SMAST Technical Report 09-0204

Transient Tidal Eddy Project Data Report: Winter 2008-09

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I. General Information

The Transient Tidal Eddy (TTE) project consisted of field and modeling components that focused on the tidal eddy motion generation and evolution in the region east of Chatham, MA as depicted in Figure 1. The project consisted of a strongly stratified phase in spring 2008 and a weakly stratified phase in winter 2008-09. The winter observation phase of TTE, which spanned 3 November 2008 to 3 February 2009, consisted of shipboard CTD and ADCP surveys, moored ADCP time series measurements, CODAR surface current mapping, and the deployment of a drifter.

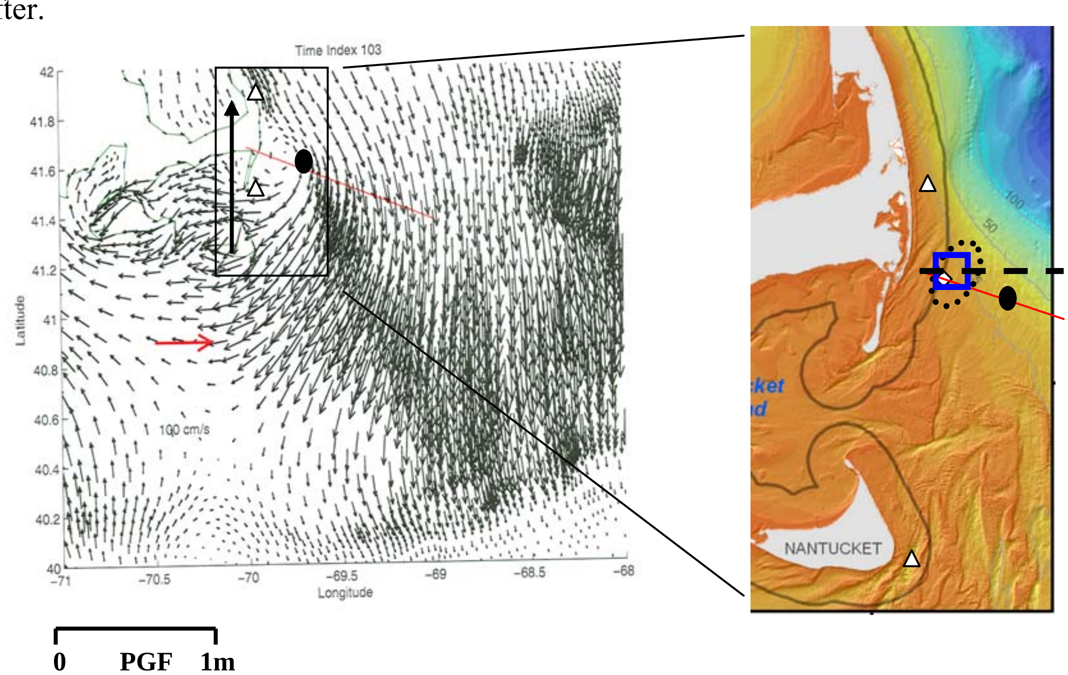


Figure 1 (right) The site of the field measurement program with elements: the Nauset and Nantucket CODAR sites (triangles), water property measurement transect (black dashed), AUV sampling box (blue), bottom-mounted ADCP/pressure 30m mooring site (diamond); and the NSD mooring site (filled oval); all relative to a schematic eddy and the reference transect (solid red) against a background of regional bathymetry (Courtesy of B. Butman USGS). **(left)** A model simulation of the full separation of the ebb flow envelop that frames a small clockwise eddy near the coast at 1.55^{hr} before the "change of tide" from ebb to flood flow. The pressure gradient force vector (PGF; northward arrow) is derived from the model sea level difference between the indicated model mesh nodes (triangles; with PGF–scale below). The current scale and reference transect are shown in red. The filled oval marks the NSD mooring site, at which proxy tidal current predictions are made (see below);

There were two phases to the field program, namely a spring, stratified Phase-1, with activities focused in May 2008; and a winter, significantly less-stratified Phase-2, with activities focused between November 2008 and January 2009 (see Figure 2). The field work described here focused on 3-4 November 2008 and 27-31 January 2009.

There were two, 2-week phases of the field program. The spring/stratified Phase 1 focused on May 2008. The winter, significantly less-stratified Phase 2 focused on November 2008 through January 2009 (see Figure 2). The field work described in this report was focused on 3-4 November 2008 and 27-31 January 2009.

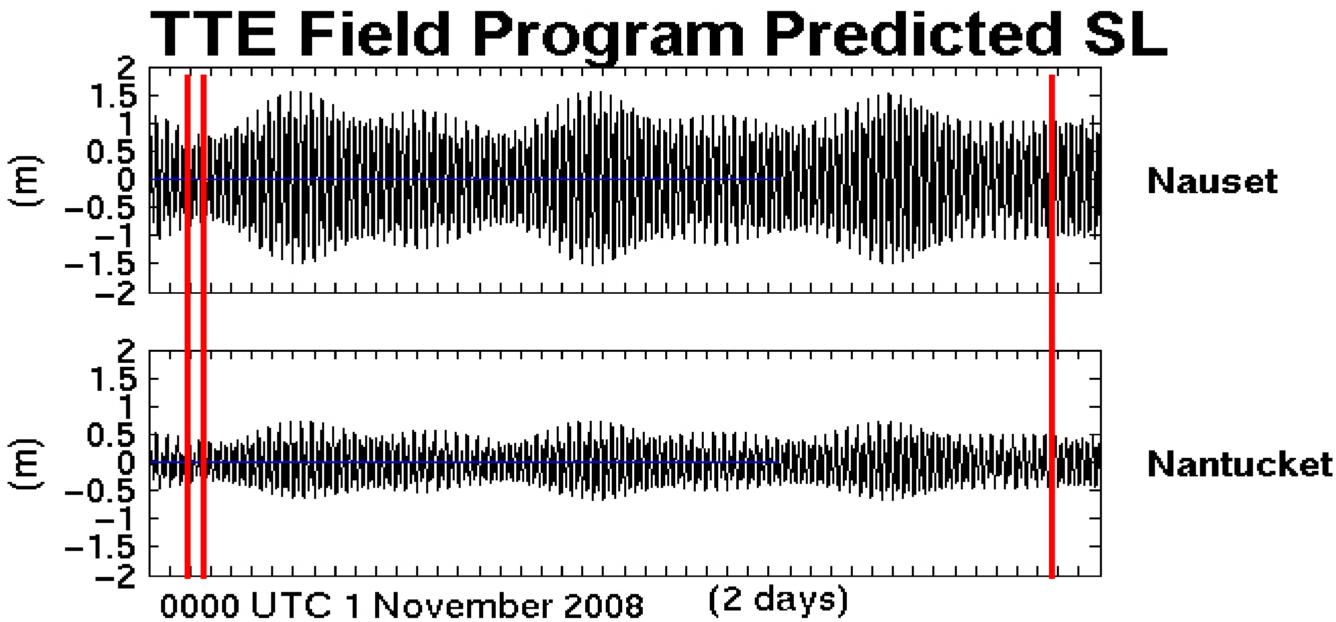


Figure 2 Predicted tidal sea level (db ~ m) at Nauset and Nantucket during October-November 2008. The dashed lines are at 10-day intervals relative to 0000 GMT 1 October 2008. The winter field phase consisted of operations on 3-4 November 2008 and 27 January 2009 (highlighted).

On 3 November 2008, (1) the bottom -mounted ADCP instrument was deployed at station 1 (see Table 1) and (2) an ADCP current profile transect at stations indicated in Table 1.The shipboard stations are located in Figure 3 and relative to the transect bathymetry in Figure 4. On 4 November 2008, we conducted 4 sets of continuous shipboard ADCP measurements along the transect between stations 1 and 3. On 27 January 2009, the bottom-mounted ADCP instrument was recovered, a station 1 to 7 shipboard CTD survey was conducted, and a surface drifter was deployed near station 7.

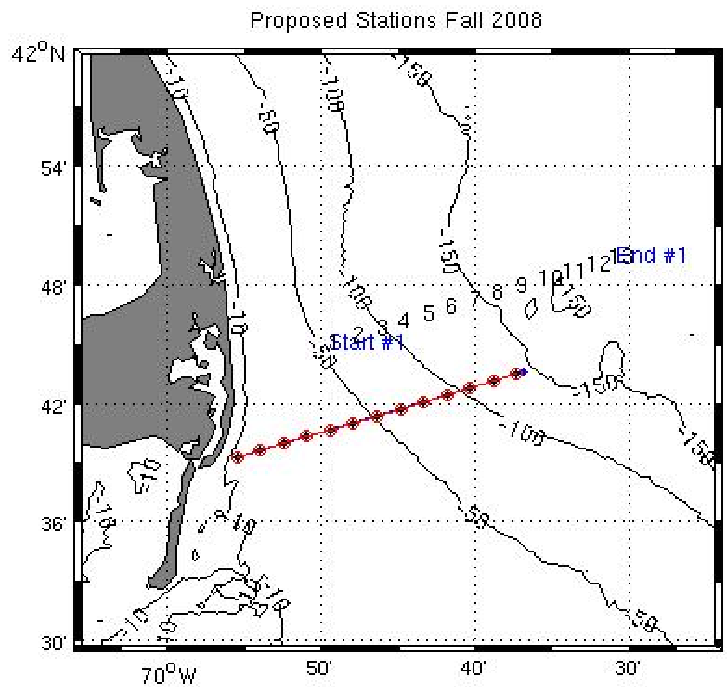


Figure 3 ADCP/CTD Survey Plan-View

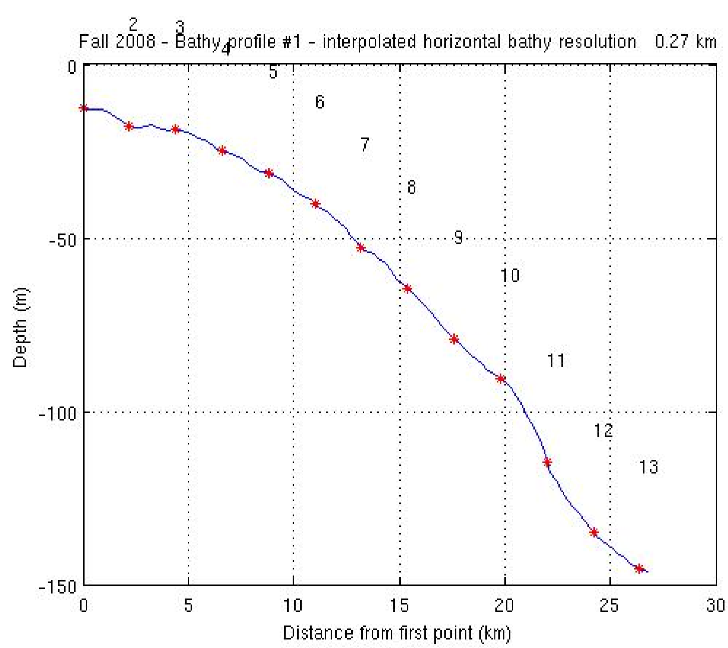


Figure 4 ADCP/CTD Survey Transect-View

II. Measurements

The 50-foot research vessel RV R&R (Figure 5) was used for the winter at-sea work. Shipboard profiling surveys were conducted on 3 and 4 November 2008 at the time that the bottom-mounted ADCP/bottom pressure instrument was deployed at station 1; and 27 January 2009 when the bottom-mounted ADCP/bottom pressure instrument was recovered. An internally-recording Sea Bird Electronics (SBE-25) Conductivity/Temperature/Depth (CTD) instrument and RDI, Acoustic Doppler Current Profiling (ADCP) were used. Also a surface drifter was deployed at Station 7 on the 27 January 2009 cruise.

Figure 5a Research Vessel R&R **Figure 5b** Research Vessel R&R fantail

A. CURRENTS

1. Moored Currents Measurements

On 3 November 200, the bottom-mounted ADCP was deployed in 12.5 m of water at 41^o 39.5'N 69^o 55.4'W (41.658^{o}N 69. 923^{o}W) – the station 1 site (see Table 3) that is about 30m from navigation buoy "C - east of Chatham, MA. It consisted of an aluminum frame (see Figure 6) on which was bolted an upward-looking RDI 300kHz Workhorse ADCP, an Aanderra pressure instrument, an Edgetech Inc. acoustic release, Benthos glass sphere buoyancy, and an 18" high 200# angle-iron anchor (see Figure 6; left). On 27 January 2009, the instrument package released from the anchor, upon acoustic command from the vessel, and floated to the surface, where it was recovered without incident. A 2-month ADCP record was recovered.

Figure 6 The bottom ADCP/pressure instrument **(left)** sitting on its anchor before launch 3 November 2008; **(right)** after recovery on 27 January 2009 (note the bio-fouling).

The time series records of the moored ADCP northward and eastward currents at 6m and 8m above-bottom (AB) in about 13m of water at station 1 are clearly dominated by the tides (see Figure 7). Visually the 6m and 8m above-bottom records look identical; consistent with the shallowness of the water column (see Appendix A for the basic statistics). A tidal harmonic analysis (see Appendix A) of the measured currents was used to predict the records in Figure 8 that were superposed non-tidal "residual" part of the measured flow. The nearly rectilinear M_2 tidal current ellipse, which is oriented at 30^{o}T, is presented in Figure 9.

The Chatham northward current record at 8m AB is compared in Figure 10 with the (1) Nantucket minus Nauset predicted sea level pressure (PSL), Nauset PSL and predicted northward current at NSD; the offshore site at 41.617^{o}N 69.733^{o}W as shown in Figure 1. The phase difference between the Chatham and NSD northward currents is significant and related to the eddy motion of interest here. The time horizons of the shipboard ADCP surveys are also indicated.

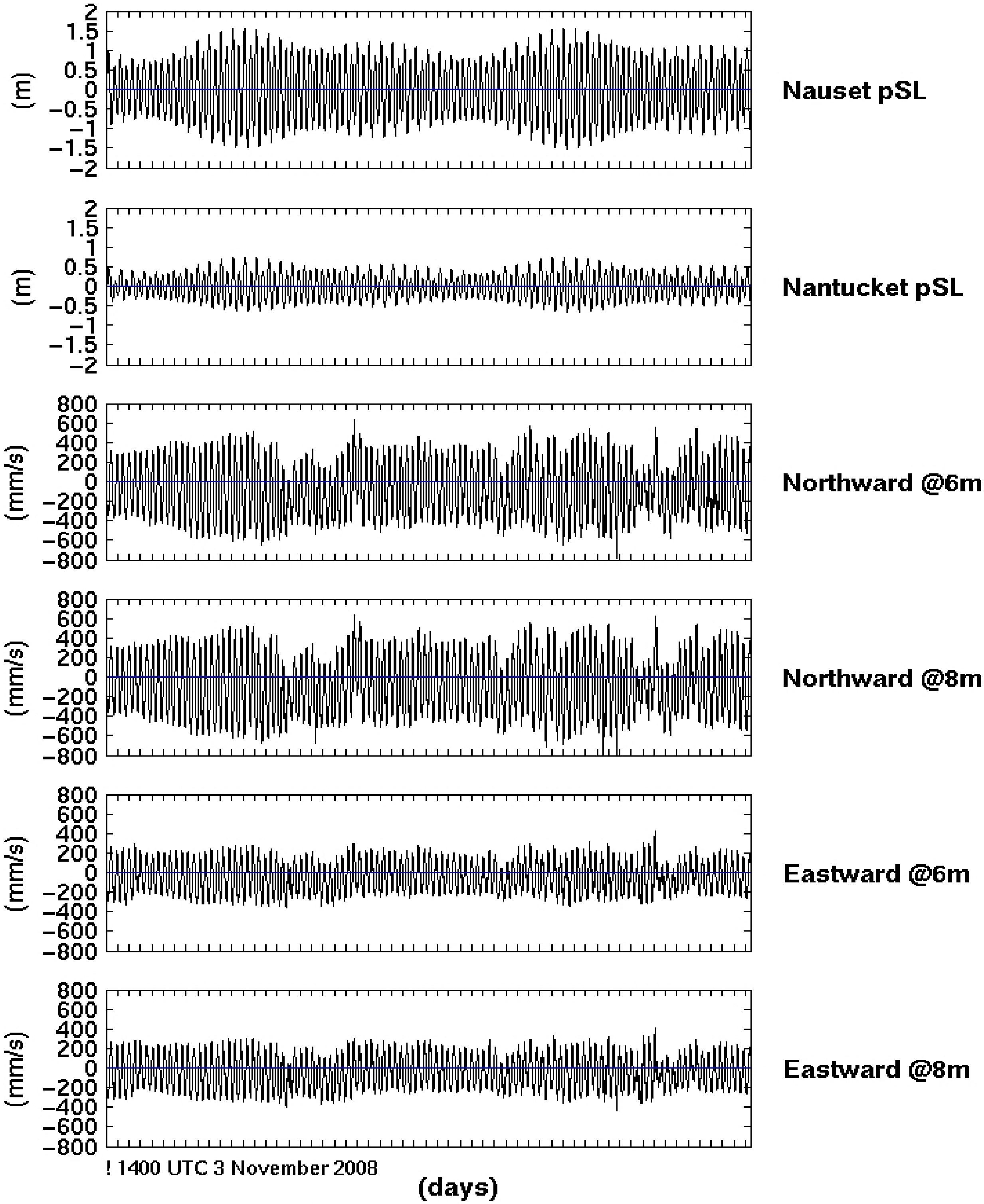


Figure 7 (**top 2 panels**) predicted tidal sea level at Nauset and Nantucket; **(middle 2 panels)** ADCP northward currents and **(bottom 2 panels**) eastward currents.

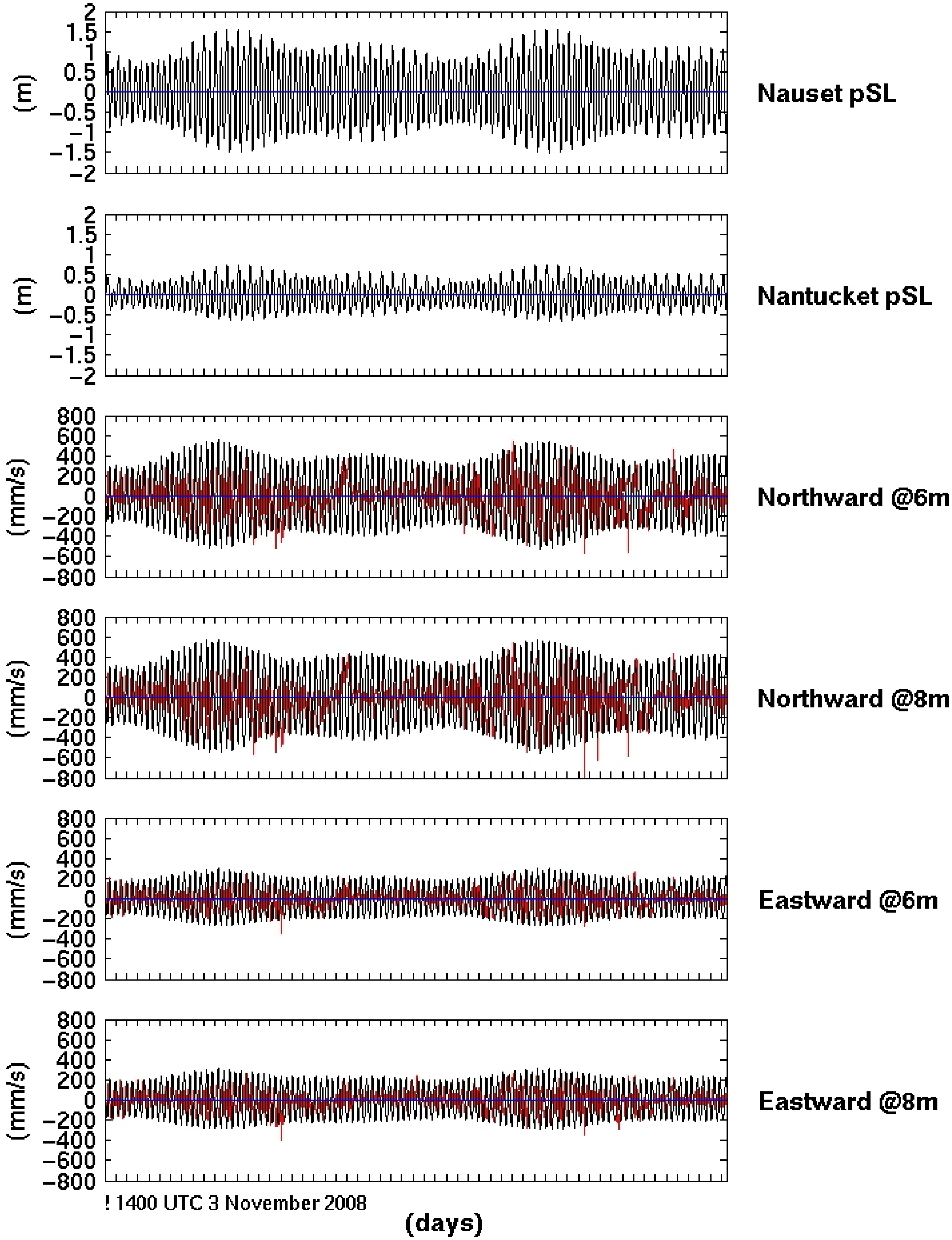


Figure 8 Time series of **(top 2 panels)** predicted tidal sea level at Nauset and Nantucket respectively; **(middle 2 panels)** predicted *northward* currents at elevations above the bottom of 8m and 6m respectively; with superposed residual current (red); and **(bottom 2 panels)** corresponding predicted *eastward* currents – with superposed residual current (red).

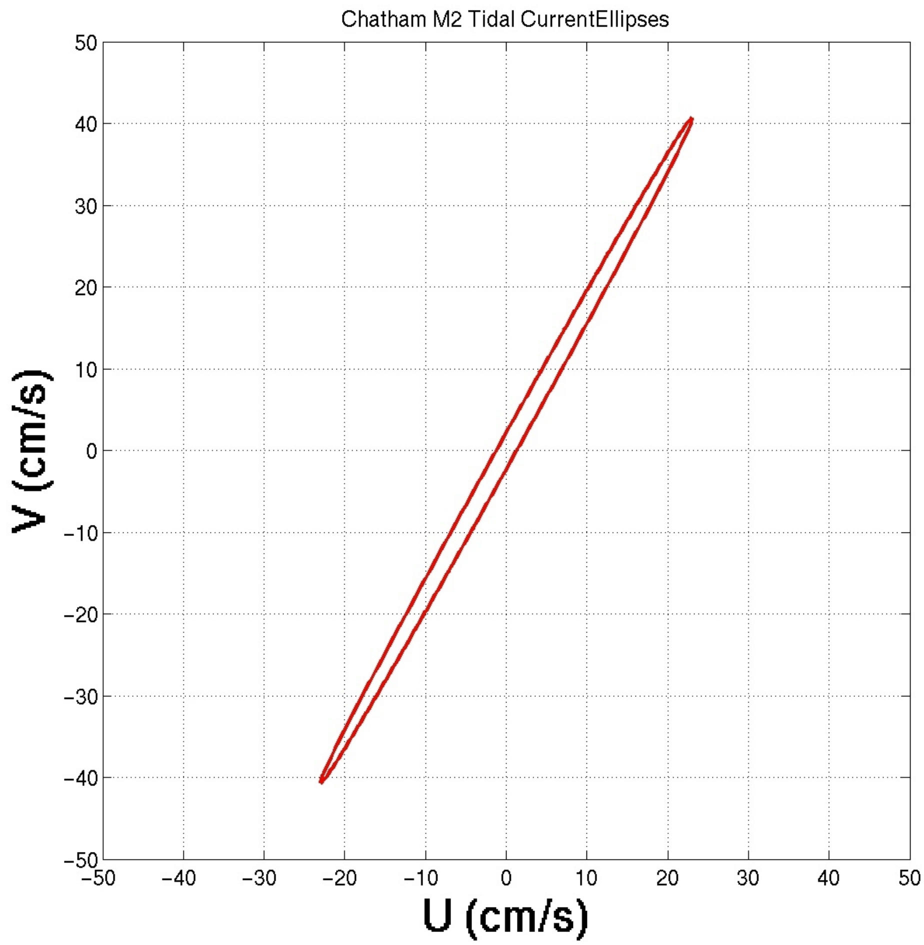


Figure 9 The M2 tidal current ellipse.

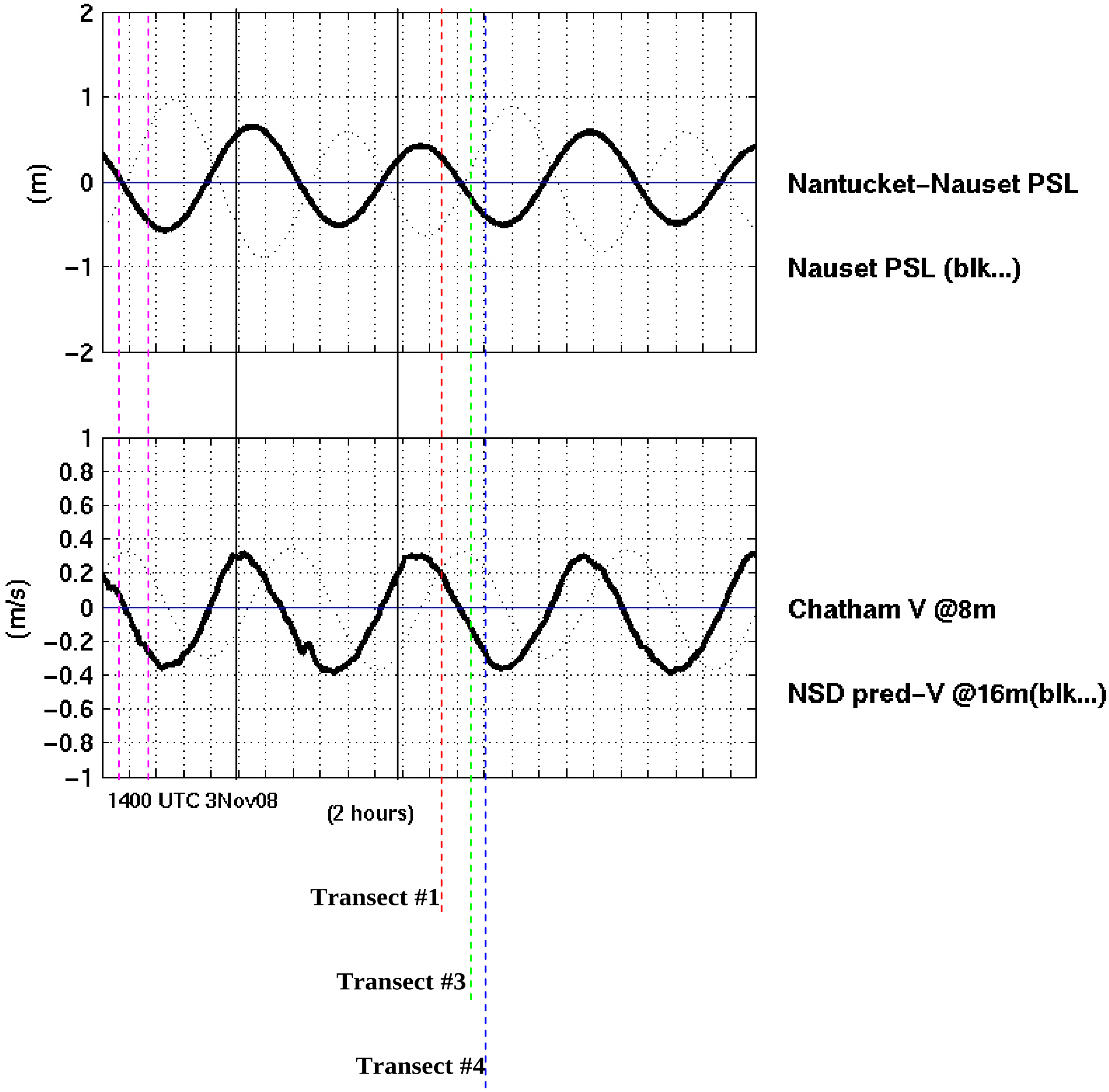


Figure 10 Time series of **(upper panel)** Nantucket minus Nauset predicted sea level difference – Nauset PSL (dotted); **(lower panel)** ADCP *northward* current 8m above bottom (AB) at station 1; predicted tidal current at station NSD (dotted) [41.617°N 69.733°W]. The dashed lines on 3 November mark the period of shipboard ADCP measurements between stations 1 and 11 (see next section). The dashed lines on 4 November mark the respective start times of a trio of shipboard ADCP transects between stations 1 and 3 (see next section)

2. Shipboard ADCP Current Profiling

Subsurface current profiles were measured using a Teledyne/RDI Instruments Workhorse Sentinel Acoustic Doppler Current Profilers (ADCP) operating at a frequency of 1200 kHz. The ADCP was bolted to a rotating spar that was mounted in a cylindrical holder (normally used for fishing rods) on the rail of the Ryan Marine's 50-foot RV R&R (Figure 11). This configuration enabled us to lower the ADCP into the water to the depth of about 1.5 m at each station and then raise it out of the water for steaming to the next station. The ADCP was powered by shipboard power supply through a waterproof cable.

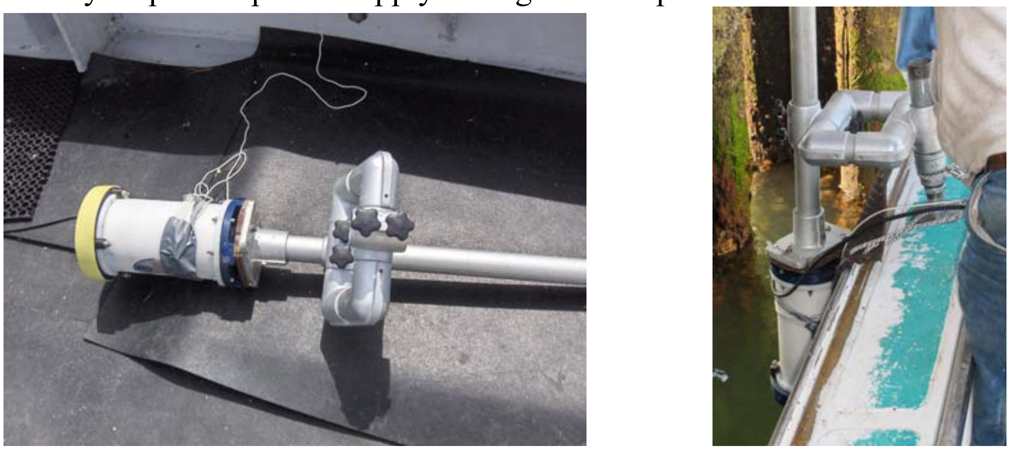


Figure 11 (left) The RDI 300 kHz ADCP mounted on the deployment spar; **(right)** At each station the downward-looking ADCP was lowered to a depth of about 1.5m.

For the 3 November 2008 measurements, the ADCP data were recorded with a sampling configuration was:

Sample Bin Size:	0.25 m
Number of Bins:	50
First Current Bin Depth:	0.62m below transducer head
Ping Rate:	3.85pings/sec
Ensemble Size	1.33sec (i.e., 4 pings/ensemble)

For the 4 November 2008 measurements, the ADCP data were recorded with a sampling configuration was:

Sample Bin Size:	1 m
Number of Bins:	15
First Current Bin Depth:	1.4m below transducer head
Ping Rate:	3.85pings/sec
Ensemble Size	2.08sec (i.e., 8 pings/ensemble)

A summary of some of the technical specifications for the Workhorse 300 kHz ADCP appears in Table 1. In general, velocity accuracy at this frequency is approximately 0.3% of the water velocity relative to the ADCP ±0.3 cm/sec with a resolution of 0.1 cm/sec. These are typical ranges and standard deviations with actual values varying significantly; depending on actual conditions.

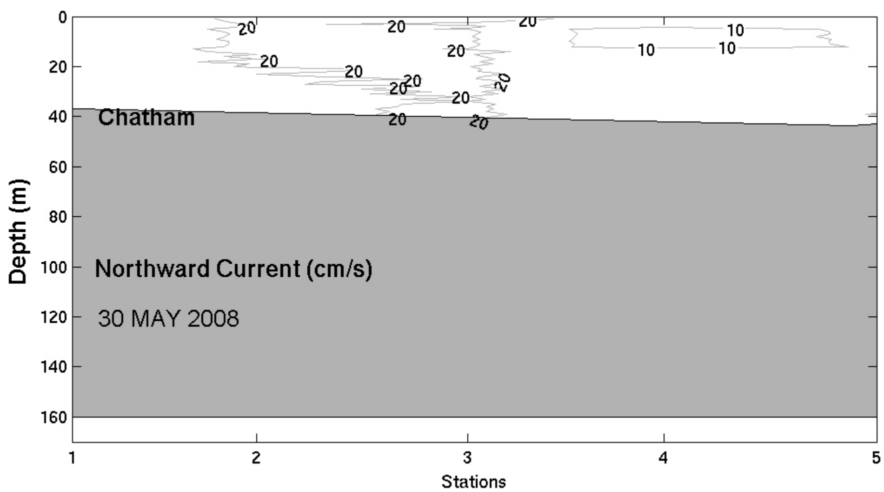
Table 1 RDI Workhorse Sentinel 1200 kHz ADCP specifications for 3 November 2009.

Bin Size(m)	0.25m	0.5m	1m	2m
Typical Range (m)	11-14	13-16	14-18	15-20
Standard Deviation (cm/sec)	12.9	6.1	3.0	2.0

Shipboard ADCP Current Profile Survey: 3 November 2008

Table 2 Station information for the **3 November 2008** shipboard ADCP survey

St #	Lat (° N)	Lon (°W)	Depth (m)	Depth (fath)	Sample Time (EST)	Station Time (GMT)	Station Time (Julian hrs)	NS Dist (nm)	Cum Dist (nm)	NSDist (km)	Cum Dist (km)
01	41 39.5 41.6583	69 55.4 69. 9233	13..5	7.4	11.0672 11.1508	1503	954087.03	1.19	1.19	2.20	-
02	41 39.7 41. 6617	69 54.0 69. 9000	18..0	9.8	11.4021 11.4858	1521	954087.35	1.19	2.38	2.20	2.20
03	41 40.0 41.6667	69 52.4 69. 8733	20..3	11.1	11.7369	1540	954087.67	1.19	3.56	2.20	4.41
04	41 40.345 41..6724	69 50.923 69..8487	26..7	14.6	11.9883	1556	954087.93	1.19	4.75	2.20	6.59
05	41 40.683 41..6781	69 49.319 69..8220	34..3	18.8	12.3235	1613	954088.22	1.18	5.93	2.18	8.79



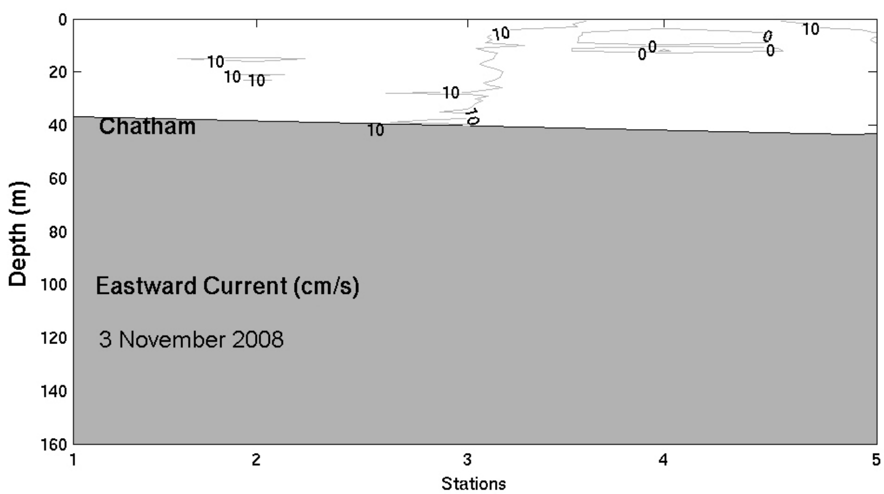


Figure 12 Vertical sections of 3 November 2008; (top) ADCP northward current (V in cm/s) and (bottom) ADCP eastward current (U in cm/s).

Shipboard ADCP Current Profile Survey: 4 November 2008

On 4 November 2008, three continuous shipboard 1200 kHz ADCP transects were run slowly (0.5 knots) between stations 1 and 3 (see Table 3 for details). The ADCP current profile data time series were resolved in 1 meter bins; with the first bin beginning at a depth of 1.4 meters below the ADCP transducer head; which was set at a depth of about 1.6m. Thus the depth of the first bin was 3m. The current profile measurement ensembles were taken over 2.08 seconds.

The shipboard ADCP current measurements are made relative to the RV R&R, which of course was moving. The vessel's motion relative to the bottom is measured by the bottom-track feature of the ADCP and used to correct the measured ADCP current profiles for vessel motion.

Table 3 Station information for the **4 November 2008** shipboard ADCP survey

St	Lat ^{o} N	Lon ^{o}W	Depth (m)	Depth (fath)	Time (GMT)	Time (Julian hrs)	NS Dist (nm)	Cum Dist (nm)	NSDist (km)	Cum Dist (km)
	TRAN #1									
01	41 39.219 41..6537	69 55.460 69. 9243	13..5	7.4	1359	954109.983	1.19	1.19	2.20	-
02	41 39.560 41. 6593	69 53.994 69. 8999	20..0	9.8	1429	954110.483	1.19	2.38	2.20	2.20
03	41 39.931 41..6655	69 52.402 69. 8734	21.1	11.1	1502	954110.033	1.19	3.56	2.20	4.41
	TRAN #3									
01	41 39.219 41..6537	69 55.460 69. 9243	13..5	7.4	1606	954112.100	1.19	1.19	2.20	-
02	41 39.560 41. 6593	69 53.994 69. 8999	20..0	9.8	1639	954112.650	1.19	2.38	2.20	2.20
03	41 39.931 41..6655	69 52.402 69. 8734	21.1	11.1	1709	954113.150	1.19	3.56	2.20	4.41
	TRAN #4									
03	41 39.931 41..6655	69 52.402 69. 8734	21.1	11.1	1711	954113.183	1.19	3.56	2.20	4.41
02	41 39.560 41. 6593	69 53.994 69. 8999	20..0	9.8	1730	954113.500	1.19	2.38	2.20	2.20
01	41 39.219 41..6537	69 55.460 69. 9243	13..5	7.4	1802	954114.033	1.19	1.19	2.20	-

The absolute ADCP current profile time series in Figure 13 show a generally northeastward current between 1000 and 1100 EST; changing to generally southwestward between 1200 and 1300 EST; and generally strong southwestward between 1300 and 1400 EST during Transect 4.

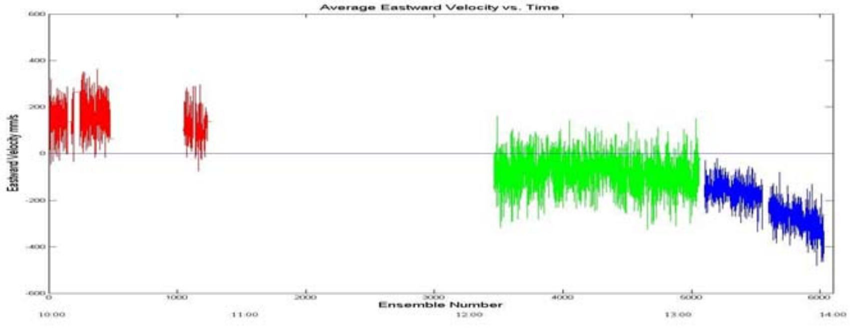


Figure 13a The 4 November 2009 **eastward** ADCP average current profile time series for the station 1-3 Transect 1 (red), station 1-3 Transect 3(green), and station 3-1 Transect 4 (blue). Times are EST.

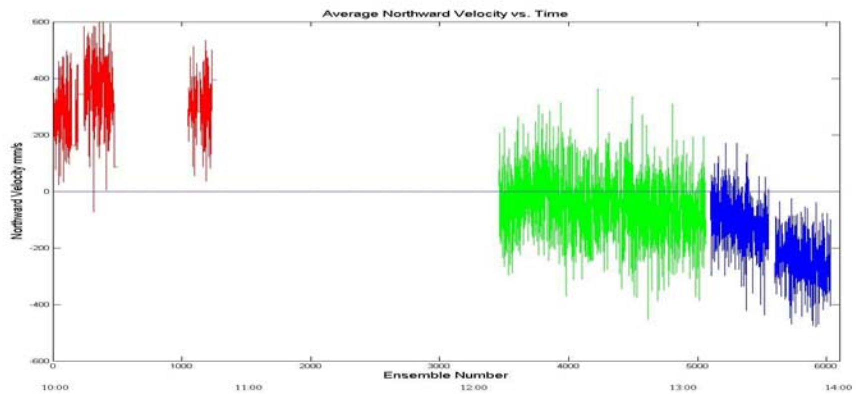


Figure 13b The 4 November 2009 average **northward** ADCP time series for the station 1-3 Transect 1 (red), station 1-3 Transect 3(green), and station 3-1 Transect 4 (blue). Times are EST.

The shipboard ADCP current measurements are made relative to the RV R&R, which of course was moving. The vessel's motion relative to the bottom is measured by the bottom-track feature of the ADCP. The crossover at the start indicates when the boat turned around at Station 1 for the beginning of Transect 3. Figure 14 shows how the measured ADCP current is corrected for vessel motion.

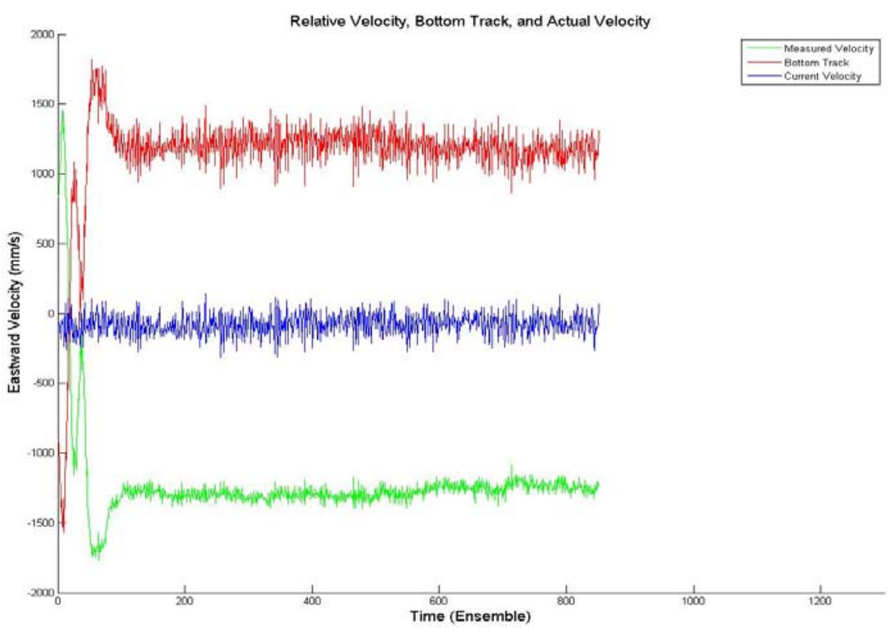


Figure 14 The 4 November 2009 ADCP bottom-track eastward velocity (red) compared to the measured ADCP current (green) and corrected or absolute current speed (blue).

The absolute northward profiles along Transect 1 (Figures 15a) show the reduction in the intensity of flood flow. As indicated by the eastward component profile in Appendix C the flood flow is northeastward - consistent with the tidal current ellipse in Figure 9. By the time of Transect 3 (Figures 15b, Appendix C), the southwestward ebb flow was established. The absolute velocity profiles along Transect 4 (Appendix C) show intensified southward and westward flow.

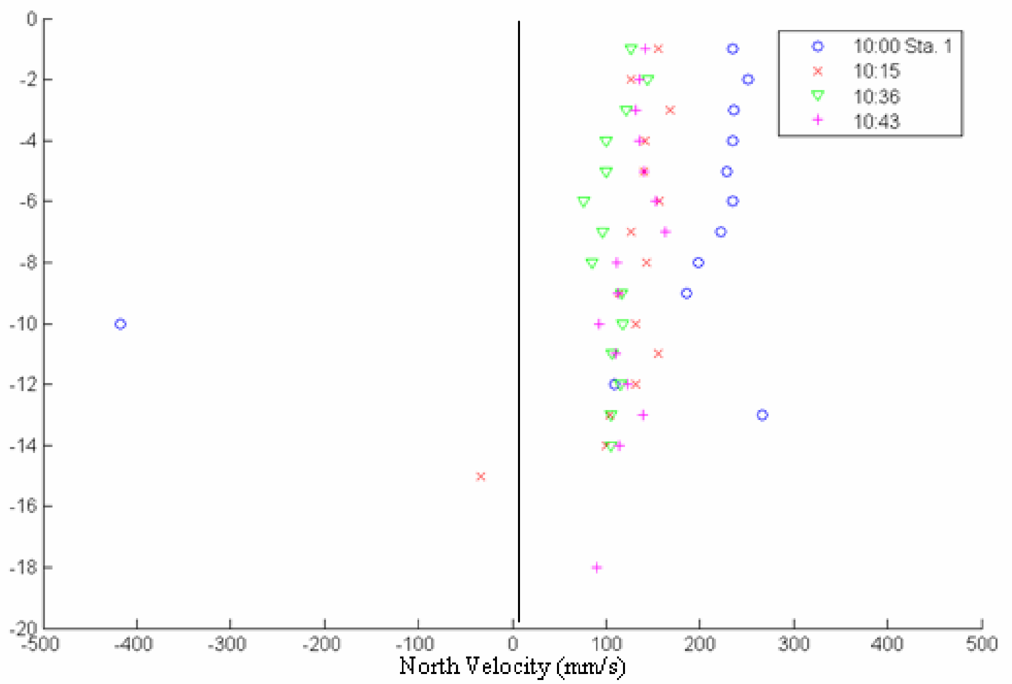


Figure 15a The 4 November 2009 **northward** ADCP current profiles for Transect 1.

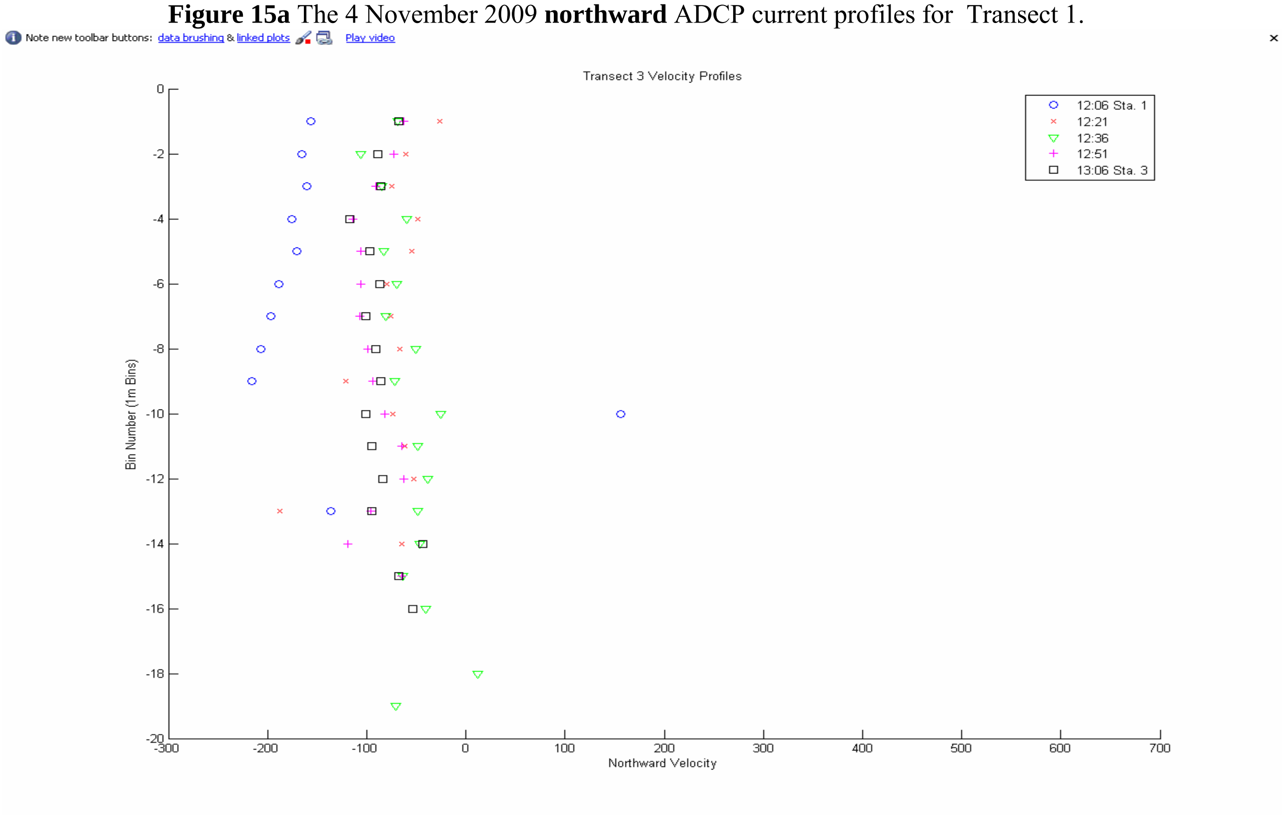


Figure 15b The 4 November 2009 **northward** ADCP current profiles for Transect 3.

3. **CODAR Surface Current Mapping**

Pairs of high frequency radar measurements, such as those made by CODAR, provide maps of surface currents over extensive region of the coastal ocean. This report describes CODAR-derived surface current measurements (supported by NOAA/IOOS) acquired during winter 2008-09 in support of an MIT Sea Grant-supported investigation of transient tidal eddy motion east of Cape Cod in the Great South Channel section of the western Gulf of Maine (Figure 1). A University of Massachusetts Dartmouth's (UMassD) 5 MHz long-range CODAR installation, located at the National Park Service's Cape Cod National Seashore station near Nauset, MA and a Rutgers University CODAR installation at the Coast Guard station on Nantucket Island (Figure 16) are used to produce the hourly surface current maps described here. A set of these maps first revealed the tidal eddy motion of interest here in April 2005.

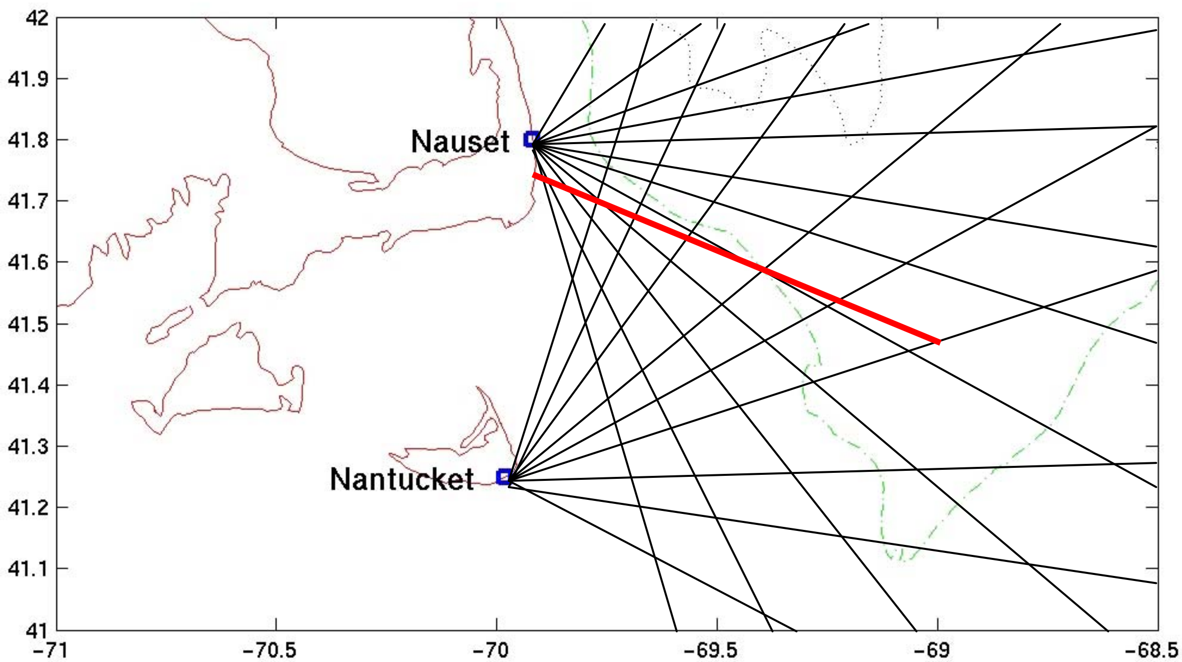


Figure 16 A schematic of CODAR radials from the Nauset and Nantucket CODAR sites. The nominal spatial resolution of the CODAR surface currents is 6 km. A southeastward-trending "reference transect" (bold line) - to locate tidal eddies - and the 100 m (dot-dash) and 200 m (dotted) isobaths are indicated.

The 100-watt CODAR transmits a continuous sequence of 40μsec sweep frequency radar pulse/blank pair eastward from Cape Cod (and Nantucket) through an approximate 150-degree azimuth. Portions of those radar transmissions are backscattered to the CODAR site receiver from surface ocean waves in the "field of view" at ranges between about 5 km beyond the beach to a maximum of about 200 km offshore (depending upon transmission conditions). Using Doppler theory, each site measures the radial components of the ocean surface velocity directed toward or away from the site (Crombie, 1955; Barrick, 1972; Barrick et al., 1977). Since the systems are using surface gravity waves to estimate these velocity components, the measured currents at this frequency are the weighted average of the currents within the upper one meter of the water column (Stewart and Joy, 1974). The radial data in the region of overlap (Figure 16) were combined into hourly averaged total surface current vector maps on a fixed grid using the CODAR Ocean Sensors software package. Experience (Kohut and Glenn, 2003) has shown that the noise in the returned radar signal can be reduced sufficiently with an hour of averaging to produce meaningful radial surface current estimates.

The quality of the UMassD's CODAR radial current measurements have been assessed through comparisons with measured currents by several investigators including (Chapman et al. 1997). They find that nominal spatial resolution of the surface currents is about 6 km, with an accuracy of about 5 cm/sec when the CODAR beam patterns for the respective sites have been measured (Kohut and Glenn, 2003). There is an expanded discussion of The CODAR measurements and their uncertainties in Brown et al., (2009a).

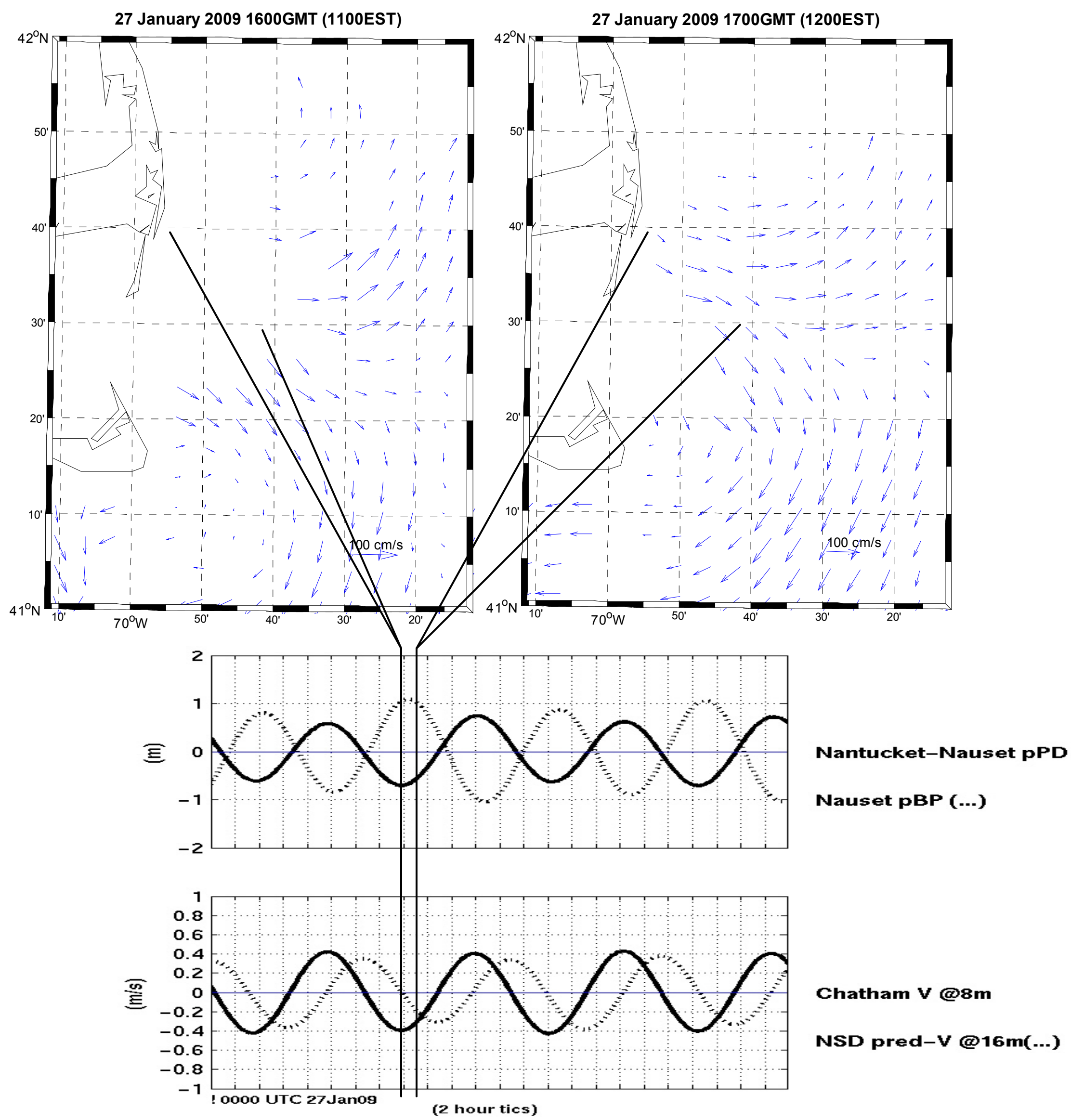


Figure 17 (upper) The CODAR-derived surface current maps for 1600 (left) and 1700 (right) GMT 27January2009 respectively. **(middle)** The predicted Nantucket-Nauset sea level pressure difference PD (and Nauset bottom pressure; ….) **(bottom)** The predicted Chatham ADCP 8m (and NSD 16m; ….) northward current. The locations of the Chatham mooring and NSD sites are indicated at both times.

The CODAR-derived surface current maps in Figure 17 depict current patterns associated with the change from flood tide to ebb tide as revealed by the NSD northward current time series at 1600 GMT on the western side of the Great South Channel. The CODAR maps are compared with the predicted northward tidal flow time series at our site near Chatham and the NSD site further offshore ; as well as Nauset sea level and Nantucket minus Nauset sea level pressure differences. The time series comparison also shows that the Chatham site flow is (1) in phase with the PD; and (2) leads the offshore flow at NSD by about 90^{o} or about 3hr. These facts suggest that the sea level PD is driving an inshore flow arm of the eddy motion at Chatham (not well-resolved in the CODAR current maps) while the offshore arm is diagnosed by the flow at NSD.

One approach to assessing the uncertainty of the CODAR surface current maps is to compare pseudo-surface drifter trajectories derived from the CODAR maps with actual drifter trajectories. A surface drifter (described in next section) was deployed at 1630 GMT 27 January 2009 at 41.6907 ^{o}N and 69.7748 ^{o}W. The set 8 hourly CODAR maps that will be used for this analysis are presented in Appendix D.

4. **Surface Drifter Trajectories**

We deployed a Manning surface drifter - a Davis-type drifter (Davis, 1985) that was manufactured by students a Southern Maine Community College (SMCC) – to make Lagrangian measurements of the water in the upper meter of the ocean in the TTE study domain. We purchased one Manning drifter and constructed another from parts provided by SMCC. The simple, rugged drifter consists of a PVC pipe that serves as the central mast for a 4 fiberglass arm framework from which four 1m x 0.5m square sails are suspended (Figure 18). A GPS unit transmits its position via the GLOBALSTAR satellite system back to a designated land-based receiver at a user-selected sample interval that can range from a minimum of 35 minutes to 12 hours. (This system was originally designed to track commercial trucks). The movement of all of the ocean-going Manning drifters can be interrogated at http://www.nefsc.noaa.gov/epd/ocean/MainPage/DrifterUpdates.html.

Figure 18 (left) The Manning Drifter consists of a PVC central mast for 4 fiberglass arms from which four 1m x 0.5m square sails are suspended. A GPS locator unit is contained in a waterproof thin box on the top of the central mast. (**right)** Fishing net floats are employed to stabilize the sail framework in a wavy ocean.

Drifter Deployment - 27 January 2009

A Manning drifter was deployed about 8 nm east of Chatham, MA at 1600 GMT on 27 January 2009. The drifter was programmed to record its location using GPS every 35 minutes. The trajectory over the following 23 days is shown in Figure 19.

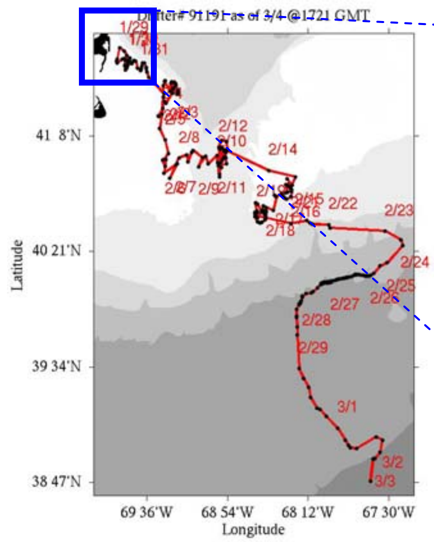


Figure 19a Surface drifter trajectory from January 27, 2009 to February 19, 2009. The time intervals between GPS fixes were very irregular: varying between 30 minutes

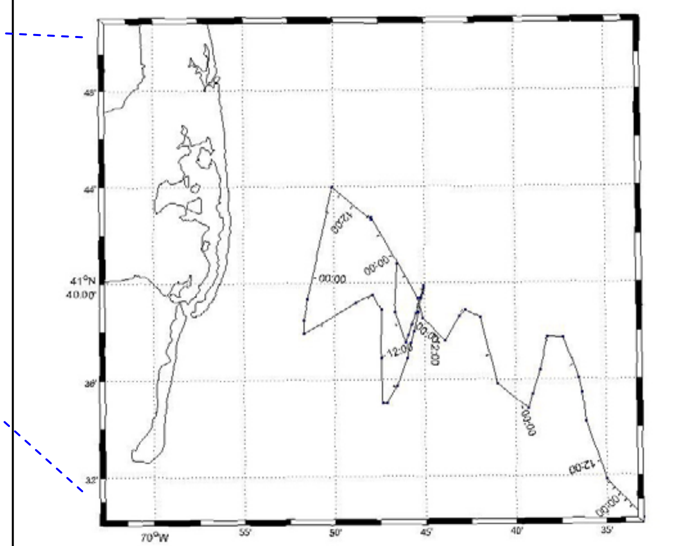


Figure 19b Surface drifter trajectory between deployment date 27 January 2009 (red dot) and 31 January 2009.

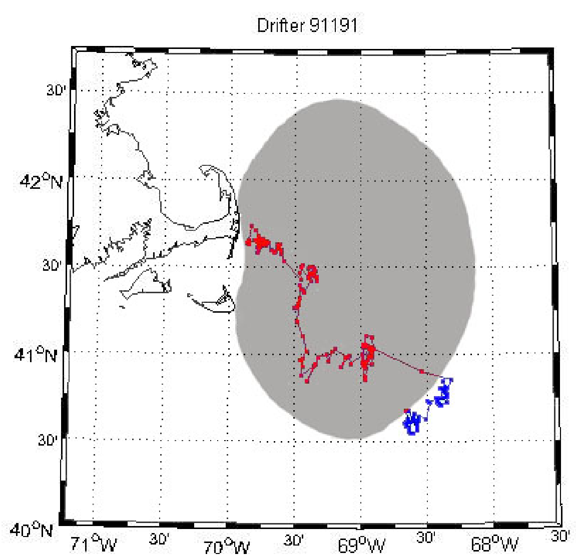


Figure 19c Surface drifter trajectory between 27 January and 19 February 2009. Red points show drifter locations within the ideal CODAR coverage region (grey area).

B. HYDROGRAPHY

The 27 January 2009 hydrographic measurements were conducted using a Seabird® SBE-25 SEALOGGER (Figure 20) that was equipped with pressure (P), temperature (T), and conductivity (C) (as well as oxygen) sensors. The sensors on the CTD were factory-calibrated on 9 October 2008. The specifications for a calibrated SBE-25 are in Table 4.

Table 4 SBE-25 specifications.

	Temperature (ºC)	Conductivity (S/m)	Pressure (dbars)
Measurement Range	-5 to +35	0 to 7	0 to 350
Accuracy	± 0.002	± 0.0003	± 0.1% of full-scale range
Resolution	± 0.0003	± 0.00004	± 0.015% of full scale range

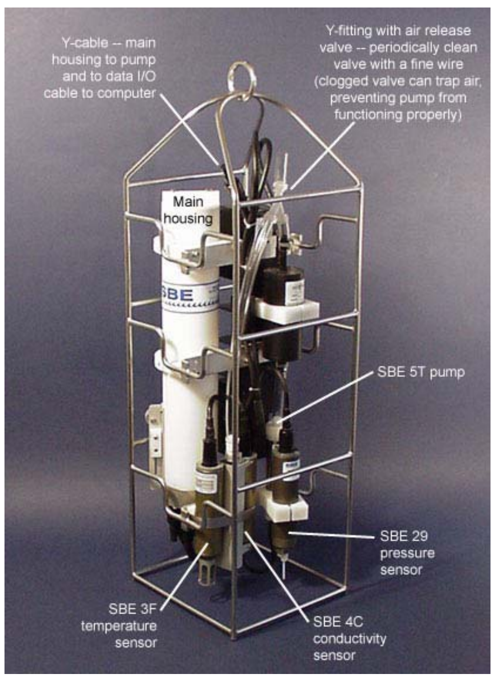


Figure 20 The internally-recording SBE-25 was used to measure temperature, conductivity, and pressure.

The SBE-25 is an internally-recording instrument that was configured for these measurements as follows:

- Sample Rate: 8 scans/sec
- Minimum conductivity frequency for pump turn-on: 4000 Hz;
- Record up-cast: on
- Record down-cast: on

This SBE-25 attached to a ¼-inch polypropylene line was lowered at the rate of about 0.5 m/s to within 5-10 meters of the bottom at each station. About every 5 stations, the data were downloaded via an umbilical to a laptop computer and processed. The SeaBird software package SEASOFT was used to convert the raw hexidecimal P/T/C time-series output into engineering units. The salinity was computed from the measured conductivity and temperature; based on the salinity scale of 1980 (Fofonoff and Millard, 1983). The T and S profiles were checked for "reasonableness" onboard.

Back in the laboratory, the down-cast data only were processed using Matlab as follows:

- The time-series P/T/C data files (*.cnv) from SEASOFT were read with the R. Signell (USGS) script called "ctd_rd.m";
- The time series P/T/S data were processed as described in Appendix E and averaged into 1-decibar (dbar) bins;
- These profile data were stored as ASCII and Ocean Format files for post-processing and plotting.

Shipboard CTD Survey: 27 January 2009

The 27 January 2009 hydrographic survey (defined in Table 5) revealed well-mixed winter conditions (Appendix E and Figure 20). What density stratification there was controlled by salinity distribution which exhibited a surface feature near Station 4 and an apparent influence of slightly higher salinities offshore of Station 7 – the site of the drifter release.

Table 5 Station information for the 27 January 2009 shipboard CTD survey

St	Lat ° N	Lon °W	Depth (m)	Depth (fath)	Time (GMT)	Time (Julian hrs)	NS Dist (nm)	Cum Dist (nm)	NSDist (km)	Cum Dist (km)
01	41 39.219 41..6537	69 55.460 69. 9243	13..5	7.4	1737	956129.62	1.19	1.19	2.20	-
02	41 39.560 41. 6593	69 53.994 69. 8999	20..0		1730	956129.50	1.19	2.38	2.20	2.20
03	41 39.931 41..6655	69 52.402 69. 8734	21.1		1721	956129.35	1.19	3.56	2.20	4.41
04	41 40.283 41..6714	69 51.009 69..8502	26..7	14.6	1713	956129.22	1.19	4.75	2.20	6.59
05	41 40.729 41..6788	69 49.504 69..8251	33.8		1700	956129.00	1.18	5.93	2.18	8.79
06	41 41.046 41..6841	69 47.916 69..7986	42.5		1644	956128.73	1.19	7.12	2.20	10.98
07	41 41.442 41.6907	69 46.488 69.7748	53.0		1618	956128.30	1.19	8.31	2.20	13.19

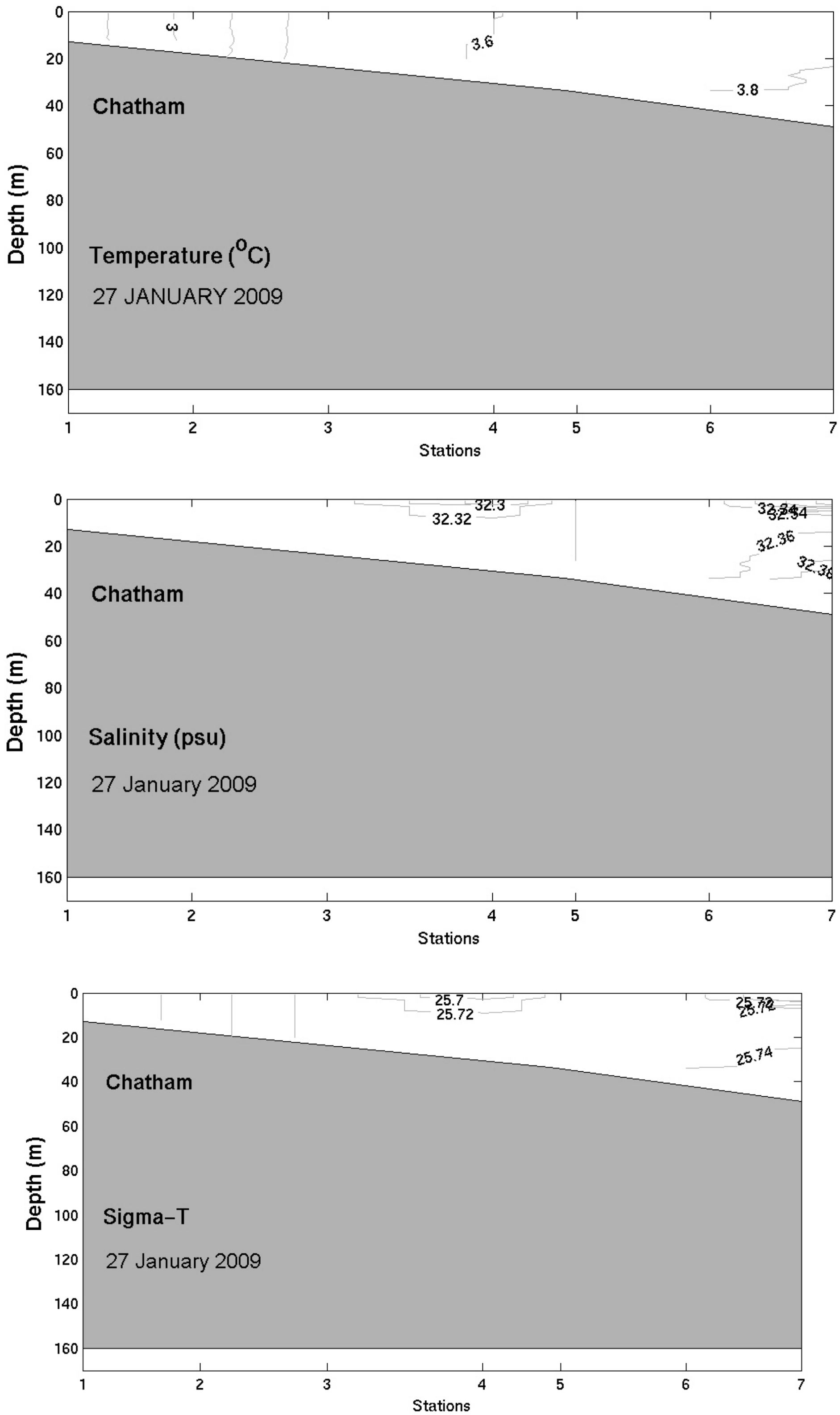


Figure 20 The 27 January 2009 vertical sections of **(top)** temperature, **(middle)** salinity and **(bottom)** density anomaly (sigma-t).

III. APPENDICES

APPENDIX A: Moored Current Record Statistics & Tidal Analysis

The moored 10-minute averaged ADCP current records, which were interpolated to an even 10-minute (or 0.166666667 hours) intervals, consisted of 8122 terms with a:
Start time: 1400 GMT 3 November 2008 (954086.00 Julian Hours rel 0000 GMT 1 January 1900)
End time: 2330 GMT 27 December 2008 (955439.50 JH). The basic statistics of these series are presented in Table A-1.

Table A-1 The moored ADCP time series basis statistics (including the variance ellipses) of the total and the residual series (tides-removed) series current components in the 2m bins at 8m and 6m above bottom (AB), which is at a nominal depth of 12.6 m. The blue numbers define the standard deviation ellipse characteristics.

Depth (m)	Mean (cm/s)	SD (cm/s)	Var $(cm/s)^2$	Total Var $(cm/s)^2$	Major Axis Amp $(cm/s)^2$	Major Axis Dir (°T)	ε
Eastward	-4.1	17.2	295				
TOTAL - 8m AB				1245	1226	19	64.5
Northward	-8.5	30.8	950		35.0	19	8.0
Eastward	-4.2	16.1	258				
TOTAL - 6m AB				1114	1100	19	78.6
Northward	-8.0	29.3	856		33.2	19	8.8
Eastward	-4.1	5.4	29				
RES - 8m AB				136	121	13	8.1
Northward	-8.5	10.3	107		11.0	13	2.7
Eastward	-4.2	5.0	25				
RES - 6m AB				113	103	14	9.3
Northward	-8.0	9.3	88		10.1	14	3.1

Table A-2 The harmonic constants for the five principal and 2 nonlinear tidal constituents of the **ADCP 6m elevation current records** between 3 November and 27 December 2008 (56 days) in terms of component amplitude and phase in Greenwich and local epochs. The tidal current ellipses are given in terms of major axis amplitude and orientation, ellipticity (ε=major/minor, and Greenwich phase of the maximum current; with a positive major axis amplitude indicating an anti-clockwise rotating current vector.

Bin Depth (m)	Total Variance $(cm/s)^2$	Eastward Amp (cm/s)	G (°)	Northward Amp (cm/s)	G (°)	Major Axis Amp (cm/s)	Major Axis Dir (°T)	ε	G (°)
M_2	**1960**	**21.5**	**257**	**38.7**	**260**	**44.3**	**29**	**36.9**	**80**
N_2	62	3.8	224	6.9	231	7.9	29	19.8	50
S_2	61	2.4	292	7.4	291	7.7	18	∞	111
O_1	0	0.5	322	0.1	273	0.5	83	-5.0	141
K_1	3	0.8	294	1.4	252	1.5	26	-3.0	81
M_4	6	1.1	115	2.2	141	2.4	24	6.0	137
M_6	1	0.8	187	0.7	160	1.0	48	∞	161

Table A-3 The harmonic constants for the five principal and 2 nonlinear tidal constituents of the **ADCP 8m elevation current records** between 3 November and 27 December 2008 (56 days) in terms of component amplitude and phase in Greenwich epoch. The tidal current ellipses are given in terms of major axis amplitude and orientation, ellipticity (ε=major/minor, and Greenwich phase of the maximum current; with a positive major axis amplitude indicating an anti-clockwise rotating current vector.

Bin Depth (m)	Total Var $(cm/s)^2$	Eastward Amp (cm/s)	G (°)	Northward Amp (cm/s)	G (°)	Major Axis Amp (cm/s)	Major Dir (°T)	ε	G (°)
M_2	**2185**	**23.0**	**257**	**40.7**	**260**	**46.7**	**30**	**42.5**	**80**
N_2	67	3.9	223	7.2	232	8.2	28	16.4	50
S_2	65	2.4	292	7.7	291	8.0	18	∞	112
O_1	0	0.3	335	0.1	43	0.3	85	3.0	156
K_1	3	0.8	288	1.6	249	1.7	24	-3.6	76
M_4	5	1.1	107	2.0	145	2.2	21	4.4	140
M_6	1	0.8	212	0.6	170	1.1	56	∞	170

Table A-4 The harmonic constants for the five principal constituents of the **NSD** currents in terms of component amplitude and phase in Greenwich epoch. The tidal current ellipses are given in terms of major axis amplitude and orientation, ellipticity (ε=major/minor, and Greenwich phase of the maximum current; with a positive major axis amplitude indicating an anti-clockwise rotating current vector.

Bin Depth (m)	Total Var $(cm/s)^2$	Eastward Amp (cm/s)	G (°)	Northward Amp (cm/s)	G (°)	Major Axis Amp (cm/s)	Major Dir (°T)	ε	G (°)
M_2		21.3	327	41.3	345	**46.1**	**27**	**7.8**	**161**
N_2		4.7	294	7.9	322	9.0	29	4.7	135
S_2		4.8	158	3.3	96	5.1	65	-1.8	144
O_1		0.1	69	0.2	104	0.0	-	-	-
K_1		1.8	33	2.4	308	2.4	9	-1.3	135

APPENDIX B. ADCP Current Profiles – 3 November 2008

The 3 November ADCP current profiles are presented in Figures B.1-B.3.

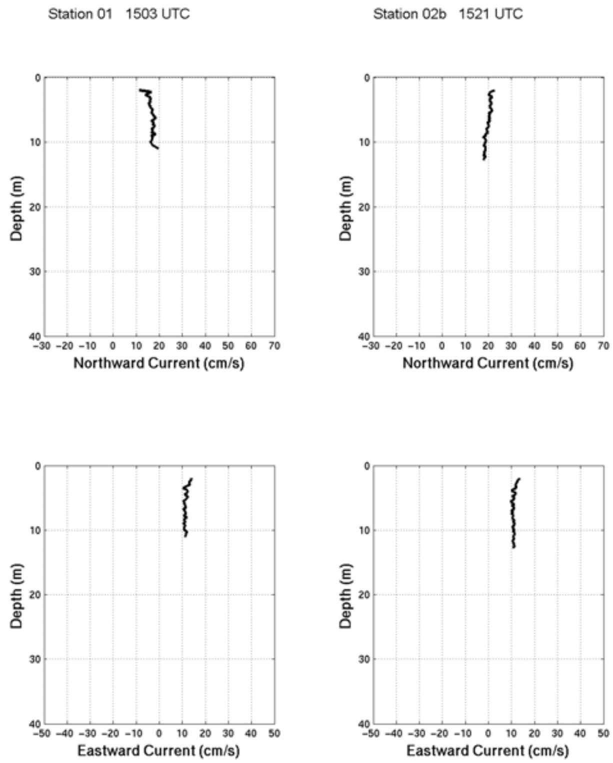


Figure B.1 Station 1 and 2 profiles of (top) northward current and (bottom) eastward current.

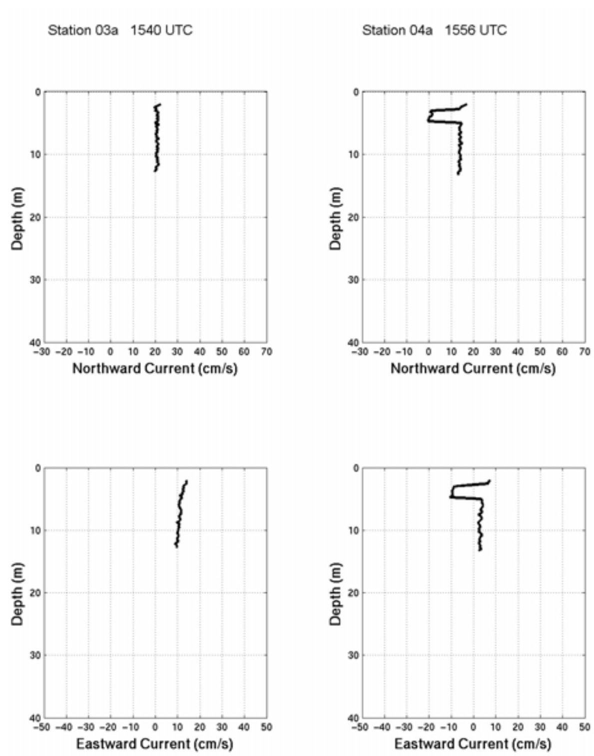


Figure B.2 Station 3 and 4 profiles of (top) northward current and (bottom) eastward current.

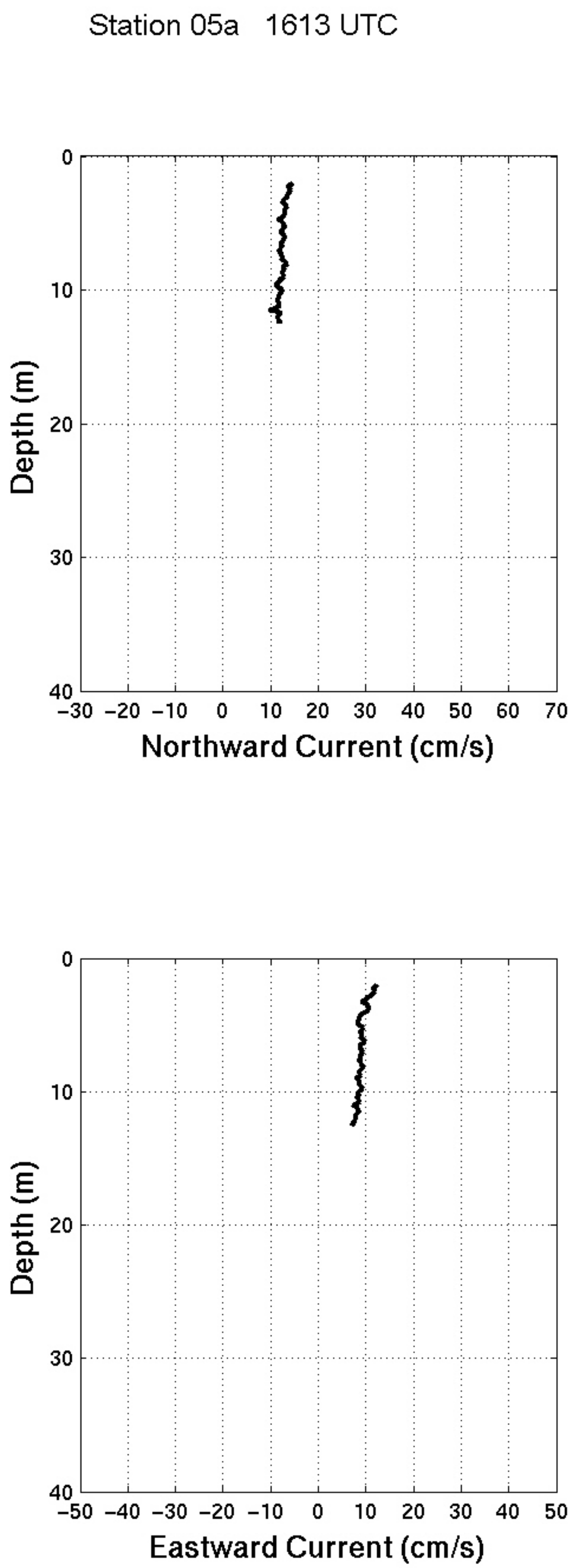


Figure B.3 Station 5 of (top) northward current and (bottom) eastward current.

APPENDIX C. ADCP Current Profiles – 4 November 2008

The 4 November ADCP current profiles are presented in Figures C.1-C.3.

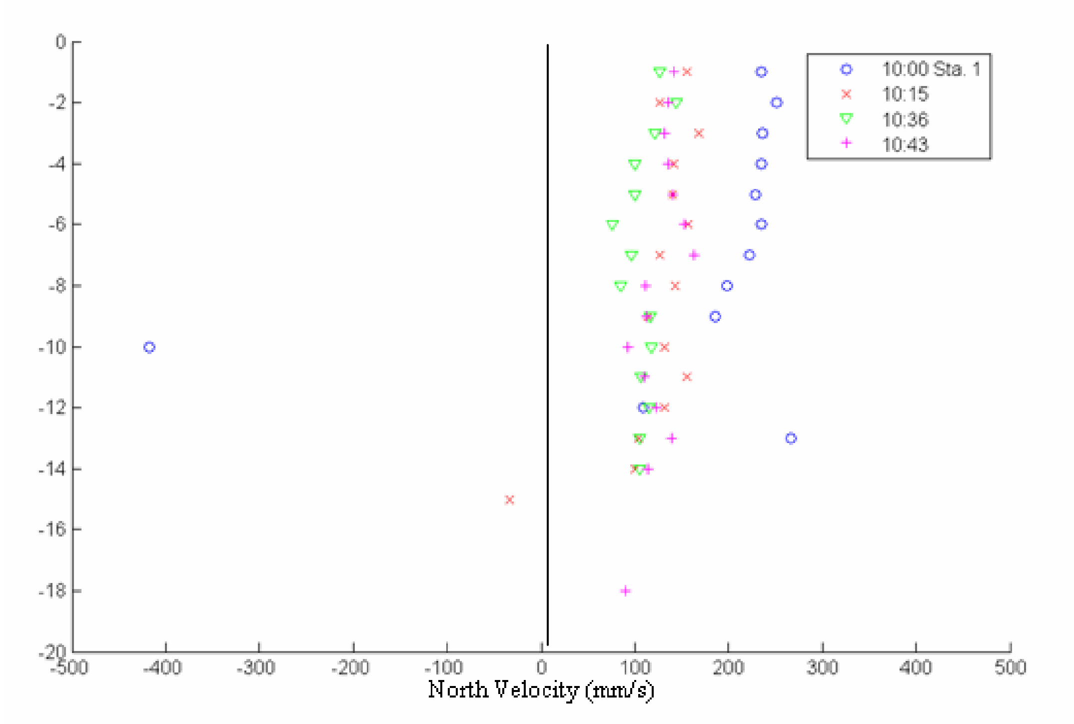


Figure C.1a The 4 November 2009 **northward** ADCP current profiles for Transect 1.

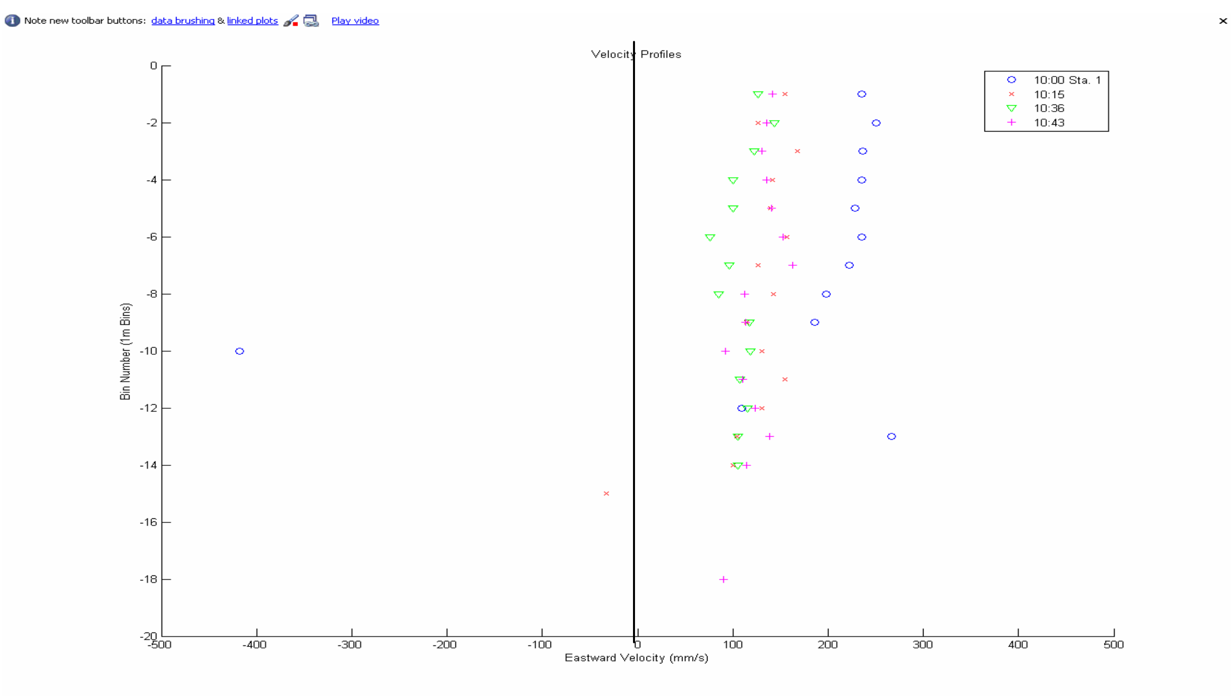


Figure C.1b The 4 November 2009 **eastward** ADCP current profiles for Transect 1.

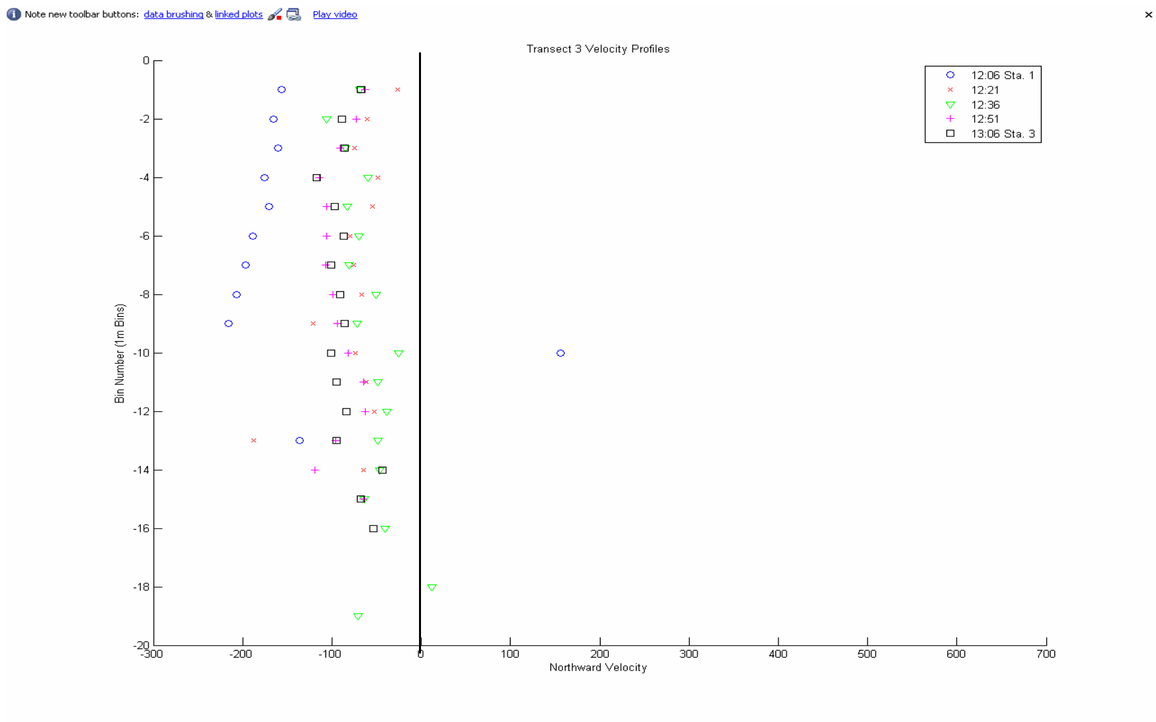


Figure C.2a The 4 November 2009 **northward** ADCP current profiles for Transect 3.

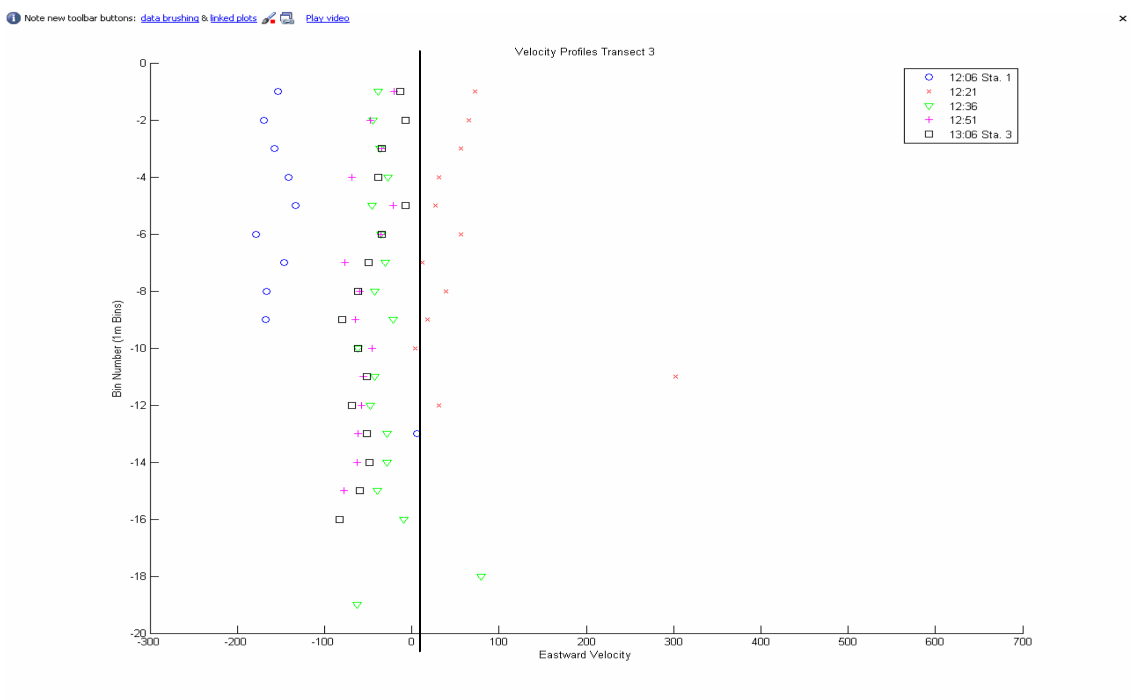


Figure C.2b The 4 November 2009 **eastward** ADCP current profiles for Transect 3.

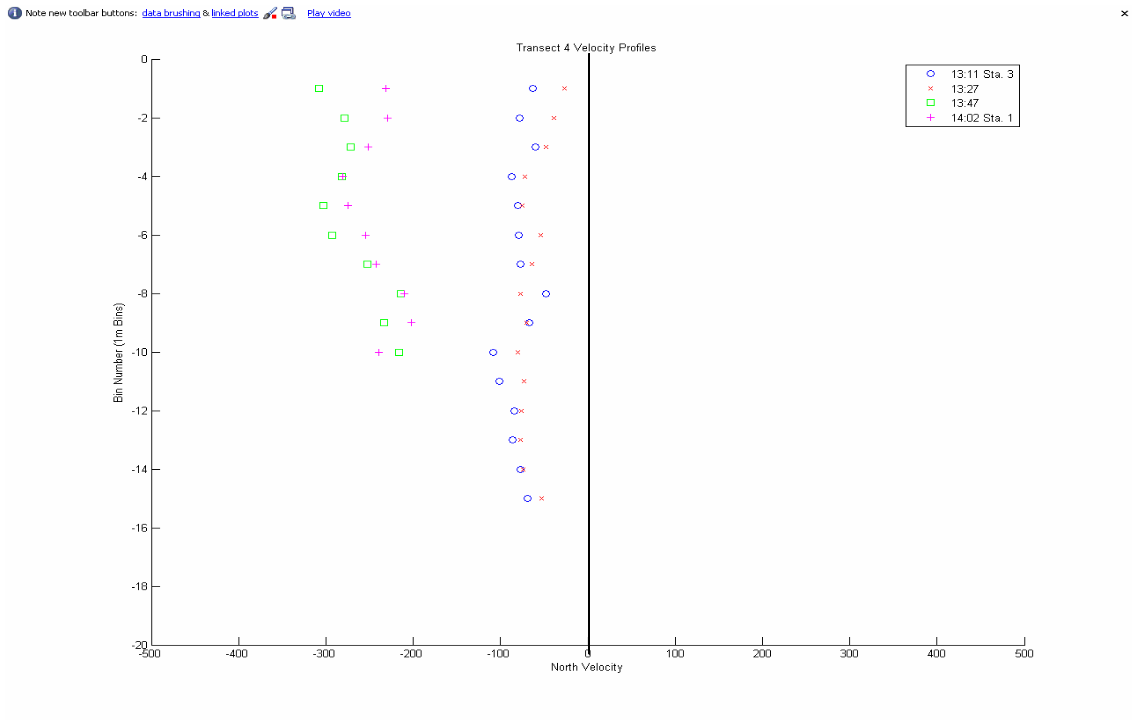


Figure C.3a The 4 November 2009 **northward** ADCP current profiles for Transect 4.

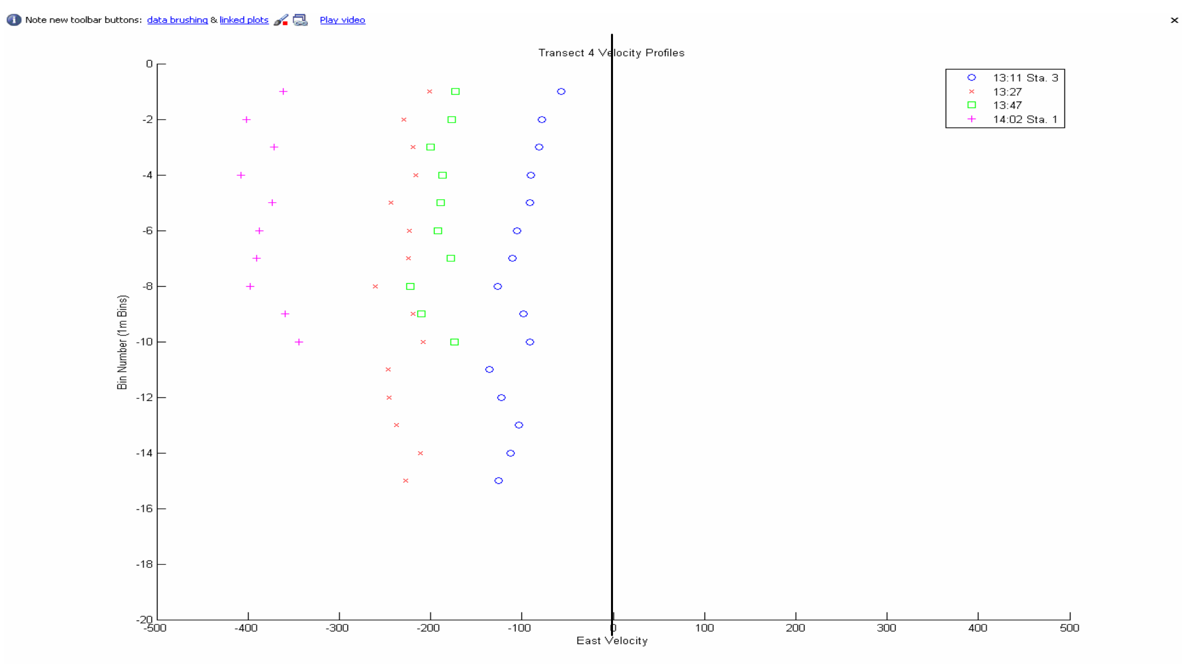


Figure C.3b The 4 November 2009 **eastward** ADCP current profiles for Transect 4.

APPENDIX D. CODAR Surface Current Maps: 27 Jan 2009

The 27 January 2009 CODAR-derived surface current maps from 1500 to 2200 GMT about ½ of semidiurnal tidal cycle are presented in Figures D.1-D.4. The CODAR current maps are compared with corresponding high-resolution, finite-element numerical coastal ocean model QUODDY surface current realizations (see Appendix F for model details)

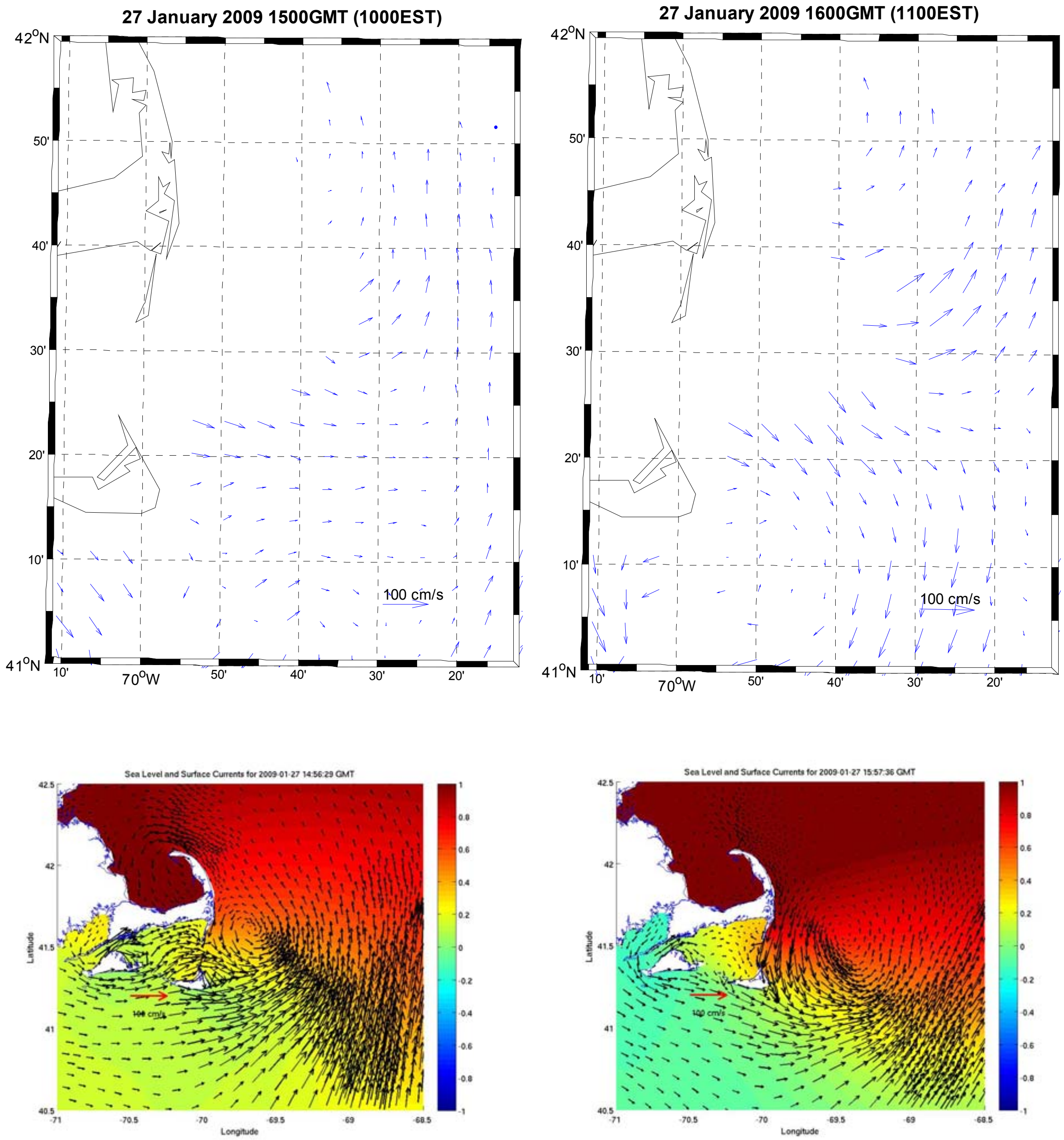


Figure D.1 (upper) The CODAR-derived surface current field for 1500 & 1600 GMT 27January2009. **(lower)** Corresponding realizations of the finite-element Quoddy model (Marques & Brown, 2009).

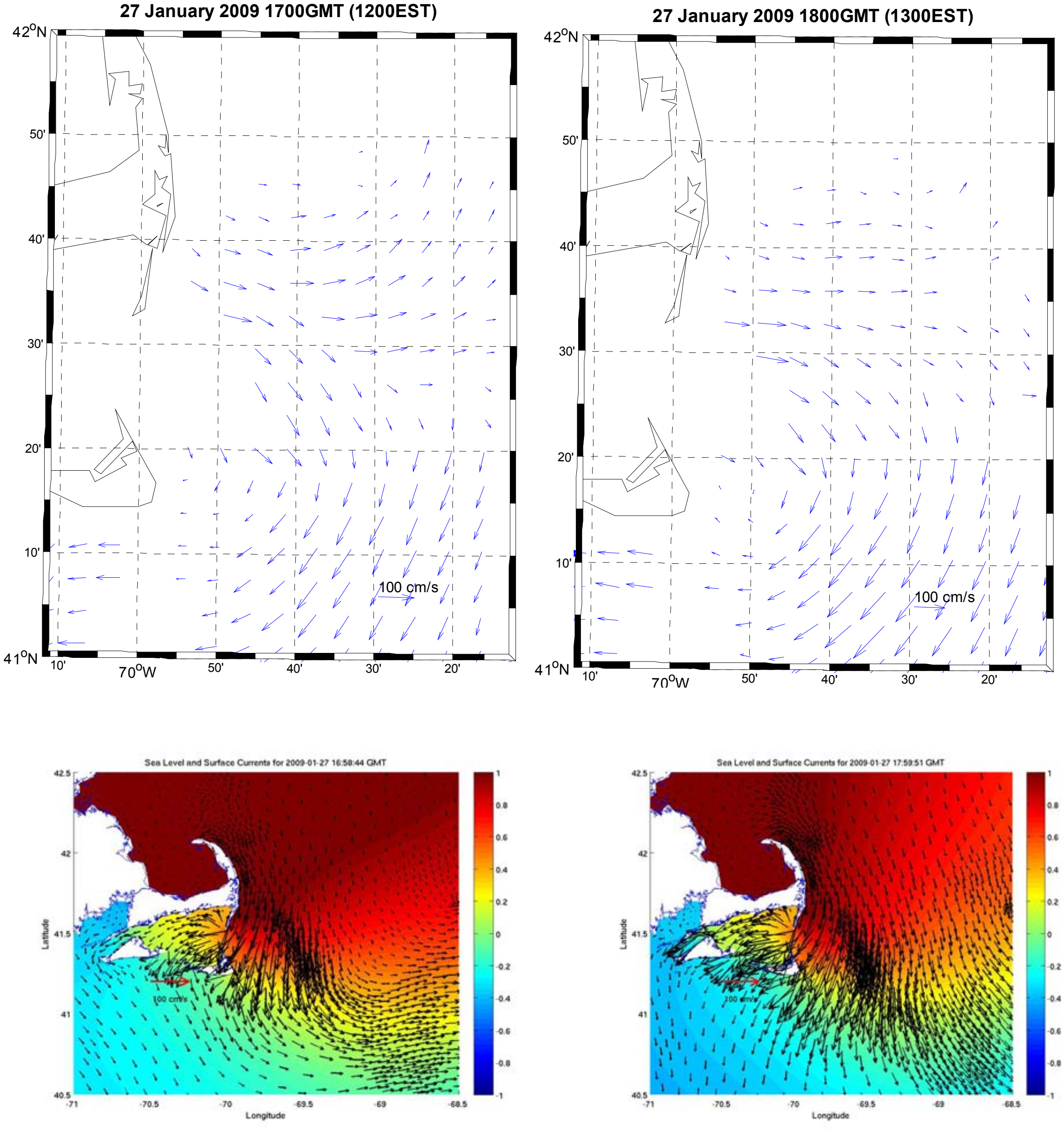


Figure D.2 (upper) The CODAR-derived surface current field for 1700 & 1800GMT 27January2009 **(lower)** Corresponding realizations of the finite-element Quoddy model (Marques & Brown, 2009).

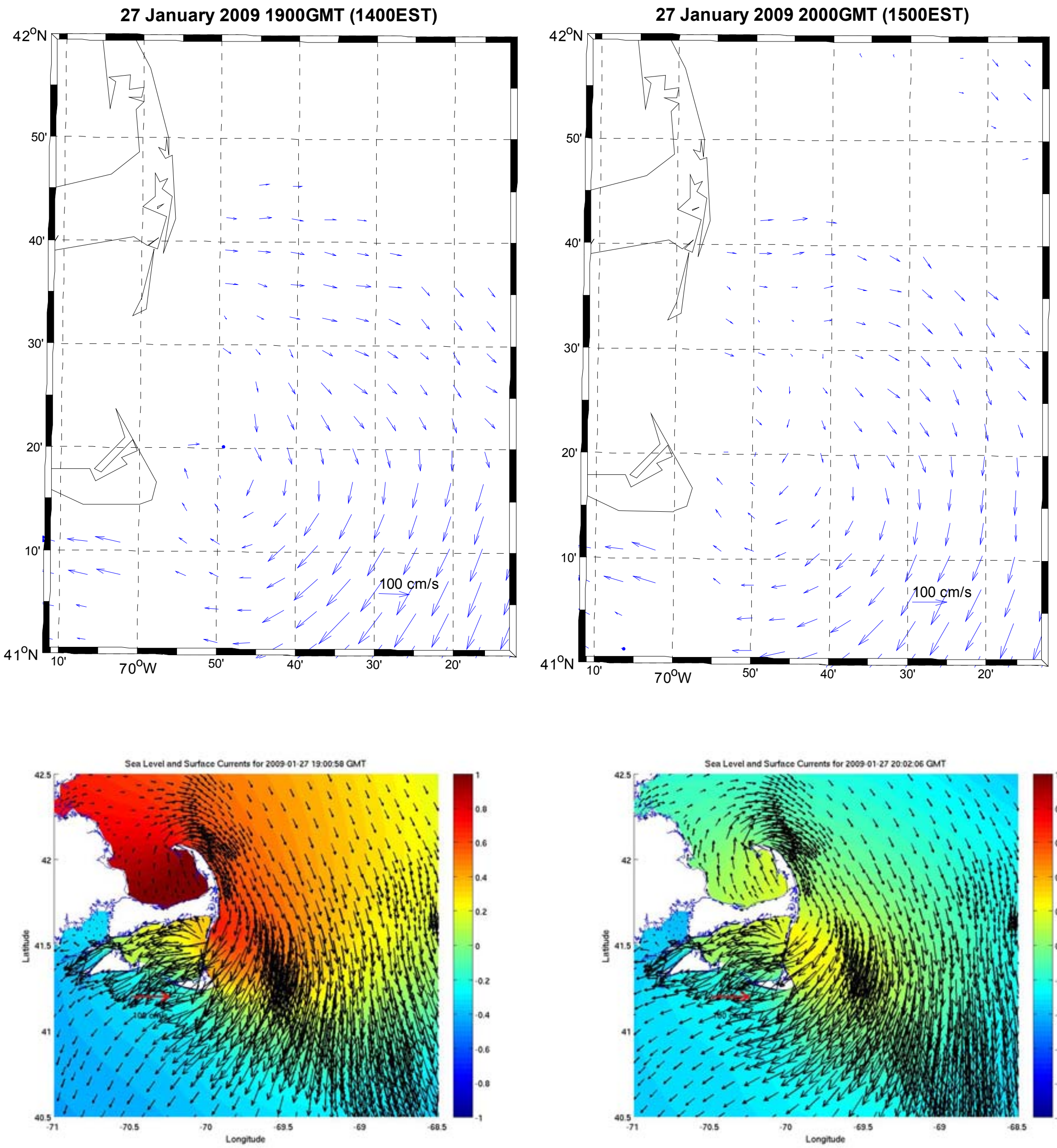


Figure D.3 (upper) The CODAR-derived surface current field for 1900 & 2000GMT 27January2009 **(lower)** Corresponding realizations of the finite-element Quoddy model (Marques & Brown, 2009).

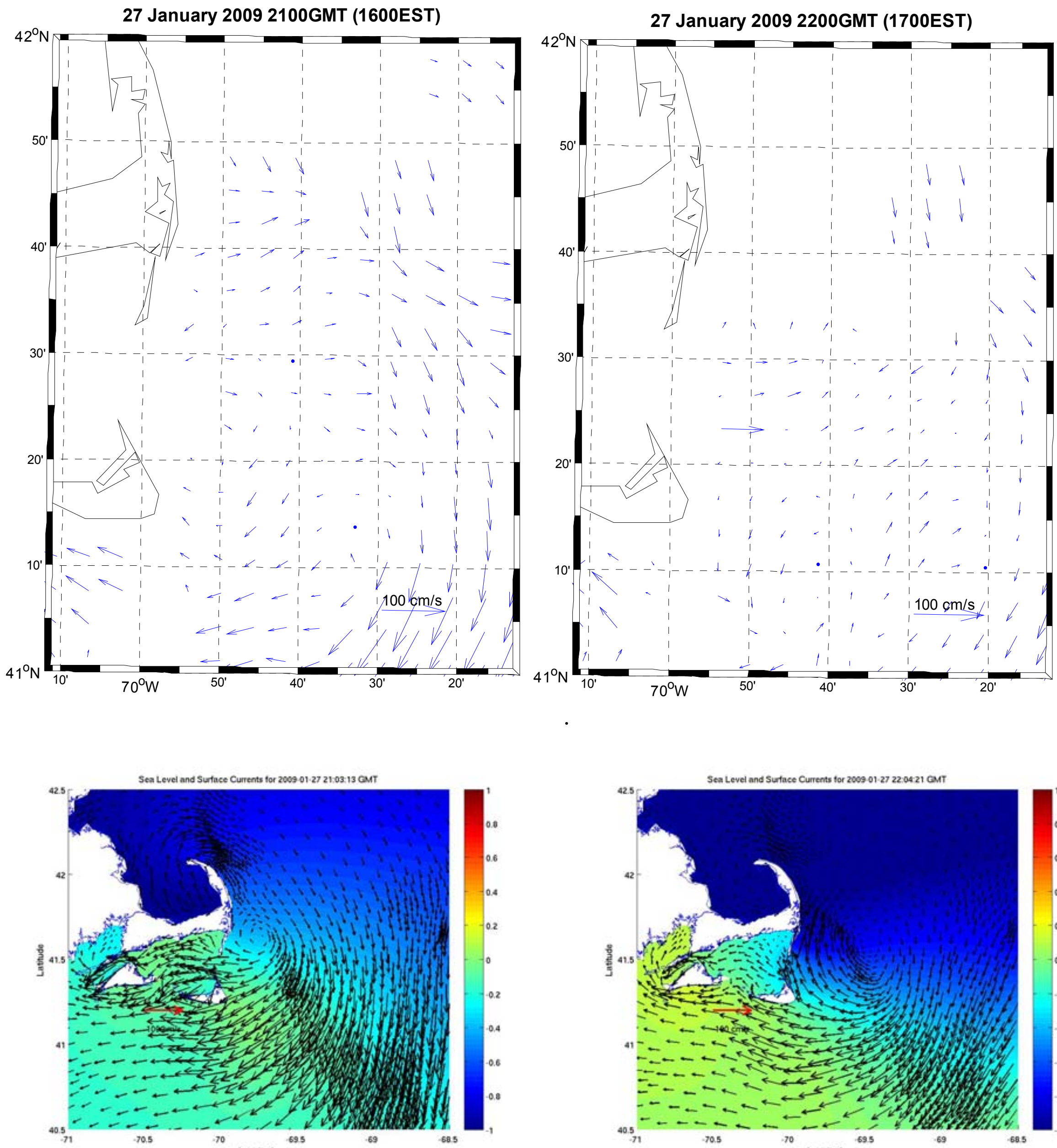


Figure D.4 (upper) The CODAR-derived surface current field for 2100 & 2200GMT 27January2009 **lower)** Corresponding realizations of the finite-element Quoddy model (Marques & Brown, 2009).

APPENDIX E. Hydrographic Profiles – 27 January 2009

Data Processing Protocols: The following is a description of the processing of the 27 Jan 2009 SBE-25 CTD data; using the station #7 example. The following operations are applied sequentially to the raw ascii data file which in this case is called: **raw_2701_st#7.cnv.**

1) Filter: Runs a low-pass filter on one or more columns of data; to smooth the high frequency variability in the data. To produce zero phase (no time shift), the filter is first run forward and then run backward through the data. As recommended by Sea Bird, the 0.5 sec filter was used on Pressure (0.5 sec); 0.03 sec filter on Conductivity. There was no need to filter the SBE-25 temperature data.

Data file name after this step: **filter_2701_st#7.cnv**

2) Loop Edit: Marks "bad data scans" by setting the scan flag value to *badflag* in input .cnv files. Many times this diagnostic is related to the "pressure slowdowns or reversals" that are typically caused by ship heave. Optionally, Loop Edit can also mark with *badflag* the scans associated with the initial surface soaking phase of the CTD measurement. The *badflag* value is documented in the input .cnv header. The user-selected parameters in this case were:

- a minimum CTD velocity: 0.25 m/s (a SeaBird suggestion)
- the Soak Depth: 2m
  (Before each cast, the CTD was held near the surface at about 2m for about 1 minute)

Data file name after this step: **loop_edit_2701_st#7.cnv**

3) Wild Edit: Marks "spurious data values" by replacing them with *badflag*. The *badflag* value is documented in the input .cnv header. The Wild Edit algorithm requires two passes through the data: First Pass - to obtain an accurate estimate of the true standard deviation of the data; Second Pass – to replace the data that fails the test with *badflag*. Following Frank Bub example, the user-selected parameters in this case were:

- First Pass Standard Deviation: 2
- Scans per block: 50
- Exclude scans marked *badflag*.

Data file name after this step: **wild_edit_2701_st#7.cnv**

4) Bin Average: Averages data (after Wild Edit) over user-specified pressure intervals. In this case, the downcast data was processed with pressure average interval of 1 dbar.

Data file name after this step: **1db_bin_2701_st#7.cnv**

The different stages of the SBE-25 CTD data processing protocol as applied to our 27 January 2009 Station #7 data is illustrated in Figure E.1. We note however that the filtered and wild-edited data could not be plotted because they have the *badflags* and spurious data.

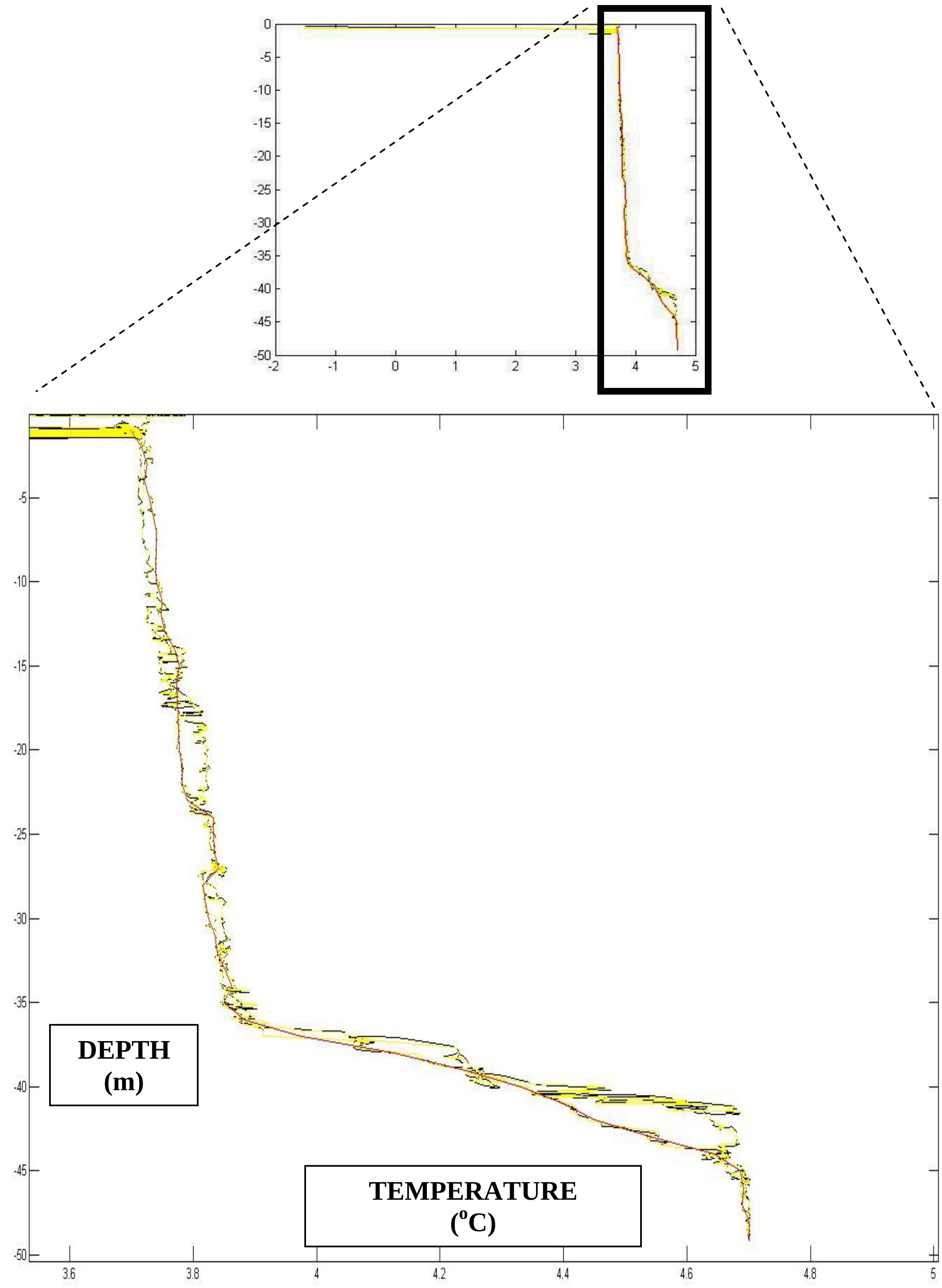


Figure E.1 The 27 January 2008 station #7 processing protocol steps: unprocessed temperature profile (black); loop-edited (yellow);and 1db bin-averaged (red).

The 1db CTD profile data for the 27 January 2009 survey appears in terms of profiles and T-S relations in Figures E.2- E.5.

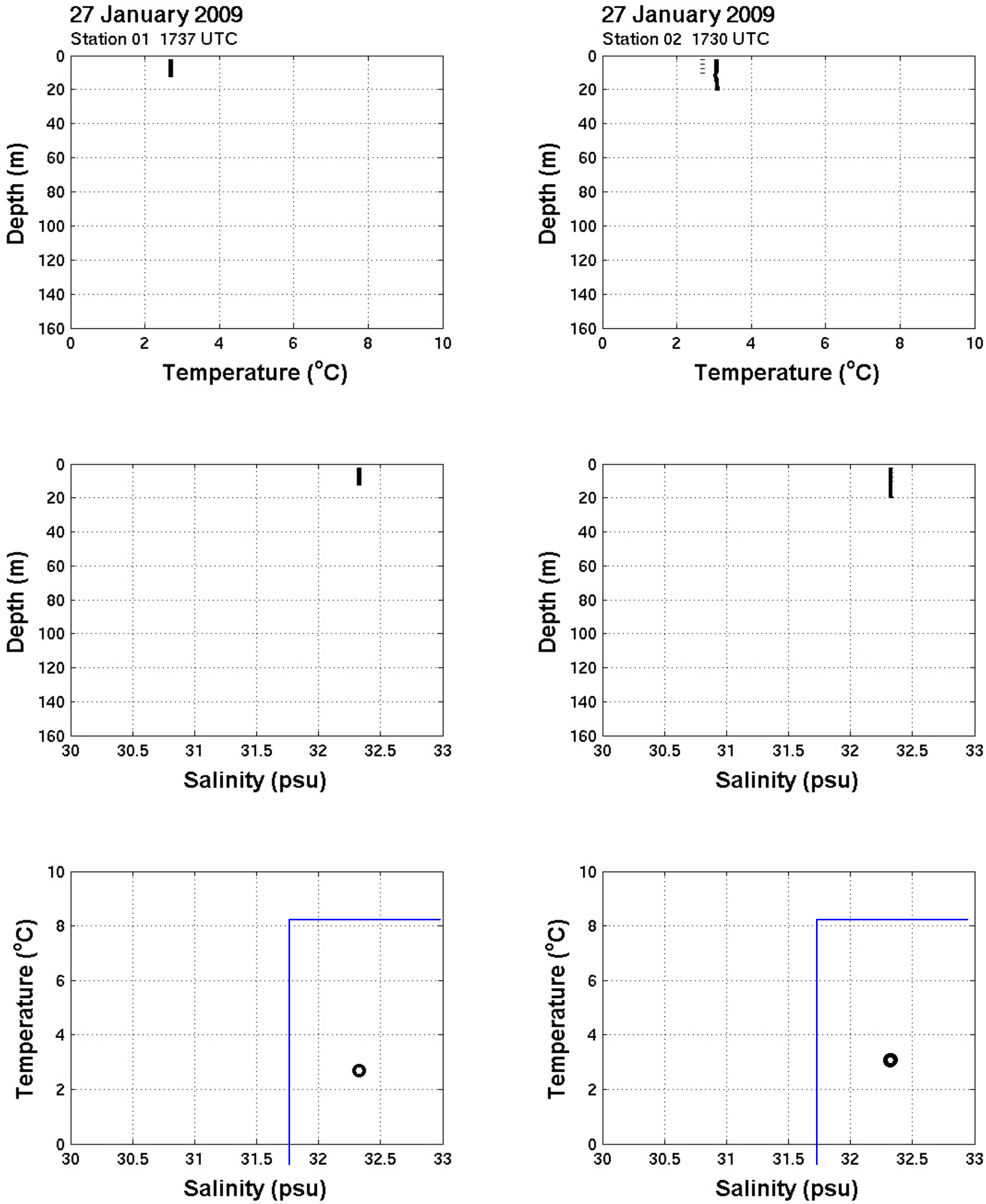


Figure E.2 The 27 January 2008 station 1 and 2 profiles of (top) temperature (T) and (middle) salinity (S); also (bottom) T-S relations. The profiles (dotted) of the preceding station are also shown. The lines define the limits of the cold, salty MIW mass as defined by Brown and Irish (1993).

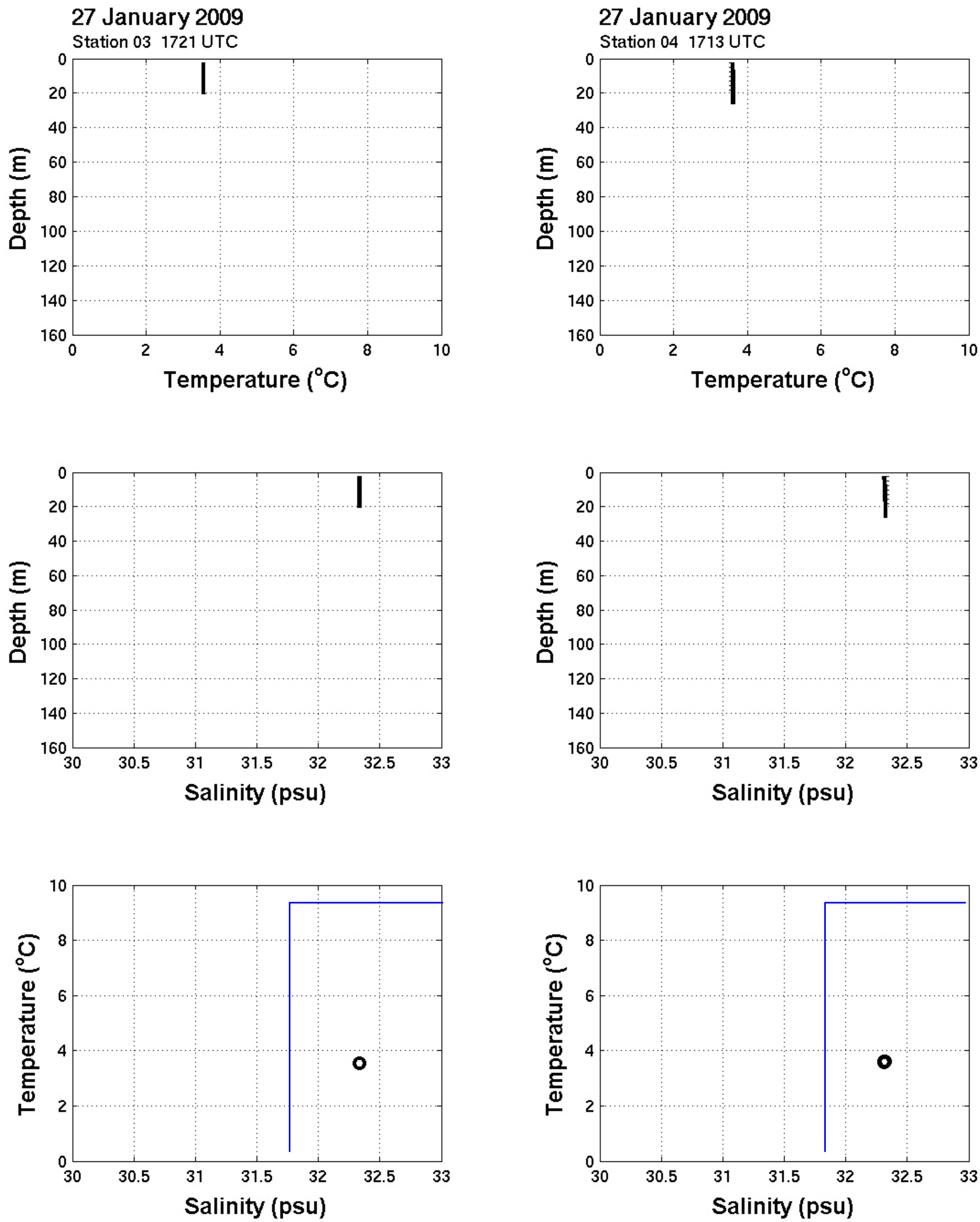


Figure E.3 The 27 January 2008 station 3 and 4 profiles of (top) temperature (T) and (middle) salinity (S); also (bottom) T-S relations. The profiles (dotted) of the preceding station are also shown. The lines define the limits of the cold, salty MIW mass as defined by Brown and Irish (1993).

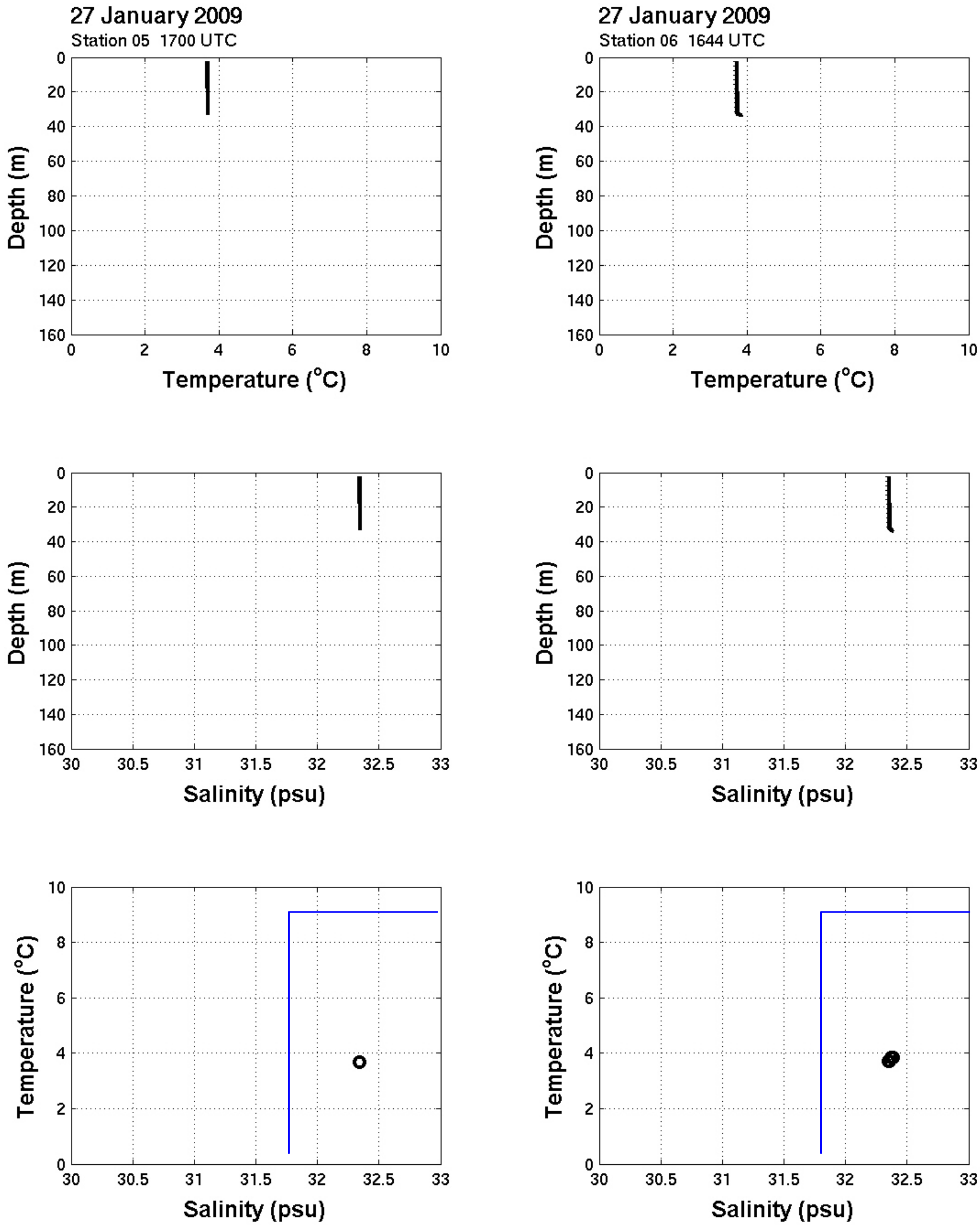


Figure E.4 The 27 January 2008 station 5 and 6 profiles of (top) temperature (T) and (middle) salinity (S); also (bottom) T-S relations. The profiles (dotted) of the preceding station are also shown. The lines define the limits of the cold, salty MIW mass as defined by Brown and Irish (1993).

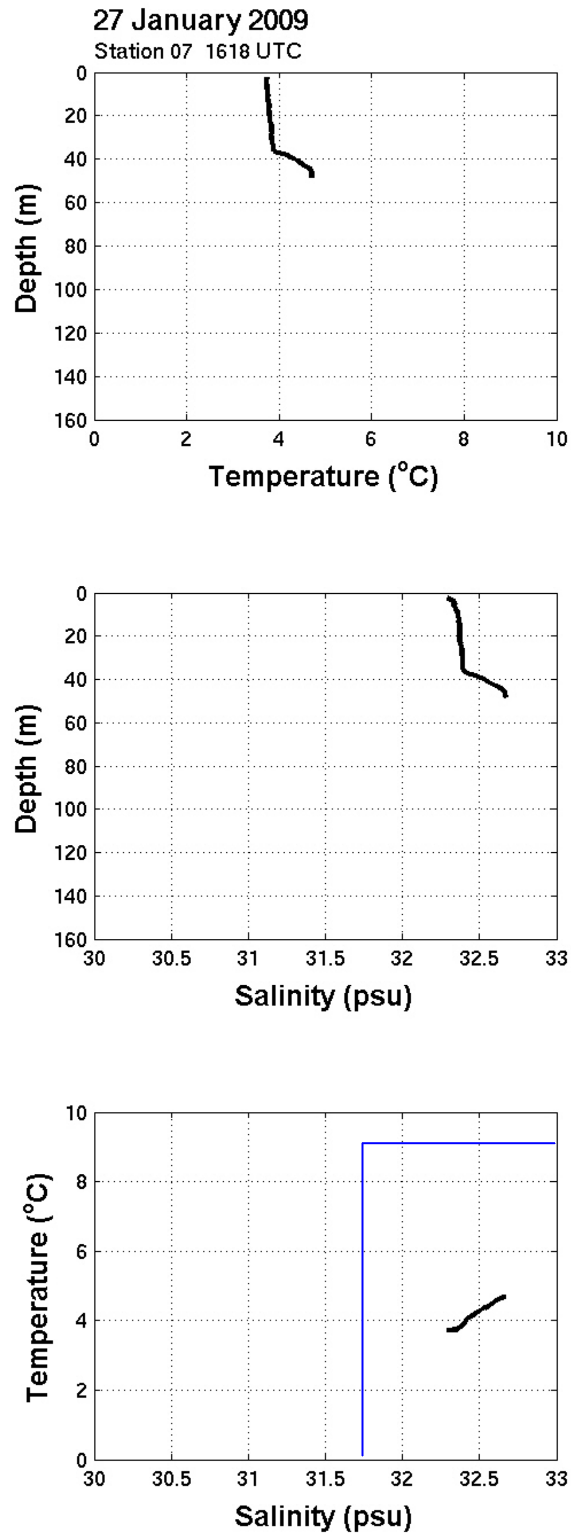


Figure E.5 The 27 January 2008 station 7 profiles of (top) temperature (T) and (middle) salinity (S); also (bottom) T-S relations. The profiles (dotted) of the preceding station are also shown. The lines define the limits of the cold, salty MIW mass as defined by Brown and Irish (1993).

APPENDIX F. QUODDY Barotropic Ocean Modeling

The Lynch et al. (1996, 1997) high-resolution finite-element coastal ocean circulation model QUODDY was employed in both its barotropic (i.e., uniform density) and baroclinic (i.e., non-uniform density) modes to simulate the tide-dominated currents in the region of the CODAR coverage (see Figure 2). The primary model forcing was 5-constituent suite of sea level tidal forcings (M_2, N_2, S_2, O_1, and K_1) along the open ocean boundaries of the model domain; as defined by the Holboke (1998) unstructured mesh called GHSD. The model lateral resolution in this application varied from about 10 km in the Gulf of Maine (GoM) interior, to about 5 km near the coastlines, with even finer kilometer-scale resolution in the regions of steep bathymetric slopes (e.g., north flank of Georges Bank). The vertical structure was resolved with 21-sigma layers from the 10m minimum depth at the coastal boundary elements throughout the model domain. The model results considered here were produced every 1/16th M_2 tidal cycle for the time periods of simulation. (See Appendix A for more details regarding the model setup and run).

Model Description: QUODDY is a 3-D, nonlinear, prognostic, f-plane, finite-element coastal ocean circulation model with advanced turbulence closure (Lynch et al., 1996, 1997). In this application, bottom flow $\overrightarrow{V_b}$ is subject to quadratic bottom boundary stress, according to $C_d\,|V_b|V_b$, where the time/space constant bottom drag coefficient C_d is 0.005. There was no surface forcing for this study.

The QUODDY model domain (see Figure 2 in main text) is defined by the Holboke (1998) GHSD mesh. The mesh resolution varies from about 10 km in the gulf to about 5 km near the coastlines with even finer resolution in the regions of steep bathymetric slopes like the north flank Georges Bank. A 10-m minimum depth was adopted for the coastal boundary elements. Vertically here are 21 sigma layers.

The conditions imposed on the different QUODDY open ocean boundaries are:
Deep Ocean and Watch Hill, RI Cross-Shelf Sections: The predicted semidiurnal (M_2, N_2, S_2) and diurnal (K_1 and O_1) tidal elevation forcing, zero steady residual or non-tidal elevation, and the Holboke (1998) inhomogeneous and barotropic radiation conditions;
Bay of Fundy Section: The predicted M_2, M_4, M_6 normal flow, constrained by a condition of zero non-tidal transport normal to the section; and
Halifax Cross-Shelf Section: The predicted semidiurnal and diurnal tidal elevations, a zero steady residual elevation, and the Holboke (1998) inhomogeneous and barotropic radiation boundary conditions .

The model, with homogeneous water density, was initialized with zero velocity and elevation fields for this barotropic calculation. It was then run with a 21.83203125 second (= the 12.42-hour M_2 tidal period/2048) time-step. So that the model nonlinearities and advection could dynamically adjust to the initial fields (Holboke, 1998), the prescribed *tidal sea level forcing-only* (due to Lynch et al., 1997) was linearly increased to full forcing (i.e. ramped-up) during the first six M_2 tidal cycles. Holboke (1998) has shown with a similar QUODDY configuration reach dynamical equilibrium after 6 tidal cycles.

Model/Observation Sea level Comparisons: For the model/observation sea level comparisons, the model was run (after ramp-up) for 2 full M_2 tidal cycles. These model sea level time series were extracted at the 49 nodes which were nearest to the selected set of Moody et al. (1984) observation stations for which tidal harmonic constants were available (see Figure F1). Two-month time series were produced at each of the 49 sites by repeatedly joining the two M_2 tidal cycle series end-to-end. The model and observed M_2 tidal *sea level* harmonic constants are compared in Table F1. For stations in the Gulf of Maine and on Georges Bank, the observed and model M_2 tidal sea level amplitude differences are typically within 10% of each other; with corresponding phase differences typically within 10 degrees of each other.

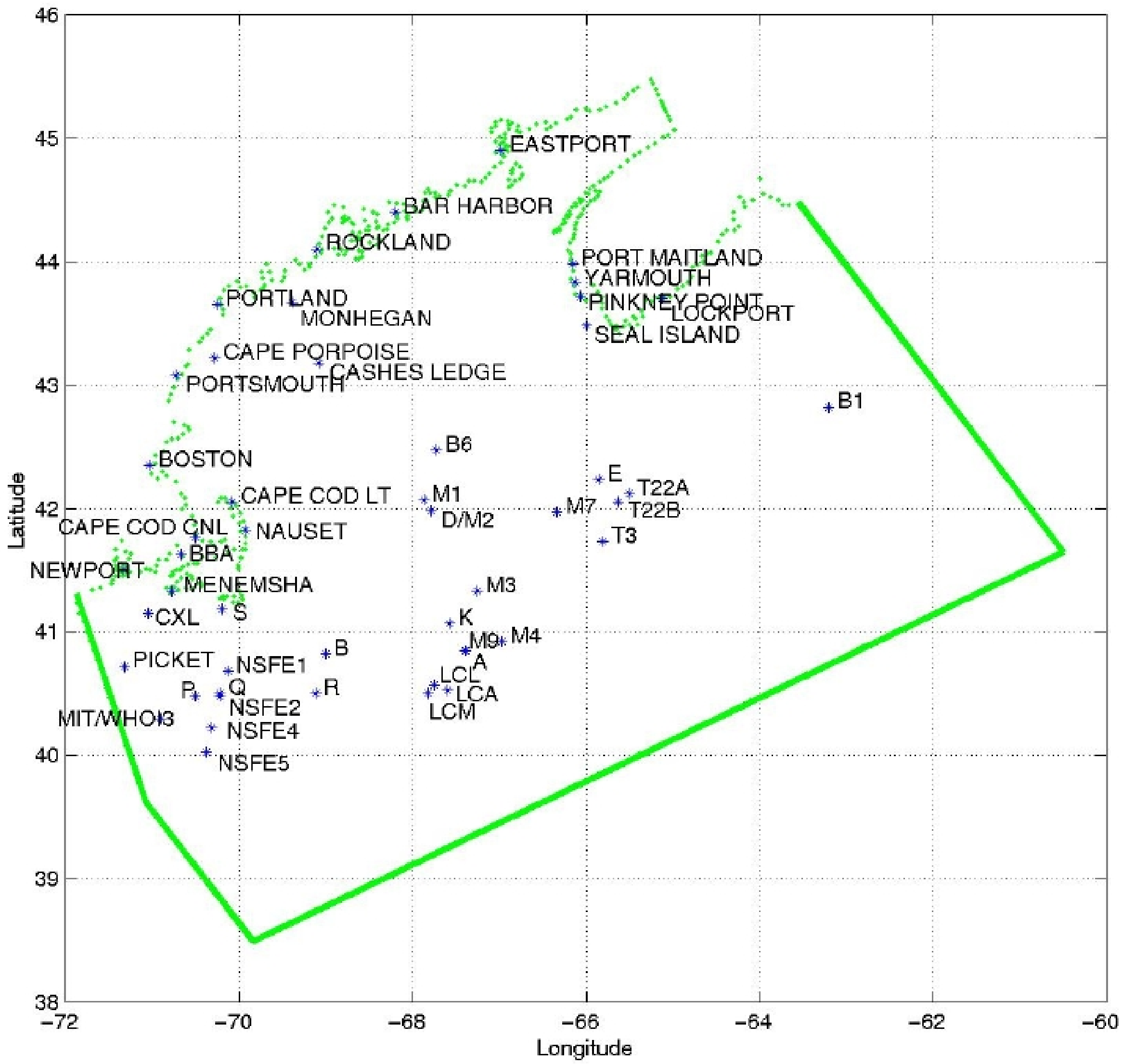


Figure F1 Location map for tidal sea level pressure observation sites (Moody et al., 1984) used for the model-observation comparison studies.

Table F1 M_2 tidal harmonic amplitudes and phases (Greenwich epoch) for observed, model, and model minus observed sea levels at stations in Figure F1. Asterisks indicate those stations in the study region.

Stations			Observations		Model Results		Model-Obs	
Coastal GoM: West	**N Lat (°)**	**WLon (°)**	**Amp (m)**	**Phase (G°)**	**Amp (m)**	**Phase (G°)**	**Amp (m)**	**Phase (G°)**
EASTPORT	44.950	66.985	2.6130	99.00	2.5285	94.94	-0.0845	-4.06
BAR_HARBOR	44.400	68.200	1.5490	93.00	1.4971	87.81	-0.0519	-5.19
ROCKLAND	44.100	69.100	1.5000	98.00	1.3980	92.10	-0.1020	-5.90
PORTLAND	43.657	70.247	1.3300	103.00	1.2628	95.95	-0.0672	-7.05
PORTSMOUTH	43.080	70.722	1.3030	107.00	1.2058	98.14	-0.0972	-8.86
Offshore Maine/NH								
CASHES_LEDGE	43.182	69.083	1.2000	98.00	1.1318	90.95	-0.0682	-7.05
MONHEGAN	43.672	69.378	1.3030	99.00	1.2375	92.28	-0.0655	-6.72
CAPE_PORPOISE	43.215	70.277	1.2720	103.00	1.2007	96.65	-0.0713	-6.35
Massachusetts/GOM								
BOSTON	42.350	71.042	1.3450	111.00	1.2300	101.71	-0.1150	-9.29
CAPE_COD_CNL	41.767	70.500	1.2440	109.00	1.2699	105.19	0.0259	-3.81
CAPE_COD_LT *	42.050	70.083	1.1600	113.00	1.0407	106.56	-0.1193	-6.44
NAUSET*	41.816	69.933	1.0320	102.00	0.9233	110.11	-0.1087	8.11
Nantucket Shoals								
MENEMSHA*	41.333	70.767	0.4510	5.00	0.4716	352.90	0.0206	-12.10
S*	41.183	70.200	0.3230	1.00	0.3102	359.74	-0.0128	-1.26
CXL*	41.150	71.050	0.4440	1.00	0.4825	358.31	0.0385	-2.69
NSFE1*	40.683	70.133	0.3870	356.00	0.3982	352.98	0.0112	-3.02
Q	40.500	70.217	0.3870	353.00	0.4126	350.00	0.0256	-3.00
P	40.483	70.667	0.4160	352.00	0.4290	349.84	0.0130	-2.16
PICKET	40.720	71.310	0.4400	349.00	0.4598	356.95	0.0198	7.95
B*	40.817	69.000	0.2590	47.00	0.2432	33.92	-0.0158	-13.08
R*	40.500	69.117	0.3140	3.00	0.3183	358.60	0.0043	-4.40
MIT/WHOI3	40.300	70.900	0.4220	347.00	0.4456	350.05	0.0236	3.05
NSFE2	40.483	70.217	0.4040	354.00	0.4126	350.00	0.0086	-4.00
NSFE4	40.217	70.317	0.4200	353.00	0.4221	347.87	0.0021	-5.13
NSFE5	40.033	70.383	0.4190	351.00	0.8024	37.83	0.3834	46.83
Buzzards Bay/RI								
BBA	41.633	70.667	0.5380	8.00	0.5225	0.94	-0.0155	-7.06
NEWPORT	41.500	71.333	0.5130	1.00	0.5760	3.03	0.0630	2.03
Central GoM								
B6*	42.467	67.717	0.8800	87.00	0.8206	78.80	-0.0594	-8.20
Georges Bank								
T22A	42.117	65.500	0.4580	4.00	0.4484	7.97	-0.0096	3.97
T22B	42.050	65.633	0.4420	9.00	0.4327	10.26	-0.0093	1.26
T3	41.733	65.800	0.3910	2.00	0.3868	4.77	-0.0042	2.77
E	42.233	65.850	0.4520	24.00	0.4740	24.98	0.0220	0.98
M7	41.967	66.333	0.4100	38.00	0.4085	35.10	-0.0015	-2.90
M1*	42.067	67.867	0.7820	92.00	0.7346	84.81	-0.0474	-7.19
D/M2*	41.983	67.783	0.7650	93.00	0.6994	85.12	-0.0656	-7.88
M4	41.917	66.967	0.3890	1.00	0.3745	356.66	-0.0145	-4.34
M3	41.333	67.250	0.3960	22.00	0.3483	21.17	-0.0477	-0.83
M9	40.850	67.383	0.3890	6.00	0.3795	1.89	-0.0095	-4.11
A	40.850	67.400	0.3890	5.00	0.3799	359.85	-0.0091	-5.15
K	41.067	67.567	0.3990	18.00	0.3832	15.11	-0.0158	-2.89
B1	42.667	63.213	0.4820	351.00	0.4675	349.78	-0.0145	-1.22
LOCKPORT	43.700	65.117	0.6980	359.00	0.7267	356.57	0.0287	-2.43
SEAL_ISLAND	43.483	66.000	1.2040	52.00	1.2650	43.90	0.0610	-8.10
PINKNEY_POINT	43.717	66.067	1.5540	59.00	1.5024	50.17	-0.0516	-8.83
YARMOUTH	43.833	66.117	1.6320	63.00	1.6363	56.94	0.0043	-6.06
PORT_MAITLAND	43.983	66.150	1.8510	66.00	1.8346	62.67	-0.0164	-3.33
Lydonia Canyon								
LCL	40.533	67.600	0.3940	354.00	0.3855	352.40	-0.0085	-1.60
LCA	40.567	67.750	0.3920	358.00	0.3832	355.47	-0.0088	-2.53

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