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Analysis of Physical Oceanographic Data from Bonne Bay, September 2002 – September 2004

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Abstract

10 Acoustic Doppler Current Profilers were deployed between September 2002 and September 2004 on the sill of the East Arm in Bonne Bay, a glacial fjord in Gros Morne National Park on the west coast of Newfoundland. The moorings were deployed over the time period to measure the velocity of water flowing over the sill, in order to better understand the exchange dynamics of the system. In addition to the current meter data, several cruises were conducted in June 2004 to collect hydrographic data in the Bay, specifically temperature, salinity and density profiles. The data reveal the structure of the tidal flow over the sill and the interannual variability of the flow structure and transport. Meteorological data from the area are also presented.

Acknowledgements

We thank the crew and captain of the Louis M. Lauzier for their help in this oceanographic study. The hydrographic data were primarily collected by Drs. P. Snelgrove and D. Deibel. Funding for this project was provided from an NSERC Grant to B. de Young.

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Introduction

We are interested in the exchange over the sill of water between the east arm of Bonne Bay and the Gulf of St. Lawrence (see Figure 1). This exchange can be regulated by many different factors, including tides, wind stress, and freshwater runoff and largely determines the properties of deep water on the landward side of the sill.

The moorings were deployed on the sill to try and get a sense of the 3 dimensional nature of the flow. The 2002 and 2003 moorings were deployed directly on the bottom, while the 2004 moorings were about 1 metre above the bottom. The mooring positions for 2002, 2003 and 2004 are shown in Figures 2, 3 and 4. The moorings were arranged to provide the best coverage of the deepest part of the sill, approximately in the middle of it. Each ADCP was also equipped with a temperature sensor that measured the temperature of the water at the location of the instrument. The instruments were all RDI 4 beam sentinel ADCP's at a frequency of 300 kHz, except for M1-2003 and M2-2003 which were 1200 kHz and 600 kHz respectively.

In addition to the current data, meteorological data were obtained from Environment Canada for the period from January 1993 to June 2004 for the nearby weather monitoring station at Rocky Harbour. Meteorological data for the summer of 2004 were obtained from a weather monitoring station installed on the roof of the Bonne Bay Marine Station.

Also, during June of 2004 several cruises were conducted to gather temperature, salinity, and density data in the area surrounding the sill, in the arms of the bay, and out into the Gulf of St. Lawrence. A cruise on June 6th and 7th collected vertical and horizontal profiles on the sill over several tidal cycles. These data are presented as plots of temperature, salinity and σ_T at and between the two stations on either side of the sill. A similar cruise was performed between June 9th and 11th, but without the horizontal surface profile. These data are plotted as time series contours.

Data Processing

The ADCP data were processed in a manner similar to the approach of Tittensor et al. 2002. First the data were extracted from the instrument output files and missing data was interpolated linearly from the data surrounding it. The data were collected in 1 metre depth bins for most instruments, though M1-2003 and M2-2003 were sampling with 0.5 metre bins. The backscatter was corrected following standard techniques (Deines, 1999) utilizing factory-set instrument characteristics as well as environmental factors such as the sound absorption coefficient and the speed of sound at each depth cell. These parameters, together with the slant range to each depth cell, were then used in the sonar equation to estimate the backscatter coefficient. The velocity was then decomposed into *u* and *v* components, and filtered using a 5th order forward and reverse Butterworth low pass digital filter with a cut-off of 30 hours (along with the backscatter) and plotted. The data were also corrected for the changing surface elevation due to tides by adjusting the data from each time step according to the level of maximum backscatter intensity. The filtered and surface-corrected data were then plotted.

The hourly wind and air temperature data for Rocky Harbour were obtained from Environment Canada as a series of text files. The data were examined for large peaks which were manually removed, and any short gaps were linearly interpolated. The data were extracted from these files, decomposed into *u* and *v* components, then converted to wind stress (Gill, 1982) and re-saved in a MATLAB format. The data set for 1997 from Rocky Harbour was incomplete and so was substituted with data from CornerBrook. Also, for a short period in 1999 the anemometer malfunctioned, but because this period did not correspond with ADCP data period it was ignored. Wind data for the period from June 19th to September 19th 2004 was obtained from a weather station installed at the Bonne Bay Marine Station. The data were extracted from text files and missing points were interpolated.

Vertical CTD profiles were collected using an SBE-25 probe, while the horizontal surface profiles were collected with an SBE-19 probe. Only the temperature, salinity and density data are presented here. The CTD data were extracted from the instrument output text files and re-saved in a MATLAB format. The up-cast portion was removed, as was the part of the data from when the instrument was sitting at the surface. The raw data were then plotted in several different ways. The data from the June 6th sill survey were plotted as vertical and horizontal profiles of temperature, salinity, and σ_T. The data from the June 9th sill survey were plotted as a time series contour at the two stations on either side of the sill. The data from the South Arm, East Arm, and out into the Gulf of St. Lawrence were plotted as two-dimensional vertical contour maps.

An analysis of the major axis direction for each mooring was performed (Emery, 1998) and the results are shown in Figures 15, 16 and 17. By solving for the eigenvalues of the covariance matrix for the *u* and *v* velocities, the angle of the principle axis θ_p can be found using:

$$\tan(2\theta_p) = \frac{\overline{2u'v'}}{\overline{u'^2} - \overline{v'^2}}$$

where $u' = u - \bar{u}$ and $v' = v - \bar{v}$. The angles calculated through this process were then used to rotate the *u* and *v* axes for each depth at each mooring to visualize the through and cross channel velocities.

Tidal analysis for the moorings was performed using Foreman tidal analysis scripts for MATLAB (Pawlowicz, 2002) and the results for selected moorings are shown in Tables 2 and 3.

References

Deines, K. L., 1999: Backscatter estimation using broadband acoustic Doppler current profilers. *Proceeding of the IEEE 6th working conference on current measurement, San Diego, CA.*

Emery, W. J. and R. E. Thomson, 1997: *Data analysis methods in physical oceanography*. 1 ed. Elsevier Science Ltd.

Gill, A. E., 1982: *Atmosphere-ocean dynamics*. Vol. 30, *International Geophysics Series*, Academic Press.

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

Tittensor, D. P., B. de Young, and J. Foley, 2002: Analysis of physical oceanographic data from Trinity Bay, May - August 2002. *Physics and Physical Oceanography Data Report 2002-2*. Department of Physics & Physical Oceanography, Memorial University of Newfoundland.

Table 1: Location and summary of Bonne Bay 2002-2004 ADCP moorings

Mooring	Latitude (°N)	Longitude (°W)	Depth (m)	Averaging period	Bin size	Start day	End day
M1-2002	49 30.640	57 52.999	12	20 min	1m	Sept. 7 2002	Nov. 21 2002
M2-2002	49 30.769	57 53.002	27.4	20 min	1m	Nov. 22 2002	July 17 2003
M3-2002	49 30.757	57 53.002	27.4	20 min	1m	Sept. 7 2002	June 6 2003
M4-2002	49 30.816	57 52.954	15	20 min	1m	Sept. 7 2002	Nov. 21 2002
M1-2003	49 30.630	57 53.000	12.5	30 min	0.5m	Nov. 10 2003	May 30 2004
M2-2003	49 30.827	57 53.077	21	30 min	0.5m	Oct. 28 2003	June 14 2004
M3-2003	49 30.750	57 52.992	27.4	30 min	1m	Nov. 10 2003	June 19 2004
M4-2003	49 30.695	57 52.996	17.4	20 min	1m	July 19 2003	Apr. 30 2004
M1-2004	49 30.604	57 53.070	12	30 min	1m	June 16 2004	Sept. 16 2004
M2-2004	49 30.804	57 53.139	17	30 min	1m	June 16 2004	Sept. 17 2004

Table 2: Serial numbers and frequencies of Bonne Bay 2002-2004 moorings.

Mooring	Instrument Serial Number	Frequency
M1-2002	2460	300 kHz
M2-2002	2477	300 kHz
M3-2002	2459	300 kHz
M4-2002	0879	300 kHz
M1-2003	1336	1200 kHz
M2-2003	2069	600 kHz
M3-2003	2459	300 kHz
M4-2003	2477	300 kHz
M1-2004	2460	300 kHz
M2-2004	2477	300 kHz

Table 3: Amplitude (cm/s) of the major axis of selected tidal constituents of the current at a depth of 1m.

	M1-02	M2-02	M3-02	M4-02	M1-03	M2-03	M3-03	M4-03	M1-03	M2-03
O1	3.293	1.483	1.769	3.843	1.678	1.149	0.602	2.464	2.719	2.937
K1	2.558	2.298	2.298	2.452	1.658	1.218	0.99	2.714	2.579	3.308
N2	4.074	2.968	2.9	4.221	2.997	2.055	1.647	3.62	4.604	3.556
M2	18.526	17.26	15.684	19.683	14.193	10.371	8.693	18.069	23.280	19.757
S2	6.544	6.031	5.544	7.729	4.807	3.451	2.847	5.545	7.247	5.193
K2	--	2.624	1.825	--	1.717	1.574	1.266	2.05	--	--
M4	1.019	0.901	0.88	0.74	0.69	0.607	0.269	0.799	4.037	2.493

Table 4: Amplitude (cm/s) of the minor axis of selected tidal constituents of the current at a depth of 1m.

	M1-02	M2-02	M3-02	M4-02	M1-03	M2-03	M3-03	M4-03	M1-03	M2-03
O1	-0.273	-0.164	-0.243	-0.196	-0.032	0.045	-0.021	0.017	0.016	0.043
K1	-0.025	0.033	-0.103	0.076	0.180	-0.042	0.203	0.012	-0.192	0.184
N2	-0.192	-0.079	-0.280	0.098	0.099	0.094	-0.050	0.109	-0.023	-0.163
M2	-0.448	-0.016	-0.393	0.220	0.463	-0.022	-0.185	-0.369	-0.918	-0.498
S2	-0.070	0.036	0.007	-0.064	-0.005	0.021	0.158	-0.454	-0.059	-0.293
K2	--	-0.062	-0.067	--	0.181	0.135	0.046	0.108	--	--
M4	-0.291	0.142	0.050	0.403	-0.029	0.164	0.044	-0.227	0.075	0.462

Table 5: Phase (degrees relative to Greenwich) of selected tidal constituents of the current at a depth of 1m.

	M1-2002	M2-2002	M3-2002	M4-2002	M1-2003	M2-2003	M3-2003	M4-2003
O1	5.6	263.81	194.03	101.96	324.44	184.51	246	346.69
K1	3.53	43.95	196.52	227.98	301.86	80.81	316.09	12.34
N2	20.25	269.54	53.06	87.66	92.12	122.93	191.82	202.43
M2	4.56	287.46	10.04	163.02	251.86	67.1	208.62	16.94
S2	12.21	244.33	110.96	142.79	307.45	95.52	20.14	20.88
K2	--	85.51	220.7	--	54.76	180.84	110.61	248.2
M4	35.03	204.9	339.62	91.9	331.61	131.01	9.97	12.81

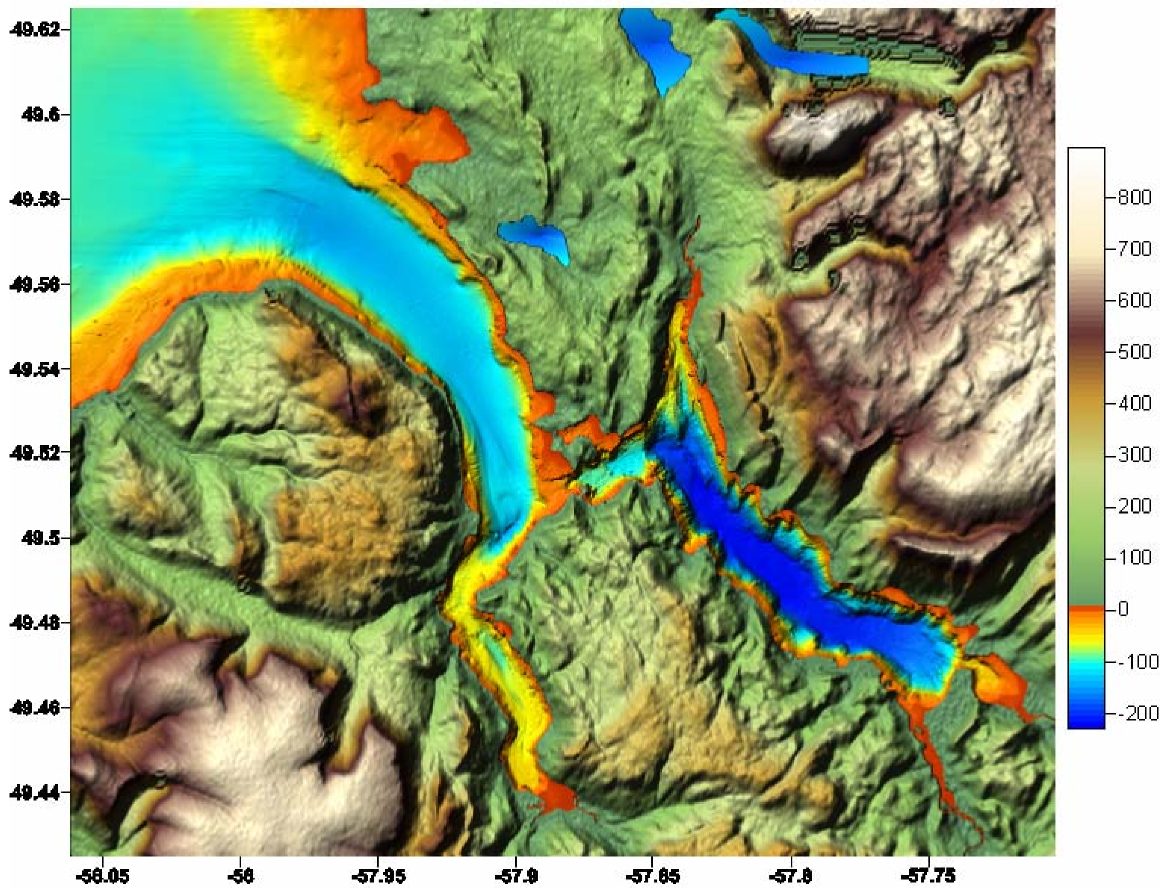

Figure 1: Bathymetry and topography of the Bonne Bay region. Bathymetry data obtained from the Geological Survey of Canada and the digitization of Chart 4658, topography data from the Shuttle Radar Topography Mission by the U.S. Geological Survey. Distance between grid points in the data set is approximately 4.3 metres.

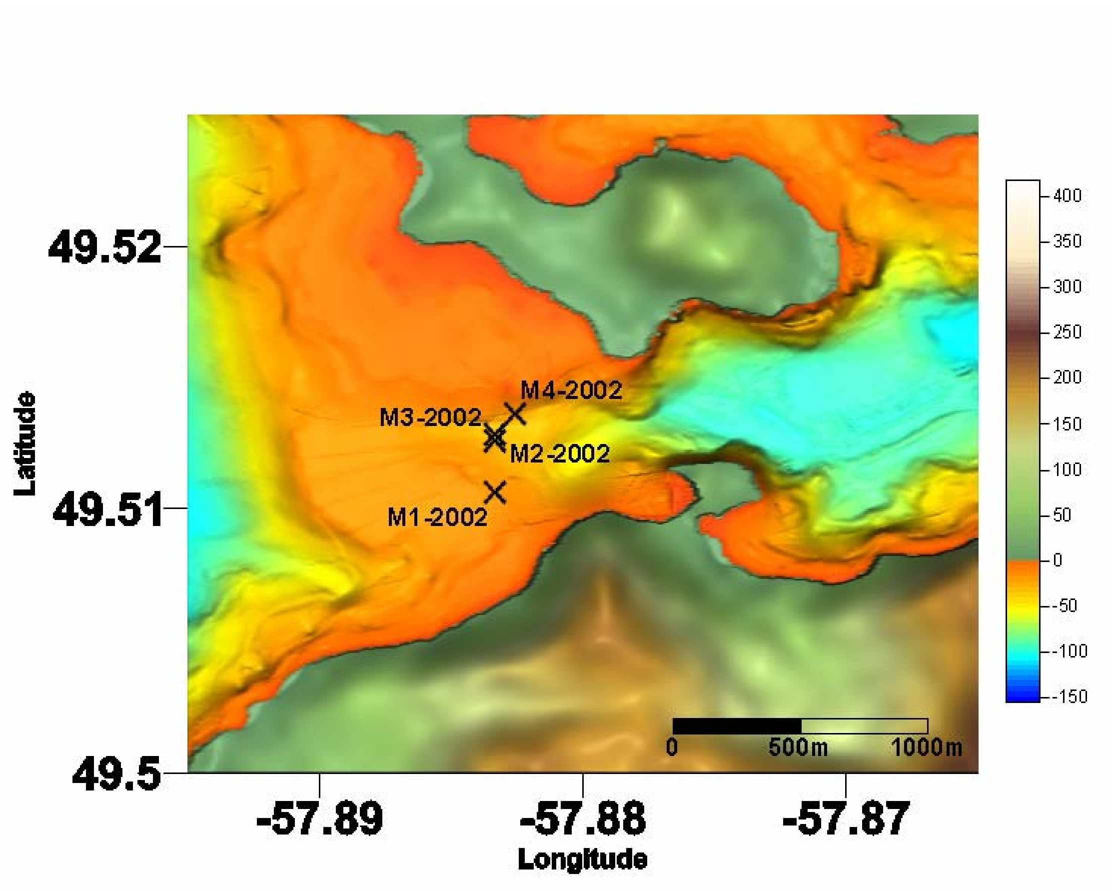

Figure 2: 2002 mooring positions

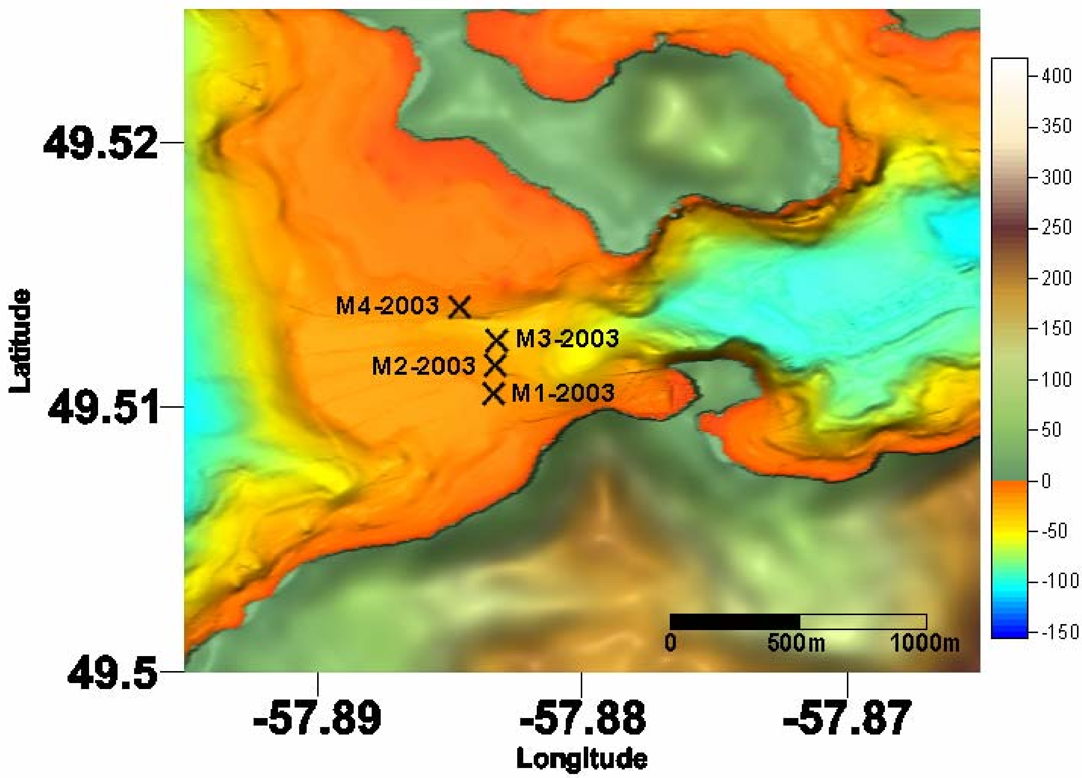

Figure 3: 2003 mooring locations

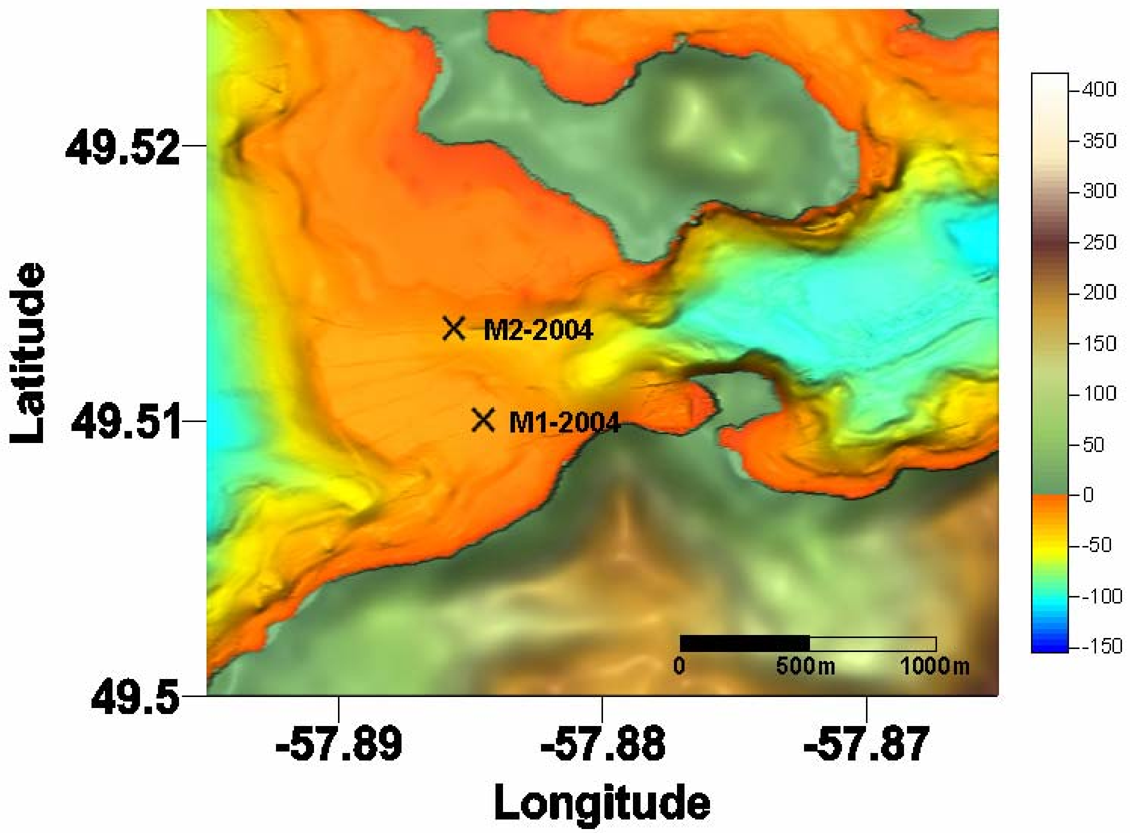

Figure 4: 2004 mooring positions

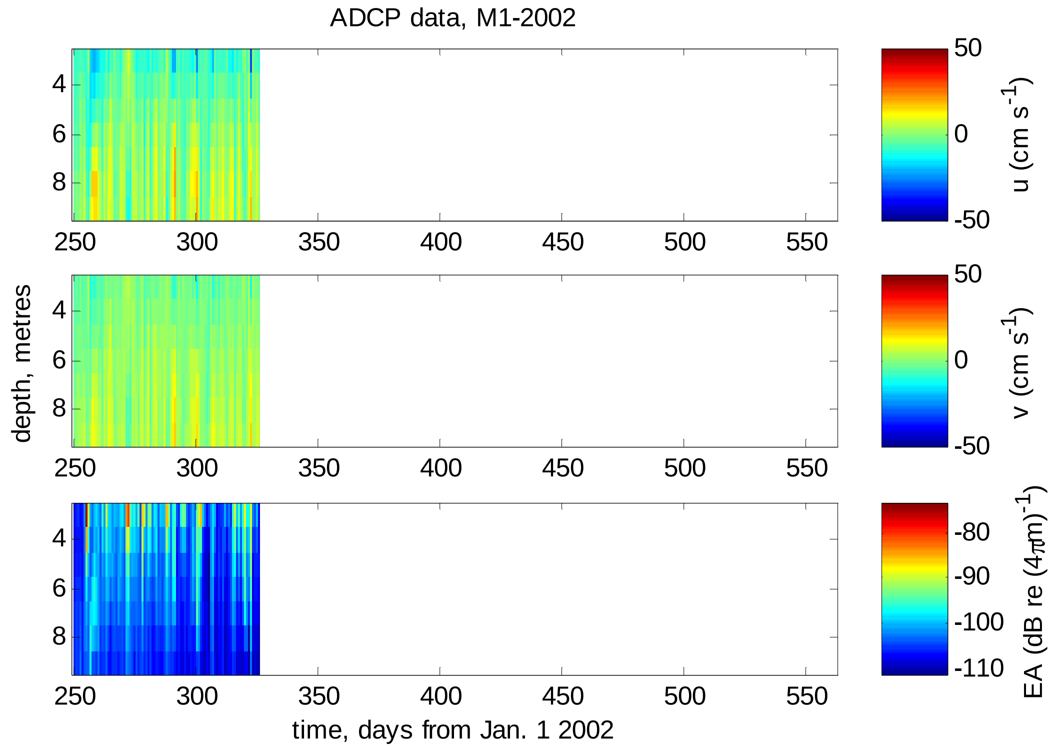

Figure 5: Low pass filtered ADCP data from mooring M1-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

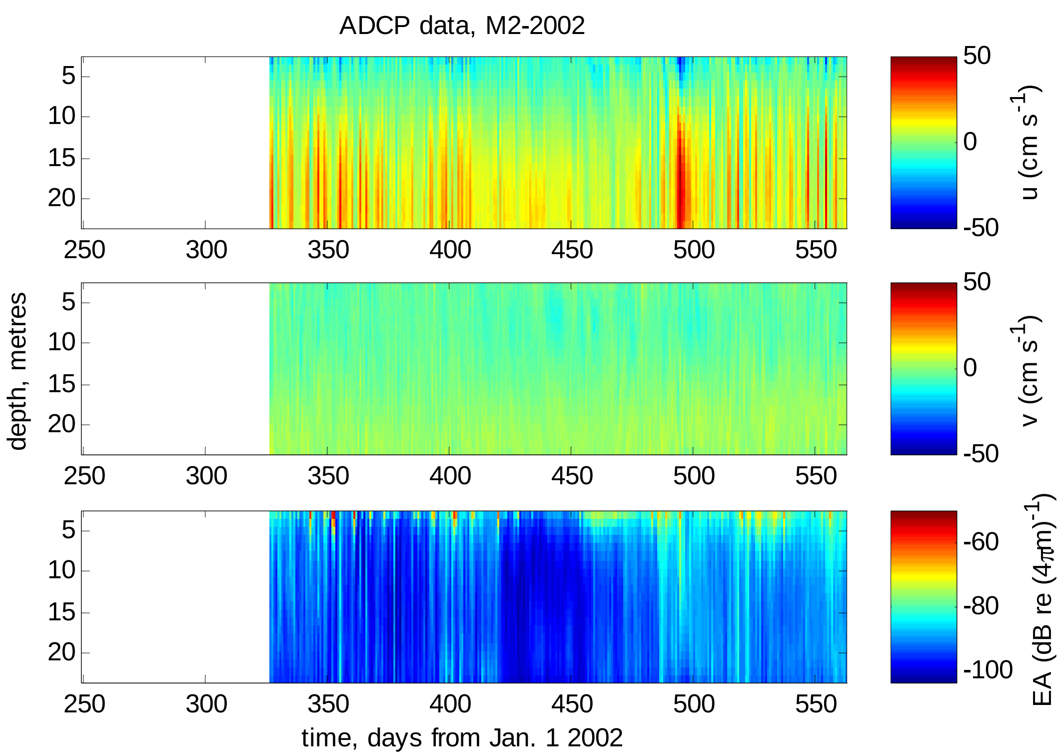

Figure 6: Low pass filtered ADCP data from mooring M2-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

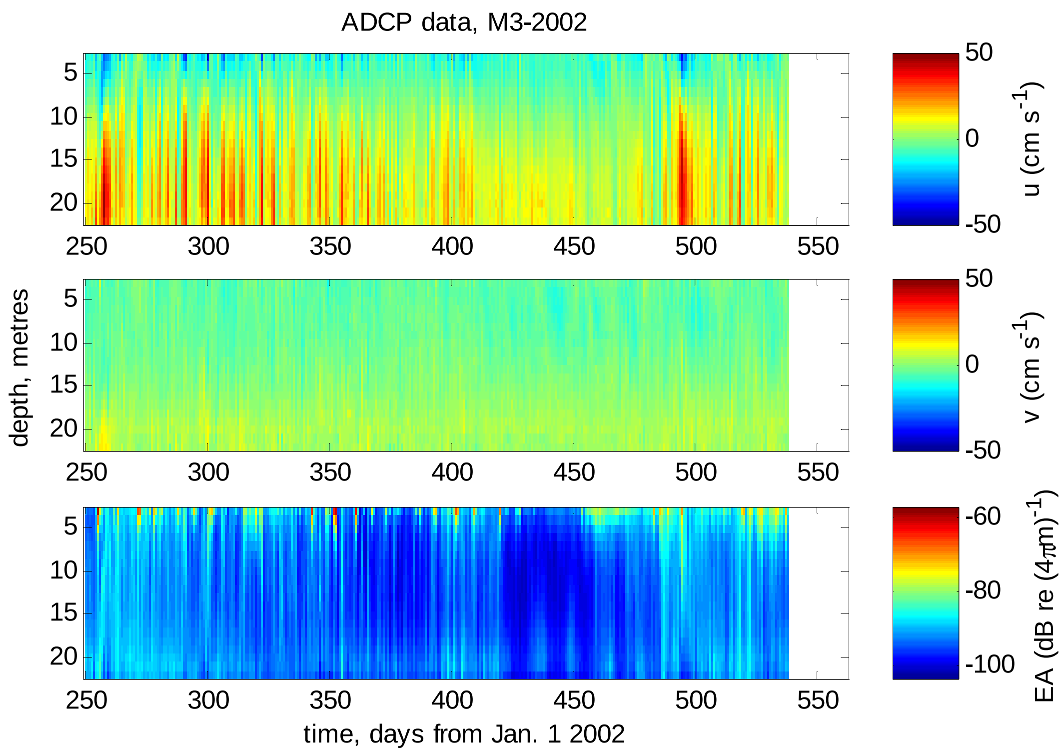

Figure 7: Low pass filtered ADCP data from mooring M3-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

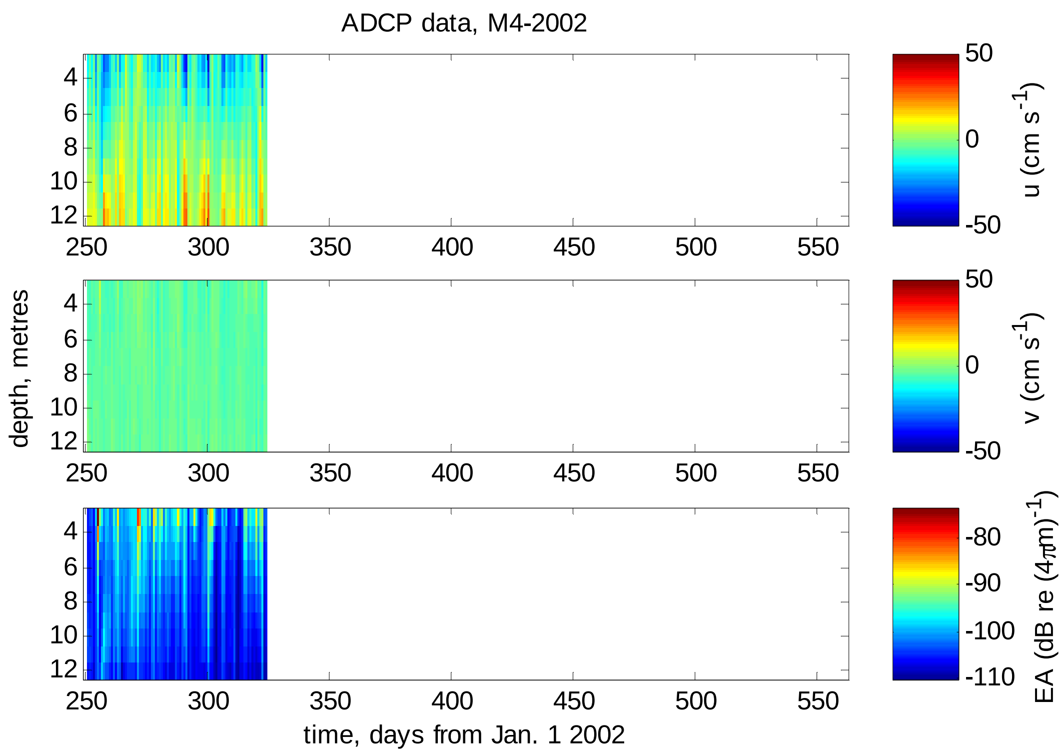

Figure 8: Low pass filtered ADCP data from mooring M4-2002. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

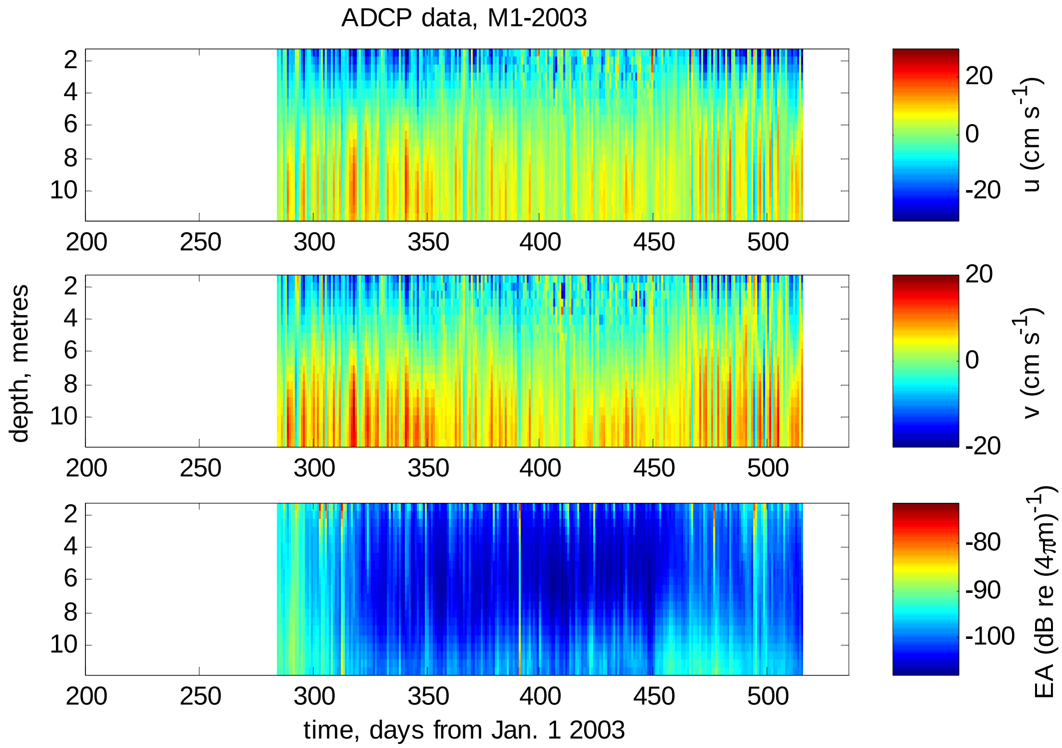

Figure 9: Low pass filtered ADCP data from mooring M1-2003. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

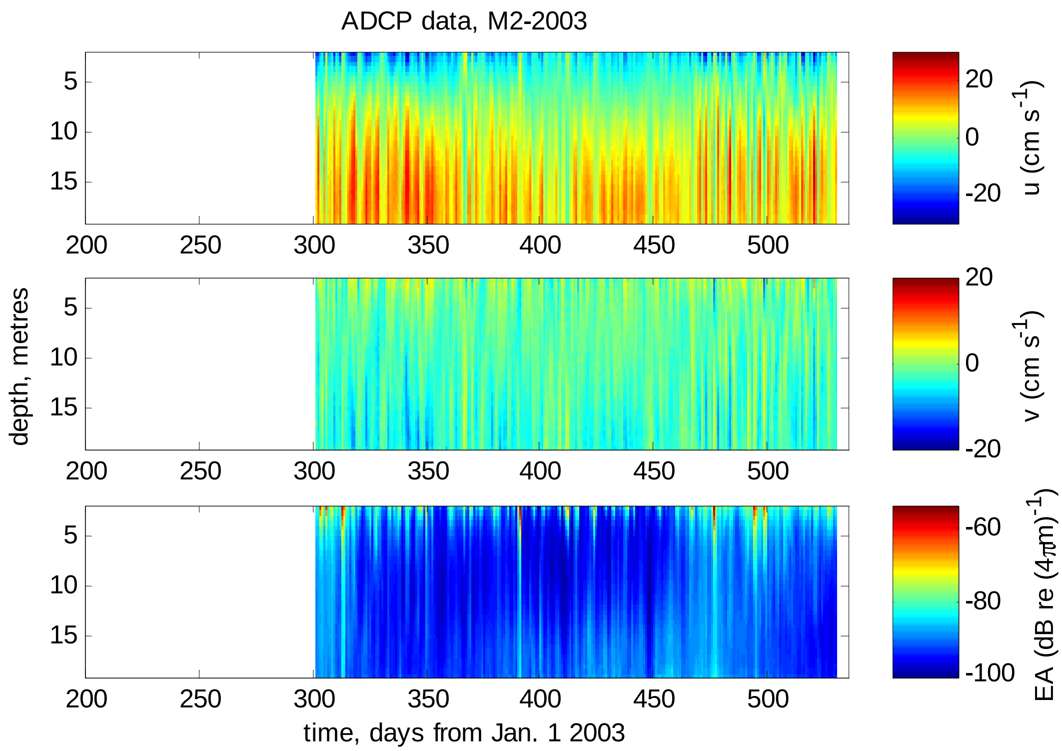

Figure 10: Low pass filtered ADCP data from mooring M2-2003. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity

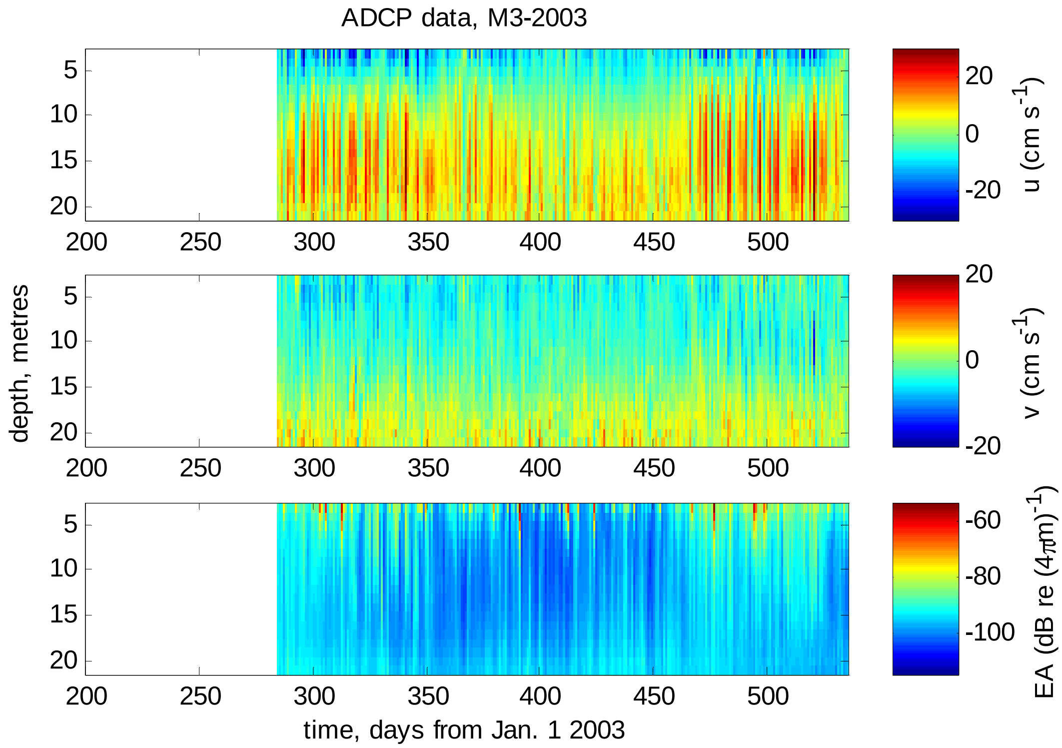

Figure 11: Low pass filtered ADCP data from mooring M3-2003. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

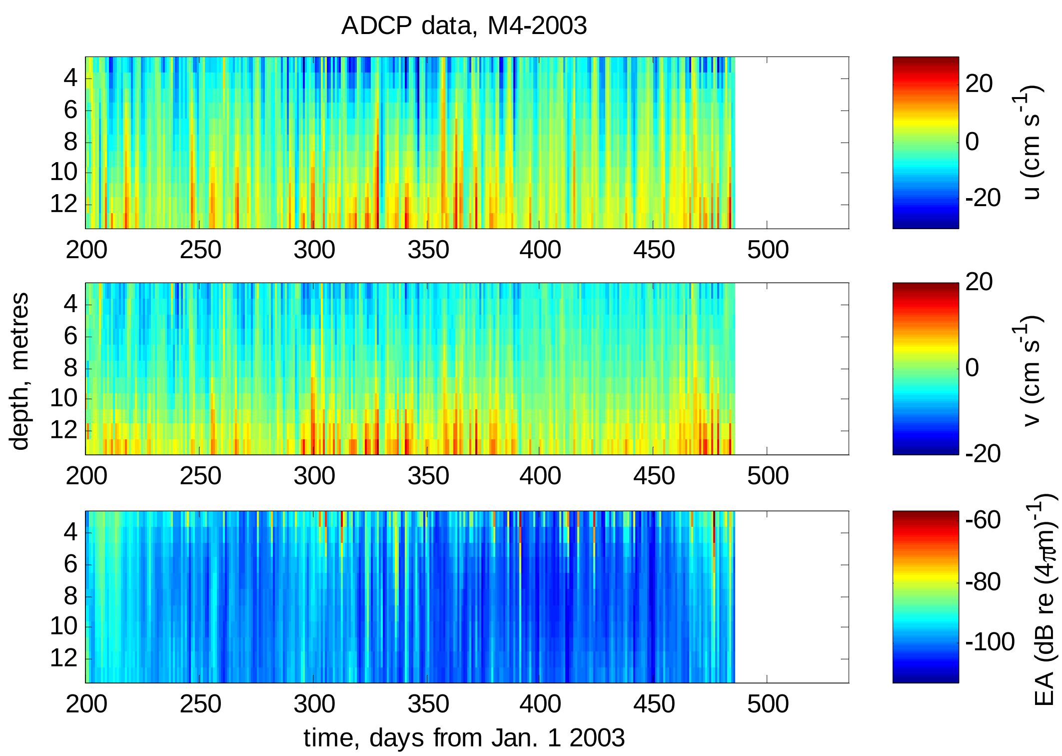

Figure 12: Low pass filtered ADCP data from mooring M4-2003. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

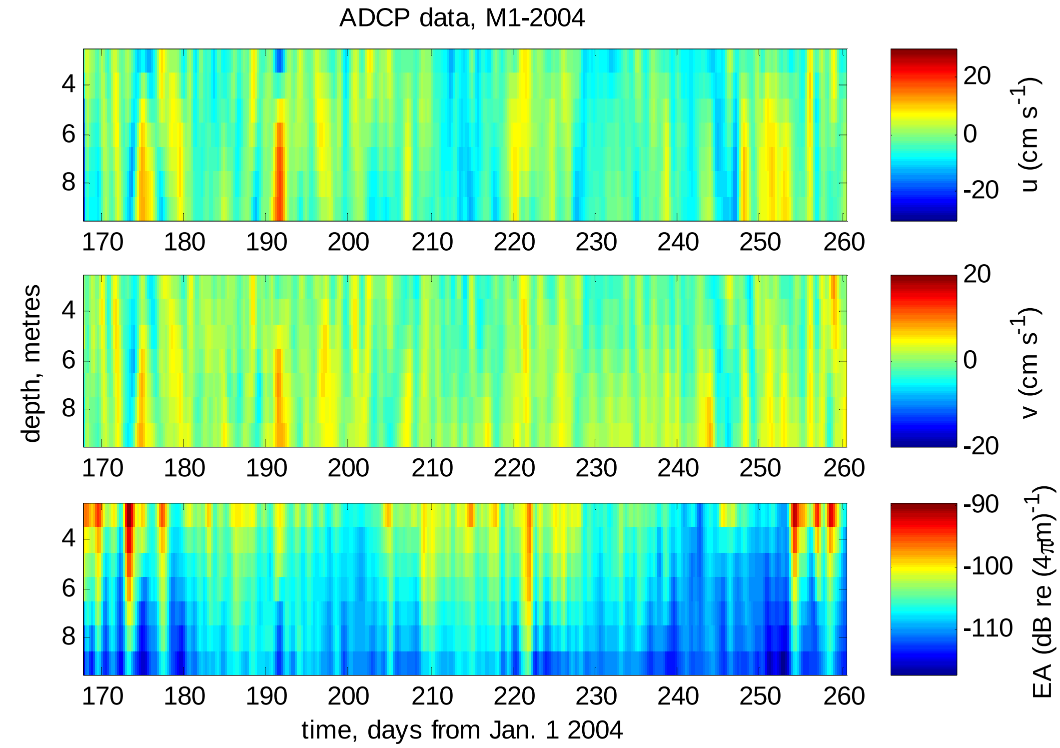

Figure 13: Low pass filtered ADCP data from mooring M1-2004. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

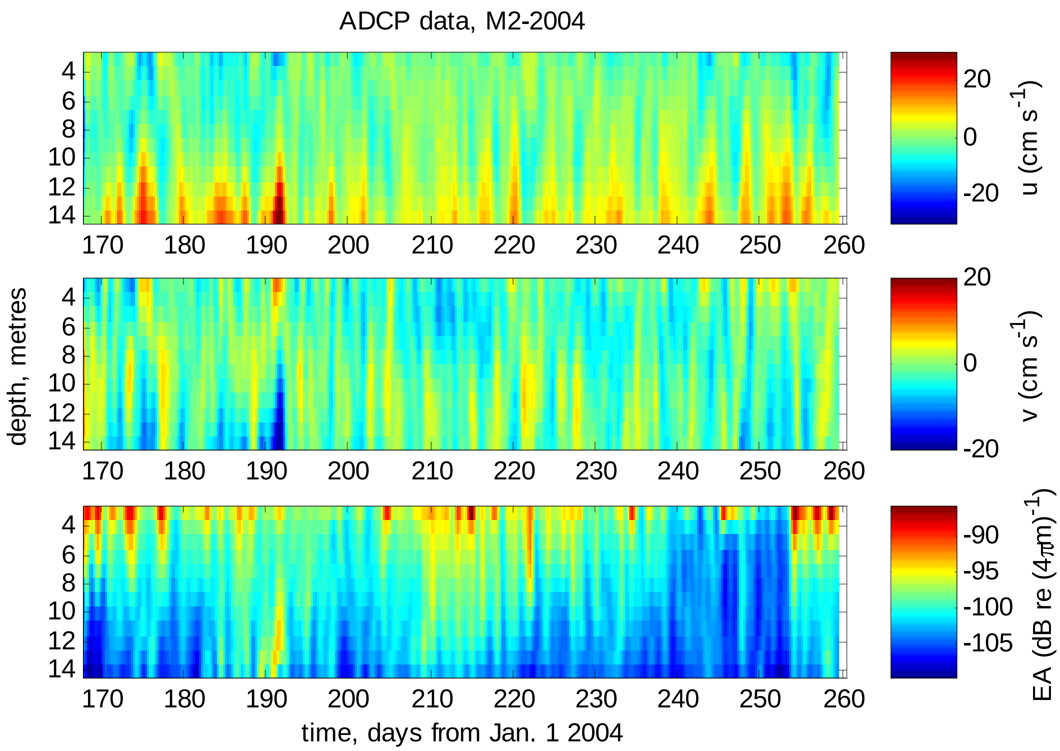

Figure 14: Low pass filtered ADCP data from mooring M2-2004. Cutoff is 30 hours. Top: East-west speed (cm/s). Middle: North-south speed (cm/s). Bottom: Spherically corrected backscatter intensity.

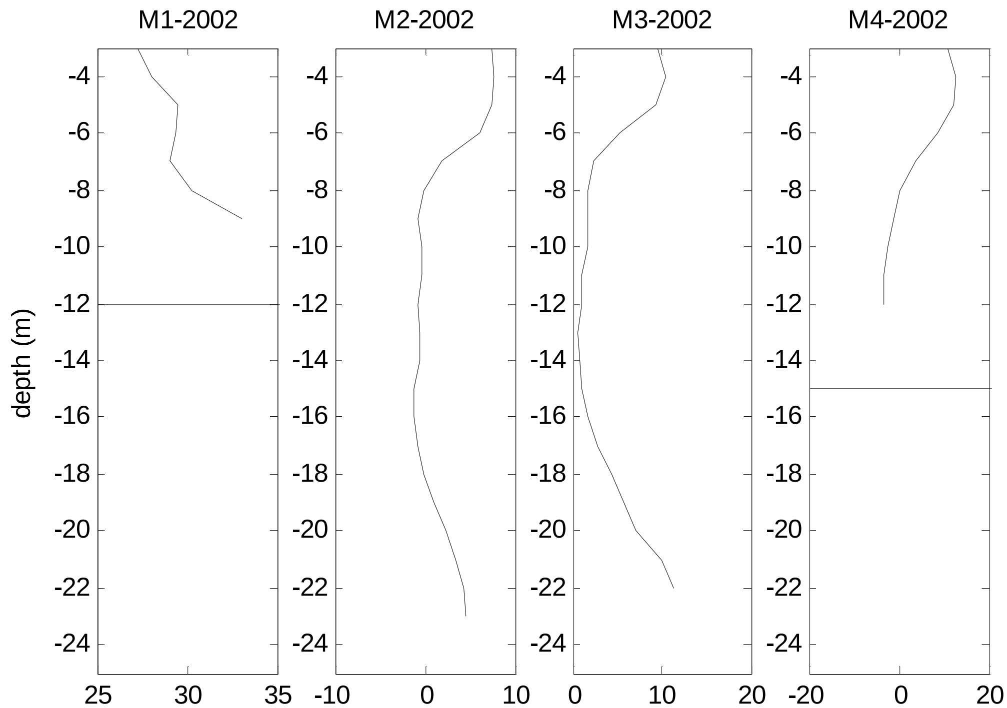

Figure 15: Major axis angles for 2002 data at each depth bin calculated using Emery, 1997 pp 325. Angles are given in degrees, where 0° is East. The horizontal line indicates the bottom.

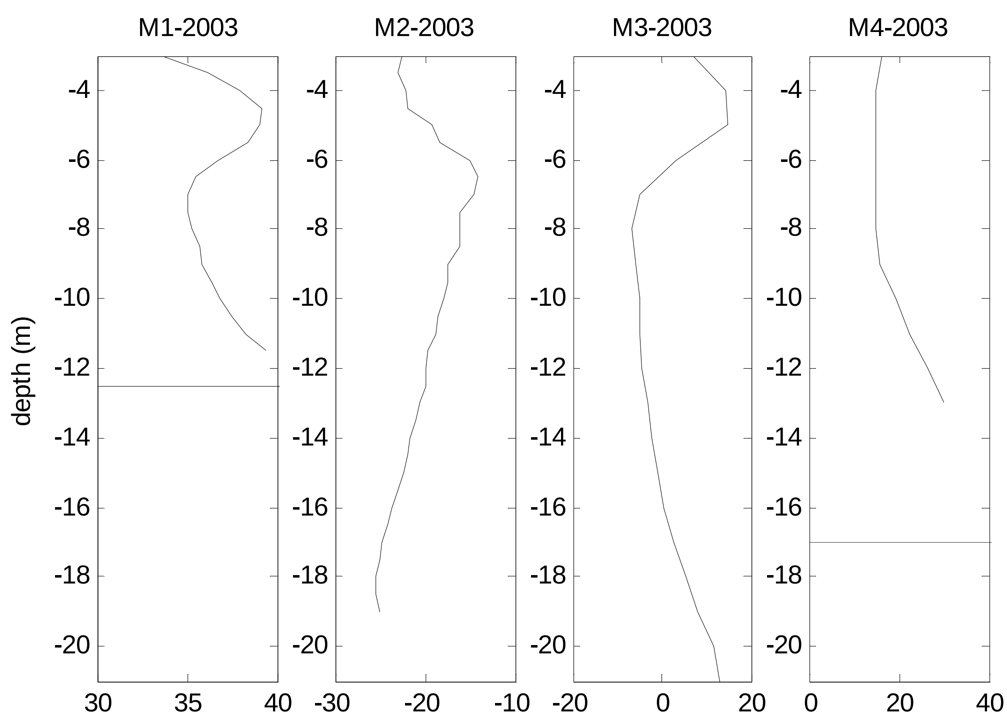

Figure 16: Major axis angles for 2003 data at each depth bin calculated using Emery, 1997 pp 325. Angles are given in degrees, where 0° is East. The horizontal line indicates the bottom.

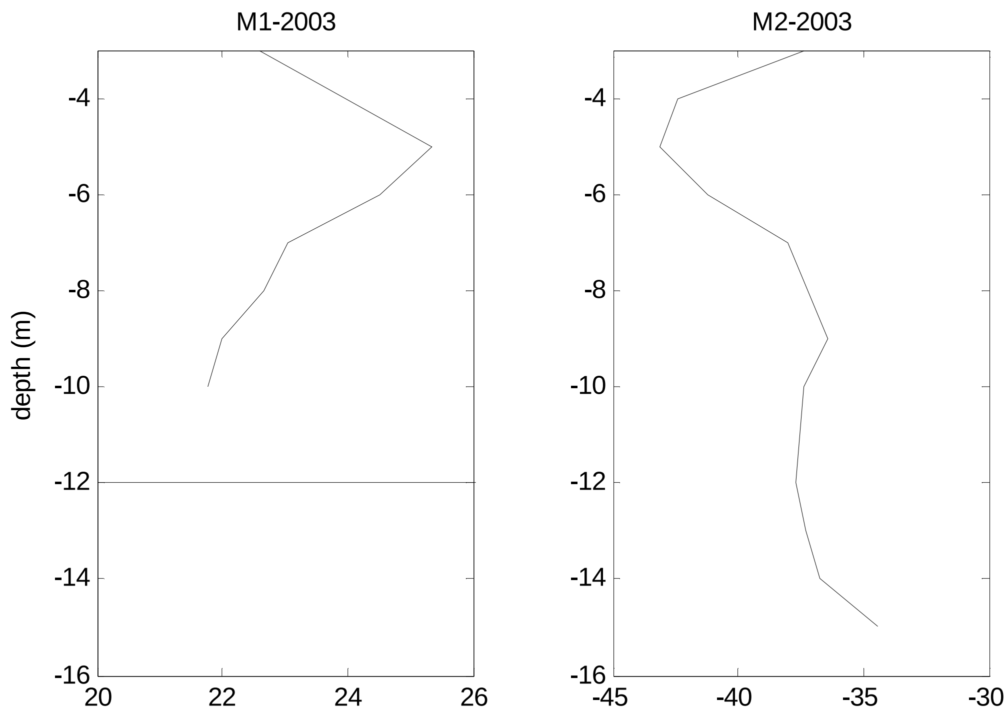

Figure 17: Major axis angles for 2002 data at each depth bin calculated using Emery, 1997 pp 325. Angles are given in degrees, where 0^o is East. The horizontal line indicates the bottom.

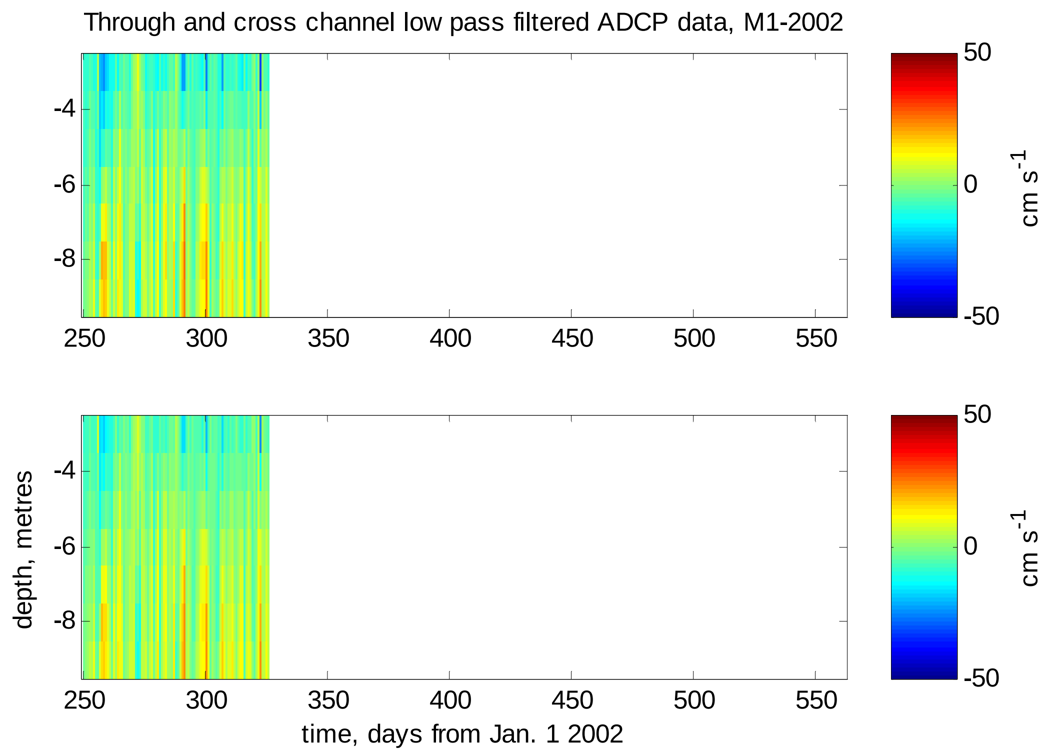

Figure 18: ADCP data for M1-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15

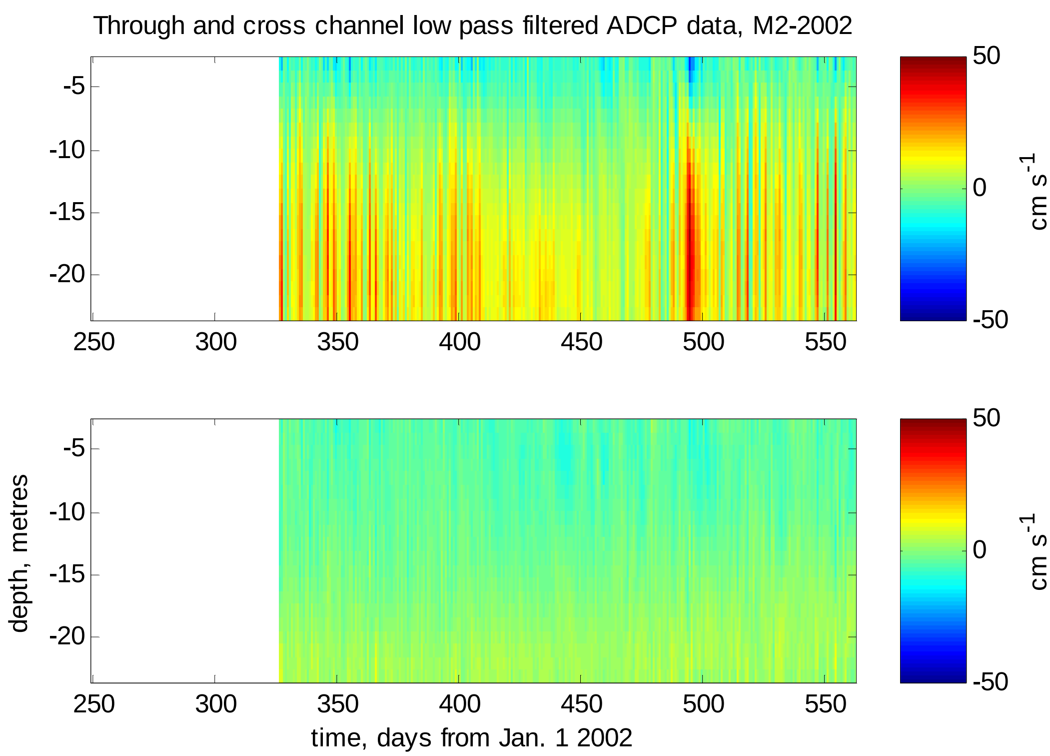

Figure 19: ADCP data for M2-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15

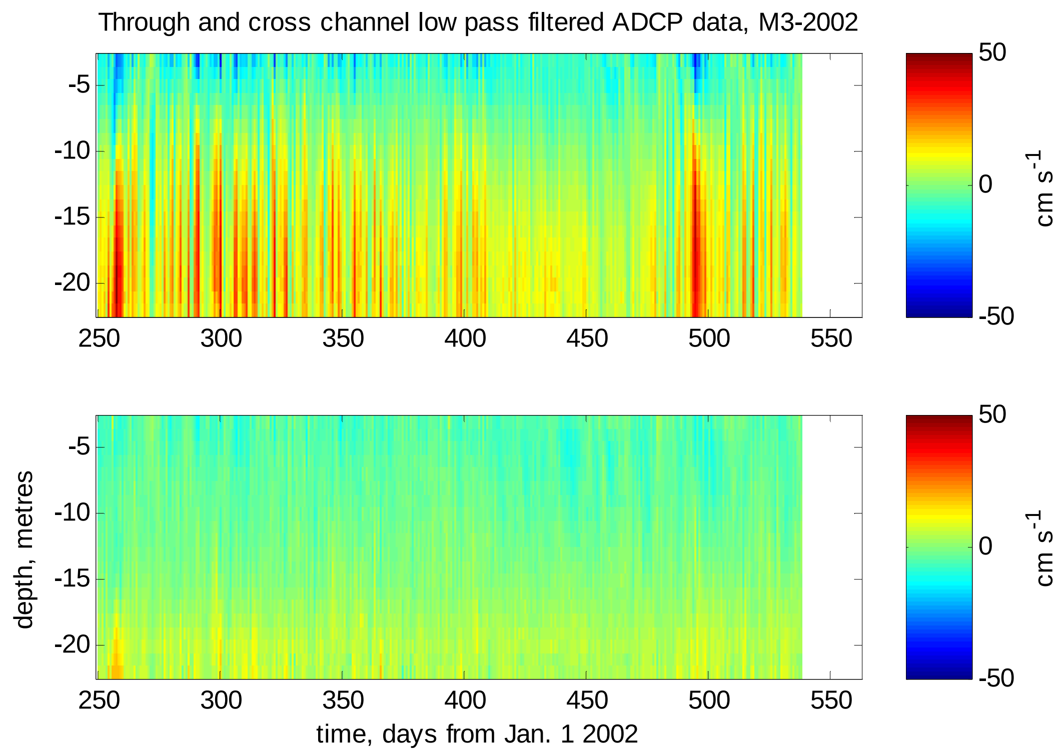

Figure 20: ADCP data for M3-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15

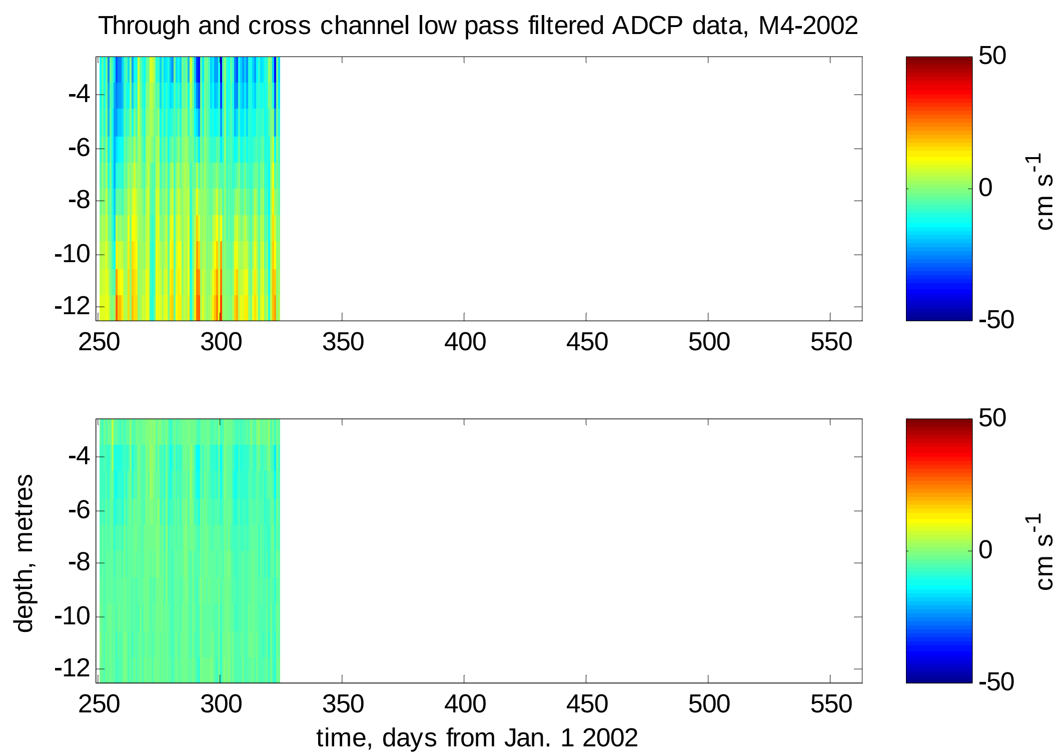

Figure 21: ADCP data for M4-2002 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 15

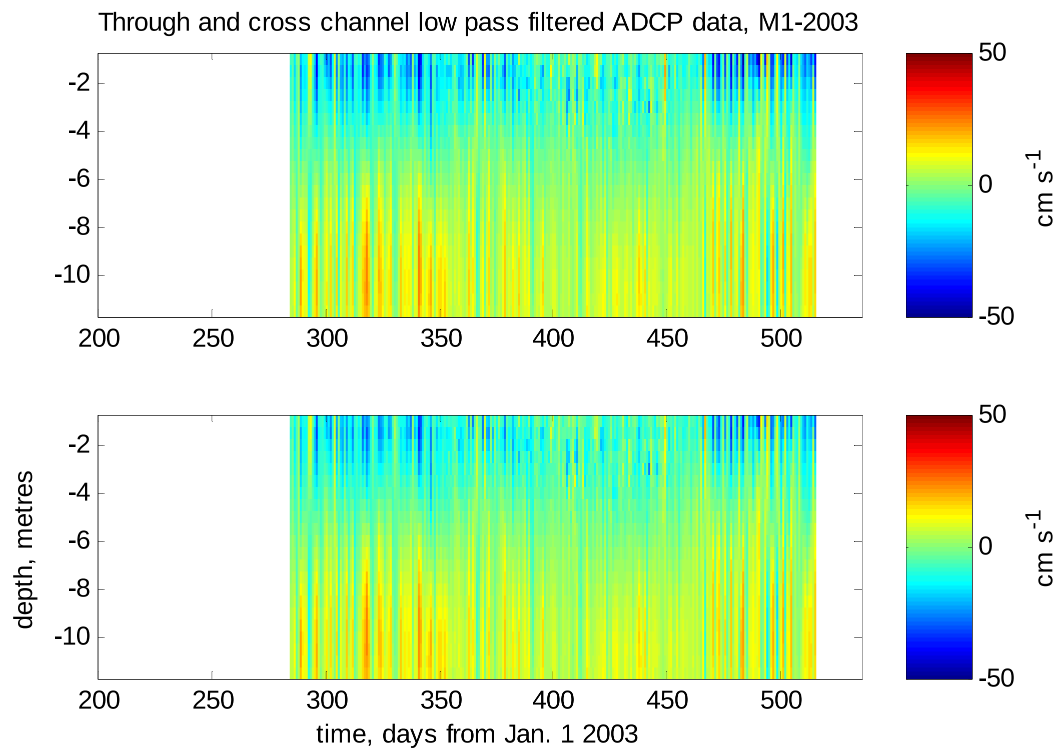

Figure 22: ADCP data for M1-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16

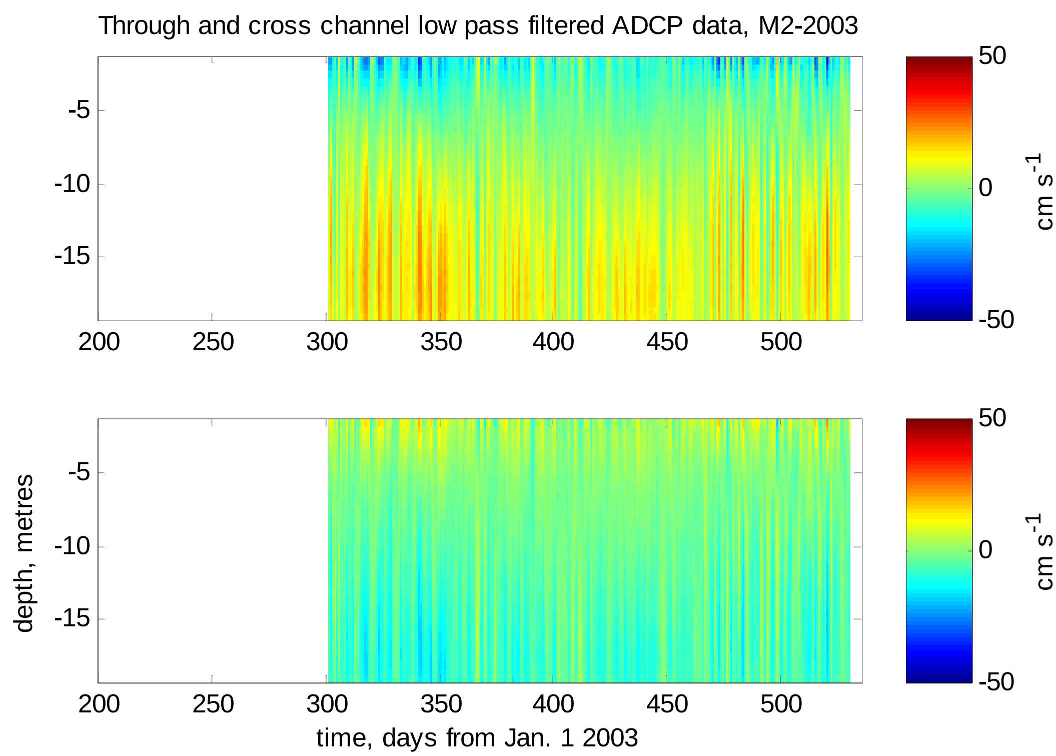

Figure 23: ADCP data for M2-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16

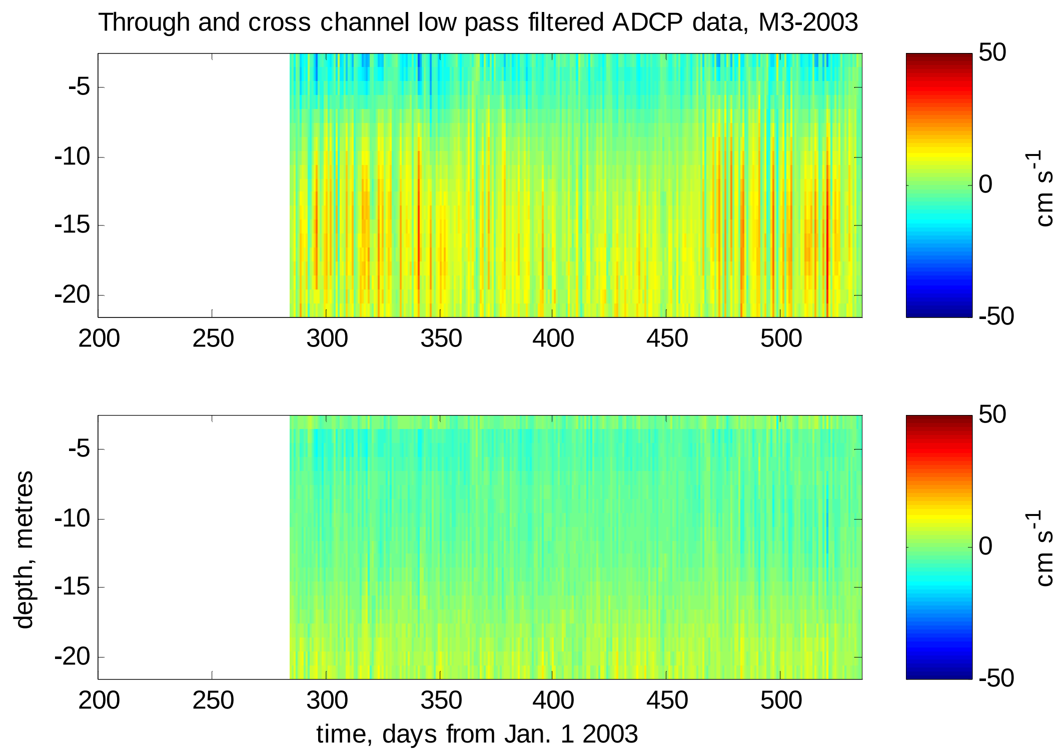

Figure 24: ADCP data for M3-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16

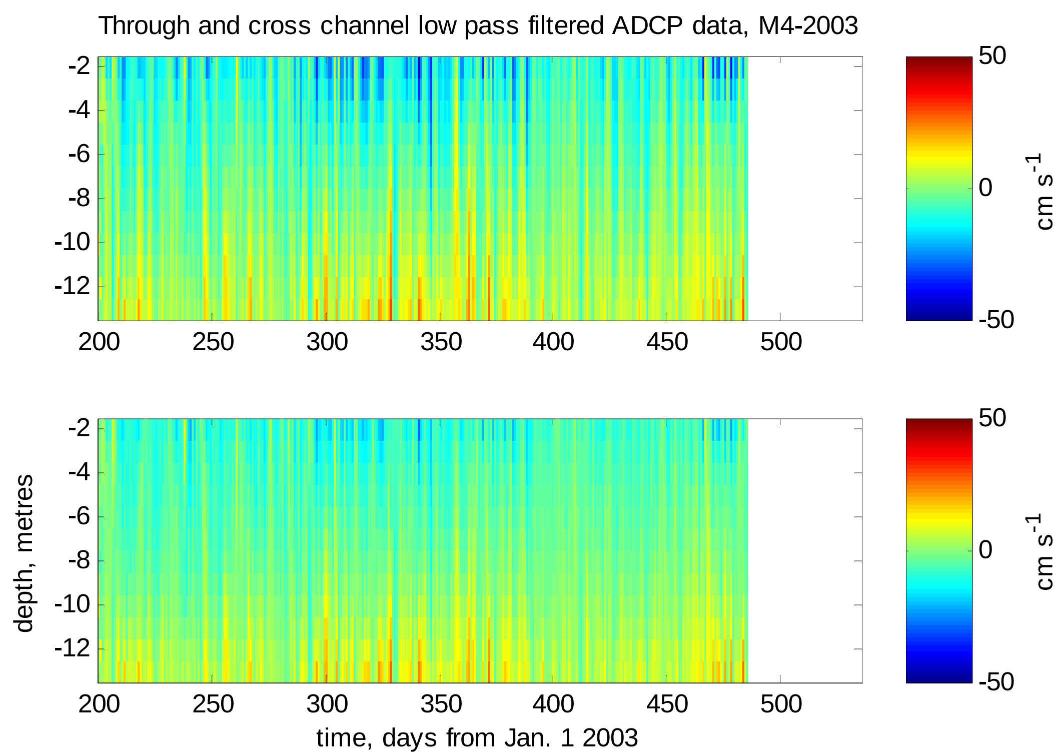

Figure 25: ADCP data for M4-2003 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 16

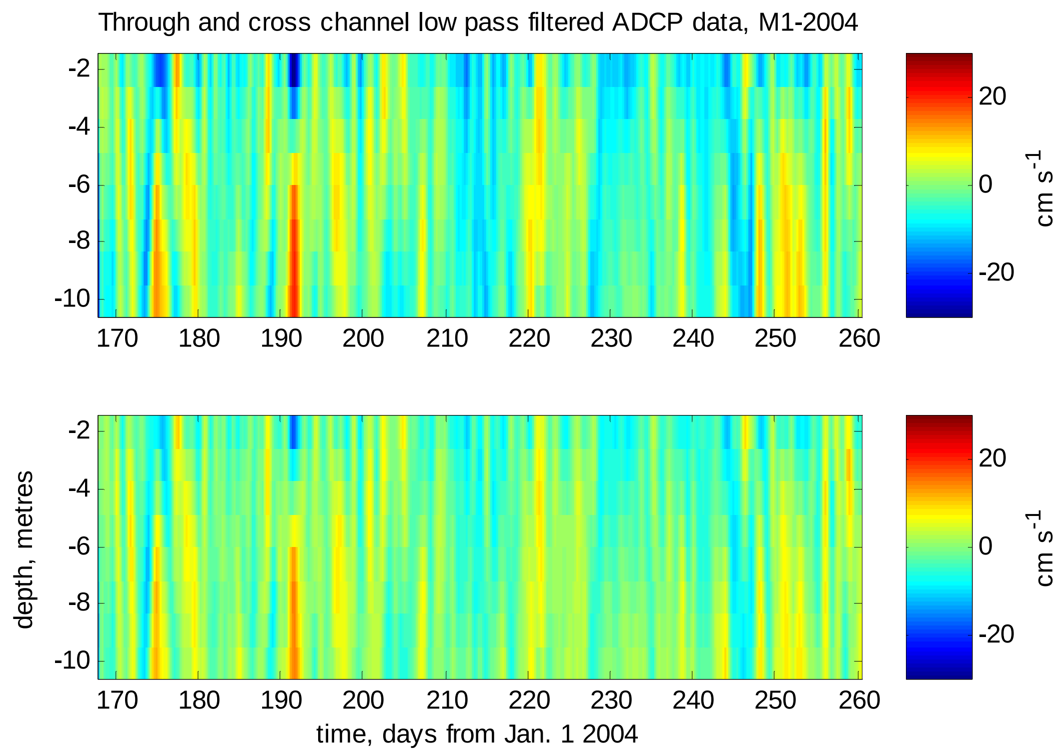

Figure 26: ADCP data for M1-2004 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 17

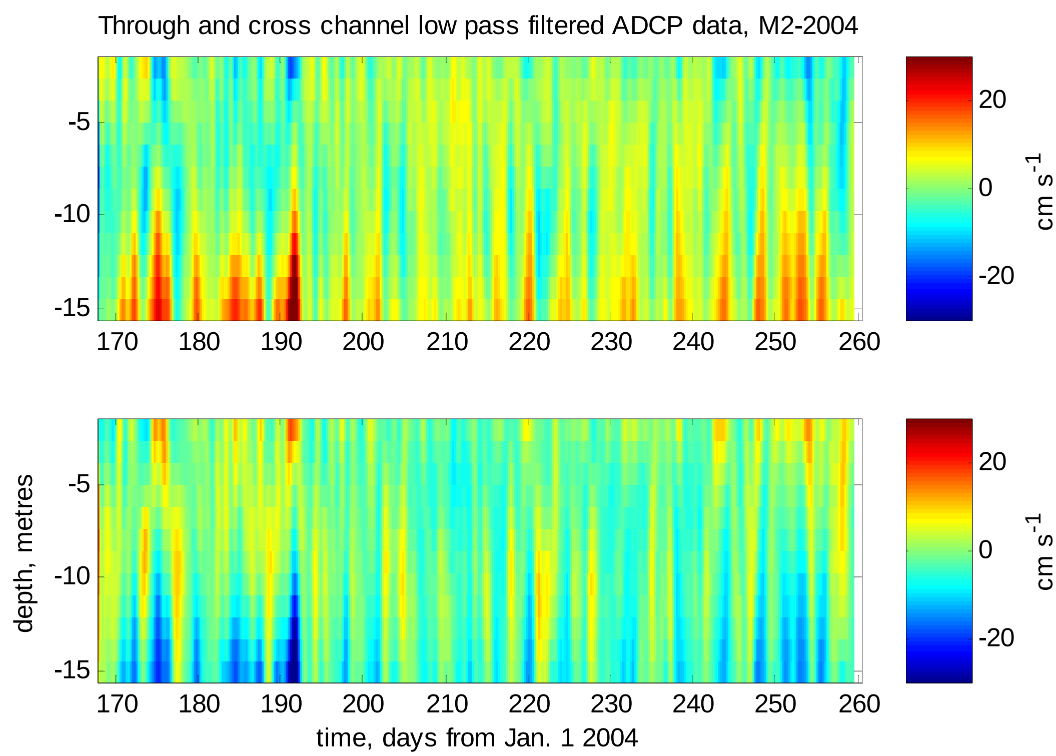

Figure 27: ADCP data for M2-2004 rotated for through and cross channel flow at each depth bin according to the angles specified in Fig. 17

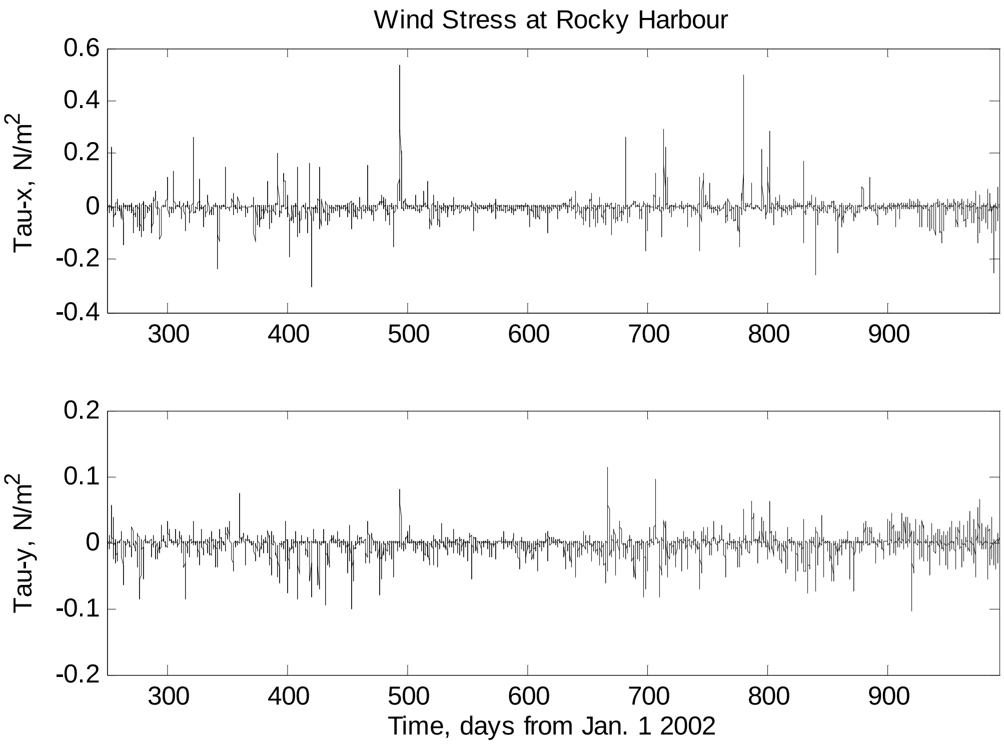

Figure 28: Wind stress at Rocky Harbour over the period for which there is ADCP data. Calculated according to Gill 1982.

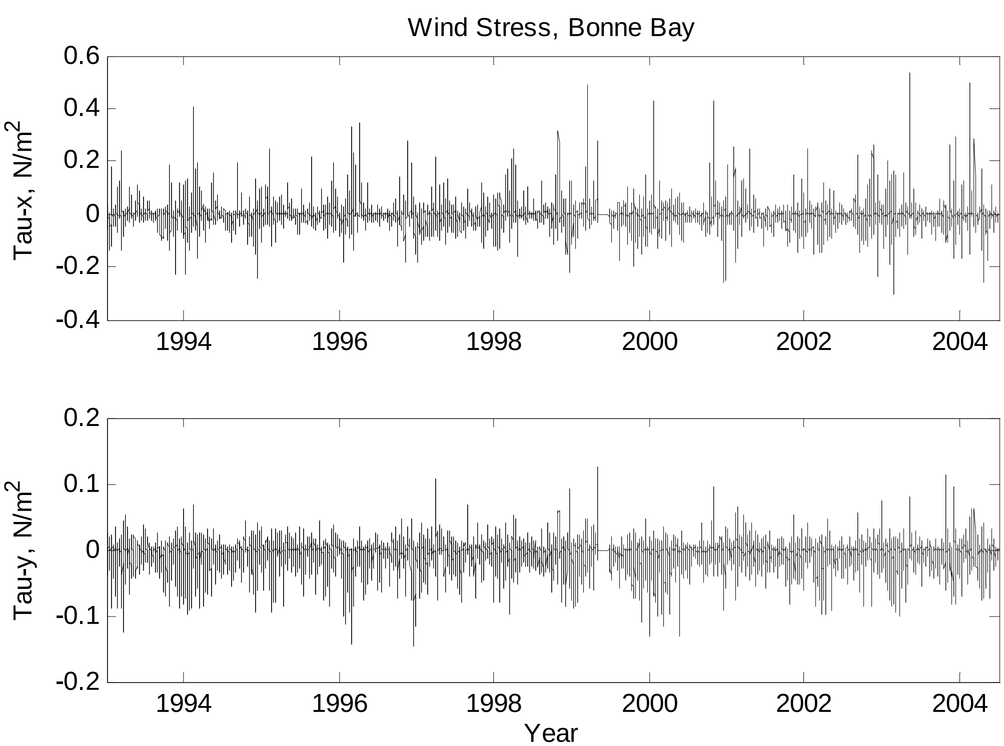

Figure 29: Wind stress at Rocky Harbour from January 1993 to September 2004. Calculated according to Gill 1982.

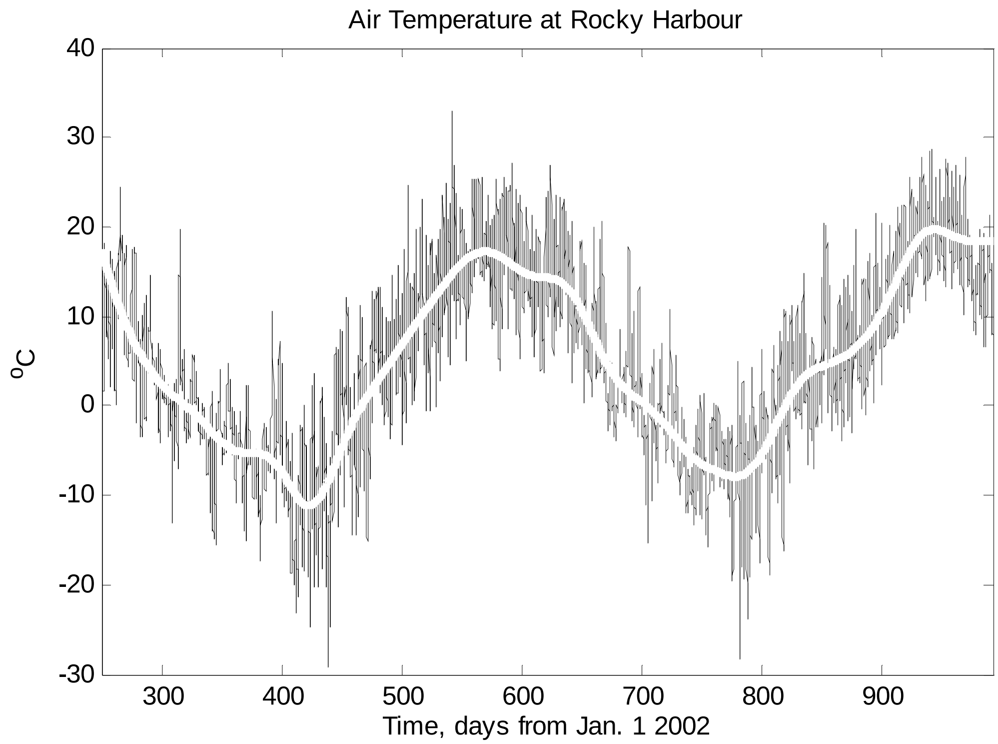

Figure 30: Air temperature at Rocky Harbour over the period for which there is ADCP data. White line is filtered with a cutoff of ~ 60 days.

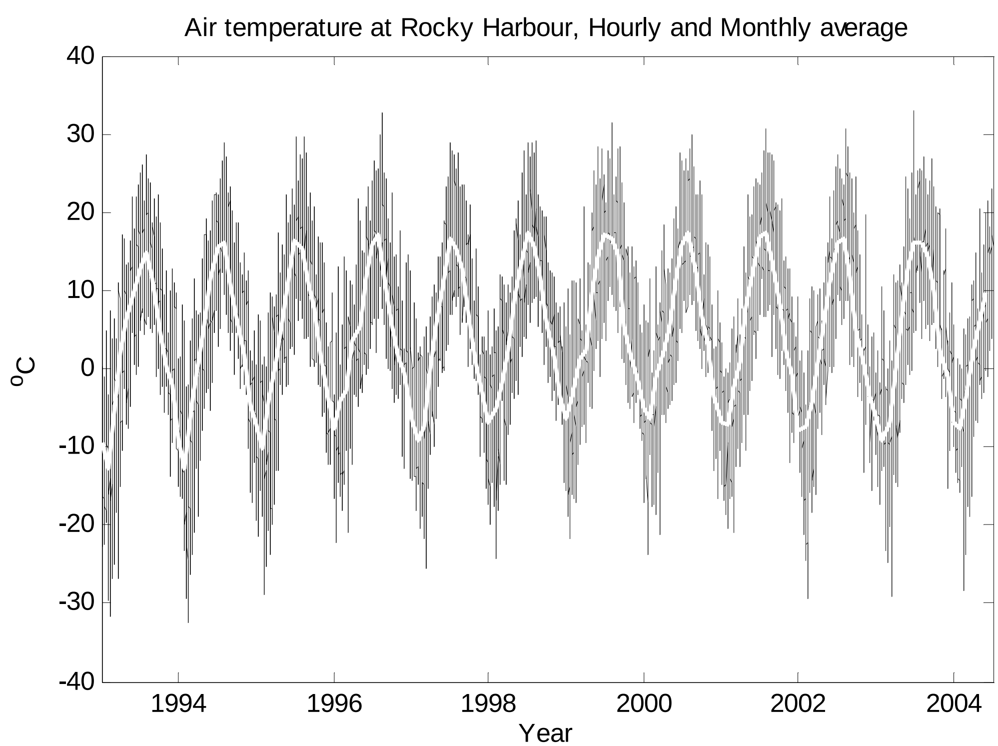

Figure 31: Air temperature at Rocky Harbour from January 1993 to June 2004. White line is a monthly average.

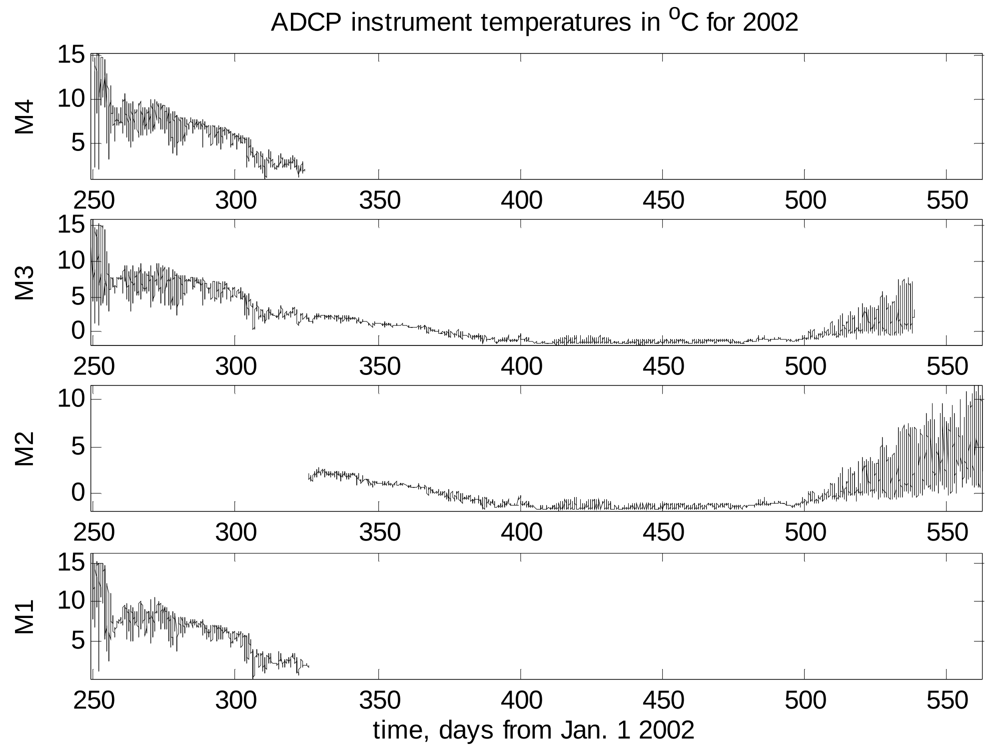

Figure 32: ADCP instrument temperatures for 2002.

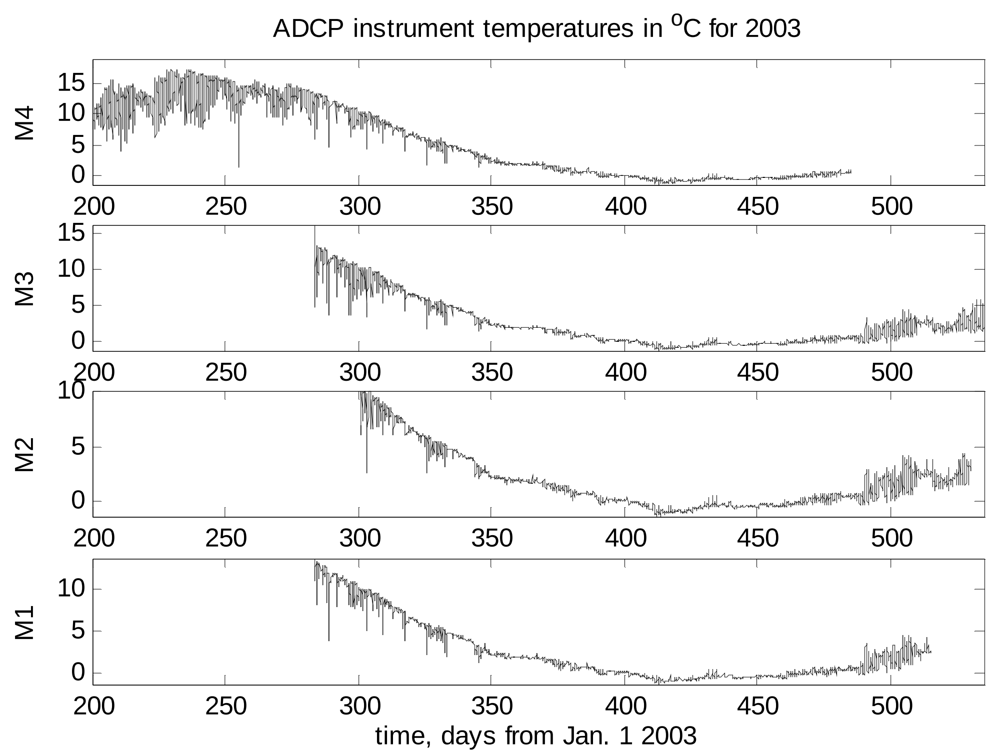

Figure 33: ADCP instrument temperatures for 2003.

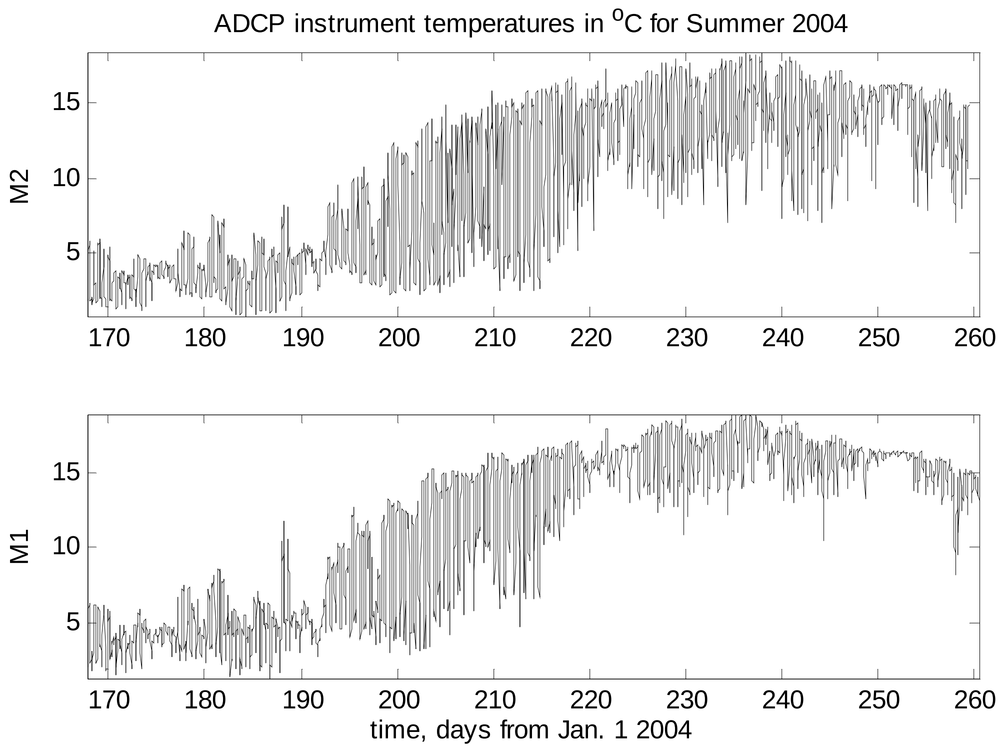

Figure 34: ADCP instrument temperatures for 2004.

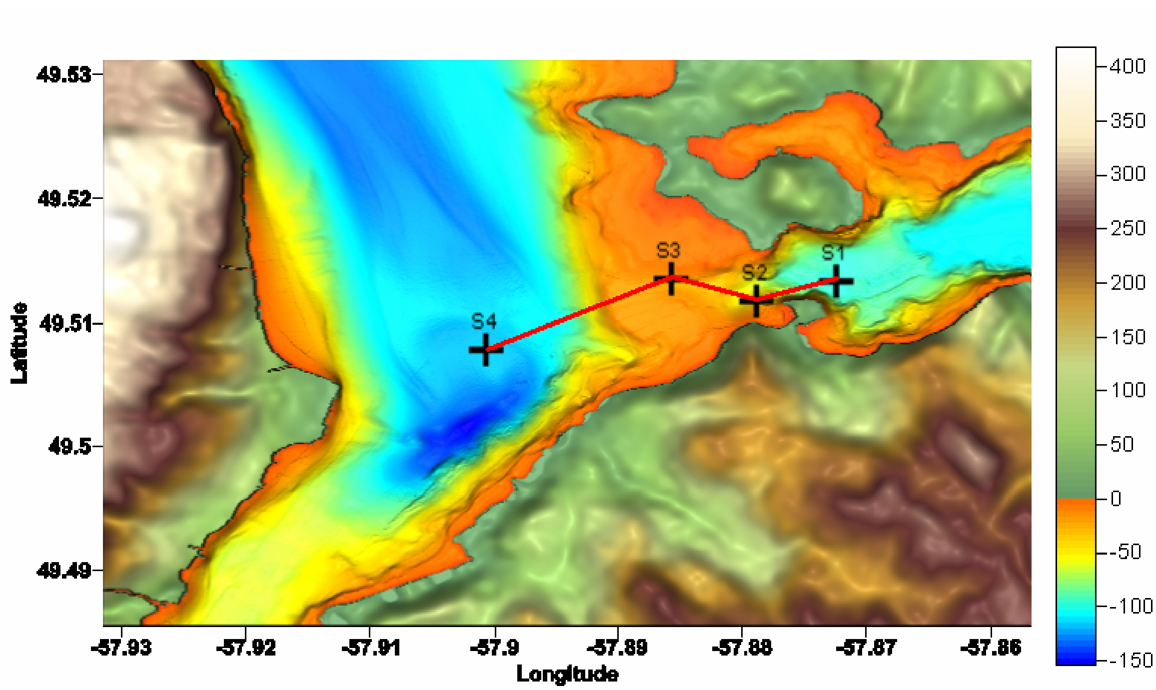

Figure 35: Transect stations from June 6/7 2004. Vertical profiles were done at S1 and S4 with a towed horizontal profile in between.

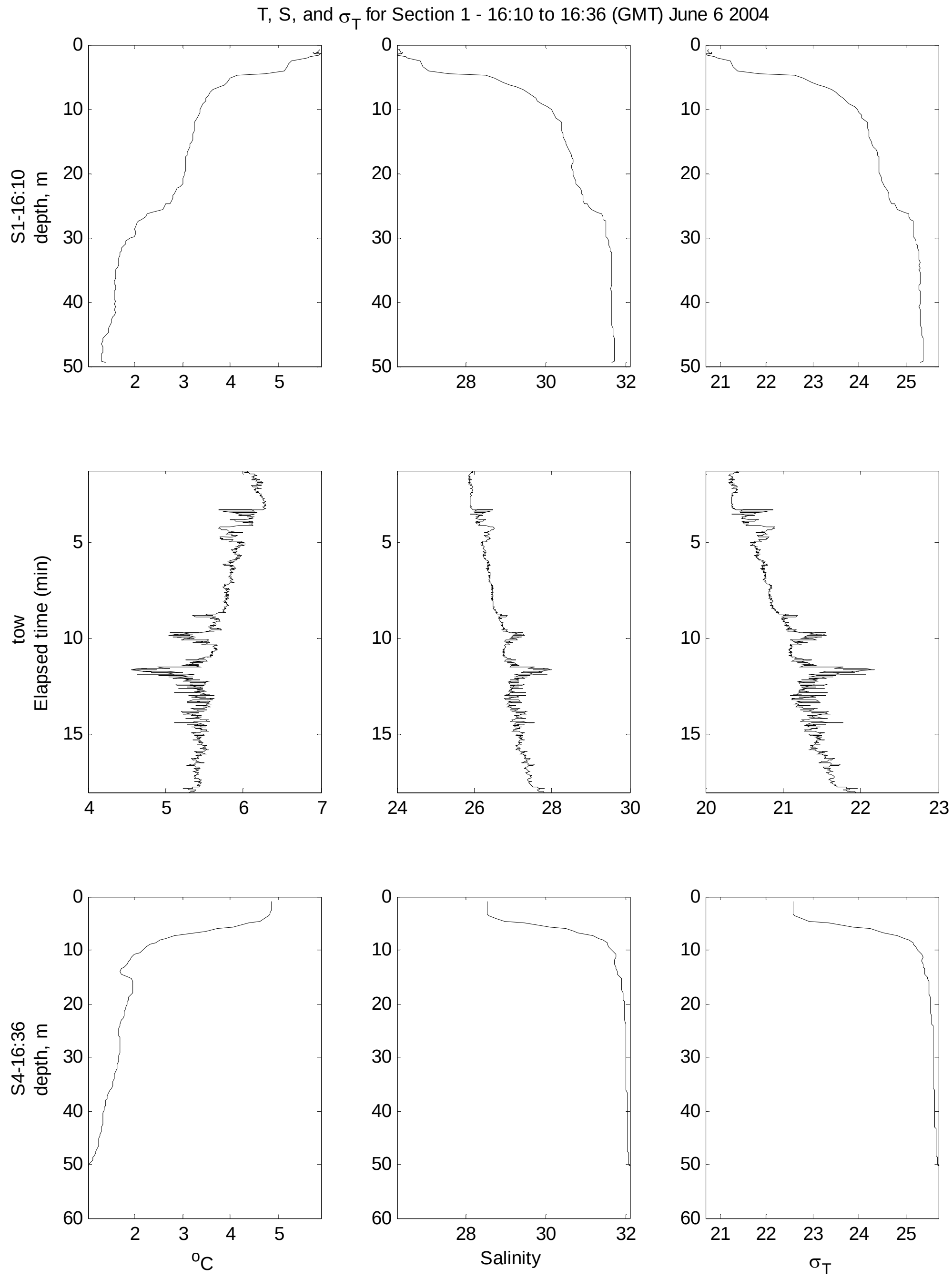

Figure 36: Vertical and horizontal temperature, salinity and sigma-t profiles from S1 to S4, 16:10 to 16:36 GMT June 6 2004.

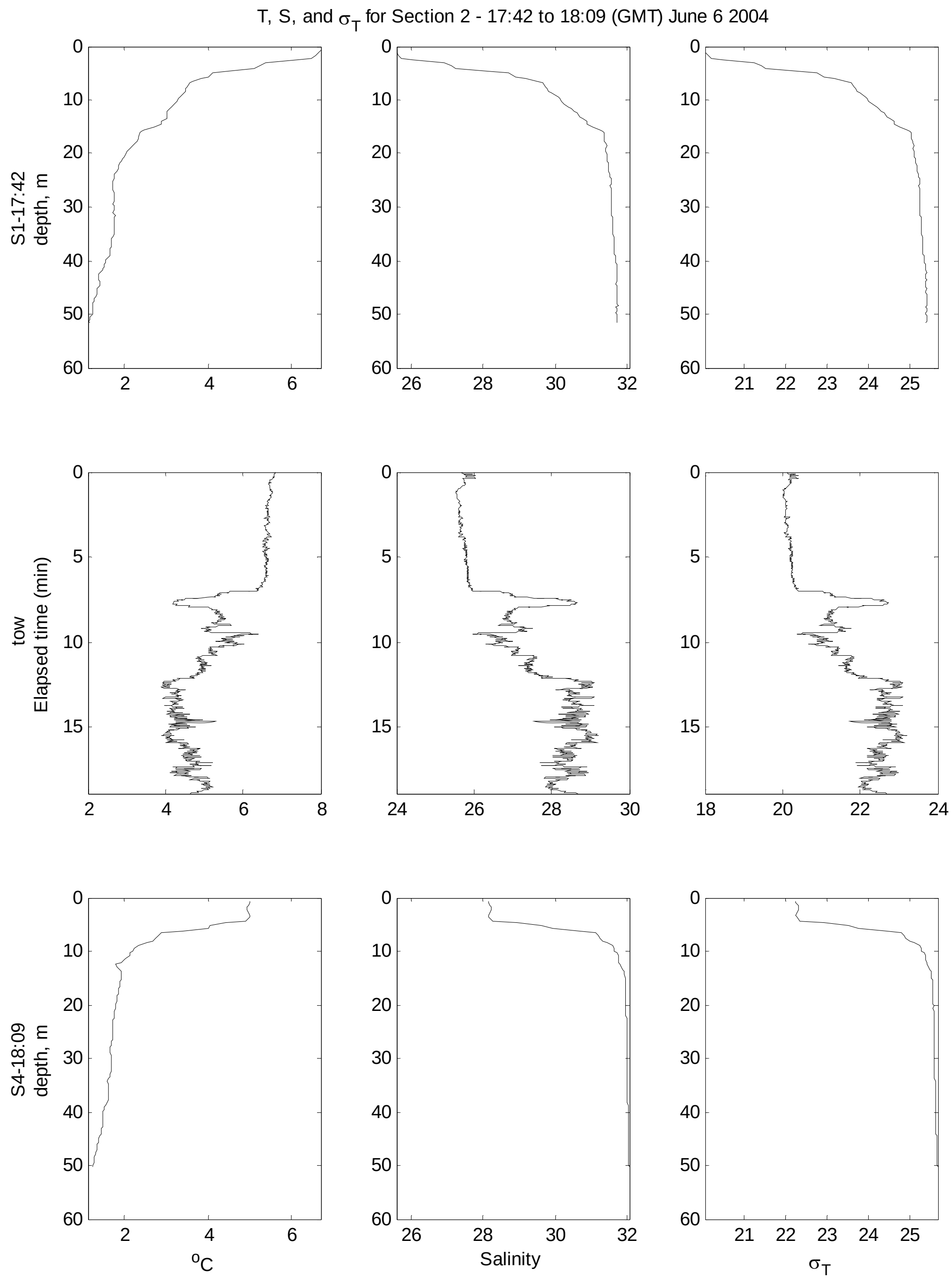

Figure 37: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 17:42 to 18:09 GMT June 6 2004.

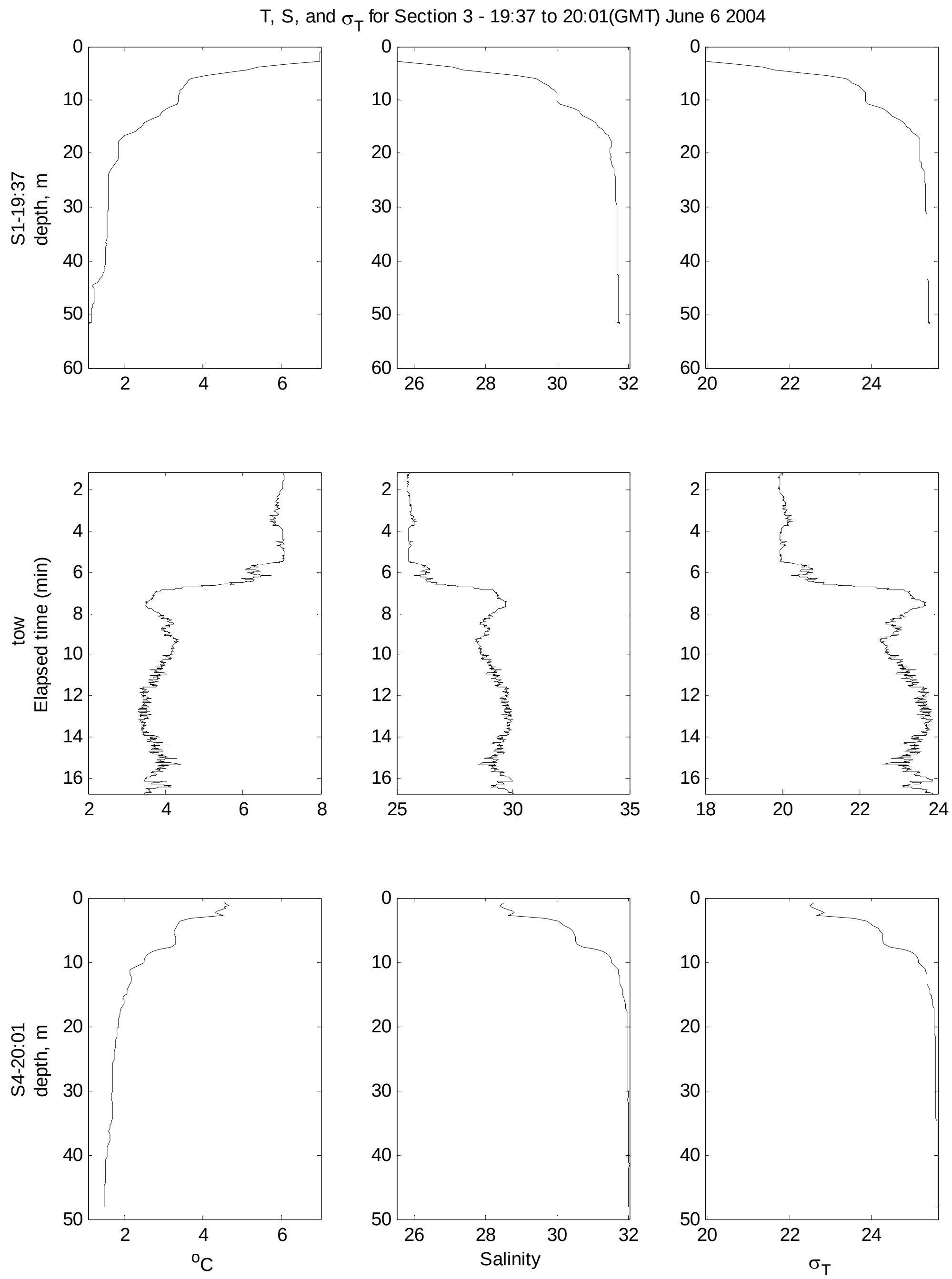

Figure 38: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 19:37 to 20:01 GMT June 6 2004.

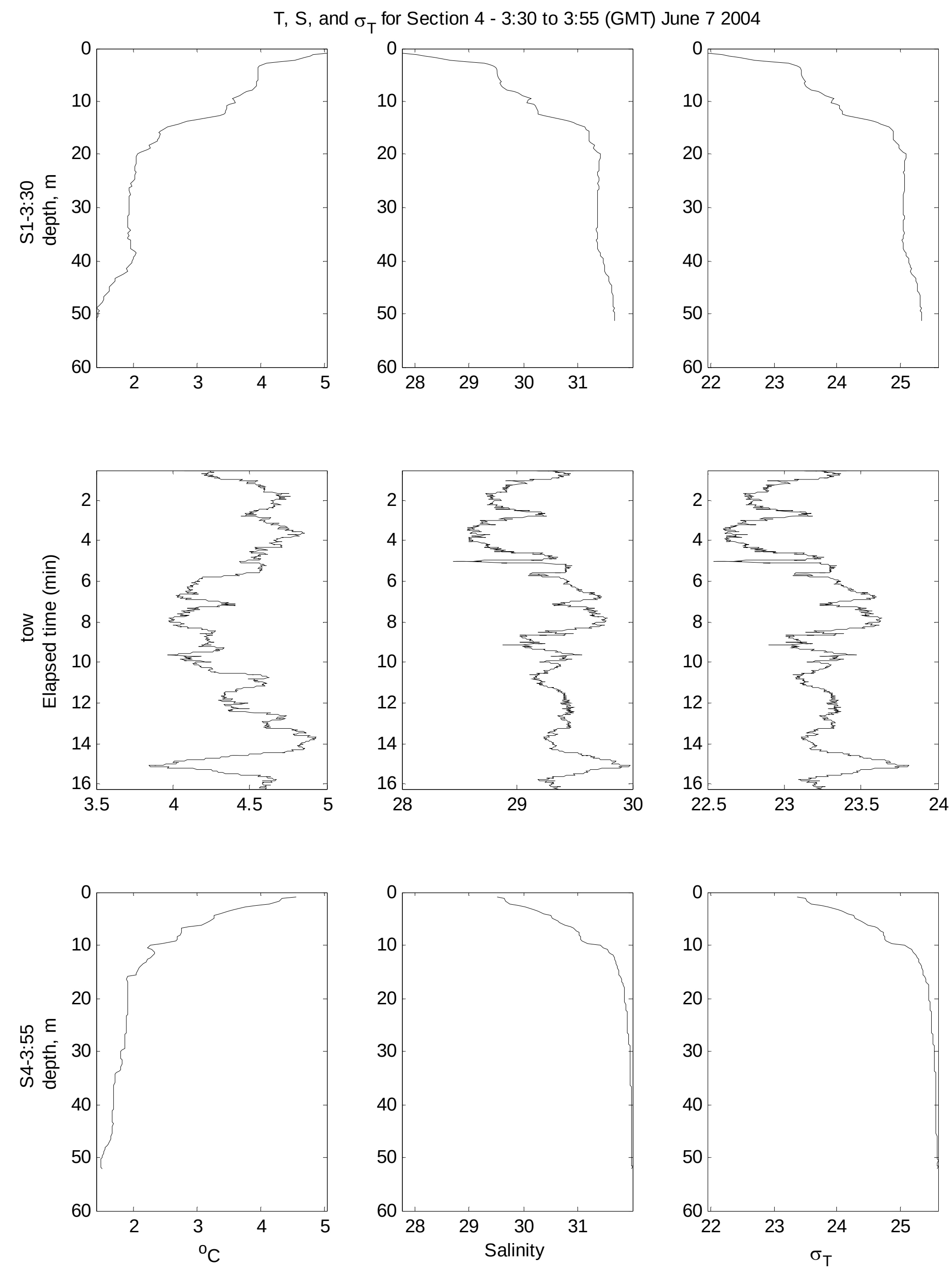

Figure 39: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 3:30 to 3:55 GMT June 7 2004.

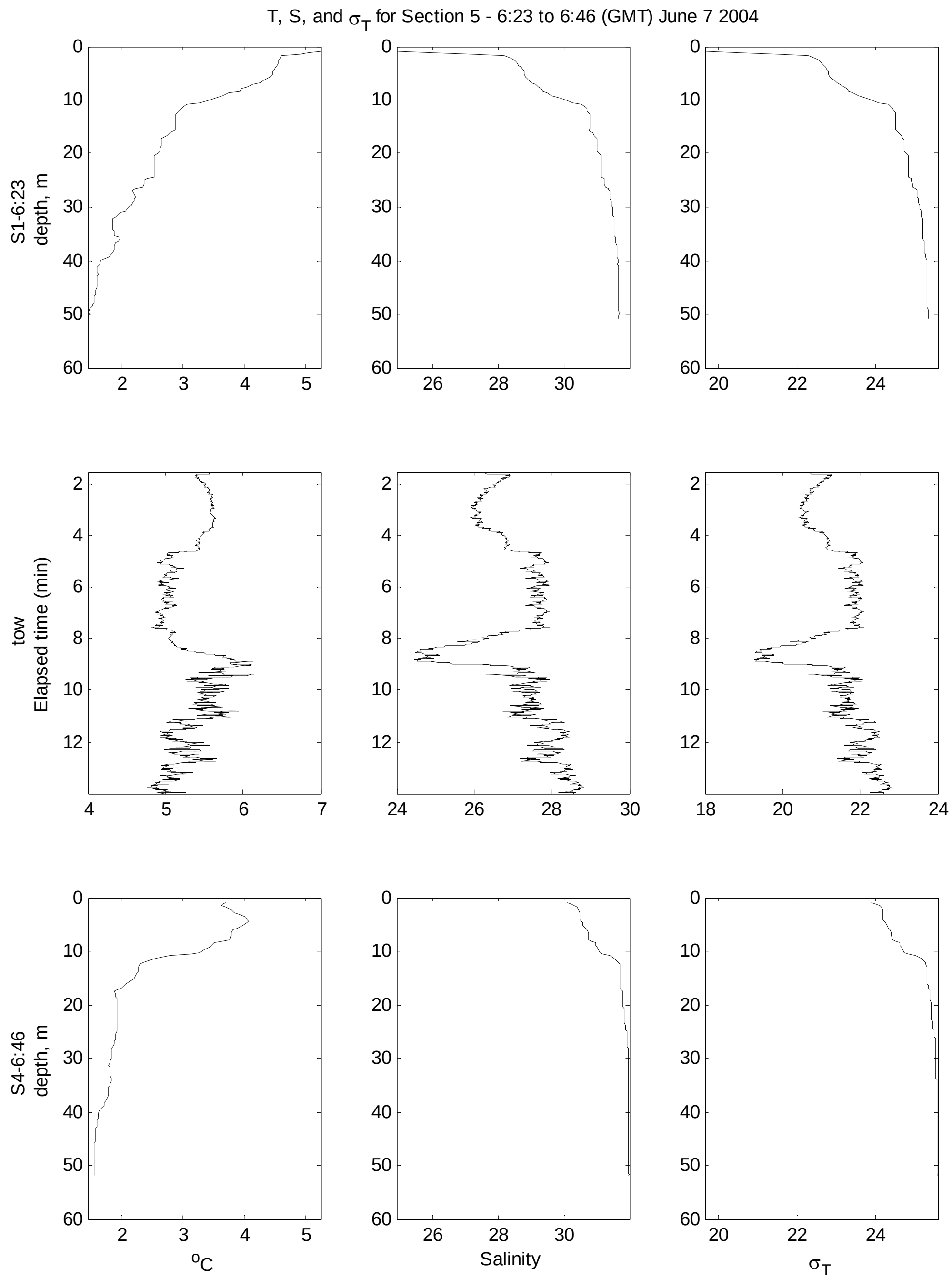

Figure 40: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 6:23 to 6:45 GMT June 7 2004.

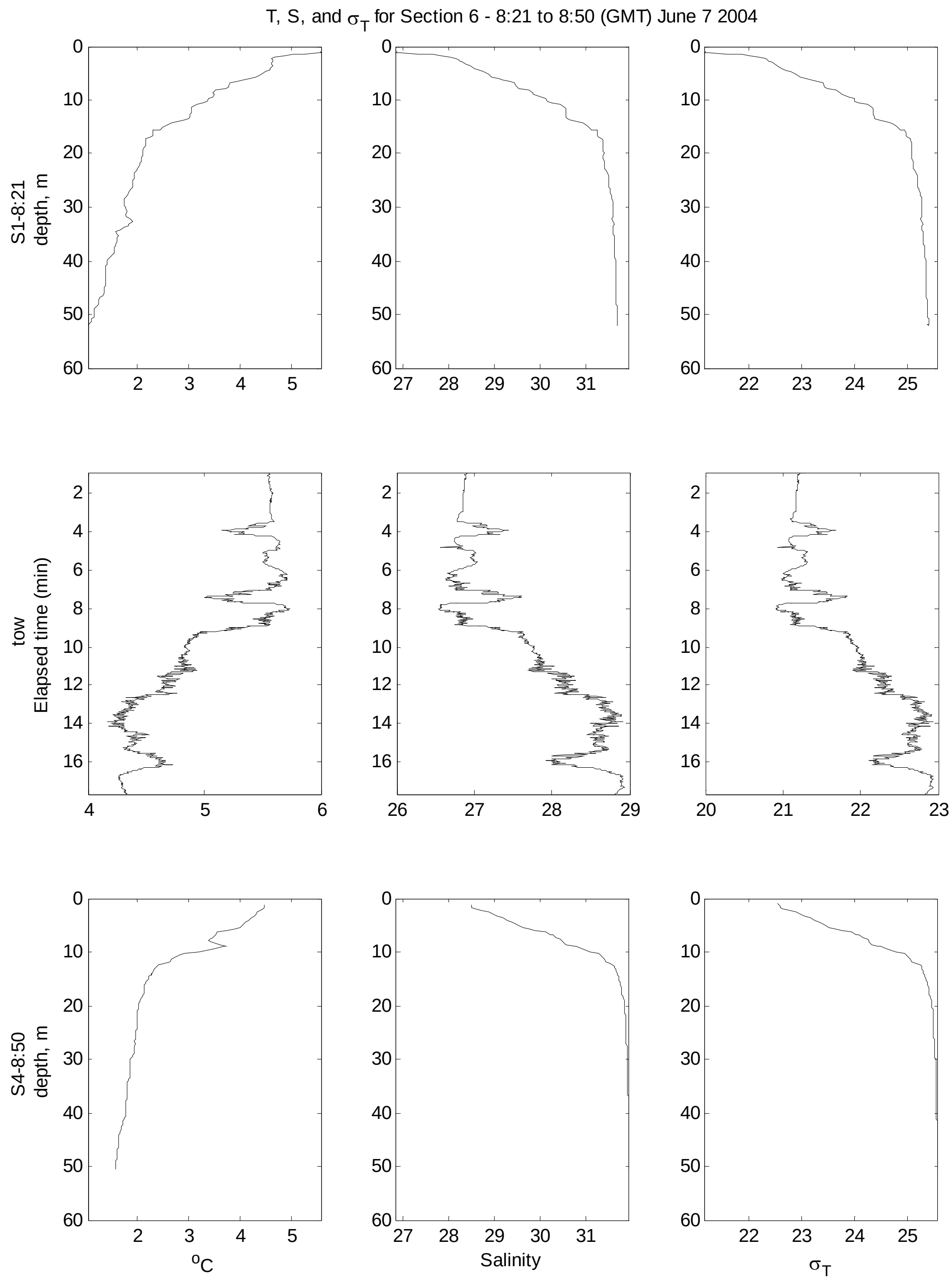

Figure 41: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 8:21 to 8:50 GMT June 7 2004.

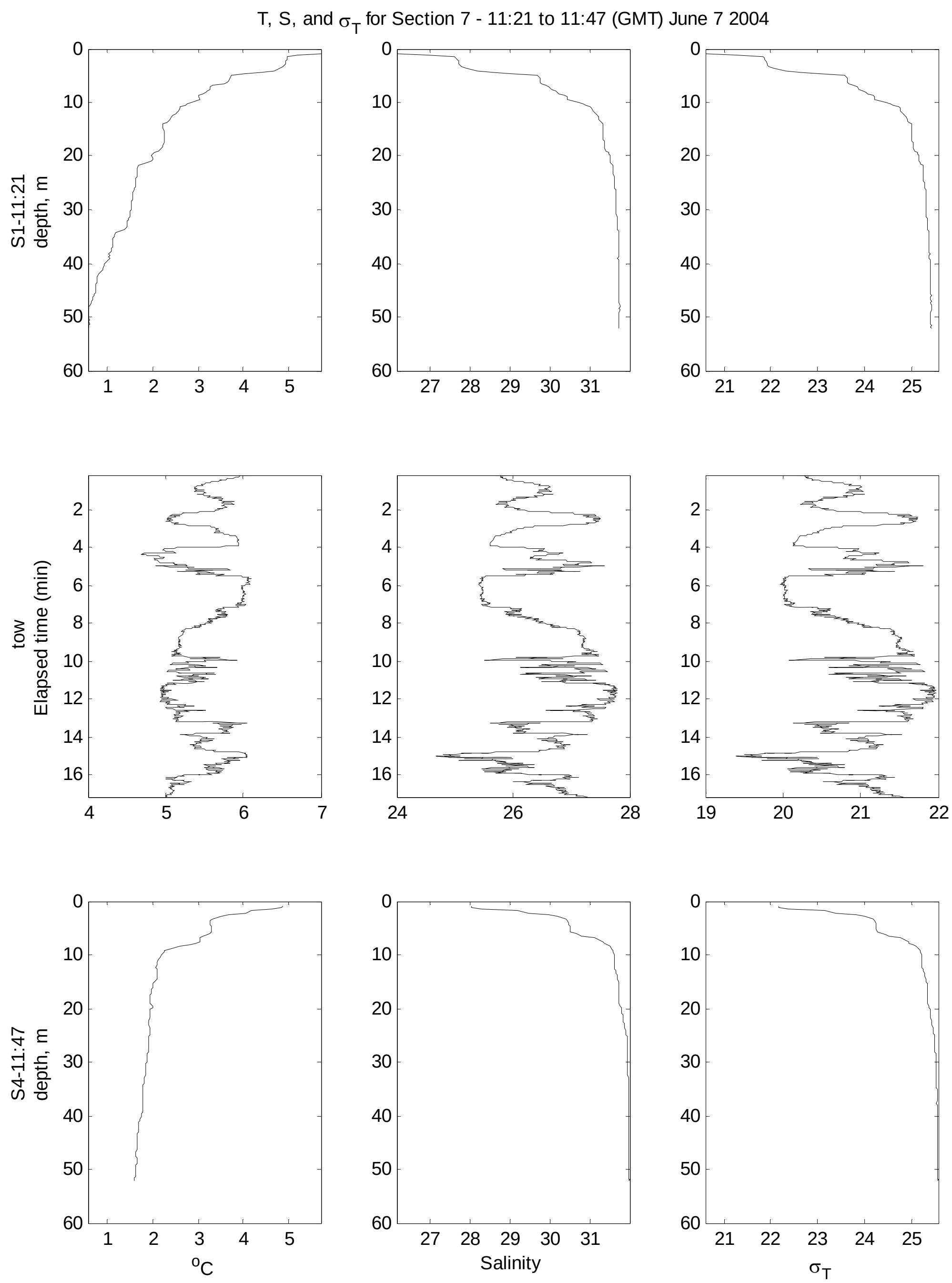

Figure 42: Vertical and horizontal temperature, Salinity and sigma-t profiles from S1 to S4, 11:21 to 11:47 GMT June 7 2004.

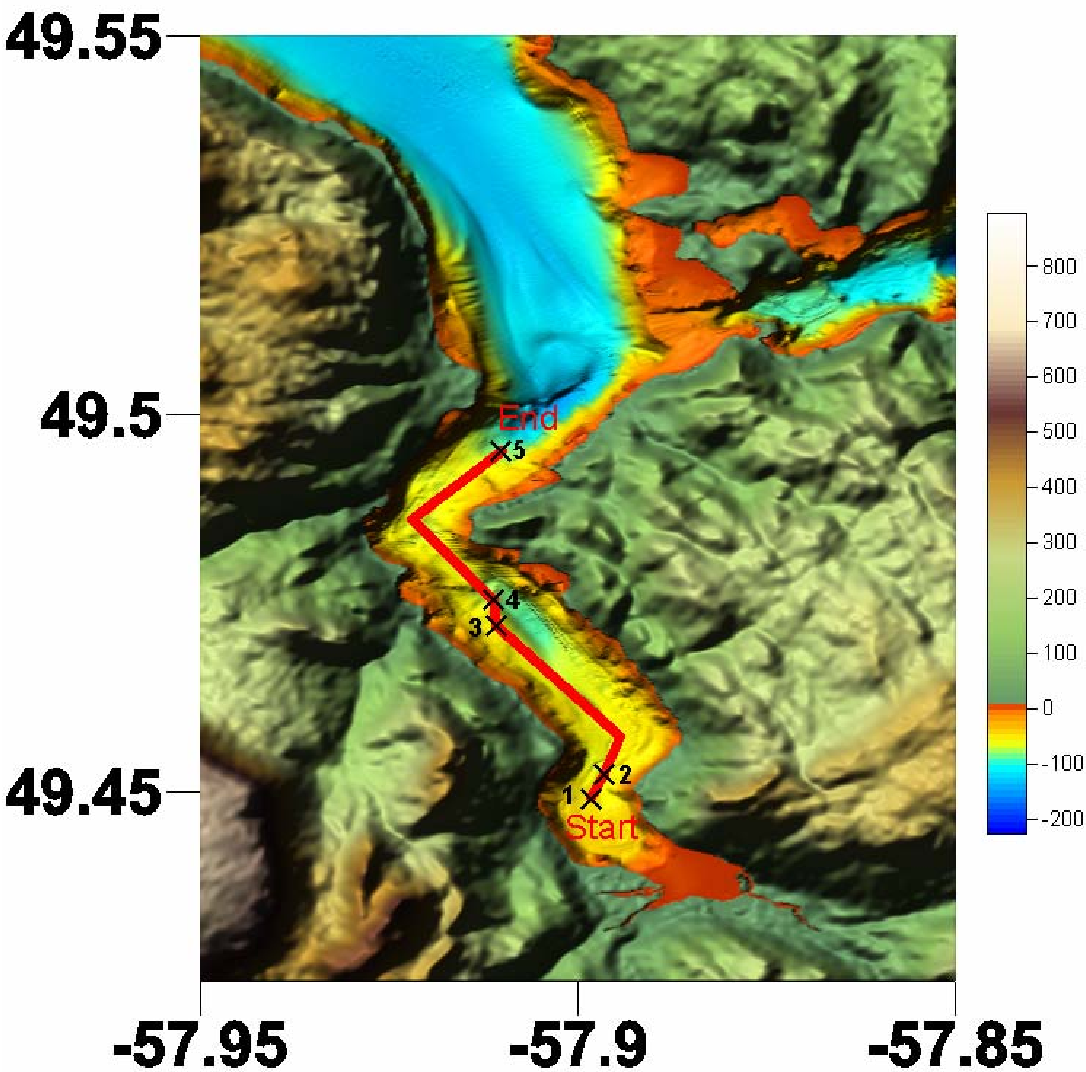

Figure 43: South arm CTD stations and vertical transect line.

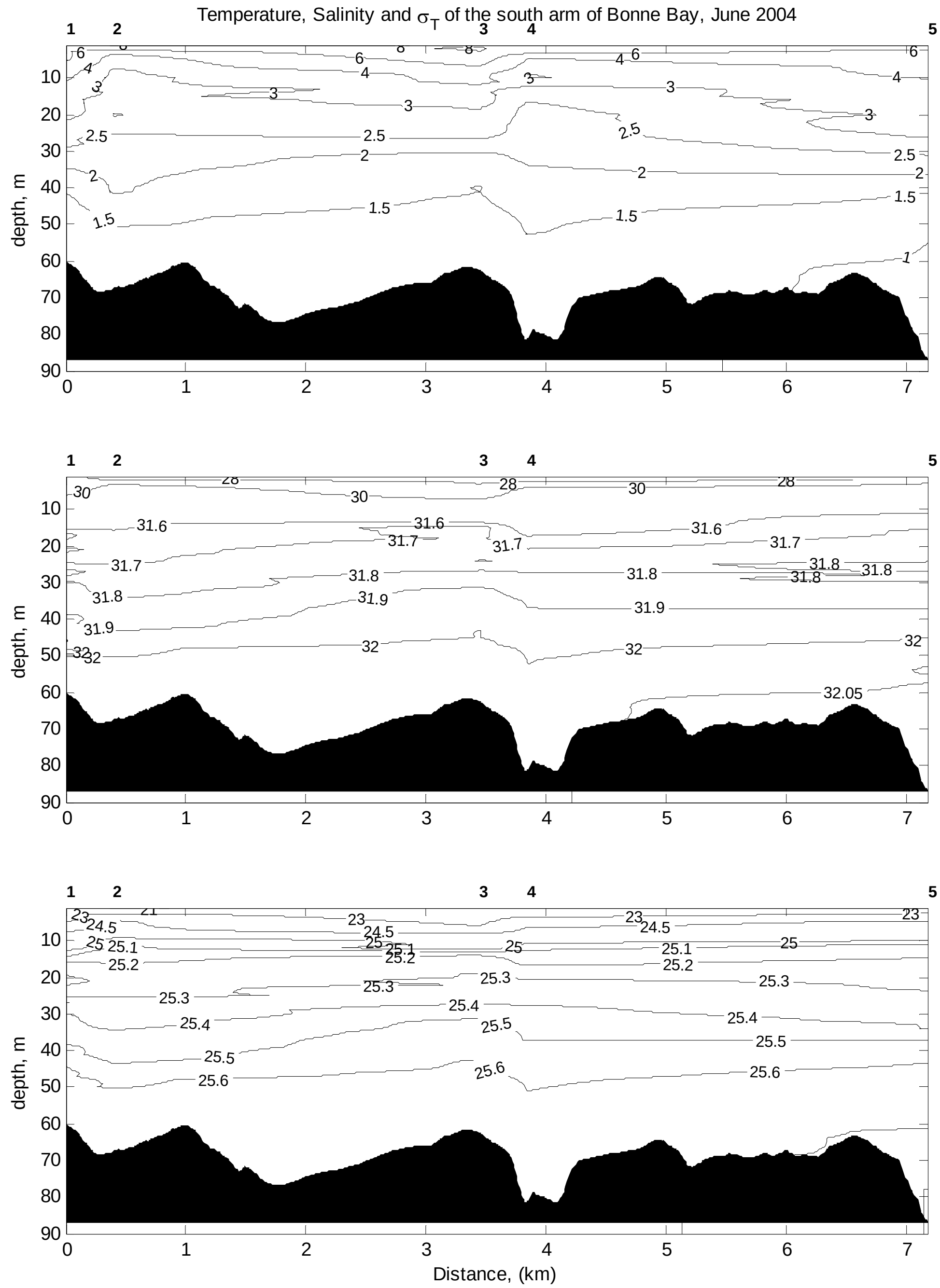

Figure 44: Temperature, salinity and sigma-t along the South arm of Bonne Bay, June 2004. Numbers indicate CTD stations in Fig. 43. Stations 2 and 4 were collected June 9 2004, while stations 1, 3 and 5 were collected June 13 2004. This is the cause of the 'bumpiness' of the contours near the stations.

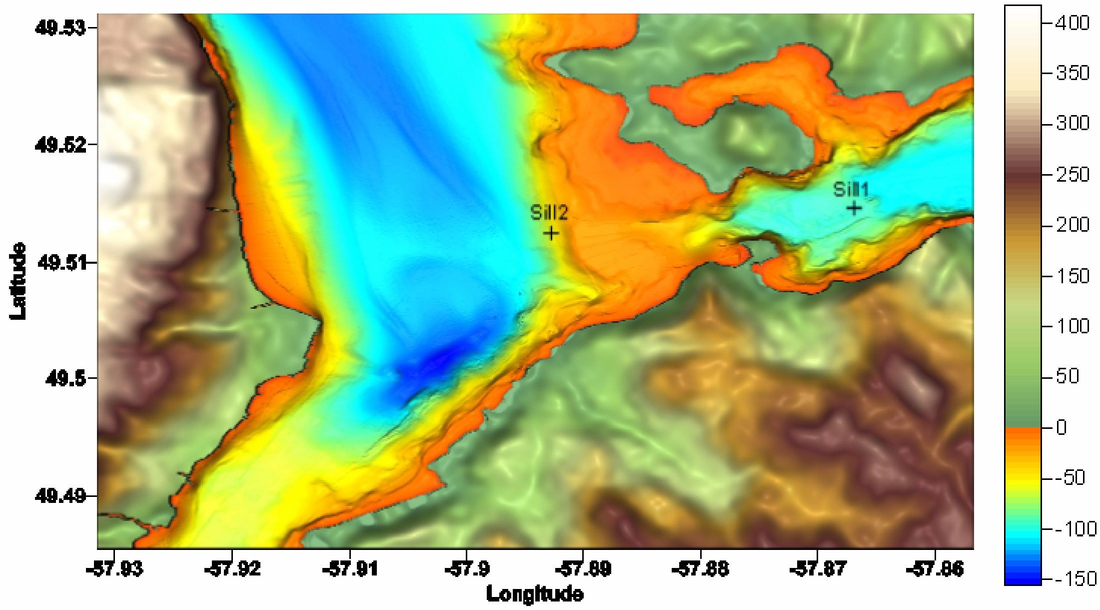

Figure 45: Sill-1 and Sill-2 positions from June 9 to June 11

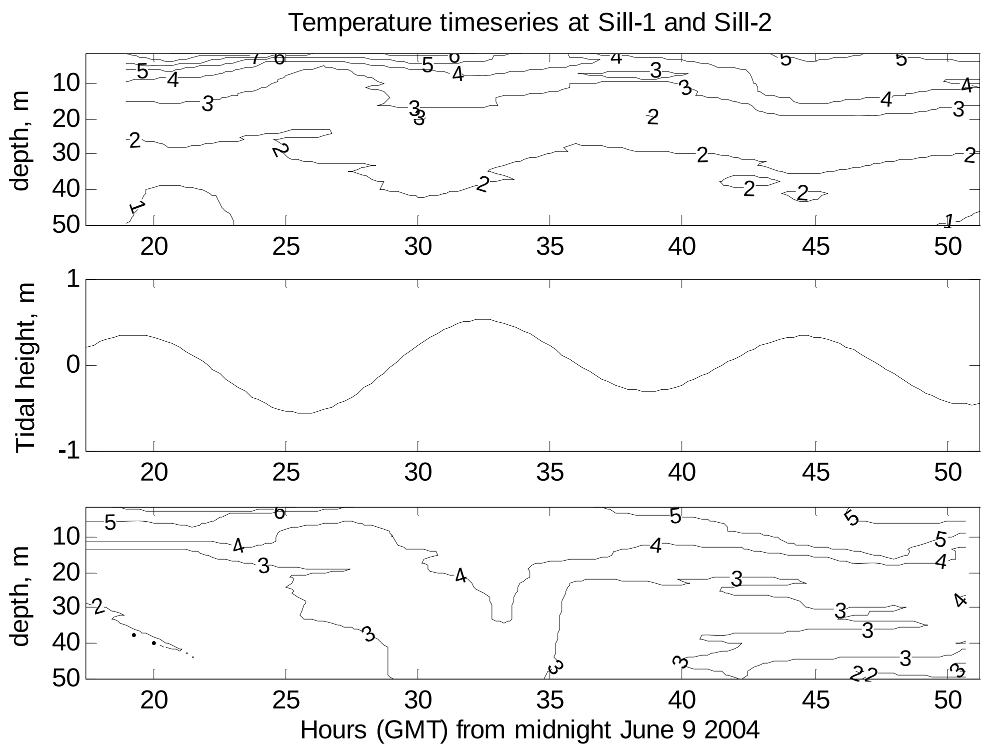

Figure 46: Temperature time series at Sill-1 and Sill-2. The middle plot indicates the tidal state.

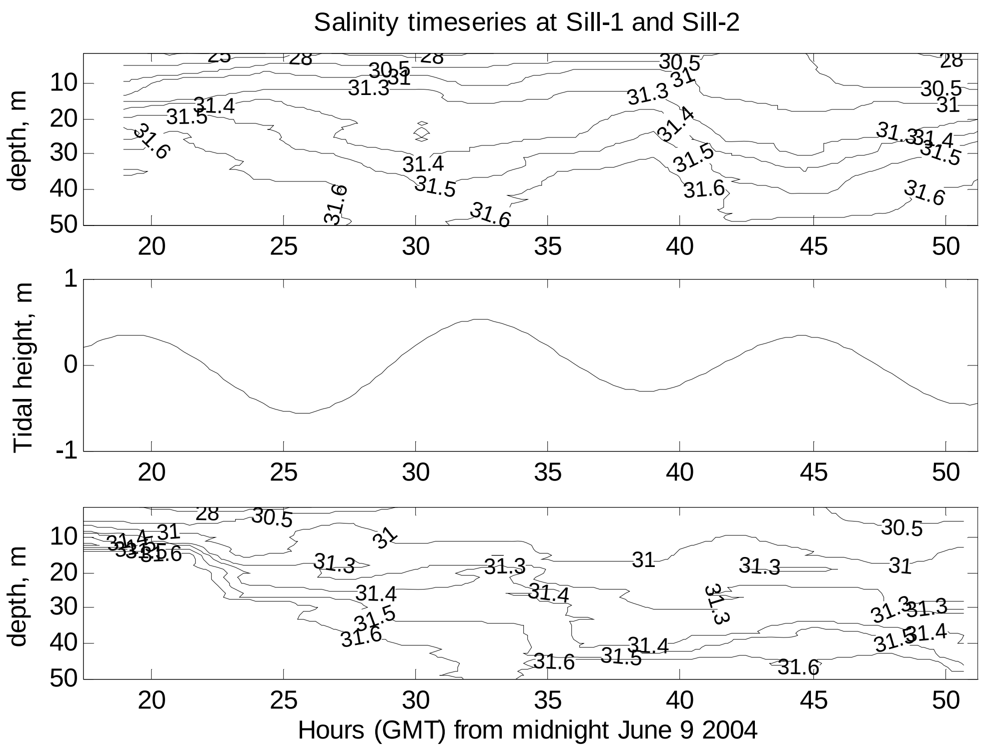

Figure 47: Salinity time series at Sill-1 and Sill-2. The middle plot indicates the tidal state.

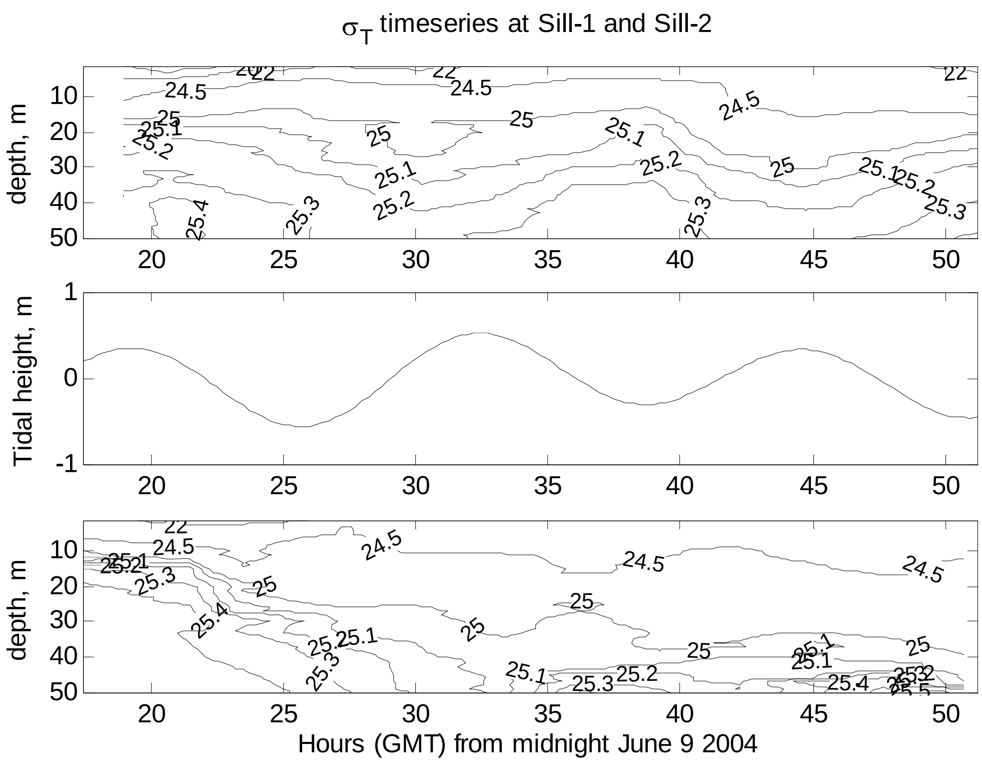

Figure 48: Sigma-t time series at Sill-1 and Sill-2. The middle plot indicates the tidal state.

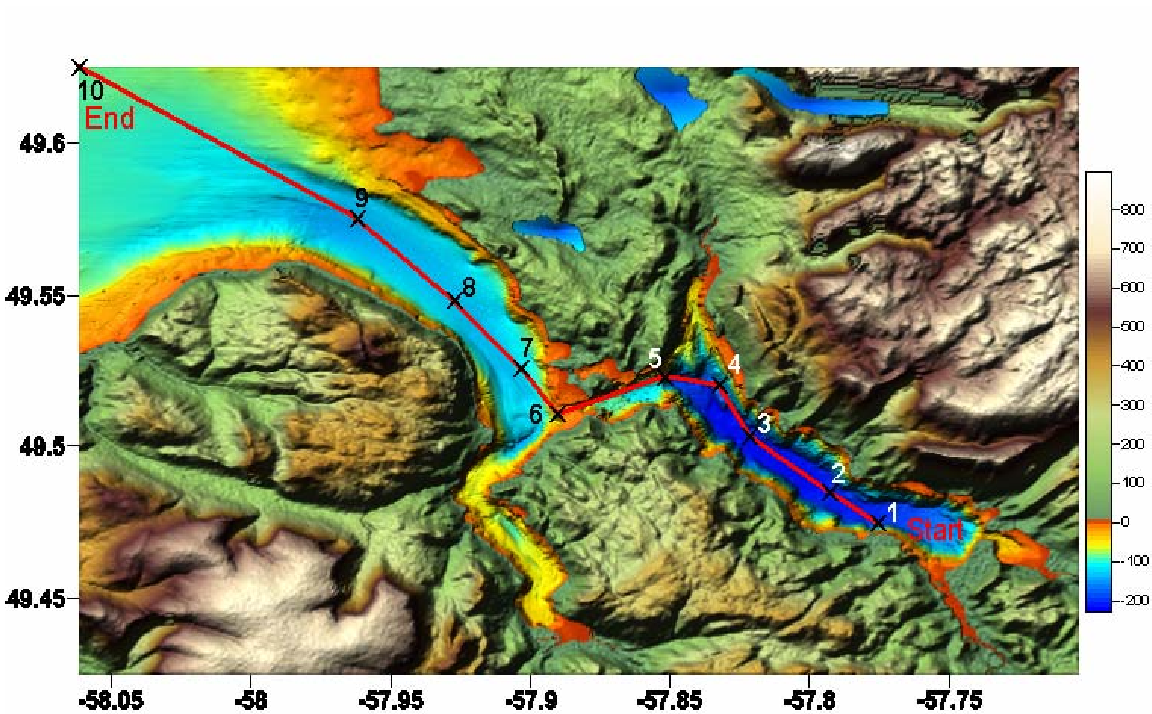

Figure 49: East arm to Gulf of St. Lawrence CTD stations and vertical transect line

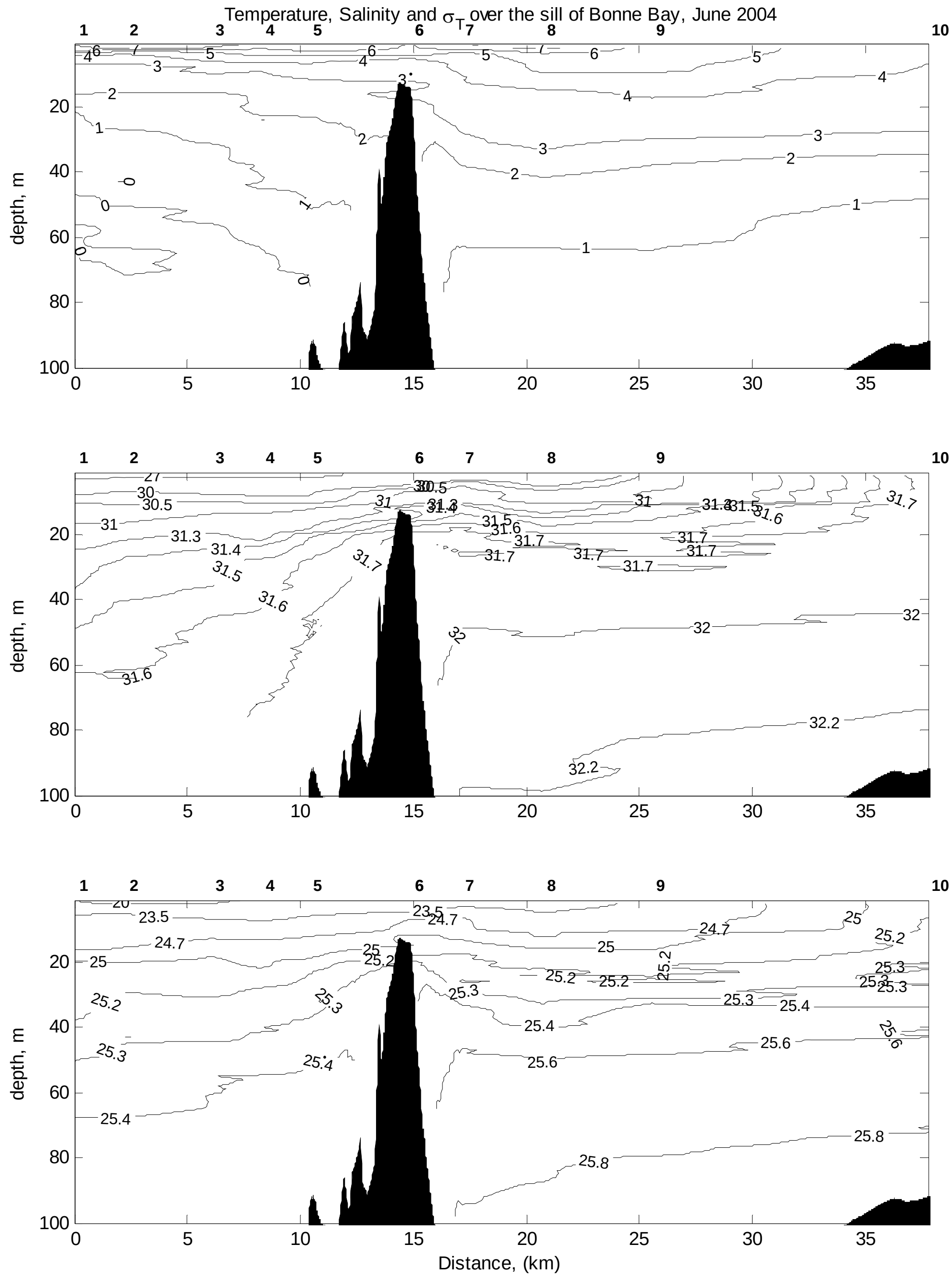

Figure 50: Temperature, salinity and sigma-t over the sill of Bonne Bay, June 2004. Numbers indicate CTD stations. Stations 1-6 were collected on June 8 2004, while stations 7-10 were collected on June 13 2004.