in current velocities and relatively persistent mixed salinity regime north of the Rainbow Bridge (figs. 27, 28, and 29). During periods of strong northward transport, juvenile (fry) Chinook entrained in high current velocities can be advected through these salinity regimes in as little as 2.1 hours, within 3.75 hours 17 percent of the time, and within 1 day 50 percent of the time. Under these transport rates, they can experience a temporal salinity gradient exceeding 4 psu per hour (fig. 31). The temporal salinity gradient calculated for the mode transport rate is ~3 psu per hour, whereas the temporal salinity gradient associated with the mean transport rate observed is ~0.5 psu per hour.

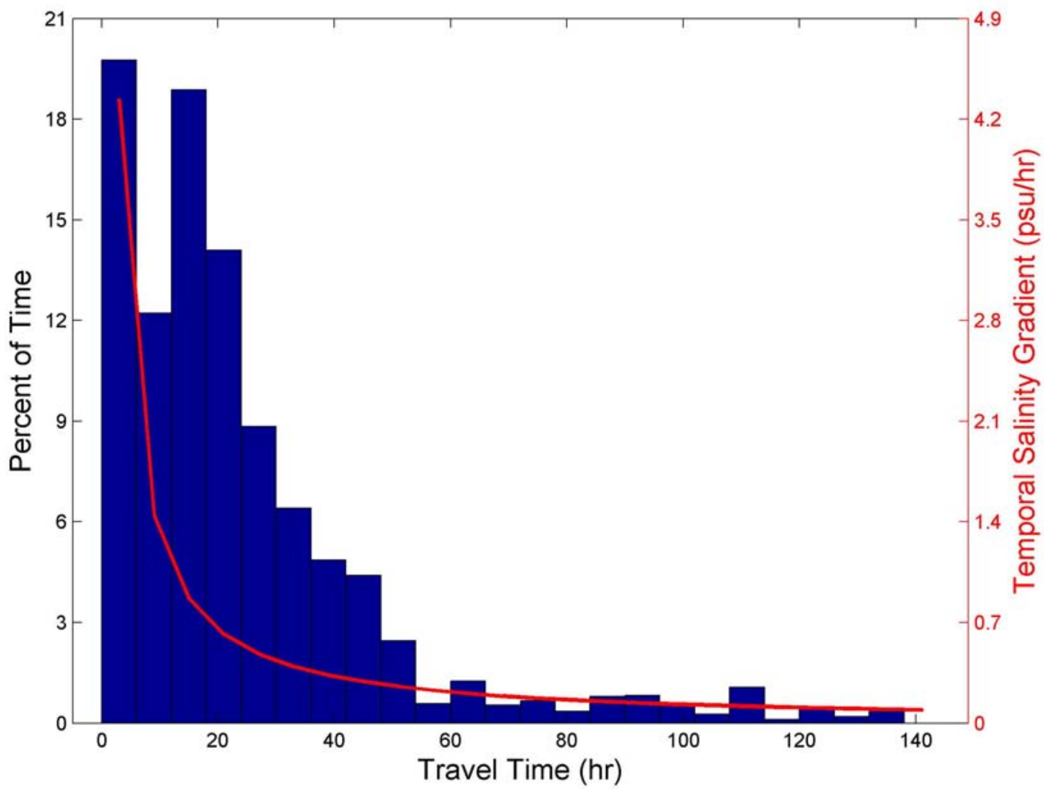


Figure 31. Distribution of surface-water travel times between McGlinn Island and Padilla Bay binned at 6-hour intervals and associated temporal salinity gradient that exists in Swinomish Channel in terms of practical salinity units of change per hour.

This information provides important constraints on determining the volume of freshwater needed to support suitable salinity gradients for migrating juvenile salmon. They will also help to guide design and placement of refuge habitats along the Swinomish Channel that can provide suitable salinity and adequate time for smolt given the rapid transport of water between southern Swinomish Channel and the high salinity waters of Padilla Bay. These results raise important questions including how do circulation processes during other climate (seasonal, interannual) and fluvial conditions modify the patterns we observed, how persistent are zones of mixing along Swinomish Channel and what are the processes responsible, and how will addition of freshwater modify the processes operating today.

Conclusions

Under the current circulation regime of the Swinomish Channel, suitable low-salinity (<15-20 psu) surface waters for fry Chinook salmon (Healey, 1991) are largely restricted to the area between the southern region near the North Fork Skagit River jetty fish passage and Hole in the Wall. Periodically, but for short duration, surface water lenses with salinity as low as 15 psu extended to the Rainbow Bridge during high river discharge and peak flood-tidal currents between March and July, 2006. Generally, however, the mean change in surface-water salinity between McGlinn Island and Padilla Bay during this time was 10-13 psu, with salinities >20 psu between the town of La Conner and Padilla Bay. Currents in the Swinomish Channel during the 2006 spring outmigration of Skagit River Chinook ranged 0 to 1.2 m/s and were generally higher in the upper 1 m surface waters. Net transport was to the north, toward Padilla Bay. Transport times for surface water to travel the 11 km from the southern end of Swinomish Channel at McGlinn Island to Padilla Bay ranged from 2.1 hours to 5.5 days. The mean travel time was ~1 day, whereas 17 percent of the time, transport of water and passive particles occurred within 3.75 hours. The high overall salinities of the channel restrict suitable habitat for pre-smolt Chinook salmon to the southern Swinomish Channel.

High northward current velocities have the capacity to transport Chinook fry into less suitable, high-salinity waters between Rainbow Bridge and Padilla Bay within hours. The rapid transport times of 2.1 to 3.75 hours between McGlinn Island and Padilla Bay which occur 17 percent of the time, are considerably less than the time considered adequate for juvenile Chinook to acclimate (Healey, 1991). Rapid transport times under the current salinity regime produce a temporal salinity gradient that exceeds 4 psu/hour during high northward current flow. Although, lower current velocities likely afford more suitable conditions along the channel edges, repeat across-channel measurements showed that flow was uniformly high across the entire channel at McGlinn Island Causeway. Therefore, refuge habitats along Swinomish Channel that provide escape from large and abrupt changes in salinity and the high current velocities may be beneficial to juvenile salmonids. In addition, increased supply of freshwater sources along this important salmon migratory pathway probably would be valuable. Important questions raised by this study include how circulation processes during other climate (seasonal, interannual) wind and fluvial conditions operate and modify the patterns and mixing zones observed. It will also be important to determine how additions of freshwater will modify the processes operating today.

Acknowledgments

We thank Steve Hinton, Eric Beamer, Greg Hood, and Karen Wolf of Skagit River System Cooperative and Todd Mitchell and Sarah Akin of the Water Resources Team of the Swinomish Indian Tribal Community Office of Planning and Community Development for their logistical support and fruitful discussions. We thank Eric Beamer, Greg Hood, and Reg Reisenbichler (U.S. Geological Survey) for insight and review of biologically sensitive material regarding salinity effects on juvenile salmon. Funding for this study was provided by the Skagit River System Cooperative through a grant from the Washington State Salmon Recovery Funding Board, the U.S. Geological Survey Coastal and Marine Geology Program and the U.S. Geological Survey Multidisciplinary Studies of Coastal Habitats in Puget Sound (CHIPS) Project.

References Cited

Beamer, E., Bernard, R., Hayman, B., Hebner, B., Hinton, S., Hood, G., Kraemer, C., McBride, A., Musslewhite, J., Smith, D., Wasserman, L., and Wyman, K., 2005, Skagit Chinook recovery plan. http://www.skagitcoop.org/

Collins, B., 2000, Mid-19th century stream channels and wetlands interpreted from archival sources for three north Puget sound estuaries—Report to Skagit River System Cooperative. 65 p. [http://www.skagitcoop.org/EB1474_Collinspercent202000.PDF].

Healey, M.,1991, Life history of Chinook salmon, in Groot, C., and Margolis, L., (eds.), Pacific salmon life histories: Vancouver, British Columbia, UBC Press, p. 311-393.

Oberg K.A., Morlock, S.E., and Caldwell, W.S., 2005, Quality-assurance plan for discharge measurements using acoustic doppler current profilers: U.S. Geological Survey Scientific Investigations Report 2005-5183, 46 p. [http://pubs.usgs.gov/sir/2005/5183/SIR_2005-5183.pdf].

Pawlowicz, R., Beardsley, B., and Lentz, S., 2002, Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE: Computers and Geosciences, v. 28, p. 929-937.

Yates, S., 2001, Effects of Swinomish Channel jetty and causeway on outmigrating Chinook salmon (*Oncorhynchus tshawytscha*) from the Skagit River, Washington: Bellingham, Western Washington University, Master's thesis, 65 p.

Appendixes

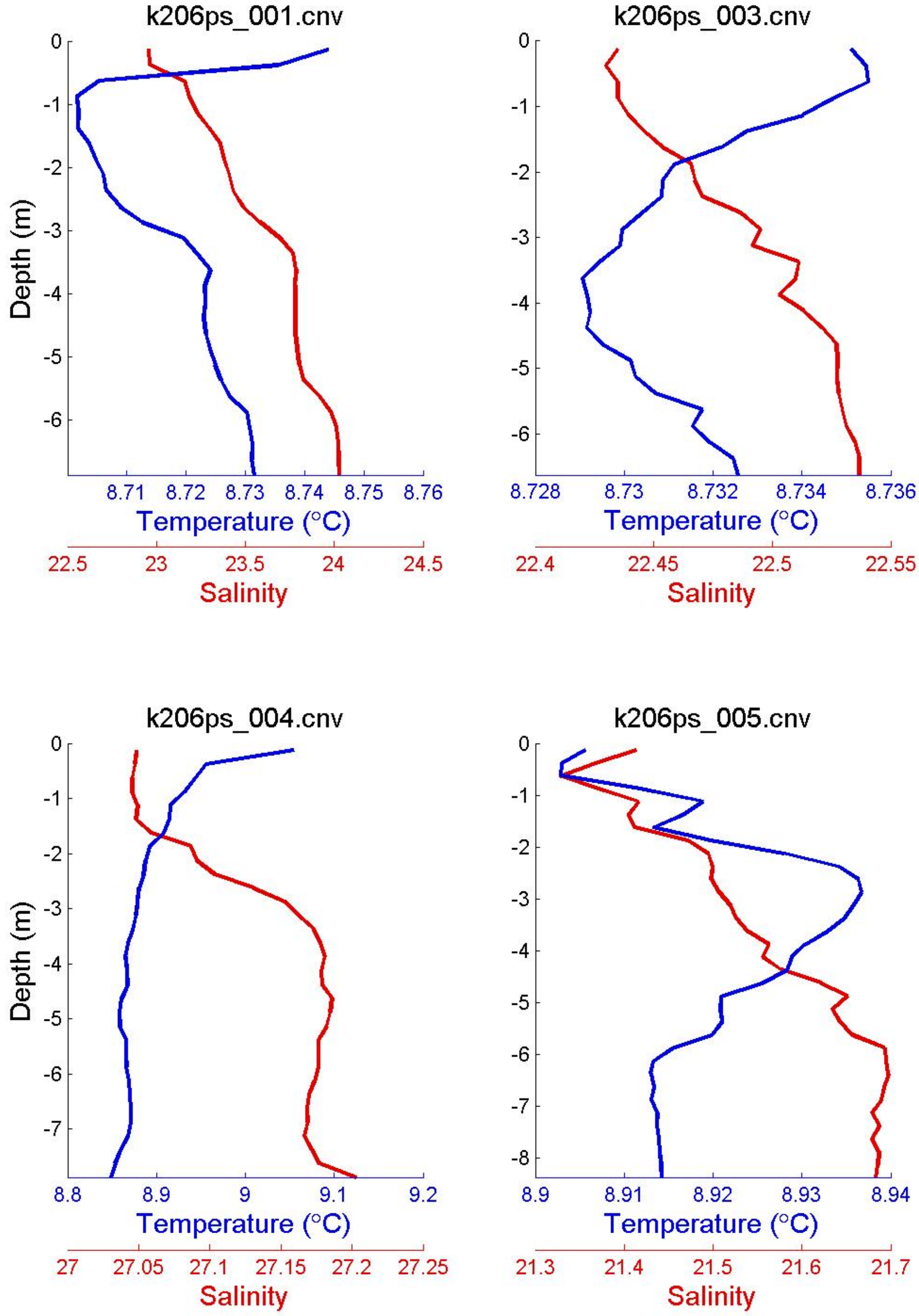
Appendix I. Conductivity, Temperature, Depth Profiles from U.S. Geological Survey Cruise Activity K-2-06-PS.

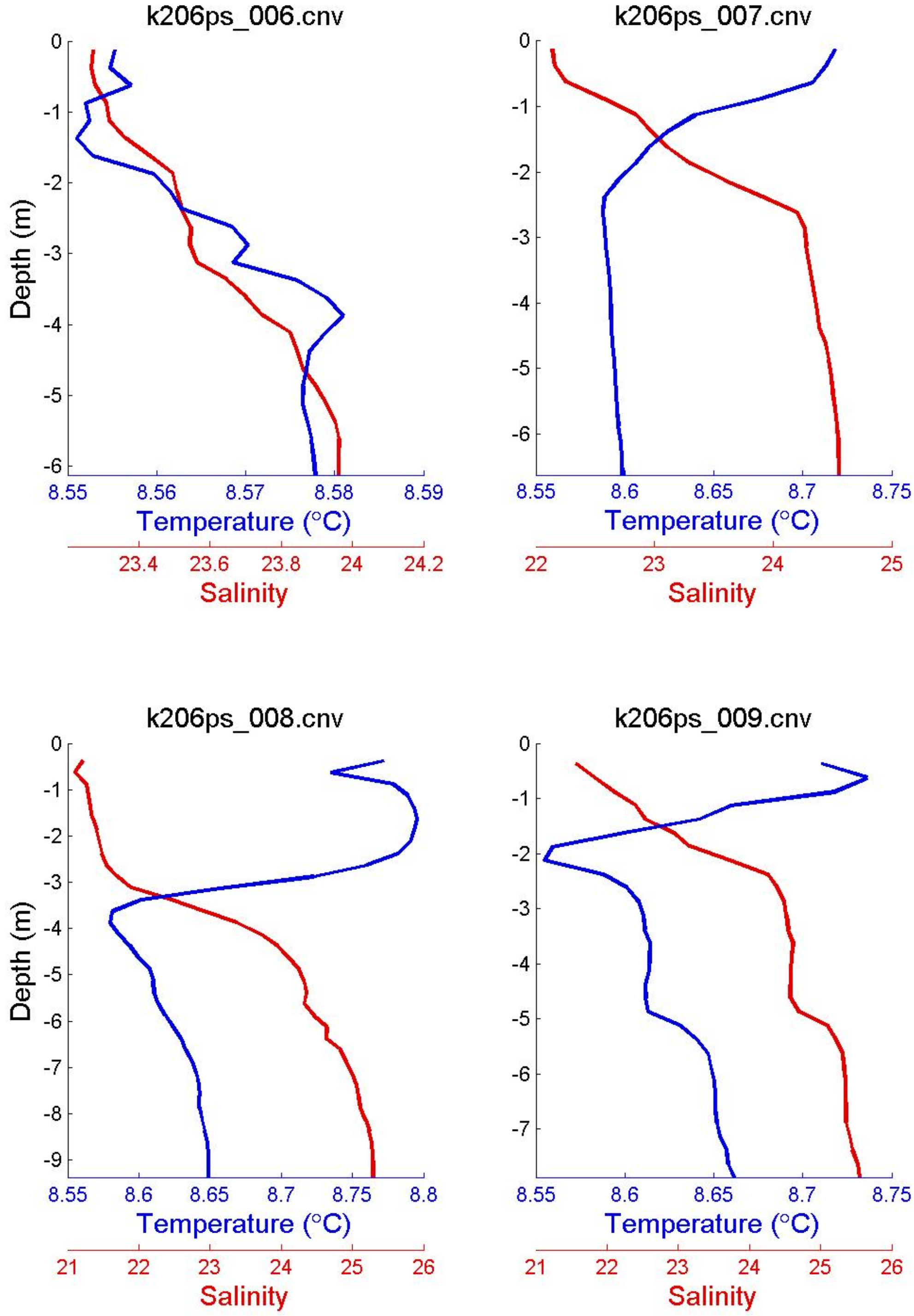
The following pages show individual plots of salinity and temperature with depth for the stations listed in the accompanying table collected during U.S. Geological Survey Cruise Activity K-2-06-PS.

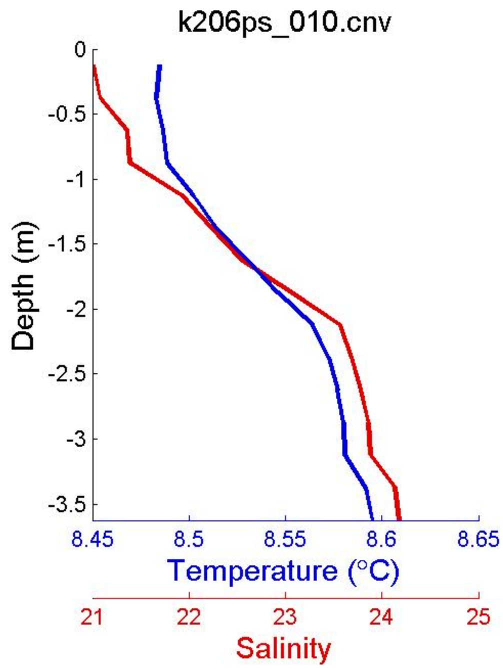
K-2-06-PS Conductivity, Temperature, Depth Measurement Log

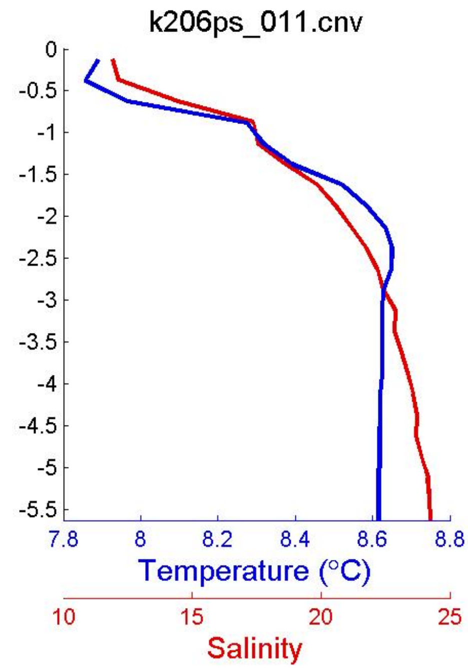
FILENAME	SITE	LON	LAT	UTC_DATETIME
K206ps_001	F_Dock	-122.49691	48.39502	3/28/2006 16:30:14
K206ps_003	Hole_in_wall	-122.50857	48.37675	3/28/2006 20:55:04
K206ps_004	-	-122.50750	48.44428	3/28/2006 22:30:46
K206ps_005	Mooring	-122.50137	48.38721	3/29/2006 0:15:43
K206ps_006	F_dock	-122.49682	48.39519	3/29/2006 16:32:27
K206ps_007	Mooring	-122.50108	48.38703	3/29/2006 16:49:21
K206ps_008	TRP_South	-122.50880	48.37672	3/29/2006 17:01:52
K206ps_009	2B	-122.51037	48.37508	3/29/2006 17:11:49
K206ps_010	2A	-122.51080	48.37551	3/29/2006 17:19:06
K206ps_011	3B	-122.50912	48.37177	3/29/2006 17:24:13
K206ps_012	4B	-122.51546	48.36983	3/29/2006 17:30:00
K206ps_013	GreenMrkr15	-122.52218	48.36879	3/29/2006 17:34:43
K206ps_014	GreenMrkr13	-122.53013	48.36712	3/29/2006 17:41:43
K206ps_015	GreenMrkr11	-122.53854	48.36516	3/29/2006 17:46:43
K206ps_016	GreenMrkr5	-122.55064	48.36255	3/29/2006 17:53:27
K206ps_017	-	-122.55789	48.35996	3/29/2006 17:59:12
K206ps_018	-	-122.55673	48.35693	3/29/2006 18:06:33
K206ps_019	-	-122.55941	48.36403	3/29/2006 18:16:28
K206ps_020	3B	-122.50930	48.37247	3/29/2006 18:45:48
K206ps_021	2B	-122.51010	48.37561	3/29/2006 18:57:17
K206ps_022	TRP_south	-122.50918	48.37631	3/29/2006 19:00:56
K206ps_023	1B	-122.50782	48.37871	3/29/2006 19:06:57
K206ps_024	5B	-122.50717	48.38234	3/29/2006 19:15:13
K206ps_025	6B	-122.50189	48.38729	3/29/2006 19:24:13
K206ps_026	7B	-122.49740	48.39296	3/29/2006 19:34:12
K206ps_027	F_Dock	-122.49688	48.39531	3/29/2006 19:47:13
K206ps_028	F_Dock	-122.49689	48.39529	3/29/2006 22:11:12
K206ps_029	NSWIN_N_RR_bridge	-122.51534	48.45912	3/29/2006 22:56:12
K206ps_030	Tripod_N	-122.50783	48.44446	3/29/2006 23:13:28
K206ps_031	11B	-122.50011	48.43499	3/29/2006 23:28:36
K206ps_032	10B	-122.50146	48.42645	3/29/2006 23:37:54
K206ps_033	9B	-122.49756	48.41323	3/29/2006 23:50:42
K206ps_034	8B	-122.49690	48.40216	3/30/2006 0:04:24
K206ps_035	7B	-122.49806	48.39370	3/30/2006 0:19:40

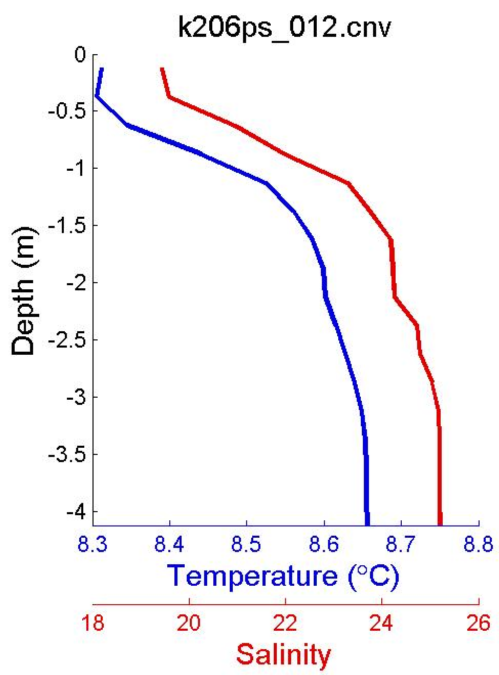
K206ps_036	6B_Mooring	-122.50105	48.38751	3/30/2006 0:30:03
K206ps_037	5B_ShelterCove	-122.50708	48.38258	3/30/2006 0:39:52
K206ps_038	1B	-122.50787	48.37911	3/30/2006 0:47:26
K206ps_039	TRP_S	-122.50958	48.37579	3/30/2006 0:54:56
K206ps_040	3B	-122.50940	48.37270	3/30/2006 1:00:45
K206ps_041	Near_fish_passage (FP)	-122.50903	48.37130	3/30/2006 1:05:48
K206ps_042	3B	-122.50861	48.37257	3/30/2006 1:11:46
K206ps_043	2C	-122.50924	48.37570	3/30/2006 1:19:17
K206ps_044	2A	-122.51041	48.37591	3/30/2006 1:25:38
K206ps_045	Mooring	-122.50119	48.38719	3/30/2006 1:35:52
K206ps_046	F_Dock	-122.49687	48.39532	3/30/2006 1:51:45
K206ps_047	F_Dock_am	-122.49687	48.39532	3/30/2006 16:03:36
K206ps_048	TRP_S	-122.50838	48.37665	3/30/2006 16:37:52
K206ps_049	3B	-122.50942	48.37223	3/30/2006 16:45:11
K206ps_050	mid_chan_FP	-122.50918	48.37190	3/30/2006 16:50:31
K206ps_051	FP	-122.50949	48.37140	3/30/2006 16:55:50
K206ps_052	center_chan	-122.51031	48.37111	3/30/2006 17:03:00
K206ps_053	near_Eagle_house	-122.51123	48.37089	3/30/2006 17:10:06
K206ps_054	Mrkr16	-122.51060	48.37049	3/30/2006 17:15:06
K206ps_055	South_side_chan	-122.50987	48.37068	3/30/2006 17:20:56
K206ps_056	South_chan_FP	-122.50957	48.37101	3/30/2006 17:28:46
K206ps_057	South_side	-122.50914	48.37162	3/30/2006 17:34:32
K206ps_058	McGlinn_Isl_Causeway	-122.50867	48.37225	3/30/2006 17:40:26
K206ps_059	3B	-122.50936	48.37219	3/30/2006 17:44:41
K206ps_060	wall_edge_3C	-122.50918	48.37391	3/30/2006 17:50:46
K206ps_061	2B	-122.51025	48.37540	3/30/2006 17:59:11
K206ps_062	2C	-122.50930	48.37532	3/30/2006 18:03:56
K206ps_063	TRP_S	-122.50852	48.37678	3/30/2006 18:08:46
K206ps_064	Mooring	-122.50127	48.38712	3/30/2006 18:20:32
K206ps_065	F_dock_late_am	-122.49687	48.39532	3/30/2006 18:33:56

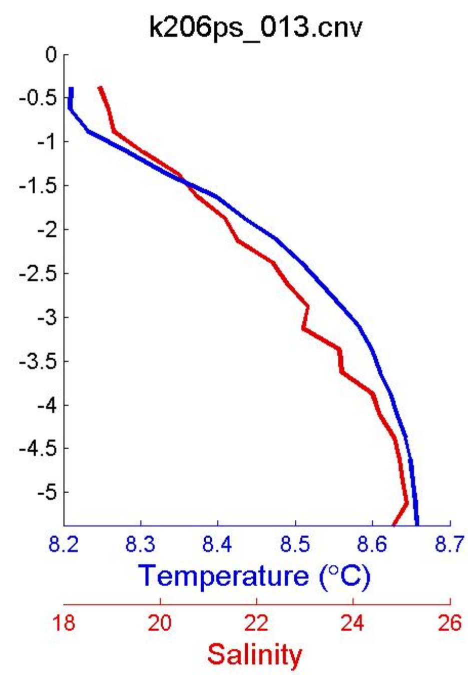

k206ps_001.cnv
Depth (m)
Temperature (°C)
Salinity
k206ps_003.cnv
Temperature (°C)
Salinity
k206ps_004.cnv
Depth (m)
Temperature (°C)
Salinity
k206ps_005.cnv
Temperature (°C)
Salinity

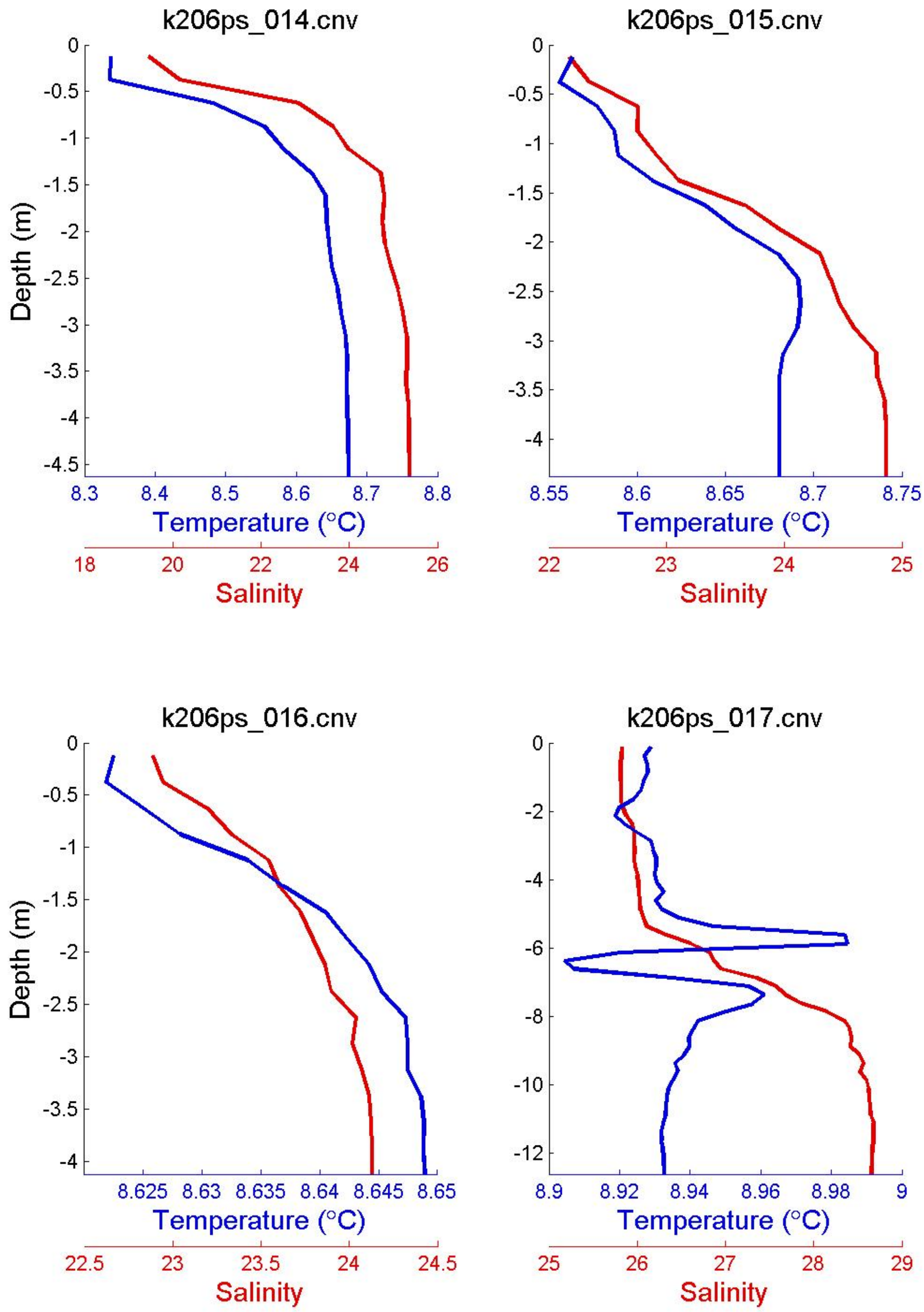

k206ps_006.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
8.55
8.56
8.57
8.58
8.59
Temperature (°C)
23.4
23.6
23.8
24
24.2
Salinity
k206ps_007.cnv
0
-1
-2
-3
-4
-5
-6
8.55
8.6
8.65
8.7
8.75
Temperature (°C)
22
23
24
25
Salinity
k206ps_008.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
8.55
8.6
8.65
8.7
8.75
8.8
Temperature (°C)
21
22
23
24
25
26
Salinity
k206ps_009.cnv
0
-1
-2
-3
-4
-5
-6
-7
8.55
8.6
8.65
8.7
8.75
Temperature (°C)
21
22
23
24
25
26
Salinity

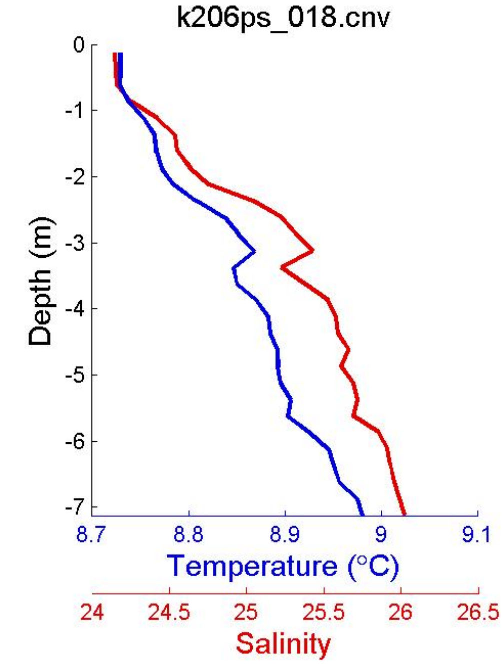

k206ps_010.cnv
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
8.45
8.5
8.55
8.6
8.65
Temperature (°C)
21
22
23
24
25
Salinity

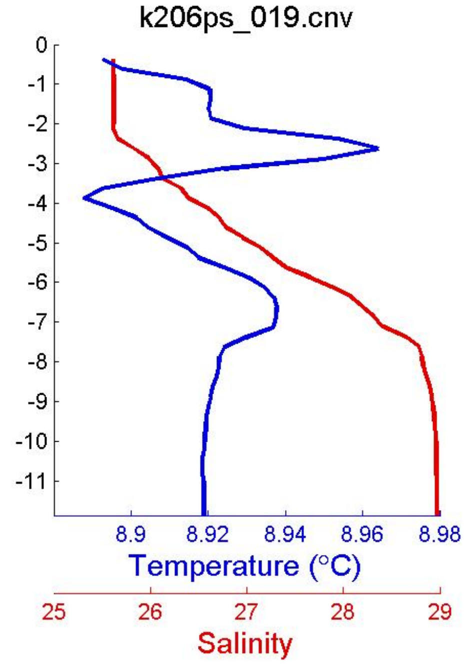

k206ps_011.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
7.8
8
8.2
8.4
8.6
8.8
Temperature (°C)
10
15
20
25
Salinity

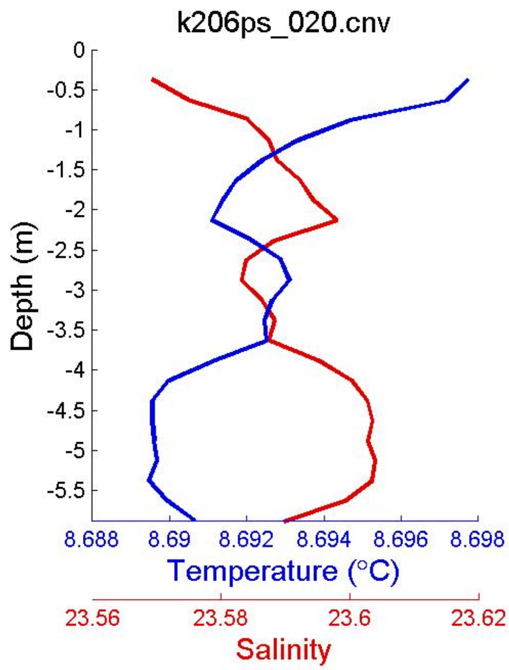

k206ps_012.cnv
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
8.3
8.4
8.5
8.6
8.7
8.8
Temperature (°C)
18
20
22
24
26
Salinity

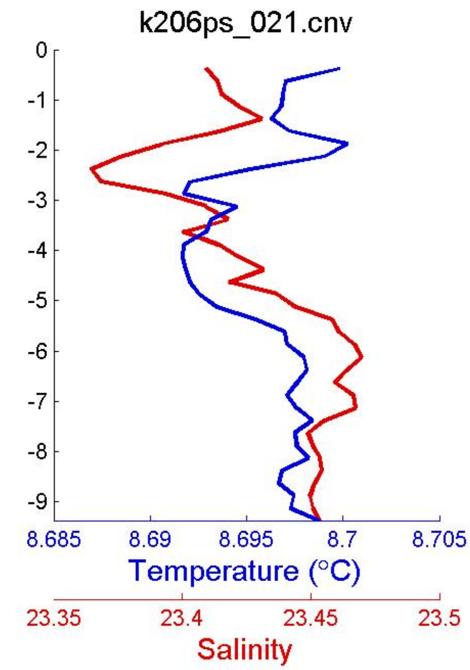

k206ps_013.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
8.2
8.3
8.4
8.5
8.6
8.7
Temperature (°C)
18
20
22
24
26
Salinity

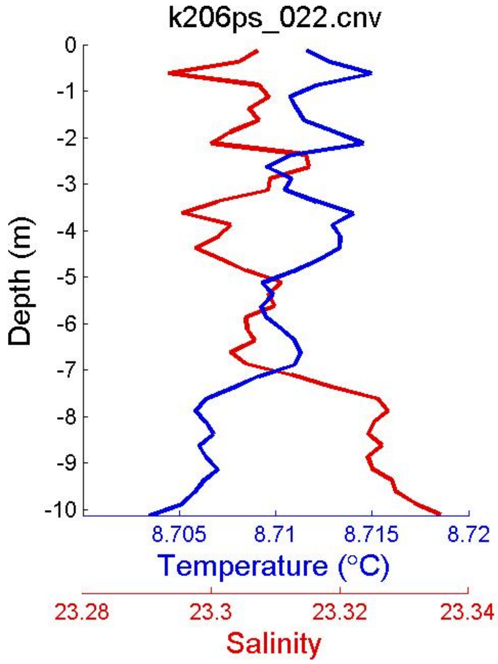

k206ps_014.cnv
k206ps_015.cnv
k206ps_016.cnv
k206ps_017.cnv
Depth (m)
Temperature (°C)
Salinity

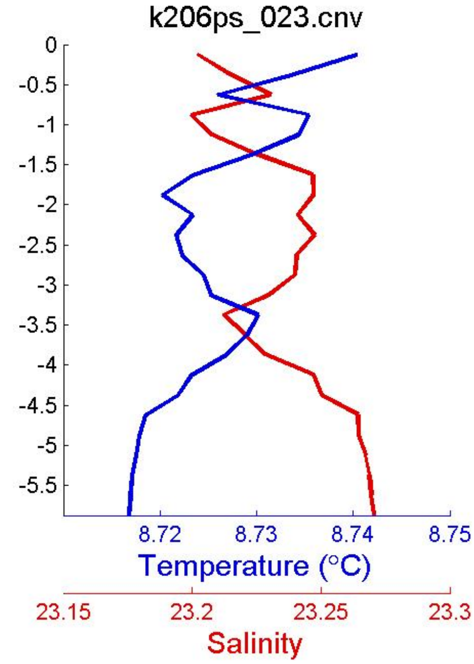

k206ps_018.cnv
Depth (m)
Temperature (°C)
Salinity
0
-1
-2
-3
-4
-5
-6
-7
8.7
8.8
8.9
9
9.1
24
24.5
25
25.5
26
26.5

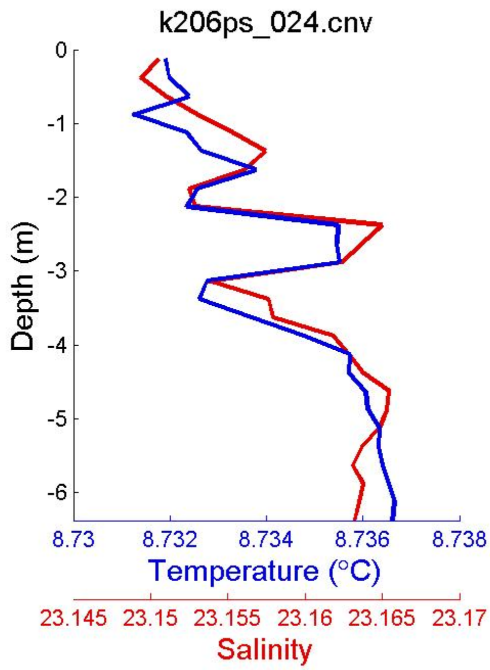

k206ps_019.cnv
Temperature (°C)
Salinity
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
8.9
8.92
8.94
8.96
8.98
25
26
27
28
29

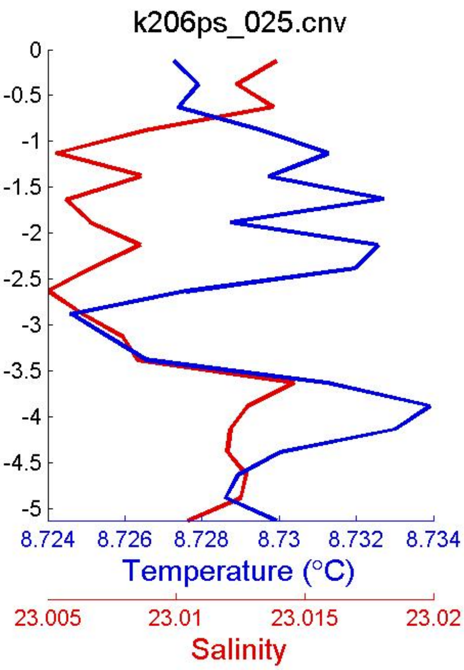

k206ps_020.cnv
Depth (m)
Temperature (°C)
Salinity
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
8.688
8.69
8.692
8.694
8.696
8.698
23.56
23.58
23.6
23.62

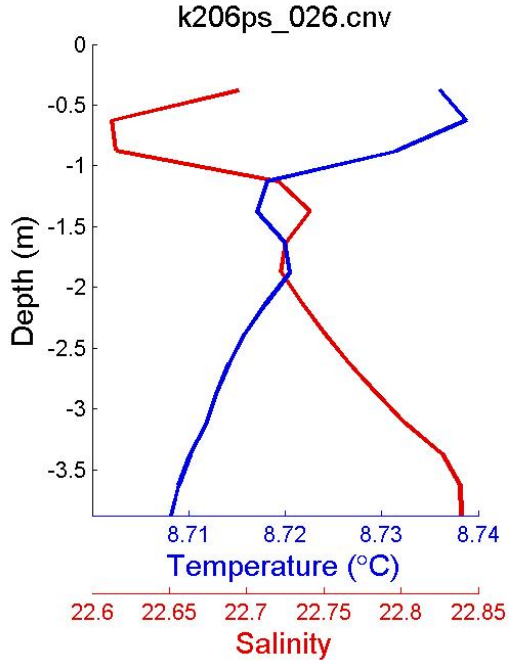

k206ps_021.cnv
Temperature (°C)
Salinity
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
8.685
8.69
8.695
8.7
8.705
23.35
23.4
23.45
23.5

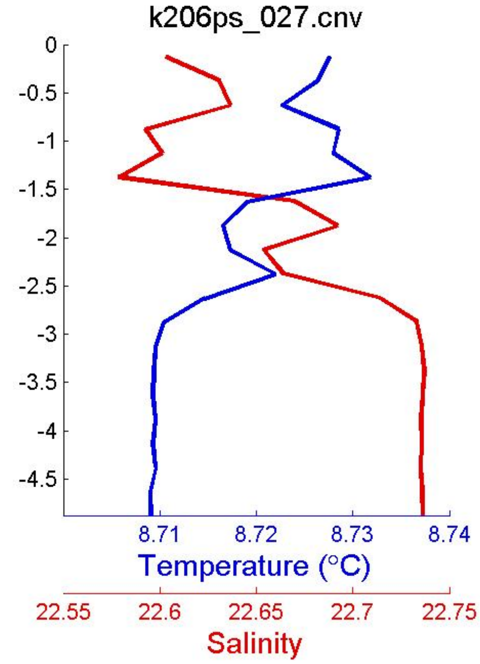

k206ps_022.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
8.705 8.71 8.715 8.72
Temperature (°C)
23.28 23.3 23.32 23.34
Salinity

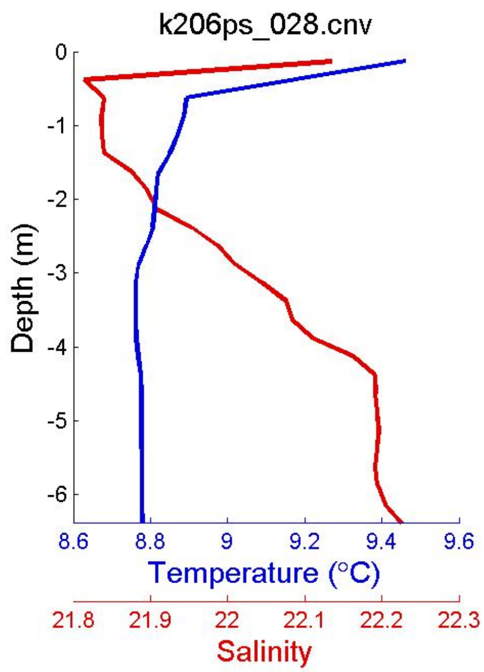

k206ps_023.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
8.72 8.73 8.74 8.75
Temperature (°C)
23.15 23.2 23.25 23.3
Salinity

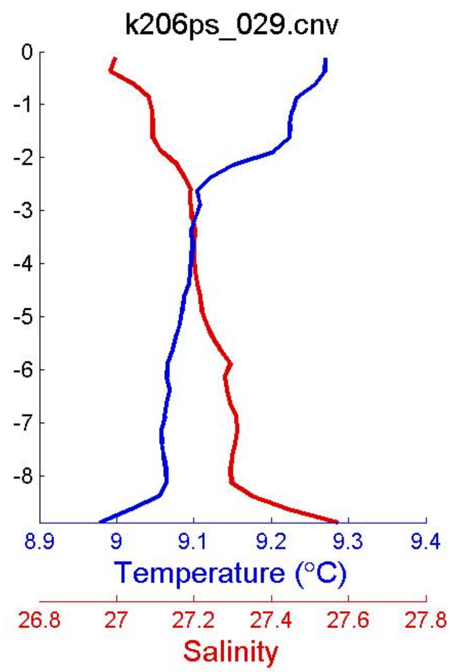

k206ps_024.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
8.73 8.732 8.734 8.736 8.738
Temperature (°C)
23.145 23.15 23.155 23.16 23.165 23.17
Salinity

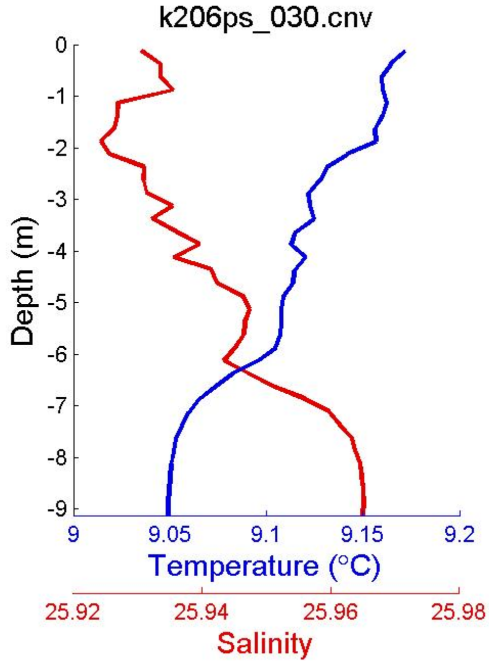

k206ps_025.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
8.724 8.726 8.728 8.73 8.732 8.734
Temperature (°C)
23.005 23.01 23.015 23.02
Salinity

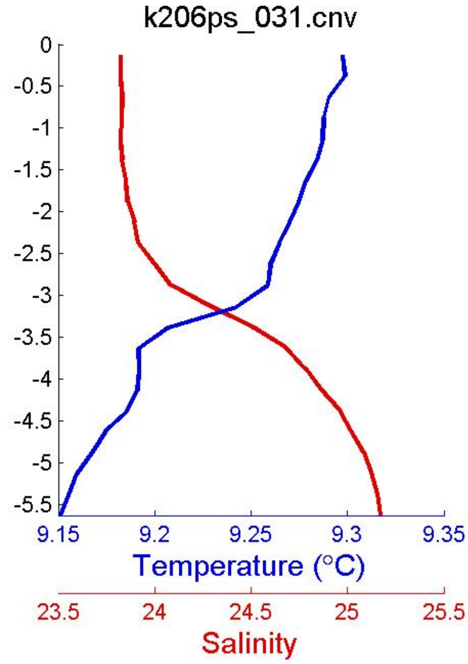

k206ps_026.cnv
Depth (m)
Temperature (°C)
Salinity

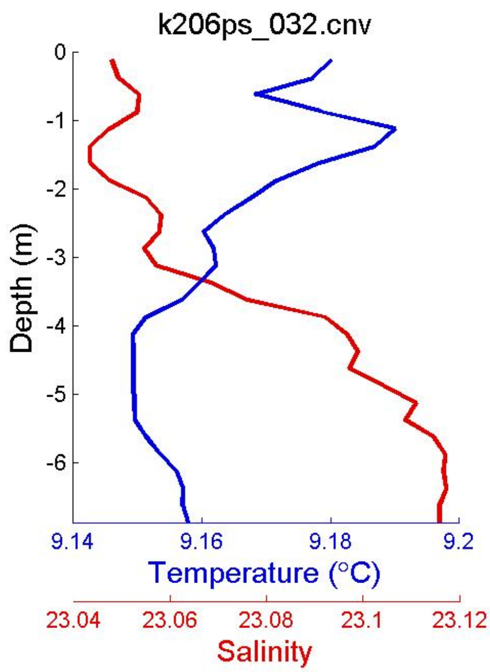

k206ps_027.cnv
Temperature (°C)
Salinity

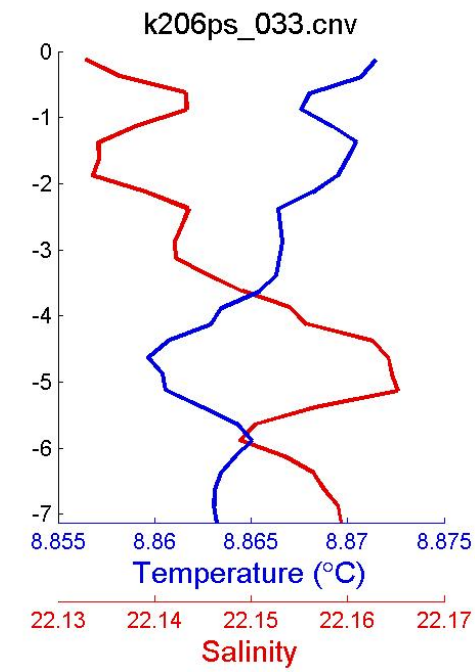

k206ps_028.cnv
Depth (m)
Temperature (°C)
Salinity

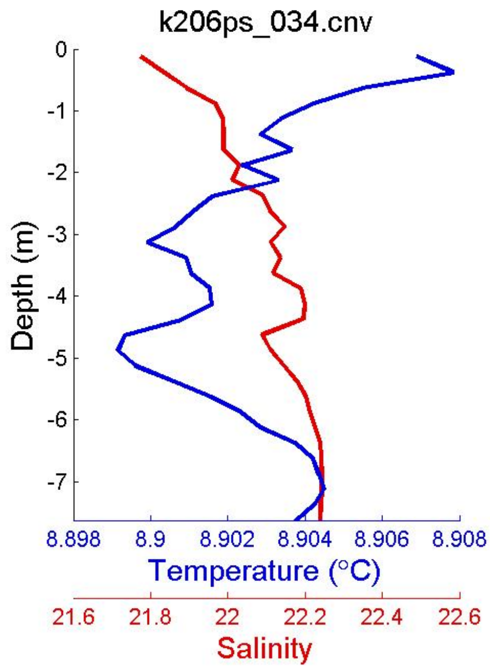

k206ps_029.cnv
Temperature (°C)
Salinity

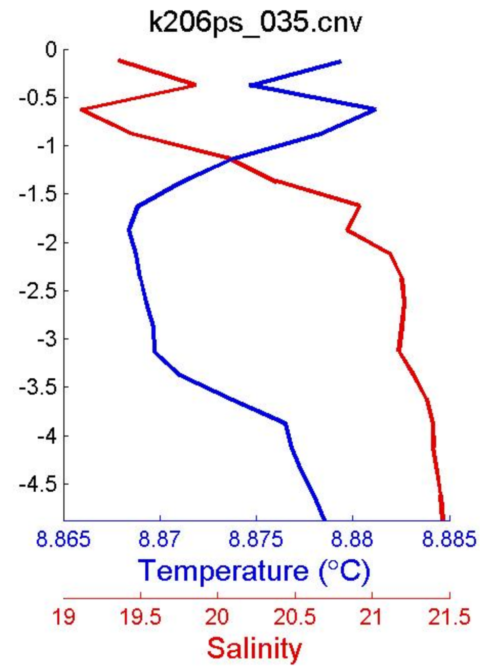

k206ps_030.cnv
Depth (m)
Temperature (°C)
Salinity
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
9
9.05
9.1
9.15
9.2
25.92
25.94
25.96
25.98

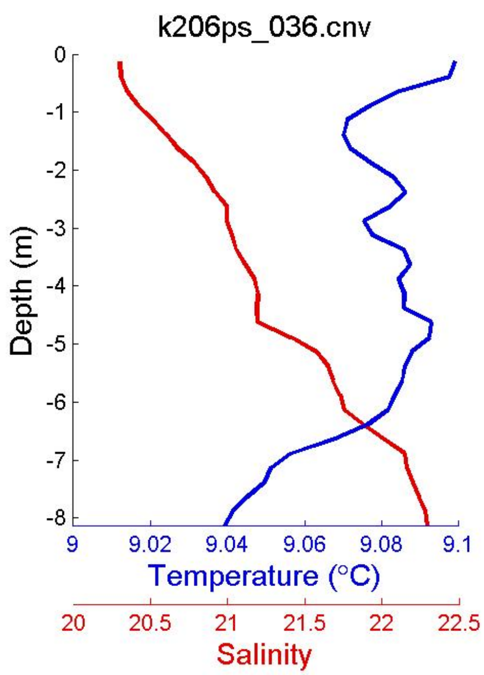

k206ps_031.cnv
Temperature (°C)
Salinity
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
9.15
9.2
9.25
9.3
9.35
23.5
24
24.5
25
25.5

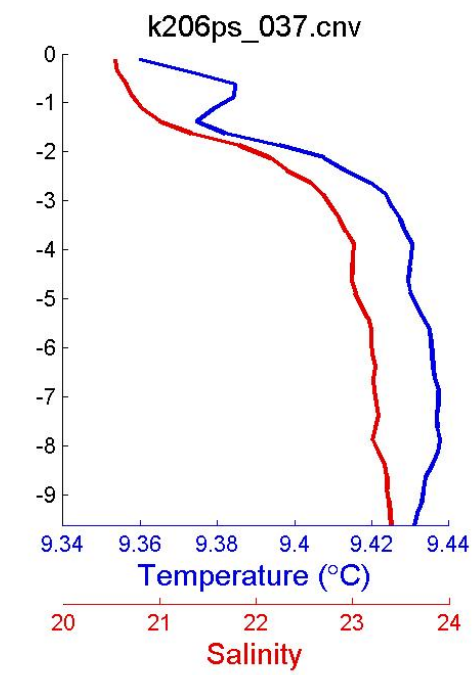

k206ps_032.cnv
Depth (m)
Temperature (°C)
Salinity
0
-1
-2
-3
-4
-5
-6
9.14
9.16
9.18
9.2
23.04
23.06
23.08
23.1
23.12

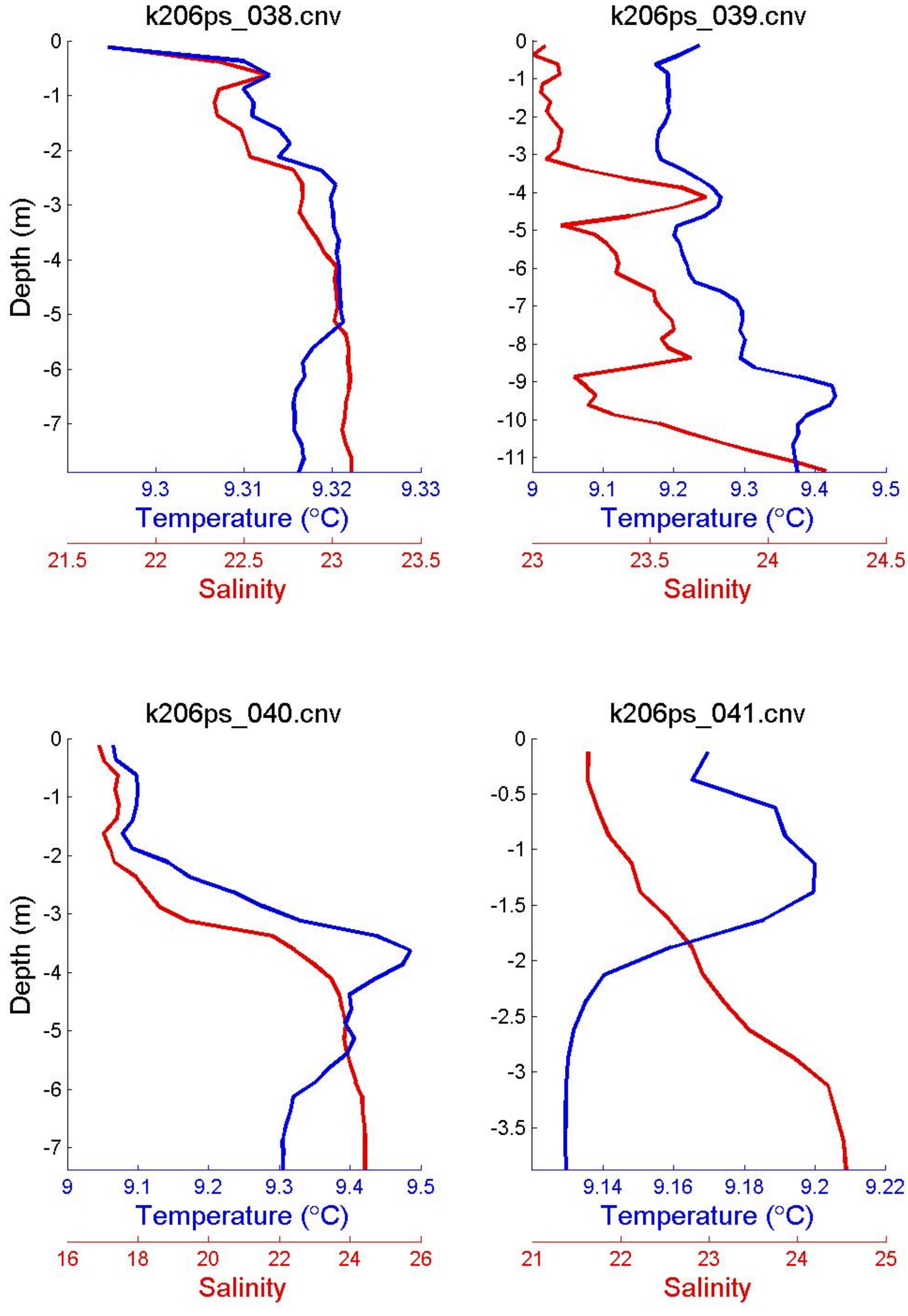

k206ps_033.cnv
Temperature (°C)
Salinity
0
-1
-2
-3
-4
-5
-6
-7
8.855
8.86
8.865
8.87
8.875
22.13
22.14
22.15
22.16
22.17

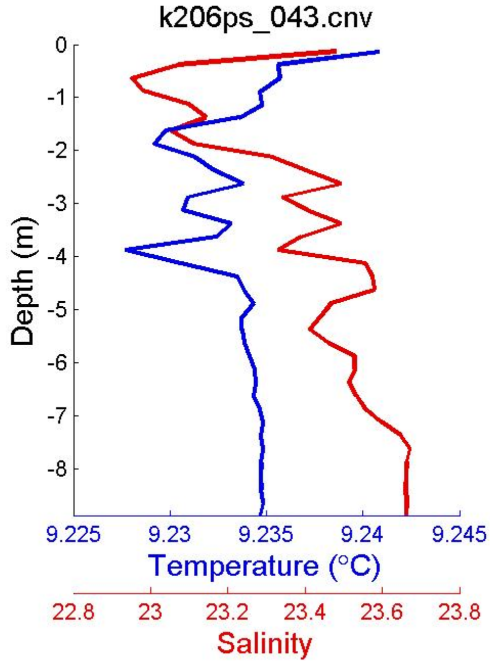

k206ps_034.cnv
Depth (m)
Temperature (°C)
Salinity

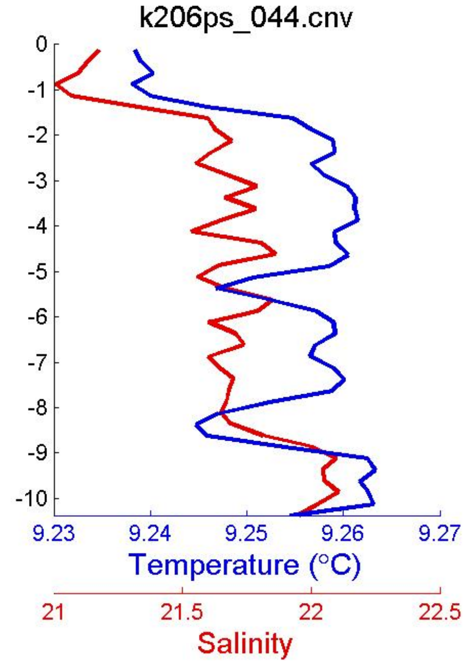

k206ps_035.cnv
Temperature (°C)
Salinity

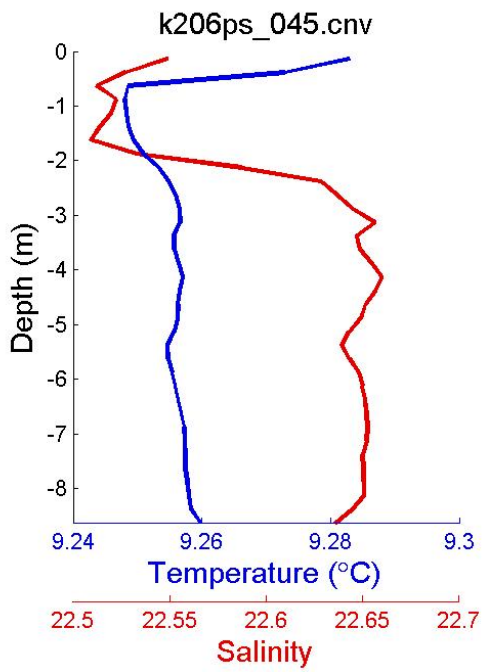

k206ps_036.cnv
Depth (m)
Temperature (°C)
Salinity

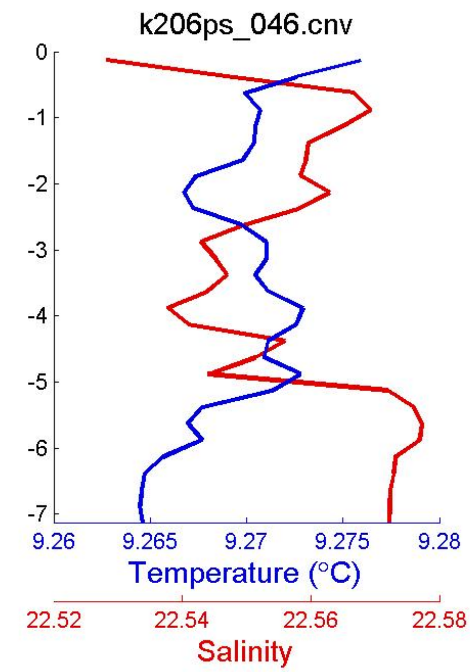

k206ps_037.cnv
Temperature (°C)
Salinity

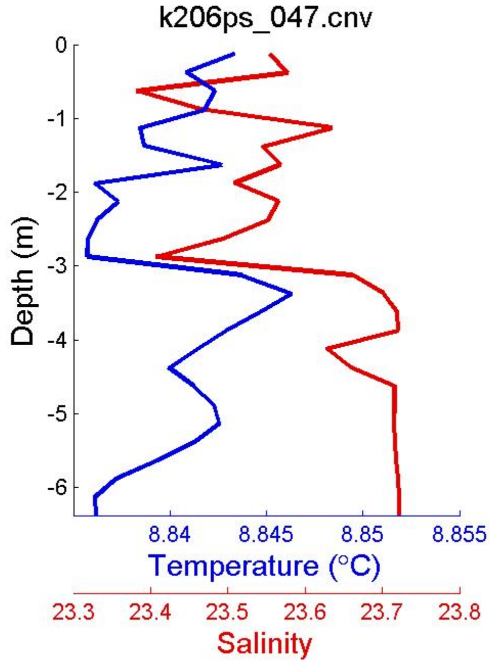

k206ps_038.cnv
k206ps_039.cnv
k206ps_040.cnv
k206ps_041.cnv
Depth (m)
Temperature (°C)
Salinity
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-0.5
-1.5
-2.5
-3.5
9.3
9.31
9.32
9.33
21.5
22
22.5
23
23.5
9
9.1
9.2
9.4
9.5
23.5
24
24.5
16
18
20
22
24
26
9.14
9.16
9.18
9.2
9.22
21
25

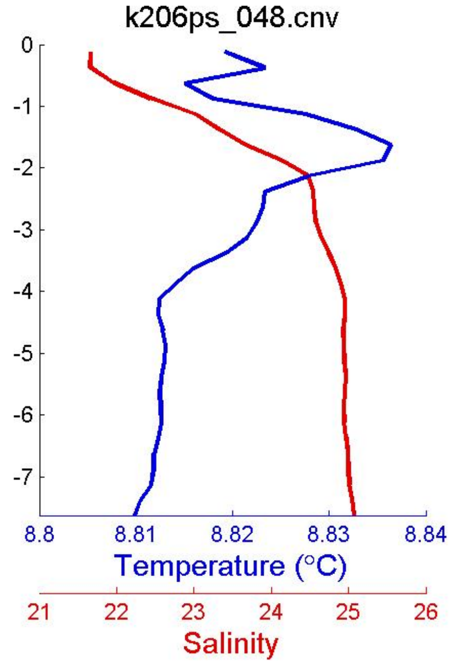

k206ps_043.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
9.225 9.23 9.235 9.24 9.245
Temperature (°C)
22.8 23 23.2 23.4 23.6 23.8
Salinity

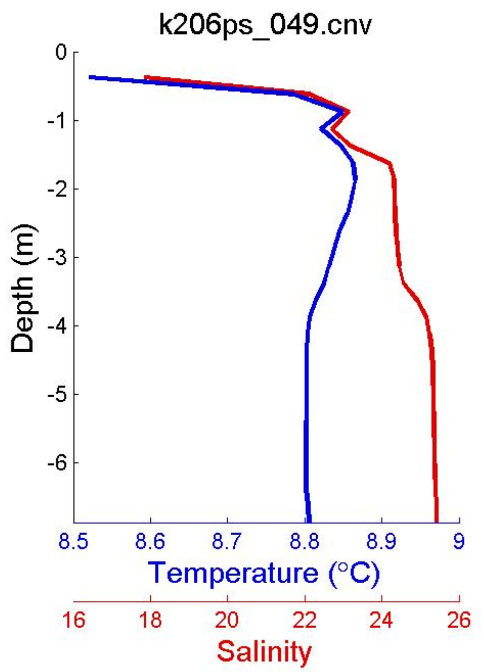

k206ps_044.cnv
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
9.23 9.24 9.25 9.26 9.27
Temperature (°C)
21 21.5 22 22.5
Salinity

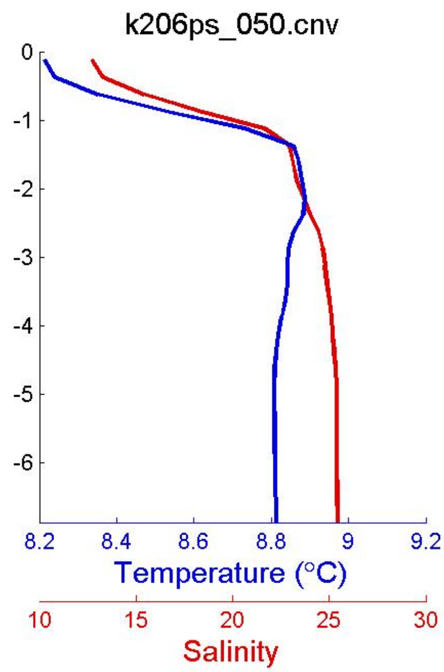

k206ps_045.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
9.24 9.26 9.28 9.3
Temperature (°C)
22.5 22.55 22.6 22.65 22.7
Salinity

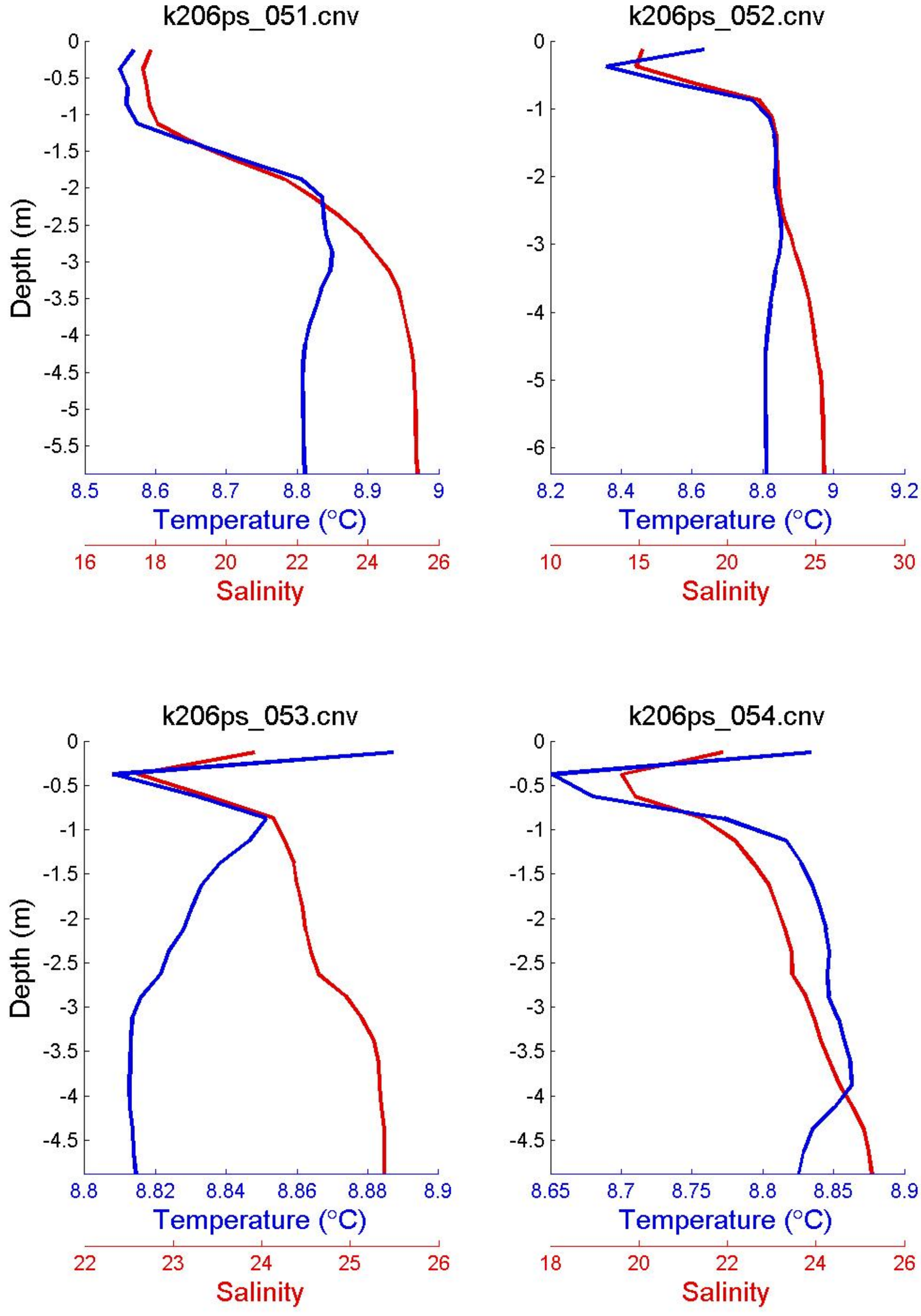

k206ps_046.cnv
0
-1
-2
-3
-4
-5
-6
-7
9.26 9.265 9.27 9.275 9.28
Temperature (°C)
22.52 22.54 22.56 22.58
Salinity

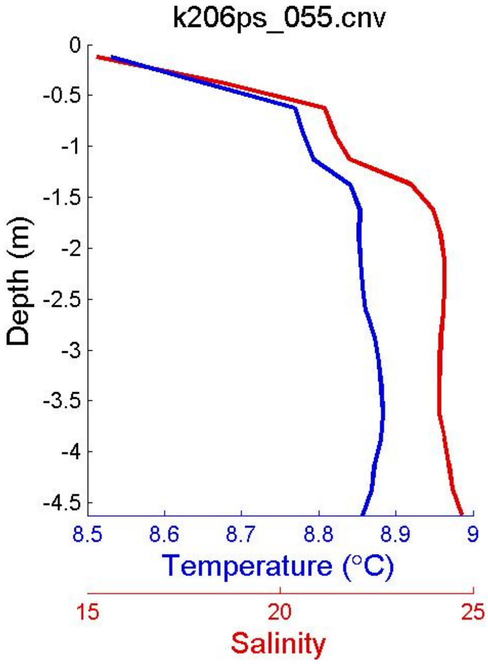

k206ps_047.cnv
Depth (m)
Temperature (°C)
Salinity

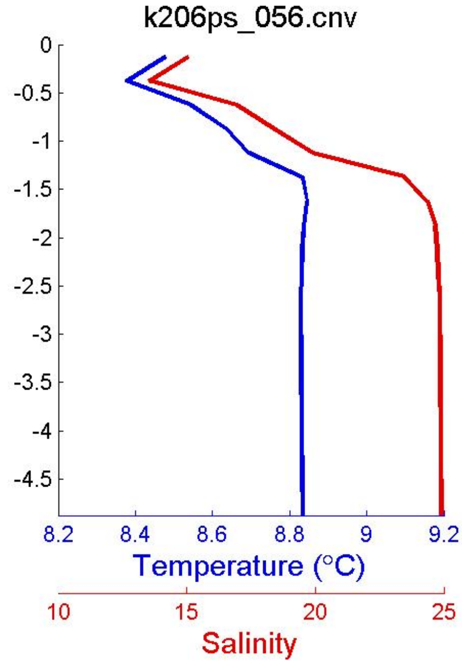

k206ps_048.cnv
Temperature (°C)
Salinity

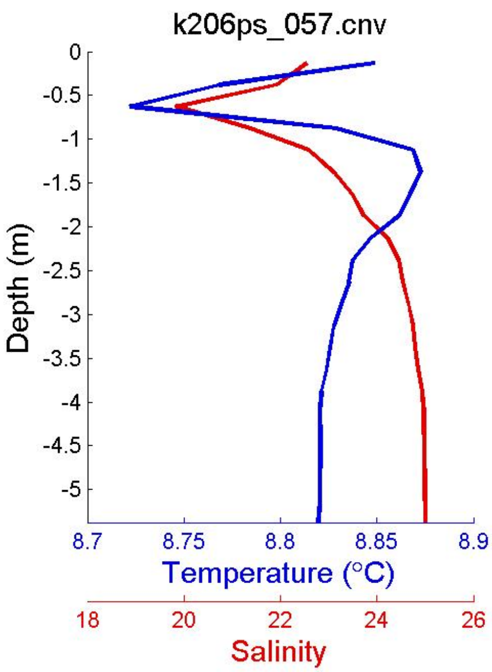

k206ps_049.cnv
Depth (m)
Temperature (°C)
Salinity

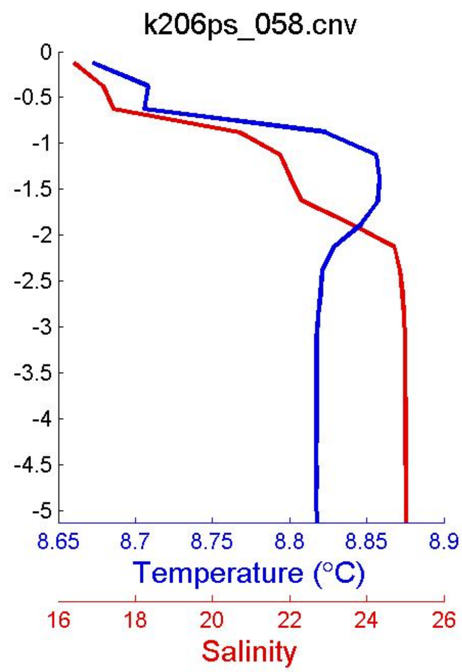

k206ps_050.cnv
Temperature (°C)
Salinity

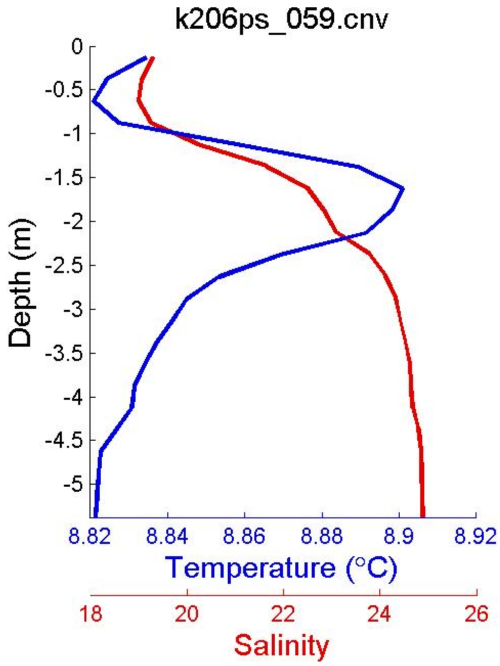

k206ps_051.cnv
k206ps_052.cnv
k206ps_053.cnv
k206ps_054.cnv
Depth (m)
Temperature (°C)
Salinity

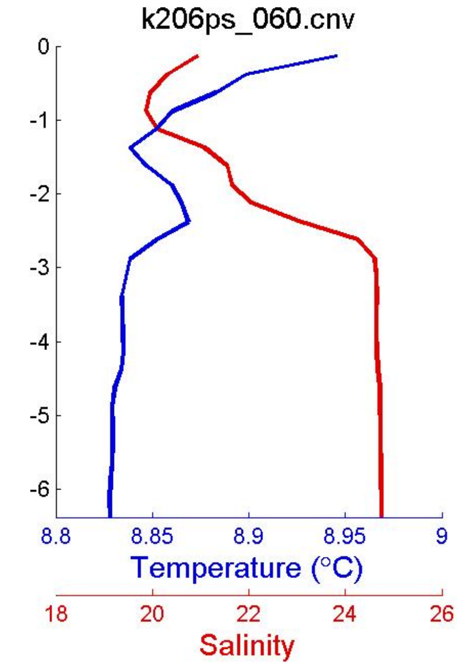

k206ps_055.cnv
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
8.5 8.6 8.7 8.8 8.9 9
Temperature (°C)
15 20 25
Salinity

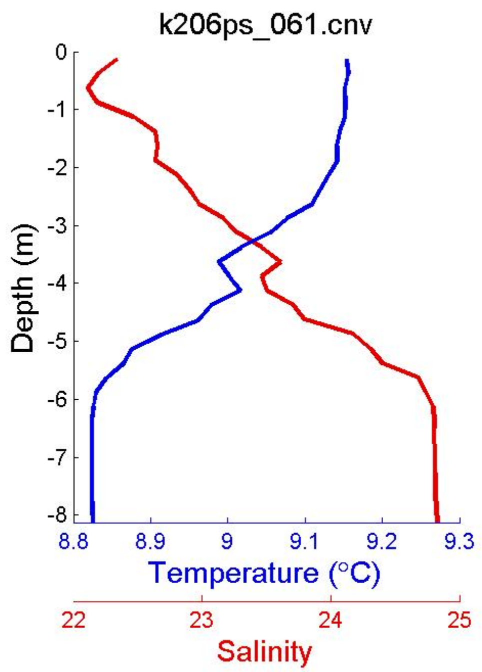

k206ps_056.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
8.2 8.4 8.6 8.8 9 9.2
Temperature (°C)
10 15 20 25
Salinity

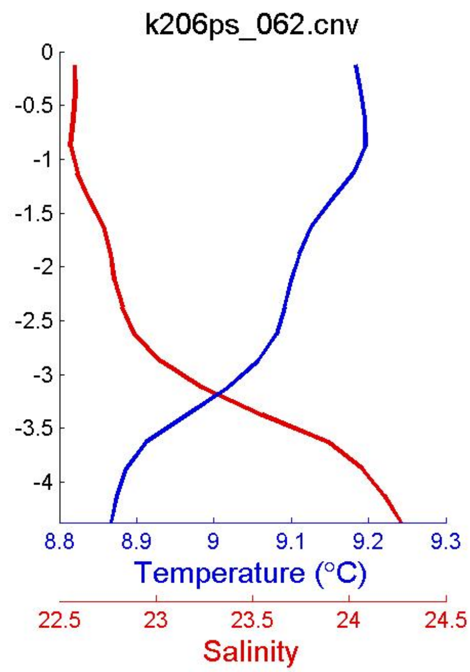

k206ps_057.cnv
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
8.7 8.75 8.8 8.85 8.9
Temperature (°C)
18 20 22 24 26
Salinity

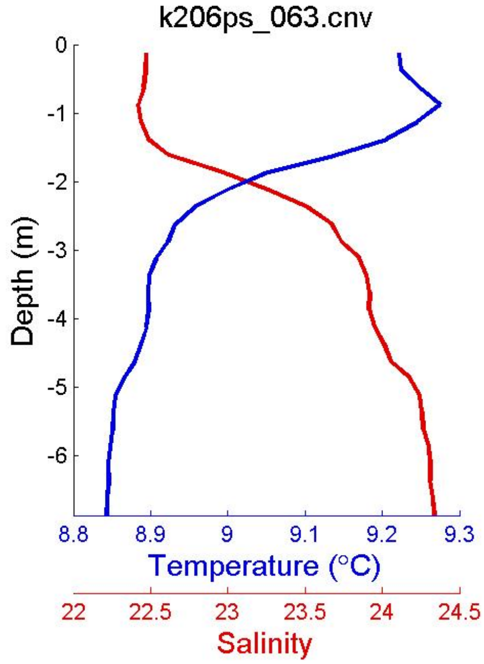

k206ps_058.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
8.65 8.7 8.75 8.8 8.85 8.9
Temperature (°C)
16 18 20 22 24 26
Salinity

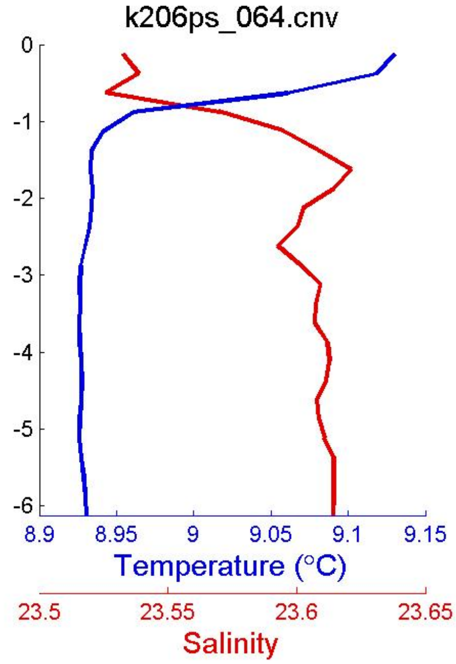

k206ps_059.cnv
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
8.82 8.84 8.86 8.88 8.9 8.92
Temperature (°C)
18 20 22 24 26
Salinity

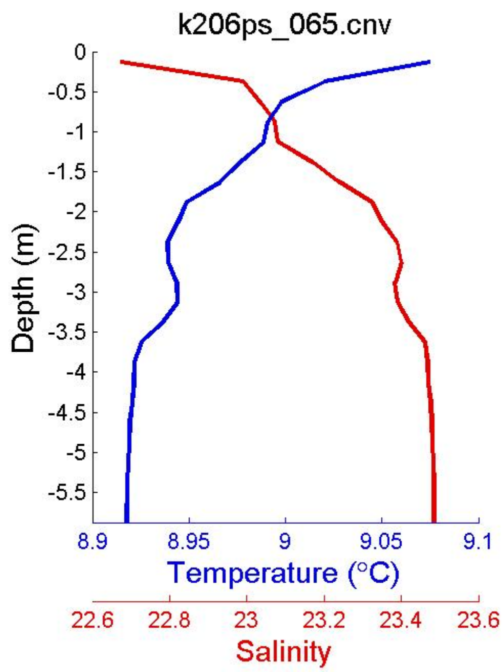

k206ps_060.cnv
0
-1
-2
-3
-4
-5
-6
8.8 8.85 8.9 8.95 9
Temperature (°C)
18 20 22 24 26
Salinity


k206ps_061.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
8.8 8.9 9 9.1 9.2 9.3
Temperature (°C)
22 23 24 25
Salinity


k206ps_062.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
8.8 8.9 9 9.1 9.2 9.3
Temperature (°C)
22.5 23 23.5 24 24.5
Salinity


k206ps_063.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
8.8
8.9
9
9.1
9.2
9.3
Temperature (°C)
22
22.5
23
23.5
24
24.5
Salinity


k206ps_064.cnv
0
-1
-2
-3
-4
-5
-6
8.9
8.95
9
9.05
9.1
9.15
Temperature (°C)
23.5
23.55
23.6
23.65
Salinity

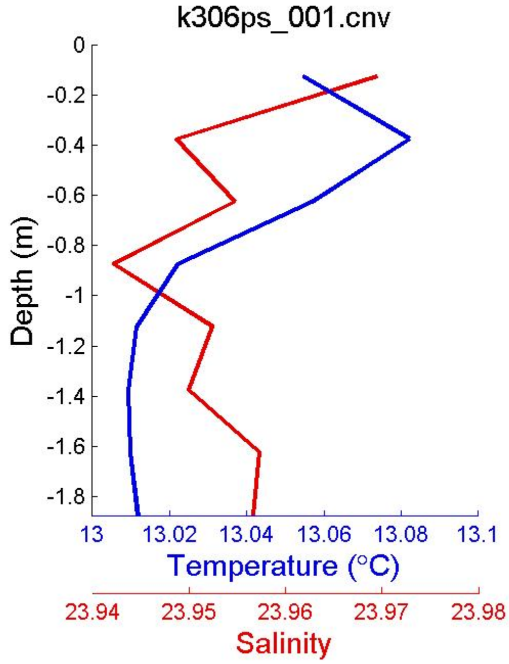

k206ps_065.cnv
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
8.9
8.95
9
9.05
9.1
Temperature (°C)
22.6
22.8
23
23.2
23.4
23.6
Salinity

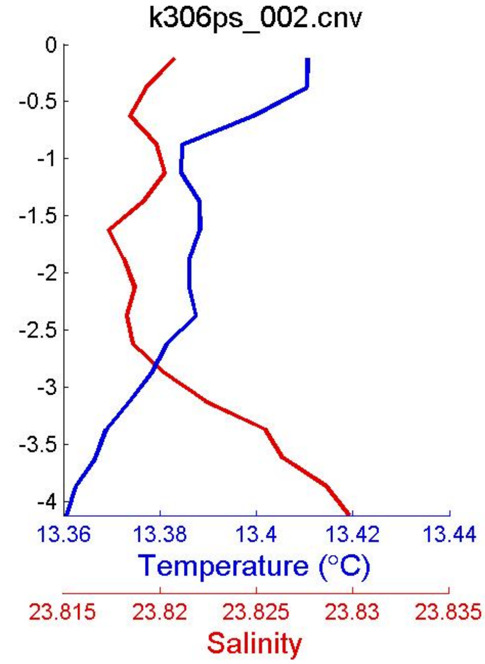
Appendix II. Conductivity, Temperature, Depth Profiles from U.S. Geological Survey Cruise Activity K-3-06-PS.

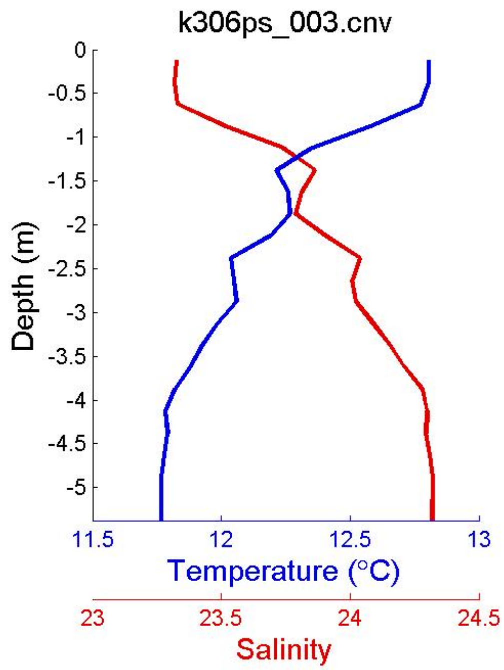
The following pages show individual plots of salinity and temperature with depth for the stations listed in the accompanying table collected during U.S. Geological Survey Cruise Activity K-3-06-PS.

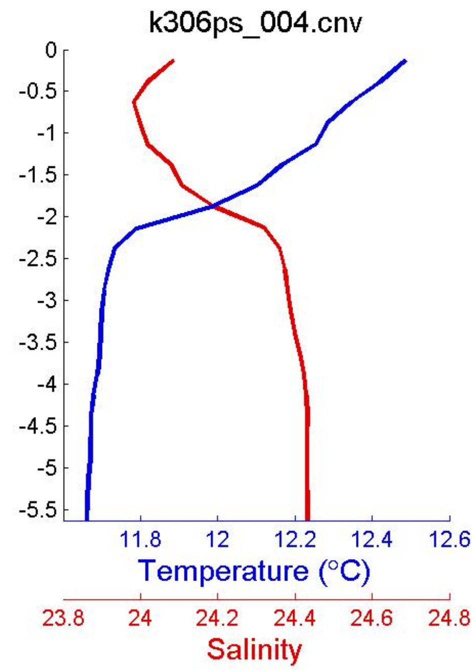
K-3-06-PS Conductivity, Temperature, Depth Measurement Log

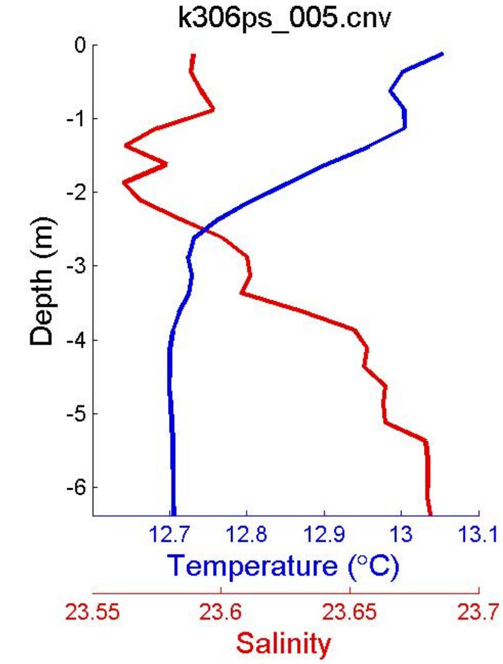
FILENAME	SITE	LON	LAT	UTC_DATETIME
k306ps_001	TRP_south	-122.50825	48.37711	5/14/2002 22:02
k306ps_002	G_Dock	-122.49643	48.39930	5/14/2002 22:44
k306ps_003	G_Dock	-122.49642	48.39925	5/15/2002 17:01
k306ps_004	Mooring_site	-122.50121	48.38692	5/15/2002 17:49
k306ps_005	TRP_north	-122.50772	48.44436	5/15/2002 18:34
k306ps_006	Tripod_SBS	-122.54442	48.34714	5/15/2002 22:35
k306ps_007	Tripod_SBN	-122.55787	48.36850	5/15/2002 23:12
k306ps_008	G_Dock	-122.49644	48.39926	5/16/2002 16:30
k306ps_009	Mooring_Site	-122.50115	48.38716	5/16/2002 17:41
k306ps_010	3B	-122.50935	48.37193	5/16/2002 18:03
k306ps_011	TRP_south	-122.50839	48.37689	5/16/2002 18:10
k306ps_012	Shelter_Bay	-122.50708	48.38200	5/16/2002 18:17
k306ps_013	Near53_Karluk	-122.49754	48.39159	5/16/2002 18:29
k306ps_014	G_Dock	-122.49643	48.39924	5/16/2002 18:41

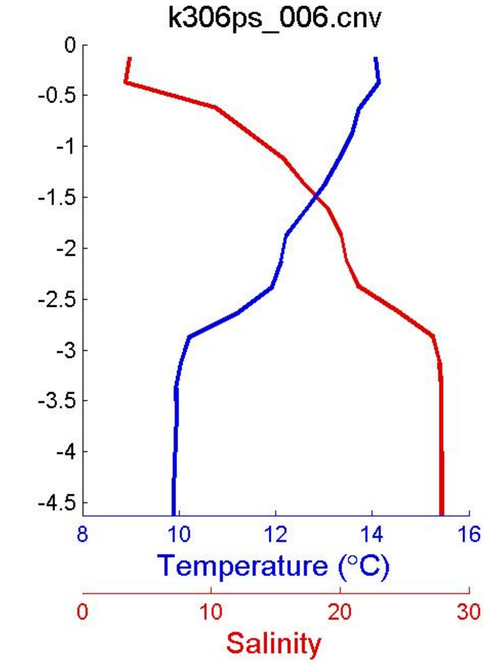

k306ps_001.cnv
Depth (m)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
13
13.02
13.04
13.06
13.08
13.1
Temperature (°C)
23.94
23.95
23.96
23.97
23.98
Salinity

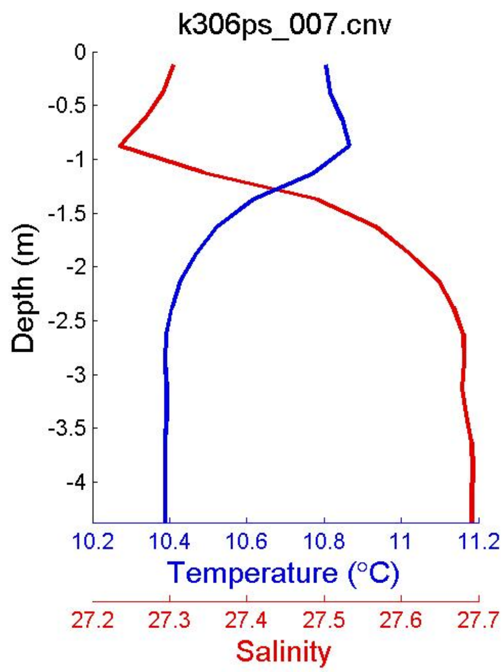

k306ps_002.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
13.36
13.38
13.4
13.42
13.44
Temperature (°C)
23.815
23.82
23.825
23.83
23.835
Salinity

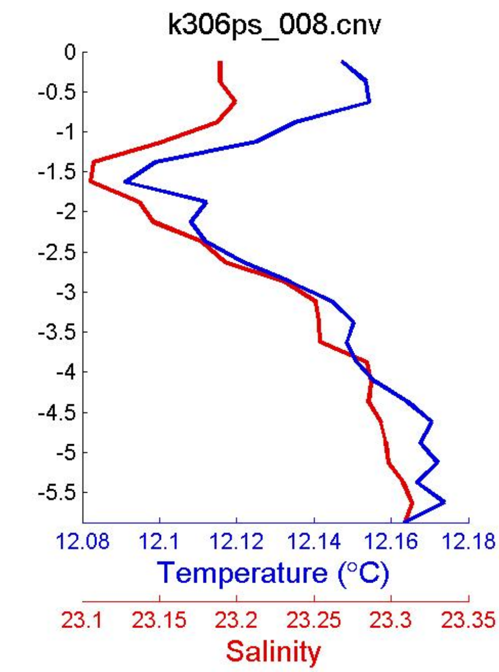

k306ps_003.cnv
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
11.5
12
12.5
13
Temperature (°C)
23
23.5
24
24.5
Salinity

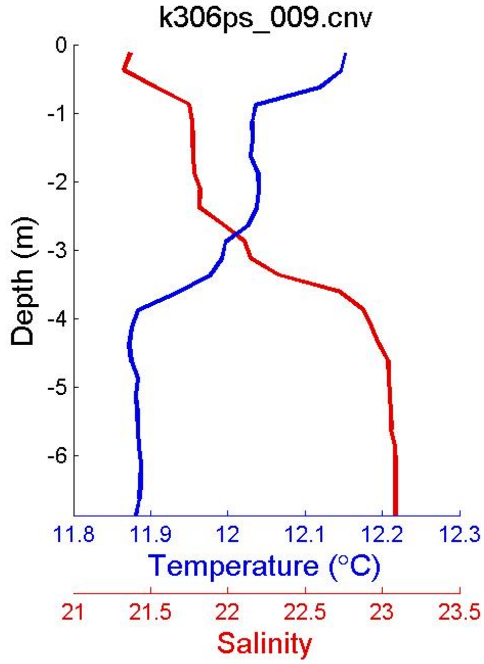

k306ps_004.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
11.8
12
12.2
12.4
12.6
Temperature (°C)
23.8
24
24.2
24.4
24.6
24.8
Salinity

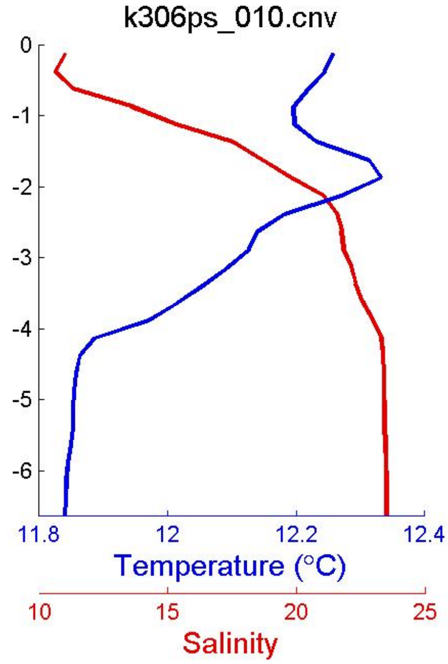

k306ps_005.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
12.7
12.8
12.9
13
13.1
Temperature (°C)
23.55
23.6
23.65
23.7
Salinity

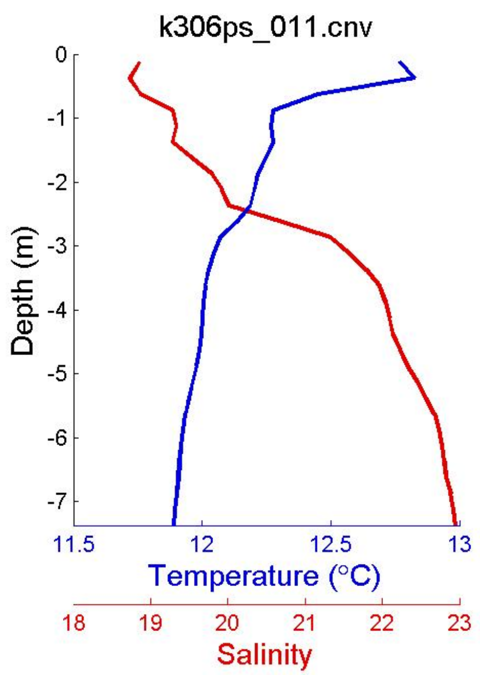

k306ps_006.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
8
10
12
14
16
Temperature (°C)
0
10
20
30
Salinity

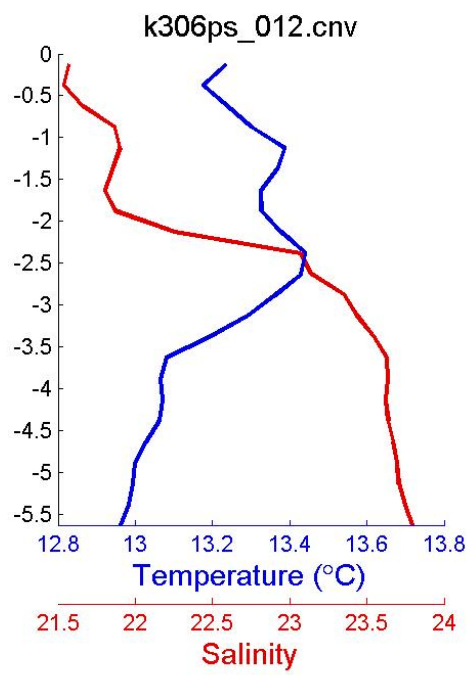

k306ps_007.cnv
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
10.2
10.4
10.6
10.8
11
11.2
Temperature (°C)
27.2
27.3
27.4
27.5
27.6
27.7
Salinity

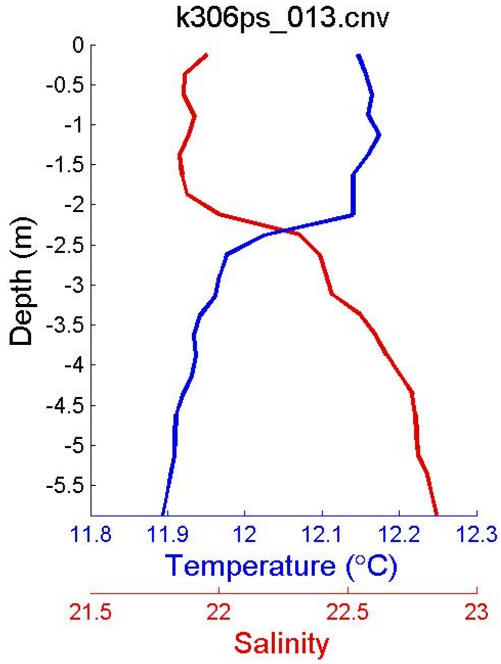

k306ps_008.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
12.08
12.1
12.12
12.14
12.16
12.18
Temperature (°C)
23.1
23.15
23.2
23.25
23.3
23.35
Salinity

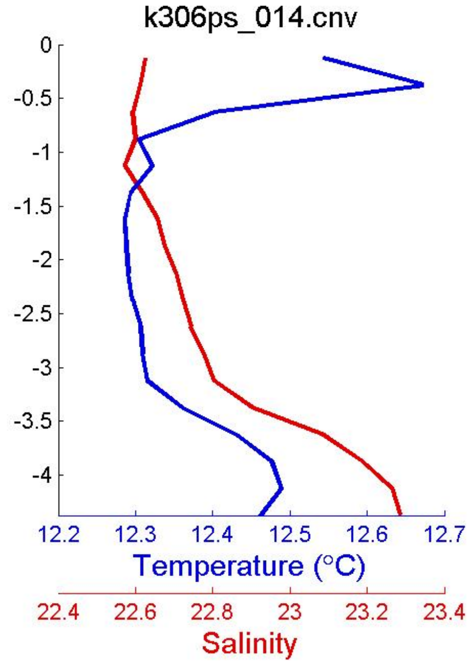

k306ps_009.cnv
Depth (m)
Temperature (°C)
Salinity


k306ps_010.cnv
Temperature (°C)
Salinity


k306ps_011.cnv
Depth (m)
Temperature (°C)
Salinity


k306ps_012.cnv
Temperature (°C)
Salinity


k306ps_013.cnv
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
11.8 11.9 12 12.1 12.2 12.3
Temperature (°C)
21.5 22 22.5 23
Salinity

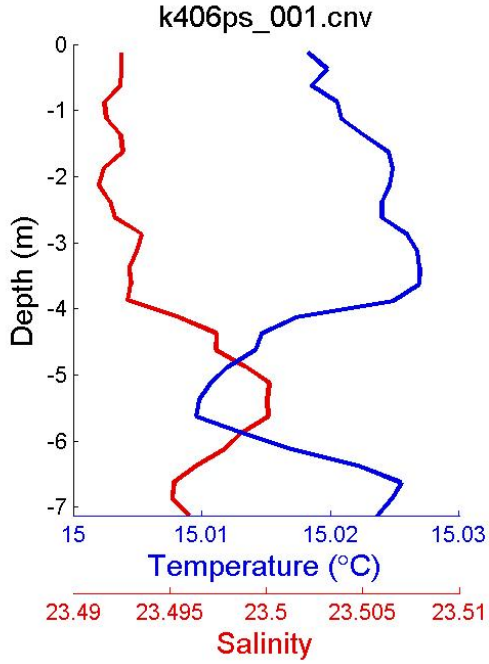

k306ps_014.cnv
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
12.2 12.3 12.4 12.5 12.6 12.7
Temperature (°C)
22.4 22.6 22.8 23 23.2 23.4
Salinity

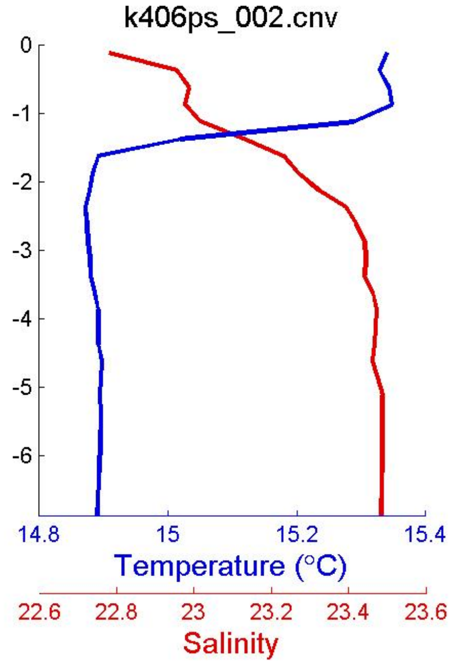
Appendix III. Conductivity, Temperature, Depth Profiles from U.S. Geological Survey Cruise Activity K-4-06-PS.

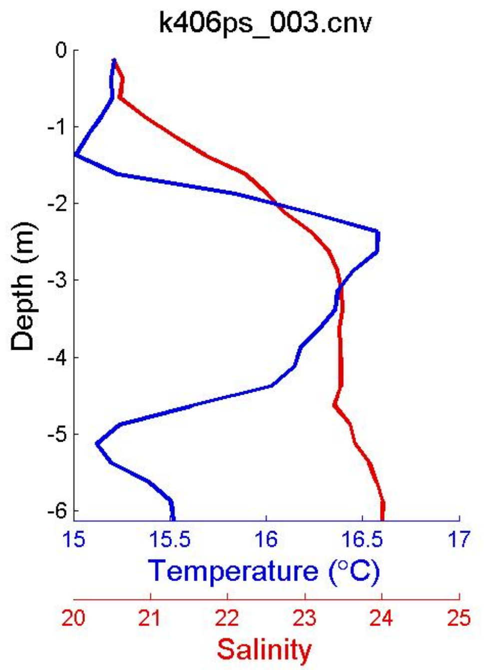
The following pages show individual plots of salinity and temperature with depth for the stations listed in the accompanying table collected during U.S. Geological Survey Cruise Activity K-4-06-PS.

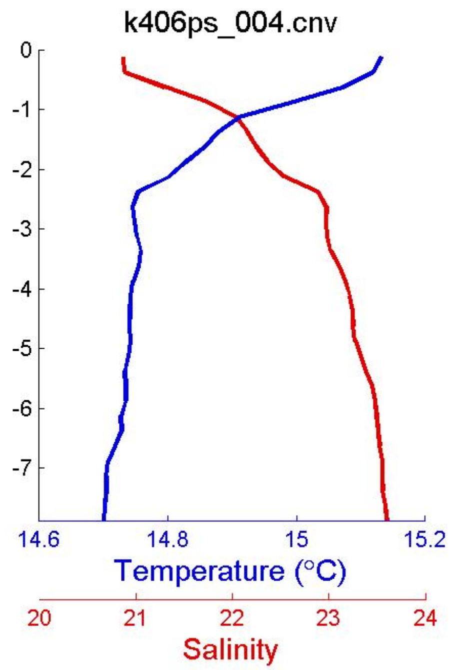
K-4-06-PS Conductivity, Temperature, Depth Measurement Log

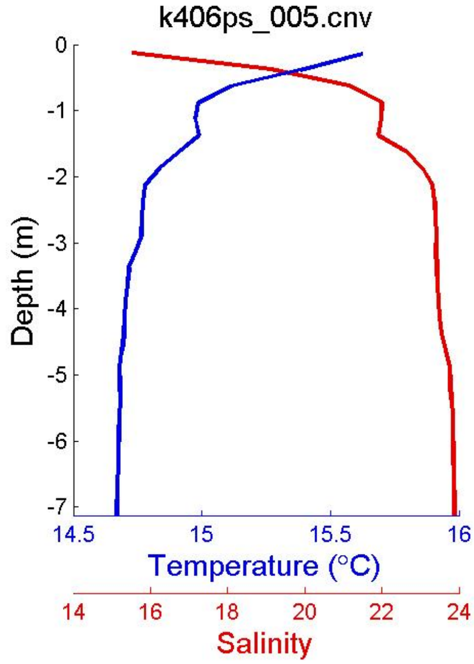
FILENAME	SITE	LON	LAT	UTC_DATETIME
k406ps_001	F_dock	-122.49687	48.39486	7/26/2006 15:54
k406ps_002	Bridge	-122.50171	48.38706	7/26/2006 16:12
k406ps_003	Shelter_Bay	-122.50707	48.38234	7/26/2006 16:22
k406ps_004	TRS	-122.50868	48.37667	7/26/2006 16:30
k406ps_005	5B	-122.51010	48.37462	7/26/2006 16:36
k406ps_006	3B	-122.50920	48.37236	7/26/2006 16:41
k406ps_007	60	-122.51043	48.37098	7/26/2006 16:52
k406ps_008	4B	-122.51548	48.37009	7/26/2006 16:58
k406ps_009	offshoreSBS	-122.54440	48.34676	7/26/2006 17:45
k406ps_010	SBN	-122.55781	48.36827	7/26/2006 18:55
k406ps_011	4B	-122.51545	48.36987	7/26/2006 20:24
k406ps_012	60	-122.51028	48.37107	7/26/2006 20:28
k406ps_013	3B	-122.50920	48.37236	7/26/2006 20:45
k406ps_014	5B	-122.51017	48.37458	7/26/2006 20:43
k406ps_015	TRS	-122.50837	48.37690	7/26/2006 20:46
k406ps_016	Shelter_Bay	-122.50696	48.38241	7/26/2006 20:52
k406ps_017	Bridge	-122.50165	48.38733	7/26/2006 20:59
k406ps_018	F_dock	-122.49680	48.39628	7/26/2006 21:18

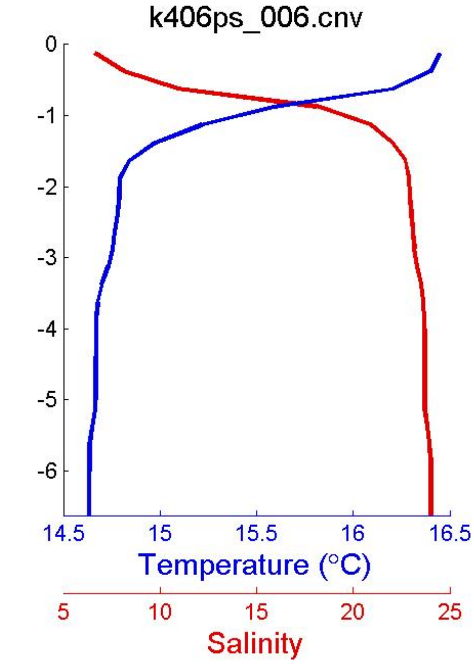

k406ps_001.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
15
15.01
15.02
15.03
Temperature (°C)
23.49
23.495
23.5
23.505
23.51
Salinity

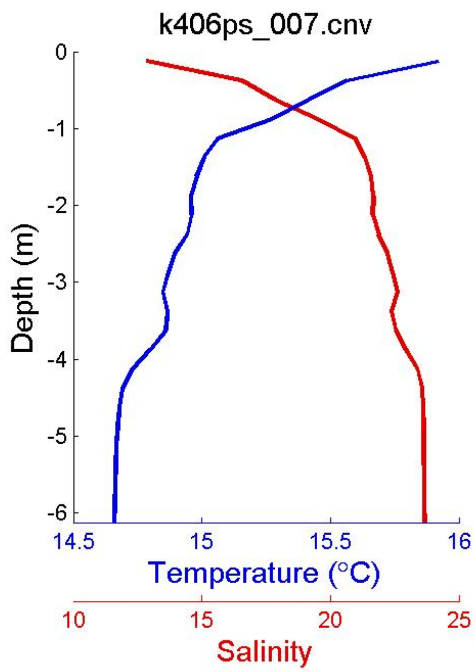

k406ps_002.cnv
0
-1
-2
-3
-4
-5
-6
14.8
15
15.2
15.4
Temperature (°C)
22.6
22.8
23
23.2
23.4
23.6
Salinity

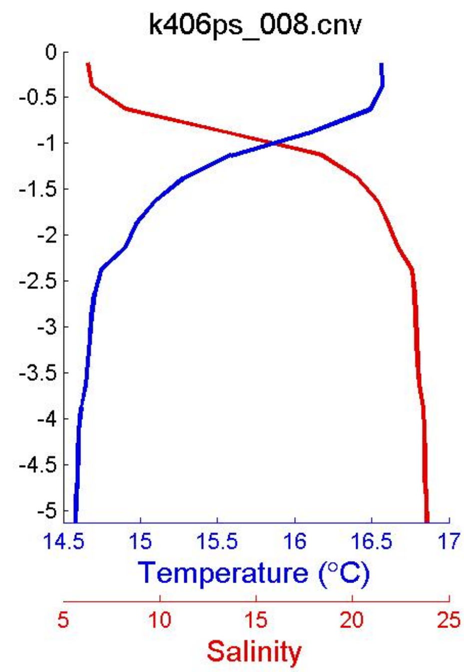

k406ps_003.cnv
Depth (m)
0
-1
-2
-3
-4
-5
-6
15
15.5
16
16.5
17
Temperature (°C)
20
21
22
23
24
25
Salinity

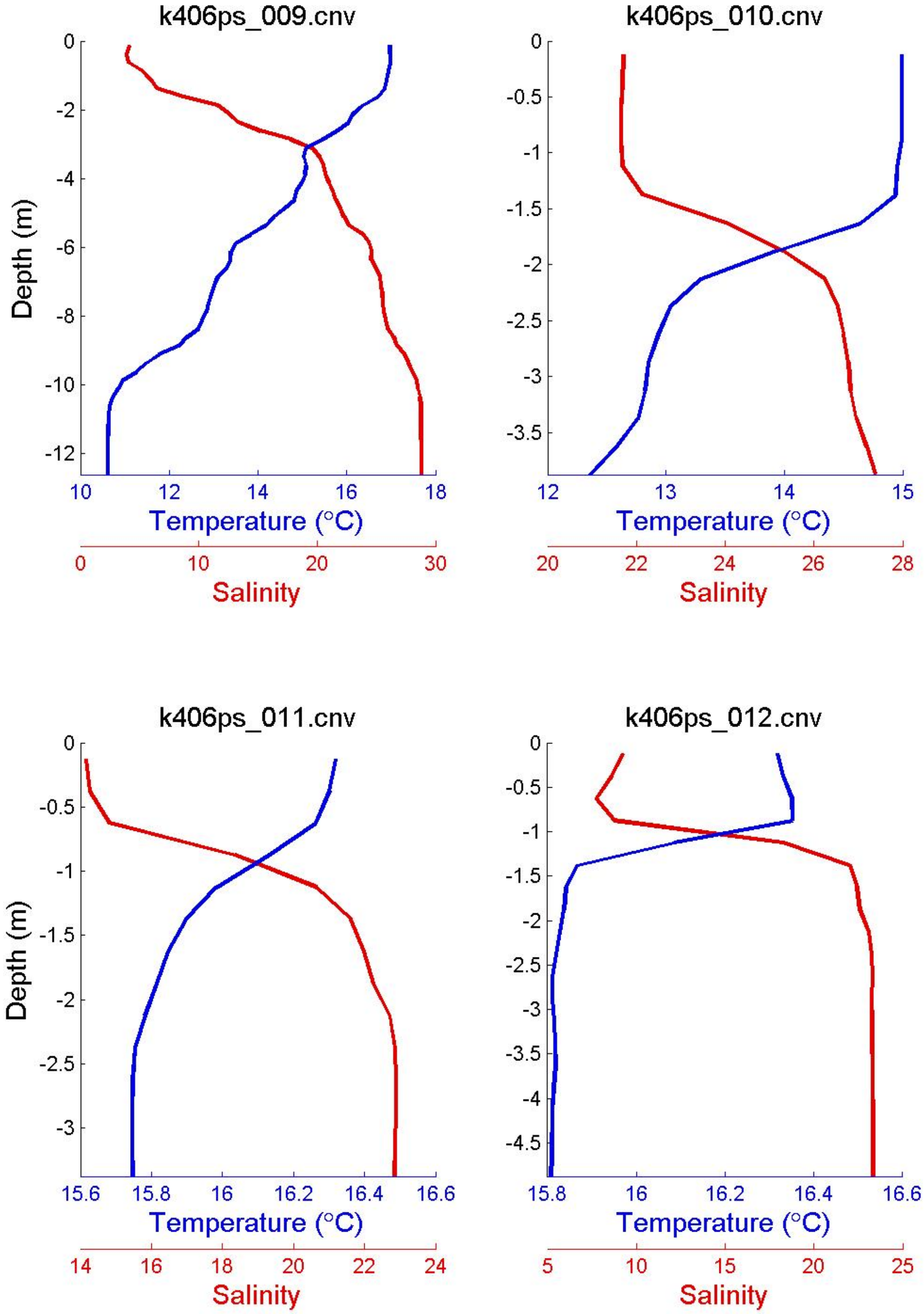

k406ps_004.cnv
0
-1
-2
-3
-4
-5
-6
-7
14.6
14.8
15
15.2
Temperature (°C)
20
21
22
23
24
Salinity

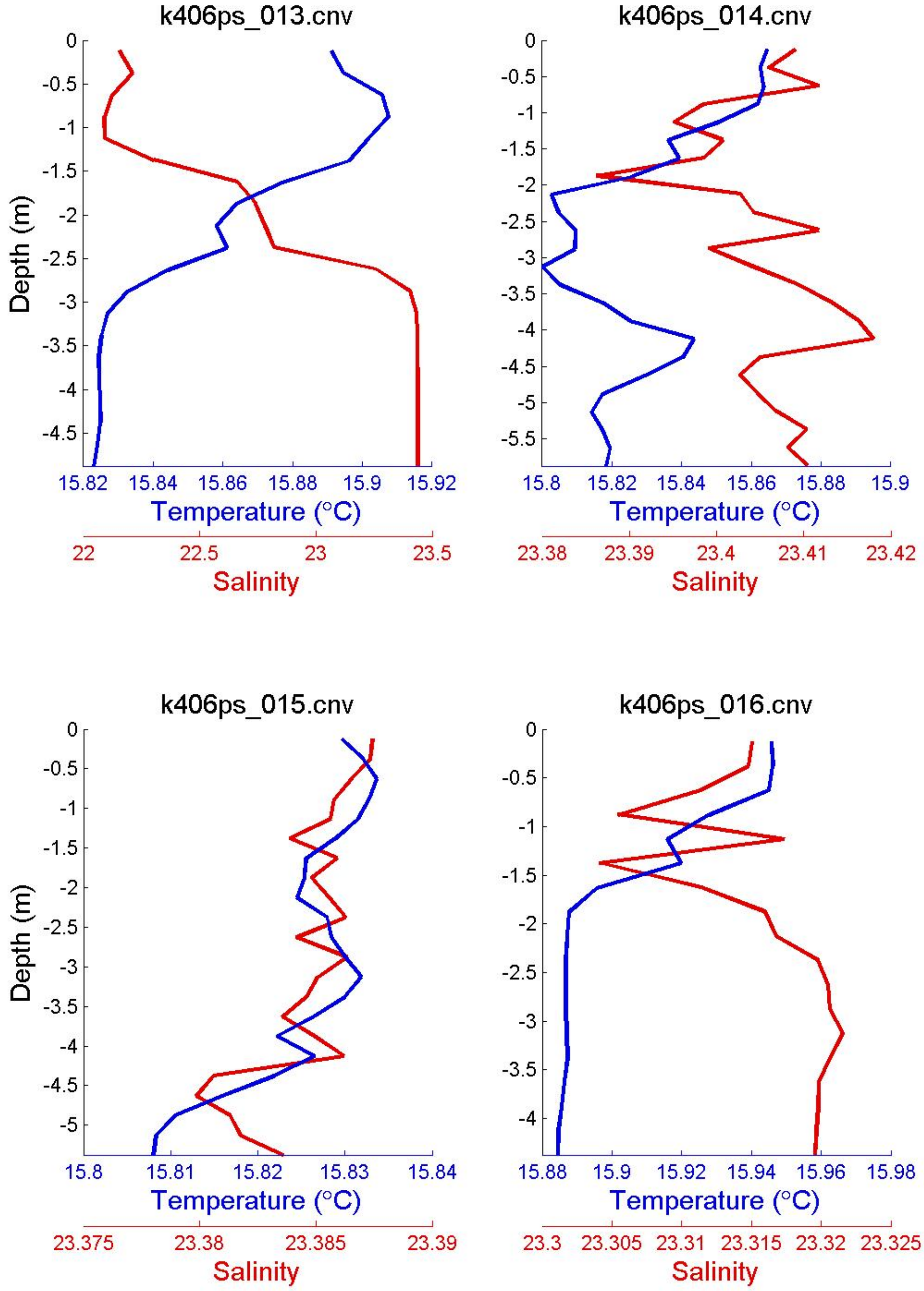

k406ps_005.cnv
Depth (m)
Temperature (°C)
Salinity

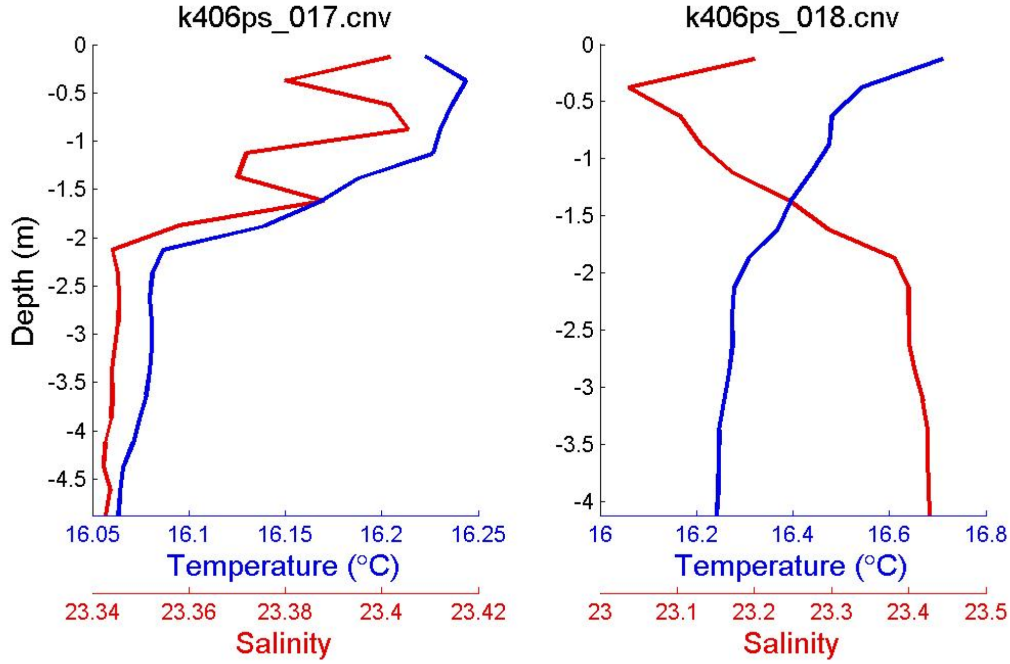

k406ps_006.cnv
Temperature (°C)
Salinity


k406ps_007.cnv
Depth (m)
Temperature (°C)
Salinity


k406ps_008.cnv
Temperature (°C)
Salinity


k406ps_009.cnv
k406ps_010.cnv
k406ps_011.cnv
k406ps_012.cnv
Depth (m)
Temperature (°C)
Salinity


k406ps_013.cnv
k406ps_014.cnv
k406ps_015.cnv
k406ps_016.cnv
Depth (m)
Temperature (°C)
Salinity


k406ps_017.cnv
k406ps_018.cnv
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
16.05 16.1 16.15 16.2 16.25
Temperature (°C)
23.34 23.36 23.38 23.4 23.42
Salinity
16 16.2 16.4 16.6 16.8
Temperature (°C)
23 23.1 23.2 23.3 23.4 23.5
Salinity

Appendix IV. Metadata

```
Metadata:
  Identification_Information:
    Citation:
      Citation_Information:
        Originator: Grossman. E.E., Stevens, A., and Gelfenbaum, G.
        Publication_Date: 2007
        Title:
          Nearshore circulation and water column properties
          in the Skagit River Delta, Northern Puget Sound,
          Washington: Tables and profiles
        Geospatial_Data_Presentation_Form: spreadsheet
        Larger_Work_Citation:
          Citation_Information:
            Originator: Grossman. E.E., Stevens, A., and Gelfenbaum, G.
            Publication_Date: 2007
            Title:
              Nearshore circulation and water column properties
              in the Skagit River Delta, Northern Puget Sound, Washington
            Geospatial_Data_Presentation_Form: spreadsheet
            Series_Information:
              Series_Name: Scientific Investigations Report
              Issue_Identification: 2007-5120
            Publication_Information:
              Publication_Place: Menlo Park, CA
              Publisher:
                U.S. Geological Survey, Coastal and Marine Geology Program
            Online_Linkage: http://pubs.usgs.gov/sir/2007/5120/
    Description:
      Abstract:
        Nearshore currents, tides, surface water temperature and salinity were
         measured at two locations continuously and at many discrete stations
         periodically throughout the Swinomish Channel between March 28 and July
         26, 2006 to examine circulation, transport and mixing of fresh water
         along a principal Chinook salmon migratory pathway during their spring
         outmigration. Results indicate that a significant spatial salinity
         gradient (14 psu) exists between the North Fork Skagit River and
         essential forage habitat in Padilla Bay that likely presents a
         formidable physiological barrier for Chinook smolts. Strong net
         northward current flow in Swinomish Channel driven by semi-diurnal
         tides, results in rapid (3.75-6.00 hr) transport of water and passive
         particles along the 11-km salinity gradient ~20percent of the time.
       Juvenile
         salmonids unable to swim against high currents may experience changes
         in salinity of several parts per thousand each hour during strong
         northward flow.
      Purpose:
        These data were collected as part of a Washington State Salmon Recovery
         Board funded project to examine nearshore circulation in the Swinomish
         Channel and the feasibility of re-introducing a connection between the
         North Fork Skagit River and Swinomish Channel for fish passage and
         Fresh water supply.
    Time_Period_of_Content:
      Time_Period_Information:
        Range_of_Dates/Times:
          Beginning_Date: 20060328
          Ending_Date: 20060726
      Currentness_Reference: ground condition
    Status:
      Progress: Complete
```

```
  Maintenance_and_Update_Frequency: None planned
Spatial_Domain:
  Bounding_Coordinates:
    West_Bounding_Coordinate: -122.55941
    East_Bounding_Coordinate: -122.49642
    North_Bounding_Coordinate: 48.45912
    South_Bounding_Coordinate: 48.34676
Keywords:
  Theme:
    Theme_Keyword_Thesaurus: ISO 19115 Topic Category
    Theme_Keyword: geoscientificinformation
    Theme_Keyword: inlandWaters
  Theme:
    Theme_Keyword_Thesaurus: none
    Theme_Keyword: nearshore circulation
    Theme_Keyword: water column properties
    Theme_Keyword: conductivity
    Theme_Keyword: temperature
    Theme_Keyword: depth
  Place:
    Place_Keyword_Thesaurus: General
    Place_Keyword: Swinomish Channel
    Place_Keyword: Northern Puget Sound
  Place:
    Place_Keyword_Thesaurus:
      Geographic Names Information System (GNIS)
    Place_Keyword: Skagit River
    Place_Keyword: Puget Sound
    Place_Keyword: Washington
Access_Constraints: None
Use_Constraints:
  Public domain data are freely redistributable
  with proper metadata and source attribution.
  Please recognize the U.S. Geological Survey (USGS)
  as the source of this information.
Point_of_Contact:
  Contact_Information:
    Contact_Organization_Primary:
      Contact_Organization: U.S. Geological Survey
      Contact_Person: Eric E. Grossman
    Contact_Address:
      Address_Type: mailing and physical address
      Address: 400 Natural Bridges Dr
      City: Santa Cruz
      State_or_Province: CA
      Postal_Code: 94060-5792
      Country: USA
    Contact_Voice_Telephone: (831)427-4725
    Contact_Facsimile_Telephone: (831)427-4748
    Contact_Electronic_Mail_Address: egrossman@usgs.gov
Browse_Graphic:
  Browse_Graphic_File_Name:
    http://walrus.wr.usgs.gov/infobank/k/k206ps/html/k-2-06-ps.nav.html
  Browse_Graphic_File_Description:
    Image showing location and extent of K-2-06-PS data.
  Browse_Graphic_File_Type: GIF
Browse_Graphic:
  Browse_Graphic_File_Name:
    http://walrus.wr.usgs.gov/infobank/k/k306ps/html/k-3-06-ps.nav.html
  Browse_Graphic_File_Description:
    Image showing location and extent of K-3-06-PS data.
  Browse_Graphic_File_Type: GIF
Browse_Graphic:
```

```
    Browse_Graphic_File_Name:
      http://walrus.wr.usgs.gov/infobank/k/k406ps/html/k-4-06-ps.nav.html
    Browse_Graphic_File_Description:
      Image showing location and extent of K-4-06-PS data.
    Browse_Graphic_File_Type: GIF
  Cross_Reference:
    Citation_Information:
      Originator:
        U.S. Geological Survey, Coastal and Marine Geology Program
      Publication_Date: 2007
      Title: InfoBank
      Online_Linkage:
        http://walrus.wr.usgs.gov/infobank/k/k206ps/html/k-2-06-ps.meta.html
        http://walrus.wr.usgs.gov/infobank/k/k306ps/html/k-3-06-ps.meta.html
        http://walrus.wr.usgs.gov/infobank/k/k406ps/html/k-4-06-ps.meta.html
Data_Quality_Information:
  Logical_Consistency_Report:
    The time-series measurements of currents and physical water properties
     Were made at two discrete tripod locations, while the surface temperature
     And salinity were made continuously at the Rainbow Bridge only. In
     contrast, individual CTD casts were made over a much broader spatial
     coverage but at discrete points in time and are used to develop a better
     understanding of spatial variability under processes constrained at the
     fixed tripod and mooring locations.
  Completeness_Report:
    All data from current, tide, and physical water property measurements
     Were included in analyses after verification and quality control
     procedures were made to ensure that data contained valid clock times and
     station location information.
  Lineage:
    Process_Step:
      Process_Description:
        Current meter data were quality checked for accurate clock times and
       non-valid data points (above water) were removed. The east and north
       components of velocity were rotated to account for the site-specific
       variation in magnetic declination (17.8 °E), then rotated into along
       and across- channel components using principle component analysis
       (PCA). A standard (33-hr) low-pass filter was then applied to the
       rotated velocities to plot current patterns occurring at subtidal
       frequencies. Cumulative along-channel transport was calculated by
       taking the cumulative sum of the product of the along-channel velocity
       component and Δt. CTD measurements were processed with standard
       Seabird protocols using Seabird calibrations and correcting for
       surface soak and instrument priming. Measurements were averaged at
       0.25-m depth intervals and merged with navigation, environmental data
       (tide stage, winds, river discharge), and current measurements. Roving
       ADCP data were processed with WinRiver software following USGS
       protocols of Oberg et al (2005).
      Process_Date: 2007
Spatial_Data_Organization_Information:
  Direct_Spatial_Reference_Method: Point
Spatial_Reference_Information:
  Horizontal_Coordinate_System_Definition:
    Geographic:
      Latitude_Resolution: 0.00001
      Longitude_Resolution: 0.00001
      Geographic_Coordinate_Units: Decimal degrees
  Vertical_Coordinate_System_Definition:
    Depth_System_Definition:
      Depth_Datum_Name: Local surface
      Depth_Resolution: 0.1
      Depth_Distance_Units: meters
      Depth_Encoding_Method: Implicit coordinate
```

```
Entity_and_Attribute_Information:
  Detailed_Description:
    Entity_Type:
      Entity_Type_Label: Filename
      Entity_Type_Definition:
        name of water column profile file for a station
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: LocalTime
      Entity_Type_Definition:
        month/day/year hour:minute of survey at a station
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: Tide
      Entity_Type_Definition:
        tide level in meters (m) for a station
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: TideState
      Entity_Type_Definition:
        tide state for a station
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: RiverFlow
      Entity_Type_Definition:
        river flow rate in cubic feet per second (cfs) for a station
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: Current
      Entity_Type_Definition:
        current velocity in centimeters per second (cm/s) for a station
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: Direction
      Entity_Type_Definition:
        direction of the current in degrees (degrees) for a station
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: Depth
      Entity_Type_Definition:
        depth in meters (m) for a station or site
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: Salinity
      Entity_Type_Definition:
        salinity in practical salinity units (psu) for a station or site
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: FILENAME
      Entity_Type_Definition:
        name of CTD log profile file for a site
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: SITE
      Entity_Type_Definition:
        name of a site
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: LON
      Entity_Type_Definition:
        longitude of CTD tripod at a site
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
```

```
      Entity_Type_Label: LAT
      Entity_Type_Definition:
        latitude of CTD tripod at a site
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: UTC_DATETIME
      Entity_Type_Definition:
        month/day/year hour:minute of survey at a site
      Entity_Type_Definition_Source: U.S. Geological Survey
    Entity_Type:
      Entity_Type_Label: Temperature
      Entity_Type_Definition:
        temperature in degrees Centigrade (¡C) for a site
      Entity_Type_Definition_Source: U.S. Geological Survey
Distribution_Information:
  Distributor:
    Contact_Information:
      Contact_Organization_Primary:
        Contact_Organization: U.S. Geological Survey
        Contact_Person: Eric E. Grossman
      Contact_Address:
        Address_Type: mailing and physical address
        Address: 400 Natural Bridges Dr
        City: Santa Cruz
        State_or_Province: CA
        Postal_Code: 94060-5792
        Country: USA
      Contact_Voice_Telephone: (831)427-4725
      Contact_Facsimile_Telephone: (831)427-4748
      Contact_Electronic_Mail_Address: egrossman@usgs.gov
  Distribution_Liability:
    Although all data have been used by the USGS,
    no warranty, expressed or implied, is made by the USGS
    as to the accuracy of the data and/or related materials.
    The act of distribution shall not constitute any such warranty,
    and no responsibility is assumed by the USGS in the use
    of these data or related materials.

    Any use of trade, product, or firm names is
    for descriptive purposes only and does not imply
    endorsement by the U.S. Government.
Metadata_Reference_Information:
  Metadata_Date: 20070515
  Metadata_Contact:
    Contact_Information:
      Contact_Organization_Primary:
        Contact_Organization: U.S. Geological Survey
        Contact_Person: Eric E. Grossman
      Contact_Address:
        Address_Type: mailing and physical address
        Address: 400 Natural Bridges Dr
        City: Santa Cruz
        State_or_Province: CA
        Postal_Code: 94060-5792
        Country: USA
      Contact_Voice_Telephone: (831)427-4725
      Contact_Facsimile_Telephone: (831)427-4748
      Contact_Electronic_Mail_Address: egrossman @usgs.gov
  Metadata_Standard_Name:
    FGDC Content Standards for Digital Geospatial Metadata
  Metadata_Standard_Version: FGDC-STD-001-1998
```