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Use of data storage tags to reveal aspects of fish behaviour important for fisheries management

Partitioning On-bottom and Off-bottom Behavior: a case study with yellowtail flounder off New England

by Steven X. Cadrin and Joshua Moser

Abstract

Archival tags deployed on yellowtail flounder indicate distinct periods of on-bottom and off-bottom behavior. Geolocation of fish during tag deployment requires accurate identification of periods when tagged fish were on-bottom (defined by a semi-diurnal tidal cycle of depth observations) and episodes of off-bottom movements (identified as an abrupt decrease in depth, interrupting the regular tidal cycle). Thirty-eight archival tags, deployed on yellowtail flounder off New England, had multiple off-bottom movements. These distinct vertical movements were typically in evening hours, lasting several hours. Tidal features (e.g., amplitude, time of high tide) can be derived from the time series of depth records and used for geolocation. However, failure to clearly differentiate on-bottom from off-bottom records confounds estimates of daily tidal features by confusing vertical movements with tidal cycles. An automated algorithm was developed to identify vertical movements, explore patterns of off-bottom movements and derive daily tidal features. Quality assurance protocols are described to assess the veracity of time, pressure and temperature records; and to optimize tag settings and specifications such as sampling frequency and resolution of measurements.

Keywords: data storage tags, archival tags, electronic tags, movement, geolocation, yellowtail flounder

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Data storage tags (DSTs) are increasingly valuable tools for fisheries research, because the technology is continually improving and becoming more affordable (Thorsteinsson 2002). Information downloaded from DSTs that are deployed on fish offer new insights into habitat preference, daily and seasonal movement patterns as well as the potential for geolocation using tidal features. However, the large volume of records archived by DSTs presents a challenge for data processing and analysis.

Two distinct patterns of depth records are typically observed from DSTs: 1) on-bottom activity, indicated by a stationary cycle reflecting regular changes in water depth from tidal rhythms (e.g., Metcalf and Arnold 1997) and 2) off-bottom activity, indicated by relatively rapid changes in depth (e.g., Cadrin and Westwood 2004, Walsh and Morgan 2004). Tidal features such as amplitude and phase can be derived from a series of on-bottom depth observations. In turn, these can be compared to a geographic grid of predicted tidal features derived from an oceanographic model to infer daily position (Arnold and Holford 1995; Metcalf and Arnold 1997; Hunter et al. 2004a, 2004b; Neuenfeldt 2004; Gröger et al. 2005).

Data collected during these two modes of behavior must be partitioned to allow accurate estimates of tidal features and improve geolocation methods by incorporating off-bottom movement. The algorithm developed by Gröger et al. (2005, which was adapted from the method used by Hunter et al. 2003) involves fitting a tidal model to a 13-hour series of depth observations, and using this 'moving window' to select the best fitting 13-hour series for each day of deployment. This method appears to perform well for plaice (Hunter et al. 2004b) and cod (Gröger et al. 2005), but preliminary applications to yellowtail flounder produced unrealistic results (e.g., unbelievable tidal amplitudes and inferred locations where yellowtail flounder have never been observed; J. Gröger and S. Cadrin, unpublished analyses). One potential source of error in geolocation is fitting a tidal model to a depth series that includes off-bottom movement.

Cadrin and Westwood (2004) inspected DST information visually, by plotting the recorded time series of depth and temperature. Periods of on-bottom observations were indicated by a semi-diurnal tidal cycle of depth observations, and episodes of off-bottom movement were identified as an abrupt decrease in depth (>1m) in one time step that interrupts the regular tidal cycle. Although useful for initial observations of off-bottom movement, the visual procedure is time consuming and somewhat subjective. The objective of this study is to develop an alternative data processing protocol to identify periods of off-bottom movement from DST records and derive tidal features from periods of on-bottom behavior. The algorithm was developed and tested using data collected during deployments on yellowtail flounder off New England.

Methods
From 2003 to 2005, commercial fishing vessels were contracted to tag and release yellowtail on fishing grounds from the Gulf of Maine to the Mid Atlantic Bight. Chartered fishing vessels used otter trawls to catch yellowtail. Tows were between 20-40 minutes in duration. Five hundred and seventy-nine yellowtail flounder were tagged externally with depth-sensing DSTs (LTD 1100, 32K memory, 8mm x 16mm x 27mm; Lotek, St. Johns Newfoundland). DSTs record pressure (+/- 1% of observed depth range) and temperature (+/- 0.3 °C) at regular time intervals. Battery life is up to 3 years. Tags have a 500m depth rating and weigh 2 grams in water. DSTs are equipped with 'Time Extension Recording,' a memory management option that adjusts the sampling interval over time to capture the full record, regardless of the length of the recording session.

Tags were recovered with observations at 4 minute intervals (from the DSTs with the shortest time at large) to 60 minute intervals (for those with the longest time at large). Most DST's were re-initialized before deployment by activating a magnetic reed switch located at one corner, tags released during our first season of release (2003) were not re-initialized and recorded data during the shelf time (this affects the Time Extension Recording interval). Time, pressure and temperature data from recaptured DST's were downloaded using Lotek software onto a computer via infrared signals from a light emitting diode in the tag to a receiver plugged into the computer that was calibrated to Eastern Standard Time.

Data Storage Tags were applied using 2 nickel pins with specially-fitted pink oval blanks (3/8" x 1-1/8" Floy Tag, Inc.). Fish length ranged from 30 to 55cm. Gender was determined by externally 'candling.' Each fish suitable to tag, either in excellent or good condition, were pierced using two nickel pins with the blank disc on the 'blind side' for backing. Piercing was done on the dorsal side of the lateral line arch on the blind side of the fish, assuring a smooth puncture at a perpendicular angle to the body to put the blank flush on the blind side (Figure 1). After placing the DST on the upward-facing pin, pliers were used to trim, crimp and bend the end of the pin to secure the tag, leaving approximately 4 mm for growth. Fish were released immediately. Most fish were out of the water less than one minute during the tagging procedure and no anesthesia was used. Tags were labeled with contact information.

Tag recaptures were reported via a toll free number. All DSTs reported with complete information were redeemable for $100. Announcements of reward winners and lottery schedules, as well as updates on the tagging project, are posted and updated regularly on the project website (www.cooperative-tagging.org).

<u>Data processing and analysis</u>
Depth (D, in meters) was calculated from pressure (psi) records (D=psi x 0.6849). Sixty tags were recaptured, and a subset of data-series from 38 tag deployments was selected for analysis. Tag selection was based on several criteria:

1. Recapture date and location were reported.
2. Time of release and recapture were reflected in pressure records.
3. Time, depth and temperature were within reasonable bounds.

Analytical settings were identical for all tags with the exception of four tags. Due to the lack of a clear settlement signal (after release), data from these four tags was trimmed to exclude the time period before a clear settlement signal was detected. Data series that had variable time intervals (a feature of 'Time Extension Recording') were standardized to the shortest common interval by deleting intervening observations at shorter intervals. Although the procedure deleted some data, it was necessary to compare derived statistics (e.g., tidal amplitude, time of high tide, variance of tidal parameters, goodness-of-fit, degrees of freedom) from periods of high frequency observations and lower frequency observations within a single time series.

Commencement of off-bottom movements were identified by a rate of change in depth exceeding a threshold rate of 10 m/hr. Time of return to the bottom after an off-bottom movement was identified as a rate of change in depth of less than 10m/h for each time step, lasting for at least one hour (i.e., successive off-bottom movements within one hour are considered a single event). Descriptive statistics of depth and temperature were calculated for each period of on-bottom and off-bottom behavior to characterize habitat and movement.

Semidiurnal tidal models (i.e., describing the 'M2' tidal component, which comprises the major source of tidal energy in the New England region; Chen et al. 2005) were fit to series of depth observations during on-bottom periods, by calendar day:

$$\hat{D} = a_0 + a_1 \cos(t) + b_1 \sin(t) + \varepsilon \quad (1)$$

where a_0 is a Y-intercept term that removes the scale from the series (i.e., mean depth) so that a_1 and b_1 coefficients can be estimated to describe the cyclical pattern, and ε is a random observation error (i.e., a residual: the difference between the value of D measured from the DST and that predicted from nonlinear estimation). Tidal amplitude (***A***) can be derived:

$$A = \sqrt{a_1^2 + b_1^2} \quad (2)$$

Results

Sixty DSTs were recaptured (Table 1). Twenty of the thirty eight data series that met the analytical criteria were successfully analyzed using the algorithm. Inspection of analytical results indicated problems for seventeen tag series: off-bottom movements were not detected for four data series, return to bottom (after an off-bottom movement) was undetected in nine data series, and four series had poor model fits during on-bottom periods.

Off-bottom movements can be identified in all tag deployments (Appendix A). Analysis of data from tag 1492 is used to illustrate summary statistics off-bottom observations (Table 2), on-bottom observations (Table 3), and results from tidal modeling during on-bottom periods (Table 4). Analytical results for all tags are reported in Table 5 (on-bottom periods) and Table 6 (off-bottom periods).

On-bottom habitats ranged from 11 to 120 m depth of bottom and 2 to 15°C bottom temperature (Table 5). A total of 1,528 off-bottom movements were observed, most often in evening (the mode was at 20:00; Figure 3), rising to an average 6 m off-bottom, and lasting and average of 1.5 hours (Table 6).

Discussion

Partitioning on-bottom from off-bottom behavior should improve estimates of tidal parameters from on-bottom depth observations, thereby improving accuracy of geolocation. Furthermore, identifying periods of off-bottom movement can also be used to impose passive drift within midwater currents as predicted from 3-dimensional oceanographic models (e.g., Chen et al. 2006). Thus, different geolocation search algorithms could be applied to periods of on-bottom and off-bottom behavior.

Another benefit of identifying periods of off- and on-bottom behavior as compared to the 13h 'moving window' approach used in other studies is that tidal analyses are not limited to a fixed period of time and can be applied to both short periods and longer series (up to an entire 24h if the fish remained on bottom the entire day). Greater degrees of freedom should help to derive better estimates, and a longer series should help to avoid fitting the tidal model to trended data caused by on-bottom movement to different depths (i.e., swimming along a sloped bottom). A short series with a single cycle that is trended may fit a tidal model well, but a longer trended series with multiple cycles will fit poorly. It is still important to inspect goodness of fit, but a longer series is more likely to produce useful diagnostics. Longer series of data may also provide enough observations to fit secondary tidal components and improve the estimation of tidal features.

Several aspects of data processing depend on tag specifications. For example, the 'time extended recording' feature meets the best compromise between the frequency of interval collection and storage space, however, it also requires further post-processing prior to an analysis bound to standard time intervals. Our analyses indicate that accurate tidal modeling requires a frequency of depth observations greater than one per hour. The choice for the optimal 'maximum time step' for geolocation is difficult, because frequencies of less than once per hour won't allow tidal modeling, but cessation of recording will not allow the recapture event (with associated location) to be recorded. Another specification that affects data processing is resolution of depth measurements, which affects detection of off-bottom movement and uncertainty in tidal features.

Uncertainty in DST measurements and derived estimates is an important consideration for the next stage of geolocation (matching DST estimates with a spatiotemporal grid of tidal features). For example, the 10m/h threshold that we used to indicate off-bottom movements may be improved by making the threshold a function of the resolution of pressure measurements (which is a function of the maximum observed depth) and the time step of recordings. Such refinements of criteria for determining start and end of off-bottom movements would likely resolve the few problematic analyses we encountered.

Measurement error for depth and estimation error of tidal parameters should also be considered in the search algorithm that matches DST data with oceanographic data. Similarly, predictions of depth and tidal features from the oceanographic model should be evaluated and included in the search criterion. On-bottom vertical movement (i.e., along a slope) continue to confound some tidal analyses, and these events require additional processing to detrend the time series.

The analyses reported here for yellowtail flounder update and generally confirm the results reported by Cadrin and Westwood (2004). The depth and temperature information from data tags offer valuable habitat information. The range of observed temperatures (2-15^{o} C) is greater than previously published for this species off New England (Johnson et al. 1999 report a range of 2-12^{o} C). The observed bottom depths (average 26m, 11-120 m range) are similar to previously reported ranges (Johnson et al. 1999 report a normal range of 10-360 m). These data illustrate that archival tags may be a more comprehensive and direct method of sampling habitat information.

The typical patterns of off-bottom movements observed for plaice (Arnold and Holford 1995; Metcalf and Arnold 1997; Hunter et al. 2004a, 2004b), yellowtail flounder (Cadrin and Westwood 2004, Walsh and Morgan 2004) and Pacific halibut (Seitz et al. 2005) involve an abrupt decrease in depth. However, physoclist species demonstrate a different pattern of vertical movement (e.g., Atlantic cod, Pálsson and Thorsteinsson 2003, Gröger et al. 2005, Neat et al. 2006; Pacific cod, Nichol and Chilton 2005; black seabass, G. Shepherd and J. Moser unpublished data), presumably limited by risk of barotraumas to swim bladders. Therefore a different data processing algorithm (e.g., alternative criteria for identifying vertical movement) may be needed for DSTs deployed on physoclist species.

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Table 1. Recaptured data-storage tags from deployments on yellowtail flounder.

Tag	Release Date	Latitude	Longitude	Gender	Length (cm)	Recapture Date	Latitude	Longitude	Days at Large	Distance Moved (km)
1464	6-May-2004	40.5	-69.2	female	39	3-Oct-2004	40.4	-69.7	150	42
1497	16-Jul-2003	41.7	-68.3	female	36	12-Sep-2003	42.0	-67.7	58	58
1540	5-May-2004	40.5	-69.2	female	36	8-Feb-2006	40.4	-68.6	644	55
1798	19-Nov-2003	41.1	-69.1	female	35	3-Oct-2005	41.5	-68.5	684	70
1870	16-Jul-2003	41.2	-67.4	female	24	25-Nov-2003	41.0	-66.6	132	64
1993	19-Nov-2003	41.1	-69.1	female	39	1-Feb-2004	40.5	-68.8	74	67
2022	8-Jun-2004	43.1	-70.5	female	39	14-Jun-2004	42.8	-70.7	6	33
2022	6-Aug-2003	42.1	-70.2	male	35	13-Dec-2003	42.3	-70.3	129	23
2031	27-May-2004	40.6	-72.3	female	43	14-Jun-2004	40.7	-72.2	18	14
3000	15-Jul-2003	41.0	-67.5	female	36	5-Jun-2004	41.3	-66.5	326	94
3008	13-Jul-2003	41.4	-67.0	female	42	7-Aug-2004	41.2	-67.2	391	26
3019	12-Jul-2003	41.4	-67.0	female	45	24-Apr-2004	41.7	-67.4	287	51
3031	16-Jul-2003	41.8	-68.2	female	38	17-Aug-2003	41.5	-68.4	32	33
3035	11-Aug-2003	42.1	-70.2	female	34	11-Sep-2003	42.0	-70.3	31	15
3038	13-Aug-2003	42.1	-70.3	female	43	12-Dec-2003	42.2	-70.3	121	13
3039	12-Jul-2003	41.3	-67.0	female	43	8-May-2004			301	
3040	22-Jul-2003	41.8	-69.8	female	38	5-Jun-2004	42.1	-70.0	319	31
3062	9-Jul-2003	42.8	-70.7	female	35	14-Dec-2003	42.4	-70.4	158	48
3113	11-Jul-2003	41.3	-67.0	female	45	3-Apr-2004	42.1	-67.4	267	89
3126	12-Aug-2003	42.3	-70.3	female	43	12-Aug-2003	42.3	-70.3	0	2
3156	12-Jul-2003	41.3	-67.0	female	47	19-Aug-2004	41.0	-67.0	404	37
3188	9-Jul-2003	42.8	-70.7	female	38	17-Oct-2003	42.8	-70.6	100	7
3198	9-Jul-2003	42.8	-70.7	female	37	4-Jan-2005	42.5	-70.5	545	37
3205	23-Jul-2003	41.6	-69.7	male	33	17-Jun-2004	42.5	-70.6	330	123
3243	9-Jul-2003	42.8	-70.7	female	36	23-Mar-2005	42.5	-70.6	623	30
3313	11-Jul-2003	41.4	-66.9	female	42	30-May-2004	41.1	-67.5	324	57
3316	14-Jul-2003	42.1	-67.5	male	40	23-Jul-2003	41.8	-67.2	9	39
8331	7-Jul-2005	41.2	-67.3	female	46	8-Jul-2005	41.2	-67.3	1	1
8339	7-Jul-2005	41.2	-67.3	female	46	9-Jul-2005	41.2	-67.3	2	2
8345	21-Jul-2004	42.1	-67.5	female	40	2-Jun-2005	42.1	-67.5	316	3
8374	7-Aug-2004	41.2	-67.2	male	38	25-Aug-2004	41.2	-67.4	18	19
8385	7-Jul-2005	41.2	-67.3	female	38	25-Jul-2005	41.3	-67.4	18	22
8386	7-Jul-2005	41.2	-67.3	female	35	1-Nov-2005	41.1	-70.4	117	259
8400	17-Jul-2004	41.4	-68.4	female	34	12-May-2005	42.0	-70.0	299	143
8405	7-Sep-2004	41.1	-67.6	female	40	15-May-2005	41.2	-67.4	250	16
8409	6-Jul-2004	42.1	-70.3	female	38	21-Jul-2004	42.1	-70.3	15	8
8418	9-Aug-2004	41.2	-67.1	female	50	4-Sep-2004	41.2	-67.2	26	2
8419	22-Jul-2004	41.1	-67.3	female	41	24-Jul-2004	41.2	-67.2	2	10
8434	6-Aug-2004	41.1	-67.2	female	41	16-Aug-2004	41.0	-67.4	10	20
8438	8-Aug-2004	41.1	-67.3	female	45	16-Aug-2004	41.2	-66.6	8	59
8440	7-Aug-2004	41.2	-67.2	female	43	15-Aug-2004	41.1	-67.3	8	10
8473	7-Jul-2005	41.2	-67.3	female	40	11-Aug-2005	41.1	-67.4	35	12
8480	22-Jul-2004	41.3	-67.0	female	47	26-Jul-2004	41.4	-66.9	4	9
8504	9-Aug-2004	41.2	-67.1	female	48	16-Aug-2004	41.1	-67.1	7	6
8506	4-Sep-2004	41.3	-67.0	female	45	13-Jul-2005	41.4	-67.4	312	34
8511	4-Sep-2004	41.3	-67.0	female	47	11-Dec-2005	41.0	-67.4	463	53
8513	4-Aug-2004	42.8	-69.3	male	42	19-Oct-2004	42.8	-69.3	76	2
8525	6-Aug-2004	41.2	-67.2	female	42	8-Aug-2004	41.2	-67.2	2	7
8550	7-Jul-2005	41.2	-67.3	female	36	30-Jul-2005	41.1	-67.3	23	10
8551	7-Jul-2005	41.2	-67.3	male	39	11-Jul-2005	41.2	-67.5	4	18
10053	8-Jul-2005	41.2	-67.3	female	48	4-Oct-2005	41.0	-67.3	88	18
10072	5-Aug-2005	41.2	-67.3	female	42	22-Nov-2005	41.1	-67.3	109	13
10076	5-Aug-2005	42.1	-67.3	female	40	12-Nov-2005	41.1	-67.4	99	116
10080	5-Aug-2005	41.2	-67.3	male	37	4-Nov-2005	41.0	-67.1	91	36
10082	5-Aug-2005	41.2	-67.3	female	45	5-Dec-2005	41.2	-67.4	122	7
10083	5-Aug-2005	41.2	-67.3	female	42	5-Jun-2006	41.2	-67.6	304	21
10099	5-Aug-2005	41.2	-67.3	female	46	15-Mar-2006	41.0	-67.4	222	26
10110	5-Aug-2005	41.2	-67.3	female	45	11-Nov-2005			98	
10113	5-Aug-2005	42.1	-67.3	female	43	2-Jun-2006	42.1	-67.4	301	4
10137	8-Jul-2005	41.2	-67.3	female	44	25-Jul-2005	41.1	-67.4	17	13
10149	8-Jul-2005	41.2	-67.3	female	42	30-Jul-2005	41.0	-67.3	22	16
10151	8-Jul-2005	41.2	-67.3	female	44	20-Jul-2005	41.1	-67.3	12	5

Table 2. Off-bottom movement events from tag 1497 with summary statistics for time of day, depth and temperature observations.

				Duration	Depth of fish (m)			Off-bottom	Temperature (C)		
Event	Start date	Start time	End time	(h:m)	average	minimum	maximum	depth (m)	average	minimum	maximum
1	18-Jul-03	18:25	5:40	11:15	51	24	95	37	10	5	12
2	18-Jul-03	18:48	19:10	0:22	93	88	98	6	5	5	5
3	19-Jul-03	20:18	2:10	5:52	87	50	118	50	7	6	9
4	20-Jul-03	18:55	2:48	7:52	74	61	86	5	9	7	11
5	21-Jul-03	23:33	2:33	3:00	74	63	84	10	9	8	10
6	22-Jul-03	23:55	2:03	2:07	75	68	79	8	8	7	9
7	22-Jul-03	19:33	20:03	0:30	73	70	75	5	6	6	6
8	23-Jul-03	1:18	1:48	0:30	72	68	77	6	8	8	9
9	24-Jul-03	18:40	19:18	0:37	62	57	70	13	10	10	10
10	25-Jul-03	0:55	2:03	1:07	61	52	82	14	10	8	11
11	25-Jul-03	18:48	19:25	0:37	67	59	76	17	9	8	9
12	26-Jul-03	1:18	2:25	1:07	69	62	81	7	9	9	9
13	26-Jul-03	19:03	20:40	1:37	63	56	74	18	10	9	10
14	31-Jul-03	19:03	19:18	0:15	74	72	75	2	9	9	9
15	1-Aug-03	22:40	22:55	0:15	75	74	76	2	9	9	10
16	2-Aug-03	19:33	20:03	0:30	74	67	82	6	8	8	8
17	4-Aug-03	1:18	1:40	0:22	77	72	82	10	9	9	9
18	5-Aug-03	23:18	2:40	3:22	76	67	86	13	9	7	11
19	6-Aug-03	0:10	2:40	2:30	80	74	92	8	9	8	11
20	7-Aug-03	1:03	2:40	1:37	78	69	87	14	9	8	9
21	8-Aug-03	2:10	2:33	0:22	72	68	76	7	9	9	9
22	22-Aug-03	19:10	19:55	0:45	68	65	70	5	7	6	7
23	24-Aug-03	21:40	1:10	3:30	63	49	79	18	8	7	9
24	29-Aug-03	18:18	18:40	0:22	70	64	81	3	10	10	10
25	31-Aug-03	20:33	21:03	0:30	76	72	84	4	11	11	12
26	2-Sep-03	21:33	23:55	2:22	92	74	103	7	9	6	11
27	3-Sep-03	1:03	1:25	0:22	91	90	93	3	7	6	7
28	3-Sep-03	21:03	21:10	0:07	91	89	92	0	8	8	8
29	7-Sep-03	13:10	13:18	0:07	78	77	79	2	10	10	10
all				1:51	74	24	118	10	9	5	12

Table 3. On-bottom periods from tag 1497 with summary statistics for depth and temperature observations.

		Depth of fish (m)			Temperature (C)			Duration
Period	Start date	average	minimum	maximum	average	minimum	maximum	(h:m)
1	17-Jul-2003	60	59	61	8	7	9	2:22
2	18-Jul-2003	94	93	95	6	5	8	12:52
3	18-Jul-2003	100	99	100	6	5	6	0:52
4	19-Jul-2003	66	65	67	8	6	10	16:30
5	20-Jul-2003	73	73	74	7	6	8	20:30
6	21-Jul-2003	77	75	83	7	6	9	21:07
7	22-Jul-2003	77	75	78	7	6	8	17:15
8	22-Jul-2003	74	74	74	7	6	8	5:00
9	23-Jul-2003	72	69	77	8	6	11	16:37
10	24-Jul-2003	67	66	67	9	8	10	5:22
11	25-Jul-2003	78	74	83	8	6	10	16:30
12	25-Jul-2003	70	69	71	7	7	9	5:37
13	26-Jul-2003	78	73	82	8	6	10	16:22
14	26-Jul-2003	69	62	76	8	6	12	22:07
15	31-Jul-2003	75	74	76	8	6	10	3:07
16	1-Aug-2003	74	73	76	8	6	11	20:22
17	2-Aug-2003	81	80	84	8	6	9	5:00
18	4-Aug-2003	80	79	81	8	7	9	21:22
19	5-Aug-2003	83	81	86	7	6	10	21:15
20	6-Aug-2003	84	82	89	7	5	9	22:07
21	7-Aug-2003	78	74	87	7	5	9	23:15
22	8-Aug-2003	69	64	77	9	6	12	16:22
23	22-Aug-2003	68	67	69	9	6	12	1:30
24	24-Aug-2003	69	66	80	9	6	13	16:52
25	29-Aug-2003	81	76	84	9	7	14	1:37
26	31-Aug-2003	82	80	85	8	6	12	0:15
27	2-Sep-2003	93	93	93	7	6	7	0:52
28	3-Sep-2003	91	89	93	7	6	11	19:22
29	3-Sep-2003	86	78	94	8	6	11	15:45
30	7-Sep-2003	76	72	79	9	6	15	3:52
all		78	59	100	8	5	14	20:24

Table 4. Estimates of tidal parameters a_0 (i.e., mean depth), a_1 and b_1, as well as tidal amplitude (A) for data from tag 1497.

Date	a0 (m)	a1	b1	A (m)
17-Jul-2003	61.7	-1.5	-0.1	1.5
18-Jul-2003	94.3	-1.2	0.5	1.3
18-Jul-2003	99.9	-2.4	0.5	2.4
19-Jul-2003	66.4	-1.0	0.5	1.1
20-Jul-2003	73.6	-1.0	0.5	1.1
21-Jul-2003	77.3	-0.2	0.5	0.5
22-Jul-2003	76.6	0.4	-0.5	0.6
22-Jul-2003	74.1	-0.6	0.5	0.8
23-Jul-2003	74.1	0.4	-0.5	0.7
23-Jul-2003	73.7	-1.2	0.1	1.2
24-Jul-2003	70.9	-0.1	-0.5	0.5
24-Jul-2003	67.5	-1.6	0.5	1.7
25-Jul-2003	66.3	-0.6	0.5	0.7
25-Jul-2003	77.5	-1.3	-0.5	1.4
25-Jul-2003	70.7	-1.6	0.5	1.6
26-Jul-2003	69.0	0.0	0.5	0.5
26-Jul-2003	77.3	-1.0	-0.5	1.1
26-Jul-2003	63.0	-1.5	0.5	1.6
27-Jul-2003	64.2	-0.1	-0.5	0.5
28-Jul-2003	64.8	-0.1	-0.5	0.5
29-Jul-2003	70.6	-0.6	-0.5	0.8
30-Jul-2003	74.3	-0.2	-0.5	0.5
31-Jul-2003	74.2	-1.2	0.5	1.3
31-Jul-2003	75.0	-0.2	-0.5	0.6
1-Aug-2003	74.9	-1.3	0.5	1.4
1-Aug-2003	75.6	0.5	-0.5	0.7
2-Aug-2003	73.6	-1.4	0.5	1.5
2-Aug-2003	82.1	-0.7	-0.5	0.8
3-Aug-2003	81.3	-1.1	0.1	1.1
4-Aug-2003	82.1	0.5	-0.5	0.7
4-Aug-2003	79.9	-1.4	0.5	1.5
5-Aug-2003	82.9	-1.1	0.5	1.2
6-Aug-2003	84.1	-1.5	0.5	1.5
7-Aug-2003	81.4	-1.8	-0.5	1.9
7-Aug-2003	78.4	-2.5	0.5	2.5
8-Aug-2003	74.3	-0.7	-0.5	0.9
8-Aug-2003	72.6	-0.9	-0.5	1.0
9-Aug-2003	68.8	-0.4	-0.5	0.7
10-Aug-2003	66.9	0.0	-0.5	0.5
11-Aug-2003	65.8	-0.1	-0.5	0.5
12-Aug-2003	65.6	-0.2	-0.5	0.5
13-Aug-2003	65.5	-0.1	-0.5	0.5
14-Aug-2003	65.0	-0.5	-0.1	0.5
15-Aug-2003	65.2	-0.2	-0.5	0.5
16-Aug-2003	66.6	-0.2	-0.5	0.5
17-Aug-2003	68.3	-0.5	-0.3	0.6
18-Aug-2003	69.8	-0.2	-0.5	0.5
19-Aug-2003	72.5	-0.4	-0.1	0.4
20-Aug-2003	72.7	-0.2	-0.5	0.5
21-Aug-2003	72.4	-0.3	-0.1	0.3
22-Aug-2003	71.0	-0.2	-0.5	0.5
22-Aug-2003	67.7	-0.6	0.5	0.8
23-Aug-2003	68.1	0.6	-0.5	0.8
24-Aug-2003	74.3	-1.3	-0.5	1.4
25-Aug-2003	69.7	-0.2	-0.5	0.5
26-Aug-2003	69.1	-0.3	-0.5	0.6
27-Aug-2003	68.1	0.1	-0.5	0.5
28-Aug-2003	67.5	-0.4	-0.5	0.7
29-Aug-2003	67.5	-1.1	0.5	1.2
29-Aug-2003	81.8	-0.4	-0.5	0.6
30-Aug-2003	81.9	-0.7	-0.3	0.8
31-Aug-2003	79.2	-1.4	0.5	1.5
31-Aug-2003	84.3	0.3	-0.5	0.6
1-Sep-2003	82.6	-1.2	0.3	1.2
2-Sep-2003	81.0	-1.4	0.5	1.5
3-Sep-2003	94.3	1.4	-0.5	1.5
3-Sep-2003	90.7	-1.4	0.5	1.5
3-Sep-2003	92.3	-0.1	-0.5	0.5
4-Sep-2003	89.0	-1.1	-0.5	1.2
5-Sep-2003	85.8	-0.8	-0.5	1.0
6-Sep-2003	84.5	-0.3	-0.5	0.6
7-Sep-2003	82.0	-2.5	-0.5	2.5
7-Sep-2003	77.9	-0.2	-0.5	0.6
8-Sep-2003	77.7	-0.1	-0.5	0.5
9-Sep-2003	77.6	0.0	-0.5	0.5
10-Sep-2003	76.3	0.1	-0.5	0.5
11-Sep-2003	75.0	-0.1	-0.5	0.5
12-Sep-2003	75.1	-0.2	-0.5	0.5
13-Sep-2003	75.3	-1.3	0.5	1.4
average	75.1			0.9
minimum	61.7			0.3
maximum	99.9			2.5

Table 5. Summary of depth (m) and temperature (^{o}C) derived from periods of on-bottom behavior.

	Depth (m)			Temperature (C)			Tidal Amplitude (m)		
Tag	average	minimum	maximum	average	minimum	maximum	average	minimum	maximum
1497	74	59	100	8	5	15	0.9	0.3	2.5
1870	68	40	91	10	8	15	0.7	0.1	3.0
2022	57	44	62	8	5	10	0.6	0.1	1.4
3000	78	23	97	8	3	13	0.6	0.1	2.3
3008	69	13	94	9	3	15	0.6	0.1	2.8
3019	68	19	82	8	3	14	0.6	0.1	2.6
3031	66	39	120	9	5	13	0.9	0.1	2.3
3039	68	35	90	8	3	15	0.6	0.1	2.8
3113	67	20	96	8	3	15	0.7	0.1	3.0
3156	66	14	85	8	3	15	0.6	0.1	2.5
3205	59	15	106	5	2	11	1.0	0.1	2.9
3313	72	30	98	8	3	15	0.7	0.1	2.8
8345	40	14	97	7	4	14	0.9	0.1	2.9
8473	61	49	70	9	7	12	0.5	0.1	2.0
10072	62	29	79	11	8	14	0.6	0.1	2.7
10080	67	11	78	11	8	14	0.6	0.1	2.3
10099	60	29	79	9	5	14	0.7	0.1	2.9
10110	62	17	72	12	9	15	0.6	0.1	2.8
10137	57	29	68	9	7	10	0.8	0.2	2.6
all	64	11	120	9	2	15	0.7	0.1	3.0

Table 6. Summary of off-bottom movements.

Tag	Days at Large	Off-bottom movements	Frequency (OBMs/d)	Start time mode	End time mode	Duration mean (h)	Off-bottom depth (m)	Temperature (C) Mean	Minimum	Maximum
1497	58	29	0.5	18:00	2:00	1.9	10	9	5	12
1870	132	147	1.1	16:00	22:00	2.7	13	11	8	15
2022	129	13	0.1	2:00	3:00	1.3	6	7	5	9
3000	325	60	0.2	20:00	22:00	1.5	6	7	3	13
3008	391	162	0.4	20:00	21:00	1.4	5	8	3	14
3019	285	104	0.4	19:00	0:00	1.4	4	6	4	13
3031	33	27	0.8	20:00	22:00	1.5	7	7	5	12
3039	301	182	0.6	19:00	1:00	1.4	6	8	4	14
3113	267	141	0.5	3:00	5:00	1.1	5	9	3	15
3156	402	129	0.3	22:00	23:00	1.5	8	7	3	14
3205	329	22	0.1	22:00	23:00	1.1	2	5	2	11
3313	325	122	0.4	20:00	21:00	1.3	2	6	4	22
8345	316	52	0.2	18:00	20:00	1.5	1	7	3	15
8473	36	20	0.5	19:00	3:00	2.8	18	9	7	10
10072	108	38	0.4	1:00	0:00	1.2	7	11	8	13
10080	90	15	0.2	14:00	15:00	1.2	4	10	9	11
10099	221	202	0.9	17:00	18:00	1.1	5	10	5	14
10110	97	53	0.5	21:00	22:00	1.6	8	12	9	15
10137	11	10	1.0	22:00	23:00	1.0	4	9	8	10
all	3856	1528	0.4	20:00	22:00	1.5	6	8	2	22

Figure 1. Data storage tag attached to a yellowtail flounder.

Figure 2. Locations of release and recapture of DSTs deployed on yellowtail flounder. Vector labels indicate tag numbers.

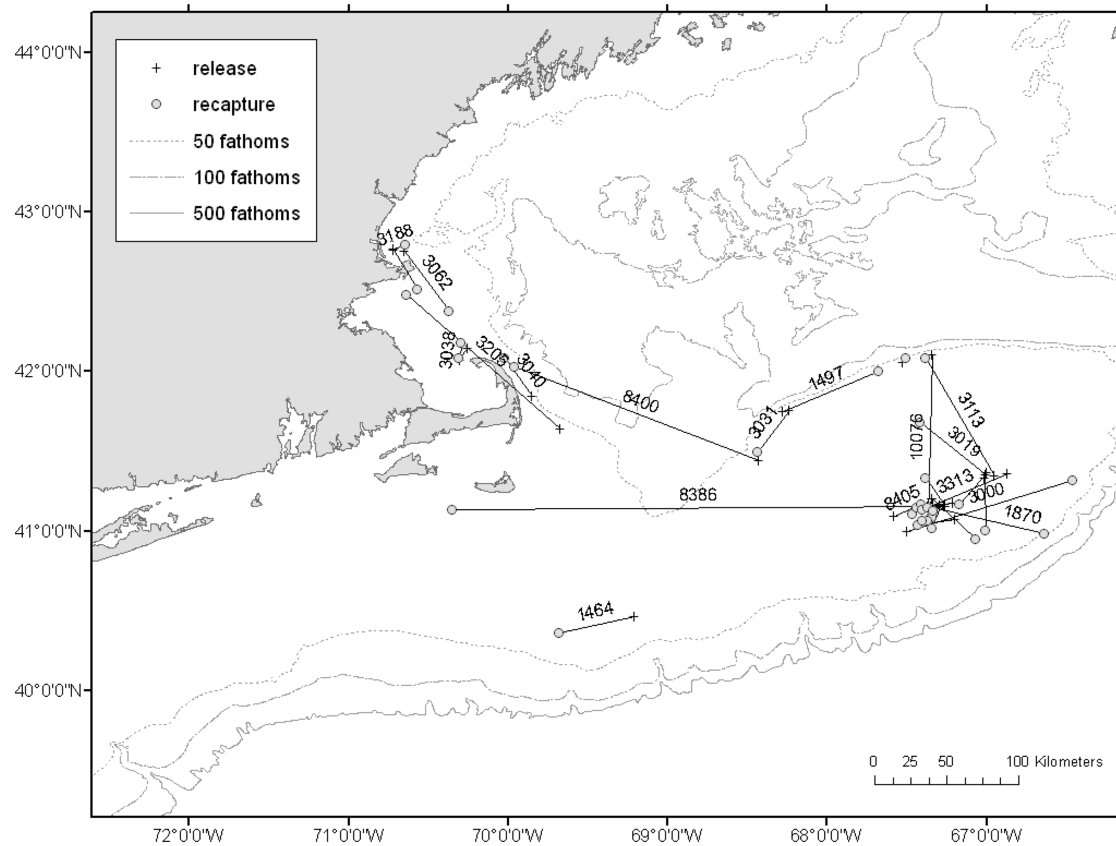
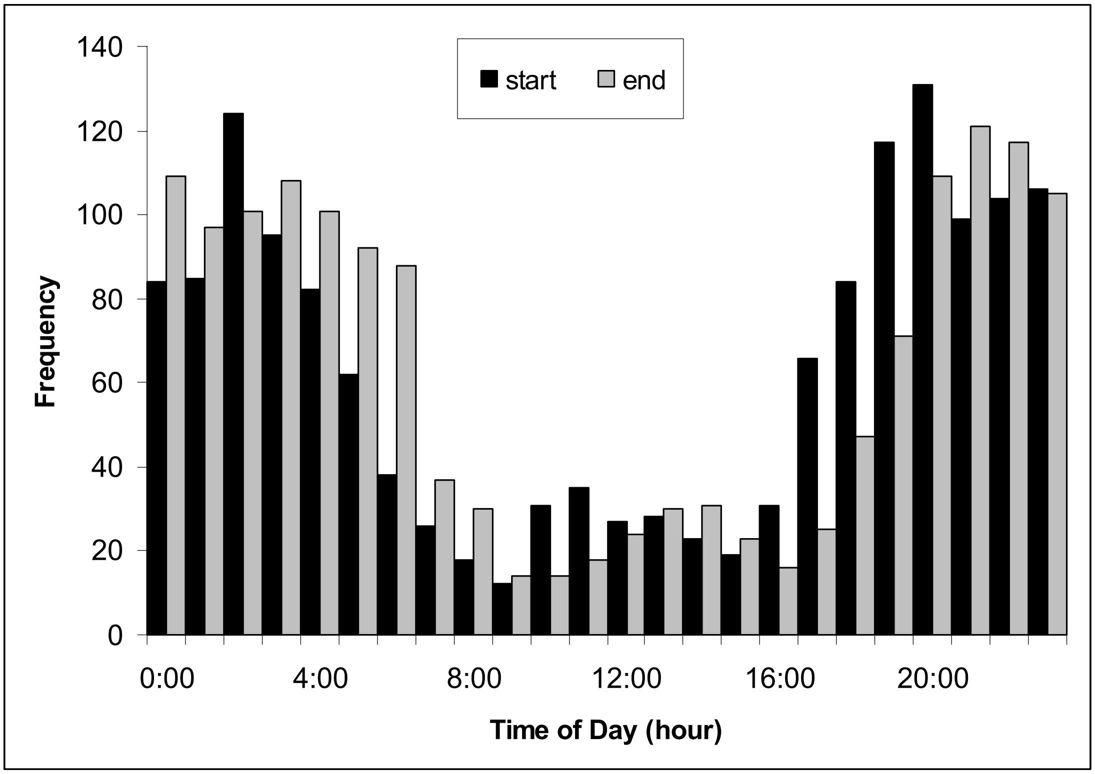
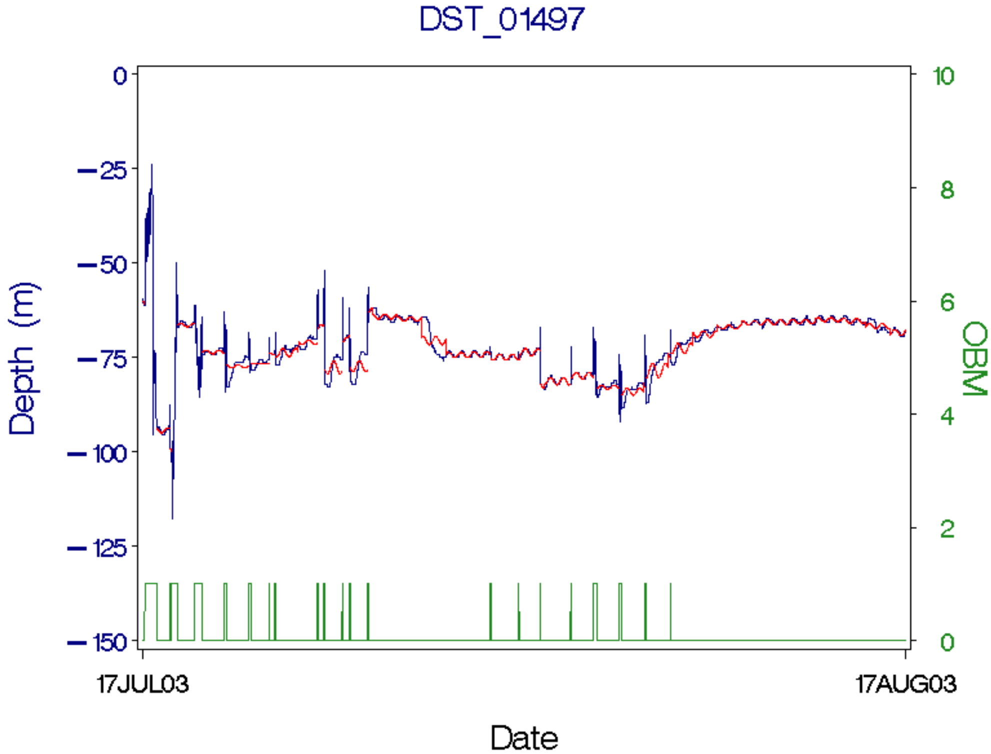
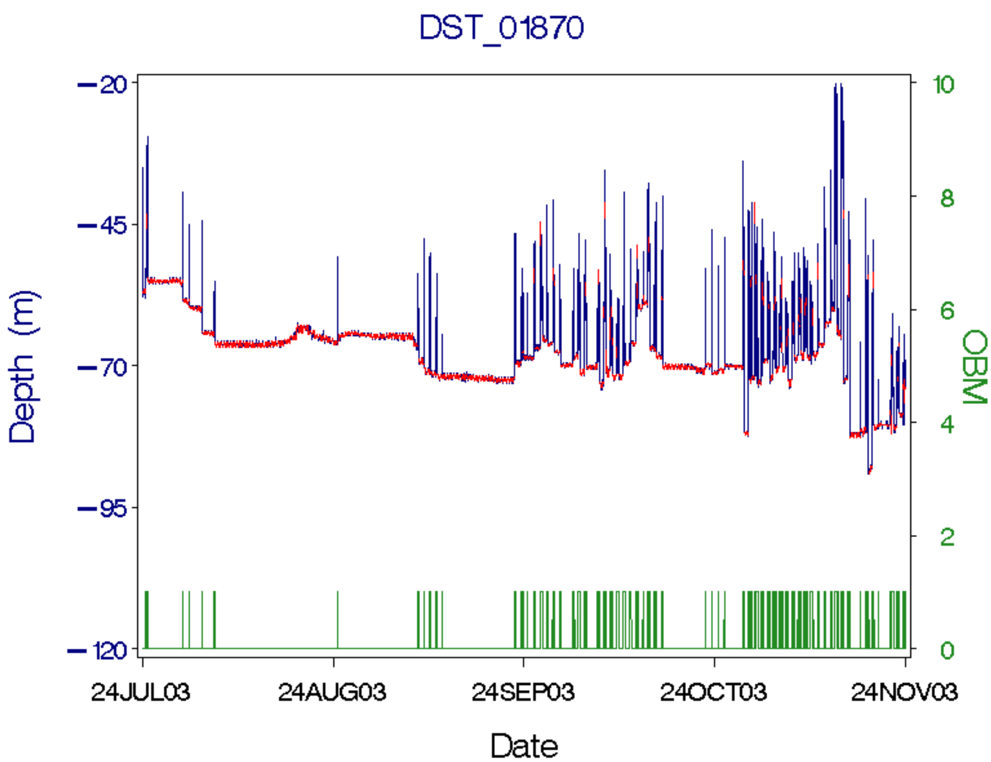


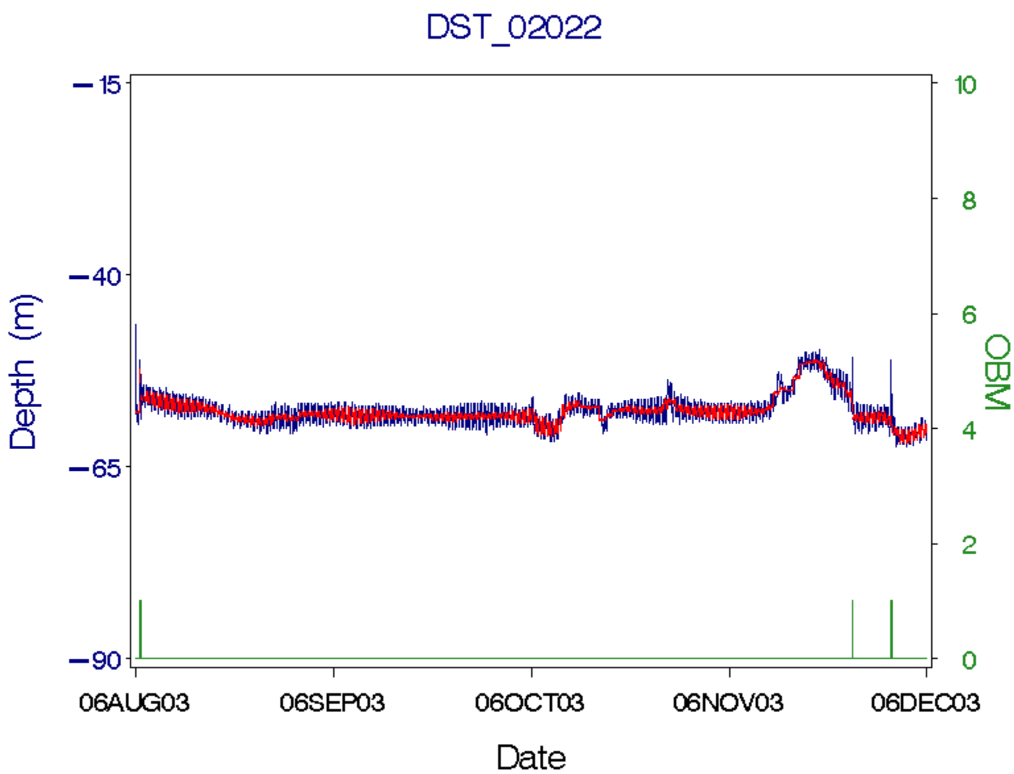
Figure 3. Frequency of off-bottom movements by time of day.

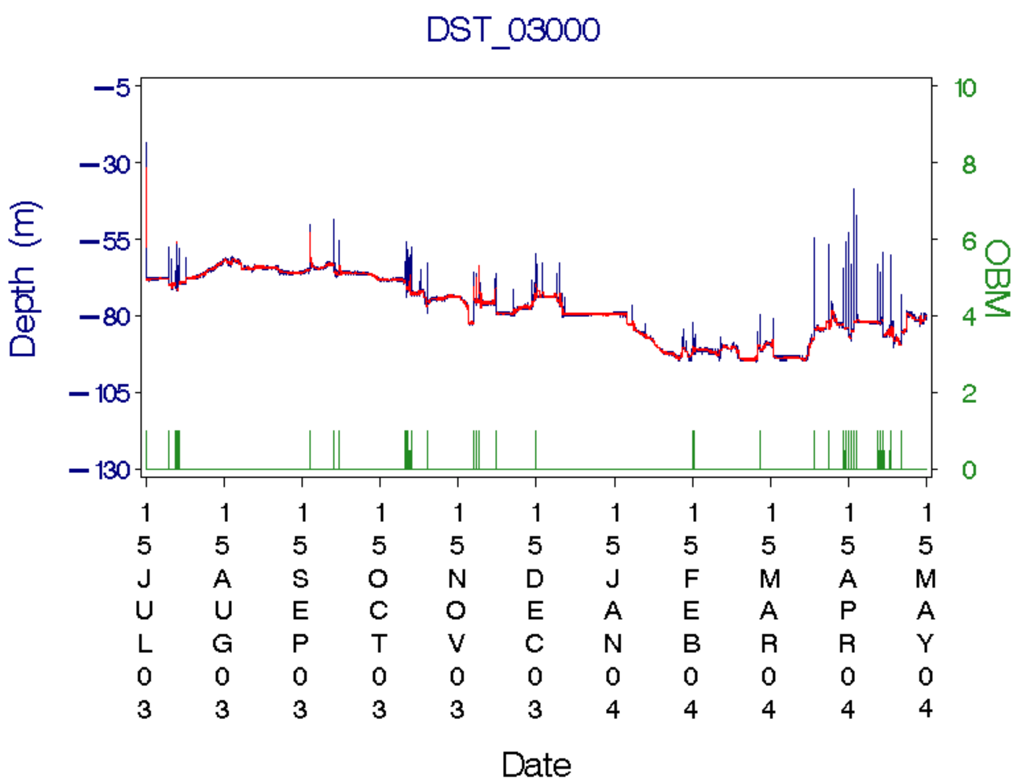


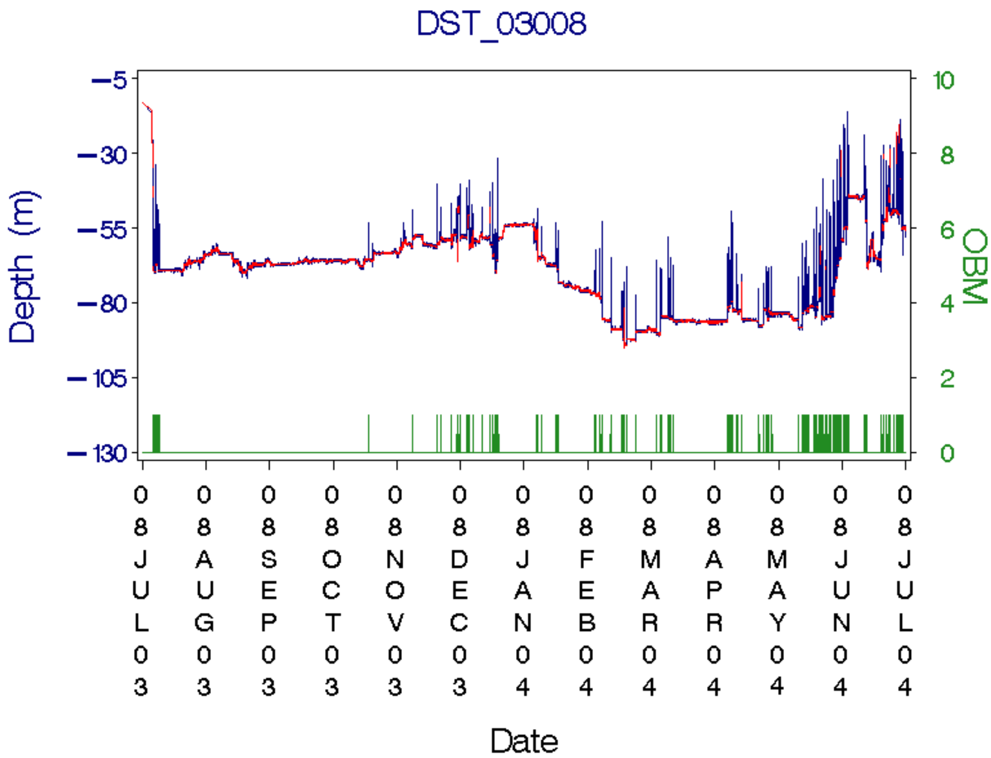
Appendix A. Observed depth from data storage tags deployed on yellowtail flounder off New England (blue line), periods of off bottom movement (OBM, green line) and predicted depth during on-bottom periods (red line).

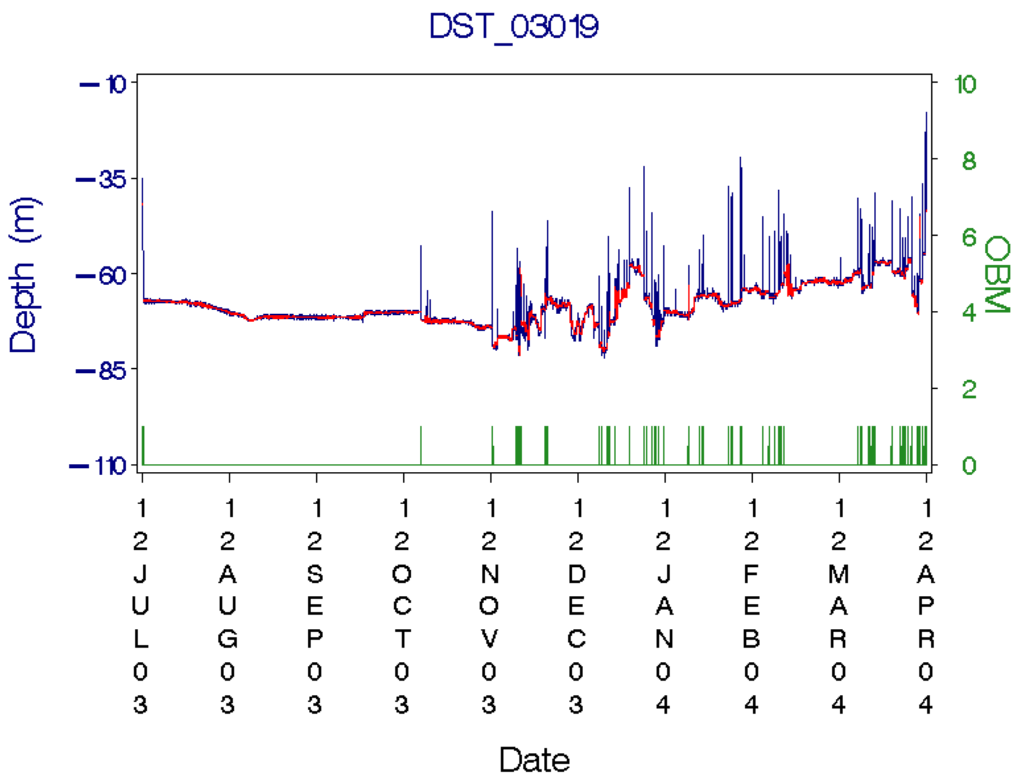


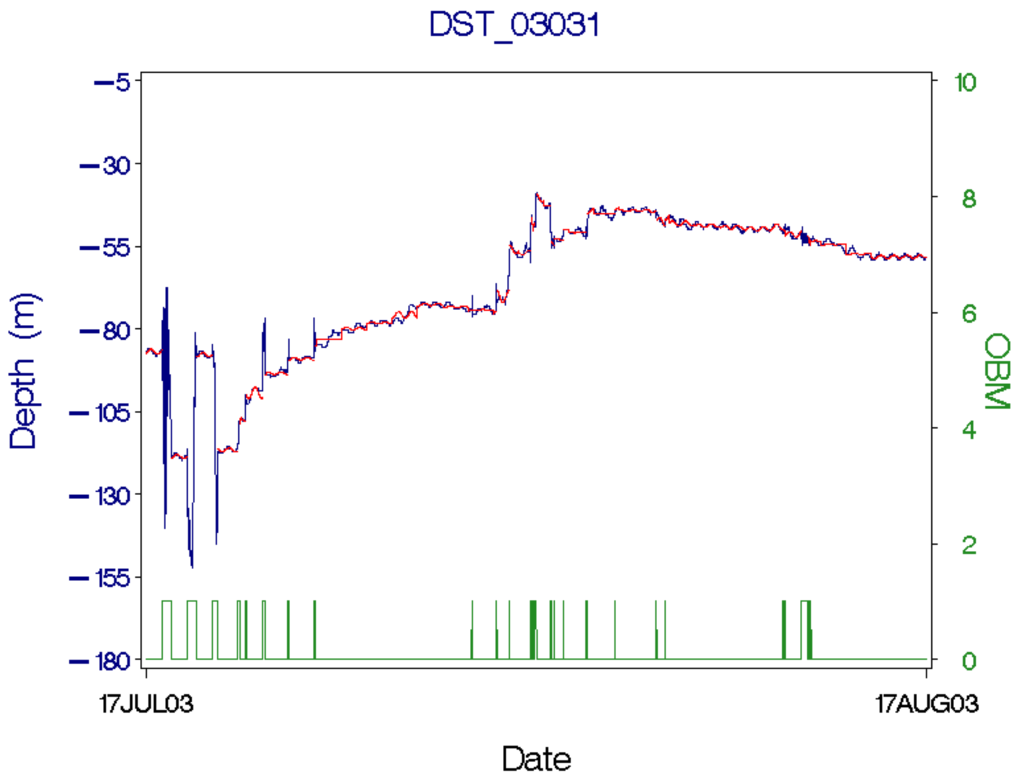


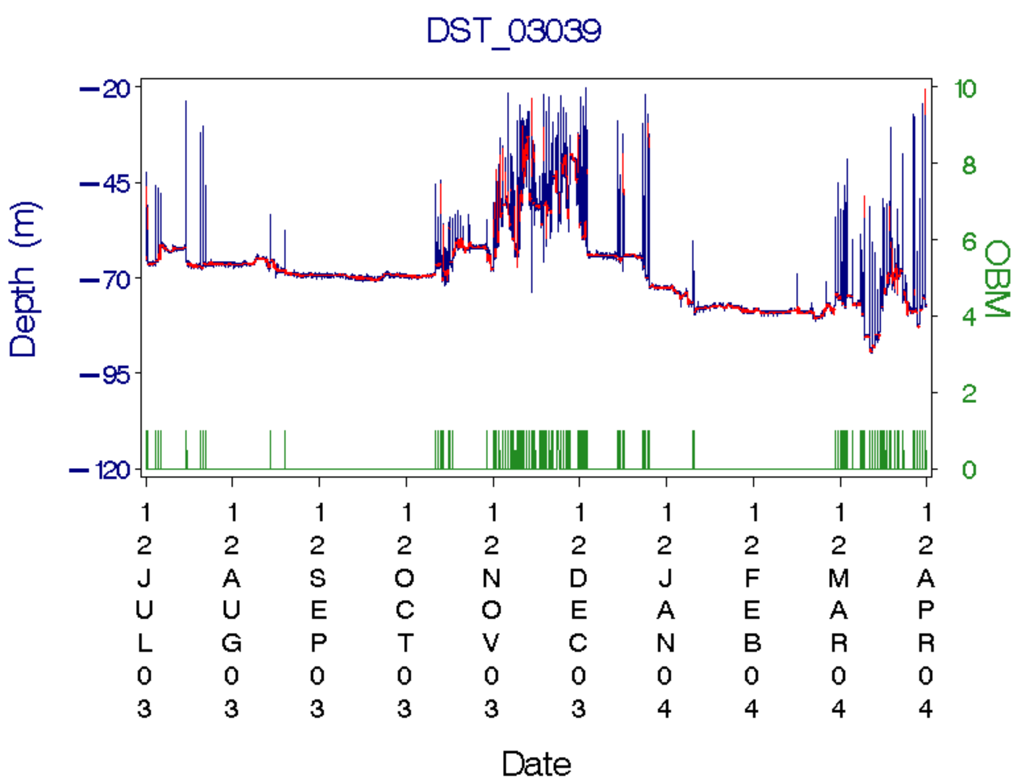

DST_02022
Depth (m)
OBM
-15
-40
-65
-90
10
8
6
4
2
0
06AUG03
06SEP03
06OCT03
06NOV03
06DEC03
Date

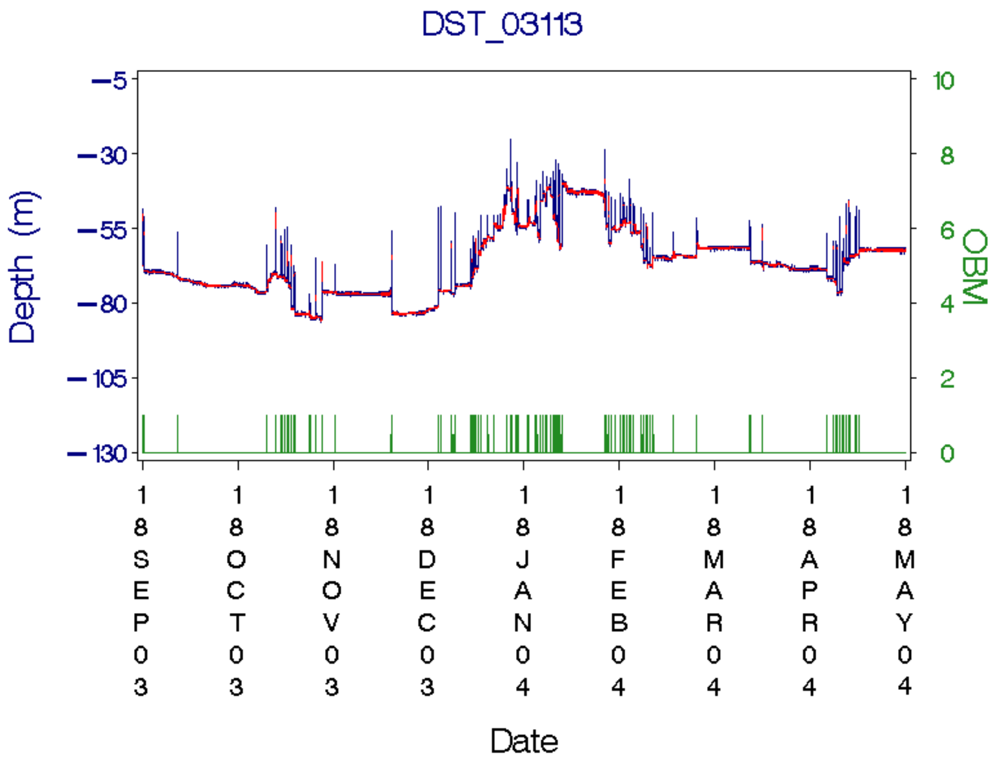

DST_03000
Depth (m)
OBM
-5
-30
-55
-80
-105
-130
10
8
6
4
2
0
15JUL03
15AUG03
15SEP03
15OCT03
15NOV03
15DEC03
15JAN04
15FEB04
15MAR04
15APR04
15MAY04
Date

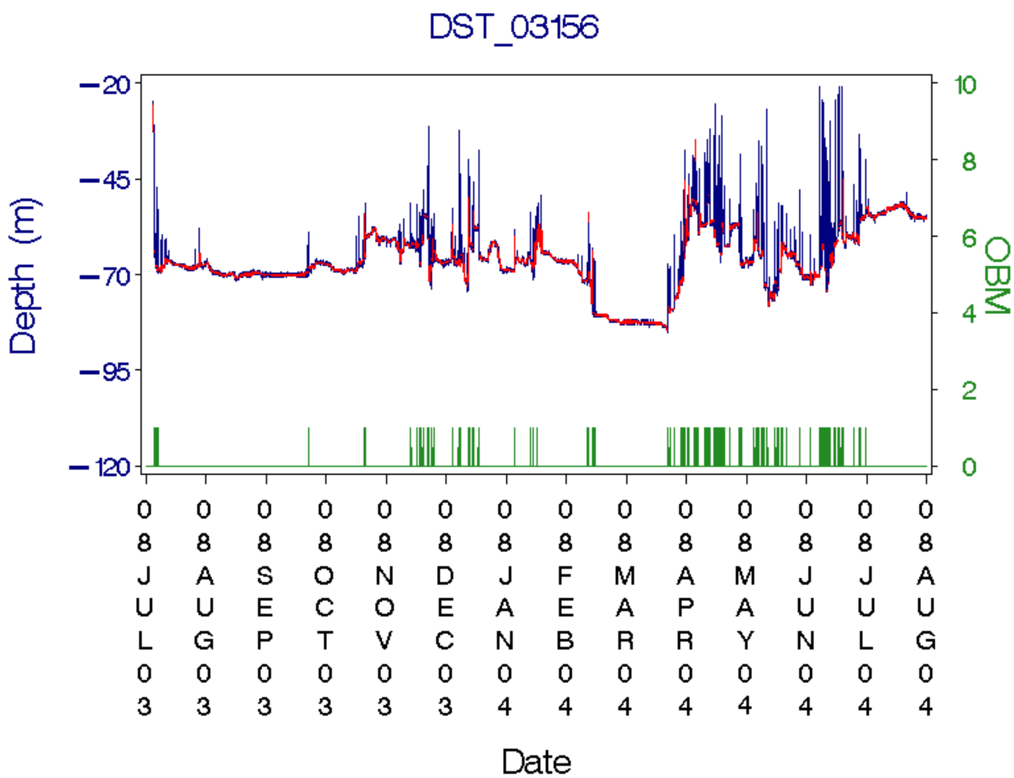

DST_03008
Depth (m)
OBM
-5
-30
-55
-80
-105
-130
10
8
6
4
2
0
08JUL03
08AUG03
08SEP03
08OCT03
08NOV03
08DEC03
08JAN04
08FEB04
08MAR04
08APR04
08MAY04
08JUN04
08JUL04
Date

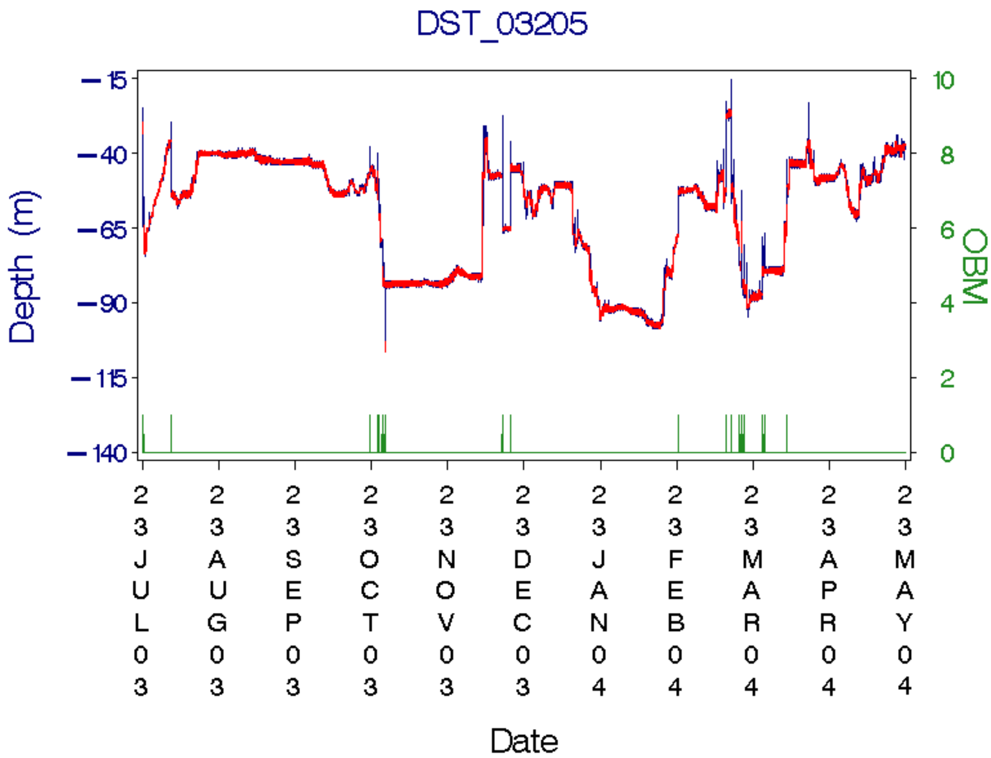

DST_03019
Depth (m)
OBM
-10
-35
-60
-85
-110
10
8
6
4
2
0
12JUL03
12AUG03
12SEP03
12OCT03
12NOV03
12DEC03
12JAN04
12FEB04
12MAR04
12APR04
Date

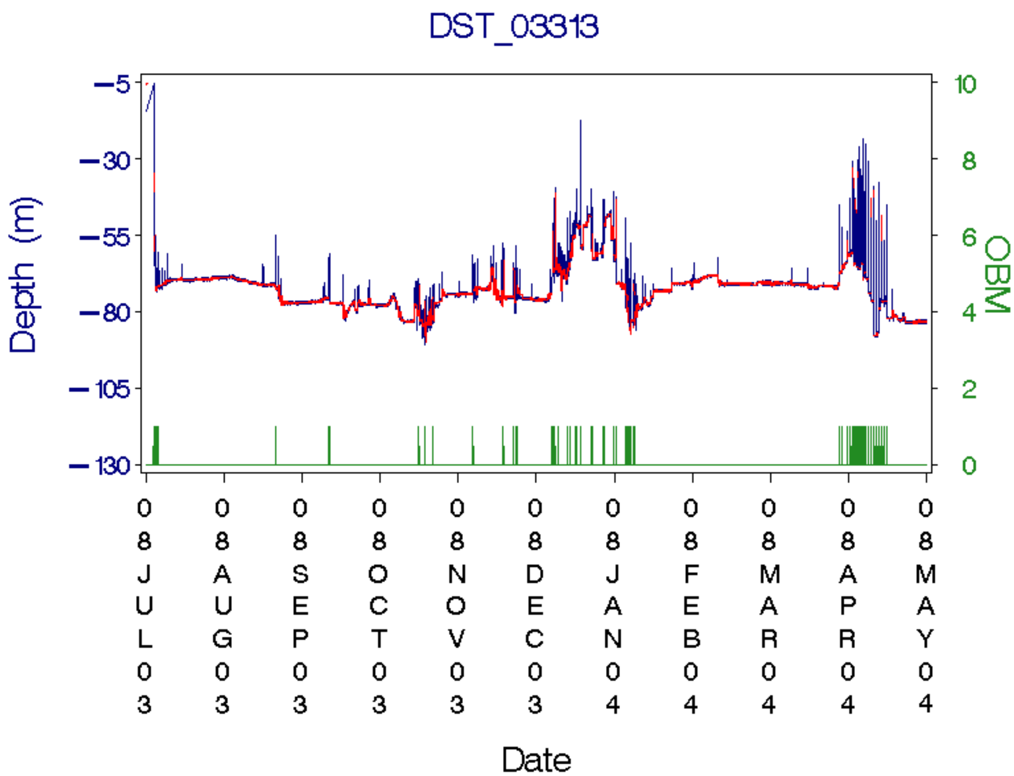

DST_03031
-5
-30
-55
-80
-105
-130
-155
-180
Depth (m)
10
8
6
4
2
0
OBM
17JUL03
17AUG03
Date

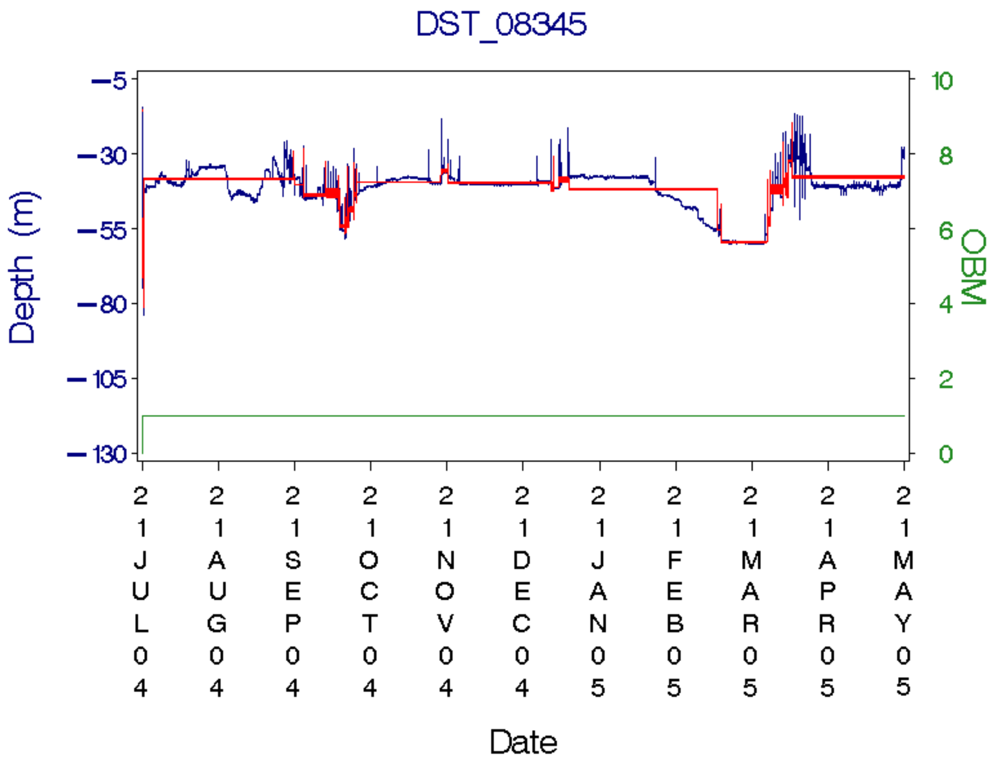

DST_03039
-20
-45
-70
-95
-120
Depth (m)
10
8
6
4
2
0
OBM
12JUL03
12AUG03
12SEP03
12OCT03
12NOV03
12DEC03
12JAN04
12FEB04
12MAR04
12APR04
Date

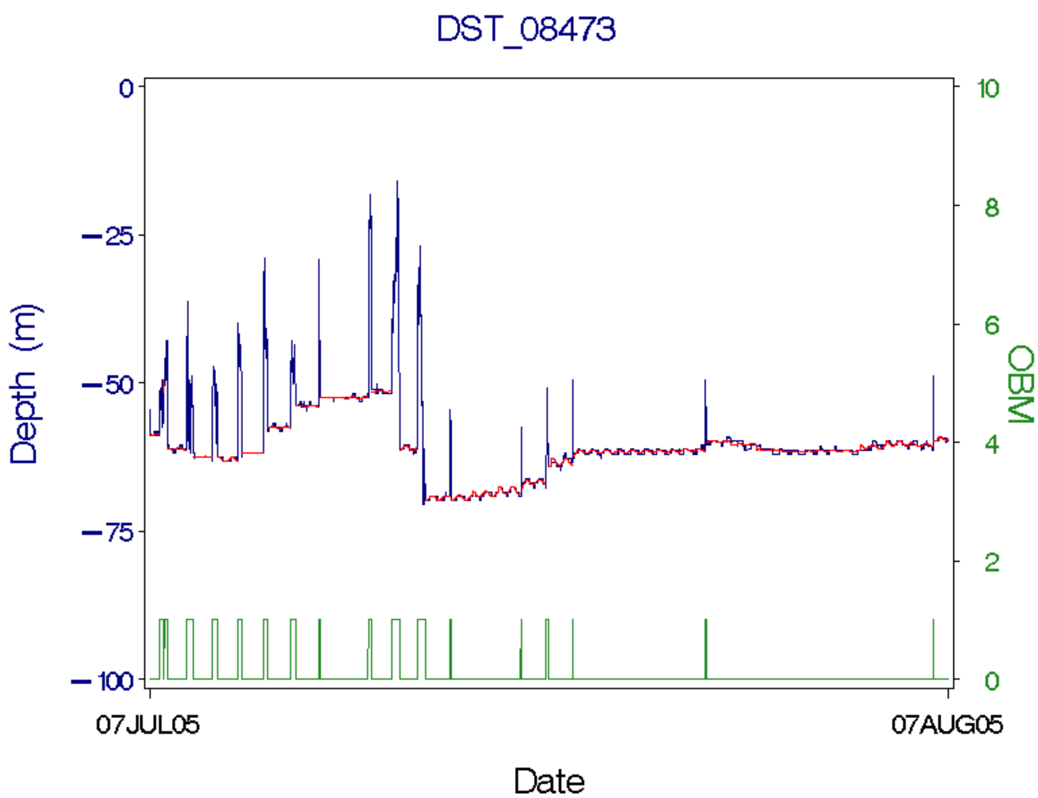

DST_03113
Depth (m)
-5
-30
-55
-80
-105
-130
OBM
10
8
6
4
2
0
18SEP03
18OCT03
18NOV03
18DEC03
18JAN04
18FEB04
18MAR04
18APR04
18MAY04
Date

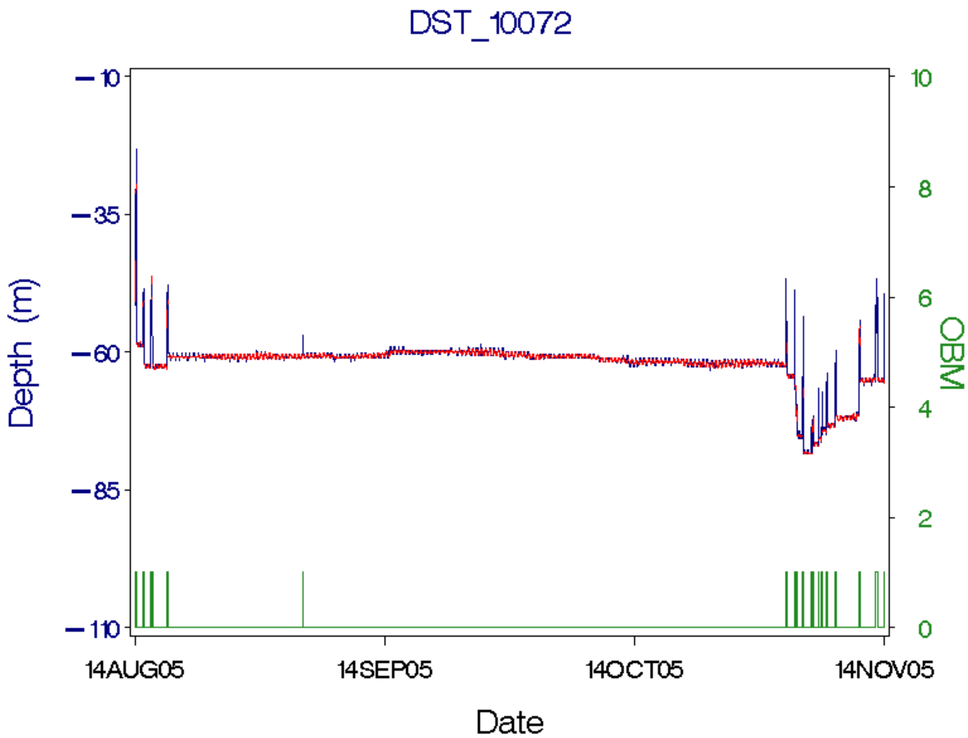

DST_03156
Depth (m)
-20
-45
-70
-95
-120
OBM
10
8
6
4
2
0
08JUL03
08AUG03
08SEP03
08OCT03
08NOV03
08DEC03
08JAN04
08FEB04
08MAR04
08APR04
08MAY04
08JUN04
08JUL04
08AUG04
Date

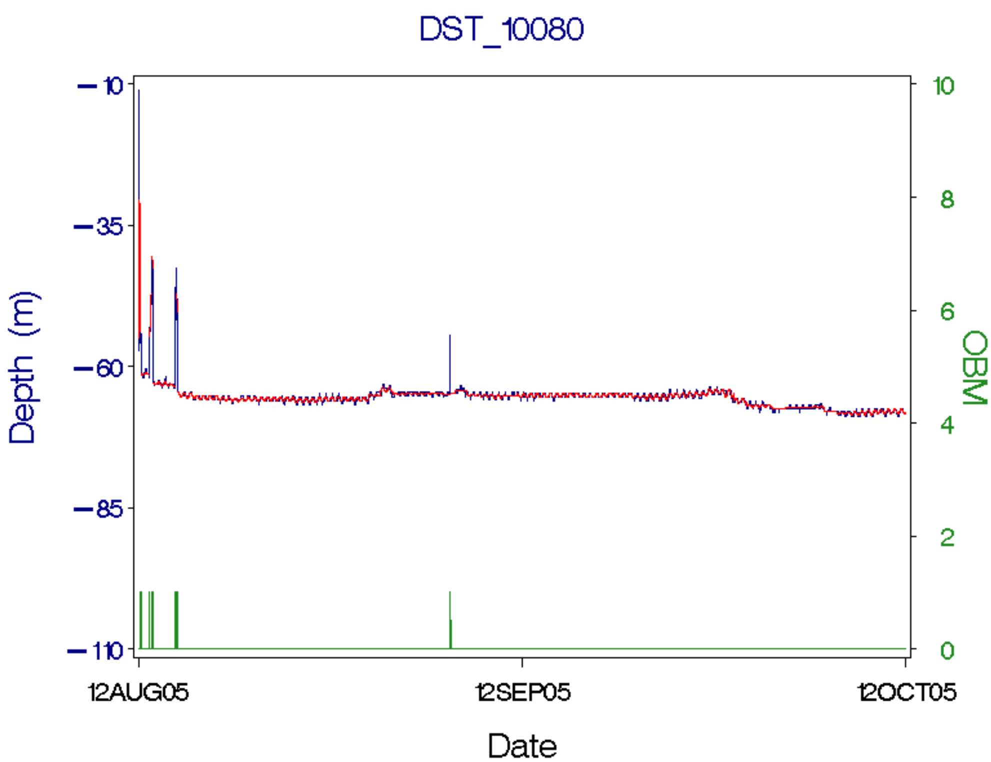

DST_03205
Depth (m)
OBM
-15
-40
-65
-90
-115
-140
10
8
6
4
2
0
23JUL03
23AUG03
23SEP03
23OCT03
23NOV03
23DEC03
23JAN04
23FEB04
23MAR04
23APR04
23MAY04
Date

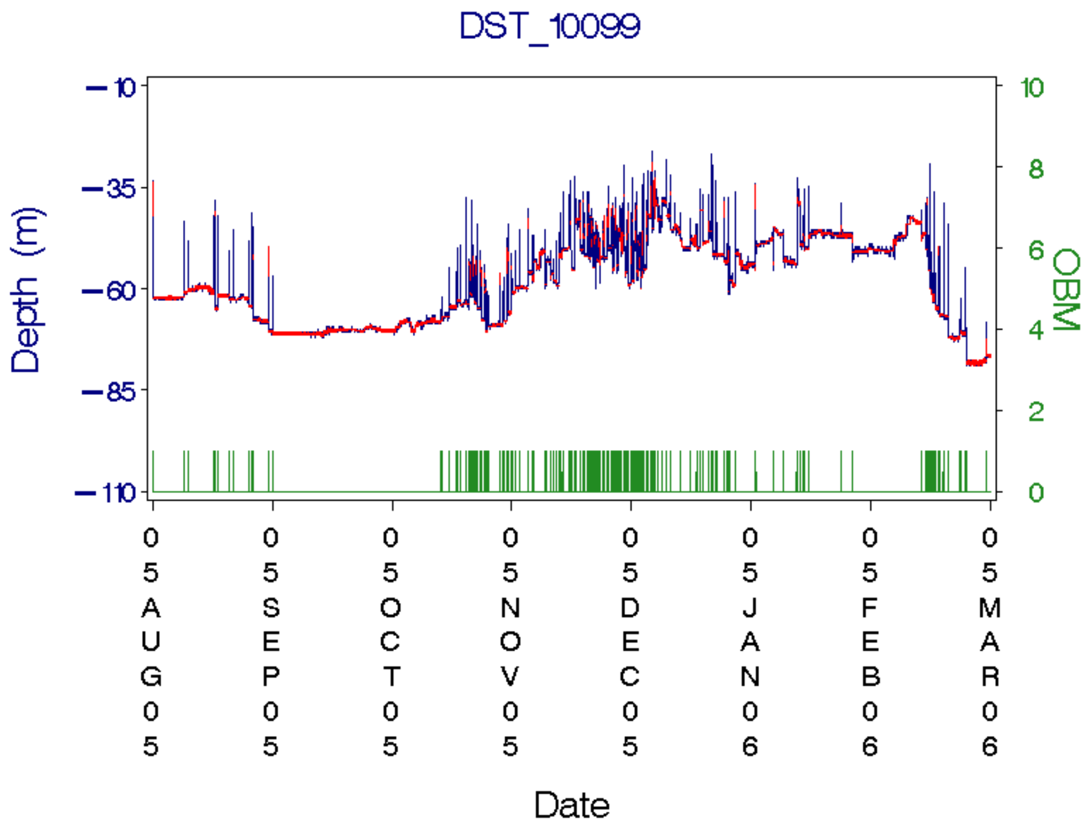

DST_03313
Depth (m)
OBM
-5
-30
-55
-80
-105
-130
10
8
6
4
2
0
08JUL03
08AUG03
08SEP03
08OCT03
08NOV03
08DEC03
08JAN04
08FEB04
08MAR04
08APR04
08MAY04
Date

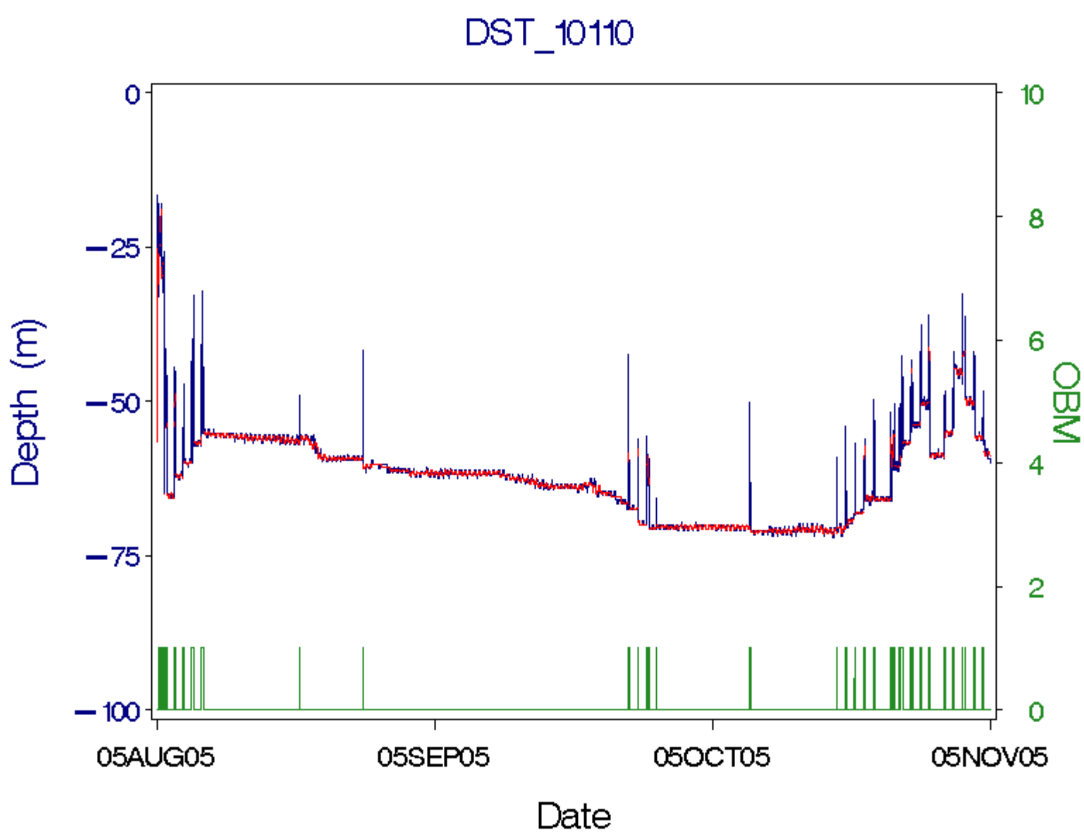

DST_08345
Depth (m)
-5
-30
-55
-80
-105
-130
OBM
10
8
6
4
2
0
21JUL04
21AUG04
21SEP04
21OCT04
21NOV04
21DEC04
21JAN05
21FEB05
21MAR05
21APR05
21MAY05
Date

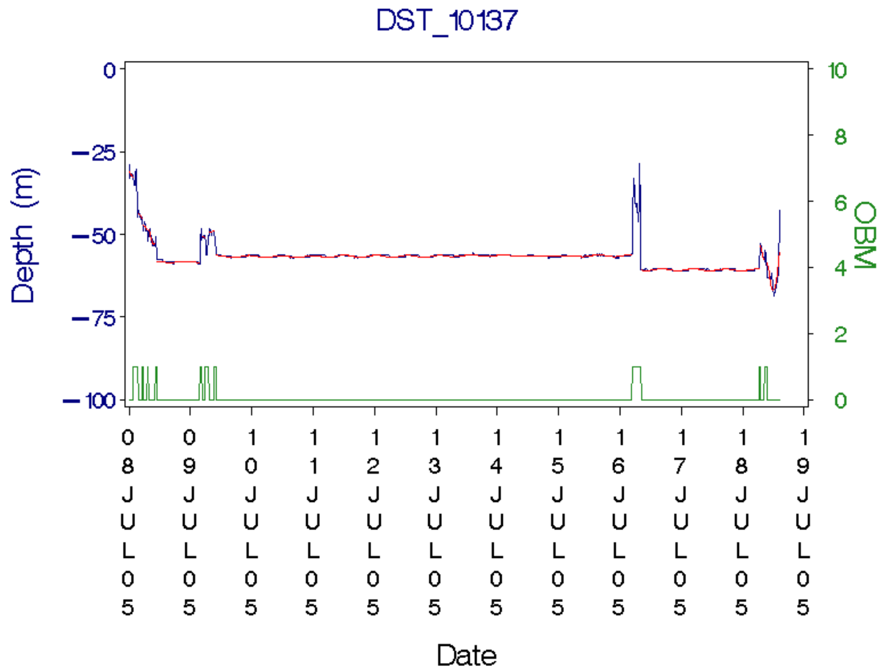

DST_08473
Depth (m)
0
-25
-50
-75
-100
OBM
10
8
6
4
2
0
07JUL05
07AUG05
Date


DST_10072
Depth (m)
OBM
-10
-35
-60
-85
-110
10
8
6
4
2
0
14AUG05
14SEP05
14OCT05
14NOV05
Date


DST_10080
Depth (m)
OBM
-10
-35
-60
-85
-110
10
8
6
4
2
0
12AUG05
12SEP05
12OCT05
Date


DST_10099
Depth (m)
OBM
Date
05AUG05
05SEP05
05OCT05
05NOV05
05DEC05
05JAN06
05FEB06
05MAR06


DST_10110
Depth (m)
OBM
Date
05AUG05
05SEP05
05OCT05
05NOV05


DST_10137
Depth (m)
OBM
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−25
−50
−75
−100
10
8
6
4
2
0
08JUL05
09JUL05
10JUL05
11JUL05
12JUL05
13JUL05
14JUL05
15JUL05
16JUL05
17JUL05
18JUL05
19JUL05
Date