Hydrographic Observations at the Woods Hole Oceanographic Institution Hawaii Ocean Time-series Site: 2007 – 2008 Data Report #4

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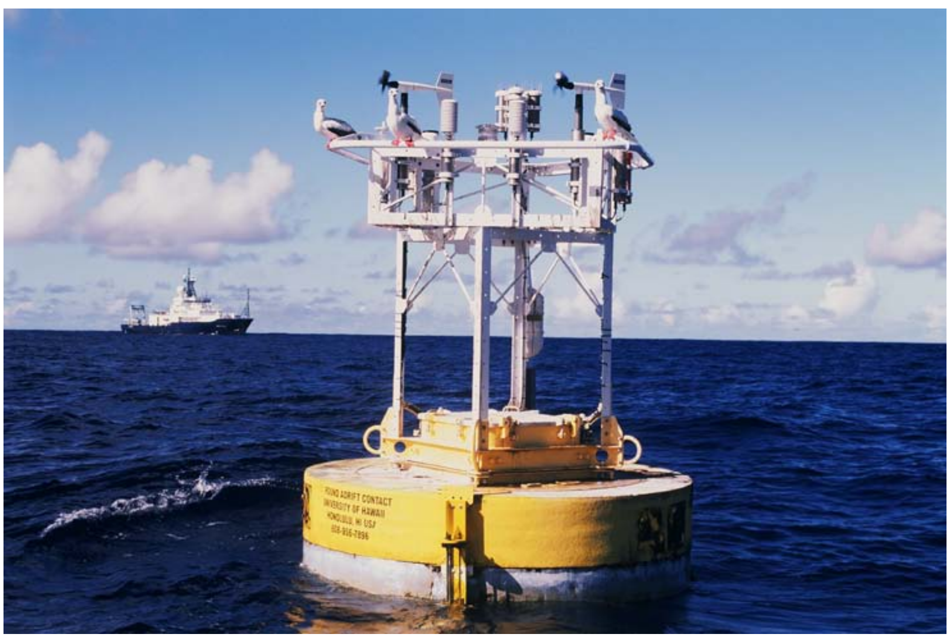

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Acknowledgments

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Table of Contents

1. Introduction

In 2003, Robert Weller (Woods Hole Oceanographic Institution [WHOI]), Albert Plueddemann (WHOI) and Roger Lukas (University of Hawaii [UH]) proposed to establish a long-term surface mooring at the Hawaii Ocean Time-series (HOT) Station ALOHA (22°45'N, 158°W) to provide sustained, high-quality air-sea fluxes and the associated upper ocean response as a coordinated part of the HOT program, and as an element of the global array of ocean reference stations supported by the National Oceanic and Atmospheric Administration's (NOAA) Office of Climate Observation.

With support from NOAA and the National Science Foundation (NSF), the WHOI HOT Site (WHOTS) surface mooring has been maintained at Station ALOHA since August 2004. The objective of this project is to provide long-term, high-quality air-sea fluxes as a coordinated part of the HOT program and contribute to the goals of observing heat, fresh water and chemical fluxes at a site representative of the oligotrophic North Pacific Ocean. The approach is to maintain a surface mooring outfitted for meteorological and oceanographic measurements at a site near Station ALOHA by successive mooring turnarounds. These observations are being used to investigate air-sea interaction processes related to climate variability and change.

The original mooring system is described in the mooring deployment/recovery cruise reports (Plueddemann et al., 2006; Whelan et al., 2007; Whelan et al., 2008). Briefly, a Surlyn foam surface buoy is equipped with meteorological instrumentation including two complete Air-Sea Interaction Meteorological (ASIMET) systems (Hosom et al.(1995), Colbo and Weller (2009)), measuring air and sea surface temperatures, relative humidity, barometric pressure, wind speed and direction, incoming shortwave and longwave radiation, and precipitation. Complete surface meteorological measurements are recorded every minute, as required to compute air-sea fluxes of heat, freshwater and momentum. Each ASIMET system also transmits hourly averages of the surface meteorological variables via the Argos satellite system and via iridium. The mooring line is instrumented in order to collect time series of upper ocean temperatures, salinities and velocities with the surface forcing record. This includes vector measuring current meters, conductivity, salinity and temperature recorders, and two Acoustic Doppler current profilers (ADCPs). See the WHOTS-4 mooring diagram in Figure 1-1.

The subsurface instrumentation is located vertically to resolve the temporal variations of shear and stratification in the upper pycnocline to support study of mixed layer entrainment. Experience with moored profiler measurements near Hawaii suggests that Richardson number estimates over 10 m scales are adequate. Salinity is clearly important to the stratification, as salt-stratified barrier layers are observed at HOT and in the region (Kara et al., 2000), so we use Sea-Bird MicroCATs with vertical separation ranging from 5-20 m to measure temperature and salinity. We use an RDI ADCP to obtain current profiles across the entrainment zone and another in the mixed layer. Both ADCPs are in an upward-looking configuration, one is at 126 m, using 4 m bins, and the other is a 48.5 m using 2 m bins. To provide near-surface velocity (where the ADCP estimates are less reliable) we deploy two Vector Measuring Current Meters (VMCMs). The nominal mooring design is a balance between resolving extremes versus typical annual cycling of the mixed layer (see WHOTS Data Report 1-2, Santiago-Mandujano et al., 2007).

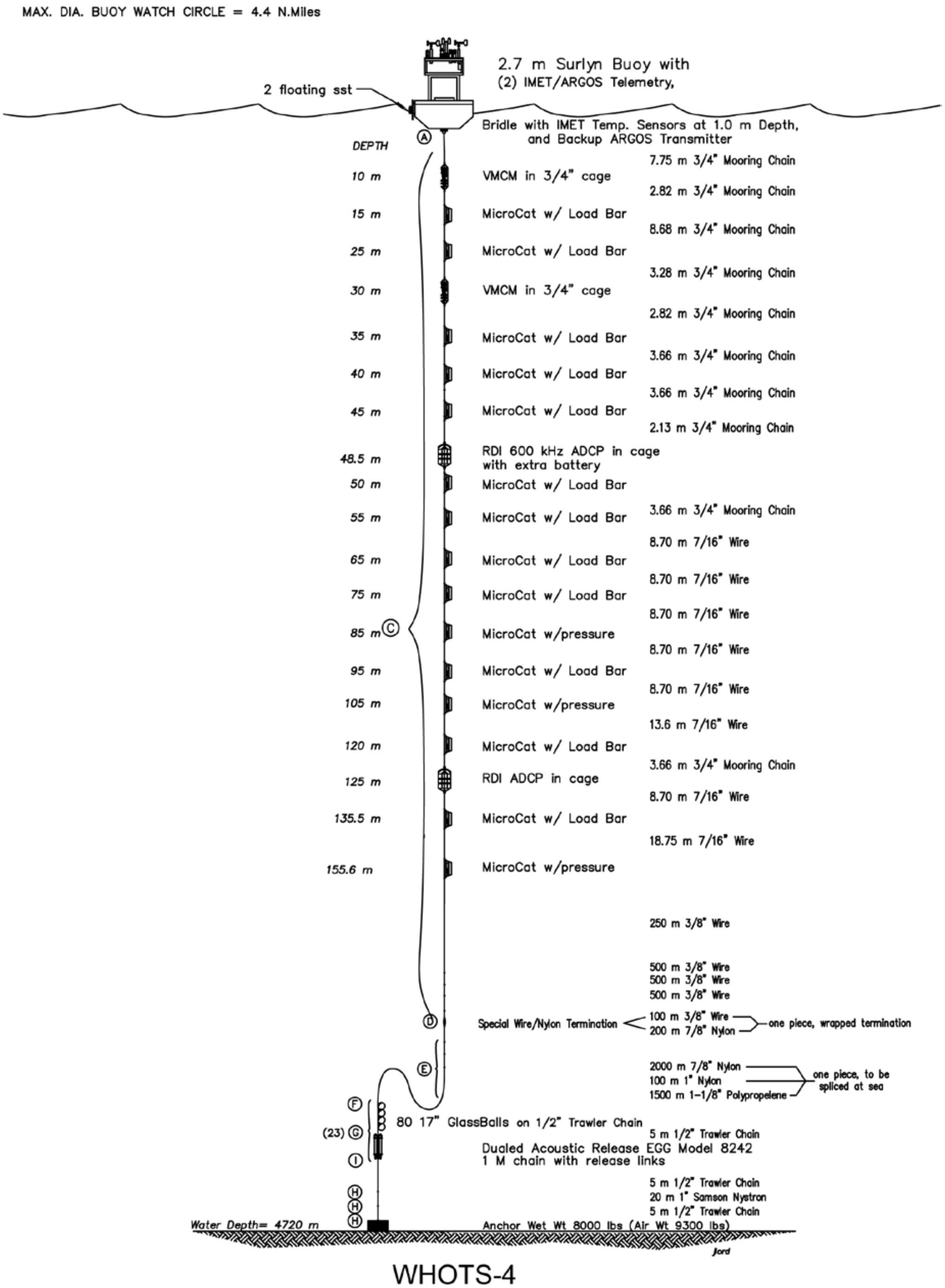


Figure 1-1. WHOTS-4 mooring design.

The first WHOTS mooring (WHOTS-1 mooring) was deployed in August 2004 aboard the UH R/V *Ka'imikai-O-Kanaloa*, and it was recovered in July 2005 during an 8-day cruise (WHOTS-2 cruise) aboard the Scripps Institution of Oceanography (SIO) R/V *Melville*. The second mooring (WHOTS-2 mooring) was deployed during the WHOTS-2 cruise, and it was recovered in June 2006 during a 8-day cruise (WHOTS-3 cruise) aboard the SIO R/V *Roger Revelle*. The third mooring (WHOTS-3 mooring) was deployed during the WHOTS-3 cruise, and it was recovered in June 2007 during a 8-day cruise (WHOTS-4 cruise) aboard the UH R/V *Kilo Moana*. The fourth mooring (WHOTS-4 mooring) was deployed during the WHOTS-4 cruise, and it was recovered in June 2008 during an 8-day cruise (WHOTS-5 cruise) also aboard the UH R/V *Kilo Moana*.

This report documents and describes the oceanographic observations made on the fourth WHOTS mooring (WHOTS-4) during a period of nearly one year, and from shipboard during the two cruises when the mooring was deployed and recovered. Sections 2 and 3, respectively, include a detailed description of the cruises and the mooring. Sampling and processing procedures of the hydrographic casts, thermosalinograph, and shipboard ADCP data collected during cruises are in Section 4. Section 5 includes the processing procedures for the data collected by the moored instruments: MicroCATs, NGVMs, and moored ADCP. Plots of the resulting data and a preliminary analysis are included in Section 6.

2. Description of WHOTS deployment cruises

A. WHOTS-4 Cruise, WHOTS-4 Mooring Deployment

The WHOI/UOP Group conducted the fourth deployment of the WHOTS mooring (WHOTS-4) during the WHOTS-4 cruise between 24 June and 1 July 2007. The shipboard oceanographic observations during the cruise were conducted by the UH group. A complete description of these operations is available in the WHOTS-4 cruise report (Whelan *et al*., 2008).

The R/V *Kilo Moana* was used to deploy the WHOTS-4 mooring on 25 June at approximately 22° 40' N, 157° 57' W in 4756 m of water. The nominal WHOTS mooring site for WHOTS 1-3 had been at 22° 45' N, 157° 54' W. Reoccupation of this site required two complete moorings to be on deck between recovery and deployment. With a smaller working area on the R/V *Kilo Moana*, it was decided to simplify logistics by deploying WHOTS-4 first, followed by the recovery of WHOTS-3 (on 28 June) thereby requiring a new anchor location.

The University of Hawaii provided CTD (conductivity, temperature and depth) and water sampling equipment. The CTD was installed inside a twelve-place rosette with six 5-liter Niskin sampling bottles. A Sea-Bird 9/11+ CTD system sampling at 24 Hz was used to measure T, S, and O_2 profiles. The time, location, and maximum CTD pressure for each of the profiles are listed in Table 2-1.

A series of CTD casts were made to obtain profiles for comparison with subsurface instruments on the WHOTS-3 mooring before recovery, and with those on the WHOTS-4 mooring after deployment. The comparison series consisted of casts to at least 200 m every four hours for over

36 hours (roughly three semidiurnal tidal cycles). In addition, 1000 m CTD profiles were made to provide a cross-calibration between the CTD and the SBE-37s that were recovered from the WHOTS-3 mooring. These casts included approximately ten-minute long stops at four selected depths to provide stable conditions for the calibration. A near-bottom cast (maximum pressure 4808 dbar) was also conducted.

Water samples were taken from all casts; four to six samples for 1000 m and near-bottom casts and two samples for the 200 m casts. The samples were analyzed for salinity and used to calibrate the conductivity sensors used for the CTD profiling.

Table 2-1. CTD stations occupied during the WHOTS-4 deployment cruise

Station	Date	Time (GMT)	Location	Maximum pressure (dbar)
1	6/26/07	04:12	22° 42.23' N, 157° 58.96' W	1022
2	6/26/07	11:50	22° 40.06' N, 157° 59.04' W	202
3	6/26/07	15:49	22° 40.11' N, 157° 58.90' W	202
4	6/26/07	19:48	22° 40.09' N, 157° 58.87' W	202
5	6/26/07	23:55	22° 40.24' N, 157° 58.88' W	206
6	6/27/07	03:55	22° 40.29' N, 157° 58.85' W	202
7	6/27/07	07:49	22° 40.08' N, 157° 58.90' W	202
8	6/27/07	11:50	22° 45.17' N, 157° 55.89' W	202
9	6/27/07	15:56	22° 45.37' N, 157° 55.80' W	202
10	6/27/07	19:56	22° 45.35' N, 157° 55.79' W	202
11	6/27/07	23:56	22° 45.24' N, 157° 55.93' W	202
12	6/28/07	03:56	22° 45.46' N, 157° 55.67' W	202
13	6/28/07	07:51	22° 45.34' N, 157° 55.59' W	210
14	6/29/07	18:04	22° 44.99' N, 158° 00.00' W	4808
15	6/29/07	21:57	22° 45.00' N, 158° 00.00' W	1020
16	6/30/07	01:54	22° 45.02' N, 158° 00.01' W	1022
17	6/30/07	05:50	22° 44.96' N, 157° 59.98' W	1022

In addition, continuous acoustic Doppler current profiler (ADCP) and near surface thermosalinograph (TSG) data were obtained while underway.

The *R/V Kilo Moana* was equipped with an RD Instruments Ocean Surveyor 38 kHz ADCP and an RD Instruments Work Horse 300 kHz ADCP. Configurations for each system are shown in Table 2-2. The two systems used input from the gyro compass and corrected using a TSS POS/MV 320 (an integrated inertial and GPS system) to establish heading information. An Ashtech ADU5 is used as a heading correction device should there be a problem with the POS/MV. Position data are provided by the POS/MV system with the Ashtech ADU5 and a Trimble GPS as backups.

Table 2-2. Configuration of the RD Instruments Ocean Surveyor 38 kHz ADCP and the Work Horse 300 kHz ADCP on board the R/V Kilo Moana during the WHOTS-4 deployment cruise.

	OS38 - Narrow	OS38 – Broad	WH300
Sample interval (s)	300	300	120
Number of bins	70	75	32
Bin Length (m)	24	12	4
Pulse Length (m)	24	13	4
Transducer depth (m)	7	7	7
Blanking length (m)	16	16	4

The TSG observations were made by the ship's underway uncontaminated seawater system, drawing water from a nominal depth of 8 meters with a sampling interval of 10 seconds. The data were acquired continuously during the WHOTS-4 cruise, with salt calibration samples taken roughly twice per day from an outlet in the flowthrough system located less than 1.5 m from the TSG. In addition, the temperature and salinity records were checked against the CTD station data.

The scientific personnel that participated during the WHOTS-4 deployment cruise are listed in Table 2-3.

Table 2-3. Scientific personnel on the R/V Kilo Moana *during the WHOTS-4 and WHOTS-5 cruises.*

Cruise	Name	Title or function	Affiliation
WHOTS-4	Aucan, Jerome	Graduate Student	UH
	Guignes, Thibault	Graduate Intern	UH
	Lethaby, Paul	Research Associate	UH
	Lord, Jeff	Senior Engineering Assistant	WHOI
	Lukas, Roger	Professor/PI	UH
	McGovern, Tim	Marine Technician	UH/OTG[1]
	Nolan, Kellee	Graduate Student	UH
	Plueddemann, Albert	Chief Scientist/PI	WHOI
	Smith, Justin	Undergraduate Student	UH
	Speicher, Elly	Marine Technician	UH/OTG
	Snyder, Jefrey	Marine Electronics Technician	UH
	Whelan, Sean	Engineering Assistant	WHOI
WHOTS-5	Bennallack, Guy	Volunteer	UH
	Bradley, Edward	Senior Scientist	CSIRO
	Buckley, Shandy	Undergraduate Student	UH
	Christman, Jim	Observer	Cons. Ocean L
	Fogaren, Kristen	Graduate Student	UH
	Fullington, Tenley	Intern	USNA/WHOI
	Kassis, Patricia	Teacher	Parker School
	Lethaby, Paul	Research Associate	UH
	Lukas, Roger	Professor/PI	UH

[1] Ocean Technical Group

Cruise	Name	Title or function	Affiliation
	Rosbrugh, Damion	Undergraduate Student	UH
	Ryder, James	Engineer Assistant	WHOI
	Santiago-Mandujano, Fernando	Research Associate	UH
	Shacat, Christine	Research Associate	UH
	Simmons, Bradley	Undergraduate Student	UH
	Snyder, Jefrey	Marine Electronics Technician	UH
	Speicher, Elly	Marine Technician	UH/OTG
	Vellalos, Kuhio	Marine Technician	UH/OTG
	Weller, Robert	Senior Scientist/PI	WHOI
	Whelan, Sean	Engineering Assistant	WHOI

B. WHOTS-5 Cruise, WHOTS-4 Mooring Recovery

The WHOI/UOP group conducted WHOTS-4 mooring recovery operations during the WHOTS-5 cruise between 3 and 11 June 2008. The shipboard oceanographic observations during the cruise were conducted by the UH group. A complete description of these operations is available in the WHOTS-5 cruise report (Santiago-Mandujano et al., 2009).

The R/V *Kilo Moana* was used to deploy the new WHOTS-5 mooring on 5 June at approximately 22° 46' N, 157° 54' W in 4702 m of water. The WHOTS-4 mooring was recovered on 6 June. This quick turnaround time was used to take advantage of a period of calmer weather. R/V *Kilo Moana* returned to the WHOTS-5 mooring for CTD operations and meteorological intercomparisons after the WHOTS-4 mooring deployment.

The University of Hawaii provided CTD (conductivity, temperature and depth) and water sampling equipment. The CTD was installed inside a twelve-place General Oceanics rosette with six 5-liter Niskin sampling bottles controlled by a Seabird carousel. A Sea-Bird 9/11+ CTD system sampling at 24 Hz was used to measure T, S, and O_2 profiles. The time, location, and maximum CTD pressure for each of the profiles are listed in Table 2-4.

A total of 15 CTD casts were conducted at stations 52 (near the WHOTS-4 mooring), and station 50 (near the WHOTS-5 mooring). The first and last casts were to a depth of 1000 m for the purpose of calibration the CTD conductivity cells. Six CTD casts were conducted to obtain profiles for comparison with the subsurface instruments on the WHOTS-4 mooring before recovery and 7 more casts were conducted for comparison with the WHOTS-5 mooring after deployment. These were sited approximately 200 to 500 m downstream from the moorings. The comparison casts each consisted of 6 yo-yo cycles between 5 dbar and 200 and 500 dbar. Station numbers were assigned following the convention used during HOT cruises. Table 2-4 provides summary information for the CTD stations.

Water samples were taken from all casts; 6 samples for 1000 dbar casts and 2 samples each for the 200 and 500 dbar casts. These samples were analyzed for salinity and used to calibrate the CTD conductivity sensors.

Table 2-4. CTD stations occupied during the WHOTS-5 cruise. Note that numbering of stations follows the HOT conventions.

Station/cast	Date	Time (GMT)	Location	Maximum pressure (dbar)
52 / 1	6/5/08	09:56	22° 40.25´ N, 157° 59.14´ W	1022
52 / 2	6/5/08	13:52	22° 39.70´ N, 157° 59.10´ W	202
52 / 3	6/5/08	17:52	22° 39.67´ N, 157° 58.84´ W	202
52 / 4	6/5/08	21:56	22° 39.61´ N, 157° 58.92´ W	202
52 / 5	6/6/08	01:51	22° 39.57´ N, 157° 58.88´ W	500
52 / 6	6/6/08	05:54	22° 39.92´ N, 157° 58.84´ W	502
52 / 7	6/6/08	09:55	22° 39.79´ N, 157° 58.87´ W	502
50 / 1	6/7/08	21:52	22° 45.94´ N, 157° 56.05´ W	502
50 / 2	6/8/08	01:56	22° 45.94´ N, 157° 56.07´ W	502
50 / 3	6/8/08	05:59	22° 45.95´ N, 157° 56.07´ W	502
50 / 4	6/8/08	09:52	22° 46.06´ N, 157° 55.94´ W	502
50 / 5	6/8/08	13:52	22° 45.69´ N, 157° 56.13´ W	502
50 / 6	6/8/08	17:56	22° 45.66´ N, 157° 56.13´ W	502
50 / 7	6/8/08	21:52	22° 45.85´ N, 157° 56.19´ W	502
50 / 8	6/9/08	1:53	22° 46.11´ N, 157° 56.61´ W	1024

In addition to CTD profiles, continuous ADCP and near-surface TSG data were obtained while underway. ADCP and TSG data were collected aboard *R/V Kilo Moana* during WHOTS-5 in the same manner as discussed in Section 2A (WHOTS-4 deployment cruise) with the exception that salinity calibration samples were taken three times per day for the TSG rather than twice per day.

The scientific personnel that participated during the WHOTS-5 deployment cruise are listed in Table 2-3.

3. Description of WHOTS-4 Mooring

The WHOTS-4 mooring deployed on 25 June 2007 from *R/V Kilo Moana* was outfitted with a full suite of ASIMET sensors on the buoy and subsurface instruments from 10 to 155 m of depth. The WHOTS-4 recovery on 06 June 2008 resulted in 348 days on station.

Internally logging Sea-Bird SBE-39 and RBR 1050 temperature sensors were mounted beneath a foam flotation cylinder on the outside face of the buoy hull. Vertical rails allowed the foam to move up and down with the waves, so that the sensor measured the SST within the upper 10-20 cm of the water column.

The WHOTS-4 mooring deployed again a Seimac GPS unit. As an improvement over previous deployment, a power cycling feature of the Seimac unit was added to the mooring logger code. Under this scheme, power to the Seimac receiver would be toggled off and on once per day. Tests at WHOI had previously shown that power cycling could revive the receiver when it had stopped recording. A burn-in period with a modified logger collected about 230 days of Seimac data before the unit was sent out to Hawaii. Unfortunately, the receiver stopped recording 9 days after being turned on in Hawaii, or 3 days after the mooring was deployed.

Instrumentation provided by UH for the WHOTS-4 mooring included 15 Sea-Bird SBE-37 MicroCATs and an RD Instruments 300 kHz ADCP. The MicroCATS all measured temperature and conductivity, with five also measuring pressure. WHOI provided two NGVMs, an RDI 600 kHz ADCP and all required subsurface mooring hardware via a subcontract with UH. Table 3-1 provides the deployment information for each C-T instrument on the WHOTS-4 mooring, including two WHOI Sea-Bird SBE-37 installed under the buoy.

Before deployment, the MicroCATs were dunked in a cold freshwater bath to generate a spike in the data to be used for synchronization of their internal clocks (Table 3-1).

The RDI 300 kHz Workhorse ADCP, SN 4891, was deployed at 125 m with transducers facing upwards. The instrument was set to ping at 4-second intervals for 160 seconds every 10 minutes. This burst sampling was designed to minimize aliasing by occasional large ocean swell orbital motions. Bin size was set for 4 m. The total number of ensemble records was 50,284. The first ensemble was at 6/25/2007 00:00:00Z, and the last was at 06/8/2008 04:30:00Z. This instrument also measured temperature.

The RDI 600 kHz Workhorse ADCP, SN 1825, was deployed at 48.5 m with transducers facing upwards. The instrument was set to ping at 1-second intervals for 120 seconds every 15 minutes. Bin size was set for 2 m. The total number of ensemble records was 34,198. The first ensemble was at 6/18/2007 01:00:00Z, and the last was at 6/8/2008 06:15:00Z. This instrument also measured temperature.

The two NGVMs, SN 034 and 040 were deployed at 10 m and 30 m depth respectively. The instruments were prepared for deployment by the WHOI/UOP group and set to record at 1-minute intervals. These instruments also measured temperature.

Table 3-1. WHOTS-4 Mooring - MicroCAT Deployment Information. All times stated are in UTC.

Depth (meters)	Sea-Bird Serial #	Parameters	Sample Interval (seconds)	Navg	Time Logging Started	Cold Spike Time	Time in the water
1.5	37SM485-1837	C, T	300	-	6/26/2007 00:50	NA	06/25/07 23:48
1.5	37SM485-1839	C, T	300	-	6/26/2007 00:50	NA	06/25/07 23:48
15	37SM31486-3382	C, T	150	2	6/19/2007 12:00	06/19/07 21:30:00	06/25/07 17:10
25	37SM31486-3621	C, T	150	2	6/19/2007 12:00	06/19/07 21:30:00	06/25/07 17:04
35	37SM31486-3620	C, T	150	2	6/19/2007 12:00	06/19/07 21:30:00	06/25/07 17:01
40	37SM31486-3632	C, T	150	2	6/19/2007 12:00	06/19/07 21:30:00	06/25/07 16:59
45	37SM31486-2965	C, T, P	180	1	6/19/2007 12:00	06/19/07 21:30:00	06/25/07 16:56
50	37SM31486-3633	C, T	150	2	6/19/2007 12:00	06/19/07 21:30:00	06/25/07 16:54
55	37SM31486-3619	C, T	150	2	6/19/2007 12:00	06/19/07 21:30:00	06/25/07 18:17
65	37SM31486-3791	C, T	150	2	6/19/2007 12:00	06/19/07 21:30:00	06/25/07 18:20
75	37SM31486-3618	C, T	150	2	6/19/2007 12:00	06/19/07 20:40:00	06/25/07 18:22

85	37SM31486-3670	C, T, P	180	1	6/19/2007 12:00	06/19/07 20:40:00	06/25/07 18:25
95	37SM31486-3617	C, T	150	2	6/19/2007 12:00	06/19/07 20:40:00	06/25/07 18:27
105	37SM31486-3669	C, T, P	180	1	6/19/2007 12:00	06/19/07 20:40:00	06/25/07 18:30
120	37SM31486-2451	C, T, P	180	1	6/19/2007 12:00	06/19/07 20:40:00	06/25/07 18:33
135	37SM31486-3634	C, T	150	2	6/19/2007 12:00	06/19/07 20:40:00	06/25/07 18:38
155	37SM31486-3668	C, T, P	180	1	6/19/2007 12:00	06/19/07 20:40:00	06/25/07 18:41

All WHOTS-4 instruments were successfully recovered. Most of the instruments had some degree of biofouling, with the heaviest fouling near the surface. Fouling extended down to the ADCP at 125 m, although it was minor at that level. The fouling appeared to be much less than in previous WHOTS deployments.

Table 3-2 gives the post-deployment information for C-T instruments. All instruments returned full data records. After recovery and before the data logging was stopped, the MicroCATs were dumped in a cold freshwater bath to create a spike in the data to check for any malfunction of the internal clock. MicroCAT SN 2451 pressure sensor drifted about 10 m during most of the deployment, and it failed a couple of months before recovery. MicroCAT SN 3668 conductivity sensor had an offset early in the record, and returned to apparently normal values near the middle of the record.

The data from the upward-looking 300 kHz ADCP at 125 m appeared to be of high quality, however the instrument's clock on retrieval was offset by 9 minutes and 5 seconds ahead of GMT. The heading, pitch and roll information from the ADCP provided useful information about the overall behavior of the mooring during its deployment. An example is that the buoy apparently was twisted one turn between May and June 2008. Pitch and roll are generally less than 5 degrees from the vertical, but there are some periods with deviations from the vertical of as much as 10 degrees.

The data from the upward-looking 600 kHz ADCP at 48.5 m appeared to be of high quality, however the instrument's clock on retrieval was offset by 3 minutes and 3 seconds ahead of GMT. The apparent twisting of the buoy during May-June 2008 observed in the 125 m ADCP is not obvious in this ADCP heading record. Pitch and roll are generally less than 5 degrees from the vertical, but there are some periods with deviations from the vertical of as much as 10 degrees.

Table 3-2. WHOTS-4 Mooring - MicroCAT Recovery Information. All times stated are in UTC.

Depth (meters)	**Seabird Serial #**	**Time out of water**	**Time of cold spike**	**Time Logging Stopped**	**Samples Logged**	**Data Quality**
1.5	37SM485-1837	6/7/2008 02:13	NA	06/6/2008 17:20:00	99847	good
1.5	37SM485-1839	6/7/2008 02:13	NA	06/6/2008 17:20:00	-	Recorder failed
15	37SM31486-3382	6/7/2008 01:13	6/7/2008 05:46:30	06/7/2008 21:30:00	204131	good
25	37SM31486-3621	6/7/2008 01:18	6/7/2008 05:11:30	06/7/2008 21:26:00	204130	good
35	37SM31486-3620	6/7/2008 01:24	6/7/2008 05:11:30	06/7/2008 06:30:30	203770	good
40	37SM31486-3632	6/7/2008 01:26	6/7/2008 05:46:30	06/8/2008 00:34:00	204205	good
45	37SM31486-2965	6/7/2008 01:28	6/7/2008 05:11:30	06/7/2008 07:39:00	169833	good

50	37SM31486-3633	6/7/2008 00:22	6/7/2008 05:46:30	06/8/2008 00:38:00	204207	good
55	37SM31486-3619	6/7/2008 00:18	6/7/2008 05:11:30	06/7/2008 21:21:00	204128	good
65	37SM31486-3791	6/7/2008 00:15	6/7/2008 05:11:30	06/7/2008 06:57:00	203782	good
75	37SM31486-3618	6/7/2008 00:10	6/7/2008 05:11:30	06/7/2008 07:45:00	203802	good
85	37SM31486-3670	6/7/2008 00:06	6/7/2008 05:46:30	06/7/2008 21:42:00	170114	good
95	37SM31486-3617	6/7/2008 00:03	6/7/2008 05:11:30	06/7/2008 06:50:10	203779	good
105	37SM31486-3669	6/6/2008 23:59	6/7/2008 05:11:30	06/7/2008 07:35:00	169831	good
120	37SM31486-2451	6/6/2008 23:55	6/7/2008 05:46:30	06/8/2008 00:41:00	170174	P sensor drifted
135	37SM31486-3634	6/6/2008 23:46	6/7/2008 05:46:30	06/7/2008 21:39:00	204135	good
155	37SM31486-3668	6/6/2008 23:40	6/7/2008 05:46:30	06/7/2008 21:35:00	170112	C offset half of record

4. WHOTS-4 and -5 Cruise Shipboard Observations

The profile observations made during WHOTS-4 and -5 cruises were obtained with a Sea-Bird CTD (conductivity, temperature, oxygen and depth) instrument with duplicate temperature and conductivity sensors. Measurements were made to better than 0.01°C in temperature, 0.01 for salinity, and 1.5 μmol/kg in dissolved oxygen below 5 m. In addition, R/V *Kilo Moana* came equipped with a thermosalinograph which provided a continuous, high-resolution depiction of temperature and salinity of the near-surface layer. Horizontal currents over a depth range of 40-800 m by the 38 kHz ADCP with a vertical resolution of 16 m during WHOTS-4 and WHOTS-5.

A. Conductivity, Temperature and Depth (CTD) profiling

Continuous measurements of temperature, conductivity and pressure were made with the UH SBE-911+ CTD (SN 91361) during WHOTS-4 and -5. Each CTD was equipped with an internal Digiquartz pressure sensor and two pairs of external temperature and conductivity sensors. Each of the temperature-conductivity sensor pairs used a Sea-Bird TC duct which circulated seawater through independent pump and plumbing installations. During WHOTS-4 and -5, the CTD configuration also included two oxygen sensors, installed in the plumbing for each sensor set. In all three cruises, the CTD was mounted in a vertical position in the lower part of a 12-place Rosette sampler, with the sensors' water intakes located at the bottom of the Rosette.

The package was deployed on a conducting cable, which allowed for real-time data acquisition and display. The deployment procedure consisted in lowering the package to 10-15 dbar and waiting until the CTD pumps started operating. The CTD was then raised until the sensors were close to the surface to begin the CTD cast. The time and position of each cast was obtained via a GPS connection to the CTD deck box. Sampling bottles were 5-liter Niskin bottles during WHOTS-4 and –5. Between two and six salinity samples were taken on each cast for calibration of the conductivity sensors.

1. Data acquisition and processing.

CTD data were acquired at the instrument's highest sampling rate of 24 samples per second. Digital data were stored on a laptop computer and, for redundancy, the analog signal was recorded on VHS video tapes.

Figure 4-1 shows a flowchart of the CTD data processing. The raw CTD data were first converted from frequencies to engineering units using nominal sensor calibrations and then screened for spikes or missing data using a 9-point median filter. After screening, the correct alignment of temperature and conductivity time-series was computed since the lag between temperature and conductivity depends on the relative position of the sensors. Both T-C pairs were also aligned with each other by cross-correlating the two temperature sensors. Conductivity measurement were corrected for thermal inertia of the glass conductivity cell as explained below, and the data were averaged to half-second values; salinity was then computed. Details of these procedures are described in the following sections. Spikes in the data occur when the CTD samples the disturbed water of its wake. Therefore, samples from the downcast were rejected when the CTD was moving upward or when its acceleration exceeded 0.5 m s^{-2} in magnitude. The data were subsequently averaged into 2-dbar pressure bins after calibrating the CTD conductivity with the bottle salinities.

The data were additionally screened by comparing the T-C sensor pairs. These differences permitted identification of problems with the sensors. The data from only one T-C pair, whichever was deemed most reliable, is reported here. Only data from the downcast are reported, as upcast data are contaminated by rosette wake effects.

Temperature is reported in the ITS-90 scale. Salinity and all derived units were calculated using the UNESCO (1981) routines; salinity is reported in the practical salinity scale (PSS-78).

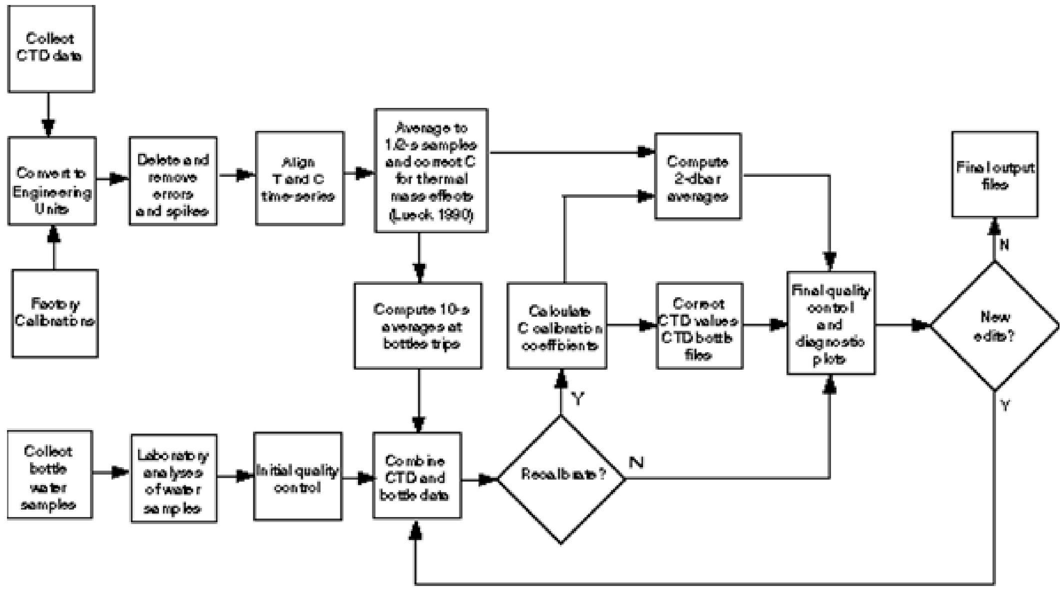


Figure 4-1. Flowchart of CTD data processing

2. CTD sensor calibration and corrections

Pressure

The pressure calibration strategy for CTD pressure transducer SN 75434 used during WHOTS-4 and -5 employed a high-quality quartz pressure transducer as a transfer standard. Periodic recalibrations of this lab standard were performed with a primary pressure standard. The only corrections applied to the CTD pressures were a constant offset determined at the time that the CTD first enters the water on each cast. In addition, a span correction determined from bench tests on the sensor against the transfer standard was applied for sensor SN 75434.

Transfer Standard Calibration

The transfer standard is a Paroscientific Model 760 pressure gauge equipped with a 10,000 PSI transducer. This instrument was purchased in March 1988, and was originally calibrated against a primary standard. Subsequent recalibrations have been performed every 2.5 years on average either at the Northwest Regional Calibration Center or at the SIO. The latest calibrations were conducted at the SIO in April 1999, May 2001, May 2003, and July 2005.

CTD Pressure Transducer SN 75434 Bench Tests

CTD pressure transducer bench tests were done using an Ametek T-100 pump and a manifold to apply pressure simultaneously to the CTD pressure transducer and to the transfer standard. All these tests generated calibration data at six pressure levels between 0 and 4500 dbar, for both increasing and decreasing pressures. Pressure sensor #75434 was used during the WHOTS-4 and

-5 cruises. The results of the bench tests on this sensor from 1998 until 2009 are shown in Table 4-1. A 0.201 dbar correction was applied to the pressure offset at 0 dbar during data collection for WHOTS-4 casts conducted with sensor #75434 (however, a more accurate offset was later determined for the time that the CTD first enters the water on each cast). The correction was changed to –0.62 for WHOTS-5 casts as bench tests suggested a significant difference over time.

The 0-4500 dbar pressure offset and hysteresis from the bench tests have been within expected values and nearly constant for sensor #75434. The 0-4500 dbar pressure offset suffered a slight increase after 2005. A span correction 0.39 dbar/4500 dbar was applied for all the WHOTS-4 and -5 casts.

Table 4-1 CTD pressure sensor #75434 calibrations against the transfer standard

Calibration Date	Offset @ 0 dbar	0-4500 dbar offset	Hysteresis
8 January 2009	-0.64	0.42	0.12
29 August 2008	-0.63	0.29	0.1
4 January 2008	-0.62	0.39	0.08
20 July 2007	-0.51	0.63	0.14
27 February 2007	-0.42	0.46	0.12
26 July 2006	-0.38	0.45	0.11
24 July 2006	-0.24	0.53	0.17
24 August 2005	0.2	0.23	NA
17 February 2005	0.1	0.4	0.08
3 July 2004	0.49	0.17	0.05
9 February 2004	0.44	0.2	0.12
28 July 2003	0.45	0.12	0.15
5 February 2003	0.39	0.05	0.15
16 July 2002	0.43	0.15	0.1
28 January 2002	0.35	0.23	0.1
1 August 2001	0.1	-0.1	0.1
6 February 2001	0.24	-0.02	0.1
15 August 2000	0.18	0.12	0.1
13 January 2000	0.1	0.13	0.08
24 June 1999	-0.03	0.2	0.1

Temperature

Three Sea-Bird SBE-3-Plus temperature transducers (#2454, #2907, and #4448) were used during WHOTS-4 and -5, and were calibrated at Sea-Bird before and after each cruise to an accuracy better than 0.5 x 10^{-3}°C. Calibration coefficients obtained at Sea-Bird are listed in Table 4-2. These coefficients were used in the following formula that gives the temperature (in °C) as a function of the frequency signal (*f*):

$$Temperature = 1/\{a+b[ln(fo/f)]+c[ln^2(fo/f)+d[ln^3(fo/f]\}-273.15$$

For each sensor, we calculated the 0-30°C average offset for each calibration relative to the oldest one, and applied a linear fit to these offsets. A single baseline calibration was chosen and a temperature-independent offset relative to the baseline calibration was applied to the data to remove the temporal trend due to the sensor drift. The maximum drift correction for WHOTS cruises was less than 0.2 x 10^{-3}°C. The baseline calibration was selected as the one for which the trend-corrected average from 0-5°C was nearest to the ensemble mean of these averages.

Table 4-2. Calibration coefficients for Sea-Bird temperature sensors. RMS residuals from calibration give an indication of calibration quality.

SN	*Date yymmdd*	*f0*	*a*	*b*	*c*	*d*	*RMS (m°C)*
2454	090204	2885.64	3.68121341e-03	6.02187404e-04	1.67767799e-05	2.39828397e-06	0.03
2454	080918	2885.67	3.68121541e-03	6.02179167e-04	1.67551187e-05	2.37764306e-06	0.03
2454	080709	2885.67	3.68121351e-03	6.02169746e-04	1.67323505e-05	2.36262665e-06	0.02
2454	080213	2885.70	3.68121253e-03	6.02190794e-04	1.67647341e-05	2.37361682e-06	0.03
2454	071025	2885.69	3.68121273e-03	6.02173482e-04	1.67415883e-05	2.36803189e-06	0.02
2454	070717	2885.73	3.68121195e-03	6.02214673e-04	1.68191091e-05	2.40340524e-06	0.06
2454	070403	2885.72	3.68121261e-03	6.02201741e-04	1.68160306e-05	2.42189383e-06	0.03
2454	061122	2885.72	3.68121318e-03	6.02193744e-04	1.67977052e-05	2.40985947e-06	0.06
2454	060801	2885.730	3.68121424e-03	6.02175648e-04	1.67513098e-05	2.36269660e-06	0.03
2454	060415	2885.752	3.68121439e-03	6.02187499e-04	1.67547819e-05	2.35423435e-06	0.07
2454	051020	2885.746	3.68121819e-03	6.02183987e-04	1.67711663e-05	2.38731519e-06	0.06
2454	050827	2885.744	3.68121676e-03	6.02187449e-04	1.67885159e-05	2.40097525e-06	0.05
2454	050706	2885.742	3.68121551e-03	6.02184381e-04	1.67859182e-05	2.39915470e-06	0.05
2454	050407	2885.757	3.68121334e-03	6.02186285e-04	1.67971302e-05	2.40912421e-06	0.07
2454	050111	2885.74	3.68121209E-03	6.02189593E-04	1.68073225E-05	2.41468487E-06	0.07
2454	041111	2885.73	3.68121193E-03	6.02184316E-04	1.68016426E-05	2.41392105E-06	0.06
2907	090204	3035.62	3.68121289e-03	5.99705320e-04	1.56922033e-05	1.94348487e-06	0.05
2907	080822	3035.56	3.68121528e-03	5.99676130e-04	1.56820898e-05	1.95397946e-06	0.05
2907	070816	3116.54	3.68121160e-03	5.99880462e-04	1.57345769e-05	1.98772693e-06	0.06
2907	070717	3116.61	3.68121113e-03	5.99887991e-04	1.57270559e-05	1.96487621e-06	0.04
2907	070608	3116.54	3.68121256e-03	5.99906913e-04	1.58387472e-05	2.09269035e-06	0.05
2907	070522	3116.52	3.68121244e-03	5.99881742e-04	1.57462776e-05	2.02173948e-06	0.05
2907	070404	3116.61	3.68121111e-03	5.99867075e-04	1.55303698e-05	1.74228373e-06	0.11
2907	061122	3116.57	3.68121265e-03	5.99891432e-04	1.57511437e-05	2.01414707e-06	0.05
2907	060801	3116.71	3.68121374e-03	5.99887879e-04	1.57306534e-05	1.97886945e-06	0.02
2907	060215	3116.61	3.68121321e-03	5.99875247e-04	1.56877843e-05	1.94182968e-06	0.07
4448	090204	2872.12	3.68121337e-03	5.97078723e-04	1.50345226e-05	1.80560668e-06	0.08
4448	080925	2872.15	3.68121498e-03	5.97052184e-04	1.49237485e-05	1.70356201e-06	0.04
4448	080708	2872.29	3.68121246e-03	5.97054438e-04	1.49426472e-05	1.72945639e-06	0.03
4448	080213	2872.30	3.68121371e-03	5.97064162e-04	1.49624007e-05	1.74802143e-06	0.02
4448	060801	2872.314	3.68121418e-03	5.97049695e-04	1.49291789e-05	1.70648232e-06	0.03
4448	060415	2872.310	3.68121431e-03	5.97077412e-04	1.50501277e-05	1.81399552e-06	0.06
4448	051110	2872.337	3.68121770e-03	5.97041275e-04	1.49263547e-05	1.72296669e-06	0.01

A small residual pressure effect on the temperature sensors documented in Tupas et al. (1997) has been removed from measurements obtained with our sensors. Another correction to our temperature measurements was for the viscous heating of the sensor tip due to the water flow past it (Larson and Pederson, 1996). This correction is thoroughly documented in Tupas et al. (1997).

Dual sensors were used during all casts of the WHOTS-4 and -5 cruises. Sensors #2454 and #4448 were used during WHOTS-5; and sensors #2454 and #2907 were used during WHOTS-4.

The temperature differences between sensor pairs were calculated for each cast to evaluate the quality of the data, and to identify possible problems with the sensors. All sensors performed correctly during the cruises, showing temperature differences within expected values. The mean temperature difference in the water column was typically less than 2 x 10^{-3} °C in the 1000 m casts, with a standard deviation of less than 0.5 x 10^{-3} °C below 500 dbar. The largest variability in temperature difference between sensor pairs was observed in the thermocline, where the standard deviation reached nearly 1 x 10^{-2} °C. These differences are not unexpected, since each sensor has independent water intakes it is possible that when the CTD passes through this steep gradient region each sensor measures water from slightly different levels, yielding significant temperature differences.

Temperature sensor #2454

This sensor was during the WHOTS-4 and –5 cruises. The calibrations from October 2005 through February 2008 were used to calculate sensor drift and drift corrections temperature sensor #2454 for WHOTS-4. These calibrations yielded a sensor drift of 1.89 x 10^{-6} °C day^{-1}. When corrected for linear drift to 30 June 2007, the 25 October 2007 calibration gave the smallest deviation in the 0-5°C temperature range from the set of all calibrations (also corrected for linear drift to 30 June 2007). A drift correction was obtained using this baseline calibration (Table 4-3). This correction is less than 0.5 m °C and therefore insignificant.

The calibrations from October 2005 through February 2009 were used to calibrate sensor drift and drift corrections for temperature sensor #2454 for WHOTS-5. These calibrations yielded a sensor drift of 1.62 x 10^{-6} °C day^{-1}. When corrected for linear drift to 30 June 2008, the 13 February 2008 calibration gave the smallest deviation in the 0-5°C temperature range from the set of all calibrations (also corrected for linear drift to 30 June 2008). A drift correction was obtained using this baseline calibration (Table 4-3). This correction is less than 0.5 m °C and therefore insignificant.

Temperature sensor #2907

This sensor was used during the WHOTS-4 cruise. The calibrations between February 2006 and August 2007 were used to calculate sensor drift and drift corrections. These calibrations yielded a sensor drift of –3.11 X 10^{-6} ºC day^{-1}. When corrected for linear drift to 1 June 2007, the 16 August 2007 calibration gave the smallest deviation in the 0-5°C temperature range from the set of all calibrations (also corrected for linear drift to 1 June 2007). A drift correction was obtained using this baseline calibration (Table 4-3). This correction is less than 0.5 m °C and deemed insignificant.

Temperature sensor #4448

This sensor was during the WHOTS-5 cruise. The calibrations from July 2007 through February 2009 were used to calibrate sensor drift and drift corrections for temperature sensor #4448 for WHOTS-5. These calibrations yielded a sensor drift of 5.8 X 10^{-6} ºC day^{-1}. When corrected for linear drift to 1 May 2008, the 13 February 2008 calibration gave the smallest deviation in the 0-5°C temperature range from the set of all calibrations (also corrected for linear drift to 1 May

2008). A drift correction was obtained using this baseline calibration (Table 4-3). This correction is less than 1.0 m °C and deemed insignificant.

Table 4-3. Temperature (T) and Conductivity (C) sensors used during the WHOTS cruises, including temperature drift correction and the thermal inertia parameter (alpha). Dual temperature and conductivity sensors were used during both cruises. The data reported here are from the sensors marked with (*).

Cruise	T-sensor #	T-correction (m°C)	C-sensor #	alpha
WHOTS-4	2454 (*)	-0.229	2959 (*)	0.020
WHOTS-4	2907	-0.159	3162	0.020
WHOTS-5	2454 (*)	0.183	2218 (*)	0.037
WHOTS-5	4448	0.655	2959	0.028

Conductivity

Three Sea-Bird SBE 4C conductivity sensors (#2218, #2959, and #3162) were used during the WHOTS cruises. Dual sensors were used during all the cruise casts. As mentioned earlier, only the data from the most reliable sensor (and its corresponding temperature sensor pair, as shown in Table 4-3) are reported here.

Sensor #2218 was calibrated at Sea-Bird in September 2007, sensor #2959 was calibrated in May 2006 and August 2007, and sensor #3162 was calibrated in May 2006. The nominal conductivity calibrations were used for data acquisition. Final calibration was determined empirically from salinities of discrete water samples acquired during each cast. Prior to empirical calibration, conductivity was corrected for thermal inertia of the glass conductivity cell using the recursive filter given by Lueck (1990) and Lueck and Picklo (1990). Sensor parameters alpha and beta, which characterize the initial magnitude of the thermal effect and its relaxation time, are needed for this correction. As recommended by Lueck (personal communication, 1990), beta was set to 0.1 s^{-1}, but alpha was calculated for each sensor to close the spread between the down- and up-cast *T-S* curves (Table 4-3).

Salinity samples were collected at selected depths during each cast and measured with a salinometer (Sect. 4.B.1). The nominally calibrated CTD salinity trace was used to identify questionable samples. Salinity samples were later quality controlled and flagged by comparing them against the empirically calibrated CTD salinities.

Calibration of each conductivity sensor was performed empirically by comparing its nominally calibrated output against the calculated conductivity values obtained from the water sample salinities, using the pressure and temperature of the CTD at the time of bottle closure. An initial estimate of bias (*b0*) and slope (*b1*) corrections to the nominal calibration were determined from a linear least squares fit to the ensemble of CTD-bottle conductivity differences as a function of conductivity, from all casts during the sensor use. This calibration was then used to identify suspect water samples. These samples were deleted from the analysis, and the calibration was repeated. Conductivity calibration coefficients for the sensors used during WHOTS cruises are given in Table 4-4.

Table 4-4 CTD Conductivity calibration coefficients obtained from comparison against bottle salinities.

Cruise	Sensor #	b0	b1
WHOTS-4	2959	0.000452	-0.000239
WHOTS-4	3162	0.000582	-0.000295
WHOTS-5	2218	-0.000422	-0.000017
WHOTS-5	2959	-0.000074	-0.000083

The final step of the calibration was to perform a profile-dependent bias correction, to allow for a drift of the conductivity cell with time during each cruise, or for sudden offsets due to fouling. This offset was determined by taking the median value of CTD-bottle salinity differences for each profile. No offset corrections were necessary for any of the WHOTS cruises casts.

The quality of the conductivity calibration is illustrated by Figure 4-2, which shows the differences between the corrected CTD salinities and the bottle salinities as a function of pressure for the WHOTS-4 and -5 cruises. Table 4-5 gives the mean and standard deviations for the final calibrated CTD minus water sample salinities.

Table 4-5 CTD-Bottle salinity comparison for each sensor. (*) Deep cast data for WHOTS-4 allowed for comparisons between 0 to 4700 dbar and 500 to 4700 dbar.

		0 to 1200 dbar*		500 to 1200 dbar*	
Cruise	Sensor #	Mean	Standard Deviation	Mean	Standard Deviation
WHOTS-4	2959	0.0000	0.0015	0.0000	0.0008
WHOTS-4	3162	0.0000	0.0016	-0.0001	0.0012
WHOTS-5	2218	0.0000	0.0013	0.0000	0.0014
WHOTS-5	2959	0.0000	0.0010	-0.0003	0.0005

Salinity differences between sensor sets were calculated the same way as for the temperature in order to identify problems with any of the sensors. These differences show a behavior similar to the temperature differences in the thermocline region. Maximum absolute salinity differences of about 5×10^{-3} were observed near the surface, decreasing to less than 2×10^{-3} below 200 dbar. This behavior is due to a combination of the residual temperature effect on the temperature sensors described in the previous section, and an additional residual temperature effect on the conductivity sensors (N. Larson personal communication, 1999). The temperature effect on the conductivity sensors is similar to that described for the temperature sensors, and affects the conductivity measurements when the sensor passes through intense temperature gradients.

The largest variability in the salinity difference between sensors was observed between the surface and the base of the halocline, with standard deviations of up to 1×10^{-2} between 50 and 200 dbar.

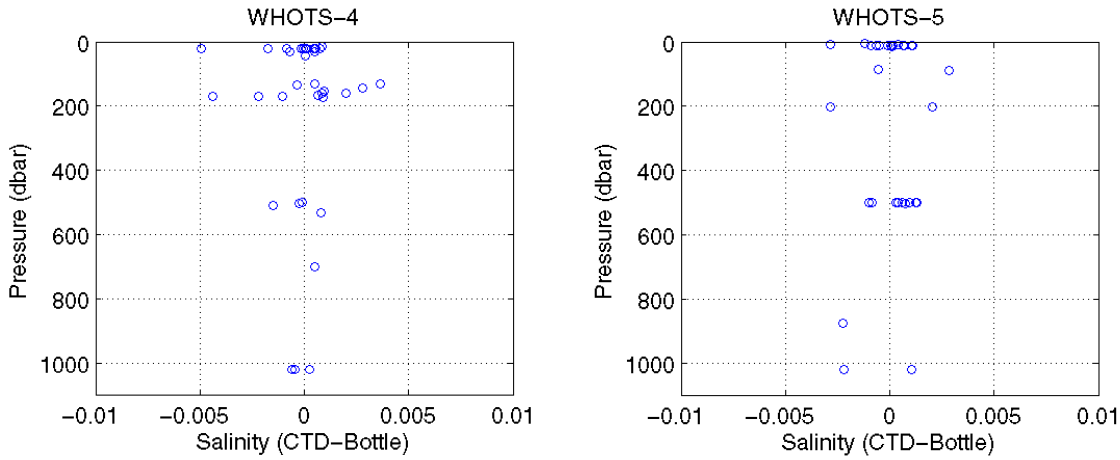


Figure 4-2. Difference between calibrated CTD salinities and bottle salinities for all the casts during WHOTS-4 and –5 deployment cruises.

Dissolved Oxygen

During the WHOTS-4 and –5 cruises two Sea-Bird SBE-43 oxygen sensors were used: #43262, and #43918. Sensor #43262 was calibrated on 22 November 2006 and 01 April 2008, and sensor #43918 was calibrated on 14 September 2007 and 19 August 2008. Data from the oxygen sensors were empirically calibrated using calibration coefficients obtained from the HOT cruise prior to the WHOTS cruise in which the same sensors were used (HOT-192 for WHOTS-4 and HOT-201 for WHOTS-5). The calibration procedure follows Owens and Millard (1985), and consists of fitting a nonlinear equation to the CTD oxygen current. The bottle values of dissolved oxygen and the downcast CTD observations at the potential density of each bottle trip were grouped together for each cruise to find the best set of parameters with a non-linear least squares algorithm. Dual sensors were used during WHOTS-4 and -5, but only the sensor whose data were deemed more reliable is reported.

B. Water samples

1. Salinity

Salinity samples were collected in 250 ml glass bottles during WHOTS-4 and -5. Samples from WHOTS-4 and -5 were stored and measured after the cruise in the laboratory at the UH using a Guildline Autosal 8400B. International Association for Physical Sciences of the Ocean (IAPSO) standard seawater samples were measured to standardize the Autosal, and samples from a large batch of “secondary standard” (substandard) seawater were measured after every 24 bottle samples of each cruise to detect drift in the Autosal. Standard deviations of the secondary standard measurements were less than ± 0.001 for the WHOTS-4 and -5 cruises (Table 4-6).

The substandard water was collected during HOT cruises from 1000 m at station ALOHA and drained into a 50-liter Nalgene plastic carboy. In the laboratory, the water was then thoroughly mixed in a glass carboy for 20 minutes, after which a 2-inch protective layer of white oil was added on top to deter evaporation. The substandard water was allowed to stand for approximately three days before it was used, and was stored in the same temperature controlled room as the Autosal, protecting it from the light with black plastic bags to prevent algae growth. Substandard seawater batches #39, #41 and #43 were prepared on 7 April 2006, 8 May 2007, and 2 May 2008 respectively and used for WHOTS-4 and -5 samples respectively. The substandard statistics in Table 4-6 include all the substandard samples measured.

Table 4-6 Precision of salinity measurements using secondary lab standards.

Cruise	Mean Salinity +/- SD	# Samples	Substandard Batch #	IAPSO Batch #
WHOTS-4	34.4756 +/- 0.00035	6	41	P146
WHOTS-5	34.4938 +/- 0.00035	7	43	P148

C. Thermosalinograph data acquisition and processing

1. WHOTS-4 Cruise

Near-surface temperature and salinity data for the WHOTS-4 cruise were acquired through the use of a thermosalinograph system aboard the R/V *Kilo Moana*. The system was comprised of a SBE-38 remote temperature sensor (#0150) located at the seawater intake situated 8 meters below the sea surface in conjunction with a SBE-21 thermosalinograph sensor (#3167) situated in the IMET lab close to the port bow of the ship.

Data were acquired every 10 seconds for the duration of the cruise and salinity samples were taken periodically throughout the cruise for calibration from an outlet in the flowthrough system located less than 1 m from the SBE-21.

Temperature Calibration

Data from the SBE-38 remote temperature sensor were used to measure temperature at the seawater intake, with an offset correction applied after comparing it with the 8 dbar CTD temperature data. This sensor was last calibrated at Sea-Bird on 11 January 2007.

Nominal Conductivity Calibration

Sea-Bird conductivity sensor #3167 was calibrated at Sea-Bird on 20 December 2006. All conductivity data from the thermosalinograph were converted with coefficients obtained from this calibration. However, all the final salinity data reported here were calibrated against bottle data as explained below.

Data Processing

The logger used to add the ship's speed and position data into the thermosalinograph data stream was not working for this cruise. Hence, navigation data from the ship's GPS system were concatenated and the relevant fields output in a format similar to that used in thermosalinograph data collected during HOT cruises. The thermosalinograph data were then screened for gross errors, with upper and lower bounds of 18 °C and 35 °C for temperature and 3 Siemens m^{-1} and 6 Siemens m^{-1} for conductivity. There were no points outside the valid temperature and conductivity ranges and no gross errors detected.

A 5-point running median filter was used to detect one or two point temperature and conductivity glitches in the thermosalinograph data. Glitches in temperature and conductivity detected by the 5-point median filter were immediately replaced by the median. Threshold values of 0.3 °C for temperature and 0.1 Siemens m^{-1} for conductivity were used for the median filter. One conductivity point was replaced after running the median filter. A 3-point triangular running mean filter was used to smooth the temperature and conductivity data after passing the glitch detection.

The thermosalinograph aboard the R/V *Kilo Moana* was set to record data every 10 seconds, but occasionally, due to an error in the acquisition software rounding routine, a record is written at a longer interval. There were 54 timing errors in total, all around 11 seconds.

Bottle Salinity and CTD Salinity Comparisons

The thermosalinograph salinity was calibrated by comparing it to bottle salinity samples drawn from a water intake next to the thermosalinograph. Sixteen salinity samples were collected and analyzed as described in Section 4.B.1. The comparison was made in conductivity in order to eliminate the effects of temperature. The conductivity of the bottle was computed using the salinity of the bottle, thermosalinograph temperature and a pressure of 6 dbar, which includes the pressure of the pump.

Salinity samples were drawn from the flowthrough system, located less than 1 m from the SBE-21 and consequently there should be virtually no delay between when the water passes through the thermosalinograph and it being sampled. Thermosalinograph data were extracted within a 60 second window around the bottle sample time minus a 10 second delay (in order to try and incorporate the reading recorded just prior to bottle sampling). The 30 second mean, centered 10 seconds before the bottle sample time was chosen for processing purposes.

In order to make the comparison in conductivity units, the CTD conductivity was calculated using the 4 dbar downcast CTD salinity, the internal thermosalinograph temperature, and a pressure of 6 dbar. There were 17 casts conducted while the thermosalinograph was running.

A cubic spline was fit to the time series of the differences between the bottle and thermosalinograph conductivity and a correction was obtained for the thermosalinograph conductivities. Salinity was calculated using these corrected conductivities, the thermosalinograph temperatures, and 6-dbar pressure. After correction, the mean difference between the bottle and thermosalinograph salinities was 0.0000 with a standard deviation of 0.001. The mean CTD - thermosalinograph difference was -0.0002 with a standard deviation of 0.001.

CTD Temperature Comparisons

There were 16 CTD casts conducted during the WHOTS-4 cruise. The 8 dbar CTD temperature data were used to compare with the remote temperature sensor. The mean difference between the CTD and the remote temperature sensor was found to be approximately –0.207 °C. Previous cruises aboard *R/V Kilo Moana* have shown similar temperature offsets as the seawater entering the ship's intake passes through a pump prior to the remote temperature sensor, which warms the water as it passes. An offset correction of -0.207 °C was applied to all the remote temperature sensor data, which were then flagged as uncalibrated data.

2. WHOTS-5 Cruise

Near-surface temperature and salinity data for the WHOTS-5 cruise were acquired through the use of a thermosalinograph system aboard the R/V *Kilo Moana*. The system was comprised of a SBE-38 remote temperature sensor (#0169) located at the seawater intake situated 8 meters below the sea surface in conjunction with a SBE-21 thermosalinograph sensor (#3292) situated in the IMET lab close to the port bow of the ship.

Data were acquired every 10 seconds for the duration of the cruise and salinity samples were taken periodically throughout the cruise for calibration from an outlet in the flowthrough system located less than 1 m from the SBE-21.

Temperature Calibration

Data from the SBE-38 remote temperature sensor were used to measure temperature at the seawater intake, with an offset correction applied after comparing it with the 8 dbar CTD temperature data. This sensor was last calibrated at Sea-Bird on 10 May 2007.

Nominal Conductivity Calibration

Sea-Bird conductivity sensor #3292 was calibrated at Sea-Bird on 11 November 2007. All conductivity data from the thermosalinograph were converted with coefficients obtained from this calibration. However, all the final salinity data reported here were calibrated against bottle data as explained below.

Data Processing

Navigation data (latitude, longitude and ship's speed) were recorded throughout the cruise every 10 seconds and were merged with the thermosalinograph data stream. The thermosalinograph data were then screened for gross errors, with upper and lower bounds of 18 °C and 35 °C for temperature and 3 Siemens m^{-1} and 6 Siemens m^{-1} for conductivity. There were no points outside the valid temperature and conductivity ranges and no gross errors detected.

A 5-point running median filter was used to detect one or two point temperature and conductivity glitches in the thermosalinograph data. Glitches in temperature and conductivity detected by the 5-point median filter were immediately replaced by the median. Threshold values of 0.3 °C for temperature and 0.1 Siemens m^{-1} for conductivity were used for the median filter. There were no points replaced by the 5-point median filter. A 3-point triangular running mean filter was used to smooth the temperature and conductivity data after passing the glitch detection.

The thermosalinograph aboard the R/V *Kilo Moana* was set to record data every 10 seconds. Previous cruises have occasionally shown errors in the acquisition software rounding routine, resulting in a record being written at a longer interval. There were no such timing errors for WHOTS-5.

Bottle Salinity and CTD Salinity Comparisons

The thermosalinograph salinity was calibrated by comparing it to bottle salinity samples drawn from a water intake next to the thermosalinograph. Twenty-three salinity samples were collected and analyzed as described in Section 4.B.1. The comparison was made in conductivity in order to eliminate the effects of temperature. The conductivity of the bottle was computed using the salinity of the bottle, thermosalinograph temperature and a pressure of 6 dbar, which includes the pressure of the pump.

Salinity samples were drawn from the flowthrough system, located less than 1 m from the SBE-21 and consequently there should be virtually no delay between when the water passes through the thermosalinograph and it being sampled. Thermosalinograph data were extracted within a 60 second window around the bottle sample time minus a 10 second delay (in order to try and incorporate the reading recorded just prior to bottle sampling). The 30 second mean, centered 10 seconds before the bottle sample time was chosen for processing purposes.

In order to make the comparison in conductivity units, the CTD conductivity was calculated using the 8 dbar downcast CTD salinity, the internal thermosalinograph temperature, and a pressure of 6 dbar. There were 15 casts conducted while the thermosalinograph was running.

A cubic spline was fit to the time series of the differences between the bottle and thermosalinograph conductivity and a correction was obtained for the thermosalinograph conductivities. Salinity was calculated using these corrected conductivities, the thermosalinograph temperatures, and 6-dbar pressure. After correction, the mean difference between the bottle and thermosalinograph salinities was 0.0000 with a standard deviation of 0.002. The mean CTD - thermosalinograph difference was -0.0005 with a standard deviation of 0.001.

CTD Temperature Comparisons

There were 15 CTD casts conducted during the WHOTS-5 cruise. The 8 dbar CTD temperature data were used to compare with the remote temperature sensor. The mean difference between the CTD and the remote temperature sensor was found to be approximately –0.296 °C. Previous cruises aboard *R/V Kilo Moana* have shown similar temperature offsets as the seawater entering the ship's intake passes through a pump prior to the remote temperature sensor, which warms the water as it passes. An offset correction of -0.296 °C was applied to all the remote temperature sensor data, which were then flagged as uncalibrated data.

D. Shipboard ADCP

1. WHOTS-4 Cruise

ADCP data from the *R/V Kilo Moana* were collected and preliminary processed real-time using the University of Hawaii's CODAS processing system. Post processing of the data, including heading correction and despiking, was performed at UH. The ADCPs operated for the entirety of the cruise (with the exception of the Broad Band 38 kHz) and the file start and end times are shown in Table 4-7.

Table 4-7 ADCP record times (UTC) for the Broad Band 38 kHz, Narrow Band 38 kHz and Workhorse 300 kHz ADCPs during the WHOTS-4 cruise.

WHOTS-4	**BB38**	**NB38**	**WH300**
File beginning time	27-June-2007 13:58	24-June-2007 22:12	24-June-2007 22:12
File ending time	01-July-2007 19:31	01-July-2007 19:31	01-July-2007 19:31

2. WHOTS-5 Cruise

ADCP data from the *R/V Kilo Moana* were collected and processed similar to WHOTS-4. The ADCPs operated for the entirety of the cruise and the file start and end times are shown in Table 4-8.

Table 4-8. ADCP record times (UTC) for the Broad Band 38 kHz, Narrow Band 38 kHz and Workhorse 300 kHz ADCPs during the WHOTS-4 cruise.

WHOTS-5	**BB38**	**NB38**	**WH300**
File beginning time	04-June-2008 01:50	04-June-2008 01:50	04-June-2008 01:47
File ending time	11-June-2007 16:57	11-June-2008 16:57	11-June-2008 16:59

5. Moored Instrument Observations.

A. MicroCAT data processing procedures

The MicroCATs temperature, conductivity and pressure sensors (when available) were calibrated at Sea-Bird prior to their respective deployments on the dates shown in Table 5-1. The internally recorded data from each instrument were retrieved on board of the ship after the mooring recovery, and the nominally calibrated data were plotted for a visual assessment of the data quality. The data processing included checking the internal clock data, pressure sensor drift correction, temperature sensor stability, and conductivity calibration against CTD data from casts conducted near the mooring during HOT cruises. The detailed processing procedures are described in this section.

Table 5-1. WHOTS--4 MicroCAT temperature sensor calibration dates, and sensor drift during deployments.

Sea-Bird Serial	**Pre-deployment calibration**	**Post-recovery calibration**	**Total Temperature drift during WHOTS deployment (m^{o}C)**
39-0716	1/29/2007	4/23/2009	-0.18
37SM485-1837	2/6/2007	4/22/2009	0.38
37SM485-1839	1/25/2007	1/31/2009	-0.43
37SM31486-2451	9/7/2006	7/31/2008	-1.30
37SM31486-2965	9/6/2006	7/31/2008	-1.50

37SM31486-3382	9/6/2006	7/31/2008	-1.13
37SM31486-3617	8/18/2006	7/31/2008	-1.09
37SM31486-3618	9/6/2006	7/31/2008	-1.13
37SM31486-3619	9/7/2006	7/31/2008	-1.55
37SM31486-3620	8/17/2006	8/1/2008	-1.02
37SM31486-3621	9/6/2006	8/1/2008	-0.94
37SM31486-3632	8/17/2006	8/1/2008	-1.21
37SM31486-3633	8/17/2006	8/1/2008	-1.09
37SM31486-3634	8/17/2006	8/6/2008	-1.70
37SM31486-3668	9/7/2006	8/1/2008	-1.83
37SM31486-3669	9/6/2006	8/6/2008	-1.64
37SM31486-3670	9/6/2006	8/1/2008	-1.66
37SM31486-3791	8/18/2006	8/1/2008	-0.99

1. Internal Clock Check and Missing Samples

Before each deployment and after each recovery (while data logging still ongoing), the SeaCATs and MicroCATs were placed in a cold freshwater bath to create a spike in the data, to check for any problem in the internal clocks, and for any missing samples (Table 3-1 and Table 3-2).

The cold freshwater spike was detected in the sensor's data by a sudden decrease in temperature and salinity. For almost all instruments, the clock time of this event matched correctly the time of the spike (within the sampling interval of each instrument).

2. Pressure Drift Correction and Pressure Variability

Some of the MicroCATs used in the moorings were outfitted with pressure sensors (Table 3-1). A bias was detected in the pressure sensors by comparing the on-deck pressure readings before deployment and after recovery. Table 5-2 shows the magnitude of the bias for each of the sensors before and after deployment. The pressure sensor for MicroCAT #2451 drifted and failed near the end of the deployment. The pressures were corrected due to the drift, and set to constant values near the end.

To correct instruments for the pre-deployment /post-recovery pressure offset, a linear fit between the initial and final on-deck pressure offset as a function of time was obtained, and subtracted from each sensor. Figure 5-1 shows the linearly corrected pressures measured by the MicroCATs during the deployment. For almost all sensors, the mean difference from the nominal instrument pressure (based on the deployed depth) was less than 1 dbar. The standard deviation of the pressure for the duration of the record was less than 1 dbar for all sensors, with the deeper sensors showing a larger standard deviation. The range of variability for all sensors was about ± 3 dbar, with some few extreme cases when the variability was near 5 dbar.

The causes of pressure variability can be several, including density variations; horizontal dynamic pressure (not only due to the currents, but also due to the motion of the mooring); mooring position, etc. The effect of the mooring position on the pressure measured by the sensors can be observed in Figure 5-2. These figures show the distance between the buoy and its anchor (calculated from the buoy’s Argos positions), as a function of pressure for each of the instruments. The red line in the plot is a quadratic fit to the median pressure calculated every 0.2 km distance bins. For the deep instruments, these plots show a decrease in pressure of about 1 dbar as the distance from the anchor increases. This pressure decrease is caused by the rising of the instruments when the mooring line deviates from its vertical position as it is being pulled by the anchor, and it is more noticeable for the sensors located deeper in the line.

Table 5-2. Pressure bias of MicroCATs with pressure sensors.

Deployment	**Depth (m)**	**Sea-Bird Serial #**	**Bias before deployment (dbar)**	**Bias after recovery (dbar)**
WHOTS-4	45	37SM31486-2965	0.03	-0.25
WHOTS-4	85	37SM31486-3670	-0.39	-0.55
WHOTS-4	105	37SM31486-3669	0.03	0.06
WHOTS-4	120	37SM31486-2451	0.23	-4.37
WHOTS-4	155	37SM31486-3668	-0.21	-0.29

A measure of the relative instrument vertical displacements with respect to each other is given by the differences between the sensor’s pressures. Figure 5-3 through Figure 5-5 show these differences for all the possible sensor pair combinations for each deployment. Scatter plots of the pressure between these same pairs of sensors give an indication of the relation between the sensors’ vertical displacements (Figure 5-6 and Figure 5-7).

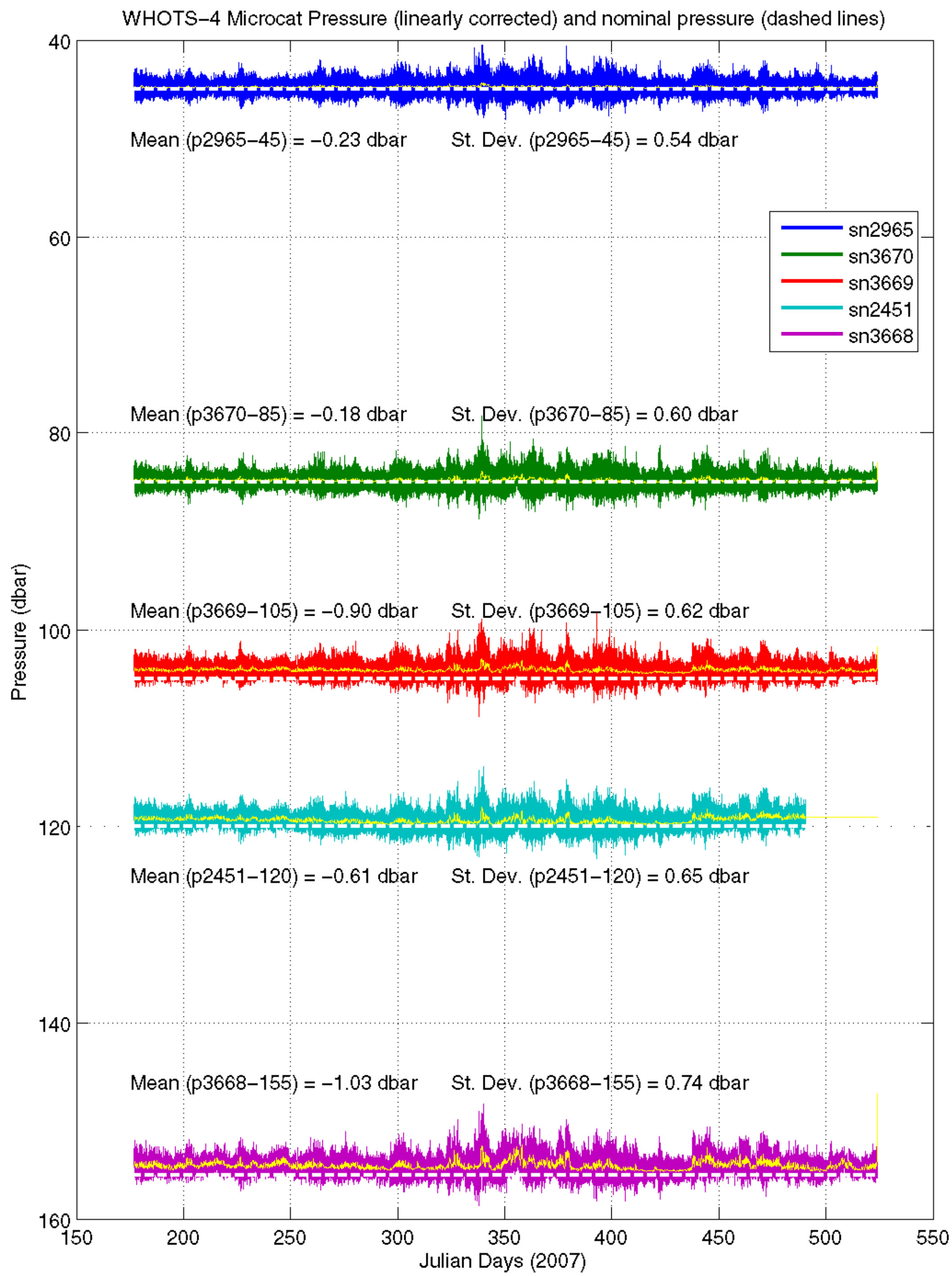


Figure 5-1. Linearly corrected pressures from MicroCATs during WHOTS-4 deployment. The yellow line is a 5-hour running mean. The horizontal dashed line is the sensor's nominal pressure, based on deployed depth.

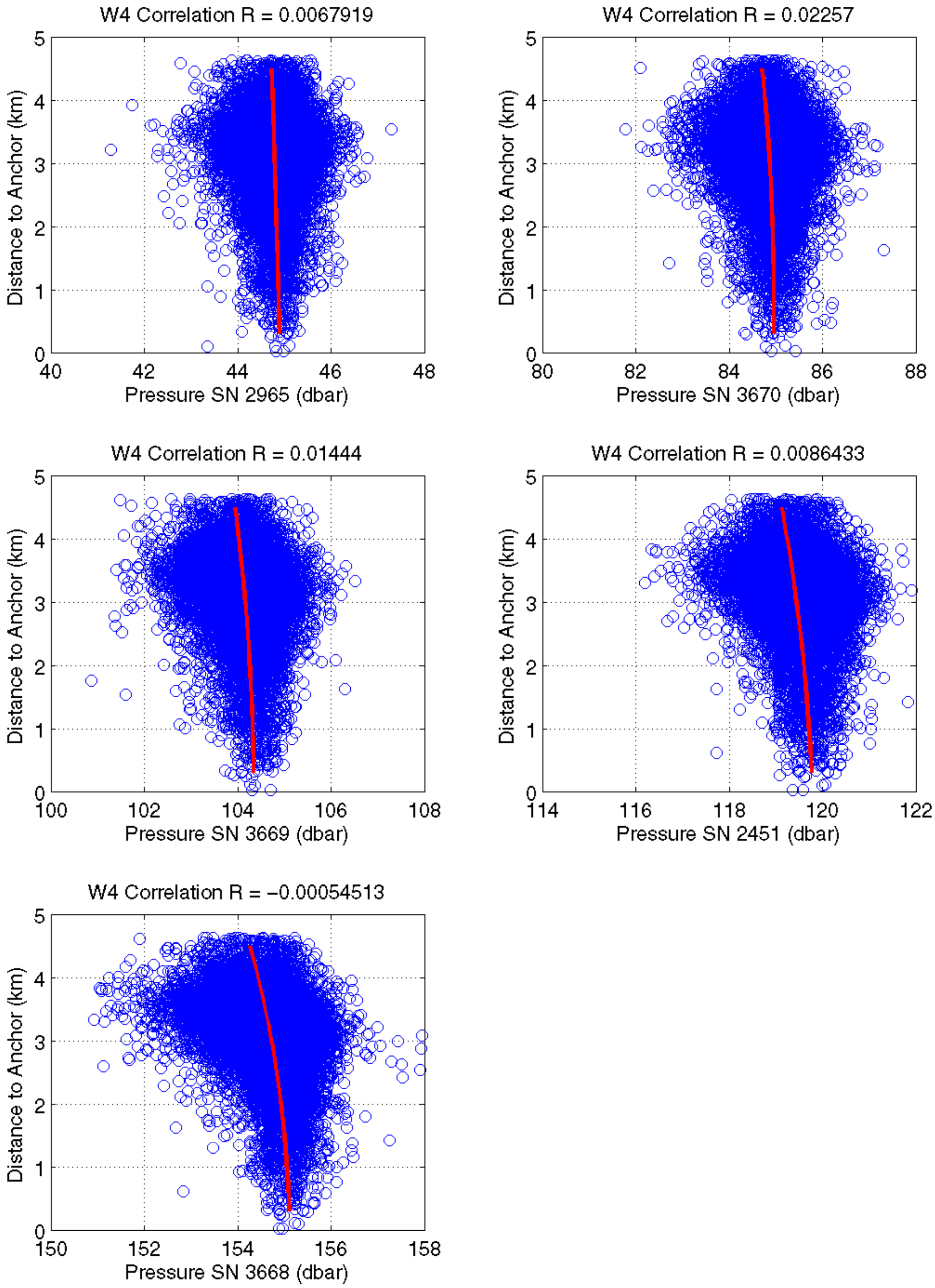


Figure 5-2. Scatter plots of the distance of the buoy to its anchor as a function of the pressure measured by each of the MicroCATs during WHOTS-4 (blue circles). The red line is a quadratic fit to the median pressure at each distance bin, for 0.2 km bins.

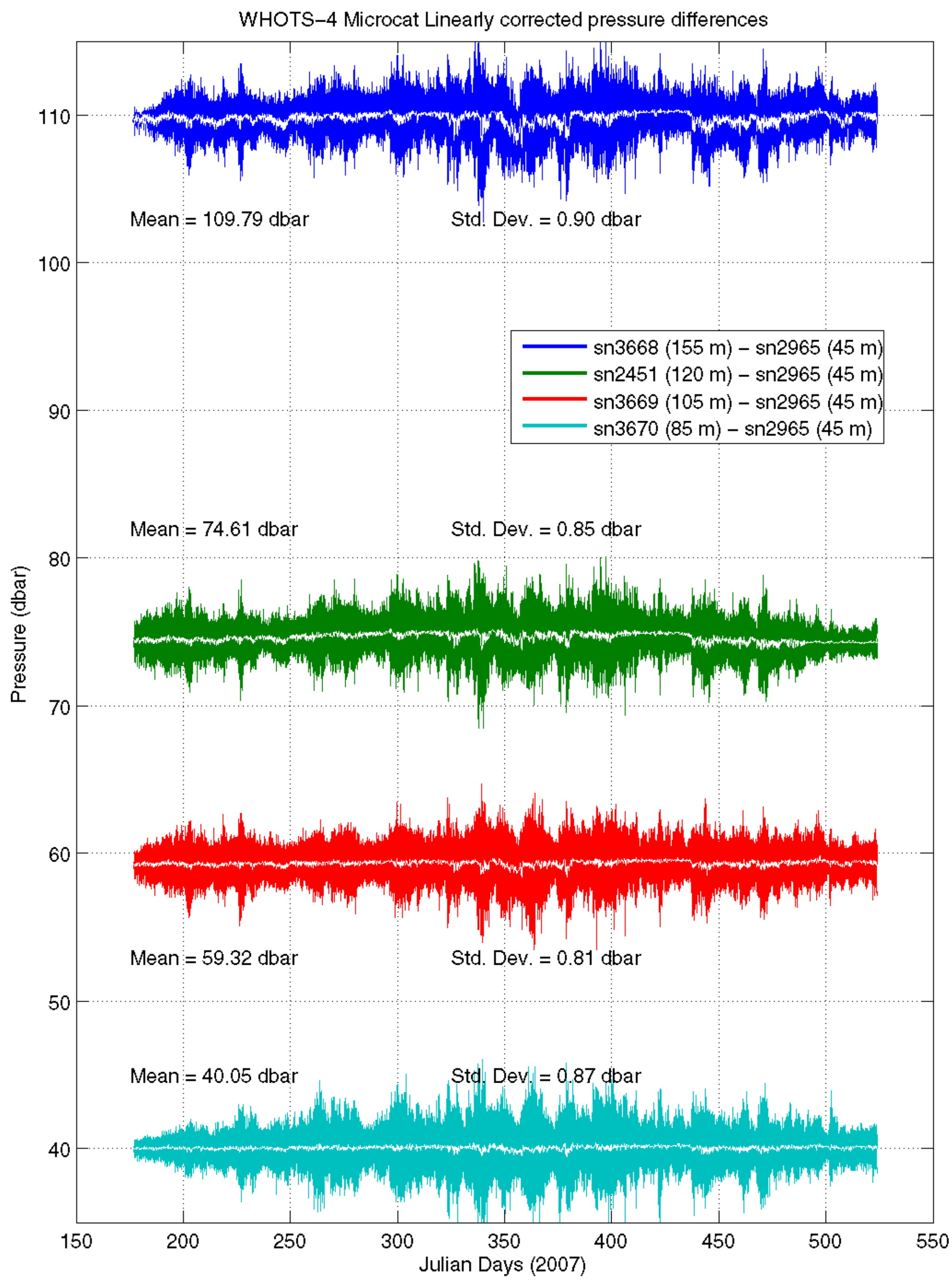


Figure 5-3. Pressure differences between MicroCATs with pressure sensors during WHOTS-4 deployment. The white line is a 5-hour running mean of the differences.

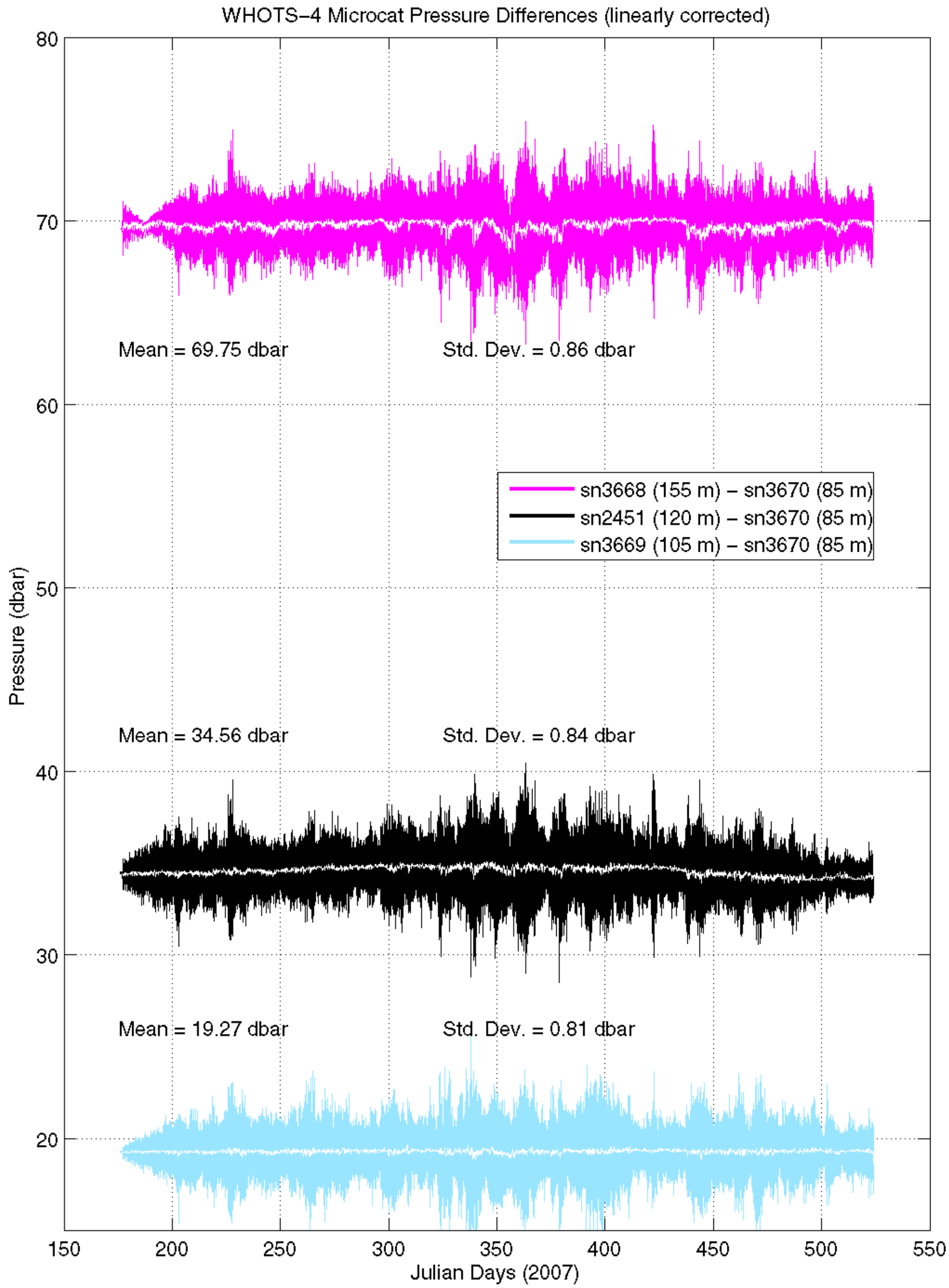


Figure 5-4. (Contd. from Figure 5-3.)

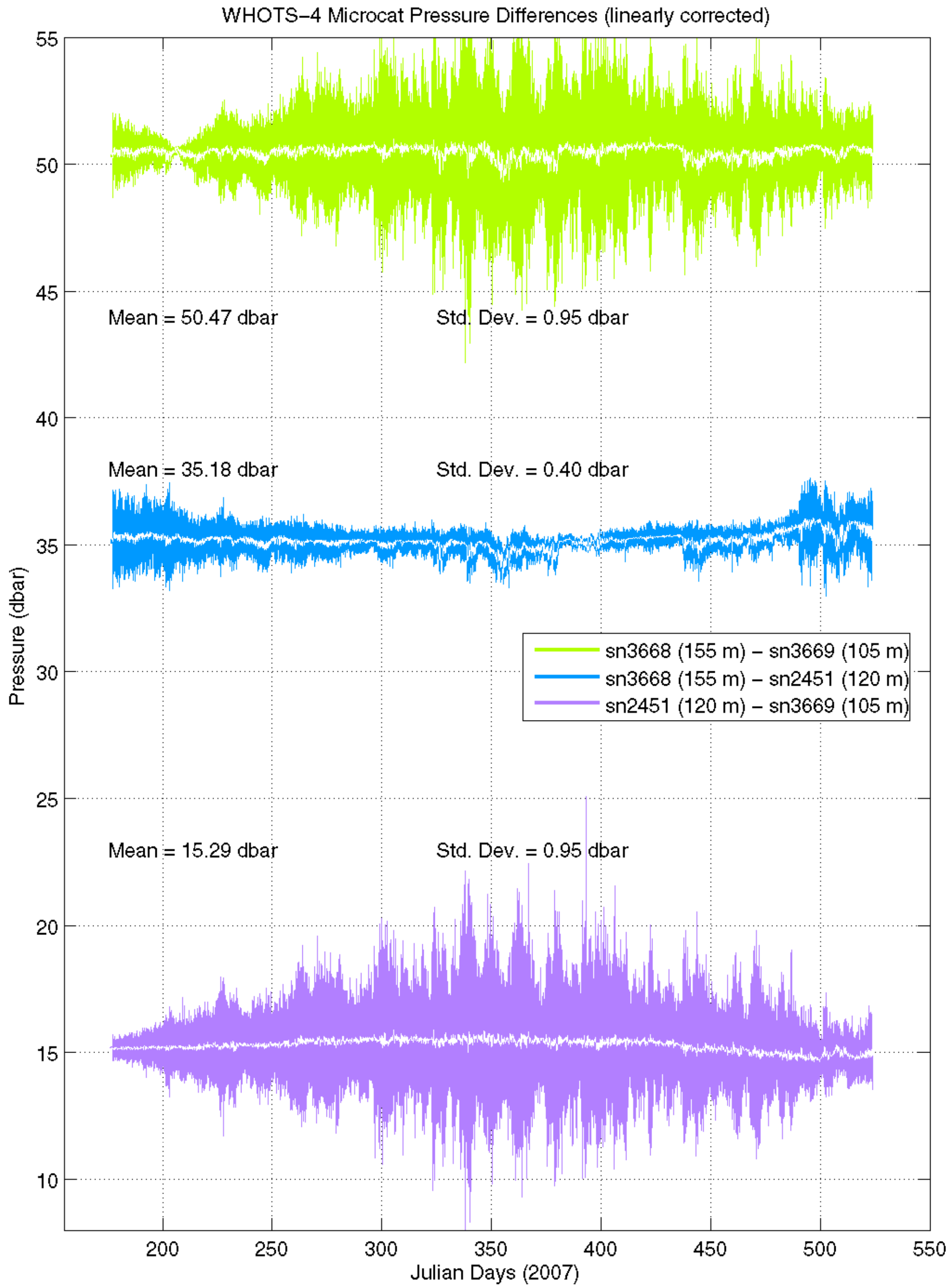


Figure 5-5. (Contd. from Figure 5-3)

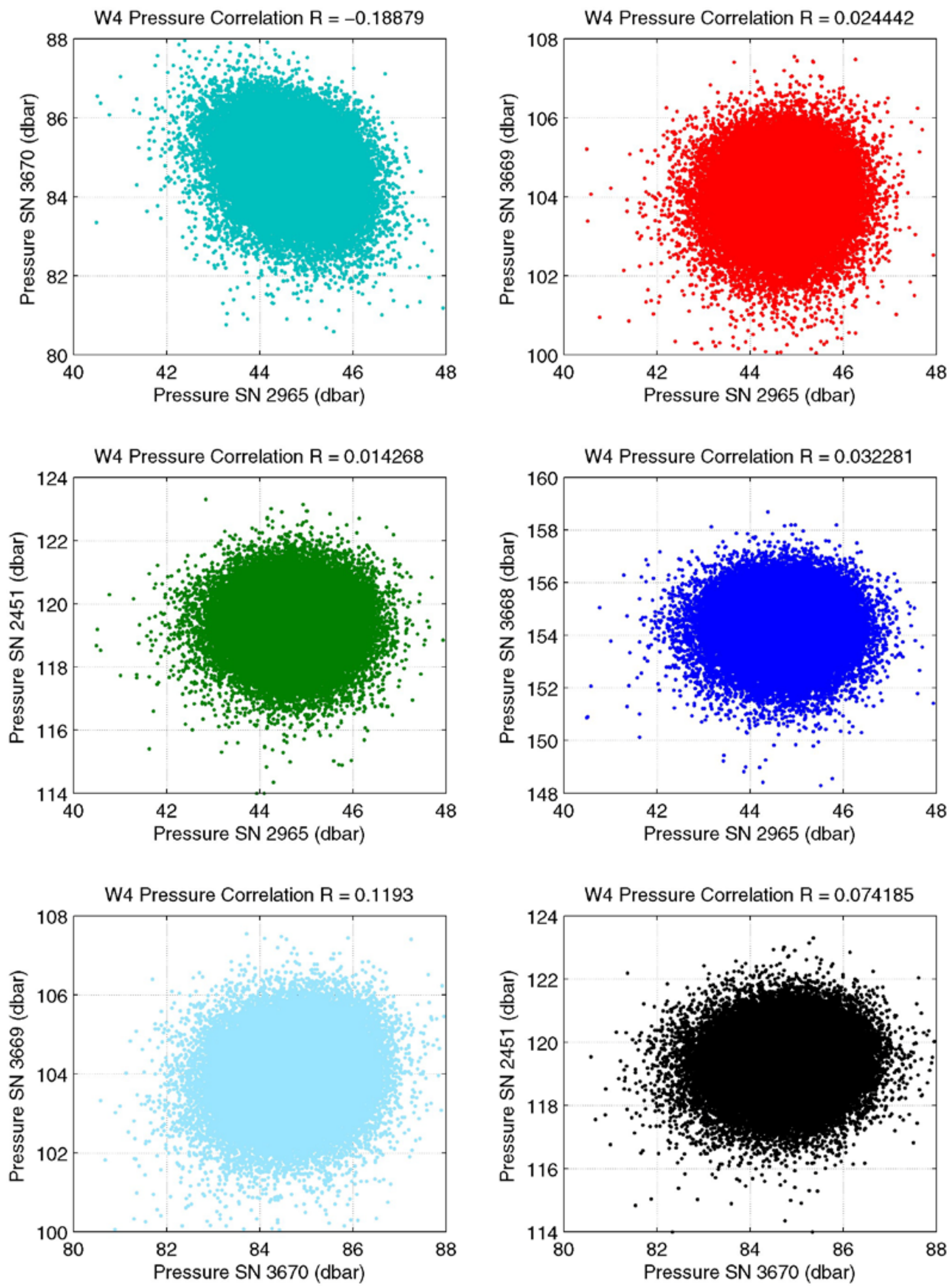


Figure 5-6. Scatter plot of pressure between MicroCATs during WHOTS-4 deployment.

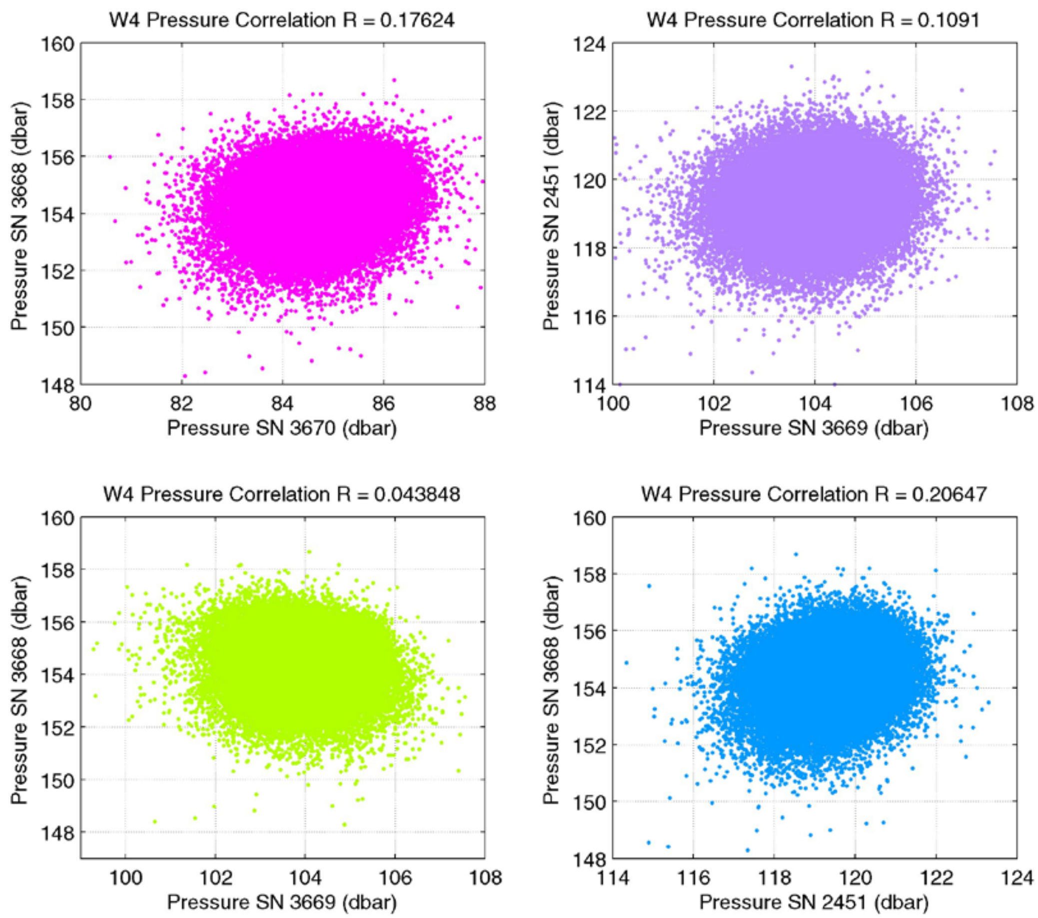


Figure 5-7. (Contd. from Figure 5-6)

3. Temperature Sensor Stability

The SeaCAT and MicroCAT temperature sensors were calibrated at Sea-Bird before and after each deployment, except for two instruments that did not function properly during deployment and post-deployment calibrations were not obtained due to either damage and/or infeasibility (see Table 5-1). Sea-Bird's evaluation of each sensor's drift was used to calculate the temperature offset for the duration of the deployment (Table 5-1). These values turned out to be insignificant (not higher than 0.0025 °C for all sensors), and no correction was applied to the data. Comparisons between the CTD and MicroCAT data from casts conducted near the mooring during HOT cruises confirmed that the temperature drift of the moored instruments was insignificant.

A temperature comparison between one of the WHOTS-4 near-surface MicroCATs (SN 1837) and the surface temperature sensor (SN 716) is shown in Figure 5-8. The comparison is shorter than the actual deployment time as the surface temperature sensor (SN 716) stopped recording data in December 2007. The WHOTS-4 comparison shows a mean surface temperature 0.02 °C lower than the near-surface temperature. In addition, the plots show various instances of large negative values of up to between -0.2 and -0.4 °C. This behavior was also observed during the WHOTS 1 and 2 deployments. These differences are caused by a decrease in the surface temperature. With the wave and buoy motions and wave breaking, the surface sensor may have measured temperatures from many different depths, including above the surface. Measuring the air temperature often enough could have biased the low temperatures registered by this sensor.

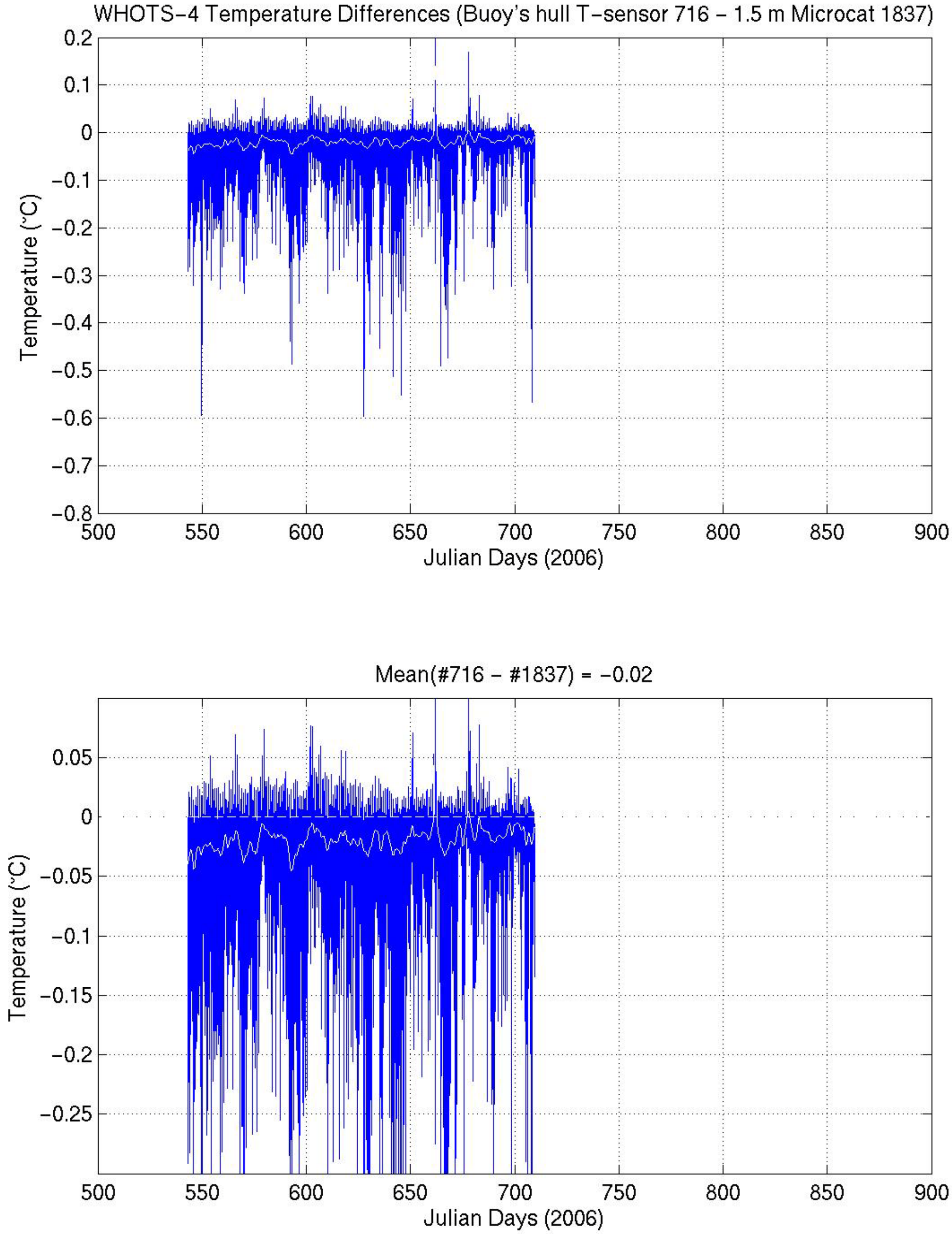


Figure 5-8. Temperature difference between MicroCAT SN 1837 at 1.5 m, and surface temperature sensor SN 716 during WHOTS-4 deployment (upper panel). The lower panel is a closer look at the same differences. The white line is a 24-hour running mean of the differences.

In addition to the temperature sensors in the Sea-Bird instruments, there were additional temperature sensors in the NGVMs (at 10 and 30 m), and in the ADCP (at 48.5 m and 125 m for WHOTS-4). In order to evaluate the quality of the temperatures from these sensors, comparisons with the temperatures from adjacent SeaCATs or MicroCATs were conducted.

WHOTS-4 NGVM and ADCP Temperature sensors stability

The upper panel of Figure 5-9 shows the difference between the 10-m NGVM and the 15-m MicroCAT temperatures during WHOTS-4. Also shown for comparison in the lower panel of the figure are the differences between MicroCAT temperatures at 15 and 25 m. The upper plot indicates a small, increasing offset (reaching about 0.004 ^{o}C) between the NGVM temperature sensor and the 15-m MicroCAT from the beginning of the deployment until about day 740. This offset can most likely be attributed to a drift in the NGVM temperature sensor as the differences between the 15 and 25 m MicroCATs do not show the same trend. After Day 740, it is possible that there is a shift in the NGVM temperature offset but the signal is masked within apparent stratification.

Temperature differences between the 30-m NGVM and the temperatures from adjacent MicroCATs at 25 and 35-m during WHOTS-4 are shown in Figure 5-10. For comparison, the differences between the MicroCATs temperatures are also shown. These plots indicate that there was a small, decreasing offset (less than 0.01 °C) in the NGVM with respect to the adjacent MicroCATs (see top and middle plots). This is particularly obvious during the long period when a relatively well-mixed layer was present from around days 625 through 775. During this period the MicroCATs temperature differences between 25 and 35 m (bottom panel) show a running mean of temperature differences fluctuating around the zero line, while the running mean of the differences between the MicroCATs and the NGVM show a 0.005 °C offset that gradually decreases.

Temperature differences between the 48.5-m ADCP and the temperatures from adjacent MicroCATs at 45 and 50-m during WHOTS-4 are shown in Figure 5-11. For comparison, the differences between the MicroCATs are also shown. The ADCP differences appear to be centered near zero when compared to the MicroCATs. However, there are periods when the ADCP appears to be recording temperatures warmer than the 45-m MicroCAT as well as periods of time when it is recording temperatures colder than the 50-m MicroCAT. Neither condition should be as prevalent as shown given that the comparison between the 45 and 50-m MicroCATs rarely show such trends. Therefore these periods of time in the 48.5-m ADCP temperature record should be considered suspect.

Temperature differences between the 125-m ADCP and the temperatures from adjacent MicroCATs at 120 and 135-m during WHOTS-4 are shown in Figure 5-12. For comparison, the differences between the MicroCATs temperatures are also shown. It is difficult to assess the quality of the ADCP temperature from these comparisons, as these sensors were located at the top of the thermocline, where we expect to find large temperature differences between adjacent sensors. Unfortunately there does not appear to be any consistent periods when the mixed layer deepens close to the level of these instruments to make comparisons as performed with other deployments. However, the 125-m ADCP temperature seems to stay, on average, cooler than the 120-m MicroCAT and warmer than the 135 m MicroCAT which is at least one positive indication that the ADCP temperature sensor maintained some stability.

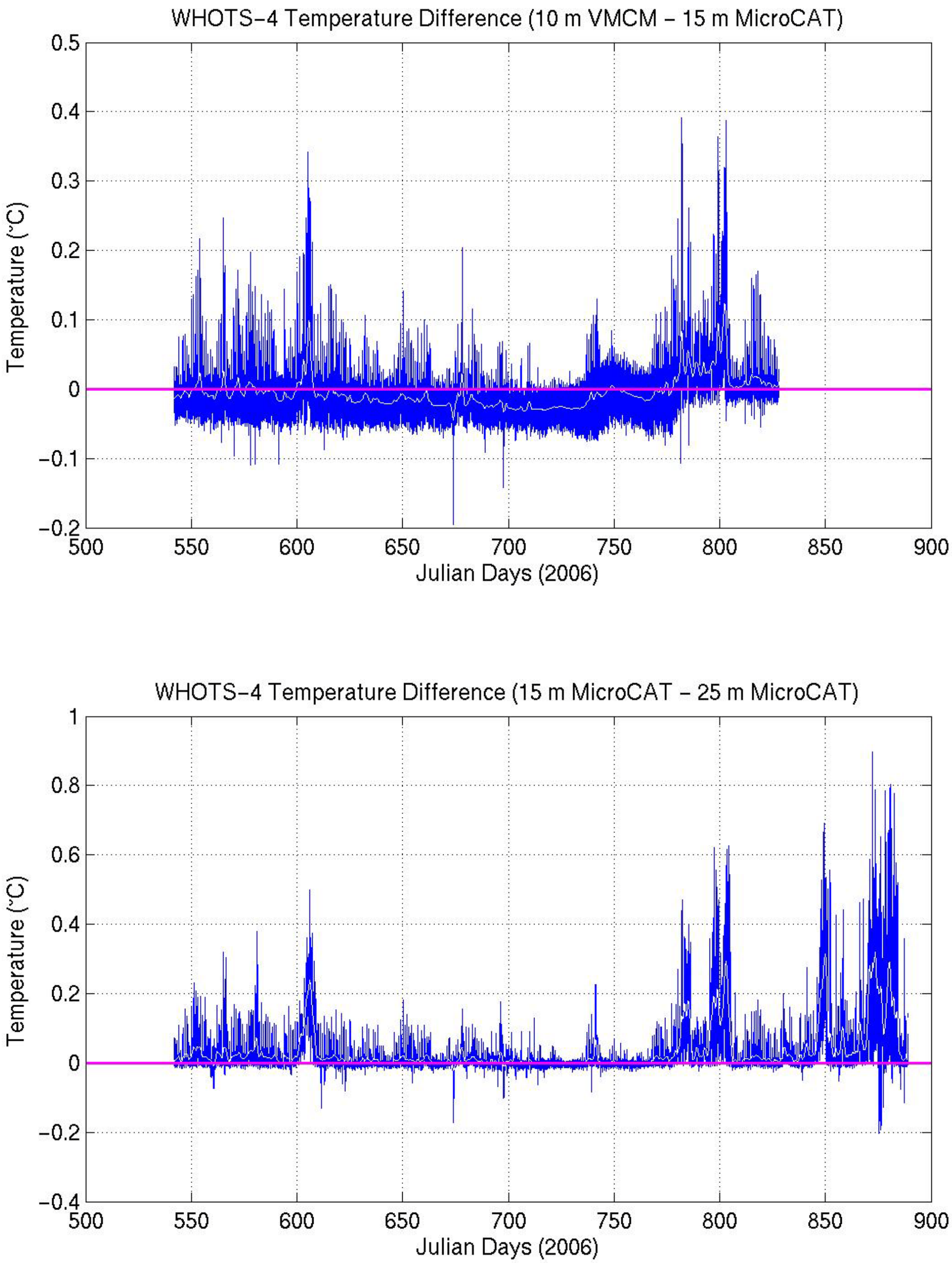


Figure 5-9. Temperature difference between the 10-m NGVM and the 15-m MicroCAT during the WHOTS-4 deployment (upper panel). Temperature difference between the 15-m MicroCAT and the 25-m MicroCAT during the WHOTS-4 deployment (lower panel). The white line is a 24-hour running mean of the differences.

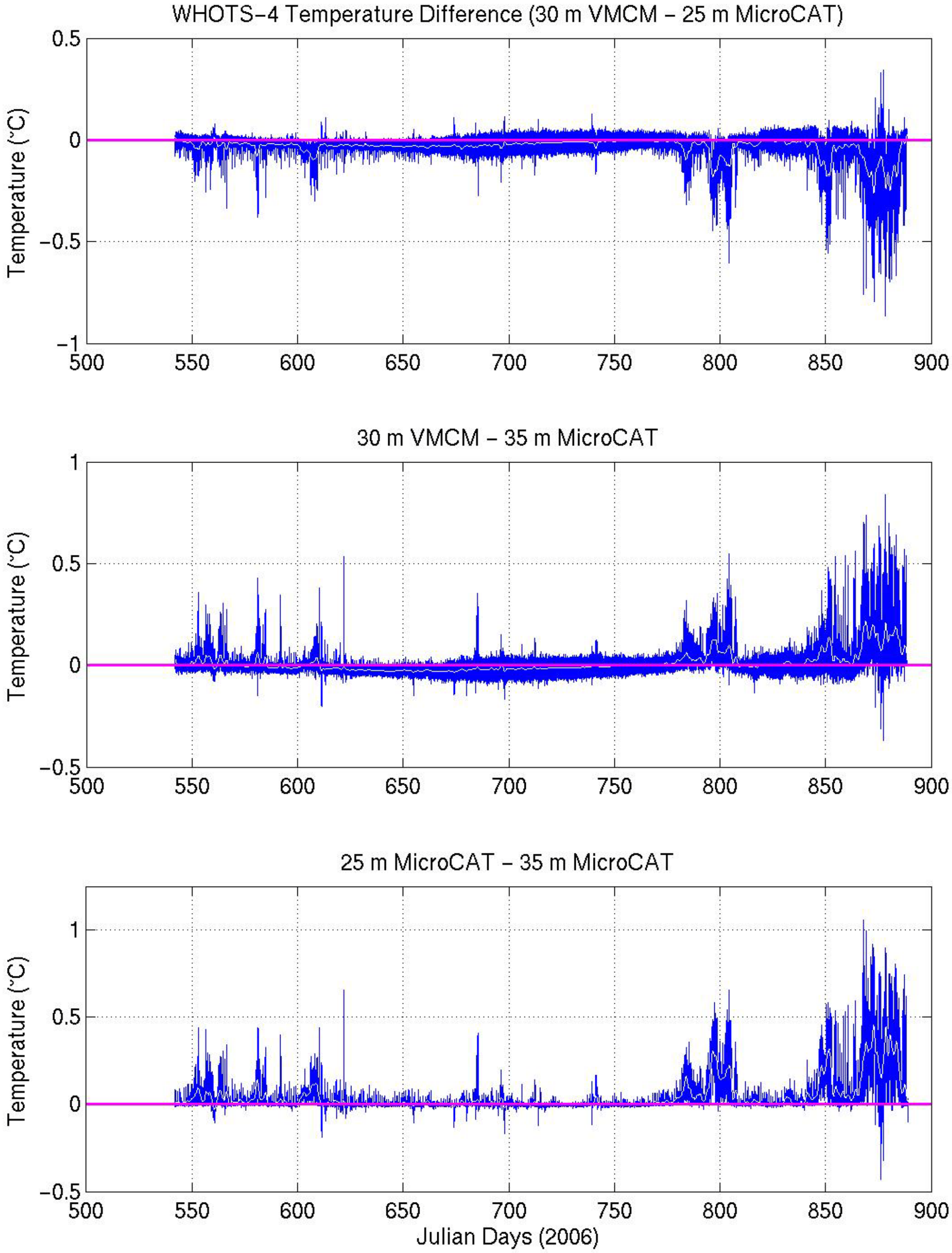


Figure 5-10. Temperature difference between the 30-m NGVM and the 25-m MicroCAT during the WHOTS-4 deployment (upper panel); between the 30-m NGVM and the 35-m MicroCAT (middle panel); and between the 25-m and the 35-m MicroCATs (lower panel). The white line is a 24-hour running mean of the differences.

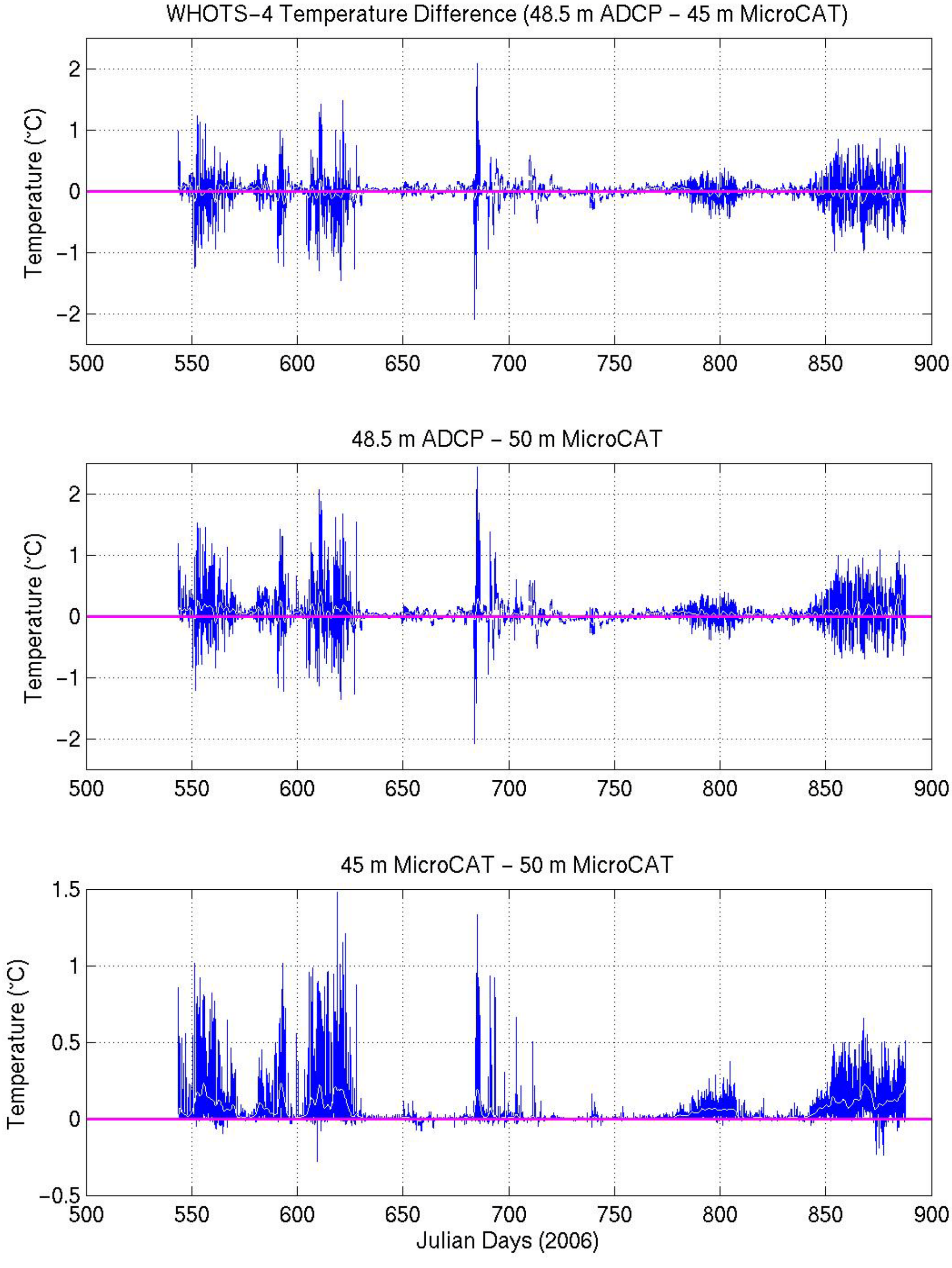


Figure 5-11. Temperature difference between the 48.5-m ADCP and the 45-m MicroCAT during the WHOTS-4 deployment (upper panel); between the 48.5-m ADCP and the 50-m MicroCAT (middle panel); and between the 45-m and the 50-m MicroCATs (lower panel). The white line is a 24-hour running mean of the differences.

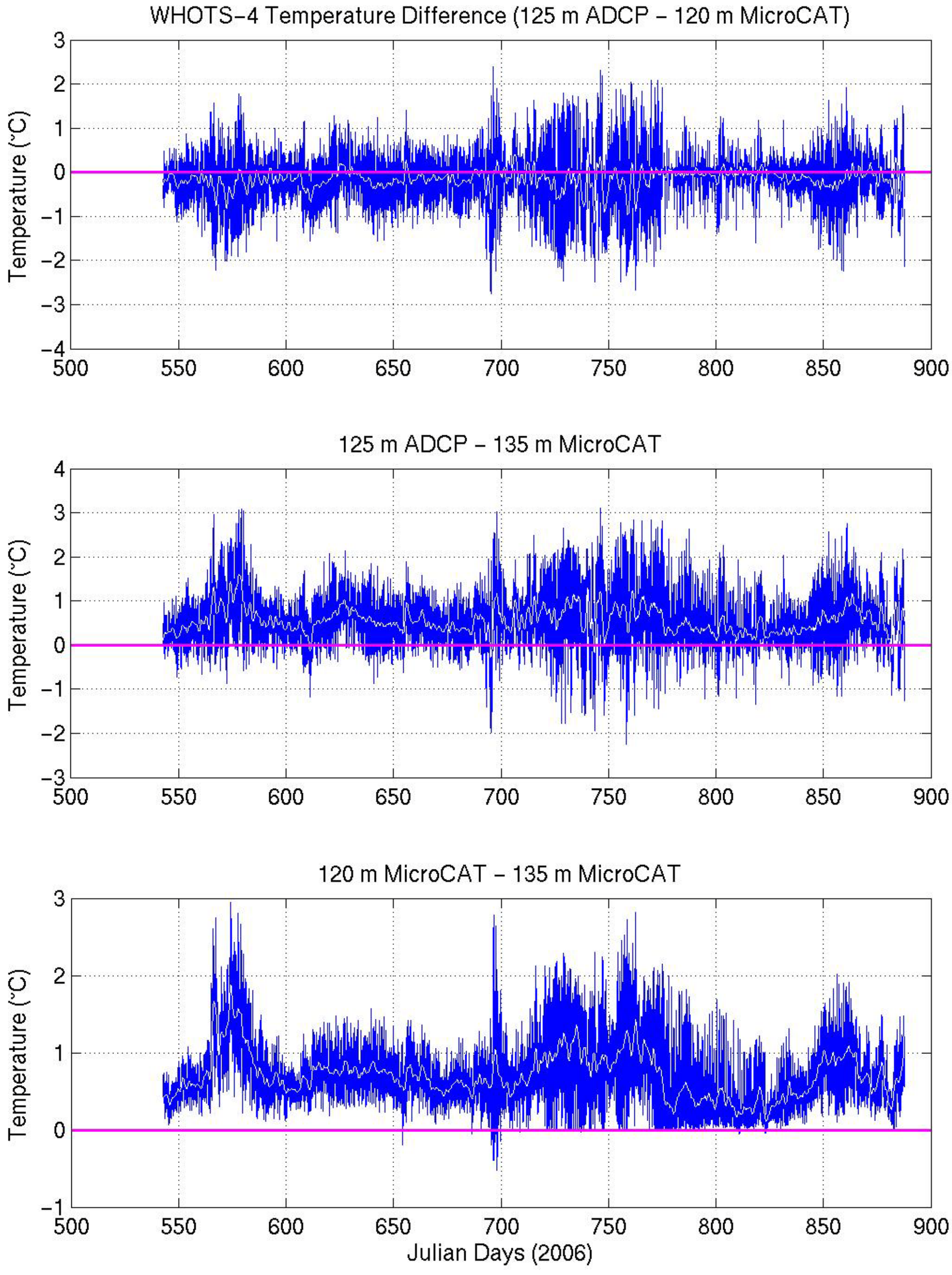


Figure 5-12. Temperature difference between the 125-m ADCP and the 120-m MicroCAT during the WHOTS-4 deployment (upper panel); between the 125-m ADCP and the 135-m MicroCAT (middle panel); and between the 120-m and the 135-m MicroCATs (lower panel). The white line is a 24-hour running mean of the differences.

4. Conductivity Calibration

The results of the Sea-Bird post-recovery conductivity calibrations indicated that some of the SeaCAT and MicroCAT sensors experienced relatively large offsets from their pre-deployment calibration. These were qualitatively confirmed by comparing the mooring data against CTD data from casts conducted near the mooring during HOT cruises, and also from the cross-calibration casts between the CTD and MicroCATs conducted after recovery. The causes of the conductivity offsets are not clear, and there may have been multiple causes. For some instruments the offset was positive, caused perhaps by biofouling of the conductivity cell while for others the offset was negative, caused possibly by scouring of the inside of the conductivity cell. Another characteristic of the offsets in the conductivity sensors is that their developments were not always linear in time.

Corrections of the conductivity data for the other SeaCATs and MicroCATs in the moorings were conducted by comparing them against CTD data from casts near the mooring, and from the cross-calibration casts between the CTD and MicroCATs. Casts conducted between 200 and 1000 m from the mooring were given extra weight in the correction, as compared to those conducted between 1 and 5 km away. Casts more than 5 km away from the mooring were not used. A quadratic fit to the CTD-MicroCAT/SeaCAT differences against time was applied for the majority of the sensors, and the corresponding correction was applied (see Figure 5-13). Some of the sensors had large offsets and/or obvious non-linear variability. For these sensors, a stepwise correction was applied using the differences between consecutive sensors to determine when this particular sensor started to drift, and matching the data to the available CTD cast data. For periods when the stratification was weak, the conductivity difference between some of the neighboring sensors was near zero because they were only between 5 and 20 m apart. These periods were used as a reference to determine instances of sudden drift.

As a final quality control of our conductivity corrections, the buoyancy frequency between neighboring instruments was calculated using finite differences. Incorrect conductivities yielded instabilities in the water column (negative buoyancy frequency) that were easy to detect and were obviously not real, and the conductivity correction of the corresponding sensors had to be revised. We also found out that this method of conductivity correction is more efficient when the deepest instruments are corrected first, and the correction is continued sequentially upwards toward the shallower instrument. Given that the deepest instruments are less likely to be affected by biofouling and the consequent sudden conductivity drift, the deep instruments serve as a good reference to find any possible malfunction in the shallower ones. The corrections applied to each of the conductivity sensors during WHOTS-4 can be seen in Figure 5-13.

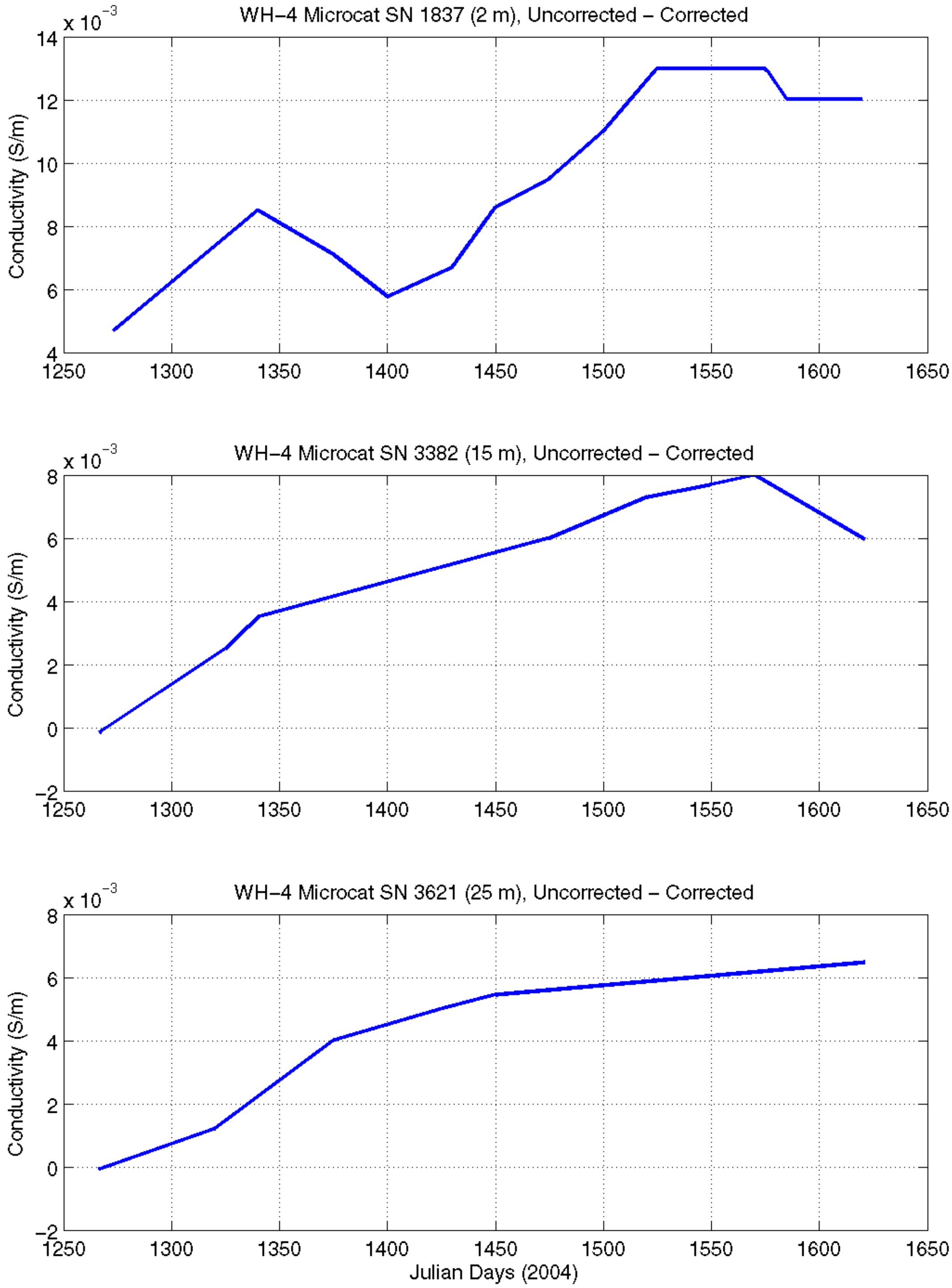


Figure 5-13. Conductivity sensor corrections for MicroCATs during WHOTS-4

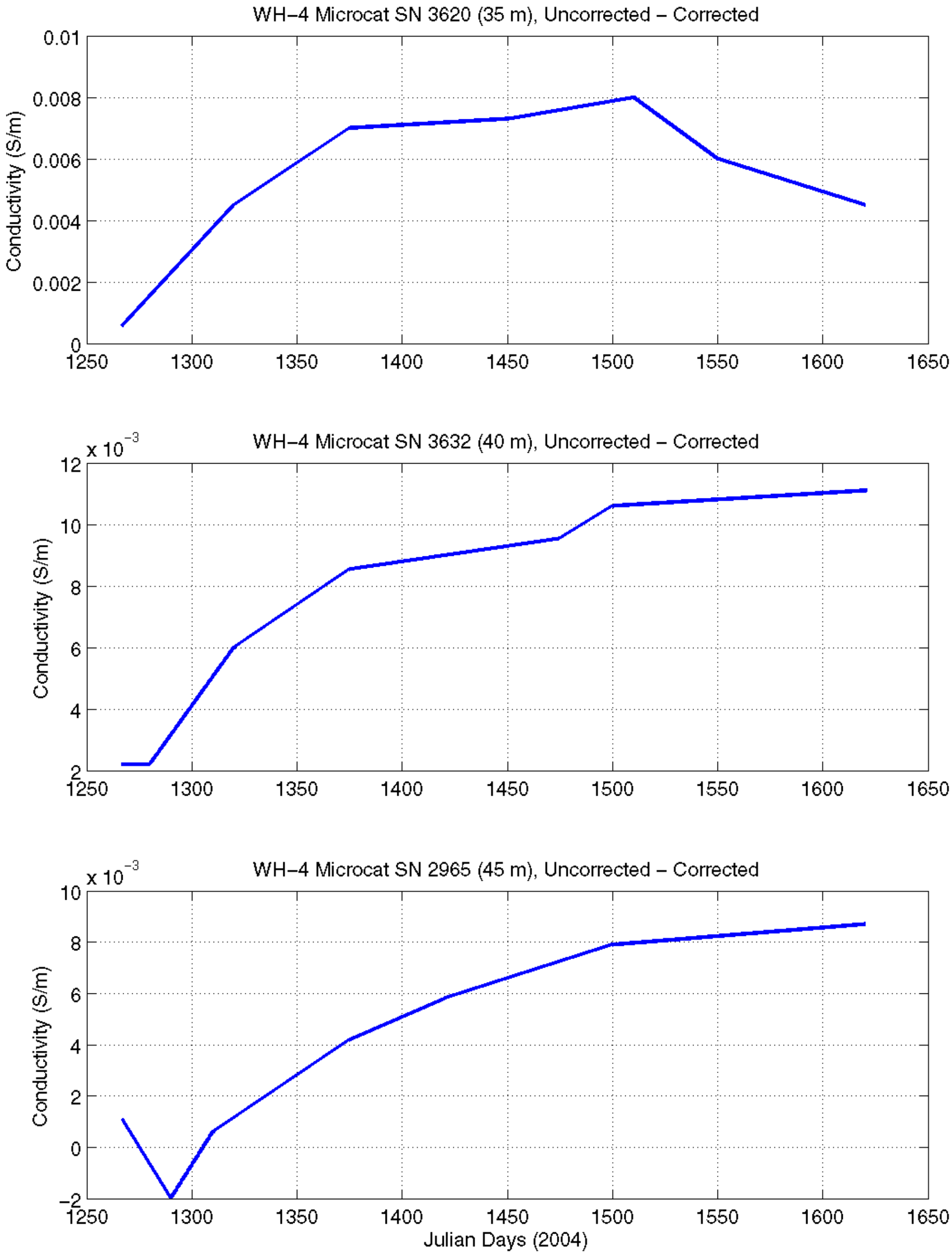


Figure 5-13 (Contd.)

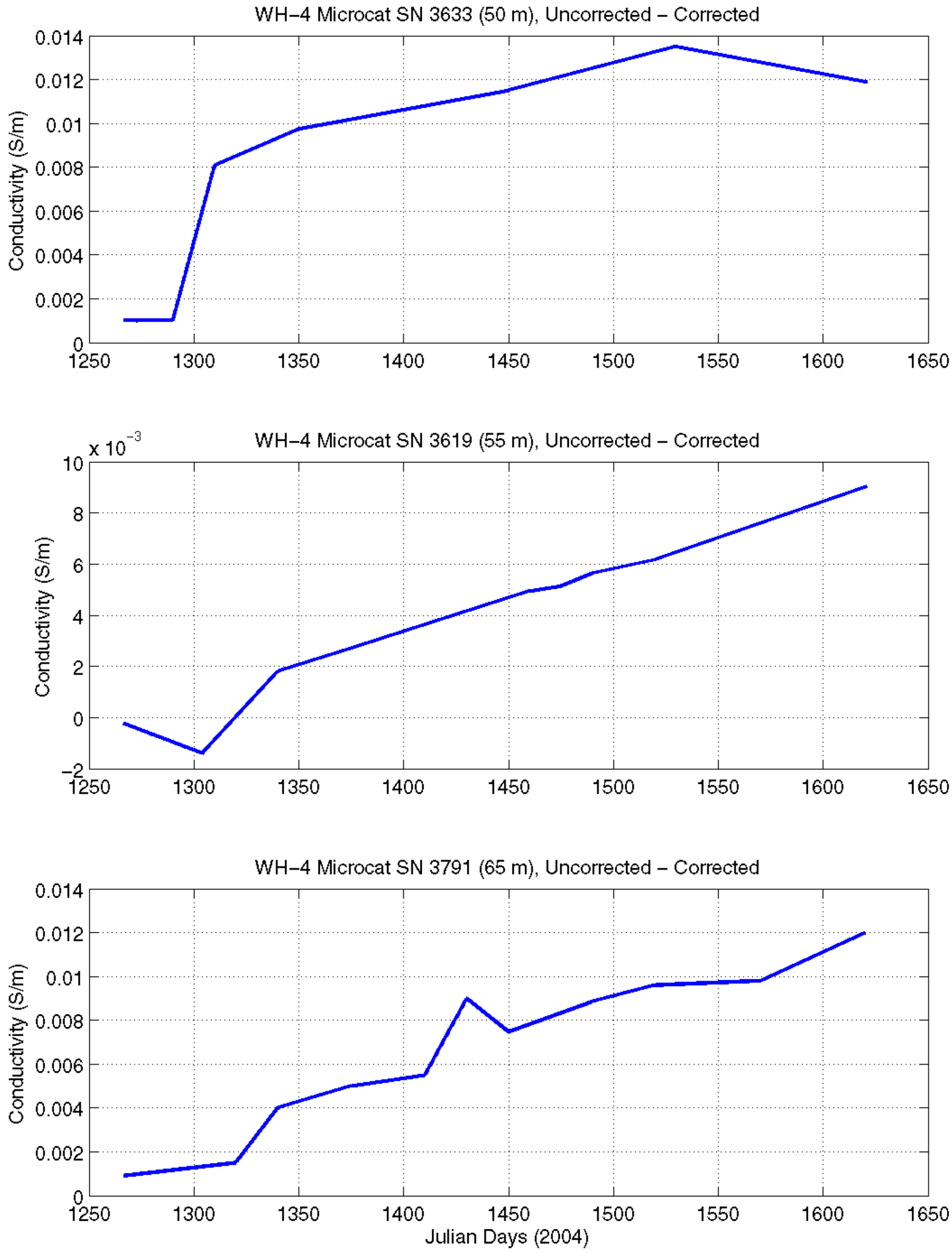


Figure 5-13 (Contd.)

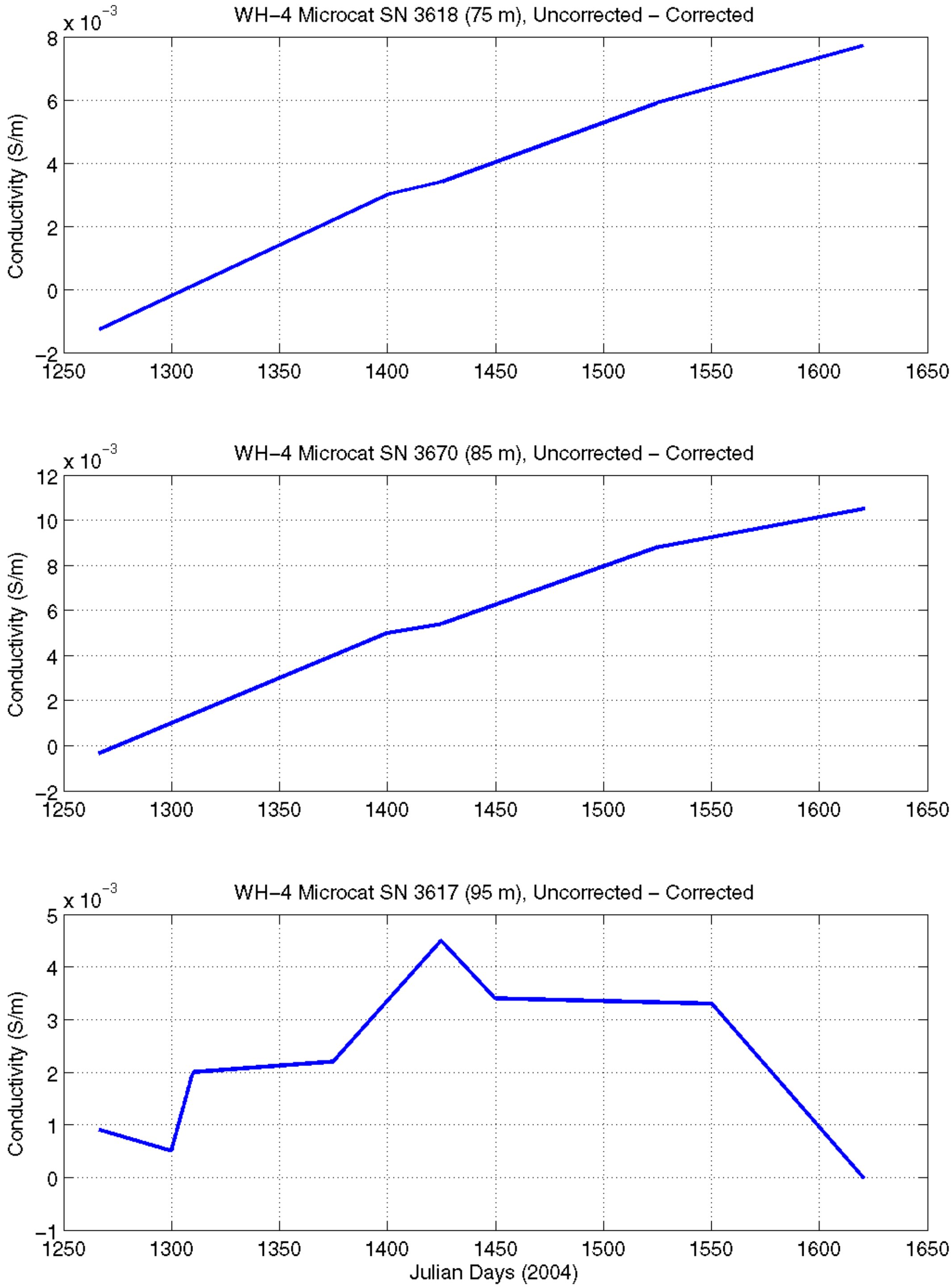


Figure 5-13 (Contd.)

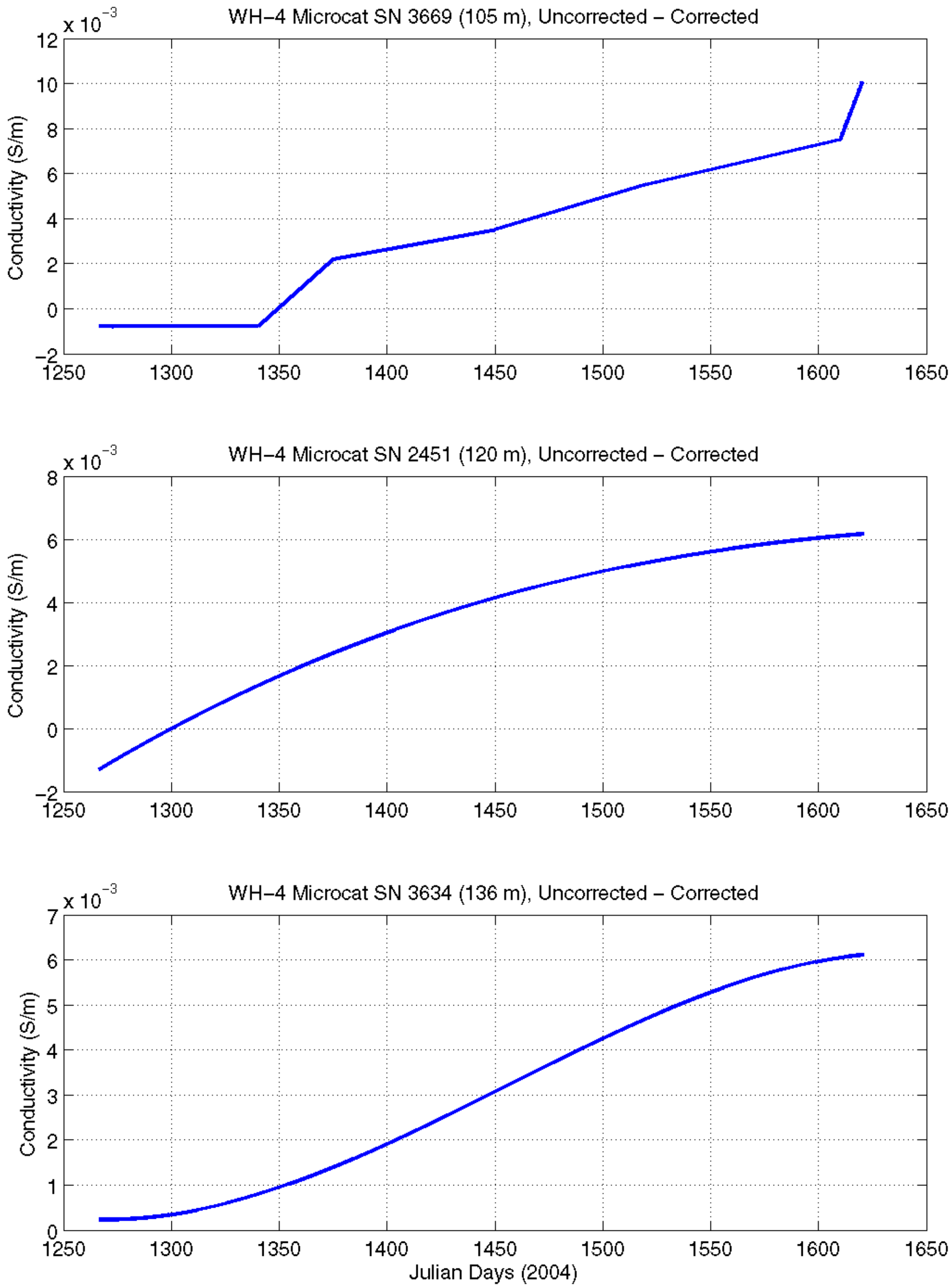


Figure 5-13 (Contd.)

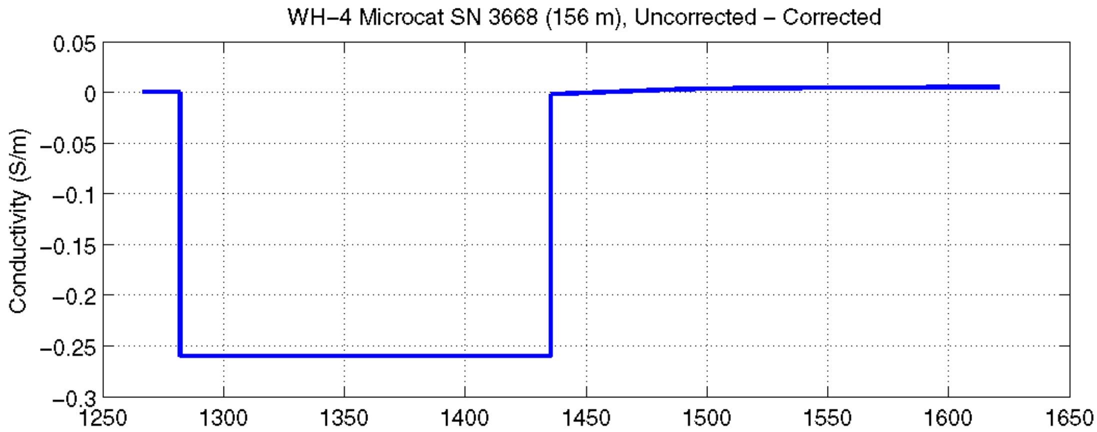


Figure 5-13 (Contd.)

B. Acoustic Doppler Current Profiler

A Teledyne/RD Instruments 307.2 kHz broadband Workhorse Sentinel ADCP was deployed in the upward looking configuration at 125 m depth on the WHOTS-4 mooring. The instrument was installed in an aluminum frame along with an external battery module to provide sufficient power for the intended period of deployment. The four ADCP beams were angled at 20° from the vertical line of the instrument. The 300 kHz ADCP was set to profile across 30 range cells of 4 m with the first bin centered 6.2 m from the transducer. The maximum range of the instrument was just short of 125 m. The specifications of the instrument are shown in Table 5-3.

Table 5-3 Specifications of the 300 kHz ADCP used for WHOTS -4 mooring.

Instrument	Description
ADCP	RDI Workhorse Sentinel, 300kHz Model: WHS300-I-UG86 Serial Number: 4891
Battery module	Model: 717-3001-00 SN:3169

An additional ADCP was installed during WHOTS-4. A Teledyne/RD Instruments 600 kHz broadband Workhorse Sentinel ADCP was provided by WHOI and deployed in the upward looking configuration at 48.5 m depth. The instrument was installed in an aluminum frame along with an external battery module to provide sufficient power for the intended period of deployment. The four ADCP beams were angled at 20° from the vertical line of the instrument. The 600 kHz ADCP was set to profile across 25 range cells of 2 m with the first bin centered 3.1 m from the transducer. The maximum range of the instrument was about 47 m. The specifications of the instrument are shown in Table 5-4.

Table 5-4. Specifications of the 600 kHz ADCP used for the WHOTS-4 mooring.

Instrument	Description
ADCP	RDI Workhorse Sentinel, 600kHz Model: WHS300-I-UG86 Serial Number:1825
Battery module	Model: WH-EXT-BCL SN:182

1. Compass Calibration

Prior to the WHOTS-4 deployment a field calibration of the internal 300 kHz ADCP compass was performed at Snug Harbor in Honolulu on 19 June 2007. The instrument was mounted in the deployment cage along with the external battery module and was located away from potential sources of magnetic field disturbances. Using the built-in calibration procedure, the instrument was tilted in one direction between 10 and 20 degrees and then rotated through 360 degrees at less than 5 ° /sec. The ADCP was then tilted in a different direction and a second rotation made. Based on the results from the first two rotations, calibration parameters are temporarily loaded and the instrument, tilted in a third direction is rotated once more to check the calibration. After the year-long deployment, an identical procedure is conducted to evaluate the drift in the internal compass. Results from the pre-deployment field calibration of the 300 kHz ADCP are shown in Table 5-5.

The 600 kHz ADCP was prepared and calibrated by WHOI. The post-deployment calibration check for this instrument was not conducted, but previous results from WHOTS mooring calibrations suggests that there is not significant compass drift over a yearlong deployment.

Table 5-5. Results from the WHOTS-4 pre and post-deployment ADCP (SN4891) compass field calibration procedure.

WHOTS-4		ADCP (s/n)	Single Cycle Error (°)	Double Cycle Error (°)	Largest Double + Single Cycle Error (°)	RMS of 3rd Order and Higher + Random Error (°)	**Overall Error** (°)	Pitch, Mean and St. Dev. (°)	Roll, Mean and St. Dev. (°)
Pre Deployment	**Before Calibration**	1825	prepared by WHOI						
		4891	4.32	0.18	4.50	0.17	**4.29**	1.07 ± 0.27	12.10 ± 0.29
	After Calibration	1825	prepared by WHOI						
		4891	0.31	0.44	0.75	0.17	**0.61**	0.16 ± 0.27	-10.07 ± 0.42
Post Deployment		1825	prepared by WHOI						
		4891	1.34	0.85	2.19	0.15	**1.72**	0.25 ± 0.34	-0.50 ± 0.25

Figure 5-14. Turntable used to test the performance of the internal compass of the ADCP SN4891 with external battery module installed.

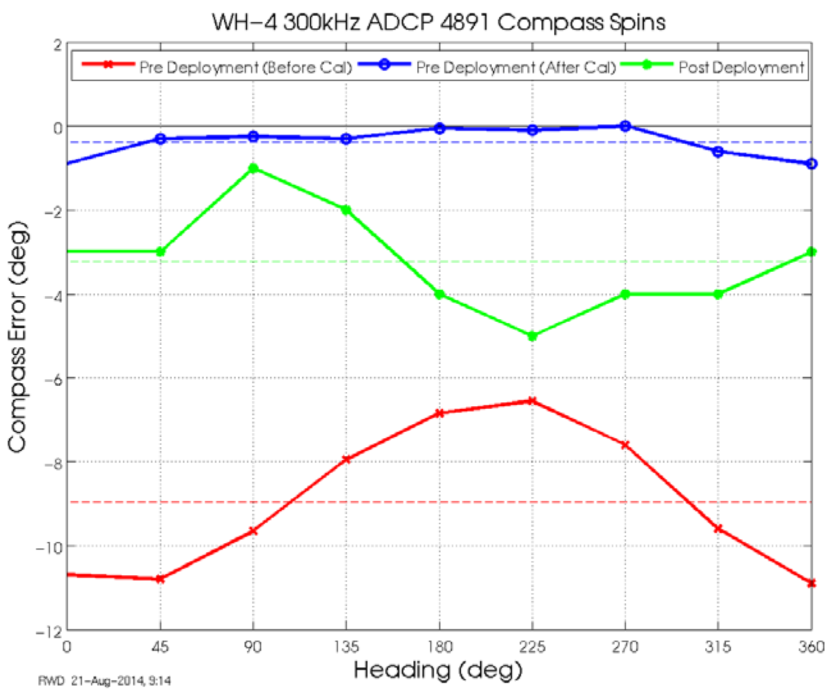


Figure 5-15. Results of the post cruise compass calibration conducted 19th July, 2006 on ADCP SN4891at Snug Harbor.

2. ADCP Configurations

Individual configurations for the two ADCP's on the WHOTS-4 mooring are detailed in Appendices 1 and 2. The salient differences for each of the ADCP's are summarized below.

300 kHz (125m)

The ADCP, set to a beam frequency of 300 kHz, was configured in a burst sampling mode consisting of 40 pings per ensemble in order to resolve low-frequency wave orbital motions. The interval between each ping was 4 seconds so the ensemble length was 160 seconds. The interval between ensembles was 10 minutes. Data were recorded in earth coordinates with a heading bias of 10.11° E used. False targets, usually fish, were screened by setting the threshold maximum to 70 counts. Velocity data were rejected if the difference in echo intensity among the four beams exceeded this threshold.

600 kHz (47.5m)

The ADCP, set to a beam frequency of 600 kHz, was configured in a burst sampling mode consisting of 80 pings per ensemble. The interval between each ping was 2 seconds so the ensemble length was also 160 seconds. The interval between ensembles was 10 minutes. Data were recorded in earth coordinates with a heading bias of 10.11° E used. The threshold maximum was also set to 70 counts. Velocity data were rejected if the difference in echo intensity among the four beams exceeded this threshold.

3. ADCP data processing procedures

Binary files output from the ADCP were read and converted to MATLAB™ binary files using scripts developed by Eric Firing's ADCP lab (http://current.soest.hawaii.edu). The beginning of the raw data files were truncated to a time after the mooring anchor was released in order to allow time for the anchor to reach the seabed and for the mooring motions that follow the impact of the anchor on the sea floor to dissipate. The pitch, roll, and ADCP temperature were examined in order to pick reasonable times that ensured good data quality but without unnecessarily discarding too much data (see Figure 5-16 and Figure 5-17). Truncation at the end of the data files were chosen to be the ensemble prior to the time that the acoustic release signal was sent to avoid contamination due to the ascent of the instrument. The times of the first ensemble from the raw data, deployment and recovery time, along with the times of the truncated records of both deployments are shown in Table 5-6.

Table 5-6. ADCP record times (UTC) during WHOTS-4 deployment.

	300 kHz	600 kHz
Raw file beginning and end times	27-Jul-2007 00:00:00 08-Jun-2008 04:40:00	18-Jun-2007 00:00:00 08-Jun-2008 06:15:00
Deployment and recovery times	25-Jul-2007 18:35 in water 25-Jul-2007 23:49 anchor over 06-Jun-2008 17:20 release triggered 06-Jun-2008 23:50 on deck	25-Jul-2007 16:54 in water 25-Jul-2007 23:49 anchor over 06-Jun-2008 17:20 release triggered 07-Jun-2008 00:22 on deck
Processed data beginning and end times	26-Jul-2009 12:00:00 06-Aug-2010 16:50:00	26-Jul-2009 12:00:00 06-Aug-2010 16:45:00

ADCP Clock Drift

Upon recovery, the ADCP clocks were compared with the ship's time server and the difference between the two was recorded. A difference of 9 minutes and 5 seconds (ahead of GMT) was observed with the 300 kHz (SN 4891) ADCP, while a difference of 3 minutes and 3 seconds (ahead of GMT) was observed with the 600 kHz ADCP. Since the drifts represents one ping from just one ensemble out of a total of over ~53,000, no corrections were made.

Heading Bias

As mentioned in the ADCP configuration section, the data were recorded in earth coordinates. A heading bias, the angle between magnetic north and true north, can be included in the setup to obtain output data in true earth coordinates. Magnetic variation was obtained from the National Geophysical Data Center 'Geomag' calculator. (http://www.ngdc.noaa.gov/seg/geomag). For a year-long deployment a constant value is acceptable because the change in declination is small, approximately -0.02° year^{-1} at the WHOTS location. A heading bias of 10.11E° was entered in the setup of the WHOTS-4 ADCP's.

Speed of sound

Due to the constant of proportionality between the Doppler shift and water speed, the speed of sound needs only be measured at the transducer head (Firing, 1991). The sound speed used by the ADCP is calculated using a constant value of salinity (35) and the temperature recorded by the transducer temperature sensor of the ADCP. Using CTD profiles close to the mooring during HOT cruises, HOT-193 to HOT-201, and from the WHOTS deployment/recovery cruises, the mean salinity at 125 dbar was 35.14 while the mean salinity at 47.5 dbar was 35.08. Mean ADCP temperature at 125 dbar was 22.25 °C and 24.98 °C at 47.5 dbar (Figure 5-18).

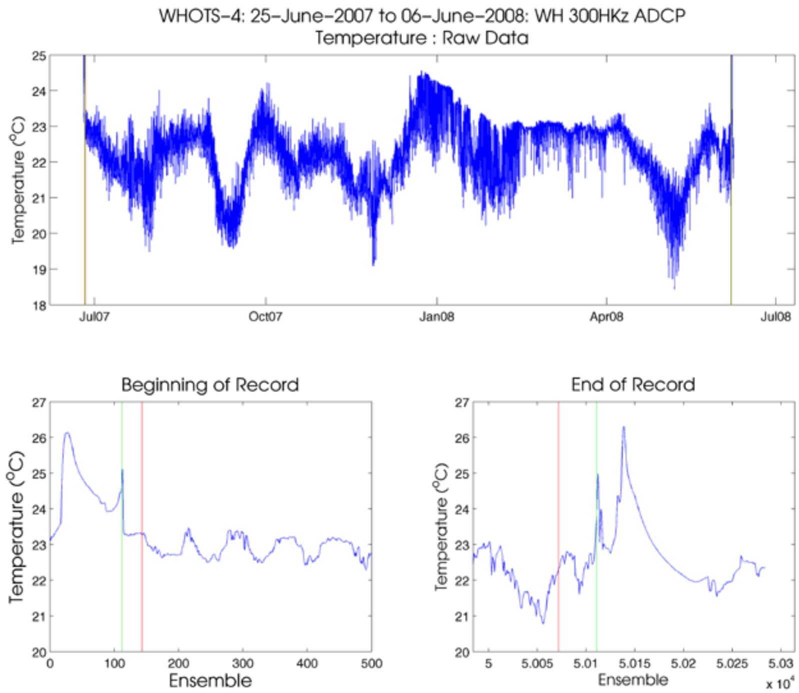


Figure 5-16. Temperature record from the 300 kHz ADCP during WHOTS-4 mooring (top panel). The bottom panel shows the beginning and end of the record with the green vertical line representing the in-water time during deployment and out-of-water time for recovery. The red line represents the anchor release and acoustic release trigger for deployment and recovery respectively.

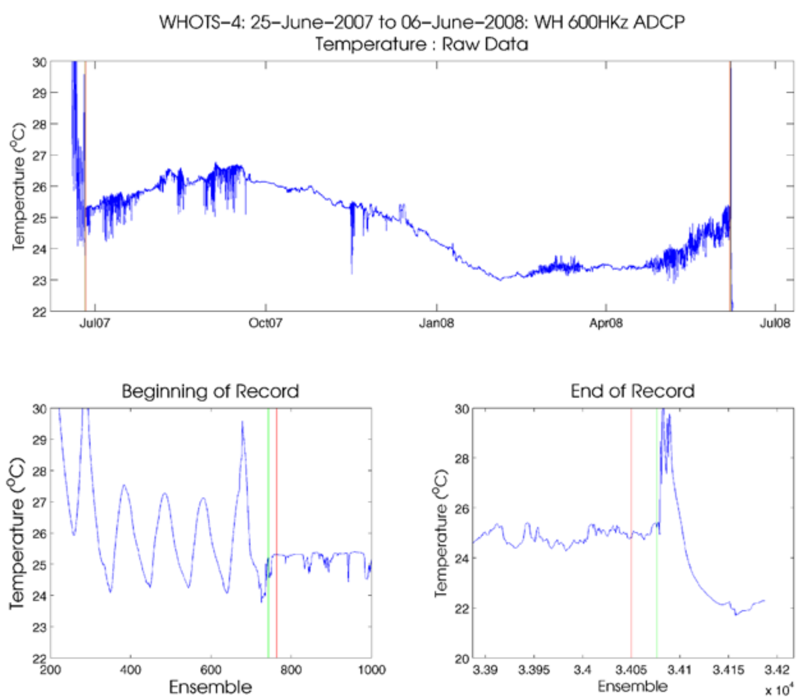


Figure 5-17. Same as Figure 5-16, but for the 600 kHz ADCP.

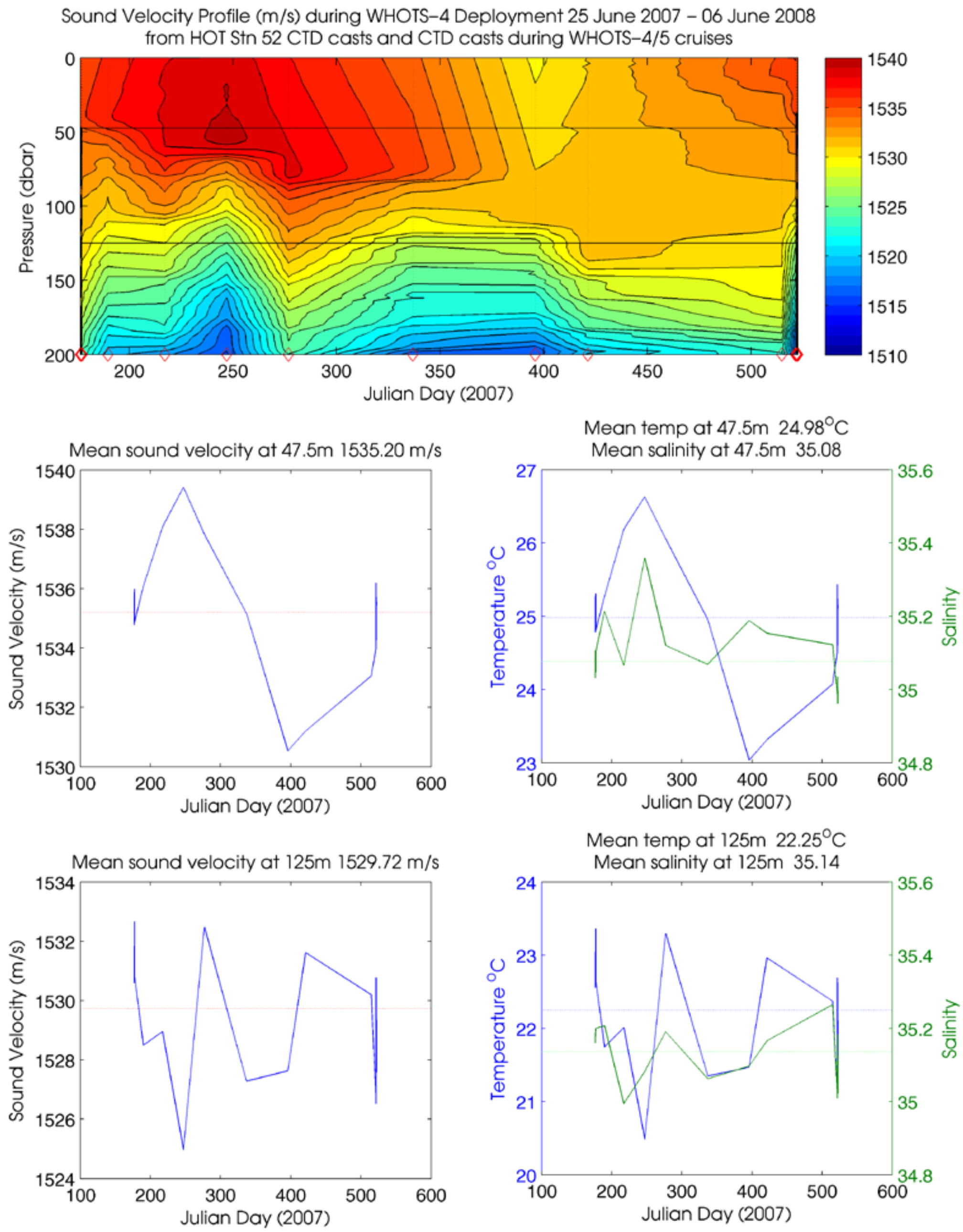


Figure 5-18. Sound speed profile (top panel) during the deployment of the WHOTS-4 mooring from 2 dbar CTD data taken during regular HOT cruises and CTD profiles taken during the WHOTS-5 recovery/deployment cruise (individual casts marked with a red diamond). The bottom left panels show the sound velocity at the depth of the ADCP's (47.5 m and 125 m), with the mean sound velocity indicated with a red line. The lower right panels show the temperature and salinity at each ADCP depth for the time series with the mean temperatures indicated with blue lines and mean salinity indicated with green lines.

Quality Control

Quality control of the ADCP data involved the thorough examination of the velocity, instrument orientation and diagnostic fields to develop the basis of the QC flagging procedures. Details of the methods used can be found in the WHOTS Data Report 1 (Santiago-Mandujano et al., 2007). The following QC procedures were applied to the WHOTS-4 deployment ADCP data.

1) The first bin (closest to the transducer) is sometimes corrupted due to what is known as ringing. A period of time is needed for the sound energy produced during a transmit pulse at the transducer to dissipate before the ADCP is able to properly receive the returned echoes. The blanking interval is used to prevent useless data from being recorded. If it is too short, signal returns can be contaminated from the lingering noise from the transducer. The default value for the blanking interval, (expressed as a distance) of 1.76 m was used for the 300 kHz ADCP, whereas an interval of 0.88 m was used for the 600 kHz ADCP. Thus bin 1 was flagged and replaced with Not a Number (NaN) in the quality controlled dataset (Figure 5-19).

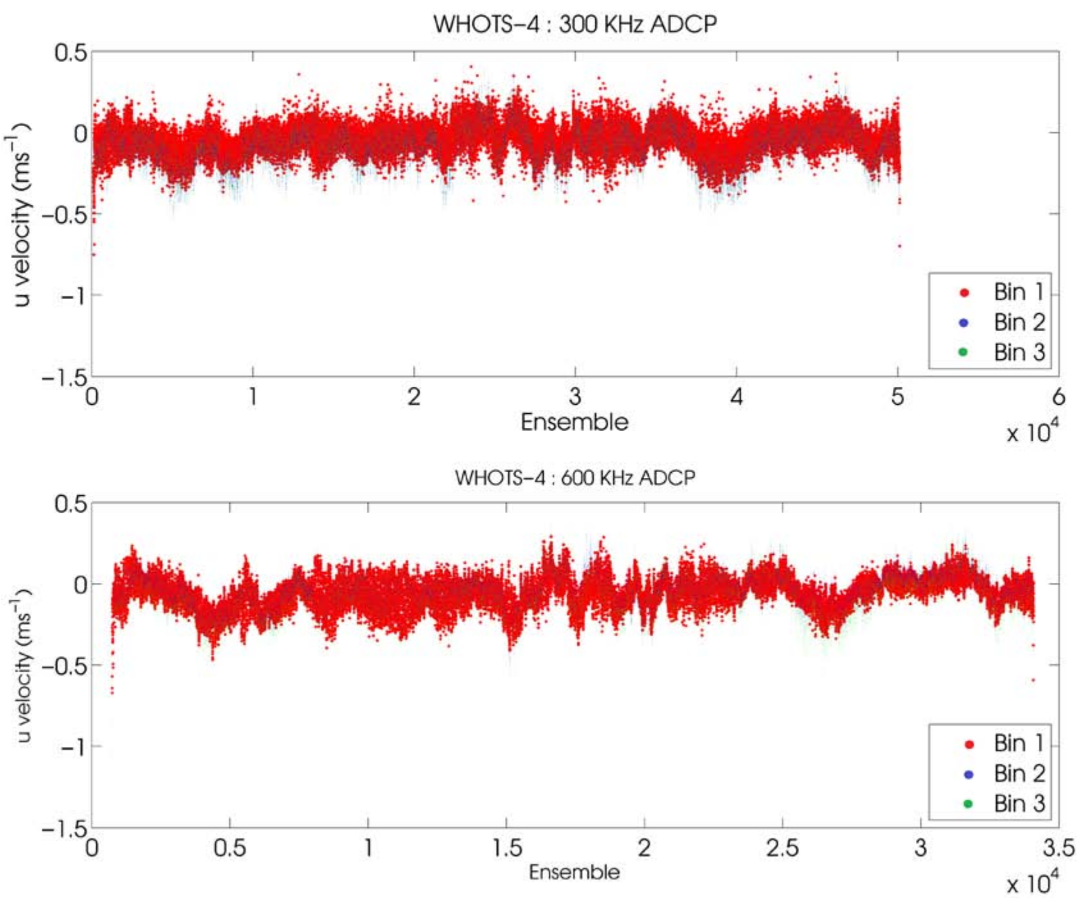


Figure 5-19. Eastward velocity component for the 300 kHz (top panel) and the 600 kHz (bottom panel) ADCPs showing the incoherence between depth 1 (red) and bins 2 (green) and 3 (blue).

2) For an upward-looking ADCP with a beam angle of 20° within range of the sea surface, the upper 6% of the depth range is contaminated with sidelobe interference (RDI, 1996). This is a result of stronger signal reflection from the sea surface (than from scatterers) overwhelming the sidelobe suppression of the transducer. Data are flagged using echo intensity (a measure of the strength of the return signal) from each beam to determine when the signal is contaminated with reflection from the sea surface. In practice, the majority of the data within the upper 4 bins (~14% of the vertical range) were flagged. These upper 4 bins range from about 15 m up to the sea surface.

3) The use of four beams (along with instrument orientation) to resolve currents into their component earth-referenced velocities provides us with a second estimate of the vertical velocity. The scaled difference between these estimates is defined as the error velocity and it is useful for assessing data quality. Error velocities with an absolute magnitude greater than 0.15 m s^{-1} (a value comparable to the standard deviation of observed horizontal velocities) were flagged and removed.

4) An indication of data quality for each ensemble is given by the "percent good" data indicator which accompanies each individual beam for each individual bin. The use of the percent good indicator is determined by the coordinate transformation mode used during the data collection. With profiles transformed into earth coordinates (as in the case of the WHOTS-4 deployment) the percent good fields show the percentage of data that was made using 4 and 3 beam solutions in each depth cell within an ensemble, and the percentage that was rejected as a result of failing one of the criteria set during the instrument setup (see Appendix 1: WHOTS-4 300 kHz ADCP Configuration). Data were flagged when data in each depth cell within an ensemble made from 3 or 4 beam solutions was 20% or less.

5) Data were rejected using correlation magnitude, which is the pulse-to-pulse correlation (in ping returns) for each depth cell. If anyone beam had a correlation magnitude of 20 counts or less, that data point was flagged.

6) Histograms of raw vertical velocity data and partially cleaned data from the ADCP [see Figure 5-20 and Figure 5-21 and the WHOTS Data Report 1 (Santiago-Mandujano et al., 2007)] showed vertical velocities larger than expected, some exceeding 1 m s^{-1}. Recall that the instruments' burst sampling (4-second intervals for the 300 kHz and 2-second intervals for the 600 kHz, for 160 seconds every 10 minutes) was designed to minimize aliasing by occasional large ocean swell orbital motions (Section 3), and therefore are not the source of these large speeds in the data. These large vertical speeds are possibly fish swimming in the beams based on the histograms of the partially cleaned data; depth cells with an absolute value of vertical velocity greater than 0.3 m s^{-1} were flagged.

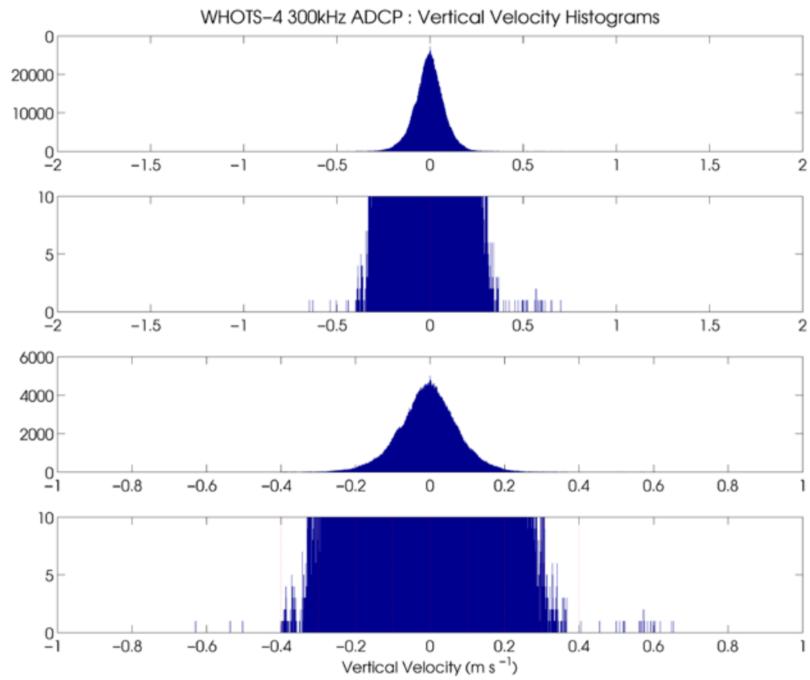


Figure 5-20. Histogram of vertical velocity of the 300 kHz ADCP for raw data (top panel) and enlarged for clarity (upper middle panel), and for partial quality controlled data (lower middle panel) and enlarged for clarity (bottom).

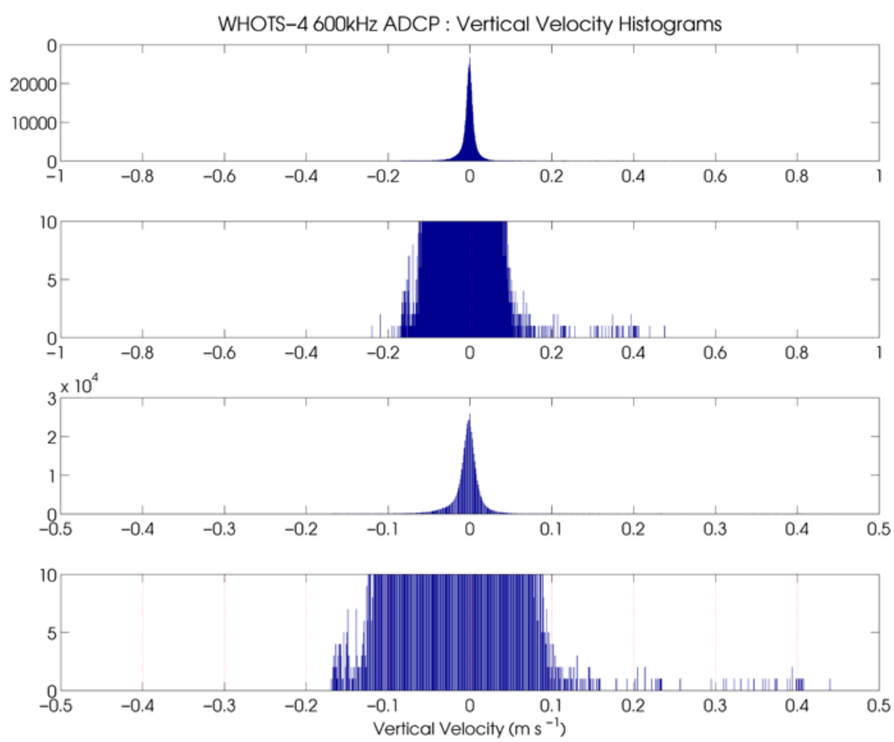


Figure 5-21. Same as Figure 5-20 but for the 600 kHz ADCP.

7) A quality control routine known as ‘edgers’ identifies outliers in surface bins using a five point median differencing method. The median velocity from surface bins was calculated for each ensemble, and then a five point running median of the surface bin median was calculated. This was then compared to individual velocity observations in the surface bins, and those differing by greater than 0.48 m/s were flagged.

8) A 5-pole low pass Butterworth filter with a cutoff frequency of 1/4 cycles/hour was used upon the length of the time-series to isolate low frequency flow for each bin independently. The low frequency flow is then subtracted giving a time series of high frequency velocity component fluctuations for each bin. Data points were considered outliers when their values exceeded four standard deviations from the mean (for each bin) and were removed.

9) A median residual filter used a 7-point (70 minute) median differencing method to define velocity fluctuations. A 7-point running median is calculated for each bin independently and the result is subtracted out giving time series of fluctuations relative to the running median. Outliers greater than four standard deviations from the mean of the 7 points are flagged and removed for each bin.

10) Meticulous verification of all the quality control routines was performed through visual inspections of the quality controlled velocity data. Two methods were utilized; time-series of u and v components for multiple bins were evaluated as well as individual vertical profiles. The time-series methodology involved inspecting u and v components separately, five bins at a time, over 600 ensembles (100 hours). Any instance showing one bin behaving erratically from the other four bins was investigated further. If it seemed that there could be no reasonable rationale for the erratic points from the identified bin, the points were flagged [see Figure 5-22 and Figure 5-23 and the WHOTS Data Report 1 (Santiago-Mandujano et al., 2007)]. The intent of the vertical inspection of vertical profiles of the u and v components was to find entire profiles that were not aligned with neighboring profiles. Thirty u and v profiles were stacked at a time and were visually inspected for any anomalous data.

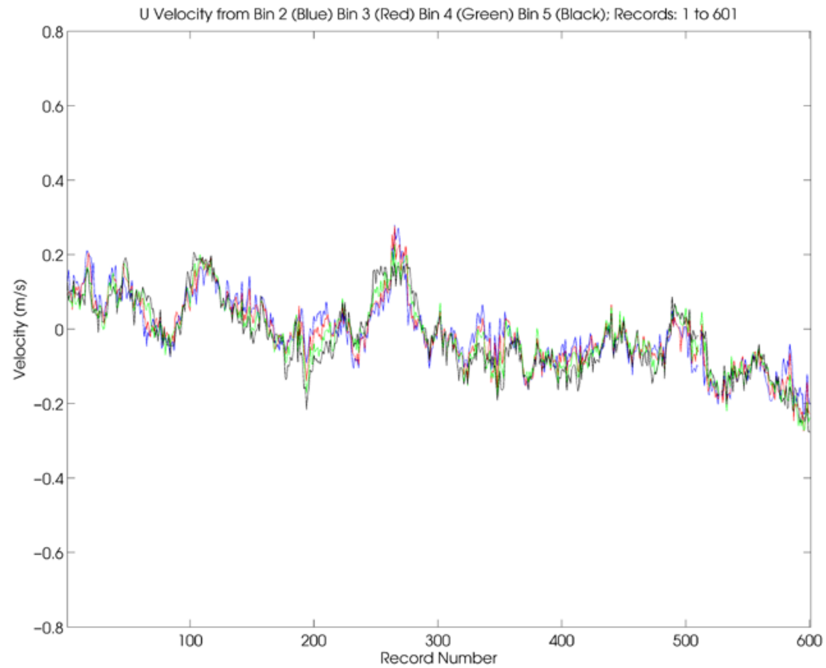


Figure 5-22. A sample of the horizontal inspection during WHOTS ADCP quality control

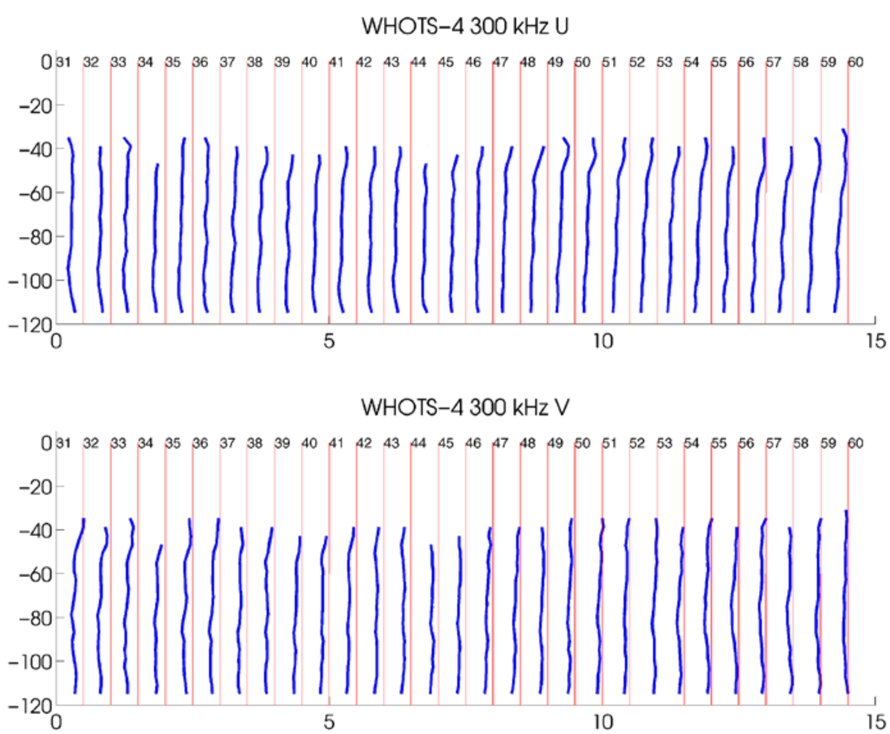


Figure 5-23. A sample of the profile consistency inspection from the WHOTS-4 ADCP quality control.

C. Next Generation Vector Measuring Current Meter (NGVM)

NGVM data from the WHOTS-4 deployment were truncated to about 8 hours after anchor deployment allowing time for mooring motions associated with the sinking anchor to die out. NGVM record times are shown in Table 5-7. Temperature and NGVM records were checked for each deployment to ensure processed data files did not begin too early (before the anchor settled) or end too late (after the release was triggered). No suspect NGVM data or spikes in temperature were found at the beginning or end of processed records. Note that during WHOTS-4, the 10 m NGVM's failed about 2 months early.

Table 5-7. Record times (UTC) for the NGVMs at 10 m and 30 m during the WHOTS-4 deployment

	WHOTS-4	
	NGVM034	NGVM040
Deployment and recovery times	25-Jun-2007 17:12 07-Jun-2008 01:08	25-Jun-2007 17:04 07-Jun-2008 01:21
Processed file beginning and end times	26-Jun-2007 12:00 07-Apr-2008 01:53	26-Jun-2007 12:00 06-Jun-2008 16:50

Daily (24 hour) moving averages of quality controlled 600 kHz ADCP data are compared to VMCM data interpolated to the ADCP ensemble times in the top panels of Figure 5-24 through Figure 5-27, and the difference is shown in the middle panels. The absolute value of the mean difference plus or minus one standard deviation is shown at the top of the middle panel. Velocities are not compared if greater than 80% of the ADCP data within a 24 hour average was flagged. Velocity differences between the VMCMs and the 600 kHz ADCP were small until March 2008, when both records began to show larger discrepancies until the date of recovery.

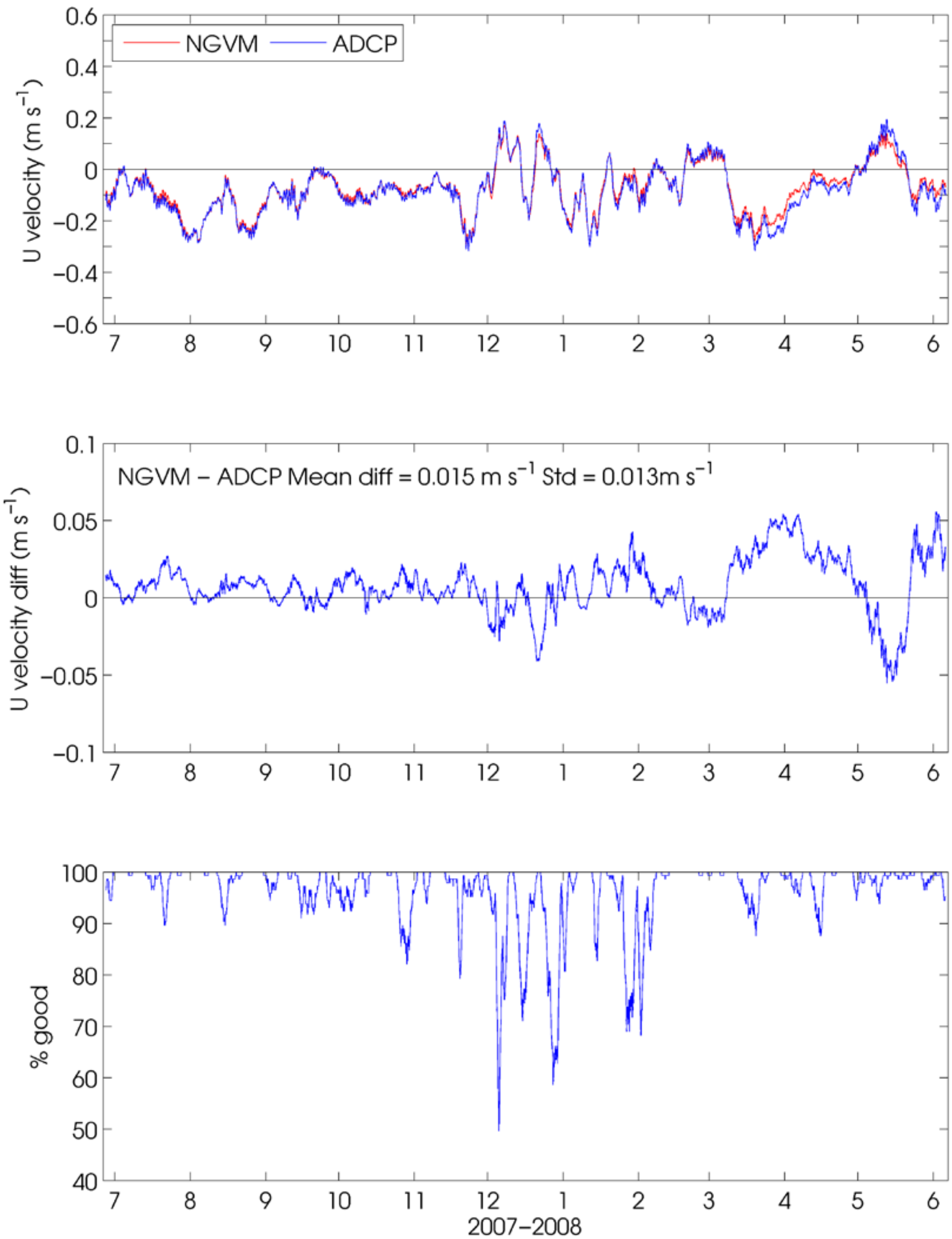


Figure 5-24. A comparison of 30 m VMCM and ADCP U velocity for WHOTS-4. The top panel shows 24 hour moving averages of VMCM zonal (U) velocity at 30 m depth (red) and ADCP U velocity from the nearest depth bin to 30 m (30.22 m). The middle panel shows the U velocity difference, and the bottom panel shows the percentage of ADCP data within the moving average not flagged by quality control methods. The dashed lines indicate a period of increased differences observed during spring months.

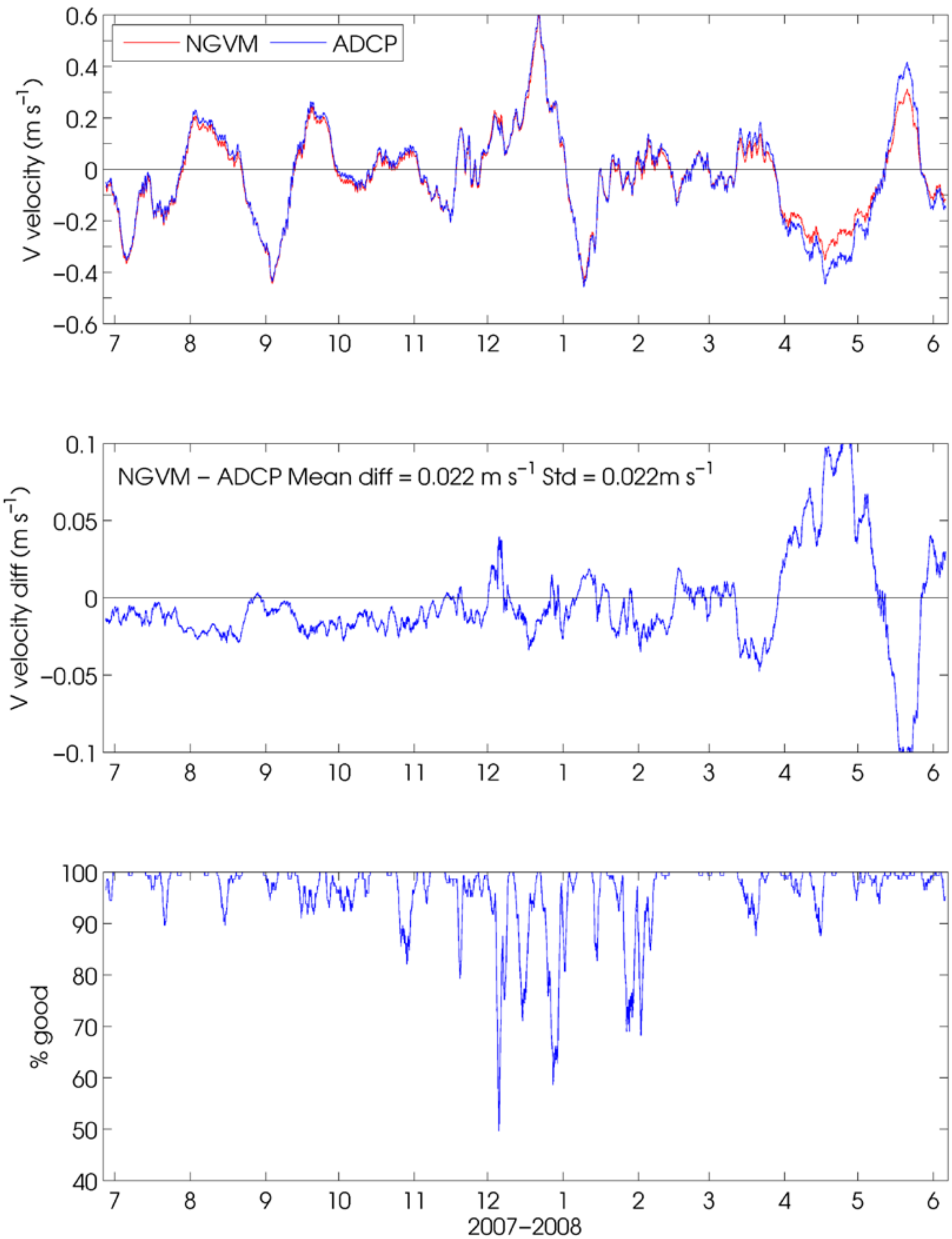


Figure 5-25. Same as in Figure 5-24 but for the meridional (V) velocity component.

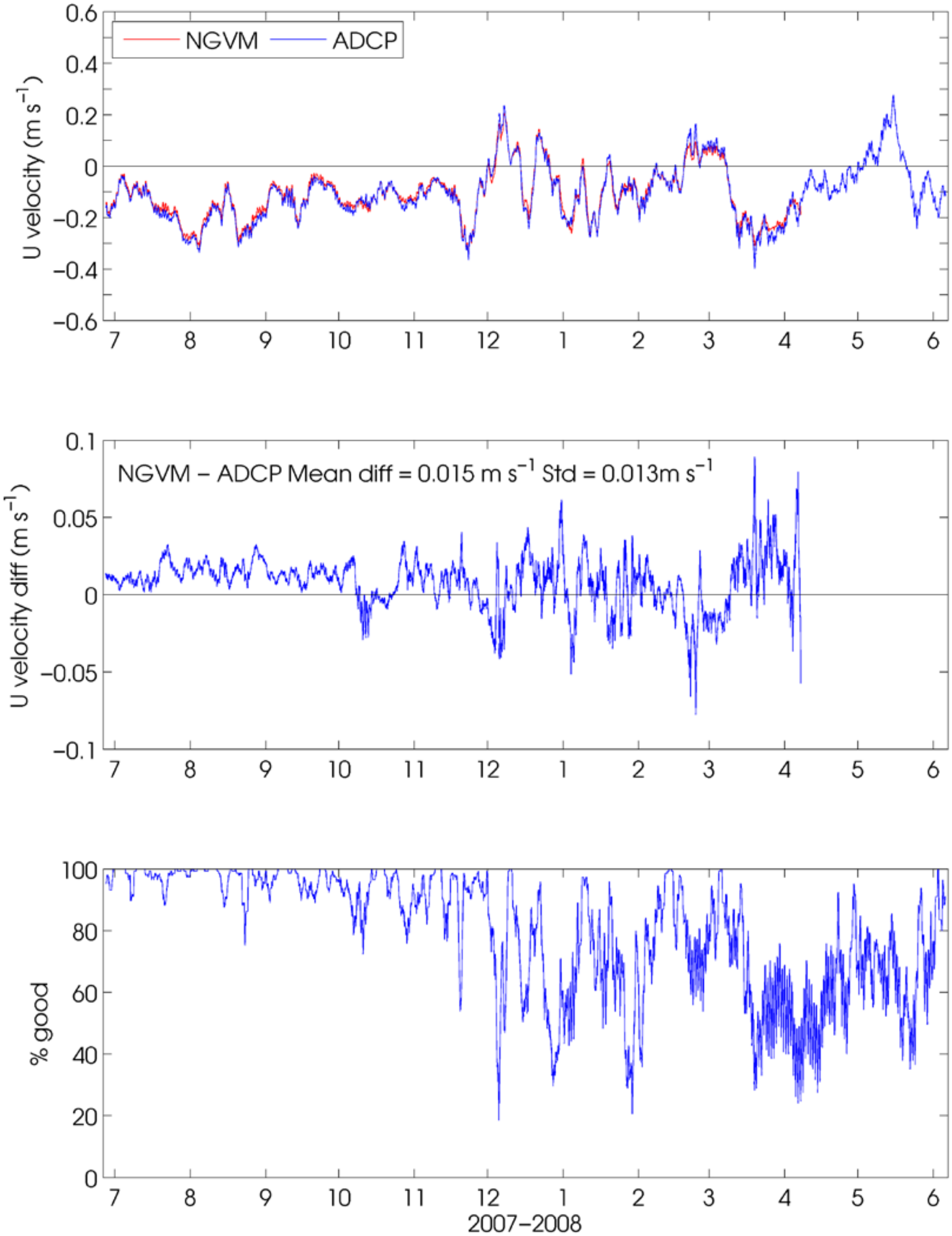


Figure 5-26. Same as in Figure 5-24 but for the 10 m VMCM.

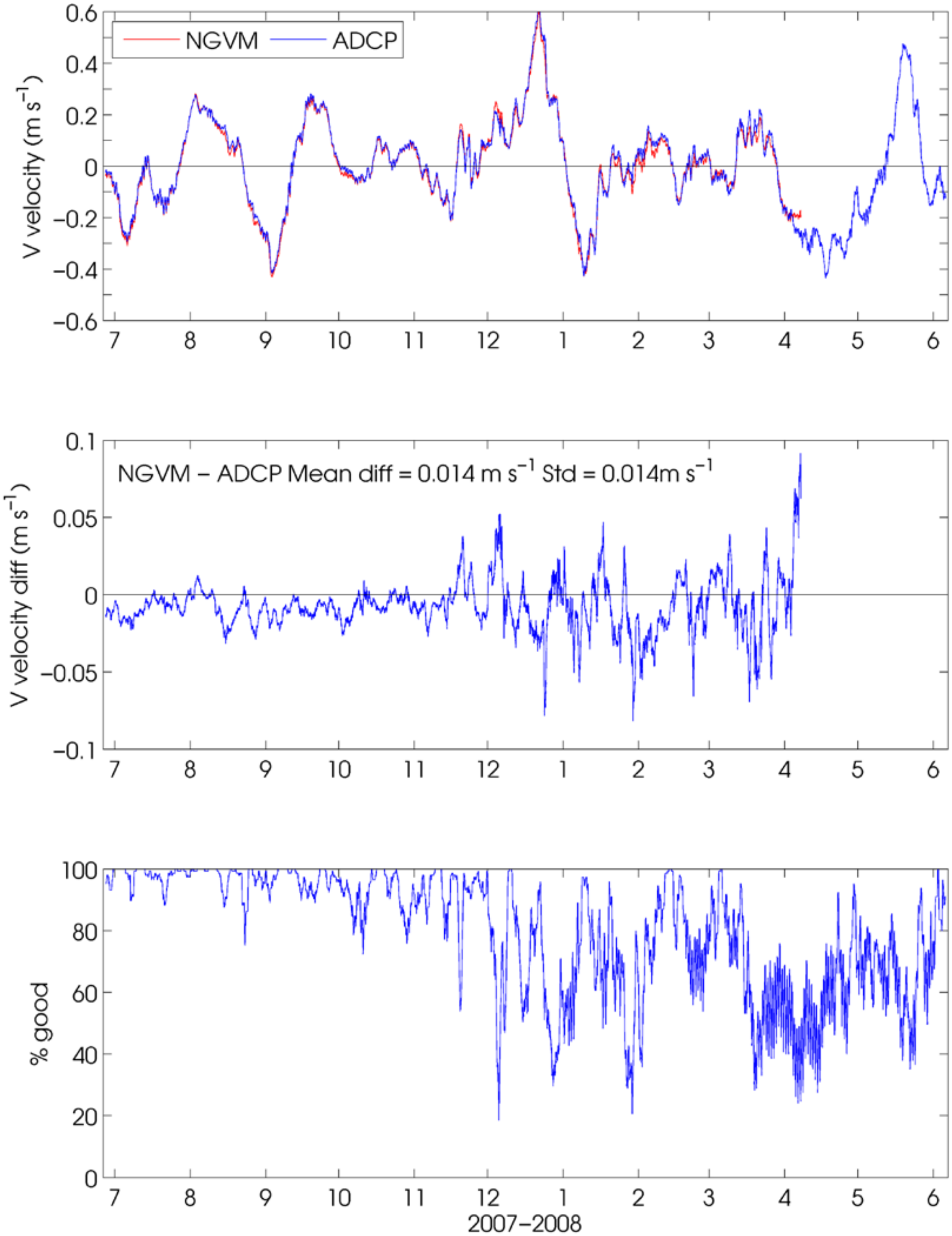


Figure 5-27. Same as in Figure 5-24 but for the V velocity component.

D. Global Positioning System Receiver and ARGOS Positions

A Seimac III Global Positioning System receiver (SN 67700) and ARGOS beacon (SN 25702) were attached to the tower top of the buoy during the WHOTS-4 deployment. Record times for both instruments are shown in Table 5-8.

Table 5-8. GPS and ARGOS record times (UTC) during WHOTS-4

WHOTS-4	Xeos GPS	ARGOS
Raw file beginning and end times	19-Jun-2007 19:06 28-Jun-2007 15:42	26-Jun-2007 01:12 08-Jun-2008 01:14

ARGOS positions were available during the WHOTS-4 deployment and they provided additional information on the buoy's motion. ARGOS data were recorded at 10 minutes intervals, although there are some small gaps at repeated times present in the records. Samples taken before mooring deployment were eliminated. Data were screened for points that were greater than 2.5 nautical miles from the surveyed anchor positions for each deployment which was considered to be the buoy watch circle radius. The velocity magnitude was calculated and positions that resulted in speeds greater than 1 m s^{-1} were removed. Data were interpolated onto a regular time grid in order to compute spectra.

For comparison, Figure 5-28 shows the ARGOS buoy's positions together with the GPS positions during the WHOTS-4 deployment. Unfortunately the Seimac GPS receiver failed 9 days into the deployment. The standard deviation of the difference between these two records is about 550m.

The ARGOS positions of the WHOTS-4 buoy for the duration of the deployment are in Figure 5-29, which shows the color-coded positions according to their data quality. The data quality is determined by its distance from the satellite track. Data of a better quality have a higher flag number: 3 is for a distance less than 150 m, 2 is for a distance between 150 and 350 m, and 1 is for a distance between 350 and 1000 m. For the duration of the deployment, the buoy had a mean position of about 3 km from the anchor, with a standard deviation of about 600 m.

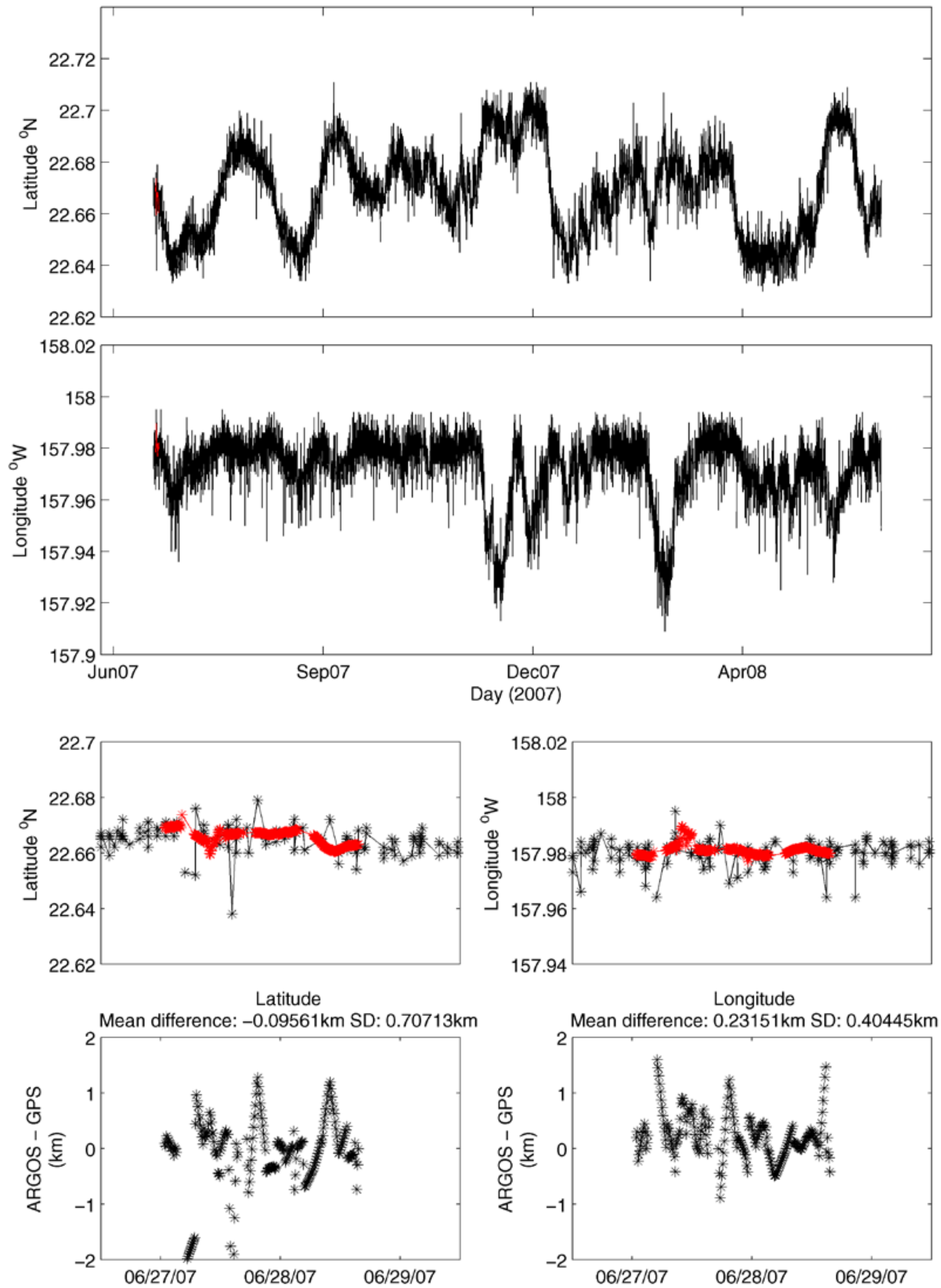


Figure 5-28. WHOTS-4 buoy position from ARGOS data (black line), and from GPS data (red line). The top and two middle panels show the latitude and longitude of the buoy. The bottom panel shows the difference between the GPS positions and the ARGOS positions interpolated to the GPS times.

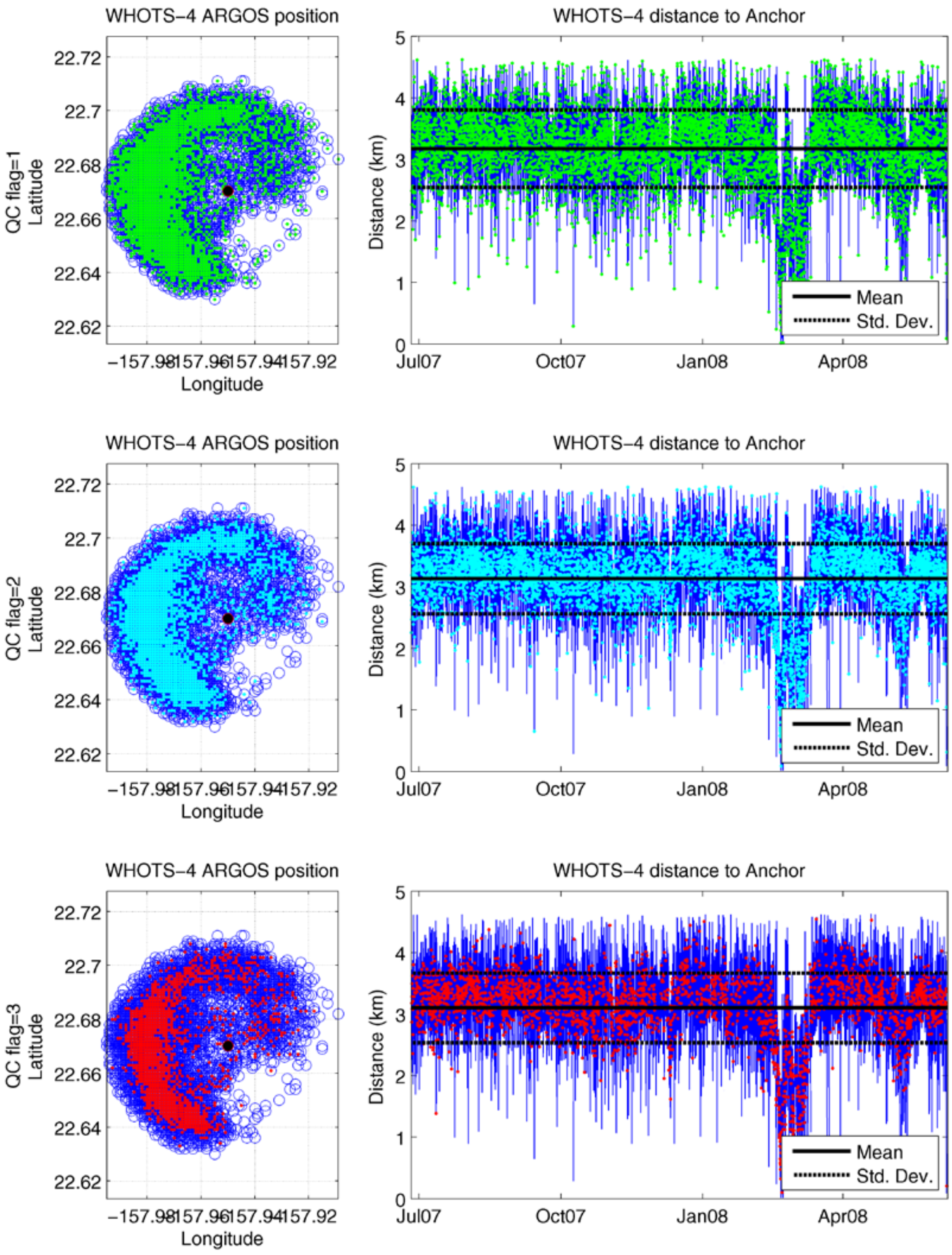


Figure 5-29. WHOTS-4 buoy ARGOS positions (circles, left panels), and distance from its anchor (dots, right panels). The data are colored according to their quality control flag, 1: green, 2: light blue, 3: red. The black circle in the center of the left side panels is the location of the mooring's anchor. The black line in the right panel plots is the mean distance between the buoy and its anchor, and the dashed line is the mean plus minus one standard deviation.

6. Results

During the WHOTS-4 cruise (WHOTS-4 mooring deployment), we observed the northwestward flow of the North Hawaiian Ridge Current during our transit from Oahu to Station ALOHA which was north of the strong flow. The NCOM analysis of 6/27/07 was consistent with the ADCP observations. The 38 kHz ADCP revealed an eastward flow of about 20 cm/s centered near 800 m, which is the core depth of the Antarctic Intermediate Water. The thickness of this feature was about 300 m.

During the WHOTS-5 cruise (WHOTS-4 mooring recovery), the northwestward flow of the North Hawaiian Ridge Current was not observed during our transit from Oahu to Station ALOHA. Instead, a southeastward flow was seen. Approaching ALOHA, the upper ocean flow intensified and veered from southward to southwestward. The 4 June 2008 NRL 1/12° HyCOM sea surface height analysis showed a cyclonic eddy centered just to the east of ALOHA, which was consistent with our shipboard ADCP measurements. Inspection of the NRL NCOM analysis for the same time revealed that it was inconsistent with our observations, which was unusual in our experience.

The temperature MicroCAT records during the WHOTS-4 deployment (Figure 6-19 through Figure 6-22) show obvious seasonal variability in the upper 100 m. The salinity records (Figure 6-23 through Figure 6-26) do not show an obvious seasonal cycle.

Figure 6-31 and Figure 6-32 show contours of the WHOTS-4 MicroCAT data in context with data from the previous deployments. The seasonal cycle is obvious in the temperature record, with record temperatures (higher than 26 °C) in the summer of 2004, and to a minor extent in the summer of 2005. Salinities in the subsurface salinity maximum were relatively low during the first 4 years of the record. When plotted in σ_θ coordinates (Figure 6-32), the salinity maximum seems to be centered roughly between 24 and 24.5 σ_θ.

Figure 6-36 through Figure 6-38 show time series of the zonal, meridional, and vertical currents recorded with the moored ADCPs during the WHOTS-4 deployment, and Figure 6-52 shows the vertical currents at 10 and 30 m collected by the VMCMs. Figure 6-33 through Figure 6-35 show contours of the ADCP current components in context with data from the previous deployments. In spite of the gaps in the data, an obvious variability is seen in the zonal and meridional currents, apparently caused by passing eddies. On top of this variability there have been periods of intermittent positive or negative zonal currents, for instance during 2007-2008. The contours of vertical current component (Figure 6-35) show a transition in the magnitude of the contours near 47 m, indicating that the 300 kHz ADCP located at 126 m moves more vertically than the 600 kHz ADCP located at 47.5 m.

Comparisons between the shipboard ADCP from HOT cruises and the mooring data are compiled in Table 6-1, and shown in Figure 6-39 through Figure 6-51. Average meridional differences were slightly larger than zonal differences, and there was significant variability in RMS and mean differences with depth.

The motion of the WHOTS-4 buoy was registered by the Xeos-GPS receiver, and its positions are plotted in Figure 6-53. The buoy was located west of the anchor for the majority of the deployment, except during December 2007, and February 2008 when it was east of it. Power spectrum of these data (Figure 6-54) shows extra energy at the inertial period (~31 hr). Combining the buoy motion with the tilt (a combination of pitch and roll) from the ADCP data (Figure 6-55), showed that the tilt increased as the buoy distance from the anchor increased. This was expected since the inclination of the cable increases as the buoy moves away from the anchor.

A. CTD Profiling Data

Profiles of temperature, salinity and potential density (σ_θ) from the casts obtained during the WHOTS-4 deployment cruise are presented in Figure 6-1 through Figure 6-8, together with the results of bottle determination of salinity. Figure 6-9 through Figure 6-14 are the results of the CTD profiles during the WHOTS-5 cruise.

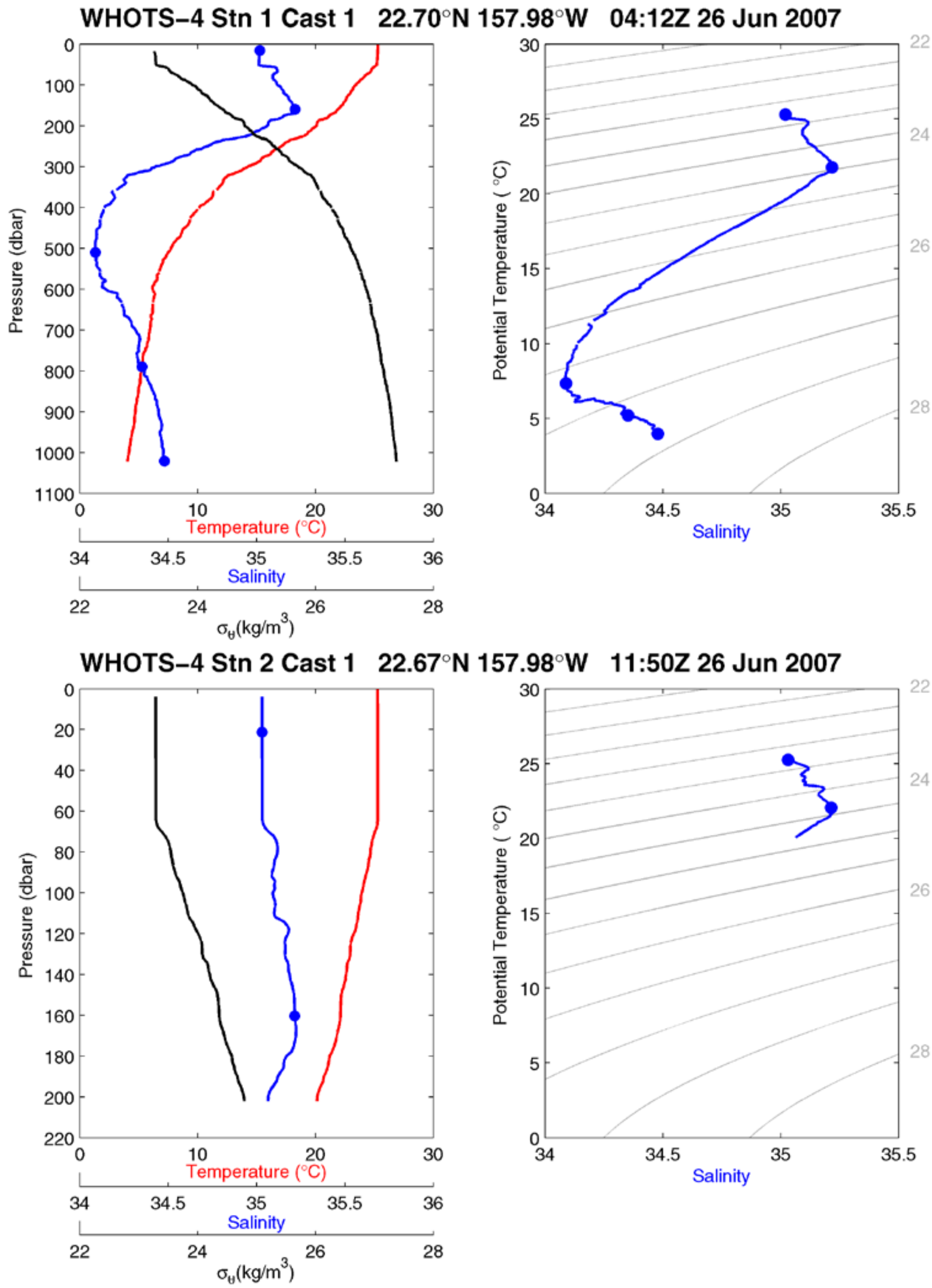


Figure 6-1 [Upper left panel] Profiles of CTD temperature, salinity, and potential density (σ_θ) as a function of pressure, including discrete bottle salinity samples for station 1 cast 1 during WHOTS-4 cruise. [Upper right panel] Profile of CTD salinity as a function of potential temperature, including discrete bottle salinity samples for station 1 cast 1 during WHOTS-4 cruise. [Lower left panel] Same as in the upper left panel, but for station 2 cast 1. [Lower right panel] Same as in the upper right panel, but for station 2 cast 1.

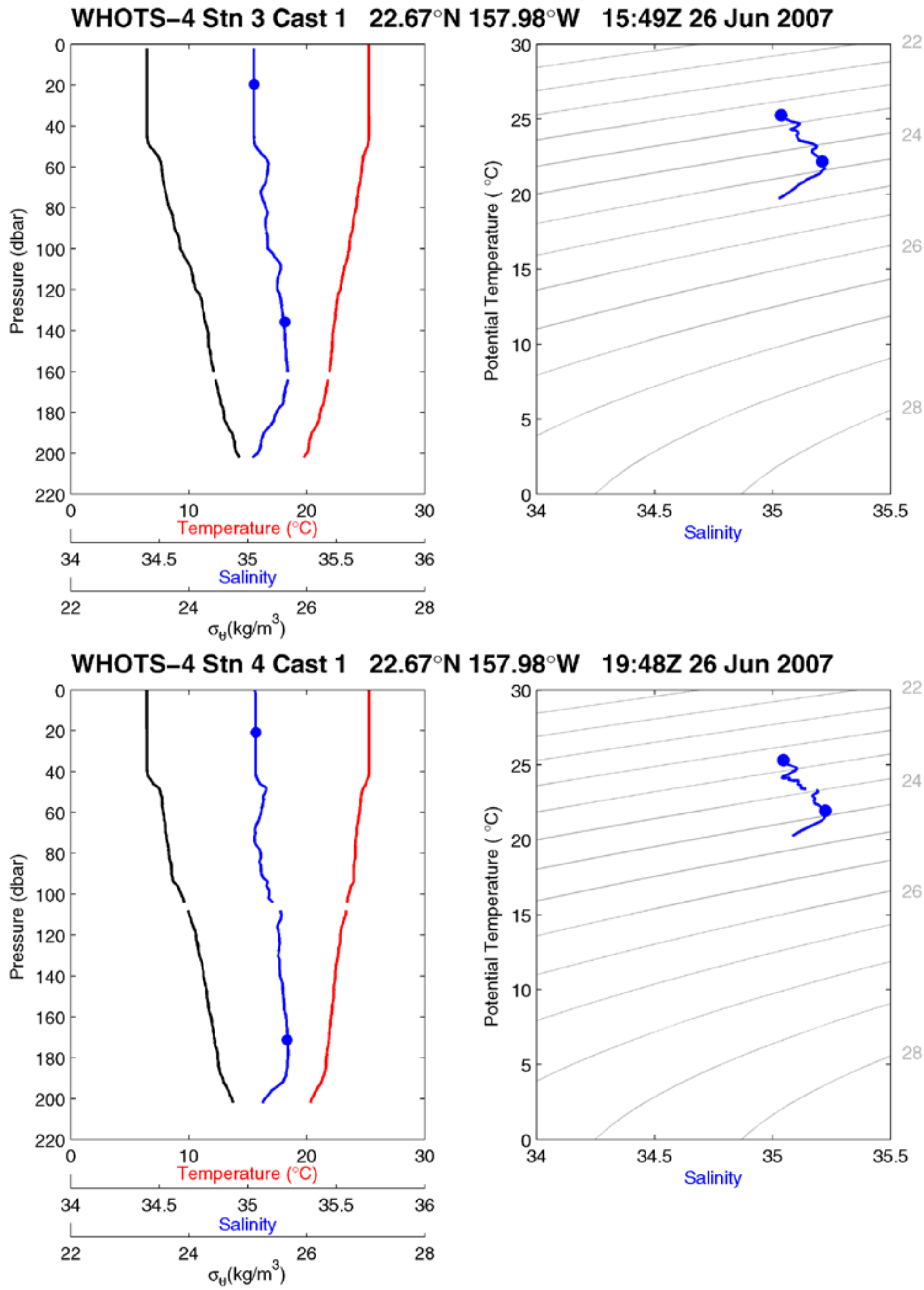


Figure 6-2 [Upper panels] Same as in Figure 6-1, but for station 3, cast 1. [Lower panels] Same as in Figure 6-1, but for station 4, cast 1.

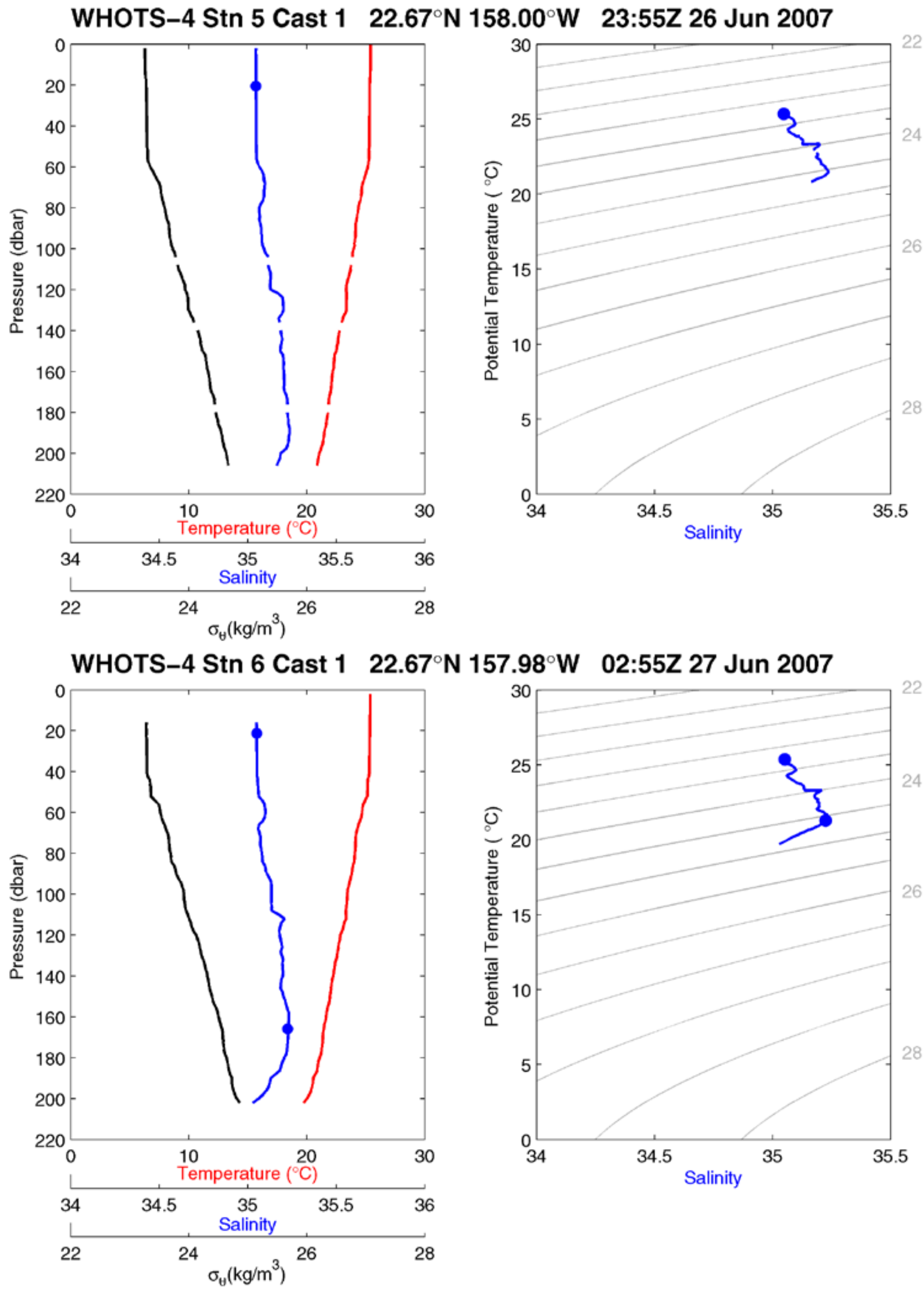


Figure 6-3[Upper panels] Same as in Figure 6-1, but for station 5, cast 1. [Lower panels] Same as in Figure 6-1, but for station 6, cast 1.

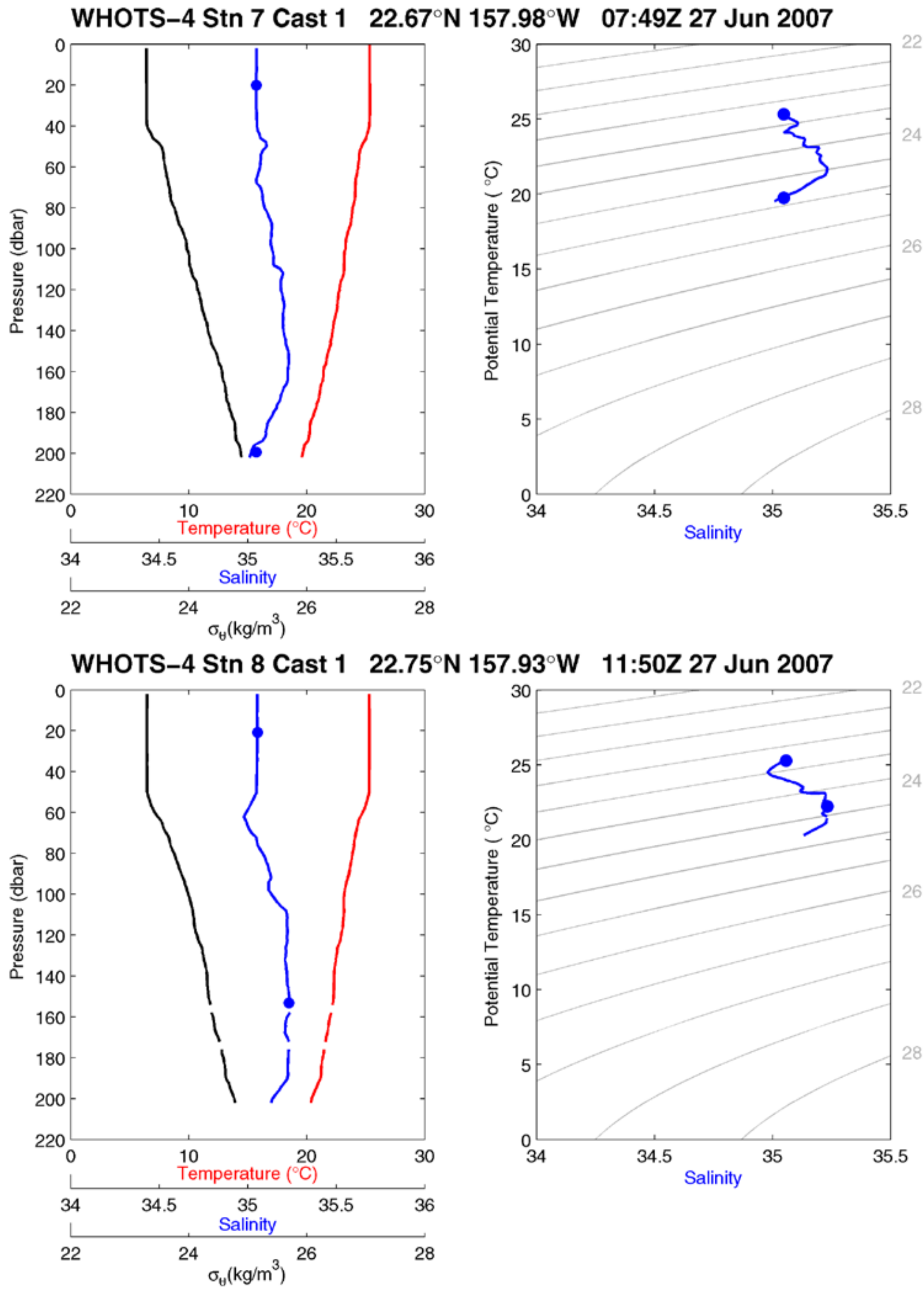


Figure 6-4[Upper panels] Same as in Figure 6-1, but for station 7, cast 1. [Lower panels] Same as in Figure 6-1, but for station 8, cast 1.

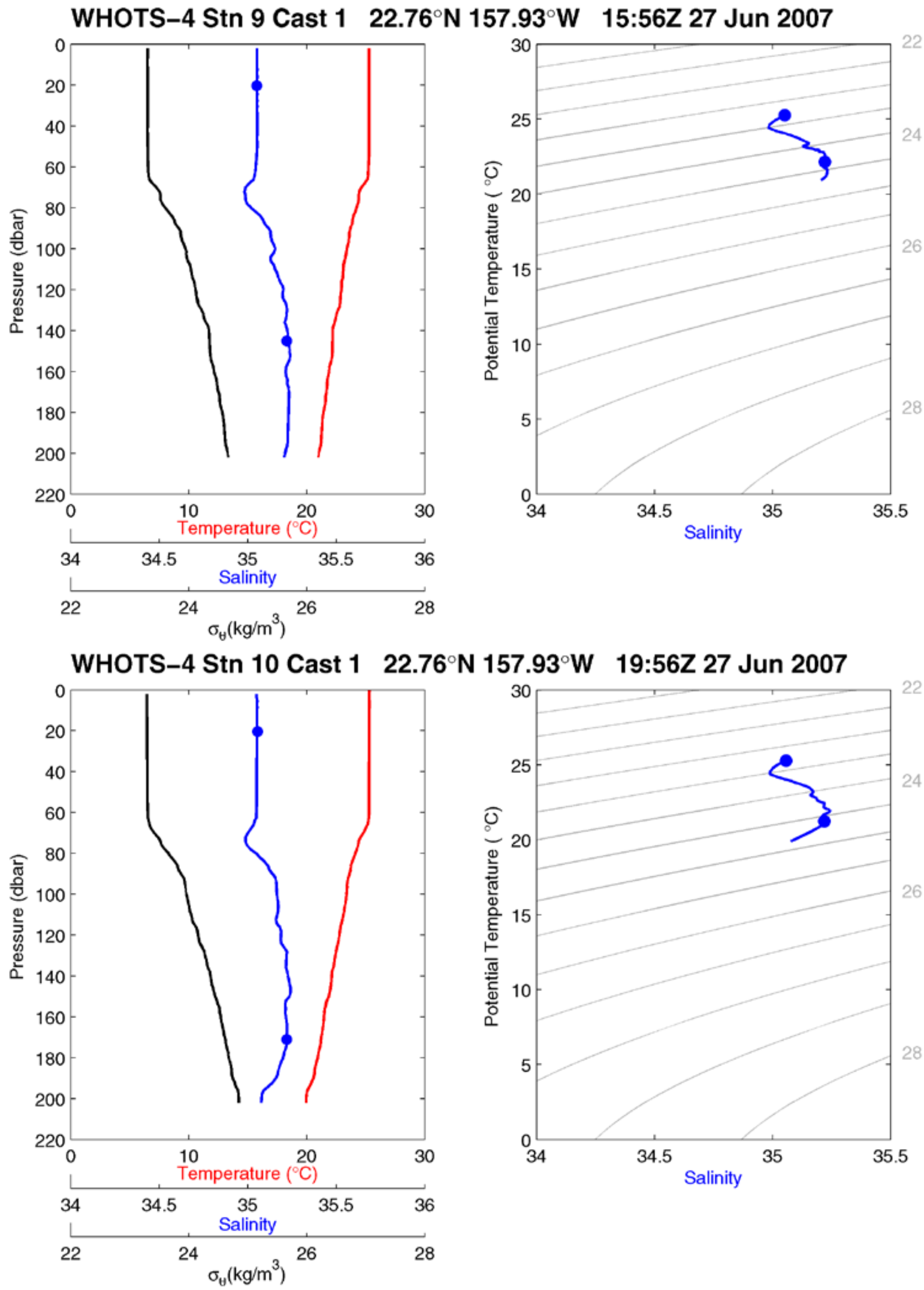


Figure 6-5[Upper panels] Same as in Figure 6-1, but for station 9, cast 1. [Lower panels] Same as in Figure 6-1, but for station 10, cast 1.

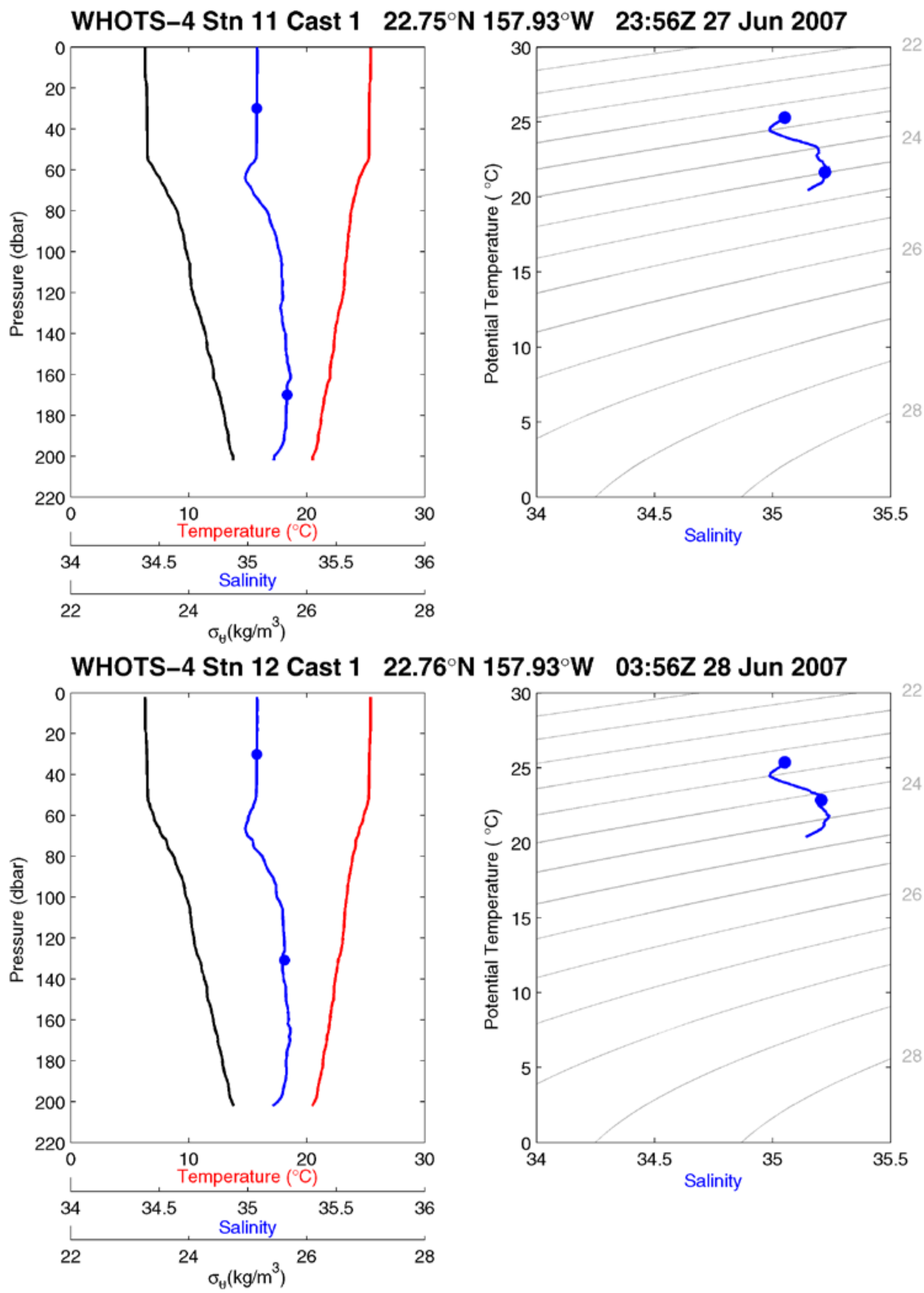


Figure 6-6[Upper panels] Same as in Figure 6-1, but for station 11, cast 1. [Lower panels] Same as in Figure 6-1, but for station 12, cast 1.

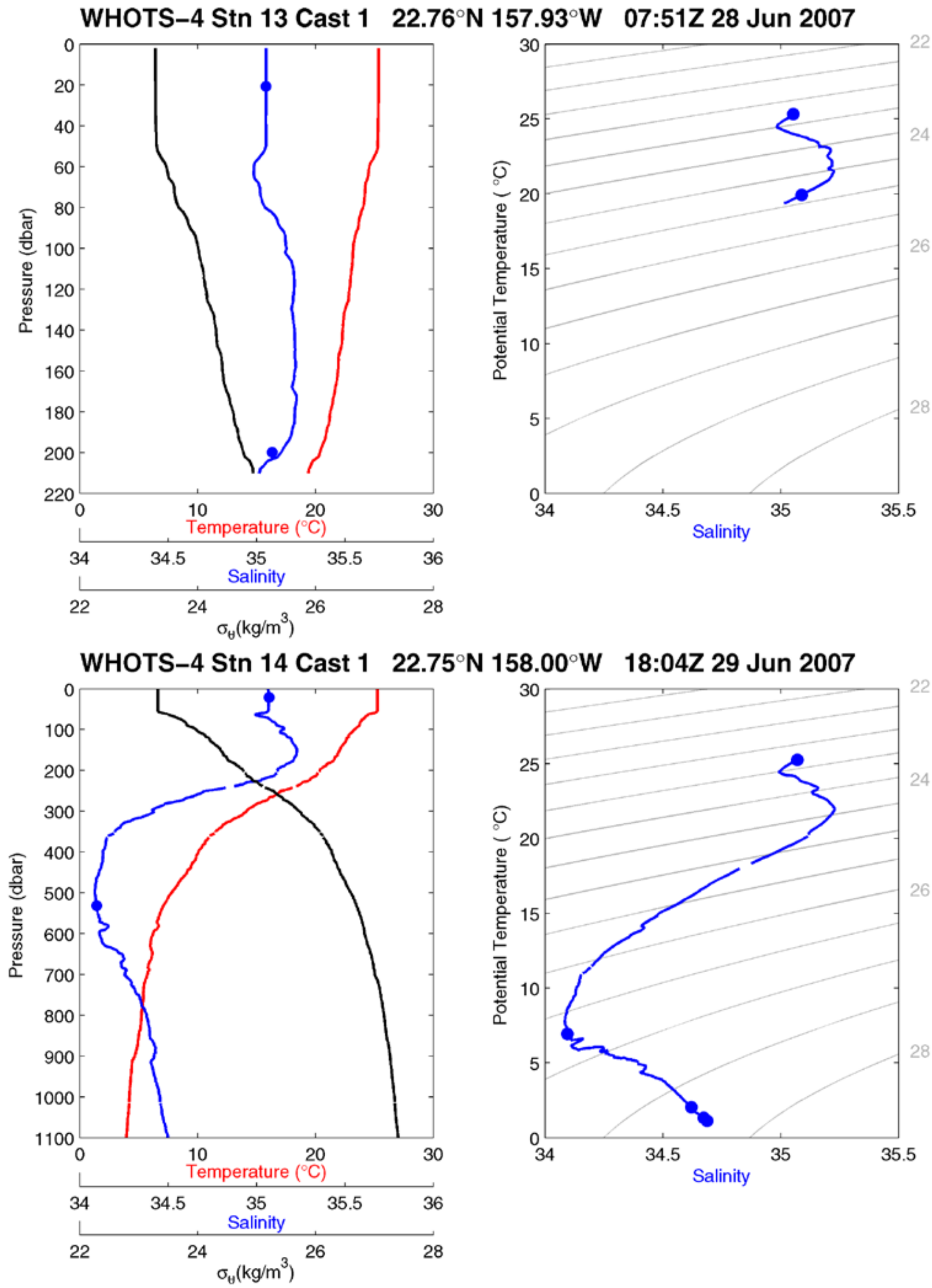


Figure 6-7[Upper panels] Same as in Figure 6-1, but for station 13, cast 1. [Lower panels] Same as in Figure 6-1, but for station 14, cast 1.

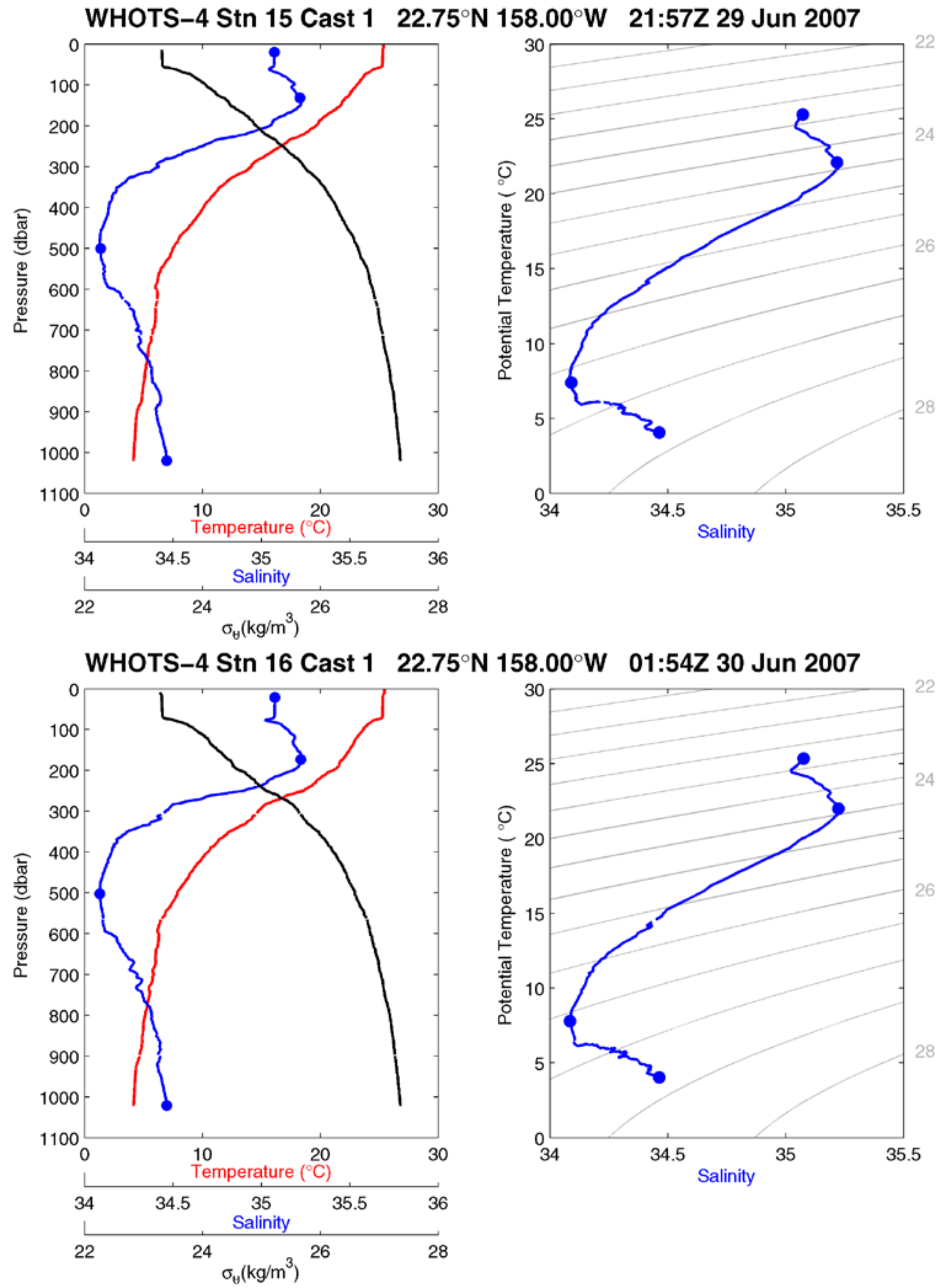


Figure 6-8[Upper panels] Same as in Figure 6-1, but for station 15, cast 1. [Lower panels] Same as in Figure 6-1, but for station 16, cast 1.

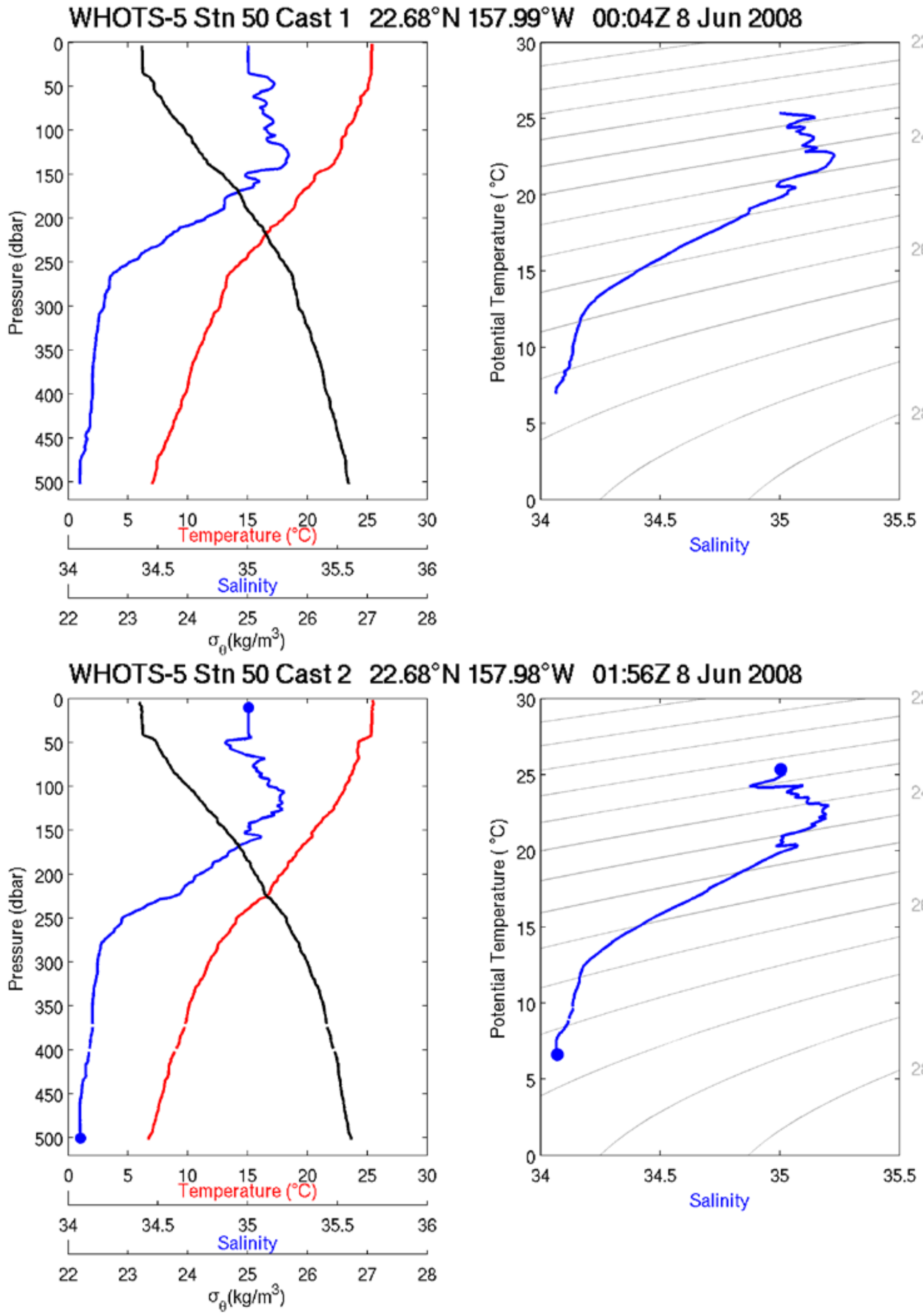


Figure 6-9 [Upper left panel] Profiles of CTD temperature, salinity, and potential density (σ_θ) as a function of pressure, including discrete bottle salinity samples for station 50 cast 1 during WHOTS-5 cruise. [Upper right panel] Profile of CTD salinity as a function of potential temperature, including discrete bottle salinity samples for station 50 cast 1 during WHOTS-5 cruise. [Lower left panel] Same as in the upper left panel, but for station 50 cast 2. [Lower right panel] Same as in the upper right panel, but for station 50 cast 2.

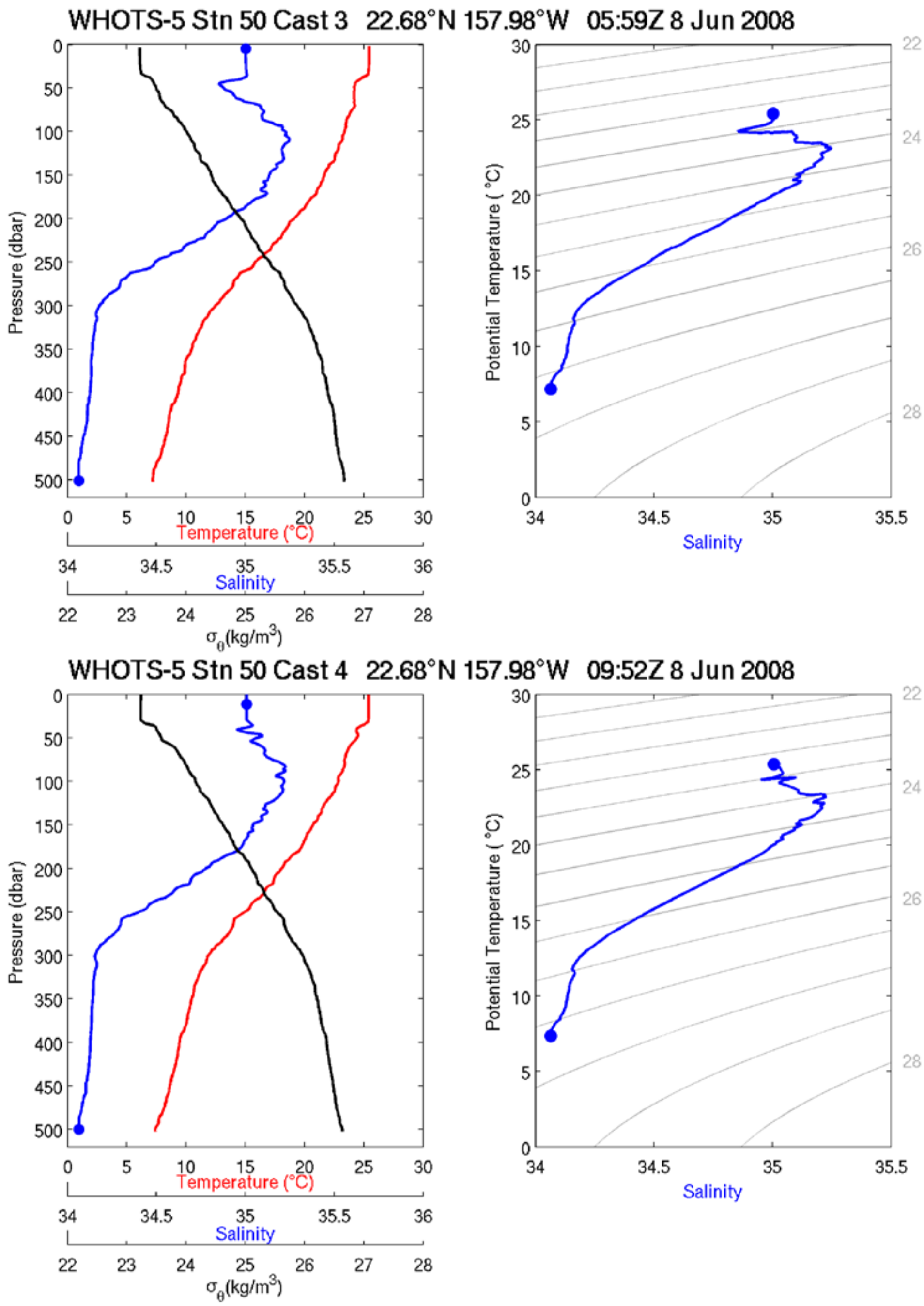


Figure 6-10[Upper panels] Same as in Figure 6-9 but for station 50, cast 3. [Lower panels] Same as in Figure 6-9, but for station 50, cast 4.

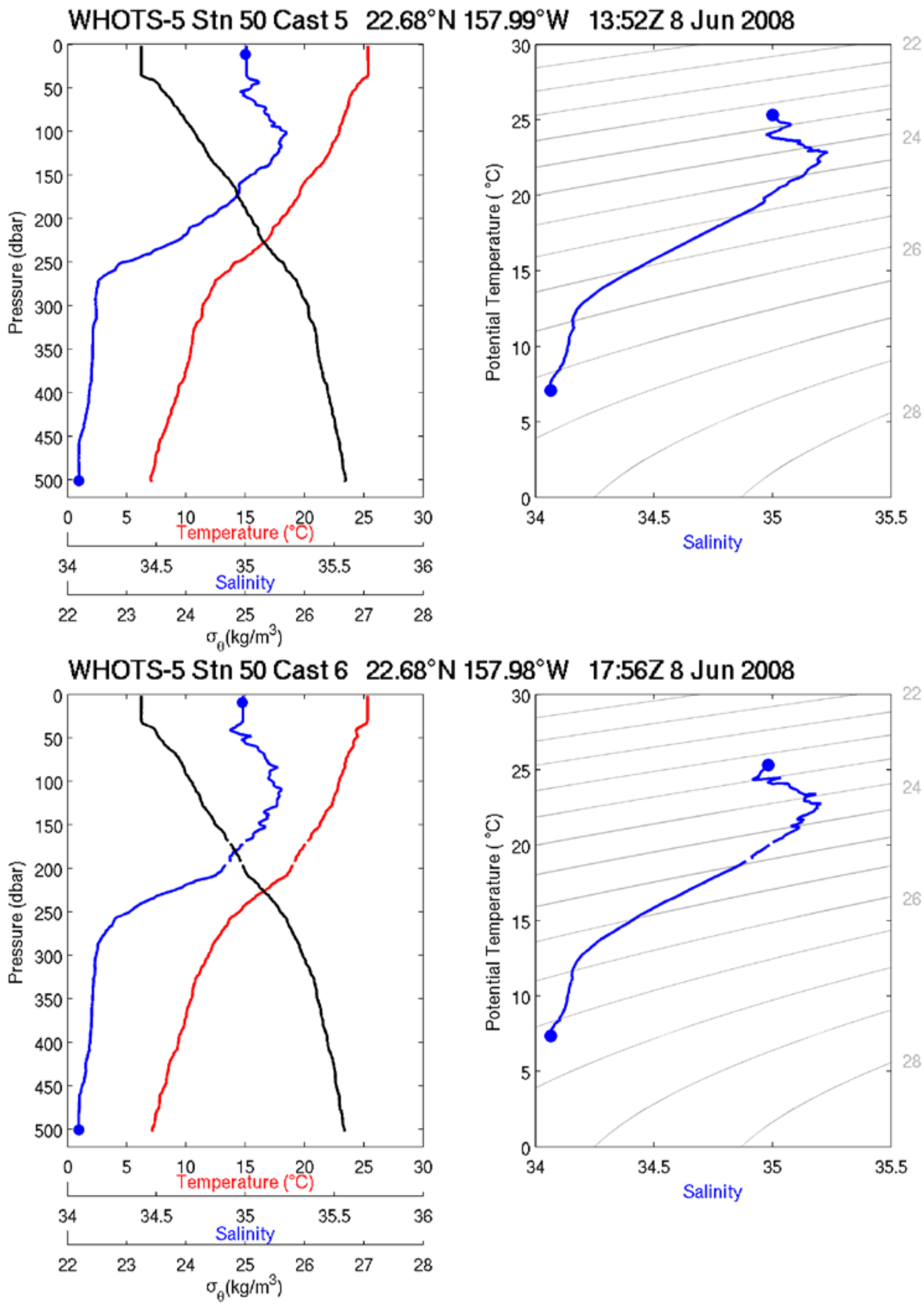


Figure 6-11[Upper panels] Same as in Figure 6-9, but for station 50, cast 5. [Lower panels] Same as in Figure 6-9, but for station 50, cast 6.

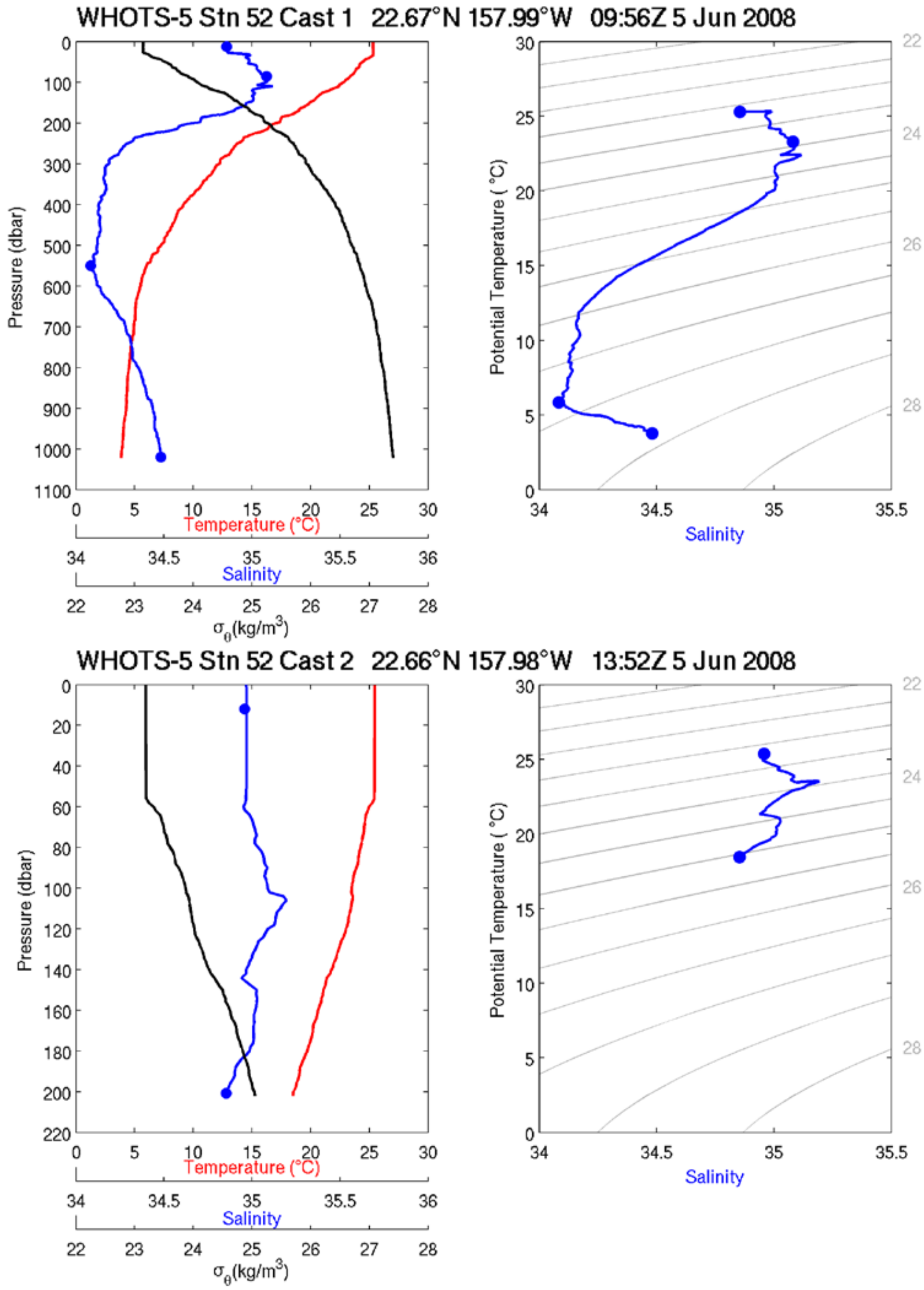


Figure 6-12[Upper panels] Same as in Figure 6-9, but for station 52, cast 1. [Lower panels] Same as in Figure 6-9, but for station 52, cast 2.

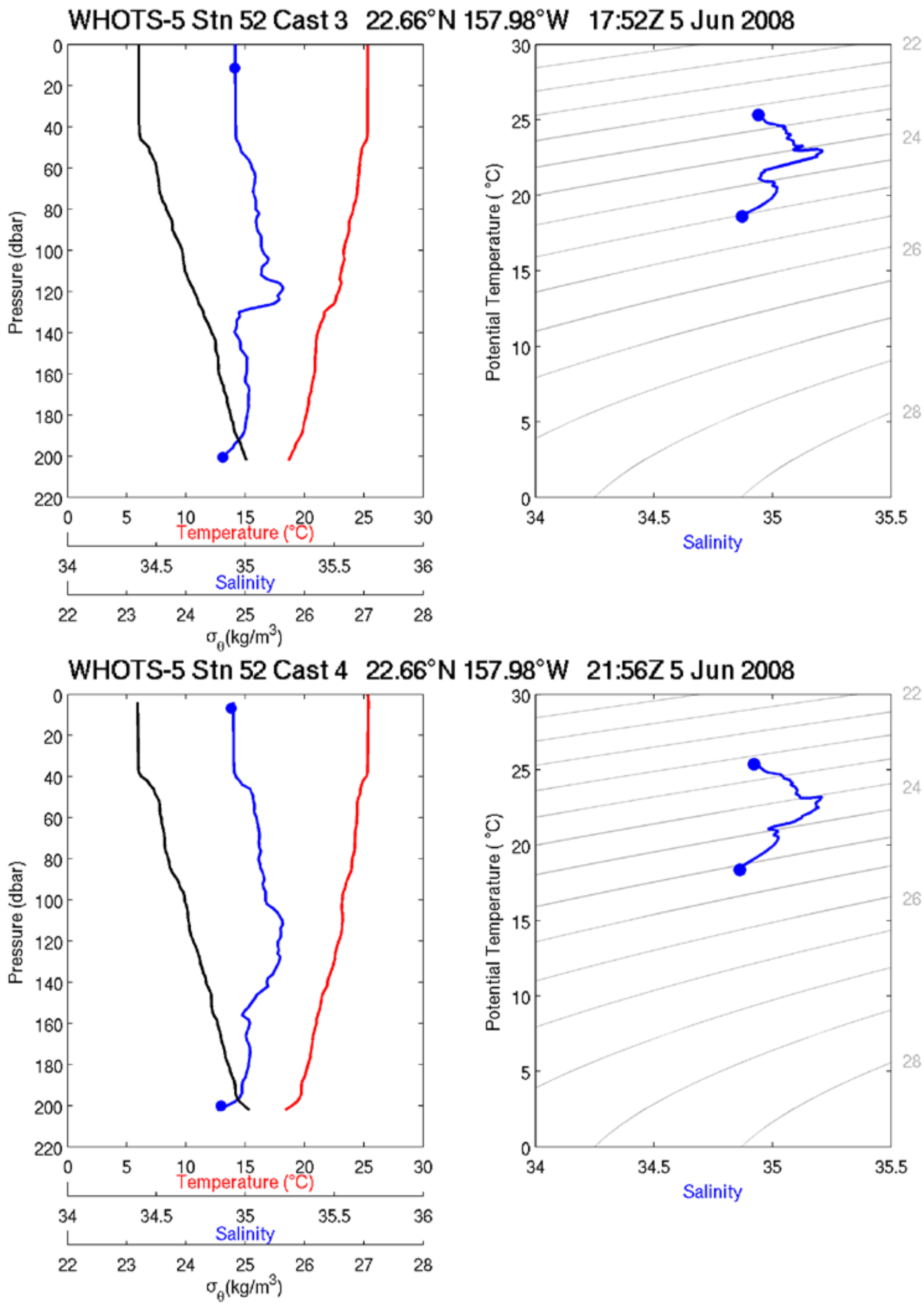


Figure 6-13[Upper panels] Same as in Figure 6-9, but for station 52, cast 3. [Lower panels] Same as in Figure 6-9, but for station 52, cast 4.

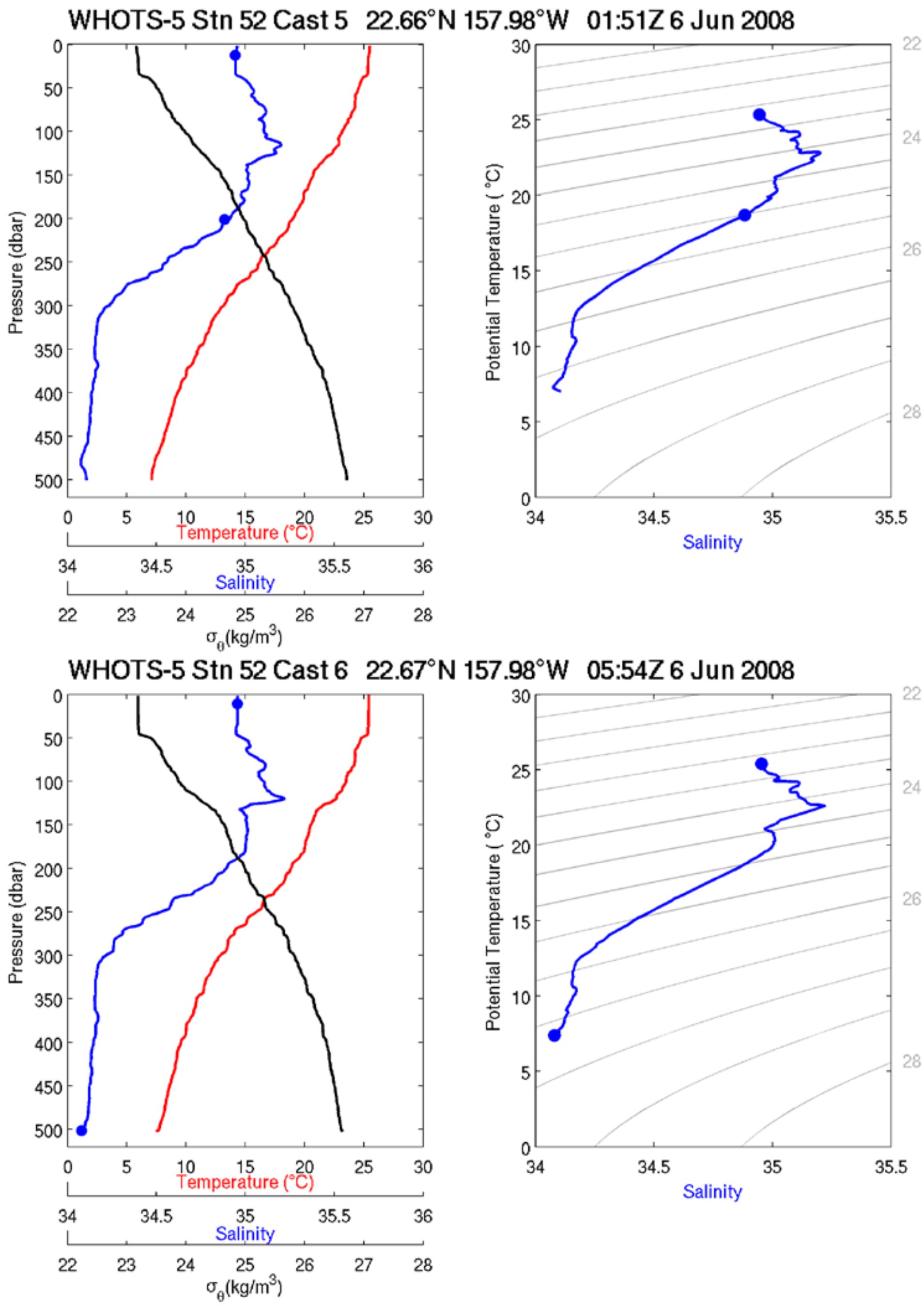


Figure 6-14[Upper panels] Same as in Figure 6-9, but for station 52, cast 5. [Lower panels] Same as in Figure 6-9, but for station 52, cast 6.

B. Thermosalinograph data

Underway measurements of near surface temperature and near surface salinity from thermosalinograph as well as navigation for the WHOTS-4 and -5 cruises are included from Figure 6-15 through Figure 6-18.

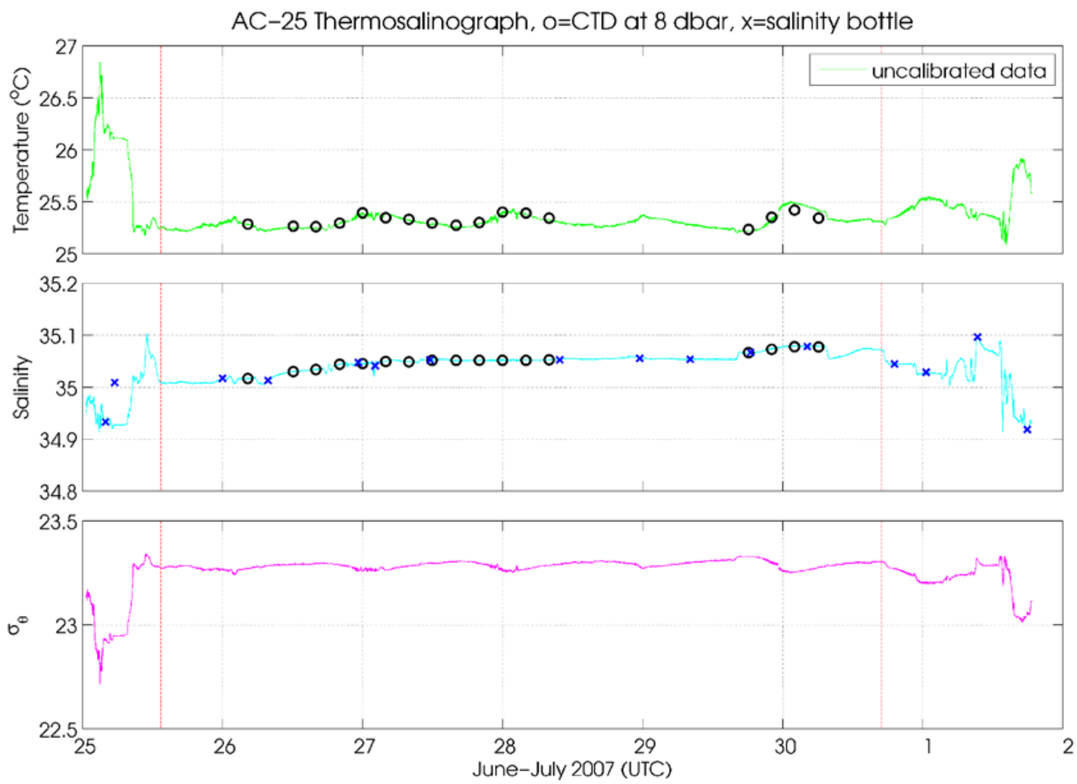


Figure 6-15 Final processed temperature (upper panel), salinity (middle panel) and potential density (σ_θ) (lower panel) data from the continuous underway system on board the RV Kilo Moana during the WHOTS-4 cruise. Temperature and salinity taken from 6-dbar CTD data (circles) and salinity bottle sample data (crosses) are superimposed. The dashed vertical red line indicates the period of occupation of Station ALOHA and the WHOTS site.

Figure 6-16. Timeseries of latitude (upper panel), longitude (middle panel), and ship's speed (lower panel) during the WHOTS-4 cruise aboard R/V Kilo Moana.

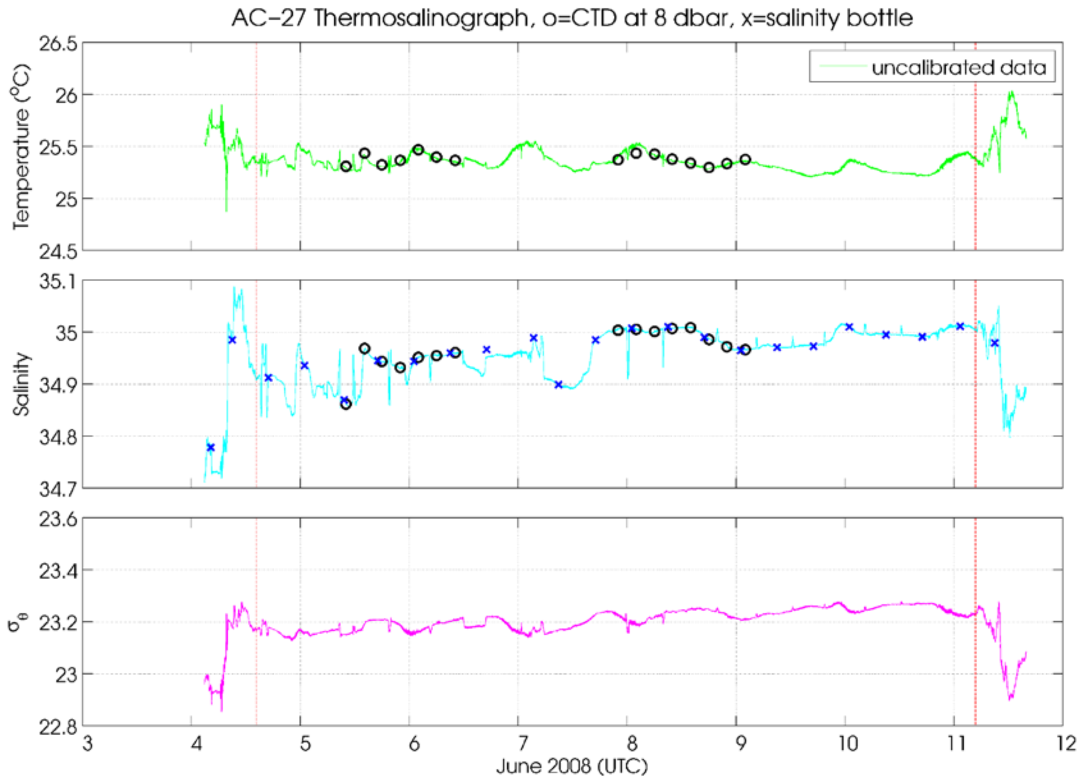


Figure 6-17. Same as Figure 6-15, but for WHOTS-5 aboard R/V Kilo Moana.

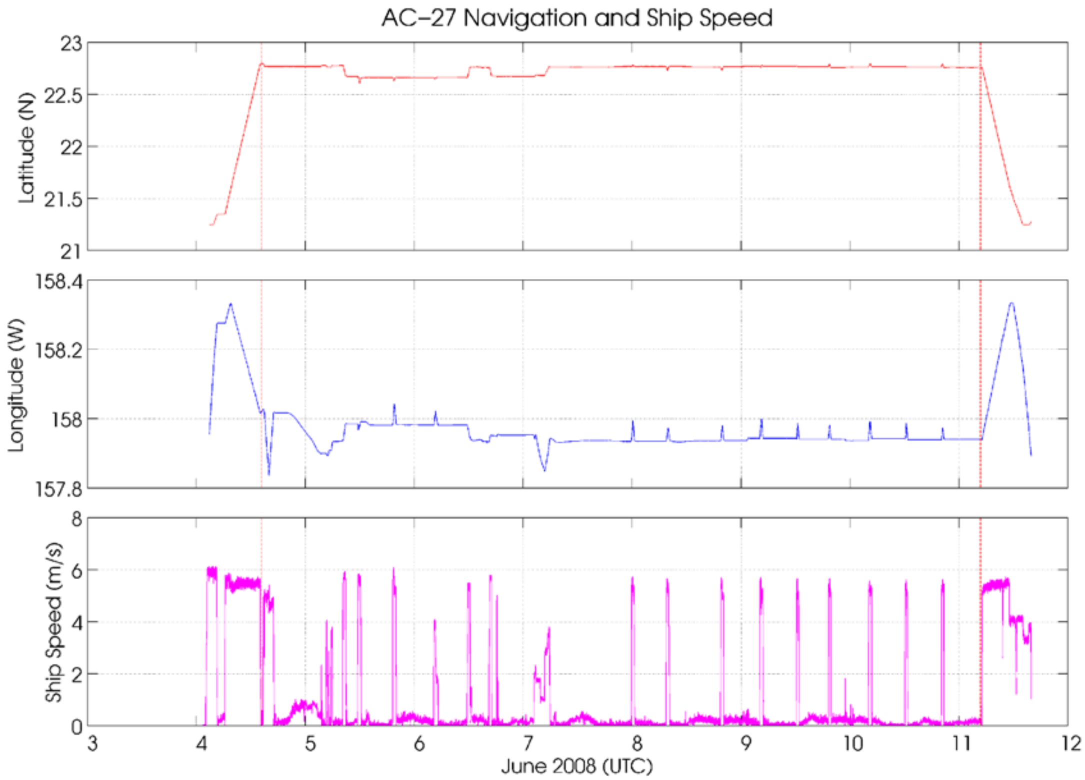


Figure 6-18. Same as Figure 6-16, but for WHOTS-5 aboard R/V Kilo Moana.

C. SeaCAT/MicroCAT data

The temperature, salinity and potential density (σ_θ) time-series measured by the SeaCATs and MicroCATs during the WHOTS-4 mooring deployments are presented in Figure 6-19 to Figure 6-30 for each of the depths where the instruments were located.

Contoured plots of temperature and salinity as a function of depth and time are presented in Figure 6-31, and contoured plots of potential density (σ_θ) and buoyancy frequency as a function of depth are in Figure 6-32.

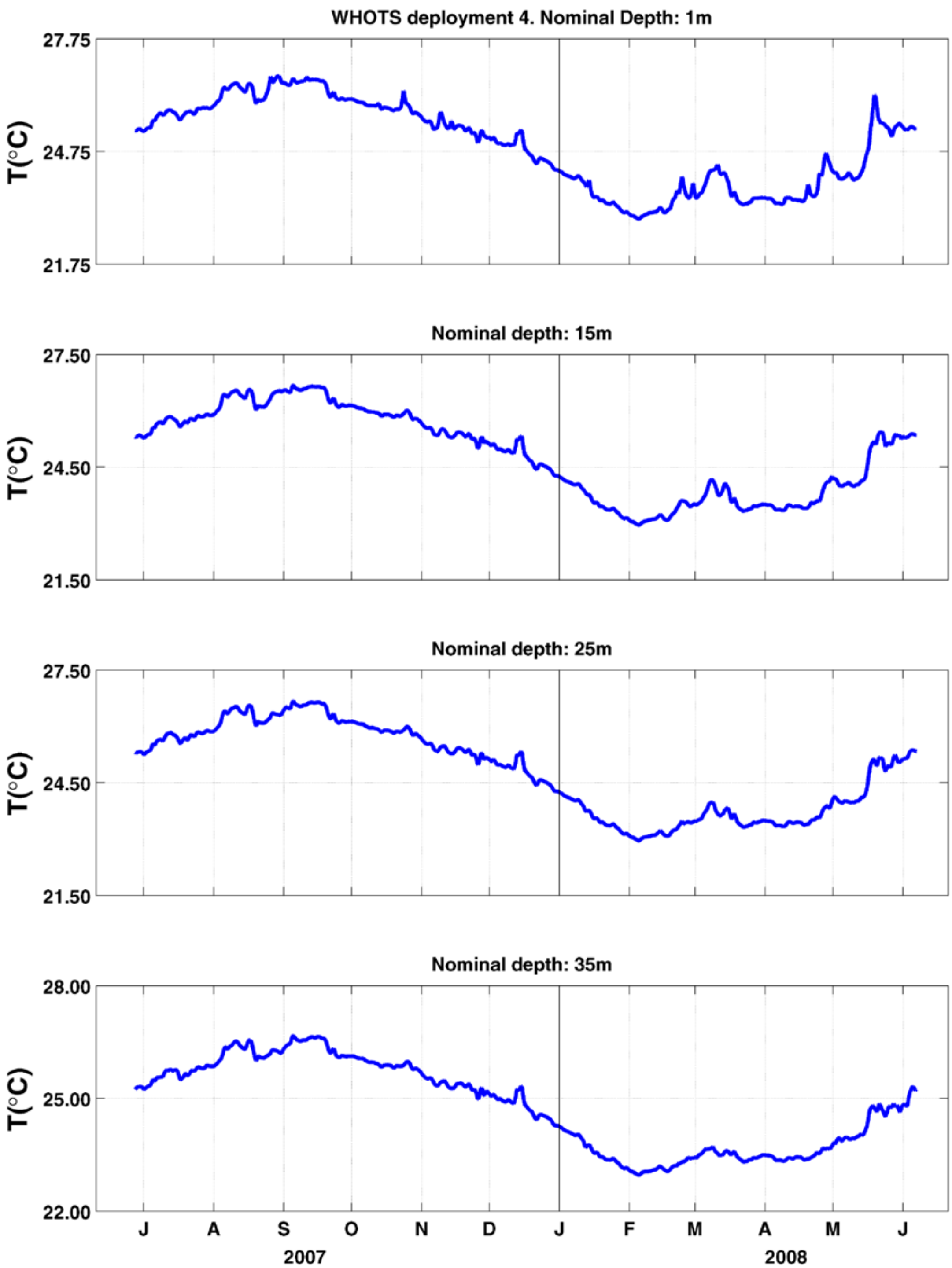


Figure 6-19. Temperatures from MicroCATs during WHOTS-4 deployment at 1, 15, 25, and 35 m.

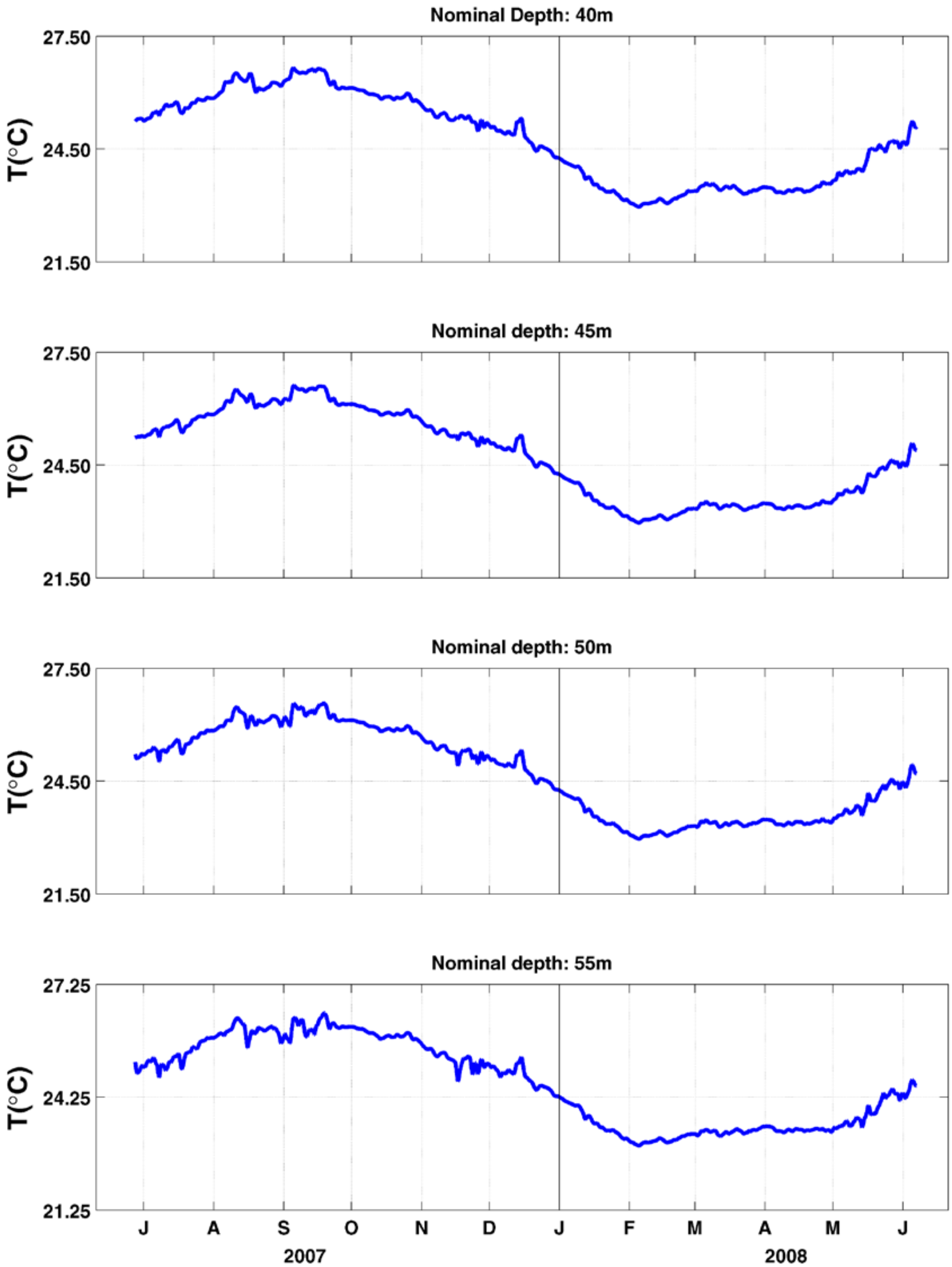


Figure 6-20. Same as in Figure 6-19, but at 40, 45, 50, and 55 m.

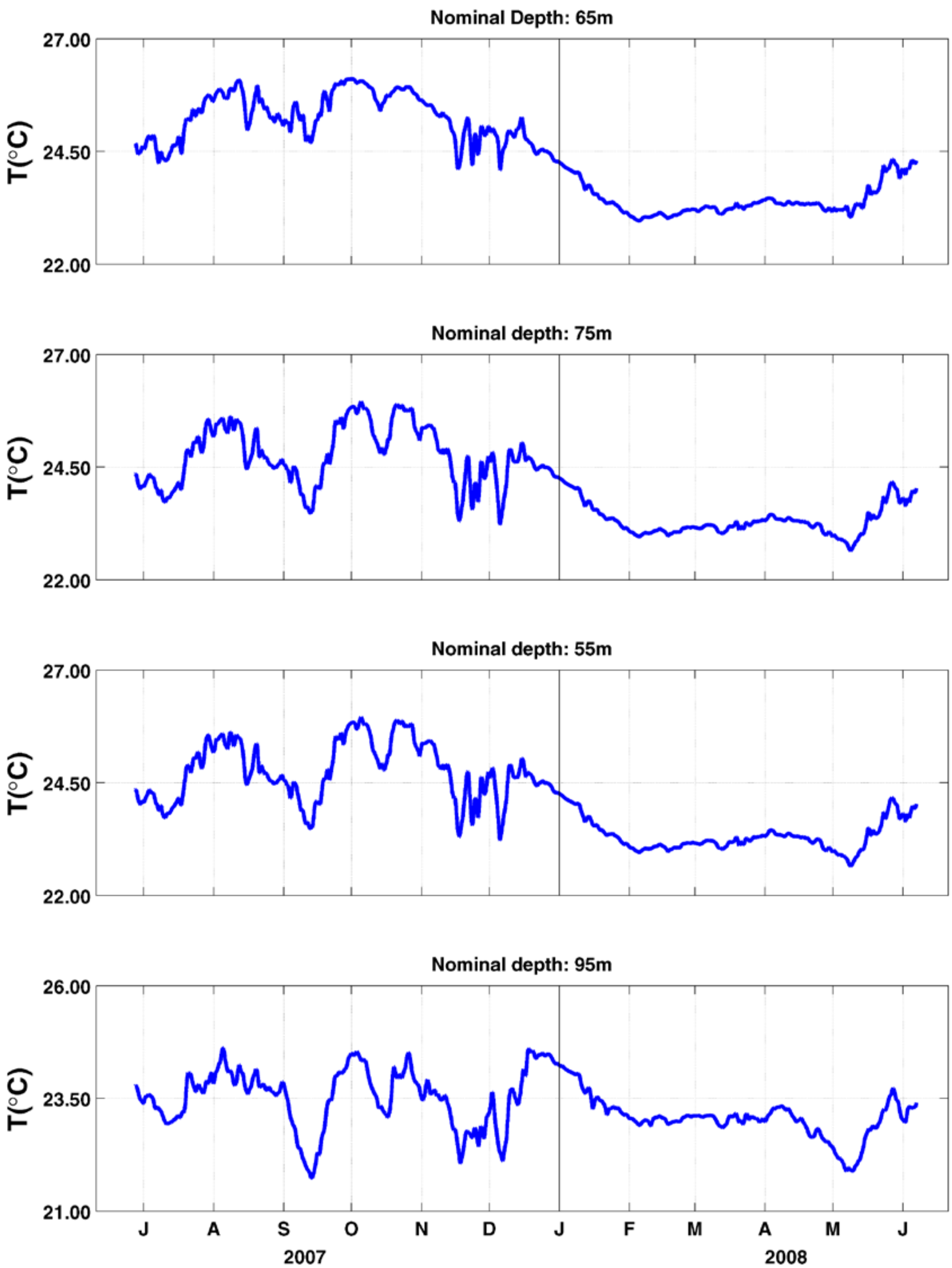


Figure 6-21. Same as in Figure 6-19, but at 65, 75, 85, and 95 m.

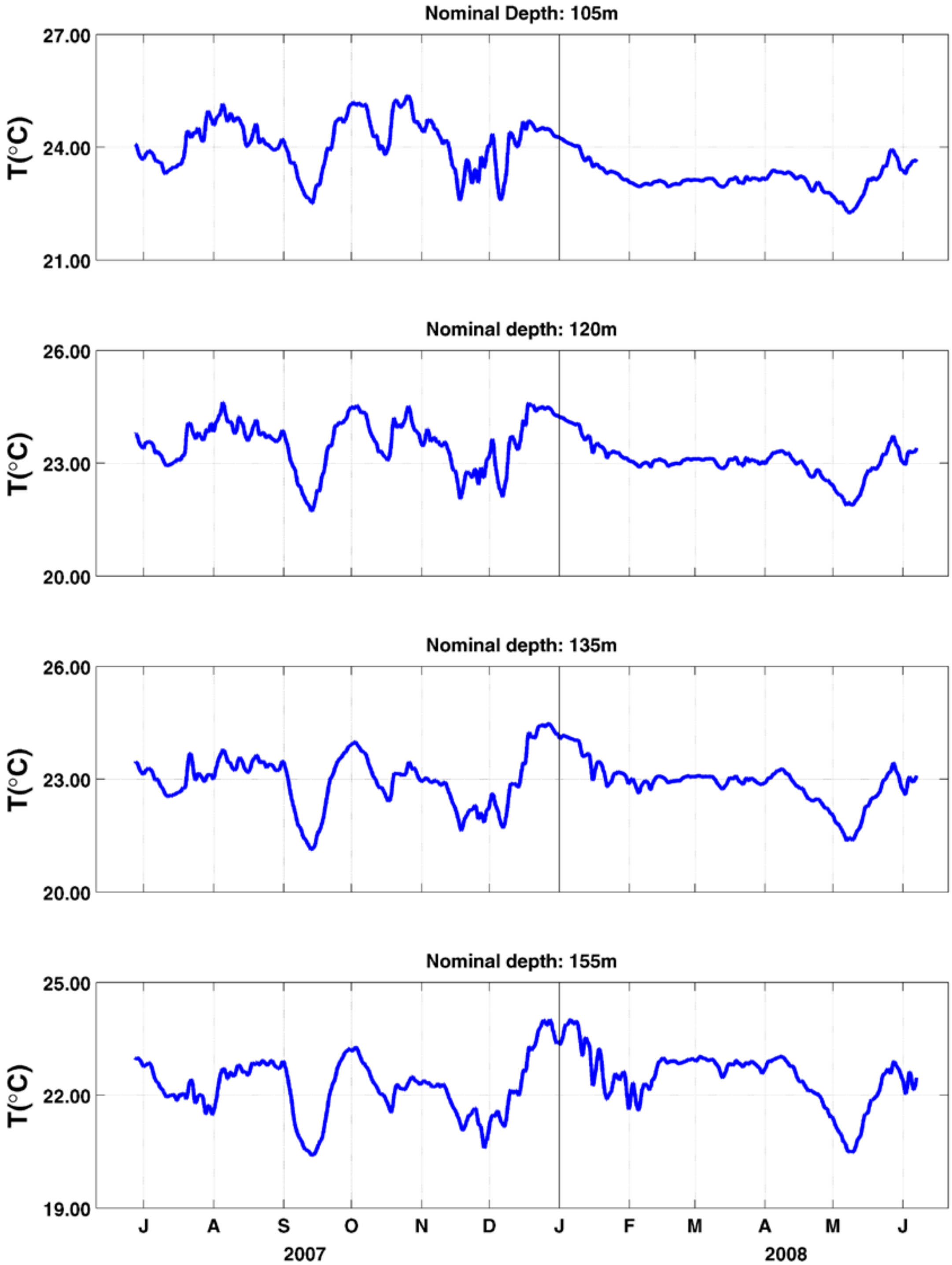


Figure 6-22. Same as in Figure 6-19, but at 105, 120, 135, and 155 m.

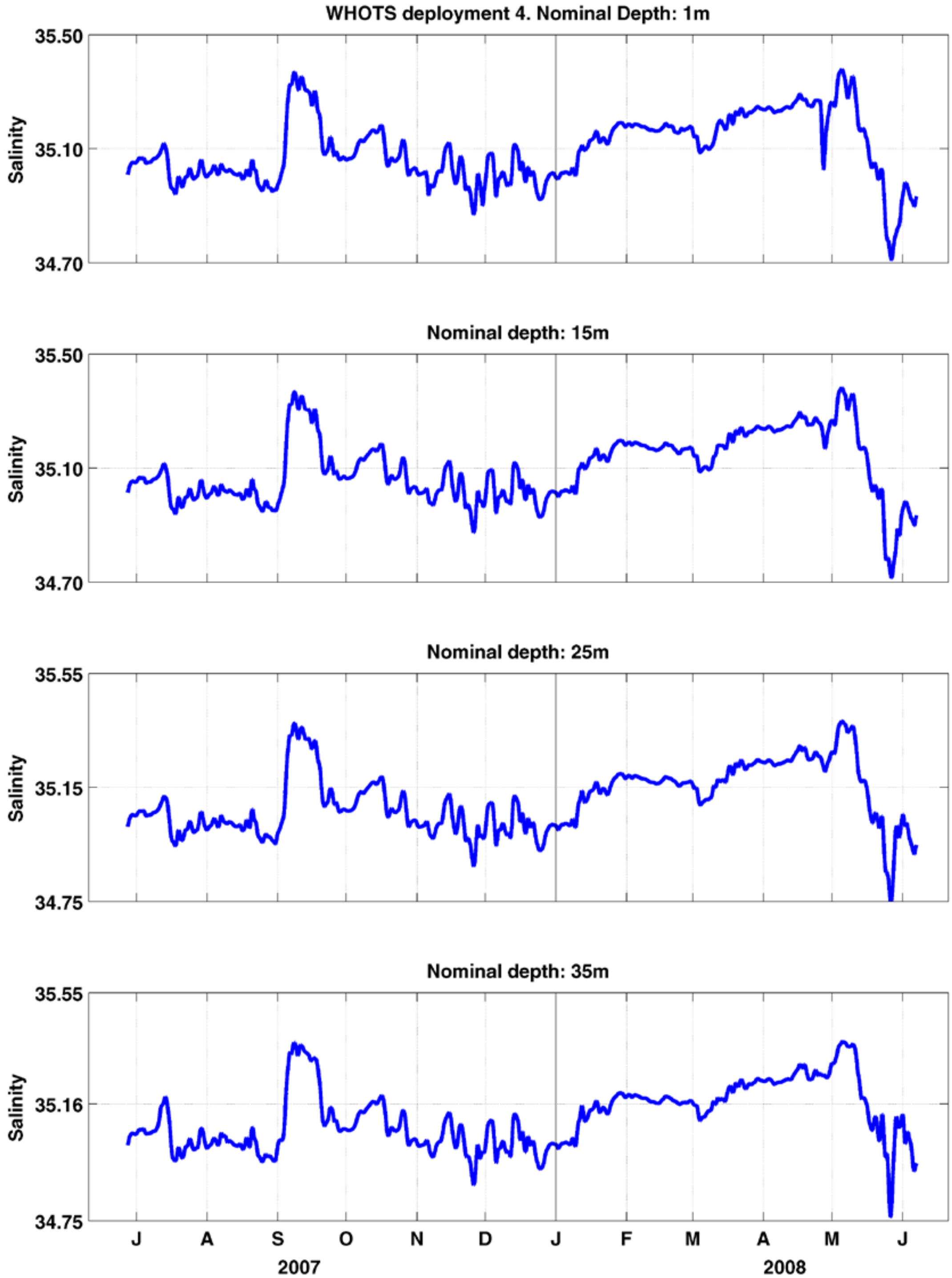


Figure 6-23. Salinities from MicroCATs during WHOTS-4 deployment at 1, 15, 25, and 35 m.

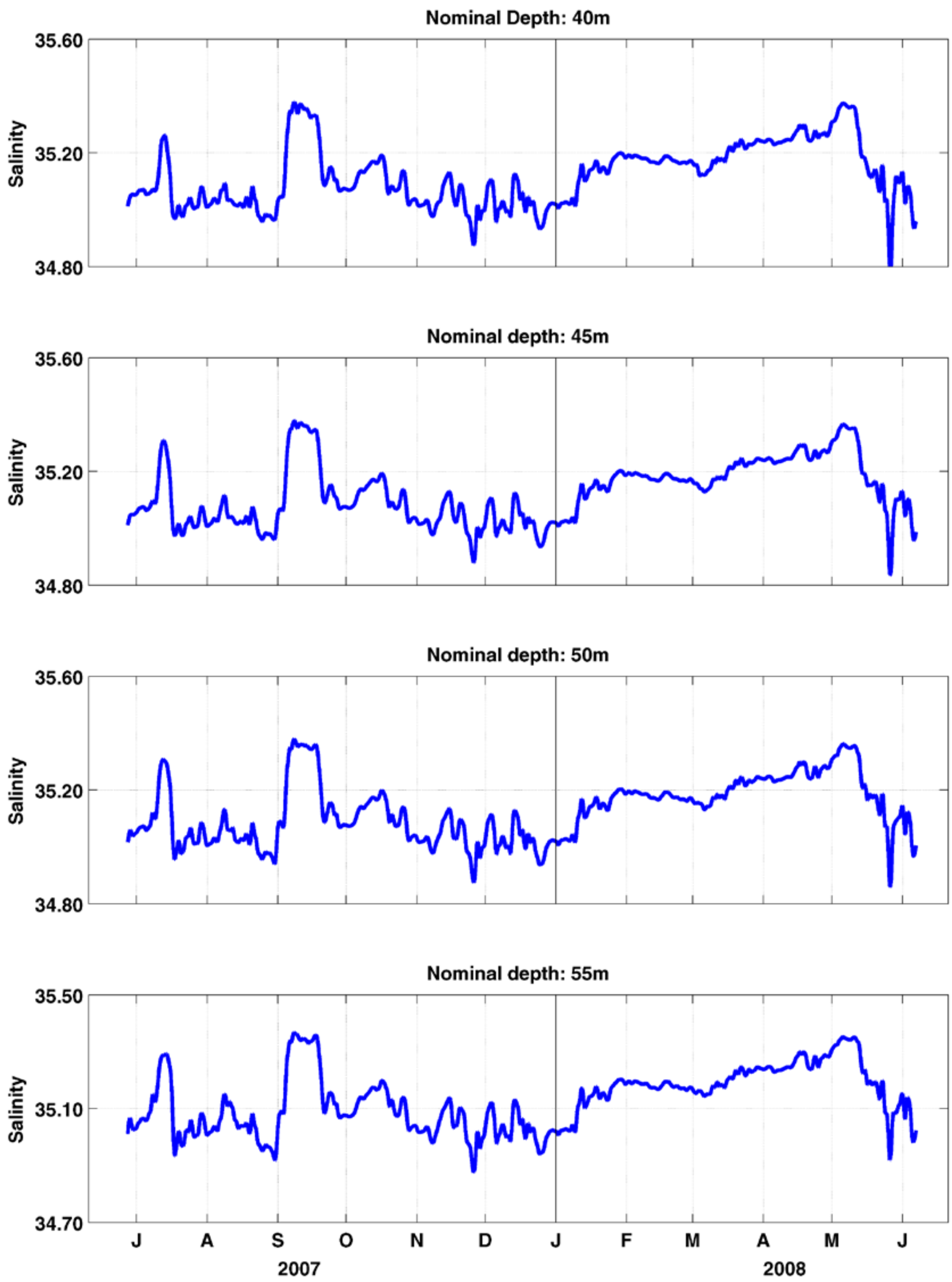


Figure 6-24. Same as in Figure 6-23, but at 40, 45, 50, and 55 m.

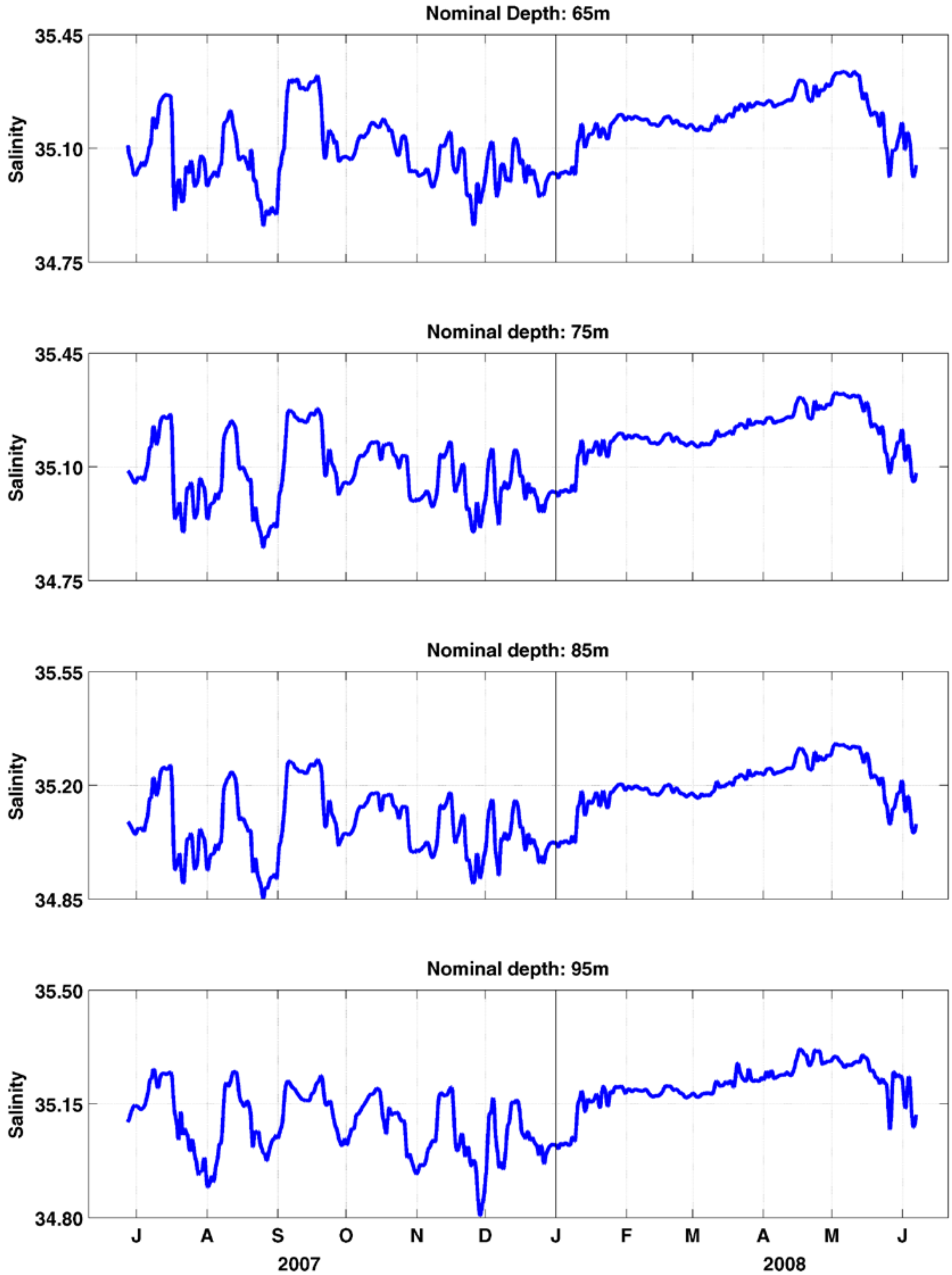


Figure 6-25. Same as in Figure 6-23, but at 65, 75, 85, and 95 m.

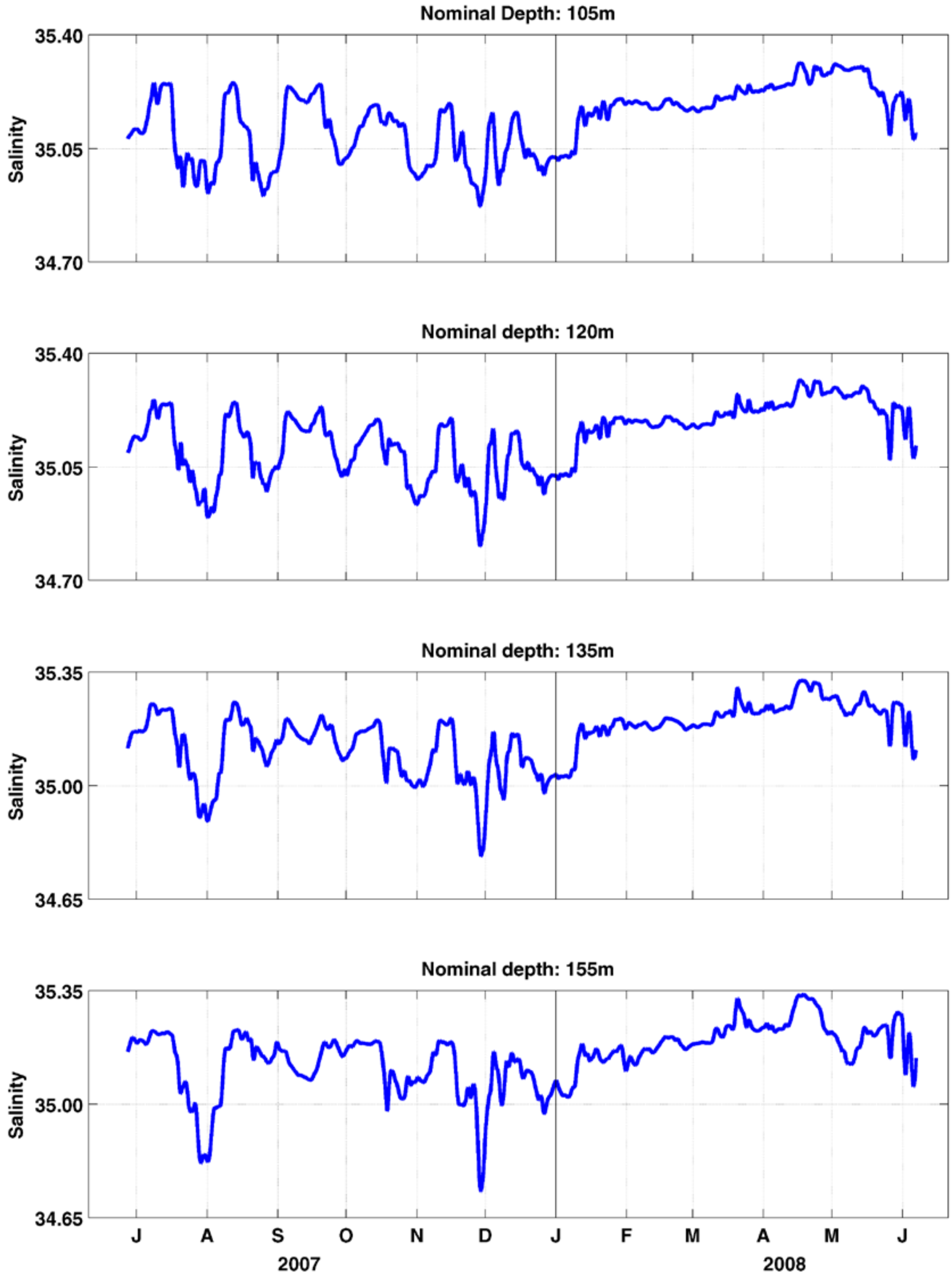


Figure 6-26. Same as in Figure 6-23, but at 105, 120, 135, and 155 m.

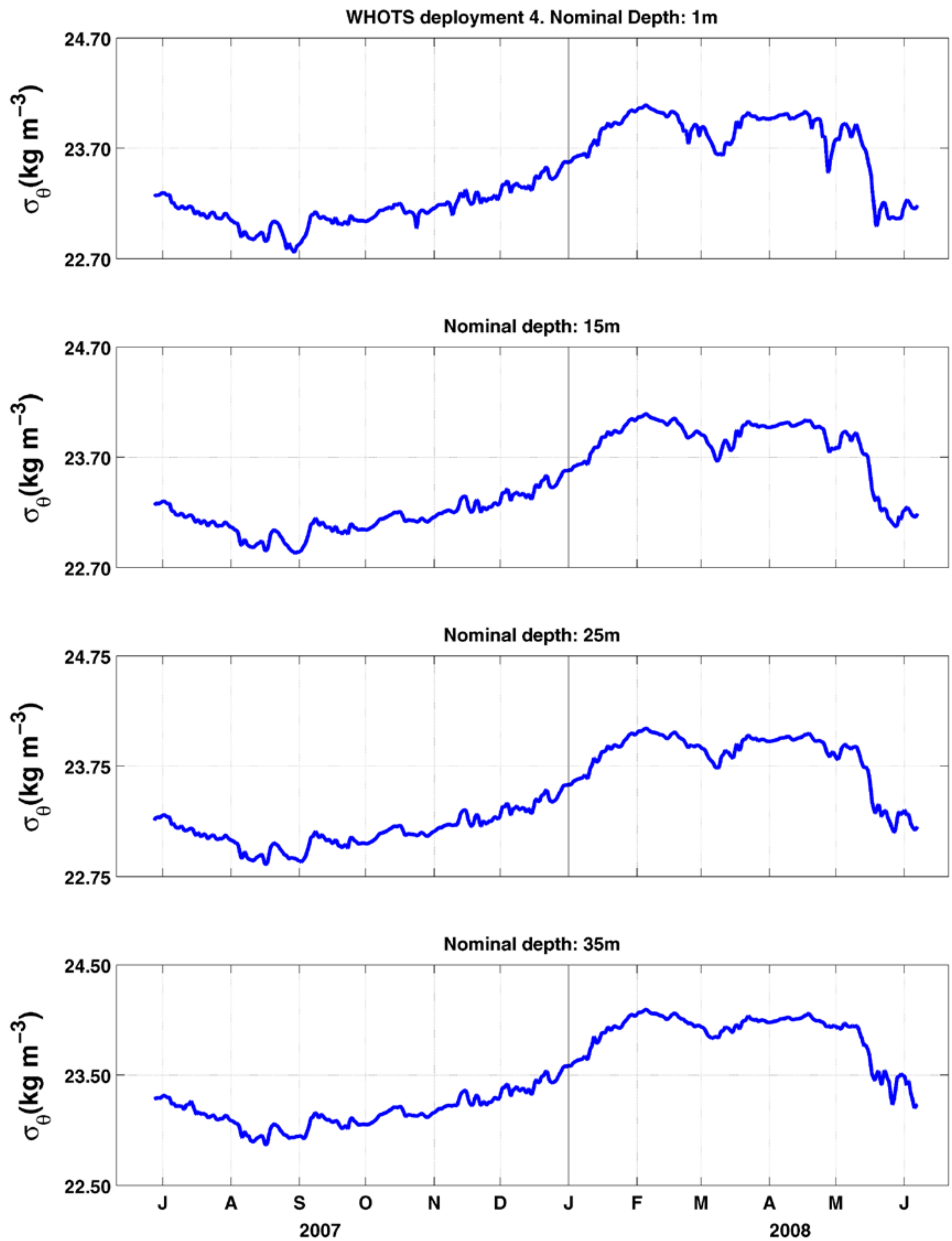


Figure 6-27. Potential density (σ_θ) from MicroCATs during WHOTS-4 deployment at 1, 15, 25, and 35 m.

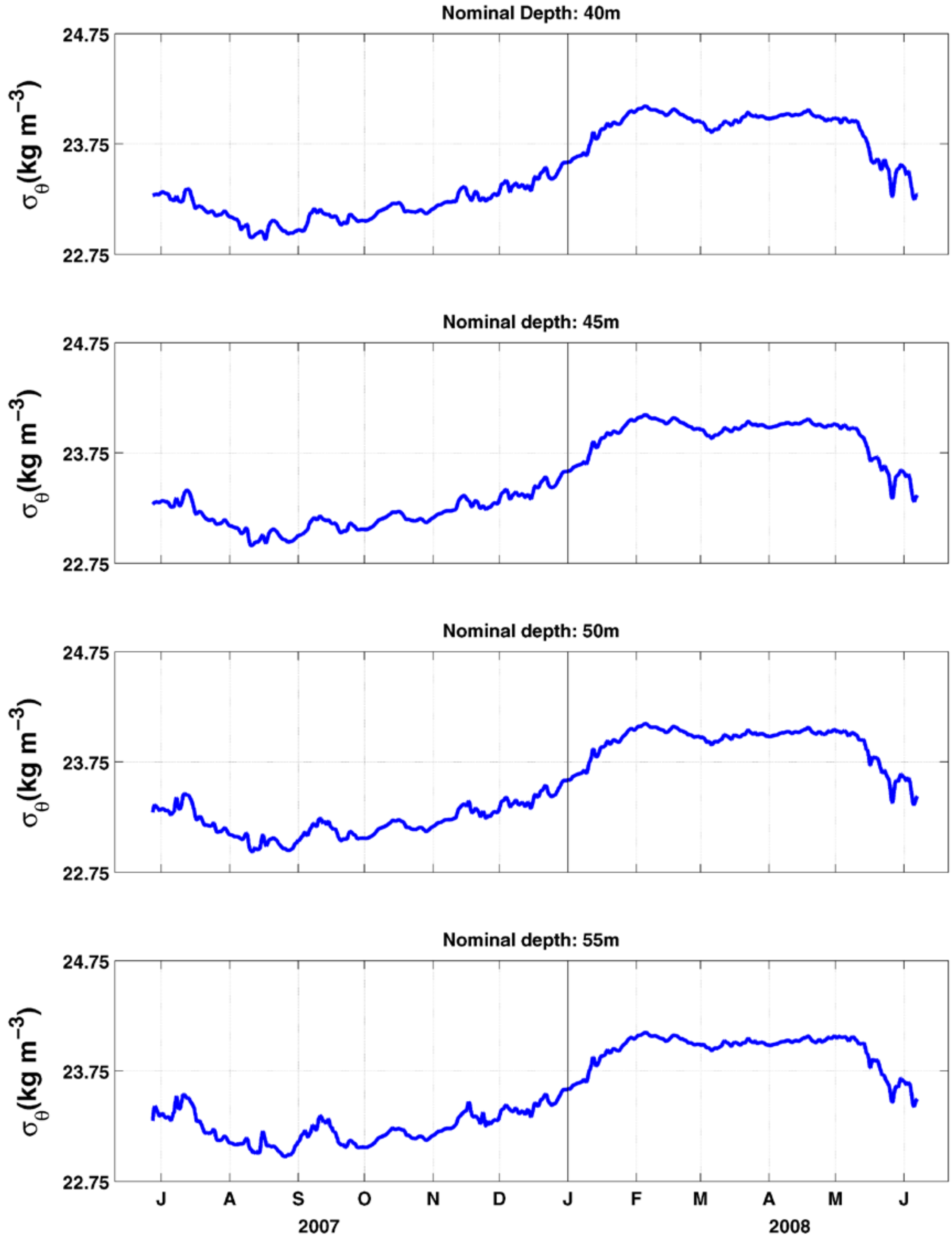


Figure 6-28. Same as in Figure 6-27, but at 40, 45, 50, and 55 m.

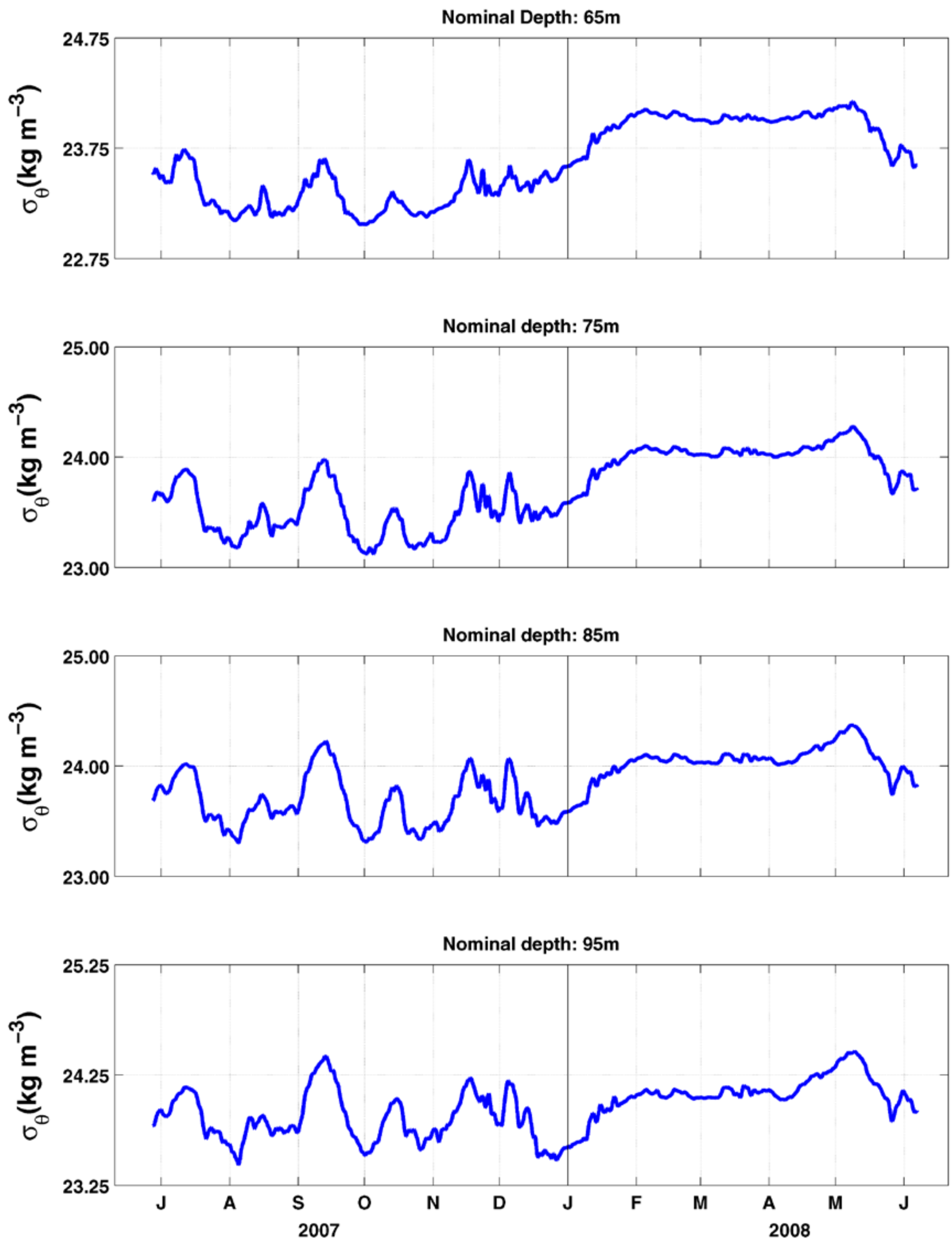


Figure 6-29. Same as in Figure 6-27, but at 65, 75, 85, and 95 m.

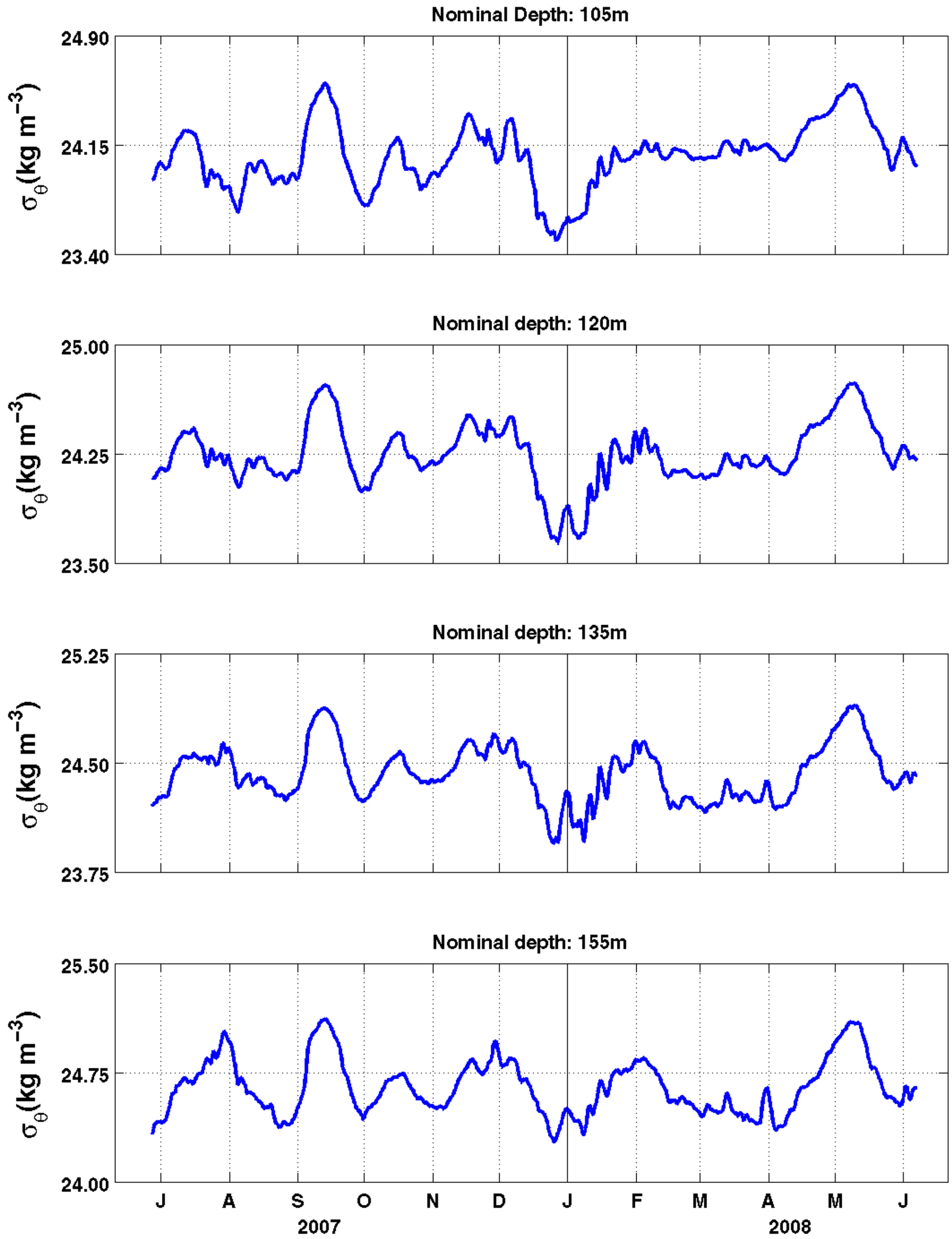


Figure 6-30. Same as in Figure 6-27, but at 105, 120, 135, and 155 m.

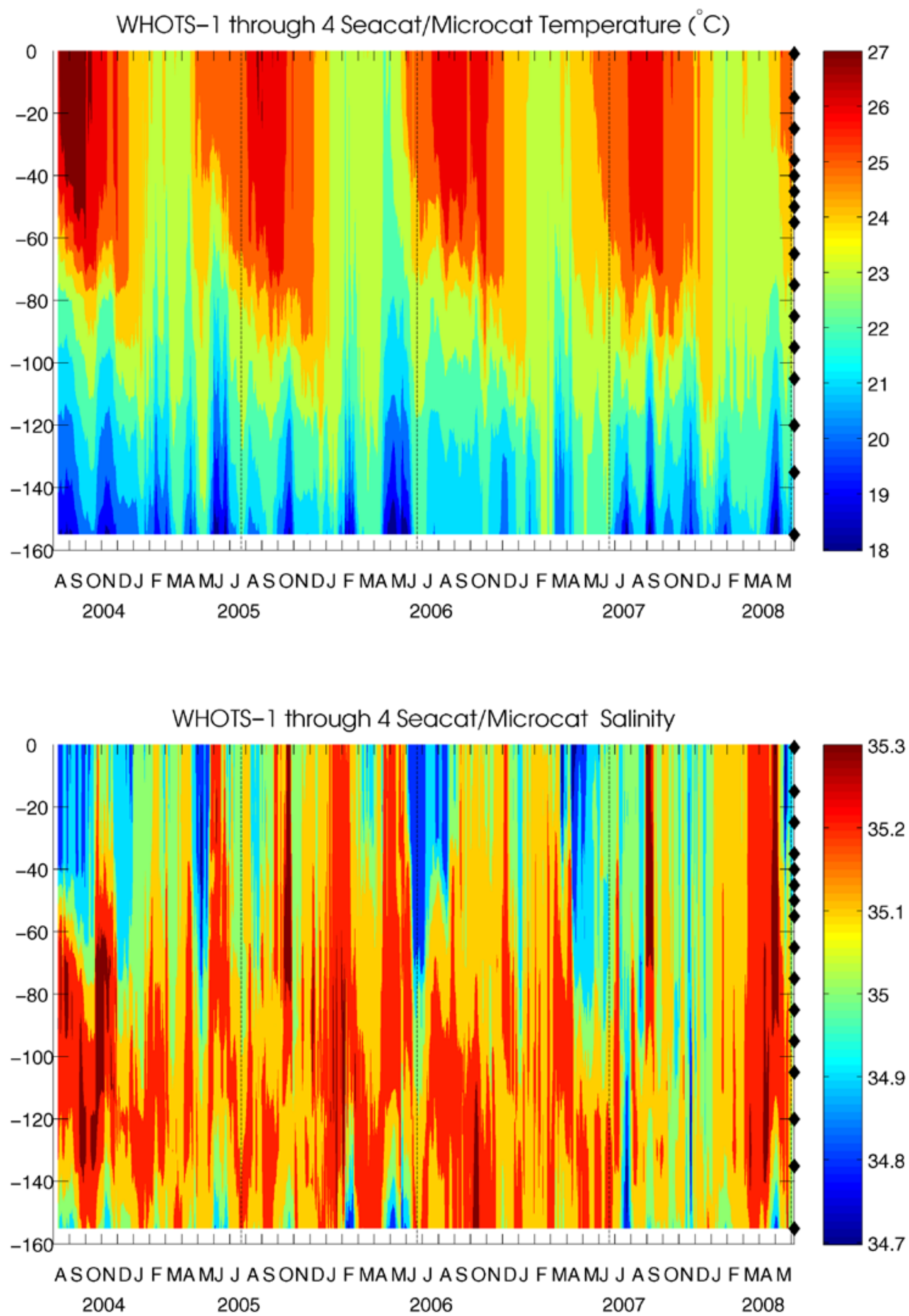


Figure 6-31. Contour plots of temperature (upper panel), and salinity (lower panel) versus depth from SeaCATs/ MicroCATs during WHOTS-1 through WHOTS-4 deployments. The vertical dashed line indicates the transition between deployments. The diamonds along the right axis indicate the instruments depths.

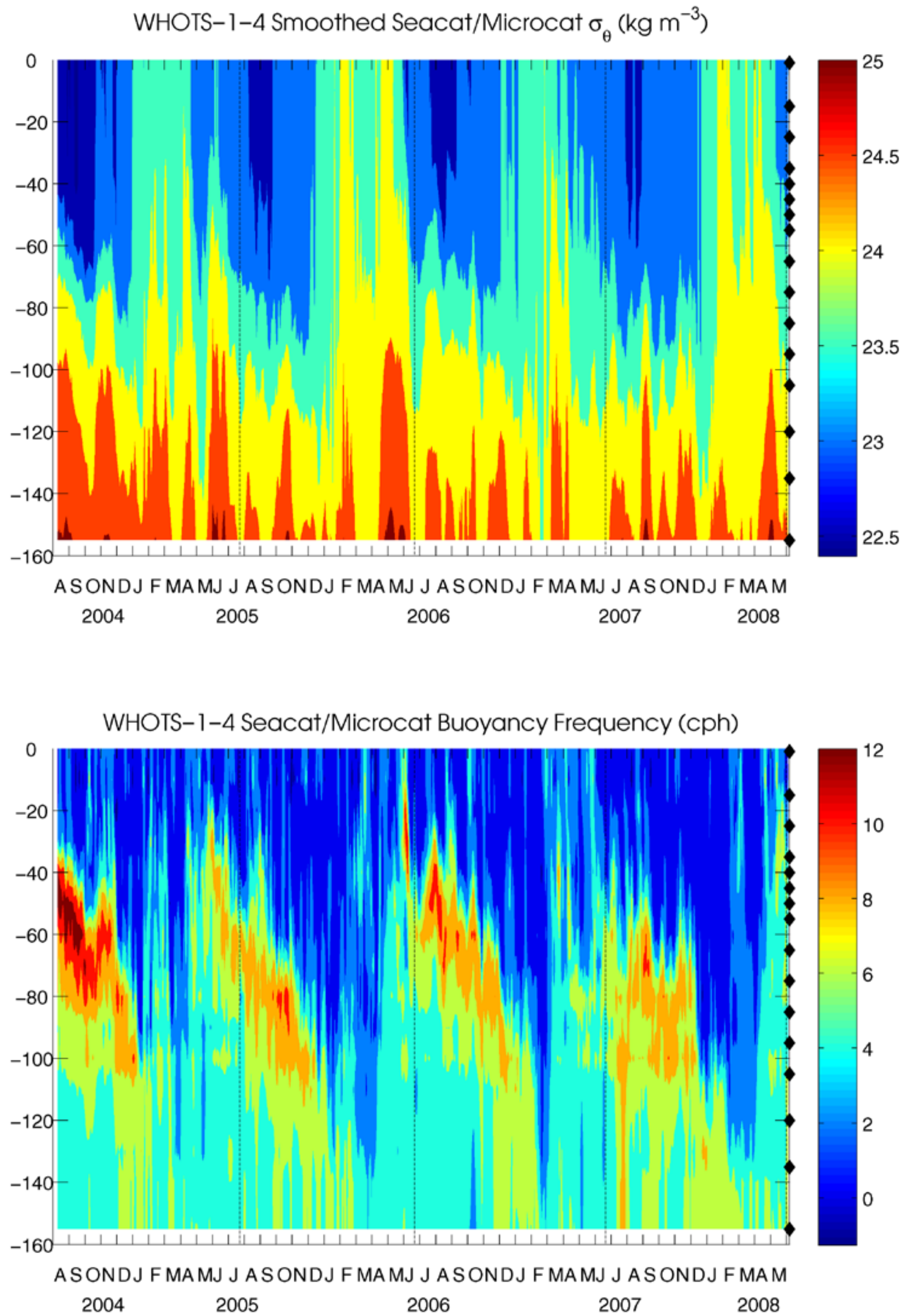


Figure 6-32. Contour plots of potential density (σ_θ , upper panel), and buoyancy frequency (lower panel) versus depth from SeaCATs/MicroCATs during WHOTS-1 through -4 deployments. The vertical dashed line indicates the transition between deployments. The diamonds along the right axis indicate the instruments depths.

D. Moored ADCP data

Contoured plots of horizontal and vertical velocity as a function of depth during the WHOTS-4 mooring deployment are presented in Figure 6-33 to Figure 6-35. The ADCP data shown are quality controlled and are gridded to a one day by five meter grid. A staggered time-series of smoothed horizontal and vertical velocities are shown in Figure 6-36 to Figure 6-38.

Figure 6-33. Contour plot of east velocity component (m s^{-1}) versus depth and time from the moored ADCPs from the WHOTS-1 through 4 deployments.

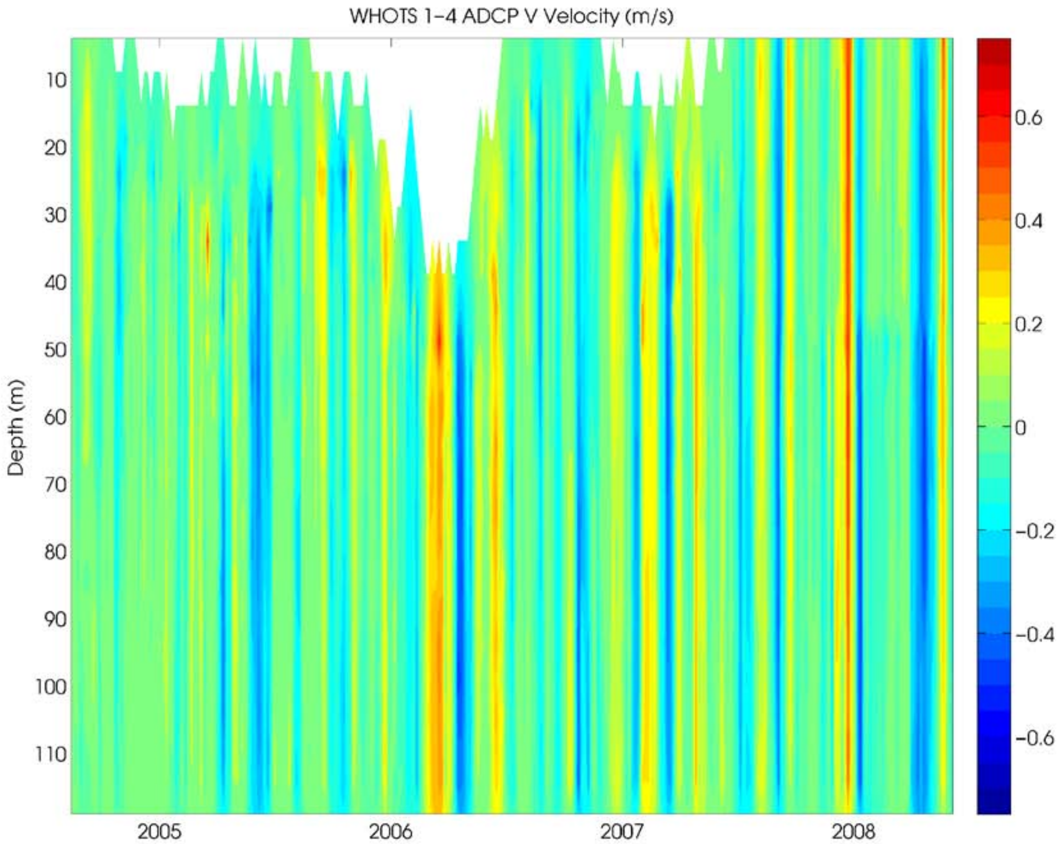


Figure 6-34. Contour plot of north velocity component (m s^{-1}) versus depth and time from the moored ADCPs from the WHOTS-1 through 4 deployments.

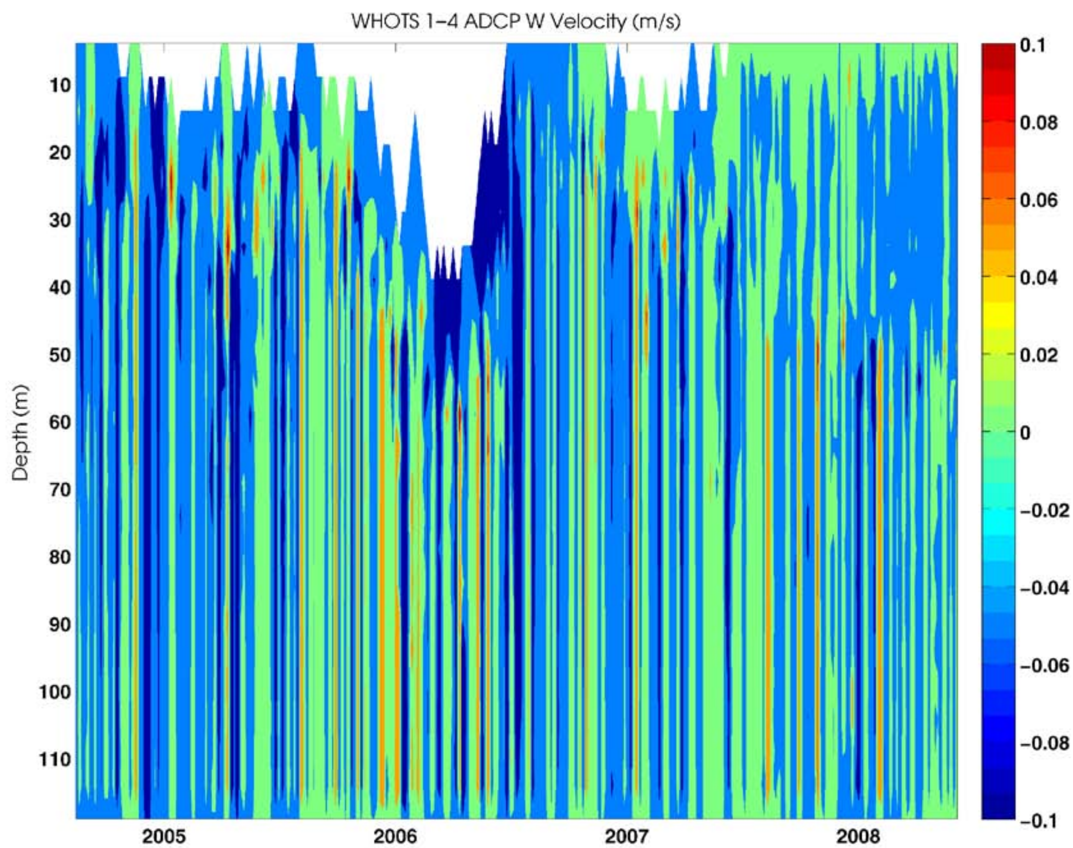
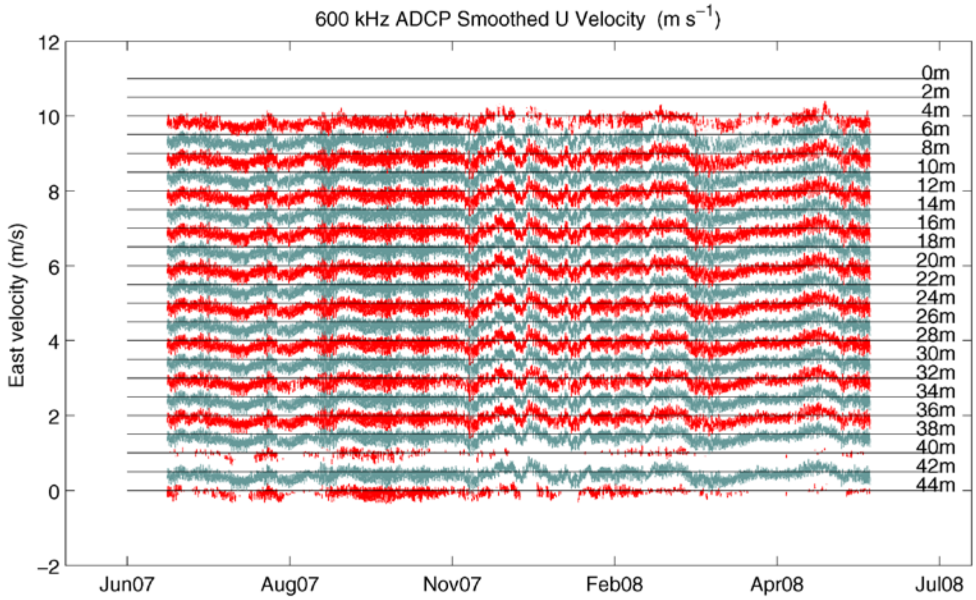


Figure 6-35. Contour plot of vertical velocity component (m s^{-1}) versus depth and time from the moored ADCPs from the WHOTS-1 through 4 deployments.



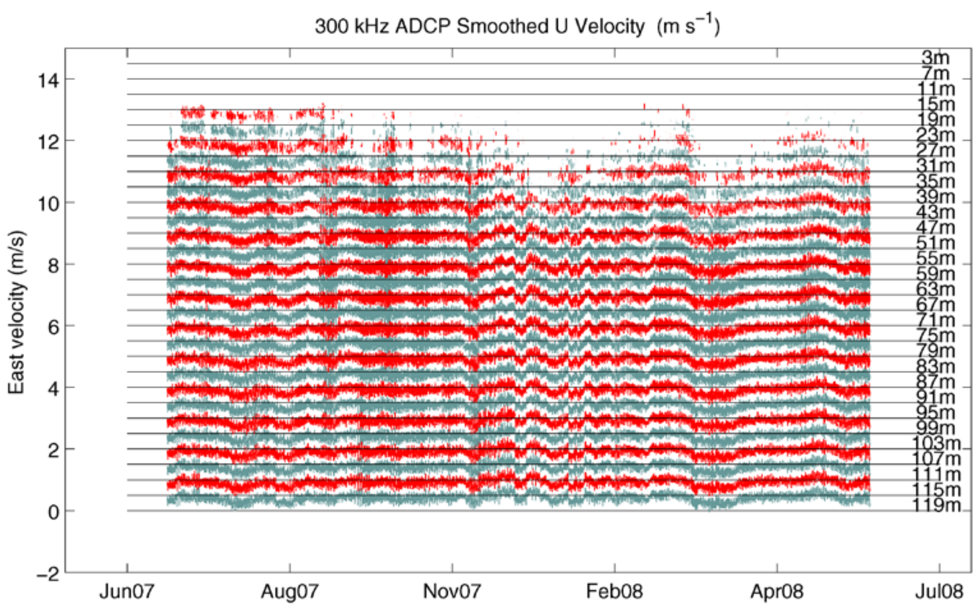
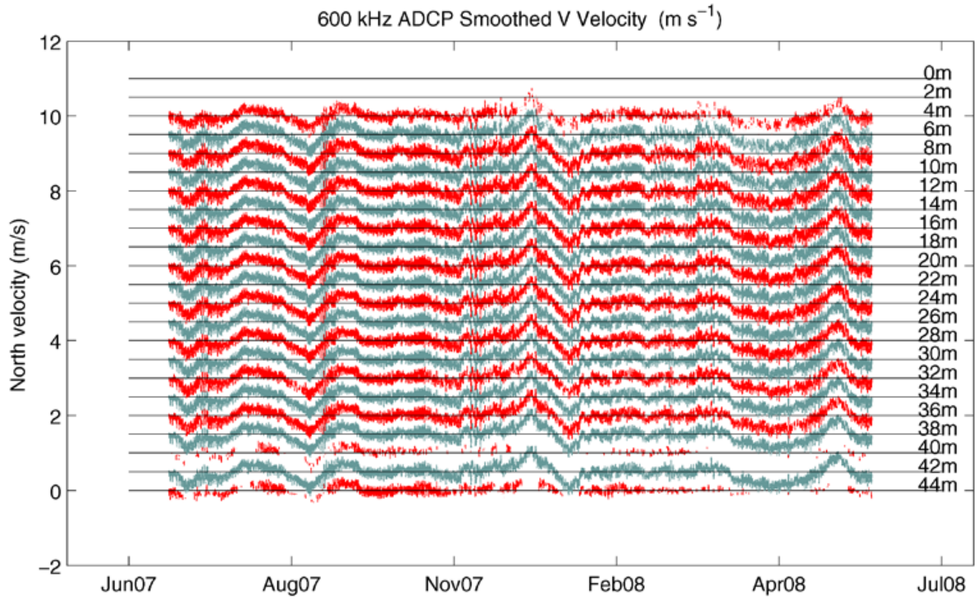


Figure 6-36. Staggered time-series of east velocity component (m s^{-1}) for each bin of the 600 kHz (upper panel), and 300 kHz (lower panel) moored ADCPs during WHOTS-4. The time-series are offset upwards by 0.5 m s^{-1}, the depth of each bin is on the right.



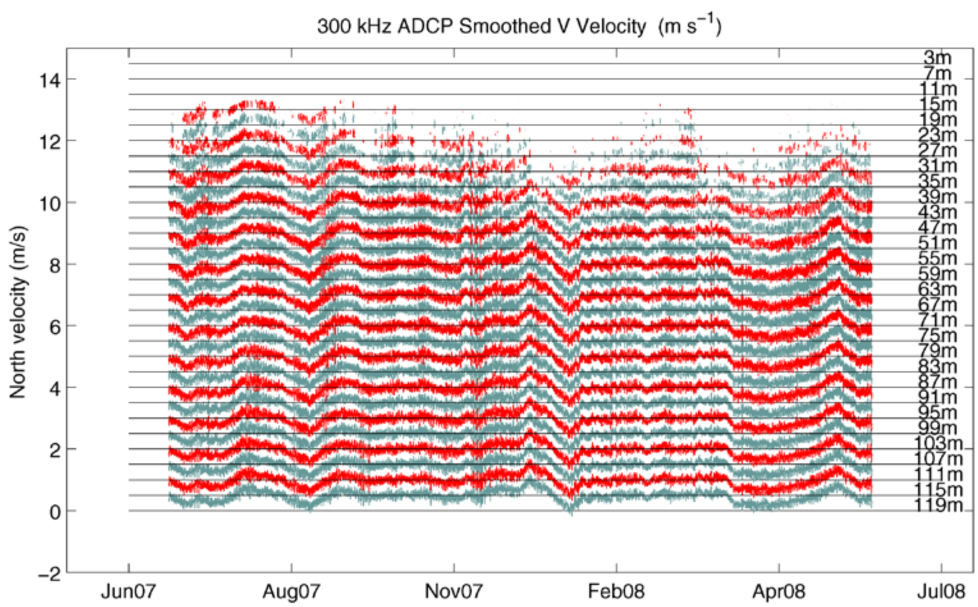


Figure 6-37. Staggered time-series of north velocity component (m s^{-1}) for each bin of the 600 kHz (upper panel), and 300 kHz (lower panel) moored ADCPs during WHOTS-4. The time-series are offset upwards by 0.5 m s^{-1}, the depth of each bin is on the right.

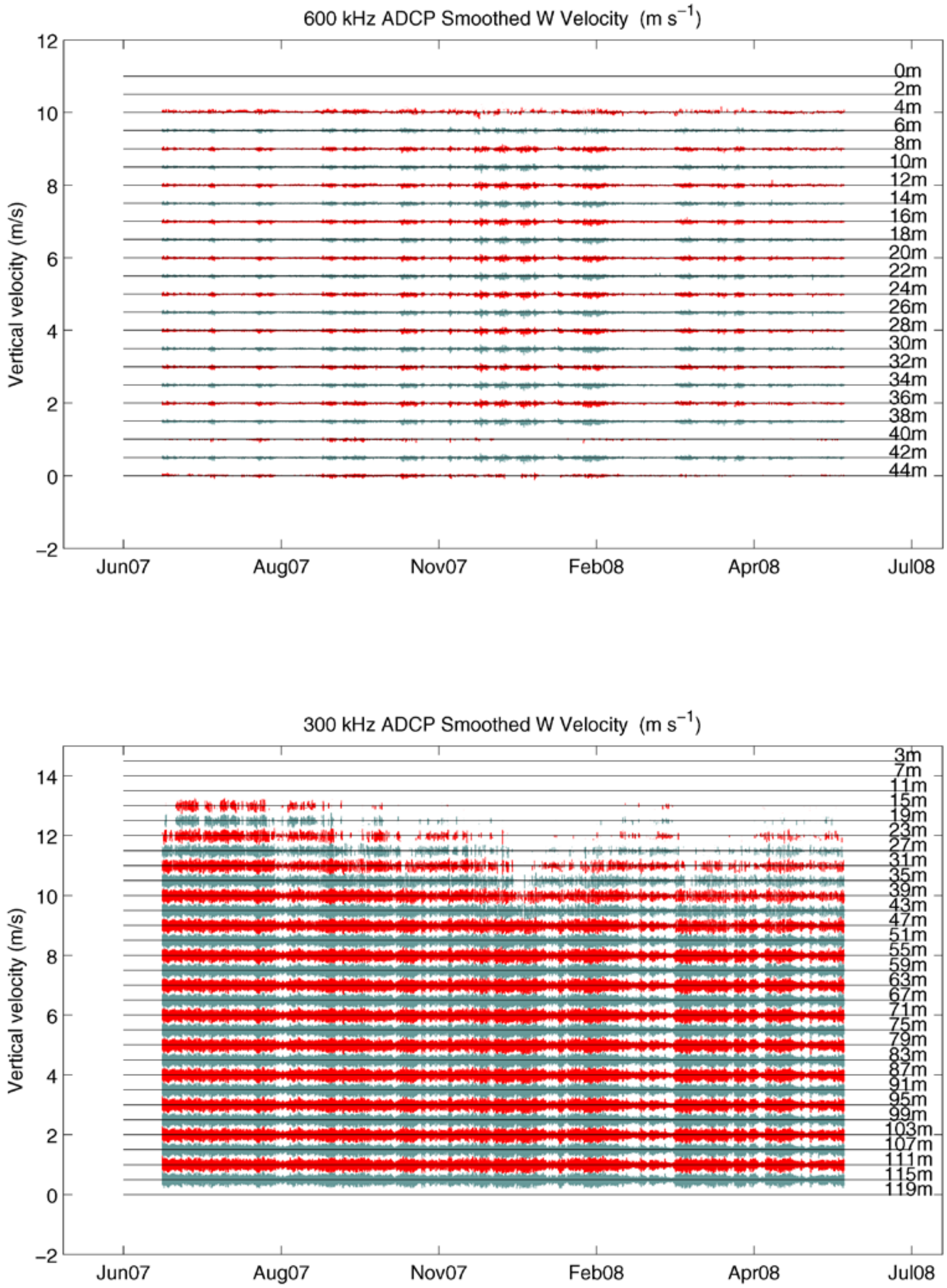


Figure 6-38. Staggered time-series of vertical velocity component (m s^{-1}) for each bin of the 600 kHz (upper panel), and 300 kHz (lower panel) moored ADCPs during WHOTS-4. The time-series are offset upwards by 0.5 m s^{-1}, the depth of each bin is on the right.

E. Moored and Shipboard ADCP comparisons

Comparisons between quality-controlled moored ADCPs during the WHOTS-4 deployment and available shipboard ADCP obtained during regular HOT cruises 193, 194, 195, 197 (600 kHz only), 198, 199, and 200 are shown in Figure 6-39 to Figure 6-44 for the 300 kHz ADCP and Figure 6-45 through Figure 6-51 for the 600 kHz ADCP. HOT cruises with comparable ADCP data were conducted on the R/V *Kilo Moana* which featured a shipboard RD Instruments Workhorse 300 kHz ADCP (wh300) with 4 m bin size, reaching 100 m, and averaging ensembles every 2 minutes. HOT-196 shipboard ADCP profiles weren't available for comparison with the moored ADCPs since this cruise was conducted on the R/V *Ka'imikai-O-Kanaloa* , which only feature shipboard ADCPs intended for deeper water column current velocity measurements. Additionally, there wasn't enough data from HOT-197 (300 kHz only) and HOT-201 (both ADCP's) for comparisons with shipboard profiles.

Current velocity profiles from each instrument were collected during the time when HOT CTD casts were being conducted near the WHOTS mooring specifically intended to calibrate moored instrumentation (see 5.A.4). In order to compare these HOT shipboard current profiles with moored ADCP data, each of the zonal (U) and meridional (V) current components from the moored vertical profiles were interpolated to the profile resolution of the shipboard ADCP. Data from depth bins were rejected if more than 30% of the available data during the cruise comparison period from either source were flagged as bad. The comparison period during each cruise was typically an hour and a half to two hours long. Mean difference and RMS difference values were then calculated for each bin. The vertical average of mean and RMS differences (moored – shipboard) for each of the U and V components are shown in Table 6-1.

Mean U differences were mostly between -0.02 and 0.02 m/s (with exception to HOT-198). Mean V differences were more variable between HOT cruises, ranging between -0.04 and 0.10 m/s. RMS difference exhibited similar characteristics in U and V, mostly ranging between 0.02 and 0.10 m/s. There was significant variability with depth for both the mean and RMS difference profiles for the majority of cruises.

Table 6-1. Vertical average of mean and RMS differences between shipboard (300 kHz) and moored (300 kHz[top] and 600 kHz[bottom])) ADCP profiles taken during HOT CTD casts next to the mooring.

HOT Shipboard ADCP vs WHOTS Moored 300 kHz ADCP					
Cruise	**Ship ADCP Type**	**Vertical average of mean U differences (m/s)**	**Vertical average of RMS U differences (m/s)**	**Vertical average of mean V differences (m/s)**	**Vertical average of RMS V differences (m/s)**
HOT – 193	wh300	-0.0070	0.0217	-0.0419	0.0442
HOT – 194	wh300	-0.0023	0.0227	-0.0093	0.0134
HOT – 195	wh300	0.0170	0.0386	0.0020	0.0385
HOT – 198	wh300	-0.0721	0.0795	0.0104	0.0248
HOT – 199	wh300	0.0028	0.0762	0.0008	0.0488
HOT – 200	wh300	0.0210	0.0252	0.0912	0.0919

HOT Shipboard ADCP vs WHOTS Moored 600 kHz ADCP					
Cruise	**Ship ADCP Type**	**Vertical average of mean U differences (m/s)**	**Vertical average of RMS U differences (m/s)**	**Vertical average of mean V differences (m/s)**	**Vertical average of RMS V differences (m/s)**
HOT – 193	wh300	0.0001	0.0116	-0.0165	0.0189
HOT – 194	wh300	0.0120	0.0144	-0.0104	0.0142
HOT – 195	wh300	0.0024	0.0145	0.0279	0.0516
HOT – 197	wh300	0.0045	0.0247	-0.0272	0.0343
HOT – 198	wh300	-0.0240	0.0268	-0.0244	0.0260
HOT – 199	wh300	0.0176	0.0707	0.0021	0.0458
HOT – 200	wh300	0.0156	0.0251	0.1003	0.1008

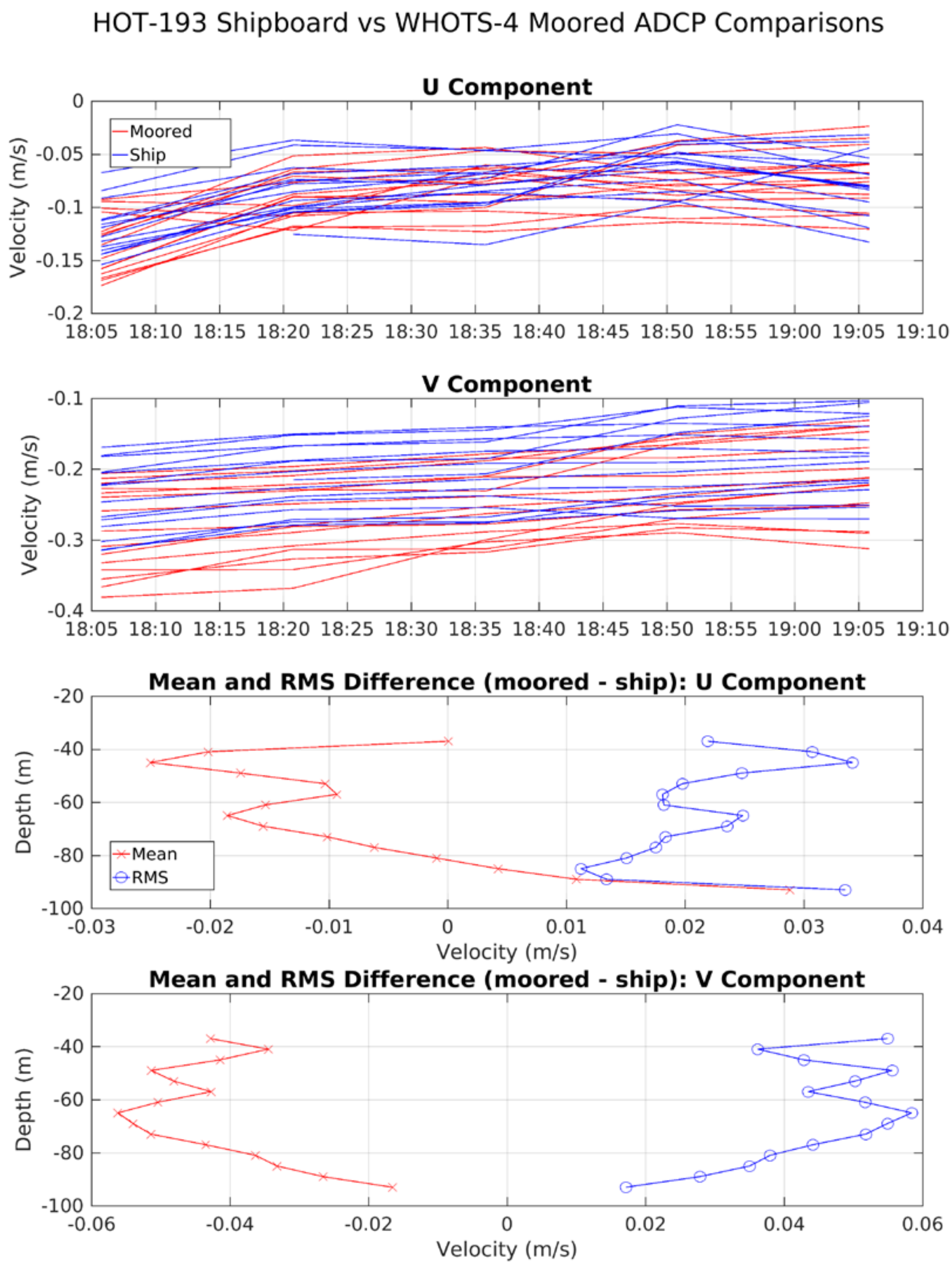


Figure 6-39. Shipboard ADCP (blue) versus moored 300 kHz ADCP (red) intercomparisons from HOT-193. Top panels show east and north velocity components (respectively) from every bin over the length of the CTD cast next to the mooring during the cruise, bottom panels show east and north (respectively) average mean difference and average RMS difference vertical profiles.

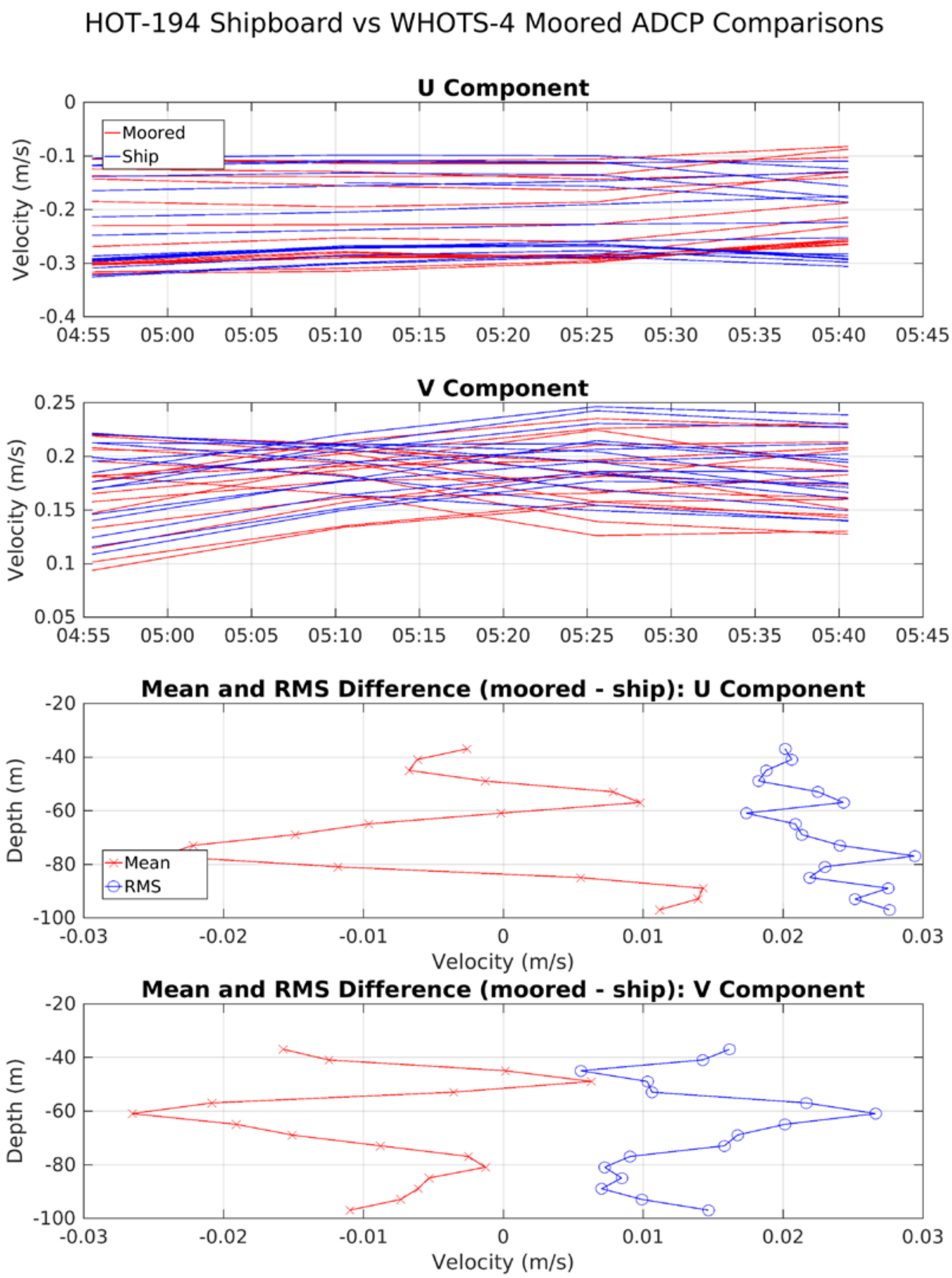


Figure 6-40. Same as in Figure 6-39, but for HOT-194.

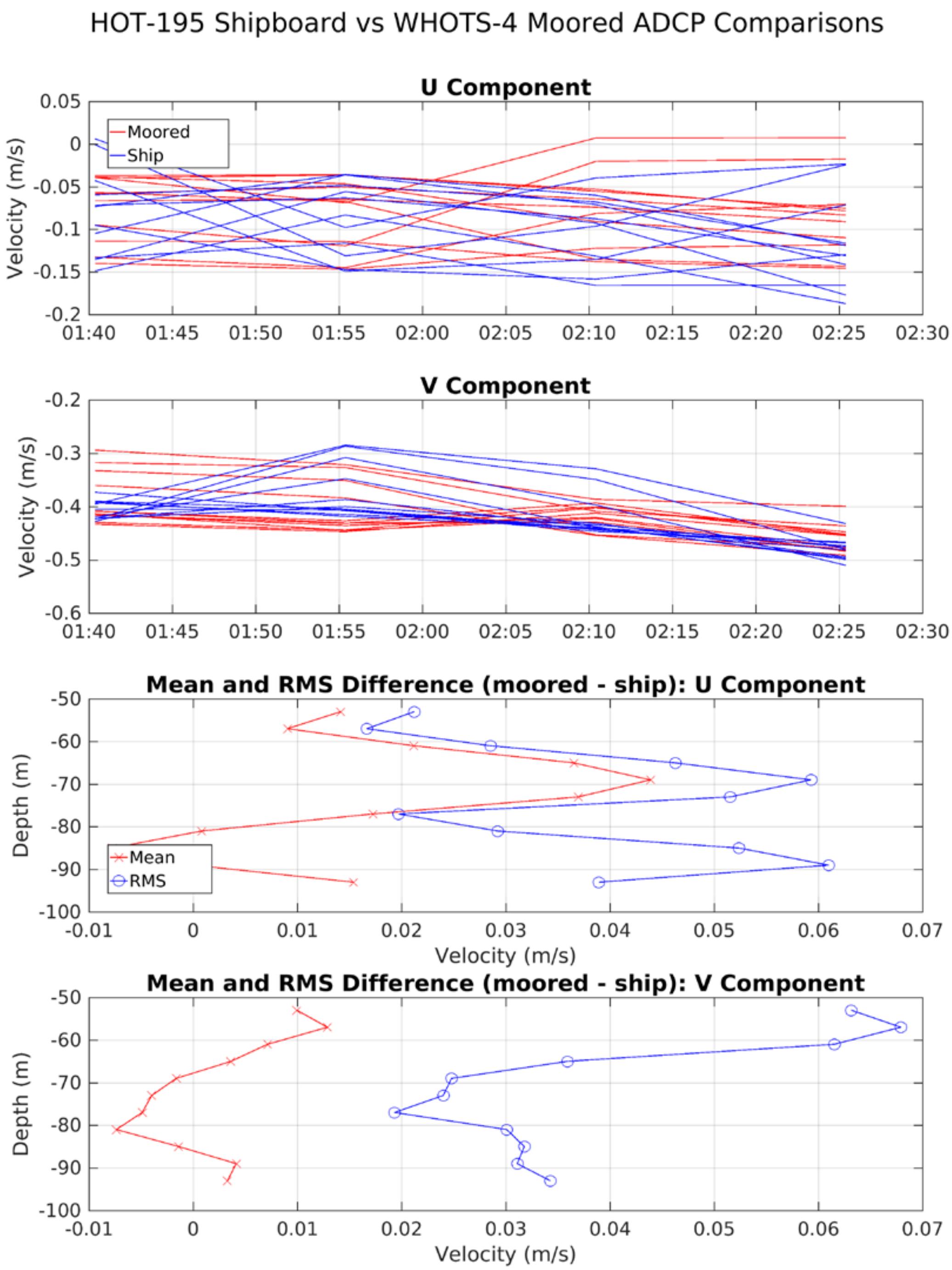


Figure 6-41. Same as in Figure 6-39, but for HOT-195.

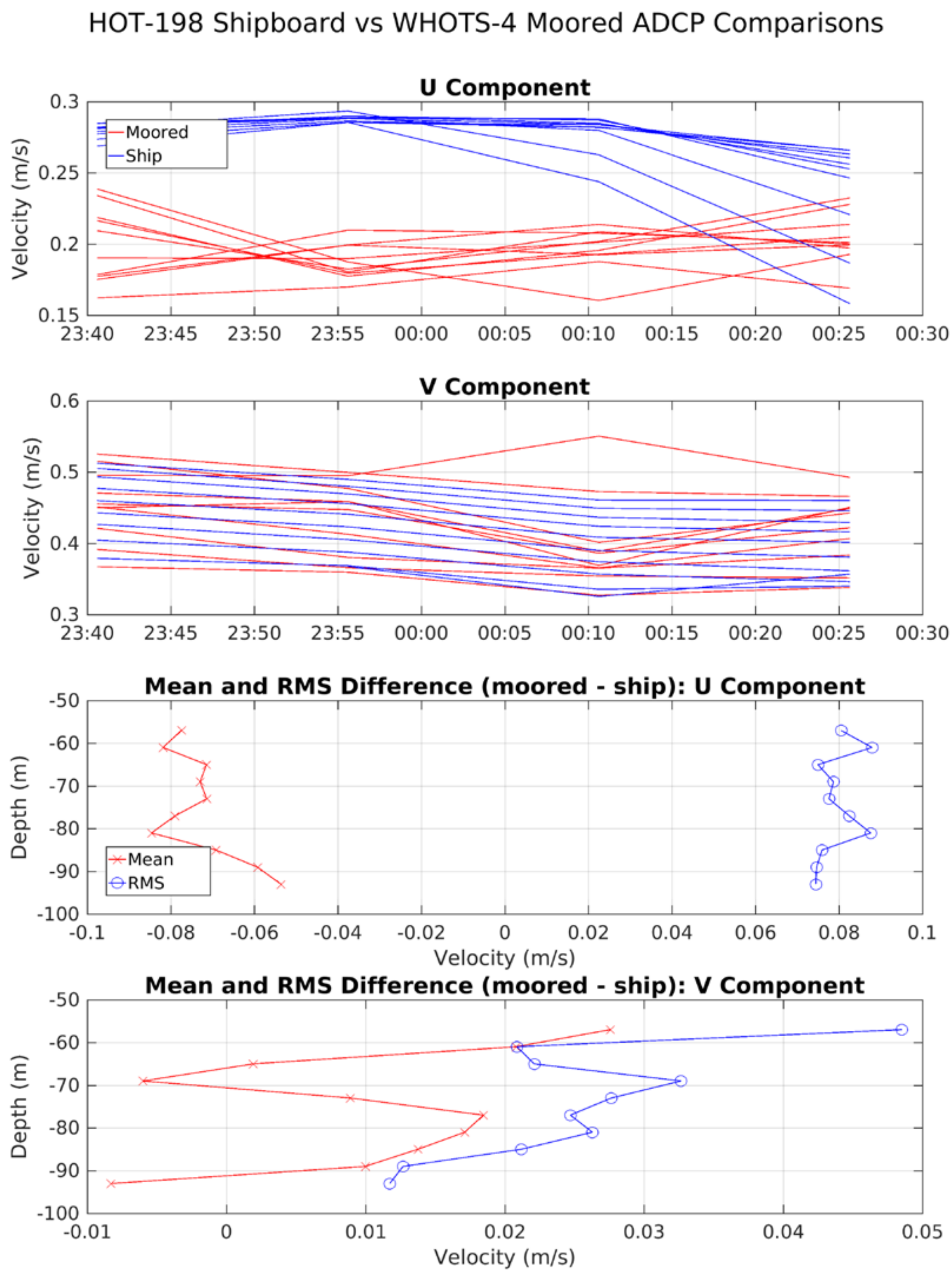


Figure 6-42. Same as in Figure 6-39, but for HOT-198.

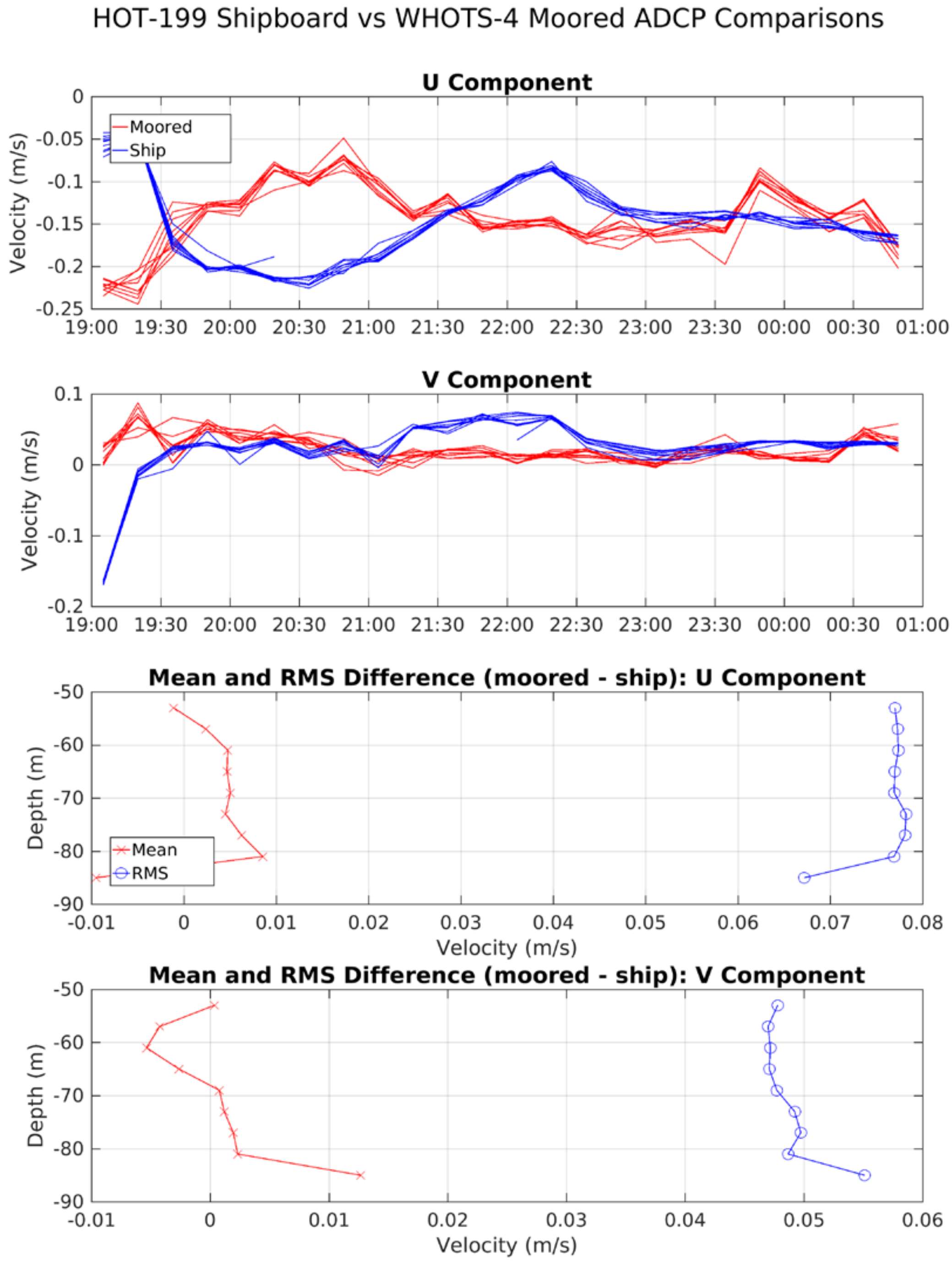


Figure 6-43. Same as in Figure 6-39, but for HOT-199.

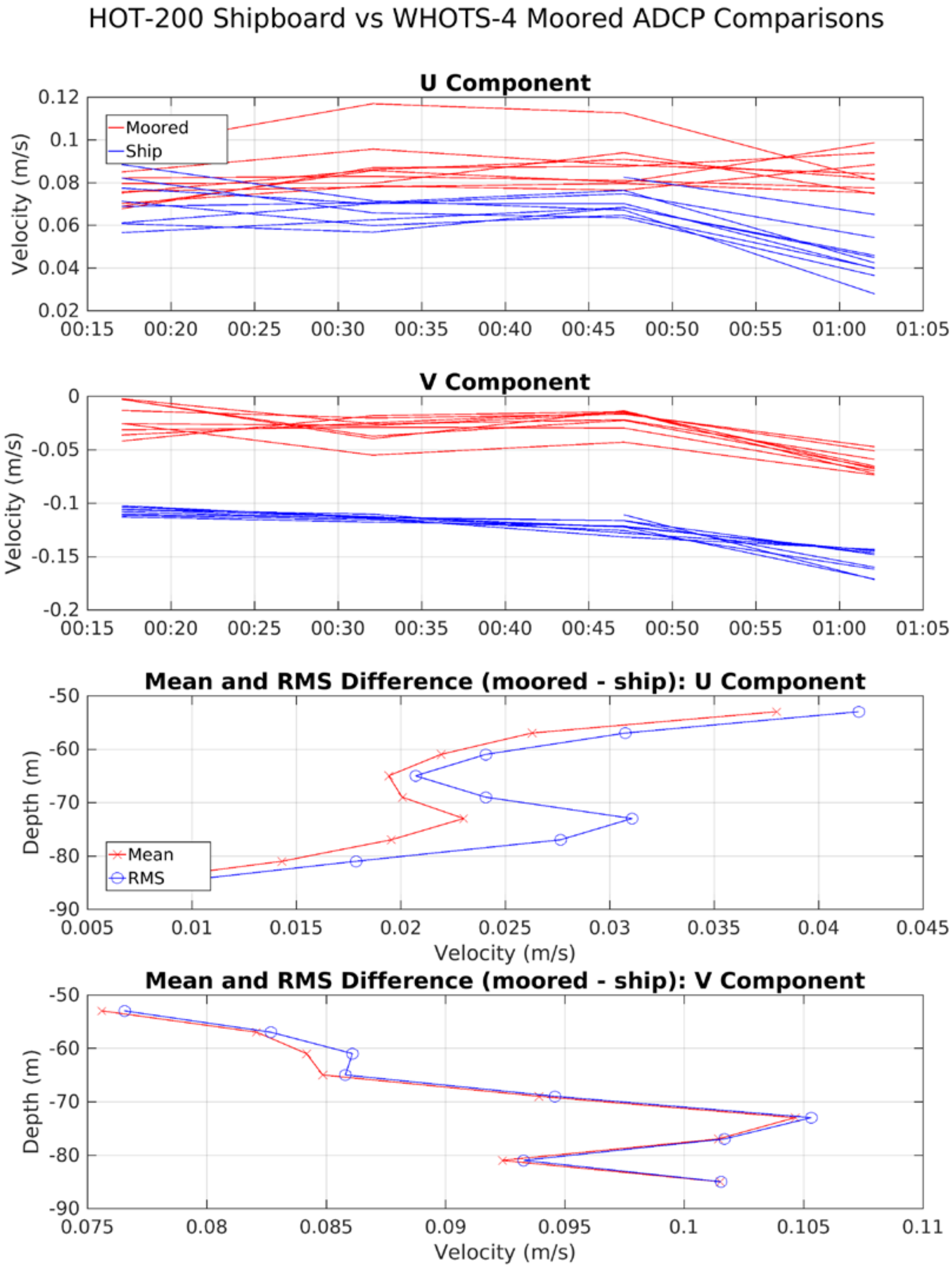


Figure 6-44. Same as in Figure 6-39, but for HOT-200.

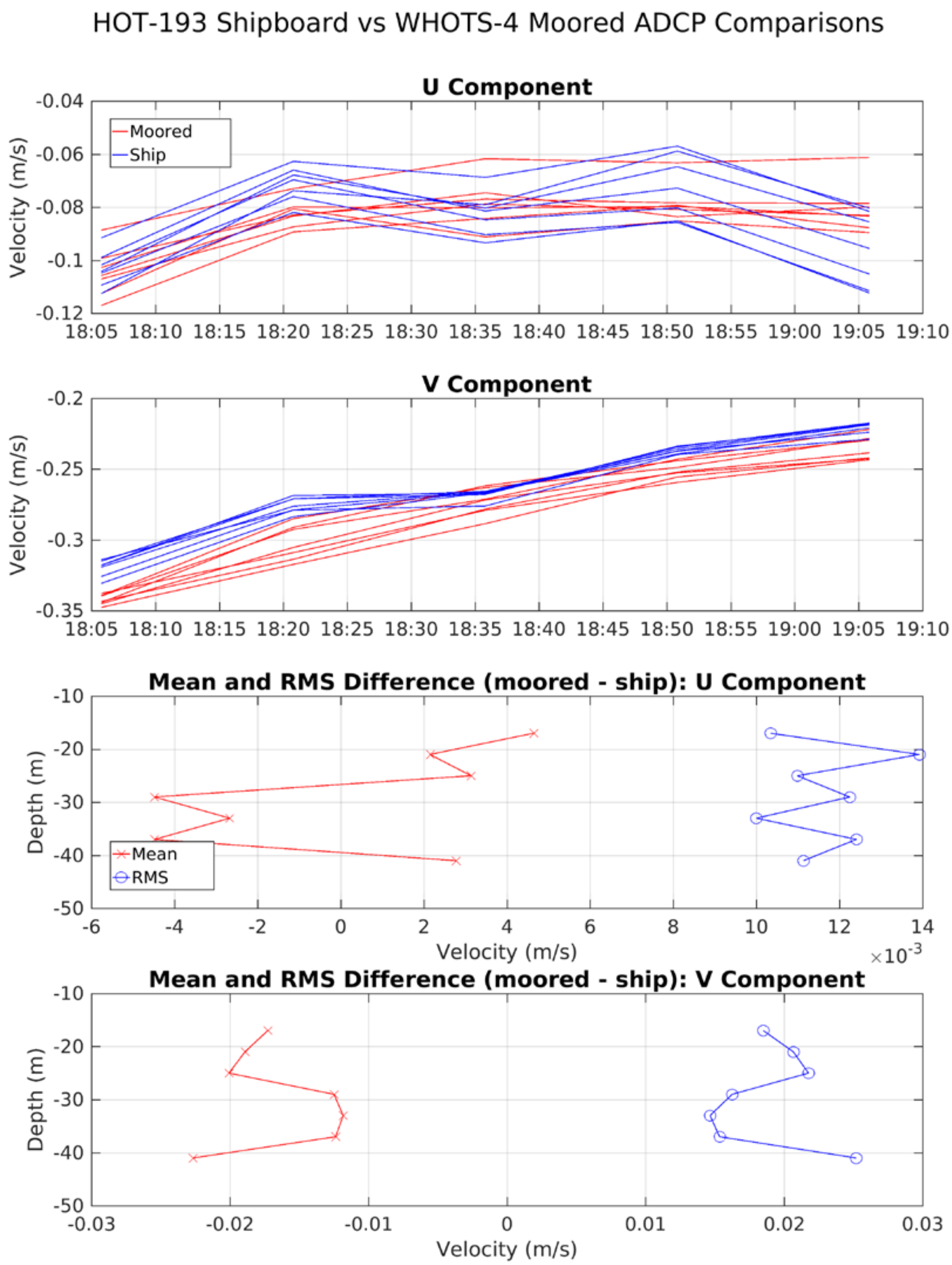


Figure 6-45. Shipboard ADCP (blue) versus moored 600 kHz ADCP (red) intercomparisons from HOT-193. Top panels show east and north velocity components (respectively) from every bin over the length of the CTD cast next to the mooring during the cruise, bottom panels show east and north (respectively) average mean difference and average RMS difference vertical profiles.

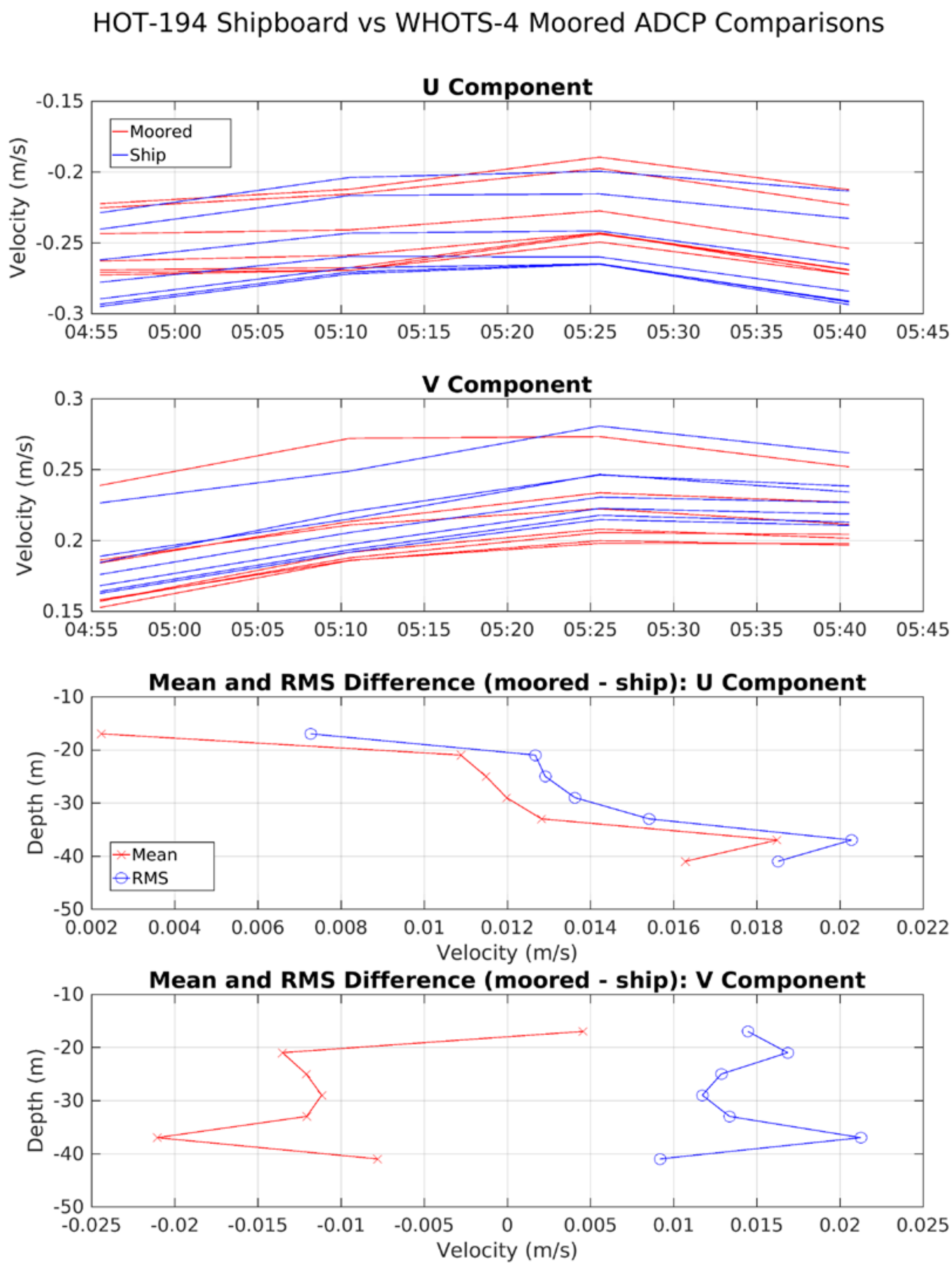


Figure 6-46. Same as in Figure 6-45, but for HOT-194.

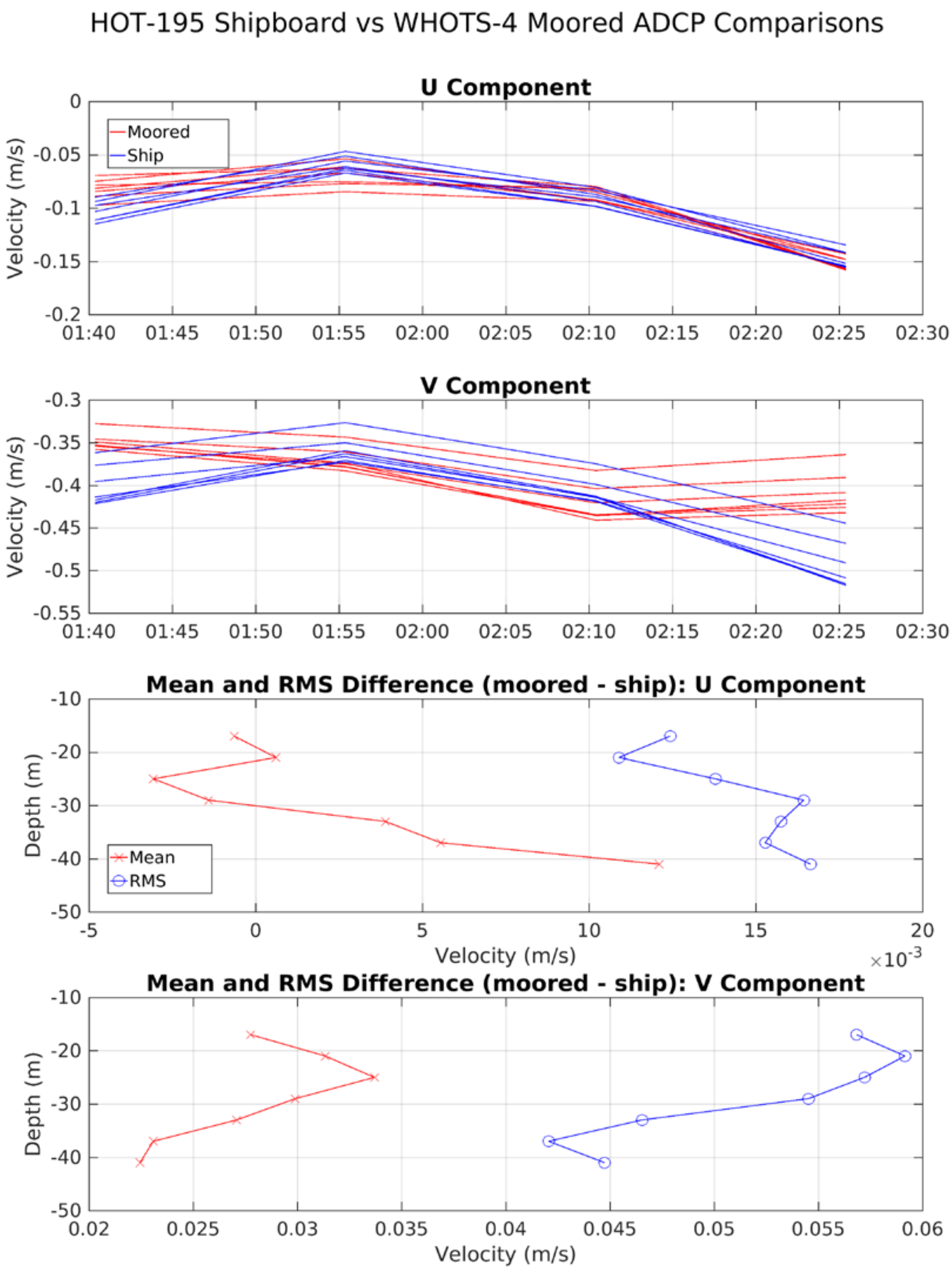


Figure 6-47. Same as in Figure 6-45, but for HOT-195.

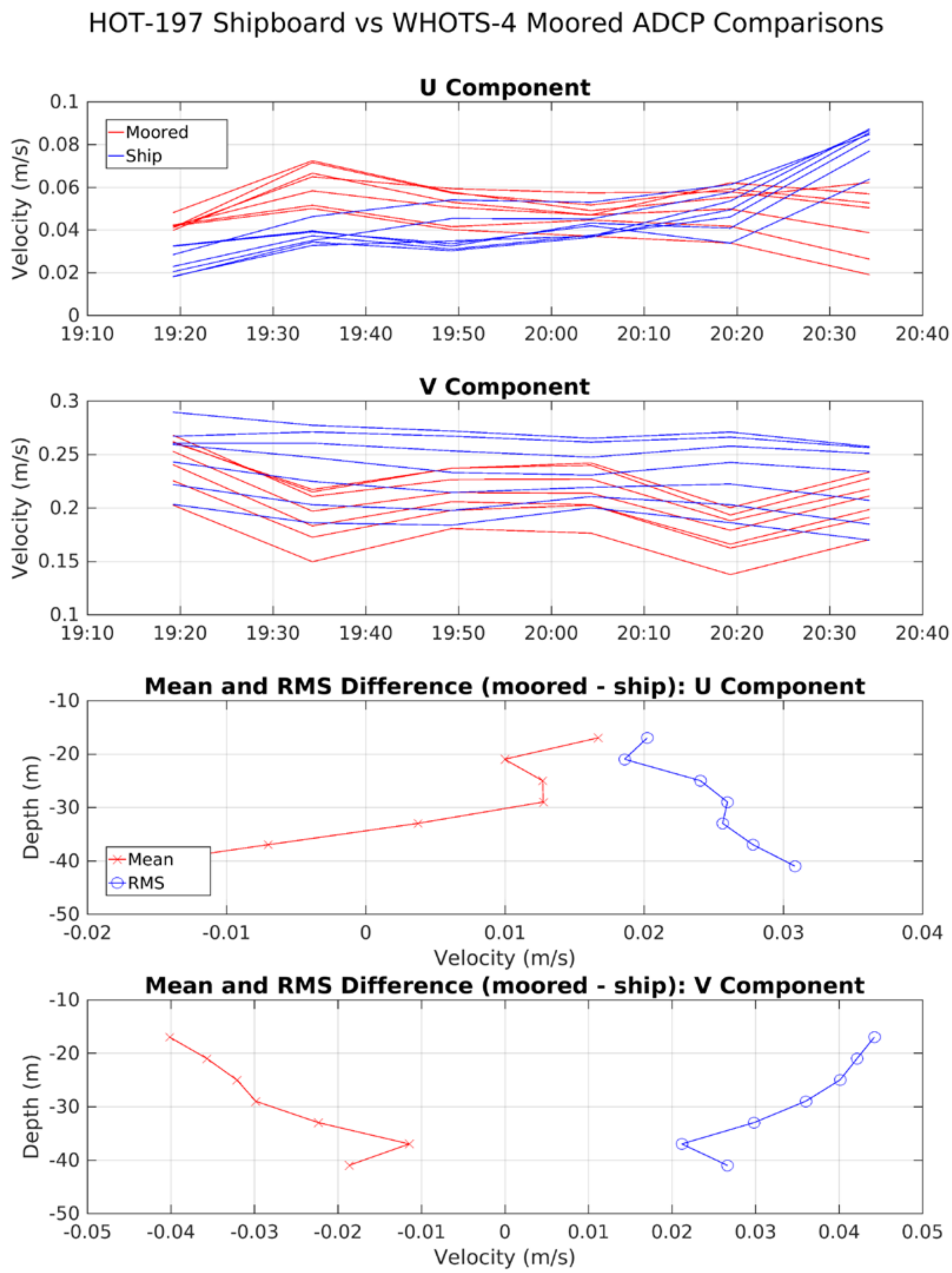


Figure 6-48. Same as in Figure 6-45, but for HOT-197.

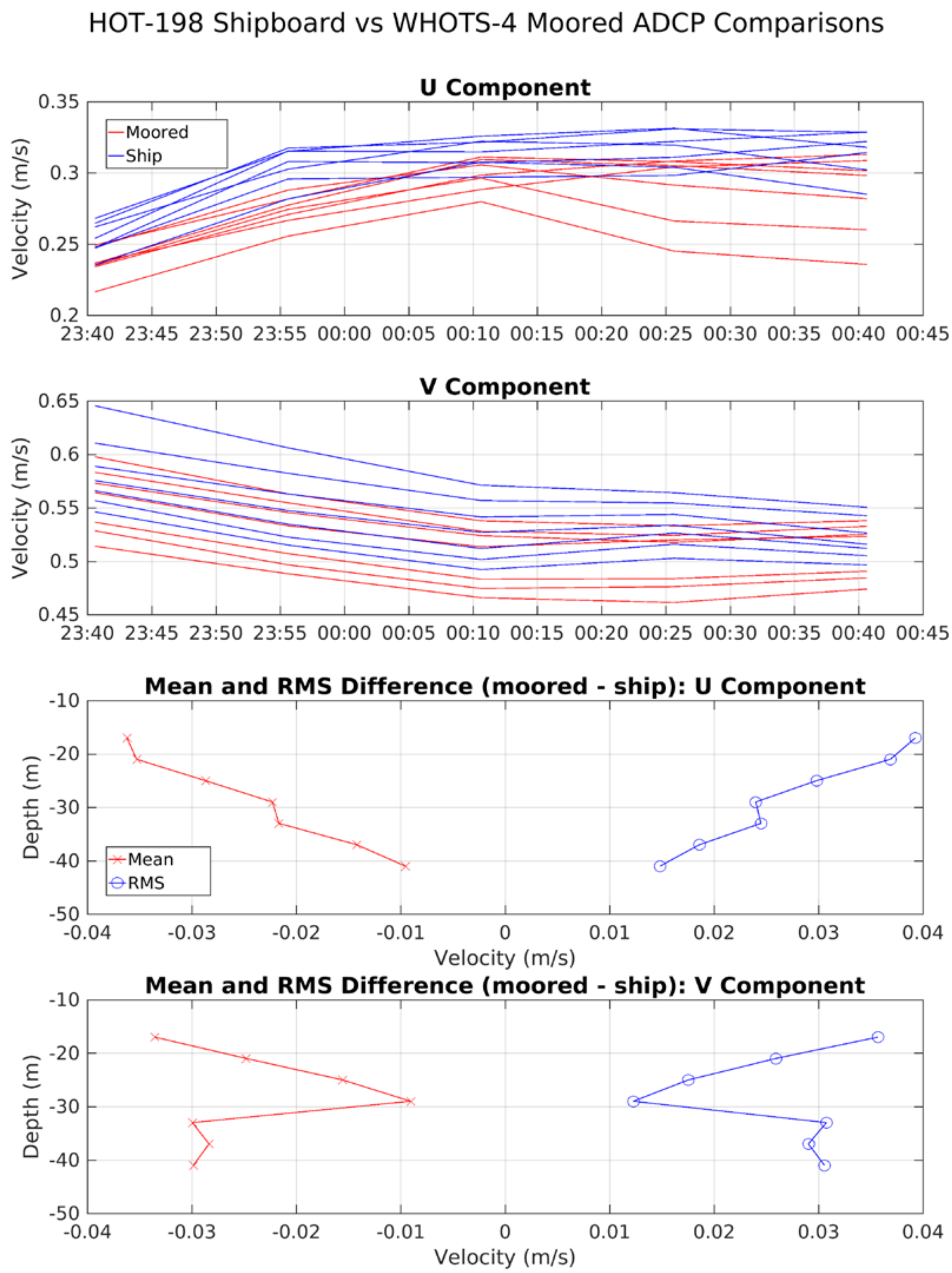


Figure 6-49. Same as in Figure 6-45, but for HOT-198.

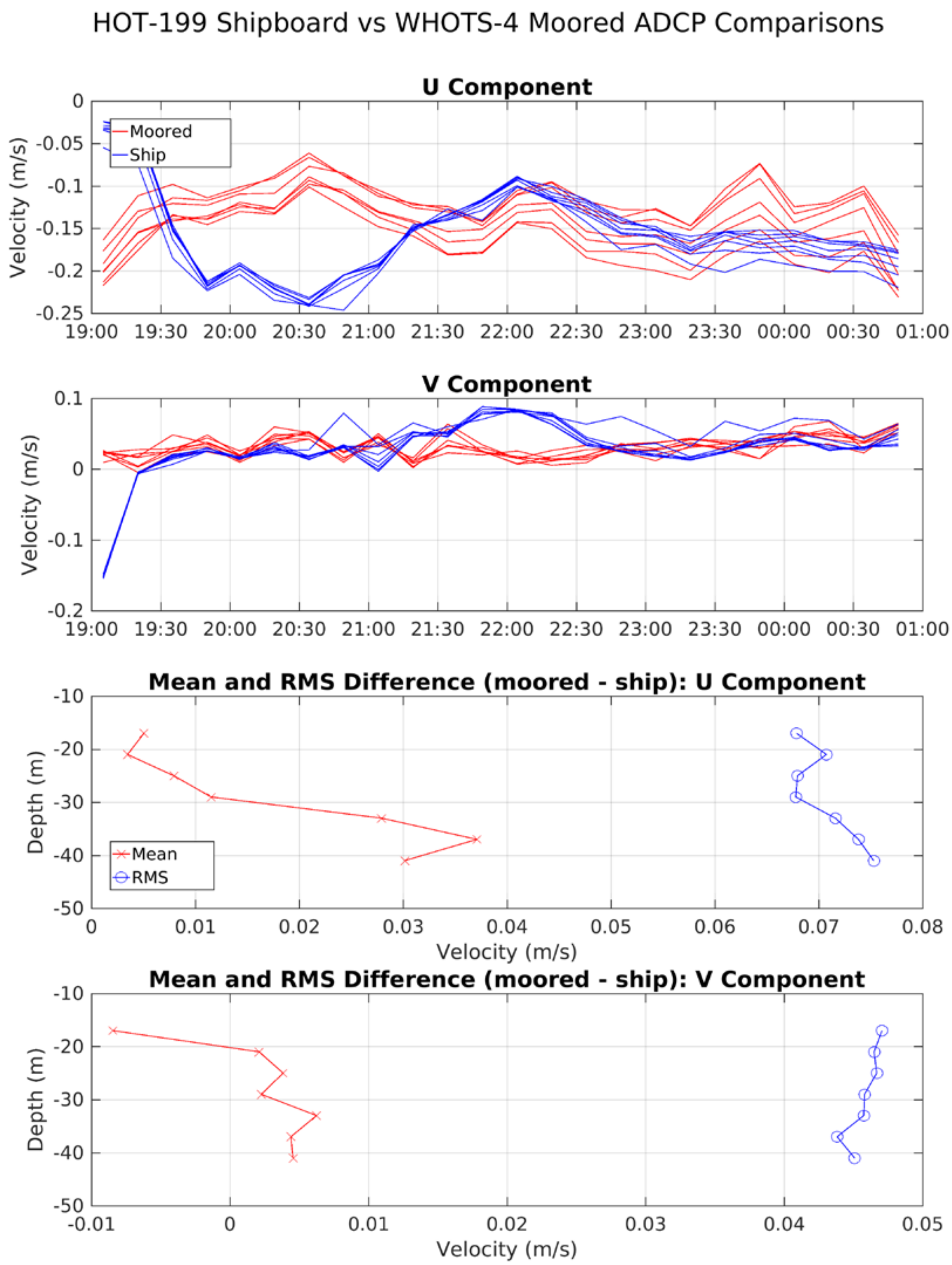


Figure 6-50. Same as in Figure 6-45, but for HOT-199.

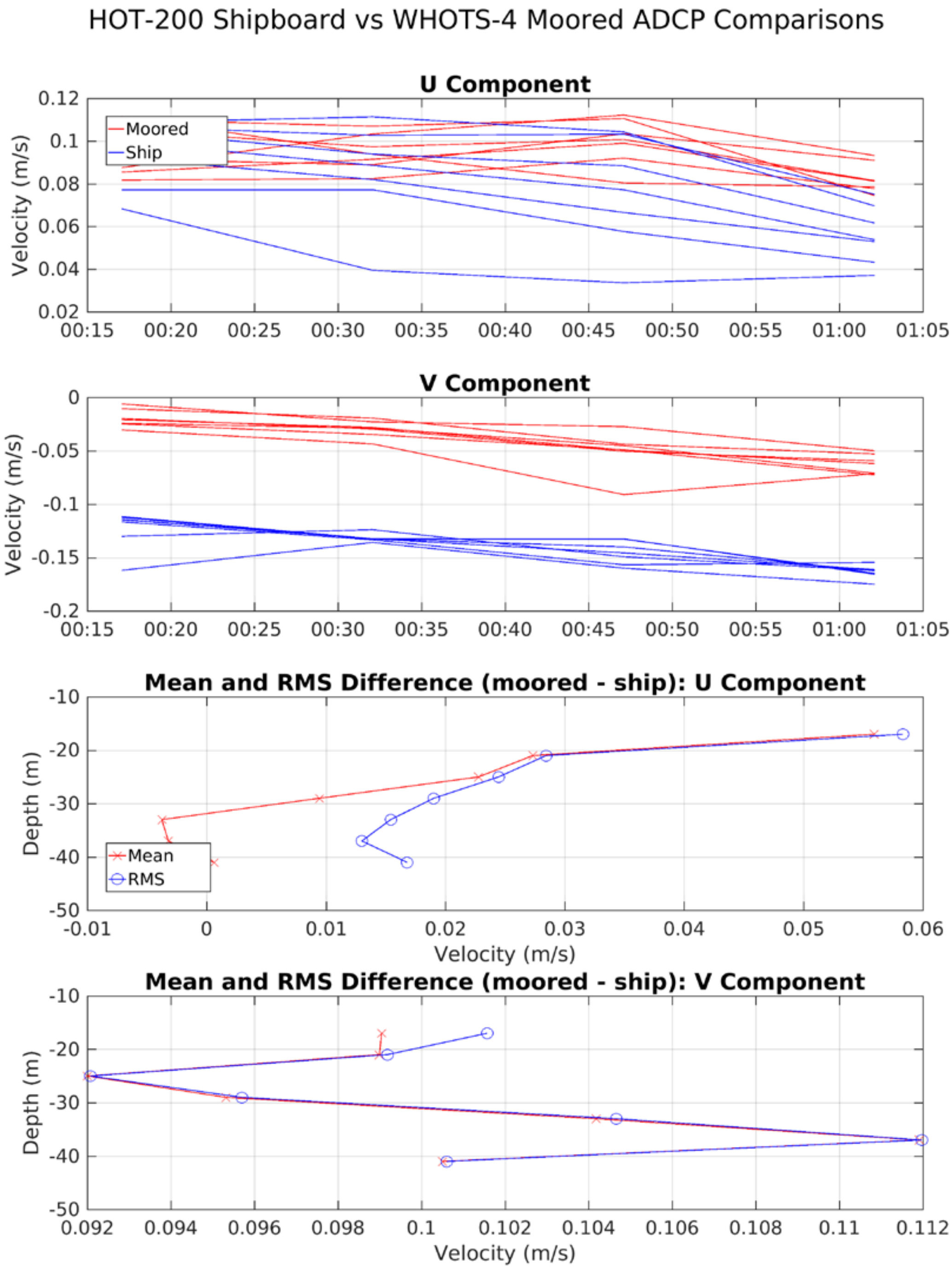


Figure 6-51. Same as in Figure 6-45, but for HOT-200.

F. Next Generation Vector Measuring Current Meter data (VMCM)

Time-series of daily mean horizontal velocity components for the VMCM current meters deployed during WHOTS-4 at 10 m and 30 m are presented in Figure 6-52. The record from the 10 m VMCM (SN 003) ends on April 7th, 2008 at 01:52:59 due to the instrument failing. The record from the 30m VMCM was later truncated to eliminate pre-deployment and post-recovery data.

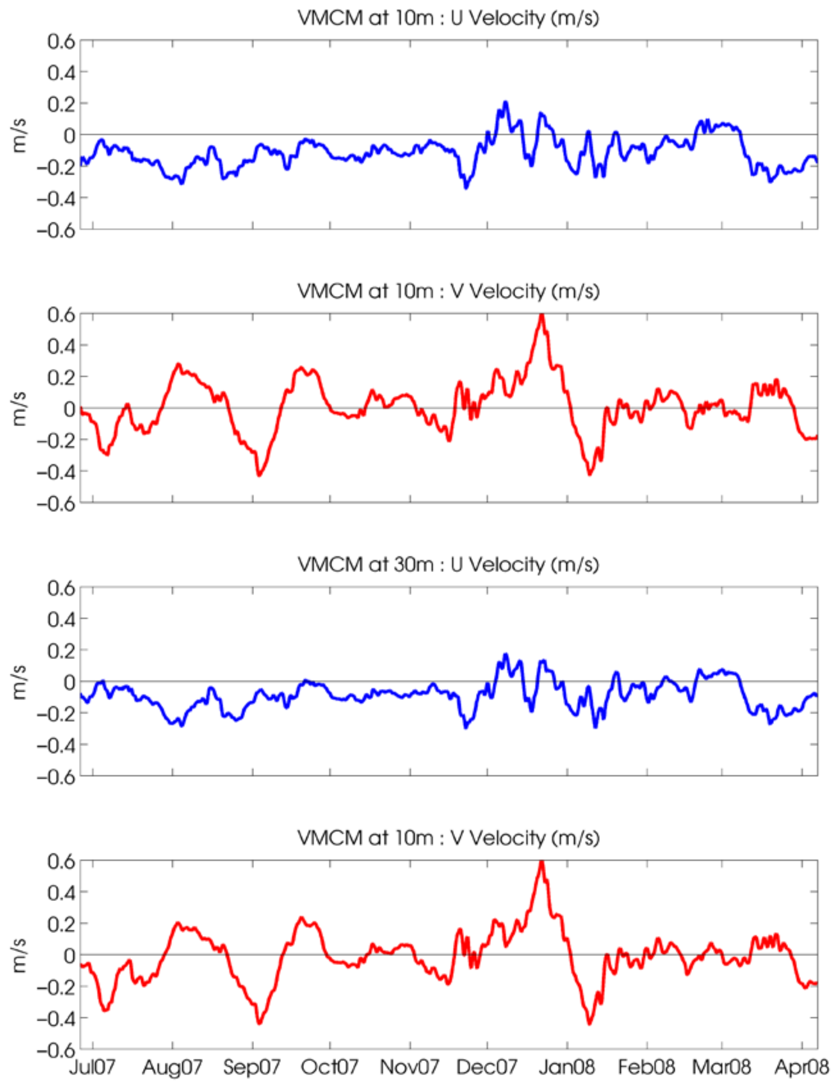


Figure 6-52. Horizontal velocity data (m/s) during WHOTS-4 from the VMCMs at 10 m depth (first and second panel) and at 30 m depth (third and fourth panel).

G. GPS data

Time-series of latitude and longitude of the WHOTS-4 buoy from GPS data are presented in Figure 6-53 and spectra of the time-series is shown in Figure 6-54.

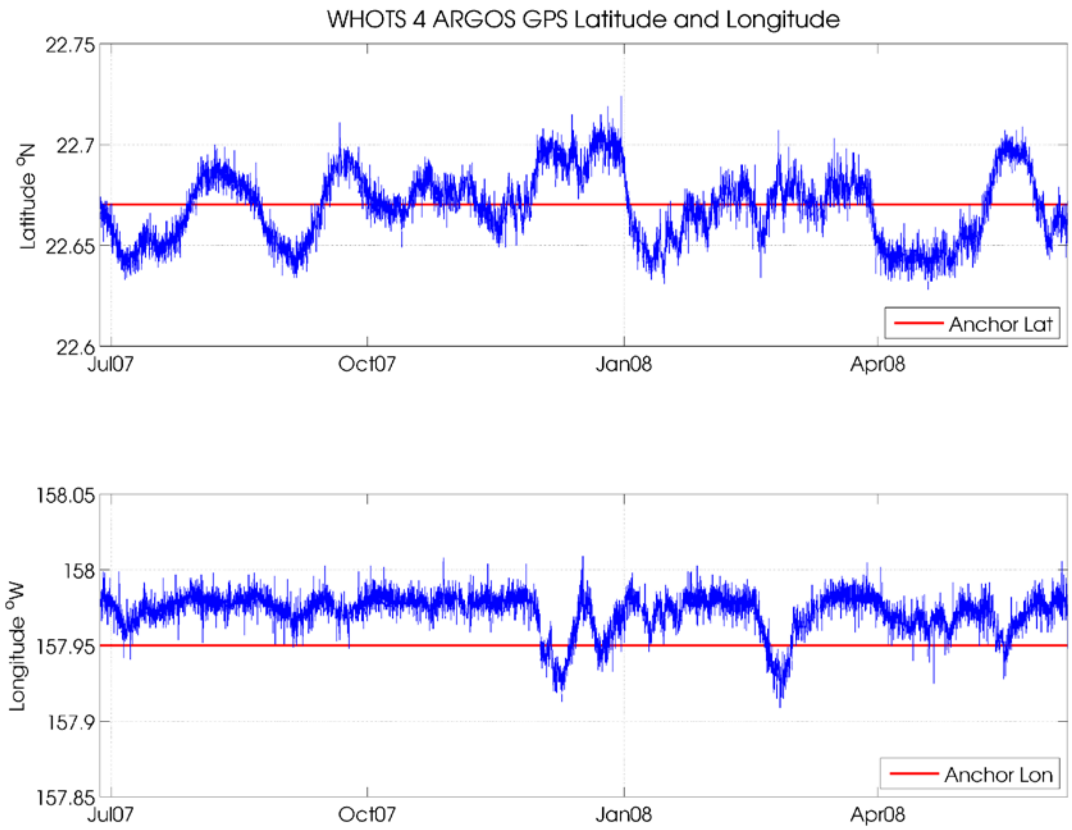


Figure 6-53. GPS Latitude (upper panel) and longitude (lower panel) time series from the WHOTS-4 deployment.

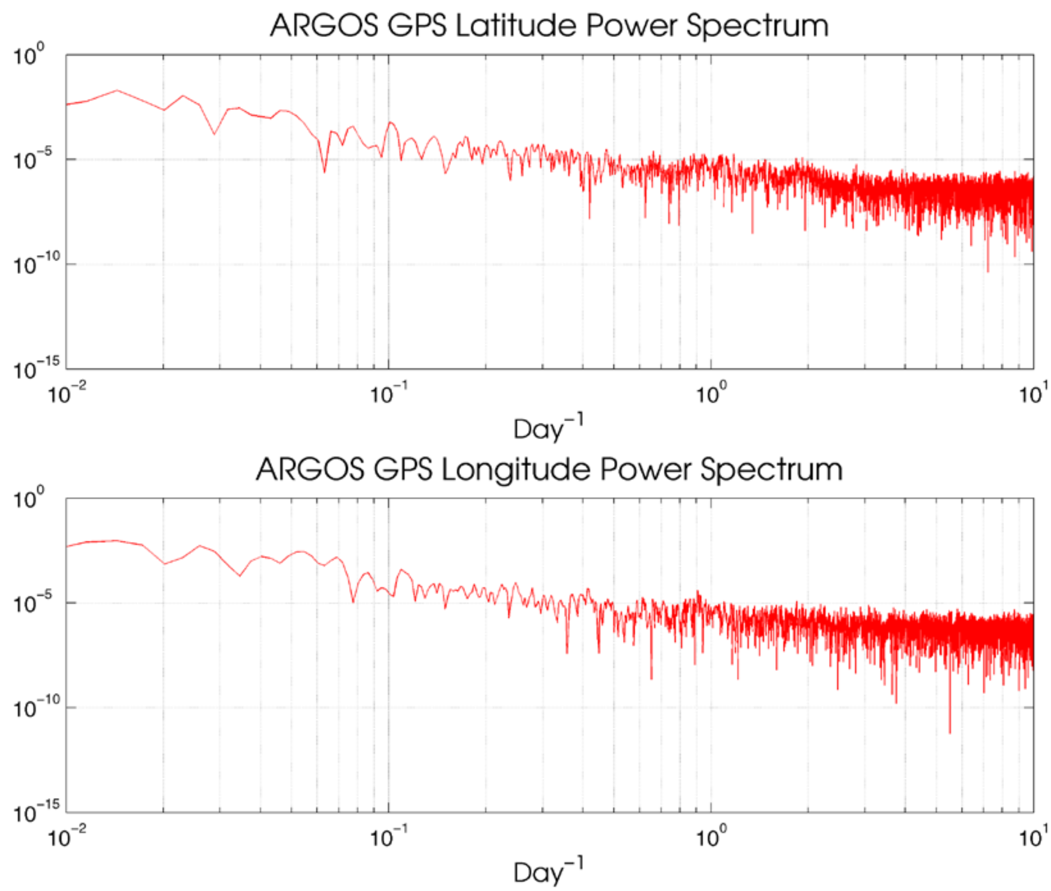


Figure 6-54. Power spectrum of latitude (upper panel) and longitude (lower panel) for the WHOTS-4 deployment.

H. Mooring Motion

The position of the mooring with respect to its anchor was determined from the ARGOS positions as shown in Section 5.D. Additional information of the mooring motion was provided by the ADCP data of pitch, roll and heading, shown in this section.

Figure 6-55 shows the ADCP data of the instrument's tilt (a combination of the pitch and roll), plotted against the buoy's distance from its anchor (derived from ARGOS positions), for both WHOTS ADCP's. The red line in the plot is a quadratic fit to the median tilt calculated every 0.2 km distance bins. The figure shows that during both deployments, the ADCP tilt increased as the distance from the anchor increased. This tilting was caused by the deviation of the mooring line from its vertical position as it was pulled by the anchor. The tilting of the line also caused the rising of the instruments attached to the line.

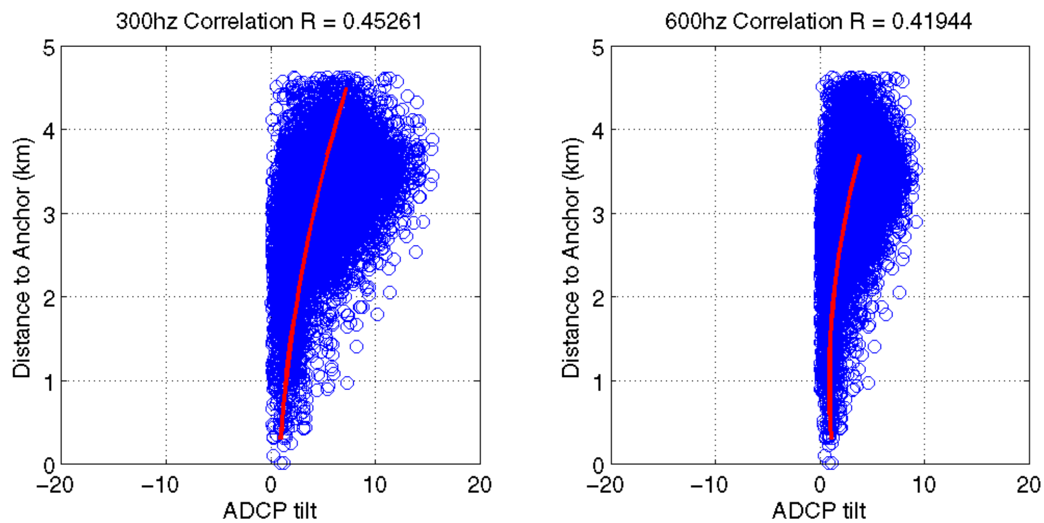


Figure 6-55. Scatter plot of ADCP tilt and distance of the buoy to its anchor for the 300 kHz [left panel] and 600 kHz [right panel] ADCP deployments (blue circles). The red line is a quadratic fit to the median tilt calculated every 0.2 km distance bins.

7. References

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8. Appendices

Appendix 1: WHOTS-4 300 kHz ADCP Configuration

File Size 37,620,703 bytes

Data Structure BB/WH/OS
Ensemble Length 752 bytes

Program Version 16.28

System Frequency 300 kHz
Convex
Sensor Configuration #1
Transducer Head Attached TRUE
Orientation UP
Beam Angle 20 Degrees
Transducer 4 Beam Janus

Real Data

CPU Serial Number: 71957

False Target(WA) 70 counts
Band Width (WB) 0
Cor. Thres. (WC) 64 counts
Err Thres. (WE) 2000 mm/s
Blank (WF) 1.76 m
Min PGood (WG) 0
Ref Layer (WL) 1, 5 first bin, last bin
Mode (WM) 1
Bins (WN) 30
Pings/Ens (WP) 40
Bin Size (WS) 4.00 m

Head Align (EA) 0.00 degrees
Head Bias (EB) 10.11 degrees
Coord Xform (EX) 00011111 Earth Coordinates Using Tilts, 3 Beam Solutions, and Bin Mapping
Sens Source (EZ) 01111101 cdhprst
Sens Avail 00011101 cdhprst

Time/Ping (TP) 00:04.00

Hardware 4 Beams
Code Reps. 9
Lag Length 0.49 m
Xmt Length 4.42 m
1st Bin 6.22 m

BT Pings/Ens (BP) 0
BT Ens Delay (BD) 0
BT Cor.Thres. (BC) 0 counts
BT Eval. Thres. (BA) 0 counts

BT PG Thres. (BG) 0
BT Mode (BM) 0
BT Err Thres. (BE) 0 mm/s
BT Max Range (BX) 0 dm

First Ensemble 00000001 25-Jun-2007 00:00:00
Last Ensemble 00050284 08-Jun-2008 04:30:00

Appendix 2: WHOTS-4 600 kHz ADCP Configuration

File Size 22,167,552 bytes

Data Structure BB/WH/OS
Ensemble Length 652 bytes

Program Version 50.36

System Frequency 600 kHz
Convex
Sensor Configuration #1
Transducer Head Attached TRUE
Orientation UP
Beam Angle 20 Degrees
Transducer 4 Beam Janus

Real Data

CPU Serial Number: 70122

False Target(WA) 70 counts
Band Width (WB) 0
Cor. Thres. (WC) 64 counts
Err Thres. (WE) 2000 mm/s
Blank (WF) 0.88 m
Min PGood (WG) 0
Ref Layer (WL) 1, 5 first bin, last bin
Mode (WM) 1
Bins (WN) 25
Pings/Ens (WP) 80
Bin Size (WS) 2.00 m

Head Align (EA) 0.00 degrees
Head Bias (EB) 10.11 degrees
Coord Xform (EX) 00011111 Earth Coordinates Using Tilts, 3 Beam Solutions, and Bin Mapping
Sens Source (EZ) 01111101 cdhprst
Sens Avail 00011101 cdhprst

Time/Ping (TP) 00:2.00

Hardware 4 Beams
Code Reps. 9
Lag Length 0.25 m

Xmt Length 2.22 m
1st Bin   3.11 m

BT Pings/Ens   (BP) 0
BT Ens Delay   (BD) 0
BT Cor.Thres.   (BC) 0 counts
BT Eval. Thres. (BA) 0 counts
BT PG Thres.   (BG) 0
BT Mode   (BM) 0
BT Err Thres.   (BE) 0 mm/s
BT Max Range   (BX) 0 dm

First Ensemble 00000001 18-Jun-2007 01:00:00
Last Ensemble 00034198 08-Jun-2008 06:15:00