WHOI-99-05

Woods Hole Oceanographic Institution

RAFOS Float Trajectories in Meddies During the Semaphore Experiment, 1993-1995

By

P.L. Richardson
C.M. Wooding

April 1999

Technical Report

Funding was provided by the National Science Foundation under Grant No. OCE-93-01234

WHOI-99-05

RAFOS Float Trajectories in Meddies During the Semaphore Experiment, 1993-1995

by

P.L. Richardson
C.M. Wooding

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

April 1999

Technical Report

Funding was provided by the National Science Foundation
under contract number OCE 93-01234.

Approved for Distribution:

Terrence M. Joyce, Chair

Department of Physical Oceanography

Abstract

As part of the Semaphore Experiment four Meddies (Mediterranean Water Eddies) were discovered in the Canary Basin and tracked with freely drifting RAFOS floats. An additional Meddy was discovered off Lisbon by Pingree (1995) and also tracked with RAFOS floats. One large and energetic Meddy, discovered 1700 km west of Cape St. Vincent, Portugal, set a distance and speed record as it translated another 1700 km southwestward at 3.9 cm/sec during 1.5 years. This Meddy traveled 57% of the distance from Cape St. Vincent toward the spot McDowell and Rossby (1978) found a possible Meddy north of the Dominican Republic. Four Meddies collided with tall seamounts which seemed to disrupt the normal swirl velocity perhaps fatally in three cases. One Meddy appeared to bifurcate when it collided with seamounts. This report describes the float trajectories in the Meddies and summarizes the main results.

Table of Contents

List of Tables

List of Figures

1 Introduction

The Semaphore experiment, which occurred in the Canary Basin during 1993–1994, provided an opportunity to identify and seed Meddies (Mediterranean Water eddies) with floats with the goals of obtaining some detailed Meddy case histories and of assessing the importance of Meddies in maintaining the Mediterranean salt tongue in the Atlantic. A description of the main Semaphore field program and some results have been given by Eymard *et al.* (1996), Hernandez and LeTraon (1995), Tychensky and Carton (1998), Tychensky *et al.*, (1998), and Richardson and Tychensky (1998). Semaphore observations were concentrated in the region roughly bounded by 31.5–36.0N, 20.5–26.0W (Figure 1). The measurements were obtained by CTD–XBT–ADCP surveys of the region (Table I), RAFOS floats, surface drifters, moored current meters, meteorological moorings and remote sensing by satellite. As part of this experiment, air–sea fluxes and the mesoscale ocean circulation were observed in the vicinity of the Azores Current. The objectives were to describe and dynamically assess mesoscale variability, to validate numerical models, to validate satellite observations and analysis methods and to evaluate assimilation techniques.

This report is a description of the float trajectories in the four Meddies discovered on the Semaphore cruises plus another Meddy discovered by Pingree (1995) and seeded with our floats. One of the interesting results is the collision of four of the Meddies with seamounts in which three of the Meddies were apparently destroyed, thus adding evidence that this may be a common phenomenon. One of these Meddies was apparently cleaved into two pieces by the seamounts. Another Meddy survived a collision with seamounts and set records for both long distance, 1700 km, and fast mean velocity, 3.9 cm/sec averaged over 1.5 years. This Meddy reached 43°W, halfway across the Atlantic.

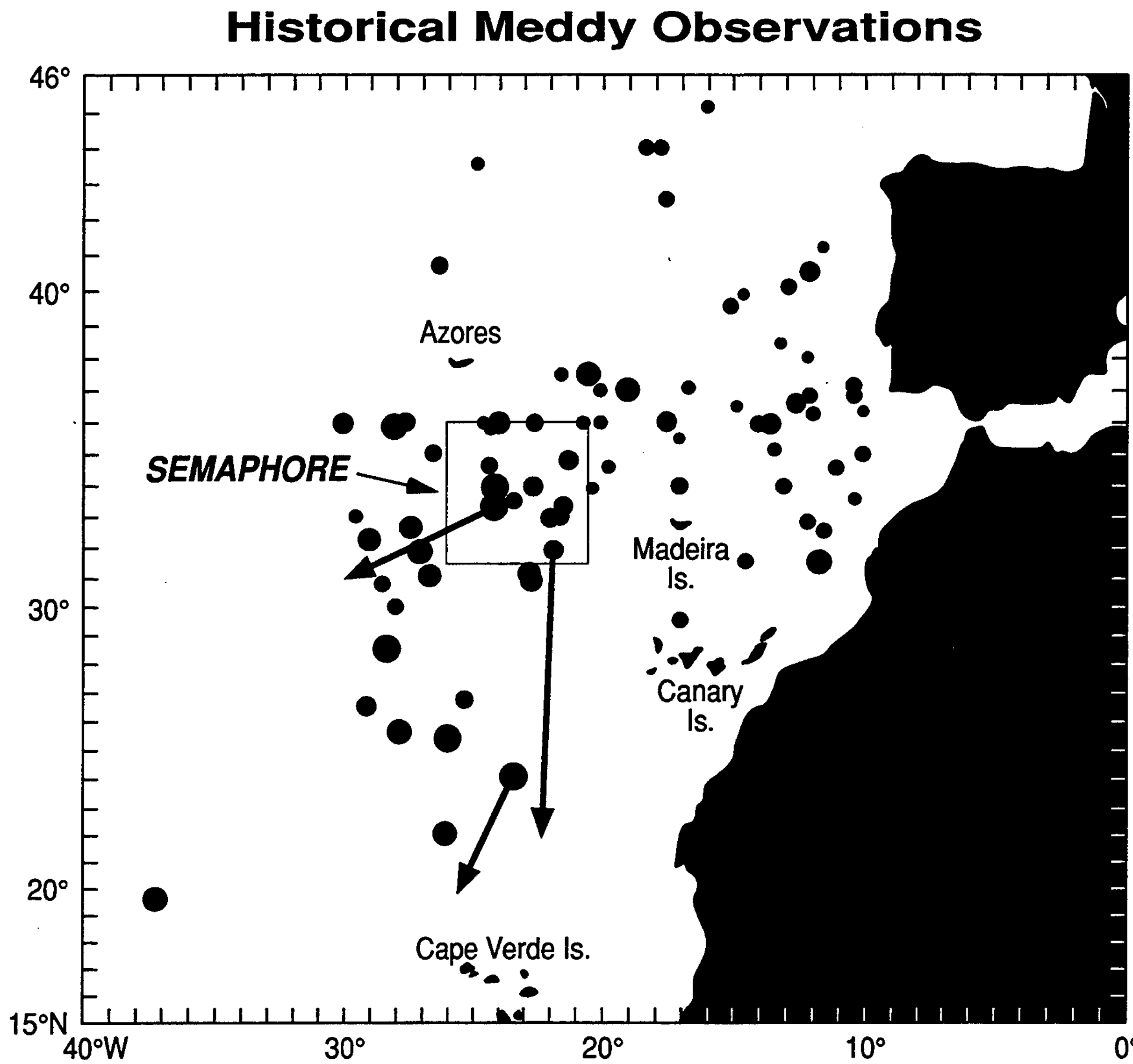


Figure 1: Positions of Meddy observations listed by Richardson *et al.* (1991) and Shapiro and Meschanov (1996) and the mean displacement vectors of three Meddies tracked with SOFAR floats during 1984–1987 as shown by Richardson *et al.* (1989). The diameter of dots indicates the magnitude of the salinity anomaly which ranges from 0.4 to 1.1 psu. The Semaphore study area is located in prime Meddy territory. The Azores Current flows eastward through the Semaphore box near 34°N and the line of Great Meteor Seamounts lies just to the west of the box near 28W.

Table I: Semaphore XBT–CTD Surveys

Phase	Ship	Dates	Meddies[a]	Floats Launched
1	*Alcyon*	5–30 July 1993	Meddy 1 (Hyperion), Meddy 2 (Ceres)	171, 172, 174, 175, 176, 177
2	*Laperouse*	4–13 September 1993[b]	Meddy 2 (Ceres), Meddy 3 (Encelade)[c]	—
3	*Ailette, Alcyon, D'Entrecasteaux, Suroît, Pr. Stockman*	12 October–20 November 1993	Meddy 2 (Ceres), Meddy 3(Encelade)[c]	168, 173
4	*D'Entrecasteaux*	14 August–22 September 1994	Meddy 4 (Zoe)	101, 133
–	*Charles Darwin*	13 December 1993–13 January 1994	Meddy 5 (Pinball)	113, 131 136, 137

a) The Meddies' names used in some of the Semaphore papers are given here so that the interested reader can match up the Meddies. Meddy Pinball was described by R. Pingree (1995).

b) XBT's only.

c) In addition to these Meddies was a small salty blob interpreted to be a piece of Meddy 3 located southwest of Meddy 3.

2 Floats

The Meddies were tracked with freely drifting RAFOS floats (see Rossby *et al.*, 1986; Anderson-Fontana *et al.*, 1996; Wooding *et al.*, 1998; and Hogg and Owens, 1998) purchased from Seascan Corp. in Falmouth, Mass., and assembled, calibrated (temperature, pressure) and ballasted at WHOI (Table II). Each float recorded temperature, pressure and times of arrival (TOAs) from moored sound sources (Tables III, IV). At the end of its 1.5 year mission the float dropped a weight, rose to the surface and transmitted the data to WHOI via the Argos satellite system. Three sound sources were deployed as part of Semaphore near 30N 24W, 36N 27W, and 37N 21W. Although the sources transmitted three times per day only two of these transmissions were recorded by the floats due to memory constraints and the relatively long float mission. The third time of arrival from each source was linearly interpolated from the recorded ones in order to obtain an evenly spaced time series. Meddies 2–4 remained in the vicinity of the Semaphore sound source array and the floats were tracked without any difficulties using a least squares fit to the distances from sources. Meddy 1 drifted far to the west of the sound source array and west of numerous seamounts. The recorded transmissions were intermittently blocked by seamounts which caused gaps in the records south of 33N. In order to supplement the tracking of this Meddy, TOAs were used from an additional source launched near 43N 36W by H.T. Rossby. Meddy 5 was tracked in the region east of the Semaphore array using additional sources in that region (see Bower *et al.*, 1997 and Hunt *et al.*, 1998). Due to the geometry of available sources and numerous seamounts which blocked acoustic signals the tracking was somewhat gappy in the eastern region. Tracking errors in position for the Semaphore region were estimated to be around 4 km based on a comparison of float launch locations and first tracked positions. West of the seamounts the errors in tracking floats in Meddy 1 could be much larger than this ($\sim$ 40 km) due to poor tracking geometry, blocking by seamounts, and interpolation. East of the Semaphore box errors in float tracking could also be larger than 4 km. Tracking errors are discussed more fully below.

In order to help resolve the looping trajectories of the floats in Meddy 1 (south of 33N) and in Meddy 5 gaps in the TOA were interpolated using an objective analysis technique called krieging (Hansen and Herman, 1989). It was necessary to specify the float looping frequency which was obtained from the TOA series before and after each gap or from the TOA series of another sound source. Problems with the technique were encountered when the looping frequency varied over a gap and when the data were noisy (e.g., low signal to noise ratio) which made it difficult to eliminate erroneous data. Some bad data caused erroneous phase shifts of the interpolated series. The floats in Meddy 1 and float 137 in Meddy 5 were tracked using the krieged TOAs. Some portions of the trajectories looked incorrect compared to good Meddy trajectories, and were discarded. These and a few gaps where two or more TOA series were not available were interpolated subjectively (~23% of the time series for float 177) using continuity and the looping frequency and diameter as observed in the available TOAs. The overall trajectories of float 177 in Meddy 1 and float 137 in Meddy 5 are judged to be qualitatively correct; the details of the loops should be viewed with caution (float 177 south of 33N).

A cubic spline function was passed through the three daily float positions to calculate velocity. The positions and velocities were smoothed to reduce noise and high frequency tidal and inertial oscillations using a Gaussian shaped filter ($\sigma = 1$ day).

Ten floats were launched in the four Semaphore Meddies (Table II). Two floats either did not surface or did not transmit. One float (168) recorded acoustic transmissions for only the first 100 days. This float sank around 200 m over its life which suggests that a slow leak could have caused the acoustic receiver to fail. Another float (173) in the same Meddy (Meddy 3) recorded poor quality data during the first 60 days. Combining the two float trajectories gave a complete series for this Meddy. Four floats were launched in Meddy 5 discovered by Robin Pingree near the continental margin off Portugal (Pingree, 1995). These floats were part of a shipment of six that we suspect was handled very roughly in transit. At least two floats (101, 133) had their glass pressure hulls broken; these two floats were returned to WHOI, repaired and launched in Meddy 4. Only one (137) of the four floats in Meddy 5 worked correctly. One float (131) was never heard, another (113) failed to record TOAs, and a third (136) prematurely stopped transmitting on the surface. This latter float provided a trajectory but positions were too sparse to resolve the detailed loops in Meddy 5.

We used hollow aluminum drop weights with the first nine floats and sealed the glass tubes with an aluminum end plate and silicone sealant. These floats tended to sink at a rate around 59 ± 33 meters over the 1.5 years which implies that either the hollow weights or float hulls leaked. Most of the mean sink rate was caused by two floats which sank 170 m (float 171) and 200 m (float 168). Based on early results in the AMUSE experiment (Bower *et al.*, 1997) we switched to solid drop weights and a better sealing technique for the last five floats. For these the end plate was sealed to the glass hull with butyl tape and a shrink-wrapped sleeve over the connection. A partial internal vacuum ($\sim$1/2 atmosphere) was created to hold the end plate tightly against the hull during air shipment and as a test for leaks.

Table II: Semaphore Meddy Floats

	Float	Launch Date	Launch Lat (°N)	Launch Lon (°W)	Surface Date[c]	Surface Lat (°N)	Surface Lon (°W)	Initial Temp (°C)	Initial Depth[d] (m)	Comments
Meddy 1	171	93 07 24	35.92	28.00	95 01 15	27.07	42.68	12.9	875	Sank 170 m
Meddy 1	175	93 07 24	35.92	28.00	95 01 15	26.00	40.71	12.3	1240	
Meddy 1	176	93 07 24	35.90	27.77	95 01 15	—	—	—	(1000)	Never heard
Meddy 1	177	93 07 24	35.92	28.00	95 01 15	26.90	43.16	12.1	1015	
Meddy 2	172	93 07 28	35.77	24.26	95 01 19	35.17	30.06	11.8	1015	
Meddy 2	174	93 07 28	35.89	24.25	95 01 19	31.08	28.27	11.8	1060	
Meddy 3	168	93 11 15	32.94	21.90	95 05 09	33.63	29.86	12.8	1040	Sank 200 m
Meddy 3	173	93 11 12	32.84	21.68	95 05 06	29.44	27.90	12.5	1070	
Meddy 4	101[abc]	94 09 09	35.99	23.89	95 09 04	33.37	32.18	11.2	760	
Meddy 4	133[abc]	94 09 09	36.00	23.60	95 09 04	—	—	—	(1200)	Never heard
Meddy 5	113[a]	94 01 07	38.45	9.70	95 07 01	43.27	12.88	11.5	910	Deaf
Meddy 5	136	94 01 06	38.40	9.92	95 07 01	32.34	16.95	12.3	1130	Stopped transmitting early
Meddy 5	137[a]	94 01 07	38.36	10.13	95 07 01	30.97	15.88	12.3	930	
Meddy 5	131[a]	94 01 07	38.43	9.96	95 07 01	—	—	—	(1200)	Never heard

a) Solid drop weights.

b) The glass hulls of floats 101 and 133 were broken during original shipping; these floats were returned to WHOI, repaired and reshipped.

c) The preset subsurface mission for floats 101 and 133 was 360 days. For all other floats it was 540 days.

d) Depth units in meters were used interchangeably with pressure units in decibars which would cause the depth in meters at 1000 m to be around 10 m too large. The floats were ballasted at WHOI using standard procedures (see Anderson-Fontana *et al.*, 1996).

Table IIIa: Sources Used to Track Floats

Float No.	M1	M2	A2	C1	S1	S2	S3	R1	I4	I5	X
101	X	X			X	X	X		X	X	
136	X	X	X	X	X		X				
137	X	X		X			X			X	X
168					X	X	X				
171					X	X	X	X			
172					X	X	X				
173		X			X	X	X	X			
174				X	X	X	X				
175					X	X	X	X			
177					X	X	X	X			

Table IIIb: Sound Sources Heard[a]

Source Site	Source Code	Pong Time GMT	Deployment	End Date	Depth	Latitude (°N)	Longitude (°W)
AMUSE 1	M1	0030	930503	—	1500	35.505	10.000
AMUSE 2	M2	0130	930502	—	1500	36.334	11.000
IFM A2	A2	0100	930101	9409	830	35.349	12.808
French C1	C1	0130	930101	940501	1500	40.008	14.993
Semaphore 1[b]	S1	0100	930630	950221	1500	35.997	27.006
Semaphore 2[b]	S2	0130	930625	950223	1500	29.995	24.001
Semaphore 3[b]	S3	0030	930621	950219	1500	36.985	21.034
Rossby 1	R1	0030	931001	9506	1560	42.948	35.973
InterRafos 4	I4	0100	950624	—	700	41.998	14.033
InterRafos 5	I5	0030	950625	—	700	38.485	14.318
French X	X	(0130)[c]	940315	940501	—	(37.700)[c]	(11.250)[c]

a) The sound sources transmitted an 80-second acoustic signal which linearly increased from 259.4 Hz to 260.9 Hz.

b) The Semaphore sound sources were deployed by the French Service Hydrographique et Oceanographique de la Marine.

(*c*) The location and pong time of source "X" were estimated from travel times.

Table IV: Float Clock Offsets and Temperature and Pressure Coefficients

Float No.	Clock Offset (seconds)	Temperature Logarithmic Coefficients			Pressure Linear Coefficients	
		a	b	c	a	b
101	-17.39	3.1510	0.2669	0.0074	0.0	277.4
113	-5.62	3.1438	0.2777	0.0062	17.3	278.4
136	4.47	3.1506	0.2681	0.0073	-11.7	277.0
137	-13.68	3.1514	0.2672	0.0073	52.2	280.1
168	27.35	3.1569	0.2597	0.0086	13.2	276.8
171	18.62	3.1571	0.2603	0.0088	11.4	278.3
172	27.27	3.1560	0.2610	0.0088	4.5	273.1
173	28.26	3.1573	0.2598	0.0087	20.1	278.5
174	3.14	3.1574	0.2596	0.0088	5.8	278.0
175	2.49	3.1587	0.2593	0.0089	13.4	276.5
177	2.55	3.1581	0.2603	0.0087	18.3	277.6

The clock offset is the net drift in the float clock over the duration of the mission. Linear clock corrections were applied to each float's TOA series. Temperature was measured with Yellow Springs Instrument Company thermistors model 44032 which were calibrated in a water bath. The overall accuracy is approximately $\pm$ 0.02°C based on the residuals to the curve through calibration points. The temperature coefficients determined by calibration are listed and corrected temperature T is calculated by using $T = [1000/(a + bt + ct^3)] - 273.16$, where $t = \log((tcounts + 1000)/1000)$. A systematic linear offset correction to the temperatures of approximately +.375°C was also applied. Pressure was measured with Data Instruments EAF pressure transducers which were calibrated in a pressure tank. Corrected pressure (db) is given by $P = a + bp$ where p is float pressure in counts divided by 1000. The residuals about the linear fit to the calibrated pressures suggest the accuracy of pressure is around $\pm$ 4 db. See Hunt *et al.* (1998) for a more complete description of the calculation of temperature and pressure.

3 Tracking Errors

Float tracking errors were estimated by calculating the distances between float launch positions and first tracked positions. Two main sources of error contribute to this distance. First, and what we are interested in determining, is the error in the acoustically tracked float positions due to inaccuracies in the speed of sound which was assumed to be constant, inaccuracies of the sound source positions, clock errors in the sources and floats, etc. Regional and temporal variations in the speed of sound could cause systematic and random tracking errors, as could horizontal displacements of the sound sources resulting from currents causing the moorings to lean over.

The mean speed of sound used to track the floats was estimated to be 1.501 km/sec ($\pm$0.003 km/sec standard error) by averaging the individual values from floats (101, 168, 172, 173, and 174) located in the central part of the Semaphore sound source array. The speed of sound between each float and each sound source was calculated using the first recorded acoustic travel time and the distance between float and source launch locations. The standard deviation of sound speed about the mean sound speed was 0.014 km/sec. If we assume that this scatter is due (primarily) to distance errors and that a typical acoustic travel time is 300 sec, then the implied standard deviation in distance is around 4 km. Part of this $\sim$2 km could be due to the drift of the floats during the (typically) six hours between the time of the float launch and the first recorded acoustic travel time and part $\sim$1 km could be due to the (unknown) Doppler shift of the first TOA (see below).

A second main source of error is the distance that a float drifted between the time of its launch and the time of the first tracked position (as opposed to first TOA), around one day for the Semaphore floats. At characteristic drift rates of 5–10 km/day this distance would be around 5–10 km. This is a large error which makes it difficult to accurately assess the float tracking errors. The random error in the position of the ship (estimated to be ~0.2 km) at the time of float launch is small compared to the error described above. The error in sound source mooring position is unknown but is probably somewhat larger than the error in ship positioning.

Another source of error is due to the Doppler shift of the TOAs recorded by the floats and caused by the floats' radial velocity relative to the moored sound sources (see Rossby *et al.*, 1986). Each TOA was corrected using the mean velocity calculated from the difference between TOAs before and after the TOA being corrected. The Doppler correction amounts to around 0.9 sec or 1.3 km for a float moving radially at 10 cm/sec relative to a source. The Doppler correction applied to the first TOA is the same as that applied to the second TOA. Since the velocity of the float at the time of the first TOA is not known there could be a position error of around one kilometer associated with the Doppler correction of the first position of a float moving at 5–10 cm/sec. This error is smaller than the systematic and random errors described below but could have contributed to them.

Distances between float launch and first tracked position along with some averages are listed in Table V. The mean distance (and standard error) is −3.6 km (± 1.5 km) in the east direction, 1.4 km (± 1.4 km) in the north direction, which amounts to 3.9 km (± 1.4 km) radially. These are measures of the systematic error in tracking (including the float drift between launch and first tracked position). Because the systematic error could vary over the Semaphore region this estimate is fairly crude. Taken at face value this result suggests that the systematic error of float positioning is around 4 km.

The standard deviation of distance values (about zero distance) is 6.0 km in the east direction, 4.7 km in the north direction or 7.6 km radially. The mean (and standard error) of the individual radial distances is 6.2 km (± 1.2 km). These values are estimates of the random errors (including the float drift between launch and first

Table V: Distance Between Float Launch Position and First Tracked Position

Float No.	**Distance East (km)**	**Distance North (km)**	**Radial Distance (km)**	**Time Difference (Days)**
101	-4.1	-5.7	7.0	0.01
136	-5.7	11.0	12.4	0.62
137	2.4	-3.7	4.4	0.54
168	2.7	0.9	2.8	2.67
171	-3.5	4.0	5.3	1.33
172	-4.5	1.4	4.7	0.71
173	-13.5	1.6	13.6	0.67
174	0.1	1.3	1.3	1.04
175	-6.2	0.4	6.2	1.33
177	-3.6	2.8	4.6	1.33
Mean	-3.6	1.4	6.2	1.02
Std Dev about mean[a]	4.7	4.5	3.9	0.72
Std Dev about zero[a]	6.0	4.7	7.6	
Std Error of Mean	1.5	1.4	1.2	

a) Using $n-1$ to calculate standard deviation.

tracked position). Since the error due to float drift (5–10 km) is approximately the same size as the calculated random error using the distances, $\sim$ 8 km radially, the random tracking error is probably smaller than this.

In order to try to reduce the size of the error due to the float drift between launch and first tracked position we extrapolated the trajectory of each float back to its launch time. An objective technique developed by Russ Davis (personal communication) and the first two days of float data were used in the extrapolation. The mean and standard deviation of the distances between the float launch and the extrapolated position were found to be slightly larger than the values given above. An inspection of the first few days of trajectories shows them to be rather erratic which leads to large errors in extrapolating the trajectories back in time. Possible sources of the erratic behavior are high frequency tidal and inertial oscillations, fluctuations in sound source locations, etc. Each float launch location looks like it was a reasonable starting point for the float trajectory which suggests that the initial float drifts caused most of the calculated error and that the real tracking errors are probably smaller than the values listed in Table V.

In summary, errors in float tracking were estimated by comparing the float launch positions and first tracked positions of ten floats. A systematic distance error was estimated to be around 4 km $\pm$ 1.4 km. Random distance errors were estimated to be around 8 km but a large part of this error is probably caused by the float drift during the one day average time between launch and first tracked position.

4 Results

Four energetic Meddies were discovered on the Semaphore surveys (Figure 2). Meddy 1 was located 200 km west of the Semaphore box; the centers of the other three Meddies were all within the box. Meddy 2 was measured on three surveys and Meddy 3 on two surveys. A fifth Meddy was discovered and seeded with floats by

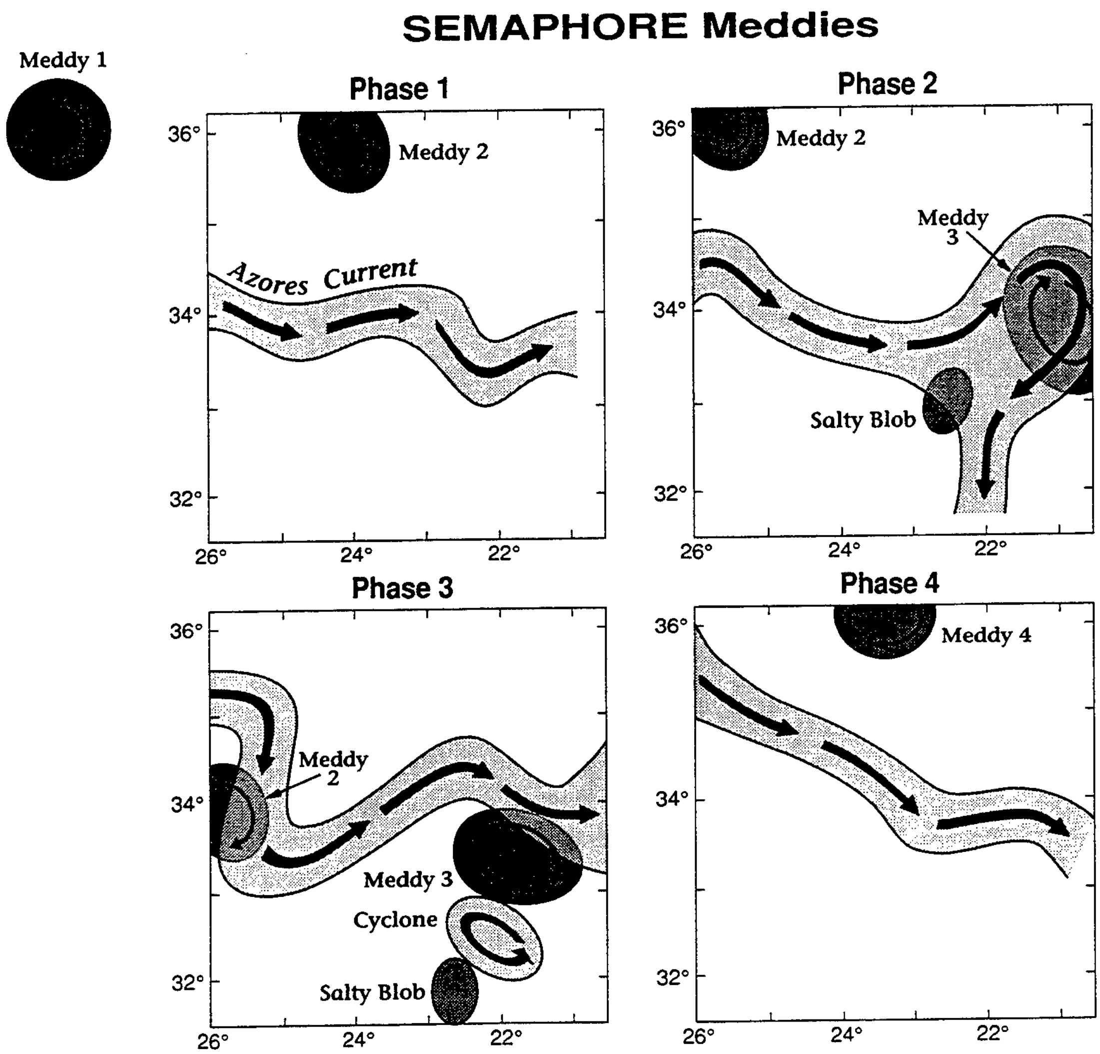


Figure 2: Schematic diagram showing the location of observed Meddies and the Azores Current within the Semaphore box based on an interpretation of CTD–XBT surveys (see Richardson and Tychensky, 1998). Meddy 2 passed underneath or through the Azores Current during phase 3. Meddy 3 passed underneath or through the Azores current during phases 2 and 3. A small salty blob which is probably a piece of Meddy 3 was observed southwest of it on phases 2 and 3. A cyclonic eddy pinched off from the Azores Current was observed adjacent to Meddy 3 on phase 3.

Robin Pingree and Bernard LeCann near 38.4N and 10.0W well east of the Semaphore box. Fourteen floats were launched in the five Meddies which enabled them to be tracked for long times. Figure 3 is a summary of all the trajectories including the portions after the floats had stopped looping in the Meddies (Meddies 2, 3 and 5). The overall float displacement vector of each float is shown in Figure 4, and the overall Meddy displacement vector of each Meddy is shown in Figure 5. Trajectories of a representative float in each of the Semaphore Meddies is given in Figure 6. Below we describe the float trajectories in each Meddy with some reference to hydrographic characteristics which are more fully discussed by Pingree (1995), Tychensky and Carton (1998) and Tychensky *et al.* (1998).

5 Meddy 1

Meddy 1 was discovered and well measured during the phase 1 XBT–CTD survey 5–30 July 1993 (Table I, Figure 2). Meddy 1 was large and energetic and contained double maxima in both temperature and salinity (Table VI). Values reached 36.5 psu at 1250 and 13.2°C at 880 m and anomalies were 1.1 psu and 4.1°C, largest of the four Meddies.

Three floats launched near Meddy 1's center revealed its 1.5 year trajectory (Figure 6). Two floats (171, 177) remained looping for the full 1.5 years. The third float (175) stopped looping after around 1.2 years. This float was deeper ~1230 m than the other two which were at 1040 m and 1125 m which suggests that the bottom of the Meddy core may have eroded by the end of the tracking. The core rotation period was 4.4 days at the beginning and 6.2 days at the end.

Meddy 1 was found roughly 1700 km west of the presumed Meddy formation region near Cape St. Vincent, and it translated another 1700 km southwestward over the 1.5 years (Figure 7). This Meddy sets records for the farthest a Meddy has been continuously tracked and the fastest mean velocity of a tracked Meddy

Float Trajectories

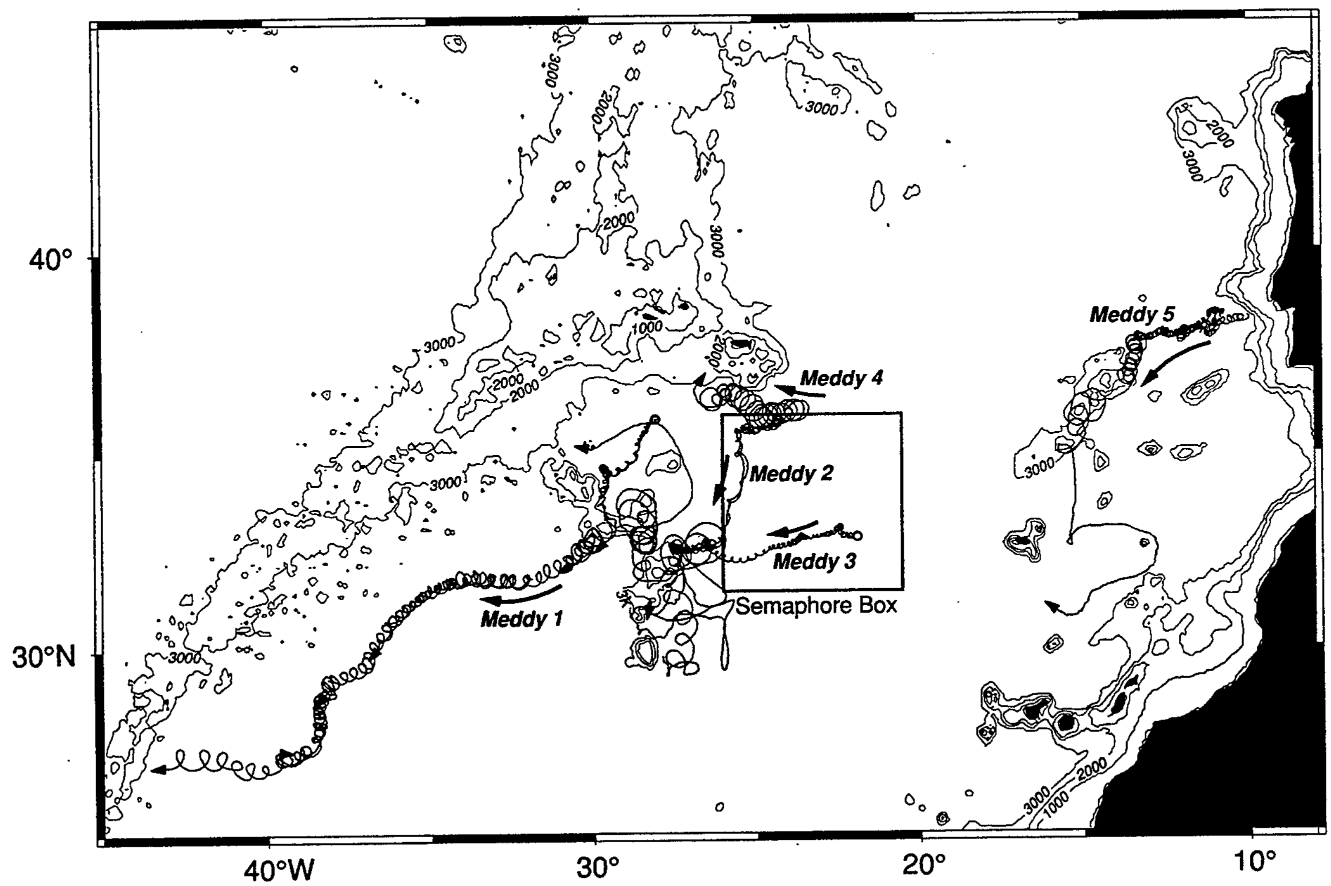


Figure 3: Summary figure showing trajectories of the floats launched in the five Meddies. Bathymetric contours are 1000 m, 2000 m, and 3000 m from ETOPO5 data.

Float Displacements and Sources

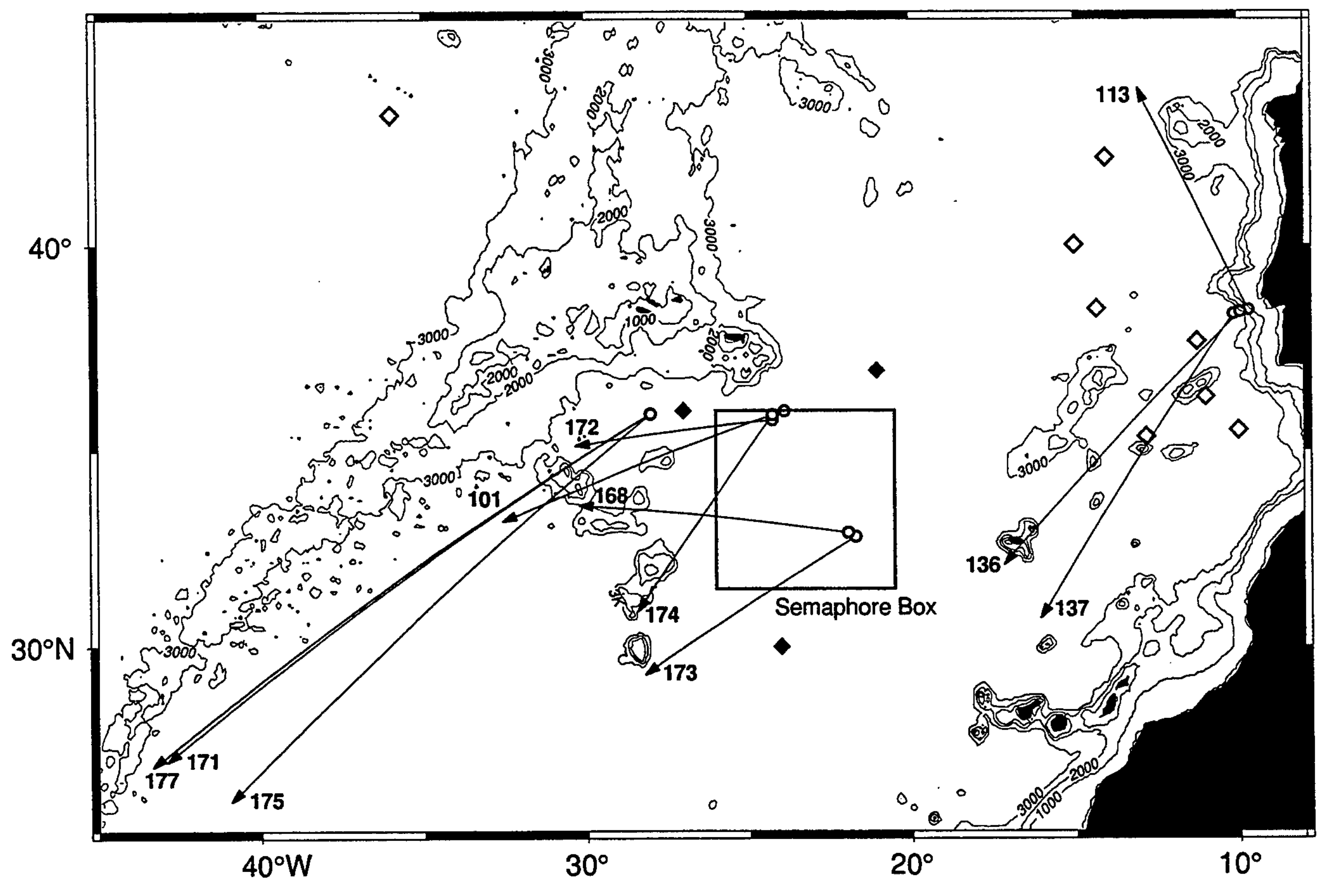


Figure 4: Displacement vectors of each float from beginning to end of each trajectory. Sound sources are indicated by diamonds. The three solid black diamonds show the locations of the Semaphore sources.

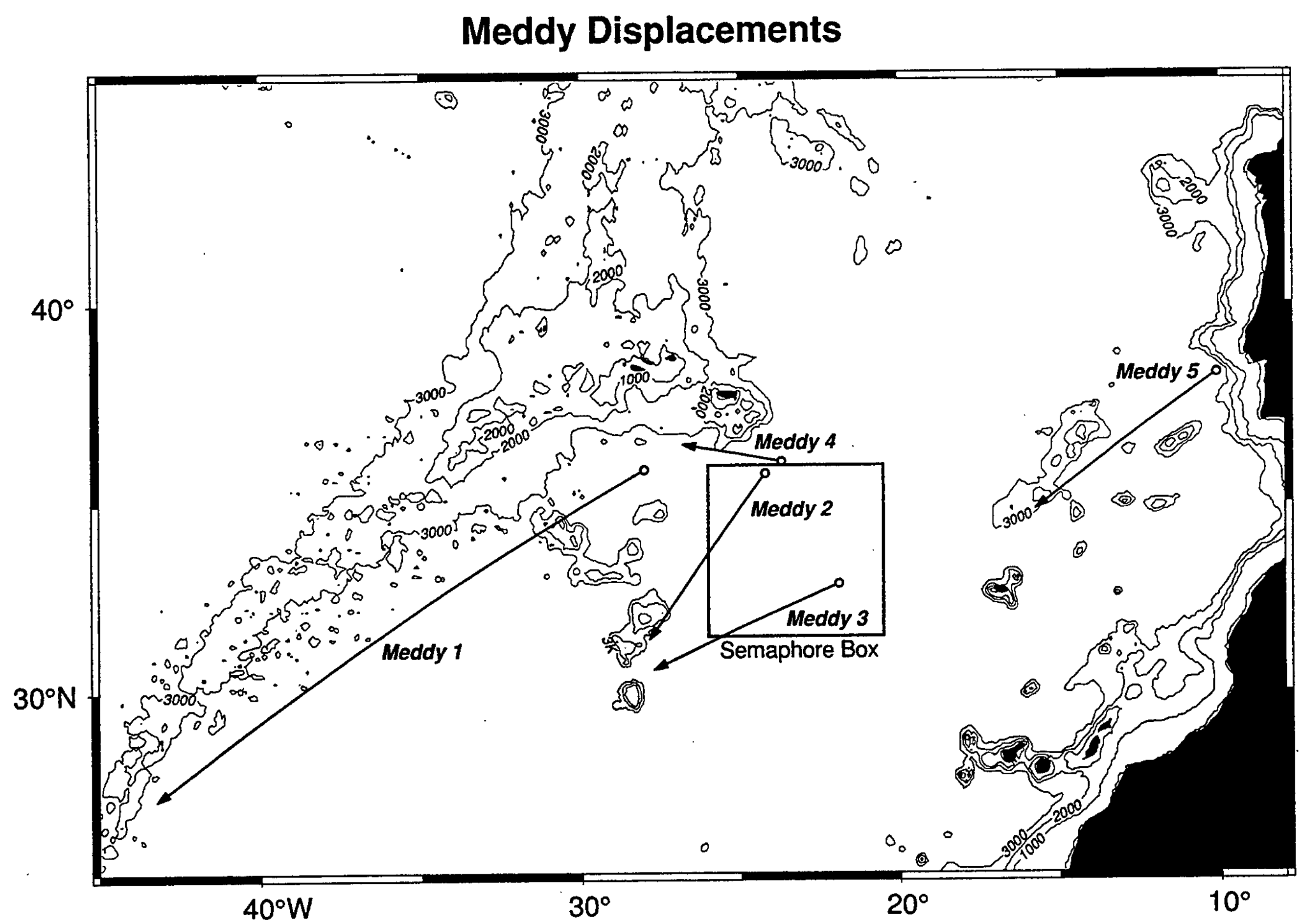


Figure 5: Displacement vectors of each Meddy from the beginning to the end of tracking.

SEMAPHORE Float Trajectories in Meddies

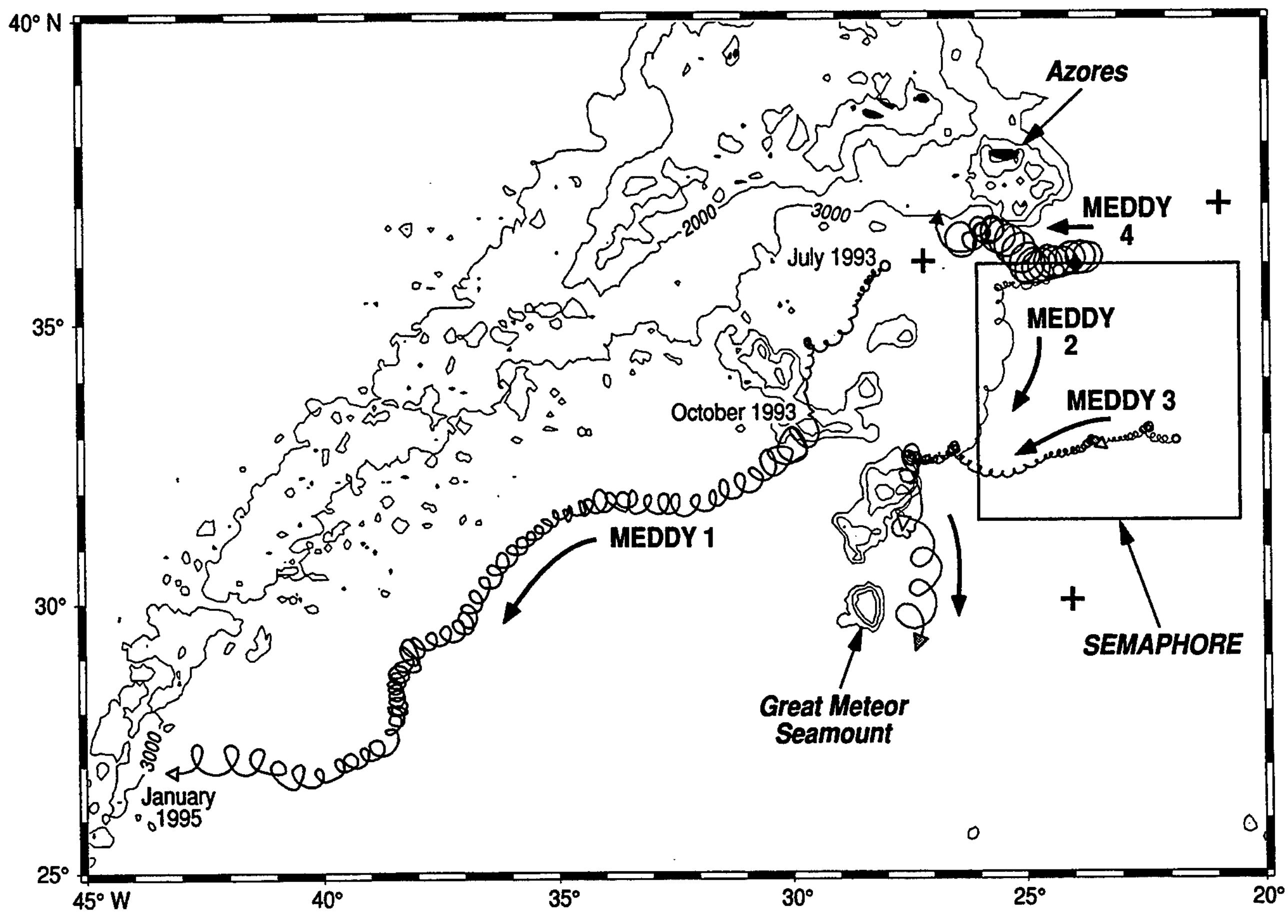


Figure 6: Translation of four Semaphore Meddies as given by the looping trajectories of floats during 1993–1995. The trajectory of float 177 in Meddy 1 stopped where the float surfaced after its 1.5 year mission. The trajectory of float 101 in Meddy 4 stopped when the sound sources were retrieved. The floats in Meddies 2 (float 174) and 3 (float 173) stopped looping after their collision with the line of Great Meteor Seamounts. The nonlooping portions of float trajectories were omitted for clarity.

Table VI: Maximum Temperature and Salinity in Each Meddy

Meddy	Depth (m)	Maximum Temperature (°C)	Maximum Salinity (psu)	Temperature Anomaly[a] (°C)	Salinity Anomaly[a] (psu)	Overall Diameter[c] (km)
1 (Hyperion)[b]	850	13.2	36.37	3.0	0.8	120
	1250	12.3	36.50	4.1	1.1	
2 (Ceres)	950	12.2	36.25	1.2	0.4	100
3 (Encelade)	950	13.1	36.45	4.0	0.9	150
4 (Zoe)[b]	900	12.4	36.28	2.4	0.6	100
	1150	12.0	36.45	3.8	0.9	
5 (Pinball)[d]	680	13.2	36.40	—	—	100
	1260	12.8	36.56	—	—	

a) The anomalies for Meddies 1–4 were estimated by A. Tychensky by comparing core profiles to profiles near the periphery of the Meddies.

b) Double maxima were observed in both temperature and salinity profiles of Meddy 1 and Meddy 4 and in the temperature profiles of Meddy 5.

c) The nominal diameter is crudely estimated from the various data sets. Fluctuations in the background temperature and salinity fields due to the Azores Current, its cut off rings and other eddies make it difficult to estimate the overall size of Meddies.

d) The listed values for Meddy Pinball were given by Pingree (1995). The 1260 m depth corresponds to the salinity maximum. The depth of the deeper of the two temperature maxima was at 1075 m.

Meddy 1

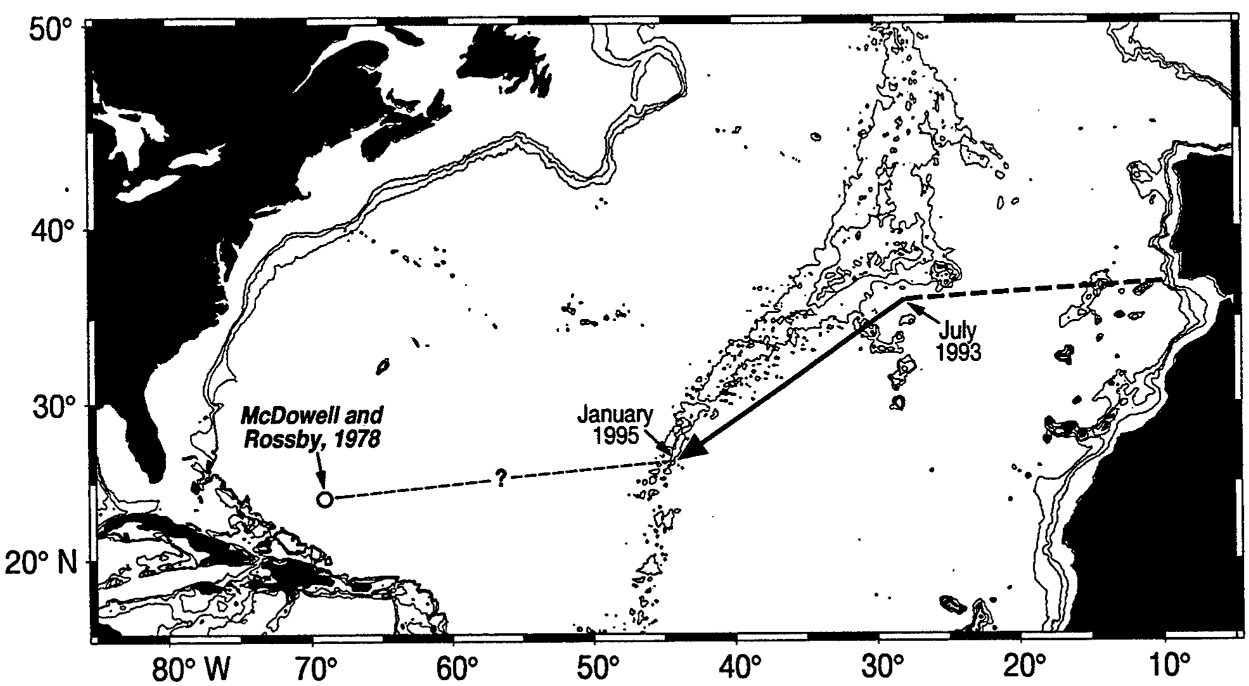


Figure 7: The solid line shows the displacement vector of Meddy 1, as it translated 1700 km southwestward from July 24, 1993, to January 15, 1995. The dark dashed line shows the displacement of Meddy 1 from its presumed formation near Cape St. Vincent (Bower *et al.*, 1997) to the beginning of continuous tracking. The 100 km diameter dot north of the Dominican Republic shows the location and size of the eddy (possibly a Meddy) found by McDowell and Rossby (1978). Meddy 1 traveled 3400 km or 57% of the distance from Cape St. Vincent to this spot. At its mean translation speed Meddy 1 would have reached the McDowell and Rossby eddy spot in an additional 2.1 years.

3.9 cm/sec toward 235°. Although Meddy 1 had traveled almost one half of the way across the Atlantic it had not yet crossed the mid-Atlantic Ridge. During the last two months Meddy 1 translated westward at roughly 4 cm/sec; at this rate it would have crossed the Ridge in about another month.

In October 1993 Meddy 1 crossed over or around Plato seamount which rises up to a depth of 476 m (Hunter *et al.*, 1983). At this time the loops of float 177 increased in diameter from about 15 km to 60 km implying a disruption of the normal Meddy circulation. Floats 171 and 175 revealed simultaneous increases in loop diameter.

One last bit of information about Meddy 1 was obtained when the floats surfaced. As they drifted at the surface each float made half of an anticyclonic loop about a common center implying that the Meddy's swirl velocity extended to the sea surface. Float 171 which had been closest to the Meddy center was also closest to the center of the surface loop. Typical surface swirl speeds were around 8 cm/sec. After three weeks and what we infer to be a gradually increasing loop diameter up to around 100 km the two floats left the surface expression of the Meddy.

6 Meddy 2

Meddy 2 was found near the northern edge of the Semaphore box during phase 1 and was well measured (Figure 2). It appeared to be the smallest of the four Semaphore Meddies and its temperature and salinity anomalies were also the smallest (Table VI). Two floats (172, 174) were launched near its center and near the same depth (1015 m, 1060 m). They both initially looped with a period of 5.6 days at diameters of 20–30 km (Figure 8). The trajectory of float 174 is shown in Figures 6 and 8 because it looped longer than float 172.

Meddy 2 remained near the edge of the Semaphore box during all three phases and was observed three times by the CTD–XBT surveys (Figure 2). For the

Meddy 2

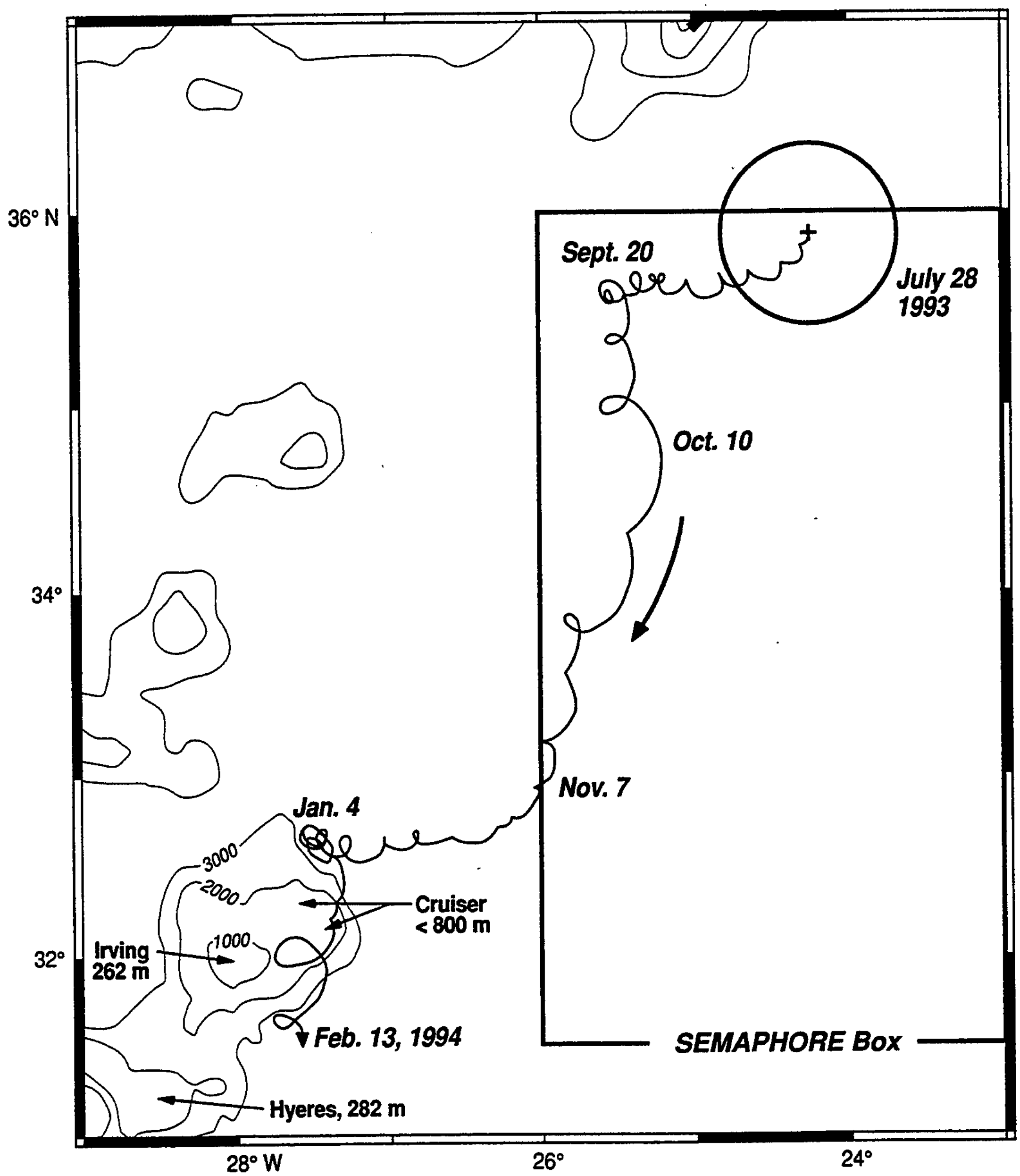


Figure 8: Trajectory of float 174 in Meddy 2 from July 28, 1993, to February 13, 1994. A 100 km diameter circle indicates the Meddy's characteristic size. Meddy 2 translated westward then southward just inside the Semaphore box and was observed during the first three phases of the experiment. In December 1993 Meddy 2 collided with Cruiser Seamount located near 28W and in February 1994 float 174 stopped looping. Depth contours are at 1000 m, 2000 m, and 3000 m from ETOPO5 bathymetric data which show the general characteristics of the seamounts. A chart by Hunter *et al.* (1983) shows Cruiser Seamount to have two peaks rising above 800 m, one near 32.28N 27.55W, the other near 32.39N 27.65W. Nearby is Irving Seamount which rises to a depth of 262 m.

first two months while it was north of the Azores Current Meddy 2 translated westward at 2 cm/sec. At the end of September (phase 2) it turned and translated 300 km southward for two months with speeds up to 10 cm/sec in October (phase 3). Because the translation rate was almost as fast as the swirl velocity the loops appear as cusps (Figure 8). Both floats remained close to each other and looped during this period providing evidence that the Meddy core (<30 km diameter) remained intact. Meddy 2 appeared to be advected southward by the Azores Current and to cross underneath or through it (Figure 2). In November Meddy 2 turned more westward again. It translated westward 150 km and at the end of the year stopped abruptly near Cruiser Seamount which has two peaks each <800 m deep according to Hunter *et al.* (1983). In January Meddy 2 turned southward and translated over or around Cruiser Seamount. Both floats stopped looping in February implying that the normal Meddy circulation had been disrupted by the seamounts.

7 Meddy 3

Meddy 3 is one of the largest Meddies ever observed ~150 km diameter. It had high values of temperature, 13.1°C, and salinity, 36.45 psu, and large anomalies, 0.9 psu 4.0°C, compared to background values (Table VI). Meddy 3 was well sampled during both phase 2 and phase 3 as it translated southwestward and interacted with the Azores Current (Figure 2). In phase 2 a main branch of the Azores Current meandered over the top of Meddy 3 forming a surface-intensified anticyclonic eddy. By phase 3 Meddy 3 had passed under or through the Azores Current which had pinched off a cyclonic eddy located adjacent to and south of Meddy 3. Another but much smaller warm and salty blob or lens was observed southwest of Meddy 3 on both phase 2 and phase 3. The evidence suggests that this could have been a piece of Meddy 3 shed during its interaction with the Azores Current.

Two floats (168, 173) launched during phase 3 gave Meddy 3's trajectory (Figure 9). Both floats looped initially with a 3.6 day period near a depth of 1050 m and within a diameter of around 15 km. This sets a record as the fastest rotation rate of the seven Meddies tracked in the Canary Basin. From November 1993 to May 1994 Meddy 3 translated westward with a mean velocity of 3.4 cm/sec. Meddy 3 passed entirely through the Semaphore box in six months, entering in September 1993 and exiting in March 1994. In early June Meddy 3 abruptly stopped in front of Cruiser Seamount almost exactly where Meddy 2 had stopped five months before. Meddy 3 then turned and translated southward (as did Meddy 2) at 3.9 cm/sec over or around Cruiser Seamount and then east of Hyeres and Great Meteor Seamounts from mid June to mid October 1994 when float 173 stopped looping. As Meddy 3 translated southward the loops of float 173 increased in diameter to around 60 km and the period of loops increased to around 25 days.

In April 1994 as Meddy 3 approached the seamounts, float 172 (which had been ejected from Meddy 2 two months previously) was entrained into Meddy 3's circulation and began to loop with a diameter which began at 120 km and eventually decreased to around 50 km (Figure 10). In June at the time of Meddy 3's collision with Cruiser Seamount float 172's loops diverged from float 173's loops implying that the Meddy was somehow cleaved by the seamounts into two roughly equal-sized smaller Meddies which then separated (Figure 11). Another possibility but one we think less likely is that float 172 was diverted from Meddy 3 into another already existing Meddy located west of Irving Seamount. Float 173 looped and translated southward, float 172 looped and translated northward (Figure 11). Both floats stopped looping in their respective Meddies at almost the same time in mid October.

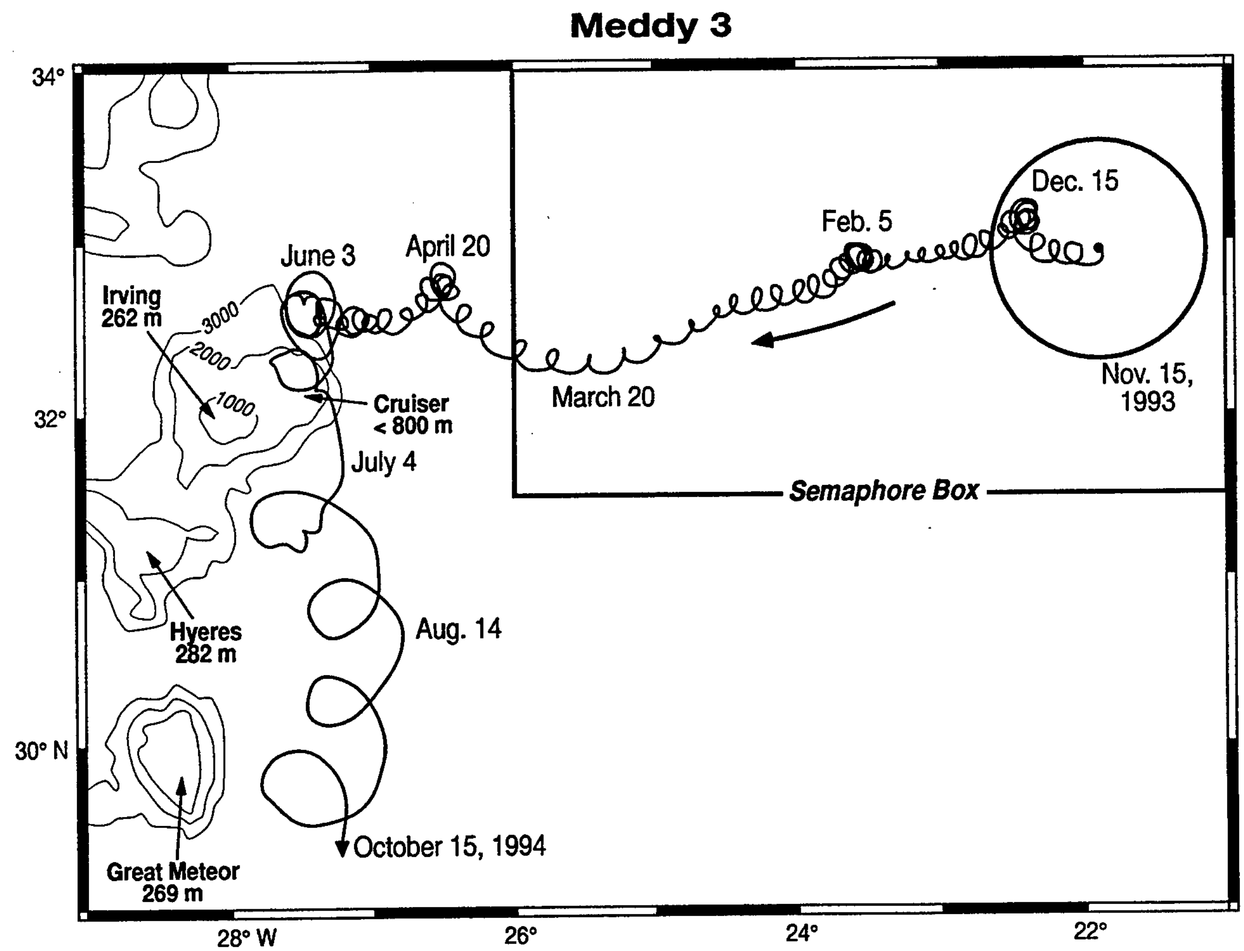


Figure 9: Trajectories of floats 168 and 173 joined to provide a continuous record of Meddy 3 from November 15, 1993, to October 15, 1994. A 150 km diameter circle was added to indicate Meddy 3's characteristic size. During Semaphore Meddy 3 translated westward all the way through the Semaphore box and collided with Cruiser Seamount five months after Meddy 2 collided with it. At that point the Meddy appeared to bifurcate as shown by floats 172 and 173 (see Figure 11). Meddy 3 then turned and translated southward over or around Cruiser Seamount. Float 173 stopped looping where the trajectory terminates east of Great Meteor Seamount.

Meddy 3

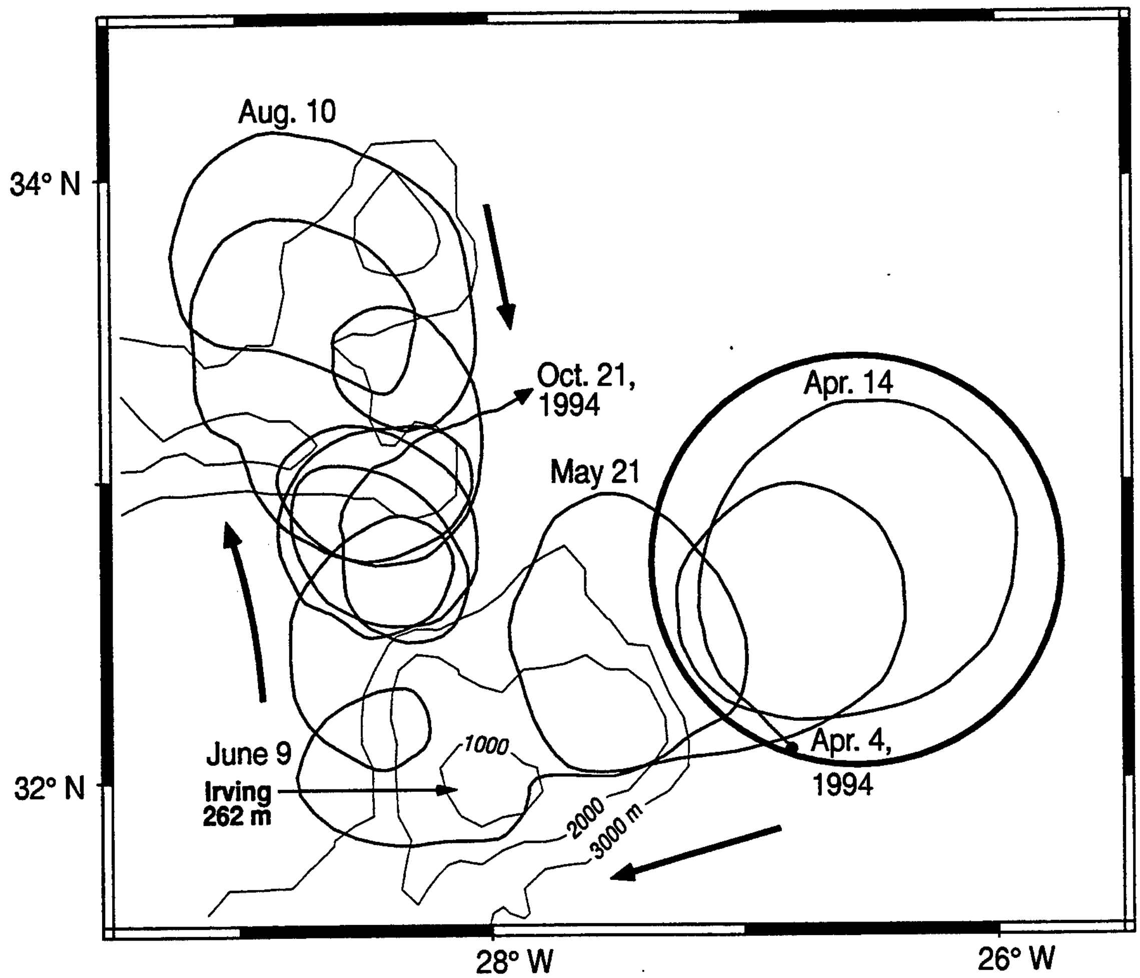


Figure 10: Trajectory of float 172 from April 4 to October 21, 1994, after it was entrained into Meddy 3 which appeared to bifurcate in early June. A 150 km diameter circle was added to show the overall size of Meddy 3 before bifurcation. Float 172 continued to loop for another 4.5 months as the bifurcated piece of Meddy 3 translated first northward then southward in the vicinity of several seamounts. After October 21 float 172 drifted in a large arc to the north and west.

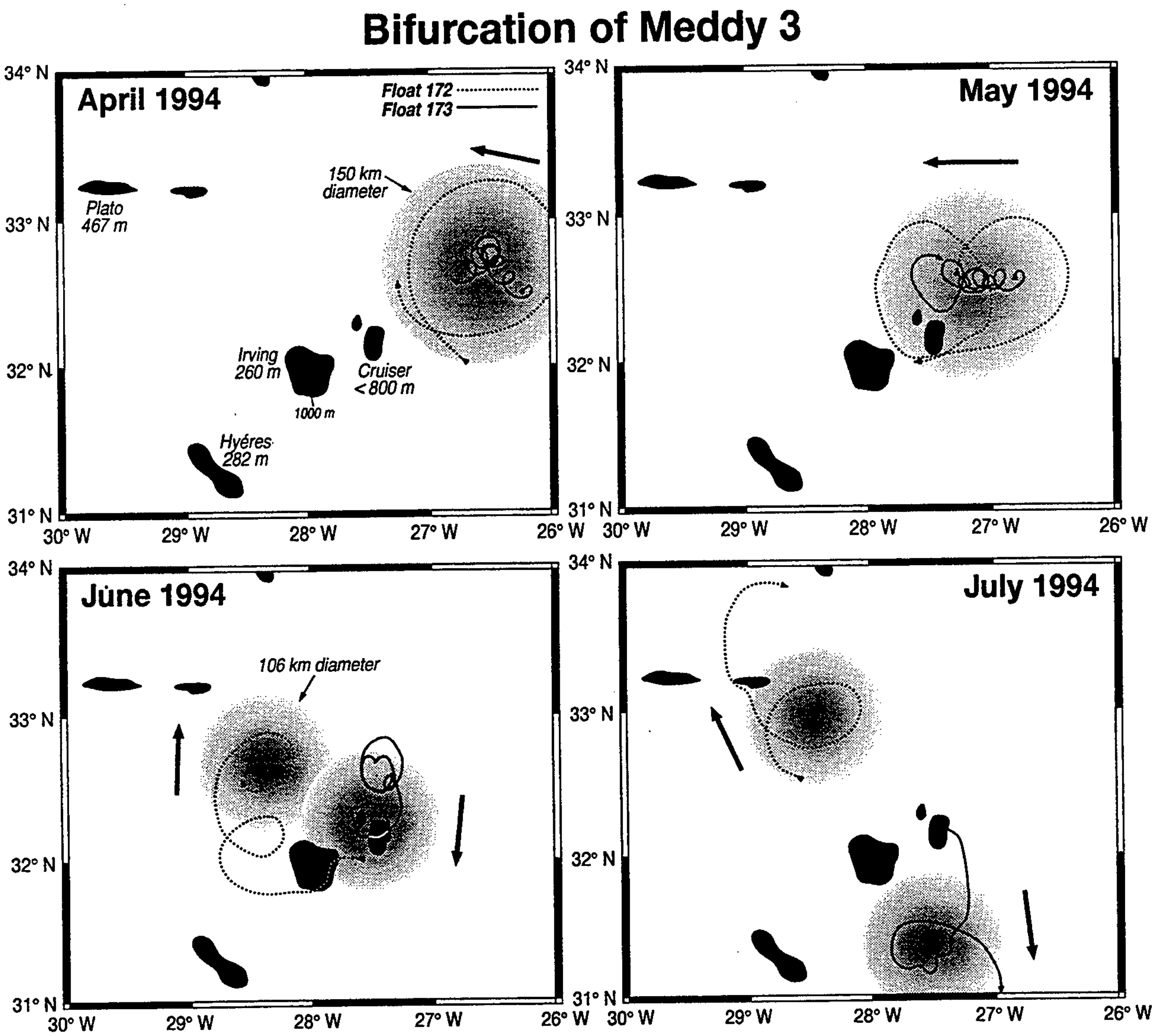


Figure 11: Bifurcation of Meddy 3 as shown by floats 172 and 173 which diverged in early June 1994 when the Meddy collided with the seamounts. Float 172 which was looping with a diameter around 100 km was diverted south of Irving Seamount and began looping with a diameter around 50 km west of Irving. During June float 173 continued to loop northeast of Irving. The overall diameter of Meddy 3 was around 150 km as seen in the largest loops of float 172 and shown by shading. Assuming conservation of Meddy area, the diameters of the bifurcated pieces would be around 106 km which is consistent with the float trajectories. The dark shading shows depths less than 1000 m based on a chart by Hunter *et al.* (1983).

8 Meddy 4

Meddy 4 was discovered near the northern edge of the Semaphore box in September 1994 during phase 4. The Meddy core contained double maxima in the temperature and salinity profiles with peak values of 12.4°C (900 m) and 36.45 psu (1150 m). The period of rotation of its core (760 m) was around 6.0 days significantly longer than that for Meddies 1 and 3. It is possible that the smaller diameter and also deeper core could have rotated faster than at 760 m where the float was located. Float 101 looped 20 times at a characteristic diameter of 60 km with swirl speeds up to 30 cm/sec as Meddy 4 translated westward at 1.8 cm/sec (Figure 12). During January 1995 as it meandered northward its center passed within around 70 km of Santa Maria Island in the Azores. Southwest of Santa Maria where the Meddy circulation impinged on the sea floor topography the loops briefly decreased to around 30 km diameter and then increased again to 60 km.

The Semaphore sound sources were retrieved in February 1995 which stopped the tracking, but float 101 continued to receive acoustic signals from a source farther east launched by Amy Bower. The TOAs imply that float 101 looped 6 more times from February 21 to May 15, 1995, at an average period of 13 days. The diameter of the last loop increased to around 90 km which suggests that the overall diameter of Meddy 4 was at least 100 km. No further hydrographic measurements are available for this Meddy.

9 Meddy 5

Meddy 5 was discovered near 38.4N 10.0W by Pingree (1995) who measured it with XBTs and CTDs and launched two deep (750 m, 1000 m) drogued surface drifters, two ALACE floats (ballasted for 718 m and 1090 m) and four of our RAFOS floats. Meddy 5 was located adjacent to the continental slope near Lisbon

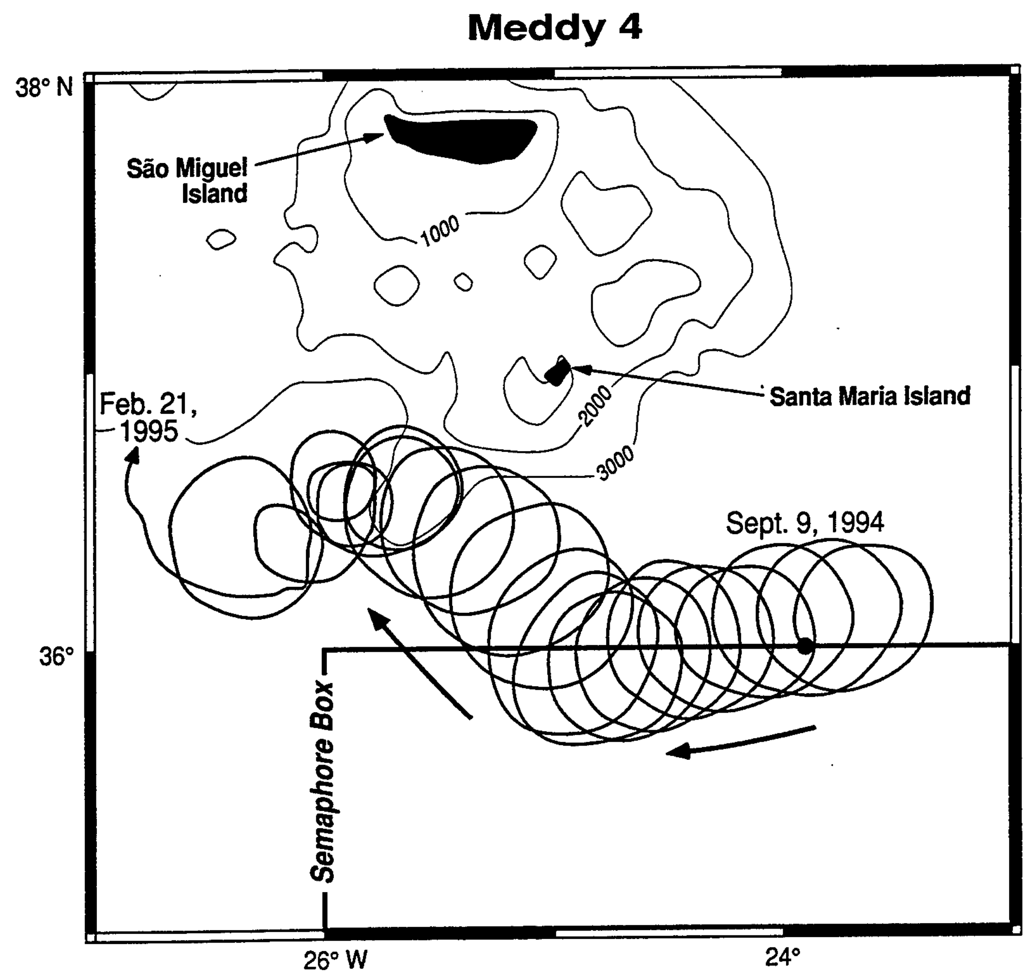


Figure 12: Trajectory of float 101 looping in Meddy 4 from September 9, 1994, to February 21, 1995. Meddy 4 translated westward along the northern edge of the Semaphore box, meandered northward and impinged on the seafloor topography southwest of Santa Maria Island in the Azores as inferred from variations in the diameter of the float loops there. Tracking ceased when the Semaphore sound source array was retrieved in February 1995, but the float continued to loop for another 80 days as shown by times of arrival from a single source located farther east.

canyon and had presumably just formed as other Meddies have been observed to do near there (see Bower *et al.*, 1997; Käse and Zenk, 1996; Zenk *et al.*, 1992). Meddy 5 was tracked by a drifter for 50 days, by an ALACE float for 7 months, and by RAFOS floats 136 and 137 for almost a year (Figure 13). Although float 136 stopped transmitting early causing the loss of some positions and a gappy trajectory which did not resolve the Meddy loops, the close correspondence between the overall trajectories of floats 136 and 137 and their similar decrease in temperature when float 137 ceased looping shows that they both remained in Meddy 5 until December 1994. Meddy 5 translated 600 km southwestward over 353 days at a mean velocity of 2.1 cm/sec. This included a three month eastward jog between 11W and 12W.

During July and early August 1994 another Meddy tracked by two floats (Bower *et al.*, 1997; Hunt *et al.*, 1998) collided and coalesced with Meddy 5. The coalescence was documented by the four floats (two in each Meddy) which began to loop around a common center by August 10. The coalescence occurred as float 137 switched from small diameter ($<$ 10 km) loops to larger (40 km) ones. Float temperatures remained warm and nearly constant during the coalescence which implies that the warm water of the two Meddies merged and that the floats did not leave one Meddy enter cooler background water and then enter another Meddy. The overall size of the Meddies before the collision was around 100 km which suggests that the diameter of the Meddy after coalescence could be around 140 km (assuming the addition of Meddy areas). Therefore after August 10 Meddy 5 is inferred to be significantly larger than it was before July.

During July–December 1994 floats 136 and 137 show that Meddy 5 collided with several of the Horseshoe seamounts. In July as the Meddies coalesced Meddy 5 collided with small Ashton seamount which rises up to a depth of around 1800 m. In September and October Meddy 5 skirted around the southeastern side of Josephine seamount ($<$ 200 m depth), and then translated over or near two other seamounts southwest of Josephine (one $<$ 800 m depth and the other $<$ 1600 m depth). In December Meddy 5 passed over or around Lion seamount ($<$ 600 m).

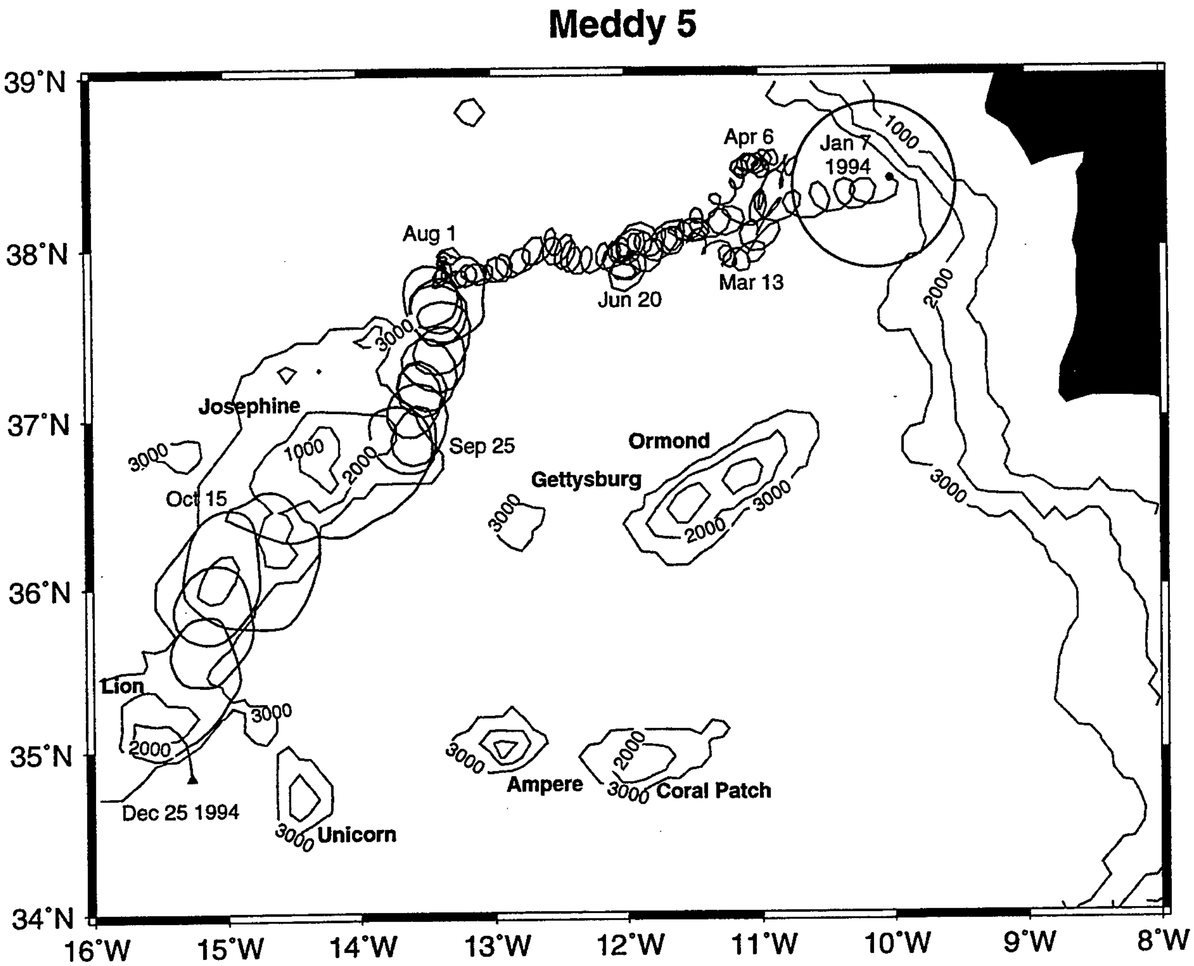


Figure 13: Trajectory of float 137 in Meddy 5 from January 7 to December 25, 1994. During July 1994 Meddy 5 stopped near 37.9N 13.3W as float 137 was looping with small (< 10 km) diameter loops (3-day period). On August 1 the diameter of the loops suddenly increased to 40 km (5-day period). This occurred as Meddy 5 coalesced with another Meddy tracked by floats AM129 and AM126b (Bower *et al.*, 1997; Hunt *et al.*, 1998). After the coalescence Meddy 5 translated southwestward into the Horseshoe Seamounts, colliding with several of them. After Meddy 5 collided with Lion Seamount in December both floats 136 and 137 stopped looping. Before this time floats AM129 and AM126b had already completed their missions.

The loops of float 137 increased in diameter from 10 km to 40 km after the coalescence with the other Meddy and the collision with Ashton, and to 50 km after Josephine. Both floats stopped looping after passing over or around Lion. By this time the two other floats had completed their missions and surfaced. The cessation of float looping after the collision with Lion Seamount implies that Meddy 5 was severely disrupted if not totally destroyed by its collisions with the Horseshoe seamounts. This suggests that at least some newly formed Meddies are strongly modified or destroyed before they can translate into the Canary Basin. Further evidence is provided by an earlier Meddy which possibly met a similar fate after colliding with Josephine (Schultz-Tokos *et al.*, 1994).

Meddy 5 had the fastest rotation rate, 2.5-day period, and the highest salinity 36.56 psu (Table VI) of the five Meddies which is not surprising considering it was probably newly formed. The rotation rate was similar to some of the newly formed Meddies observed by Bower *et al.* (1997) and the Meddy observed by Prater and Sanford (1994). The maxima in temperature and salinity in Meddy 5 are quite close to those of Meddy 1 located 1600 km west southwest of Meddy 5 showing that some Meddies can go that far with very small changes in their properties.

10 Discussion and Summary

The Lifetime and Fate of Meddies

The trajectory of Meddy 1 sets records for both long length, 1700 km, and fast mean velocity, 3.9 cm/sec averaged over 1.5 years. Meddy 1 illustrates that a Meddy starting near the Azores can thread its way through the seamount chain and travel a long distance southwestward along the eastern flank of the mid-Atlantic Ridge. Backtracking Meddy 1 to Cape St. Vincent suggests that Meddy 1 was around 2.8 years old when tracking stopped. At that point Meddy 1 appeared to be still going strong despite an earlier disruptive encounter with tall seamounts.

Meddy 4 was tracked for too short a time to determine its long-term fate. Backtracking Meddy 4 suggests that it was 2.5 years old when the tracking stopped. At that point Meddy 4 was 150 km from and heading towards the spot Meddy 1 was found implying that Meddy 4 could have followed a similar long-term trajectory.

Both Meddies 2 and 3 translated westward and collided with Cruiser Seamount five months apart. At the time of impact both Meddies came to a complete stop, then turned and translated southward over or around Cruiser Seamount. Evidence from two floats suggests that Meddy 3 split into two smaller Meddies at the time of collision. Within a few months after impact all five of the floats in these Meddies had stopped looping. The implication is that around twice a year Meddies collide with these seamounts which causes a major if not fatal disruption of the normal swirl circulation of the Meddies. One earlier Meddy tracked with SOFAR floats collided with nearby Hyeres Seamount and was also destroyed (Figure 14). These three new case histories plus some hydrographic measurements of a Meddy which collided nonfatally with these seamounts (Shapiro *et al.*, 1995; Dykhno *et al.*, 1991) suggest that Meddies often collide with the seamounts but not always fatally. Backtracking Meddies 2 and 3 suggests that they were 1.8 years and 2.8 years old when the floats stopped looping.

Meddy 5 was tracked from the time of its formation near the eastern boundary off Lisbon until the floats 136 and 137 stopped looping implying a lifetime of around a year. The implication is that this Meddy was also severely disrupted if not fatally destroyed by the impact with several seamounts before it could reach the Canary Basin.

The total lifetimes of Meddies which hit seamounts in the Canary Basin would appear to be roughly 2–3 years, although it is possible for a remnant Meddy to have continued after the floats ceased looping. The lifetimes of Meddies which did not fatally collide with seamounts could be significantly longer than three years, perhaps as long as the four (or more) years estimated from earlier Meddies which

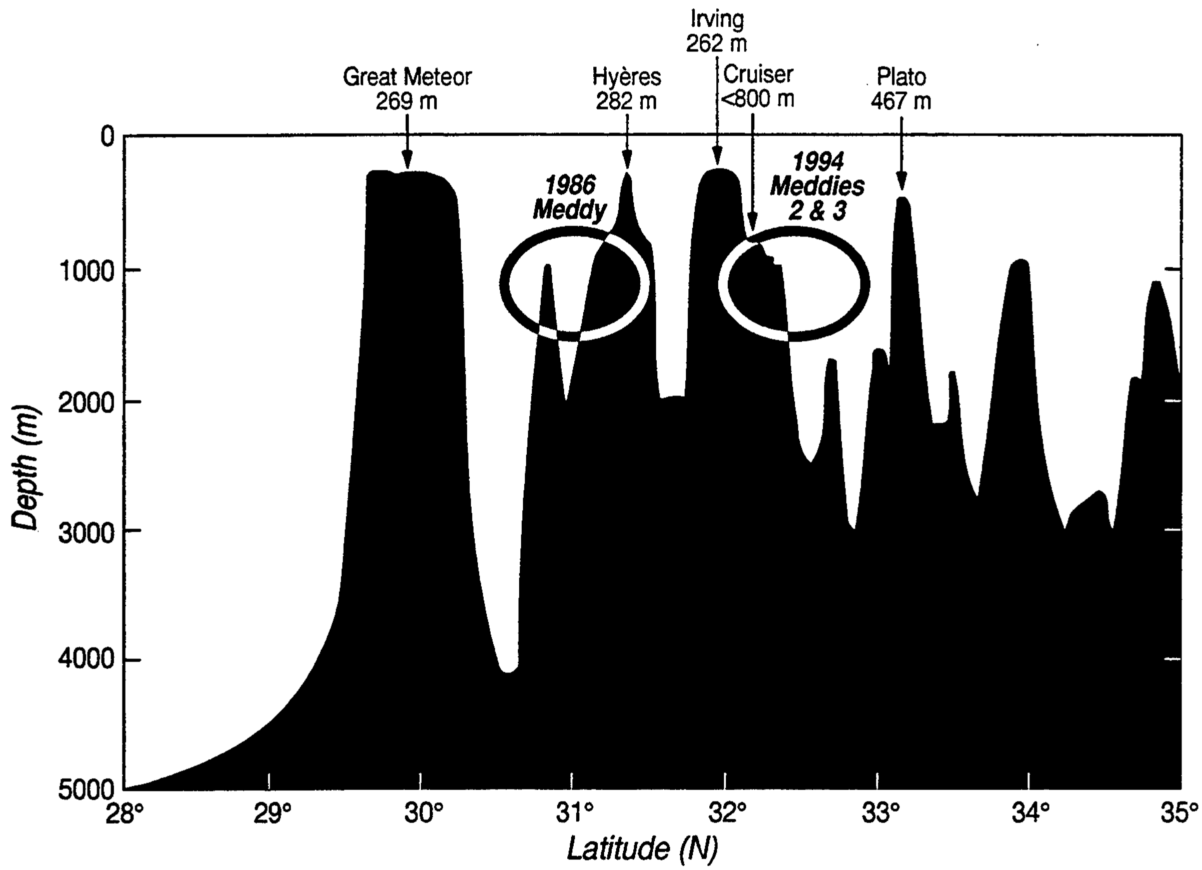


Figure 14: A north–south section showing the projected sea floor depth profile along the Great Meteor Seamounts from a chart by Hunter *et al.* (1983). These are the seamounts faced by a Meddy translating westward between 28N and 35N. Two Meddies are shown schematically, each one 100 km in diameter and 800 m thick; the southern Meddy collided with Hyeres Seamount in 1986 and was destroyed (Richardson *et al.*, 1989); the northern Meddy shows where Meddies 2 and 3 translated westward between 32N and 33N and collided with Cruiser Seamount in 1994. Also shown is Plato seamount which was hit by Meddy 1 as it translated southward in October 1993. Another tall seamount, Atlantis, located near 34.4N 30.0W rises up to a depth of around 400 m. Most of this seamount is off the edge of the Hunter *et al.* chart and therefore the seamount is not plotted here.

translated southward into the Canary Basin and decayed there (Armi *et al.*, 1989; Richardson *et al.*, 1989; Hebert *et al.*, 1990; Schultz-Tokos and Rossby, 1991).

Meddy Paths

Combining the Semaphore Meddy trajectories with the three earlier ones (Richardson *et al.*, 1989) suggests three general paths. First, some Meddies translate southward into the southern Canary Basin near 24N 24W where they decay (earlier Meddies 1 and 3). Second, some Meddies translate westward into the area just south of the Azores (Meddies 1, 2, 4). When they are not interacting with the Azores Current, these Meddies tend to translate westward counter to the mean Azores Current (Meddies 2, 3, and 4). Some of these can continue through the seamounts far westward to at least 43W (Meddy 1), possibly across the mid-Atlantic Ridge. Third, Meddies often translate westward between 29N–35N near 28W and collide with the Great Meteor Seamounts (Meddies 2, 3 and earlier Meddy 2). These Meddies can be severely disrupted (sometimes fatally) by the collision. The seamounts appear to be a major obstacle preventing Meddies from freely translating westward between 29N–35N (Figure 14). By blocking the Meddies and causing their early death seamounts could have an important local influence on the transport of heat and salt and the structure of the Mediterranean salt tongue.

Meddy Translation Velocity

The mean translation rate of the Semaphore Meddies ranged from 1.9 cm/sec for Meddy 4 up to 3.9 cm/sec for Meddy 1. Meddy 1 seems a little faster than the others, but the mean velocity of Meddies 2 and 3 before they hit seamounts was 3.9 cm/sec and 3.4 cm/sec, respectively, which suggests that Meddy 1 was not anomalous. The velocity obtained by averaging the four Meddy velocities is 2.5 ± 0.5 cm/sec toward 236°. Semaphore Meddies were swifter than the three earlier ones especially the slow one located near 24N 24W which translated at only 1.1 cm/sec during 1.5 years.

Meddy Population

Before Semaphore began we estimated from earlier studies that we would find 4–6 Meddies in the Semaphore region. We actually found four major Meddies including one west of the Semaphore box and one smaller piece of a Meddy. One Meddy was found in the box in phases 1 and 4, two Meddies (plus a piece) in phases 2 and 3. By assuming an overall diameter of 100 km and estimating the fraction of each Meddy in the Semaphore box (excluding the piece), we estimate that an average of 4% of the box contained Meddies. This is in agreement with earlier studies (Armi and Zenk, 1984; Richardson *et al.*, 1991; Käse and Zenk, 1996) which suggested that Meddies comprise 4–8% of the region. Therefore the population of Meddies observed during Semaphore appears to be rather typical.

11 Acknowledgments

Funds were provided by the National Science Foundation Grant OCE 93-01234. J. R. Valdes, R. D. Tavares, and B. J. Guest of the WHOI float operations group prepared the RAFOS floats. C. M. Wooding tracked the floats and created many of the figures. We thank the Captains, crew, and scientific parties who launched the floats from the *Alcyon* (phase 1), *D'Entrecasteaux* (phases 3 and 4) and *Charles Darwin* (off Lisbon). Yves Camus initiated and coordinated the WHOI float contribution to Semaphore. Aude Tychensky and Bruno LeSquere were very helpful collaborators on the Meddy part of Semaphore (Meddyphore). Robin Pingree and Bernard LeCann launched our floats from the *Darwin*. M.A. Lucas typed the manuscript.

12 References

Anderson–Fontana, S., M. Prater and H. T. Rossby, 1996. RAFOS float data report of the North Atlantic Current Study 1993–1995. Technical Report No. 96-4, Graduate School of Oceanography, Narragansett Marine Laboratory, University of Rhode Island, 241 pp.

Armi, L. D., D. Hebert, N. Oakey, J. F. Price, P. L. Richardson, H. T. Rossby and B. Ruddick, 1989. Two years in the life of a Mediterranean salt lens. *Journal of Physical Oceanography*, **19**, 354–370.

Armi, L., and W. Zenk, 1984. Large lenses of highly saline Mediterranean Water. *Journal of Physical Oceanography*, **14**, 1560–1576.

Bower, A. S., L. Armi, and I. Ambar, 1997. Lagrangian observations of meddy formation during A Mediterranean Undercurrent Seeding Experiment. *Journal of Physical Oceanography*, **27**, 2545–2575.

Dykhno, L. A., Y. G. Morozov, S. V. Nikitin, B. N. Filyushkin, and I. A. Shilov, 1991. Breakup of lenses of Mediterranean Water on interaction with bottom relief. *Oceanology*, **31**(1), 38–41.

Eymard, L. *et al.*, 1996. Study of the air-sea interactions at the mesocale: the SEMAPHORE experiment. *Annalae Geophysicae*, **14**, 986–1015.

Hansen, D. V., and A. Herman, 1989. Temporal sampling requirements for surface drifting buoys in the Tropical Atlantic. *Journal of Atmospheric and Oceanic Technology*, **6**, 599–604.

Hebert, D., N. Oakey, and B. Ruddick, 1990. Evolution of a Mediterranean salt lens: Scalar properties. *Journal of Physical Oceanography*, **20**, 1468–1483.

Hernandez, F., and P. Y. LeTraon, 1995. Mapping mesoscale variability of the Azores Current using TOPEX/POSEIDON and ERS 1 altimetry, together with hydrographic and Lagrangian measurements. *Journal of Geophysical Research*, **100**, 24,995–25,006.

Hogg, N. G., and W. B. Owens. Direct measurement of the deep circulation within the Brazil Basin. *Deep-Sea Research*, in press.

Hunt, H. D., C. M. Wooding, C. L. Chandler, and A. S. Bower, 1998. A Mediterranean Undercurrent Seeding Experiment (AMUSE): Part II: RAFOS Float Data Report May 1993–March 1995. *Woods Hole Oceanographic Institution Technical Report* WHOI-98-14, 123 pp.

Hunter, P. M, R. C. Searle, and A. S. Laughton, 1983. Continental margin off northwest Africa, bathymetry of the northeast Atlantic, sheet 5. Published at Taunton, U.K., under the superintendence of Rear-Admiral D. N. Haslam, Hydrographer of the Navy.

Käse, R. H., and W. Zenk, 1996. Structure of the Mediterranean water and Meddy characteristics in the northeastern Atlantic. In: *The Warmwatersphere of the North Atlantic Ocean*, edited by W. Krauss, Gebrüder Borntraeger, Berlin, Chapter 12, 365–395.

McDowell, S. E., and H. T. Rossby, 1978. Mediterranean Water: An intense mesoscale eddy off the Bahamas. *Science*, **202**, 1085–1087.

Pingree, R. D., 1995. The droguing of Meddy Pinball and seeding with ALACE floats. *Journal of Marine Biological Association of United Kingdom*, **75**, 235–252.

Prater, M. D., and T. B. Sanford, 1994. A Meddy off Cape St. Vincent. Part 1: Description. *Journal of Physical Oceanography*, **24**, 1572–1586.

Richardson, P. L., M. S. McCartney, and C. Maillard, 1991. A search for Meddies in historical data. *Dynamics of Atmospheres and Oceans*, **15**, 241–265.

Richardson, P. L., and A. Tychensky, 1998. Meddy trajectories in the Canary Basin measured during the Semaphore Experiment, 1993–1995. *Journal of Geophysical Research*, **103**, 25,029–25,045.

Richardson, P. L., D. Walsh, L. Armi, M. Schröder and J. F. Price, 1989. Tracking three Meddies with SOFAR floats. *Journal of Physical Oceanography*, **19**, 371–383.

Rossby, T., D. Dorson, and J. Fontaine, 1986. The RAFOS system. *Journal of Atmospheric and Oceanic Technology*, **3**, 673–679.

Schultz-Tokos, K. L., H.-H. Hinrichsen, and W. Zenk, 1994. Merging and migration of two Meddies. *Journal of Physical Oceanography*, **24**, 2130–2141.

Schultz-Tokos, K., and H. T. Rossby, 1991. Kinematics and dynamics of a Mediterranean salt lens. *Journal of Physical Oceanography*, **21**, 879–892.

Shapiro, G. I., and S. L. Meschanov, 1996. Spreading pattern and mesoscale structure of Mediterranean outflow in the Iberian Basin estimated from historical data. *Journal of Marine Systems*, **7**, 337–348.

Shapiro, G. I., S. L. Meschanov, and M. V. Emelianov, 1995. Mediterranean lens "Irving" after its collision with seamounts. *Oceanologica Acta*, **18**(3), 309–318.

Tychensky, A., and X. Carton, 1998. Hydrological and dynamical characterization of Meddies in the Azores region: A paradigm for baroclinic vortex dynamics. *Journal of Geophysical Research*, **103**, 25,061–25,079.

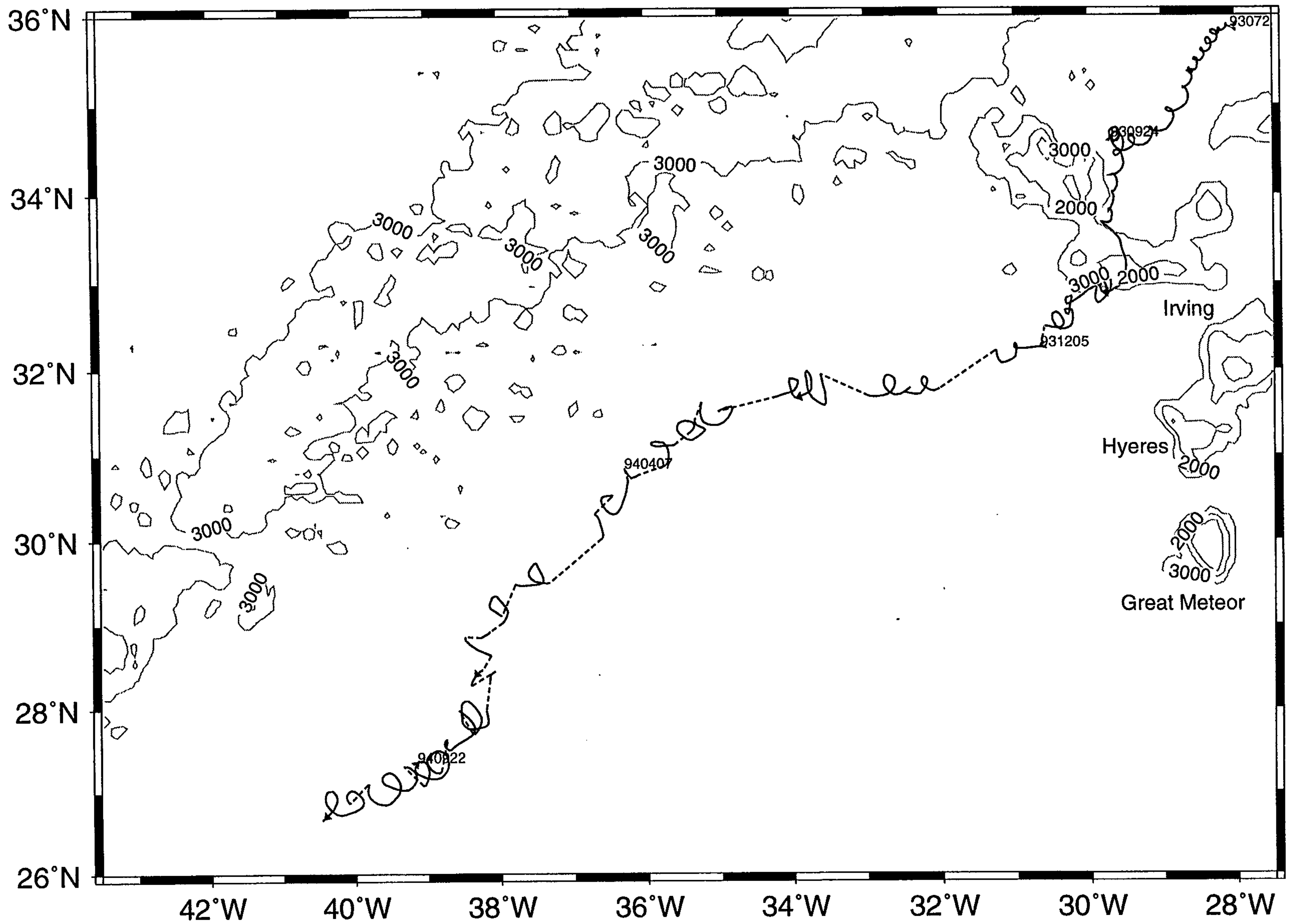
Tychensky, A., P. Y. Le Traon, F. Hernandez, D. Jourdan, and P. Canceill. Structure and temporal change in the Azores front during the Semaphore experiment. *Journal of Geophysical Research*, submitted.

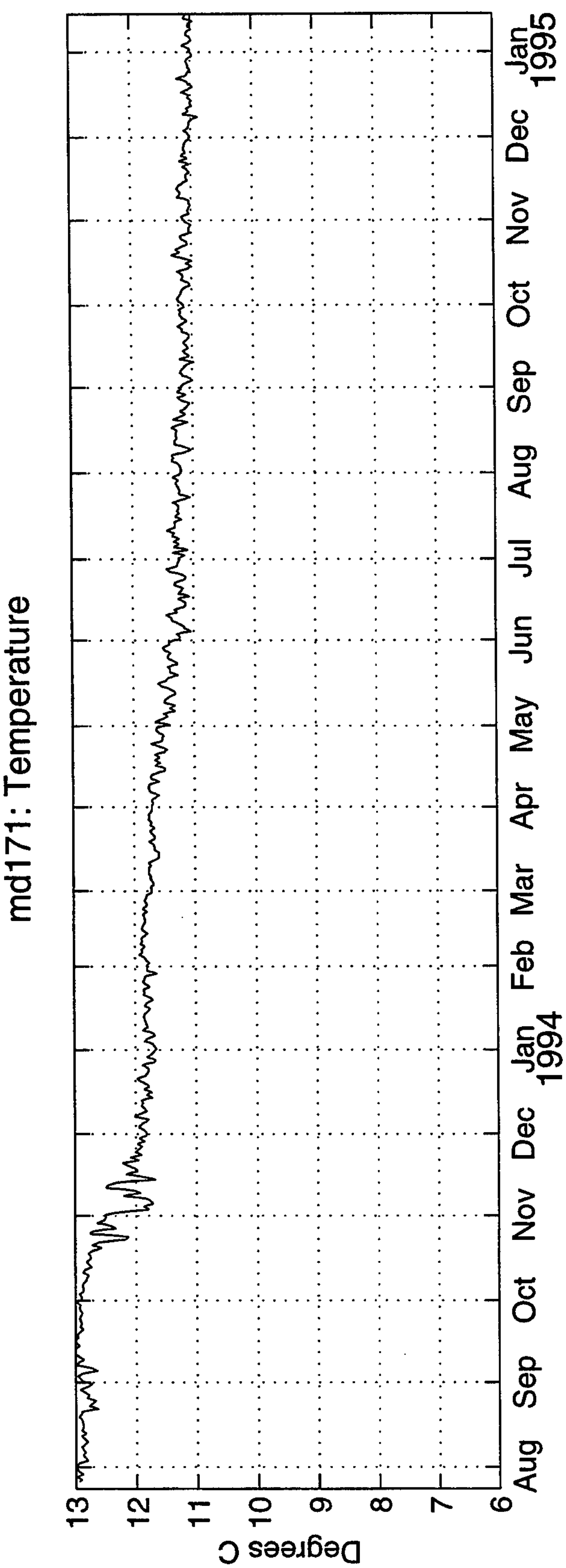
Zenk, W., K. Schultz-Tokos, and O. Boebel, 1992. New observations of Meddy movement south of the Tejo Plateau. *Geophysical Research Letters*, **19**, 2389–2392.

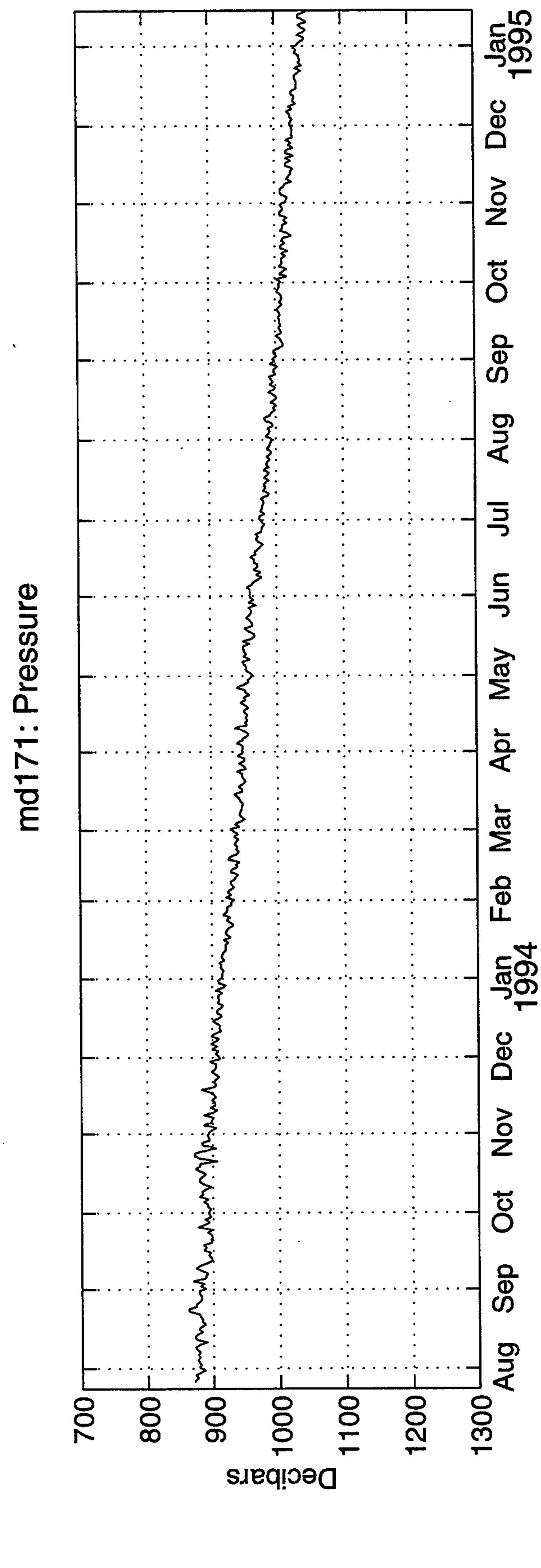
13 Appendix: Float Trajectories and Time Series

The following figures show detailed trajectories and time series of temperature, pressure and velocity for each float. The figures are ordered by Meddy number and then float number starting with Meddy 1 floats 171, 175, and 177, etc. Some float trajectories in Meddies 1 and 5 were interpolated as described in the text. For these floats the original and the interpolated trajectories are given along with the corresponding velocity series. Float 171 in Meddy 1 has a third subjectively interpolated trajectory and the resulting velocity time series.

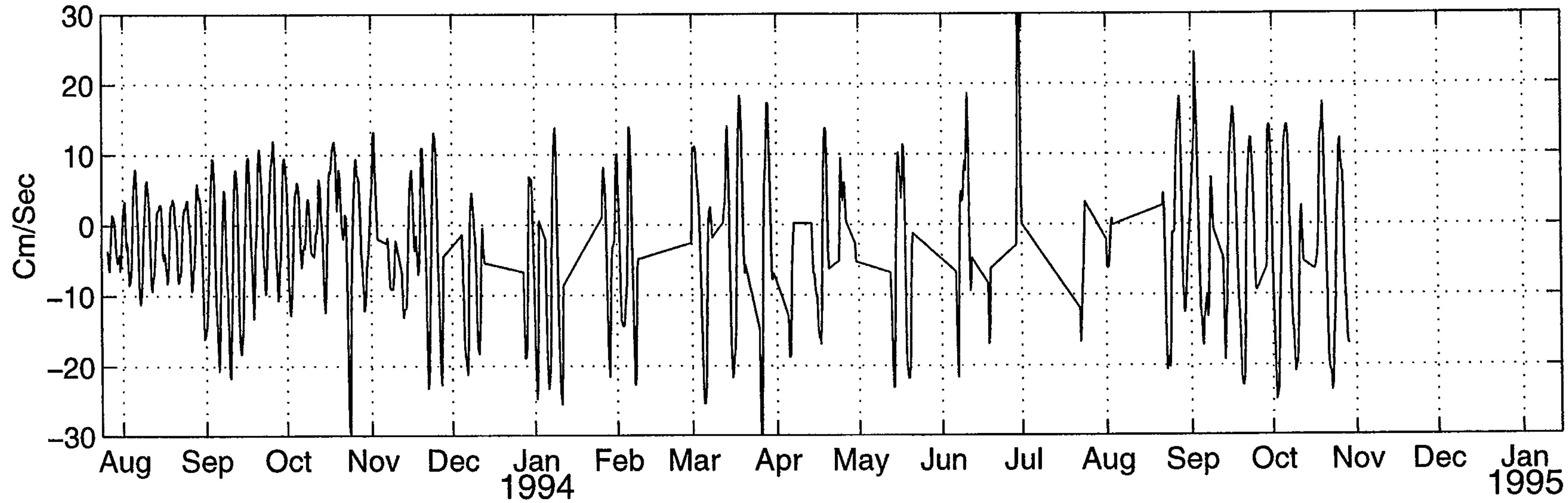
Meddy 1 Float 171



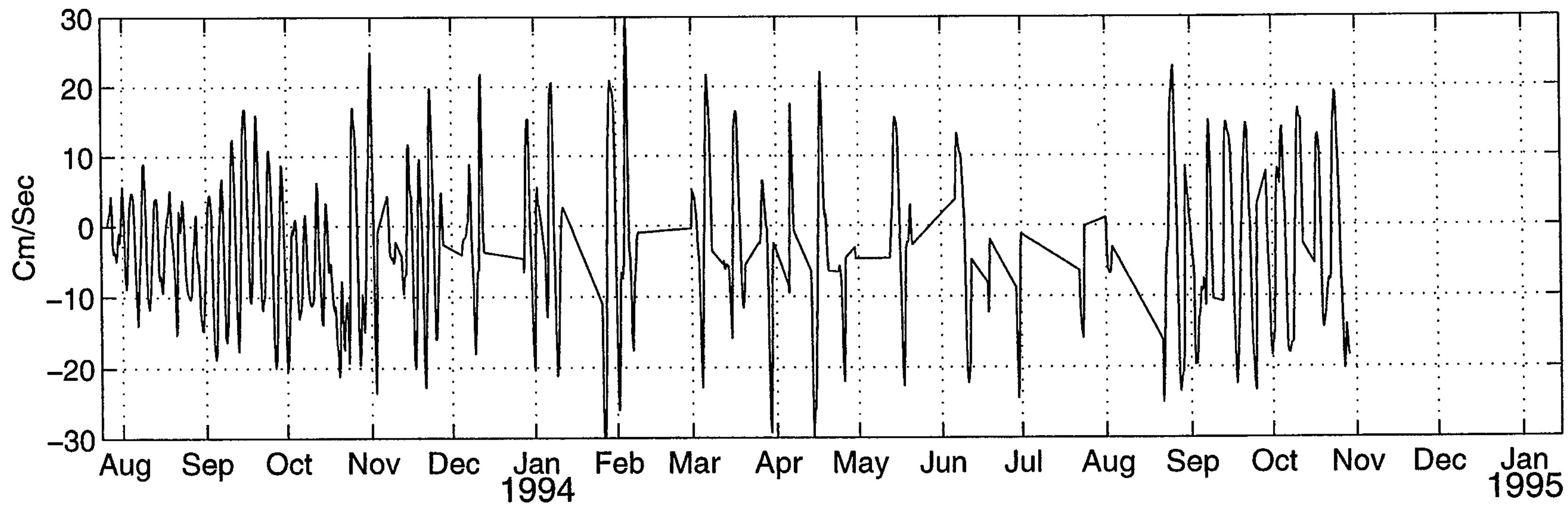

md171: Temperature
Degrees C
13
12
11
10
9
8
7
6
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995


md171: Pressure
Decibars
700
800
900
1000
1100
1200
1300
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995

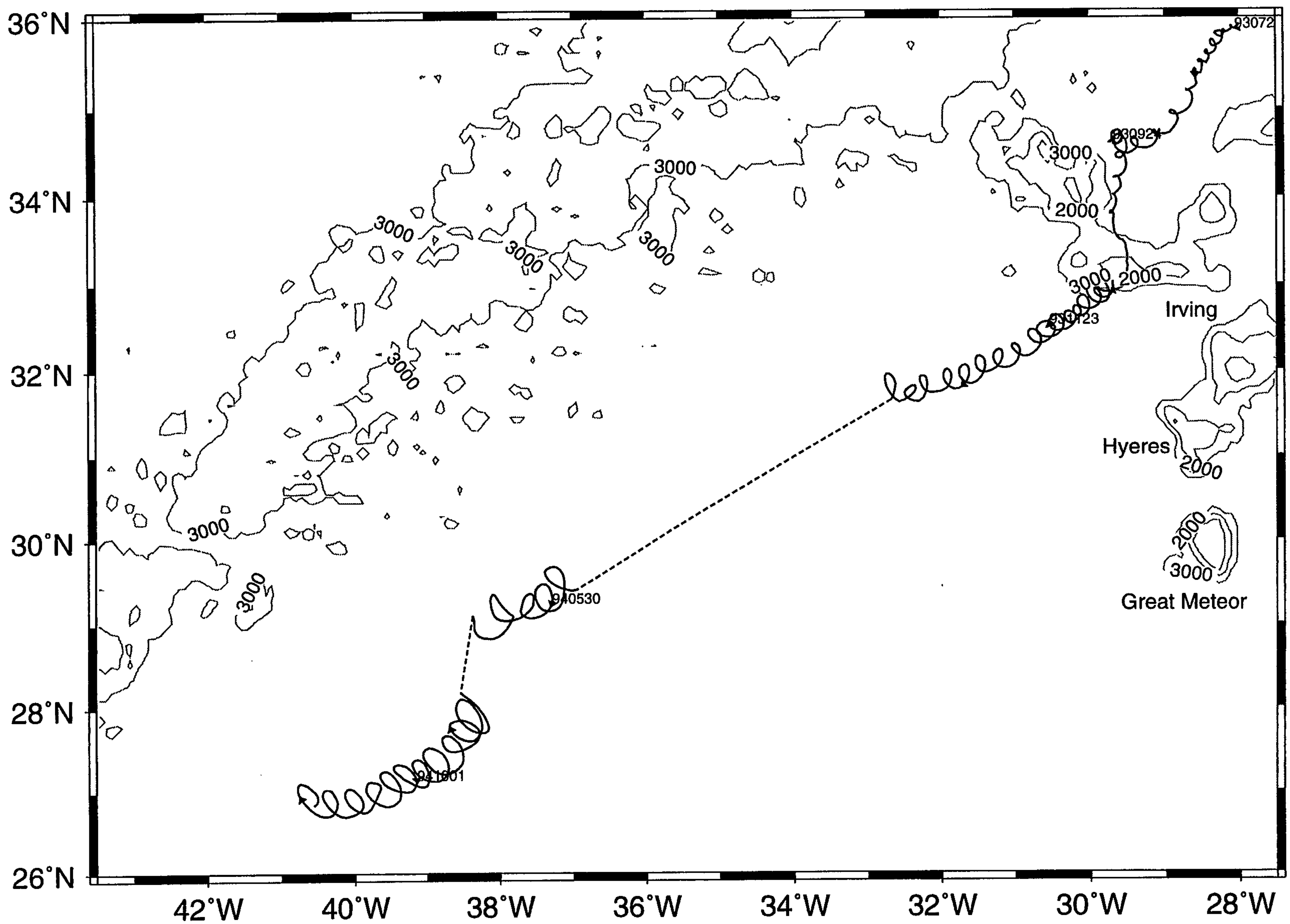
md171: Velocity East

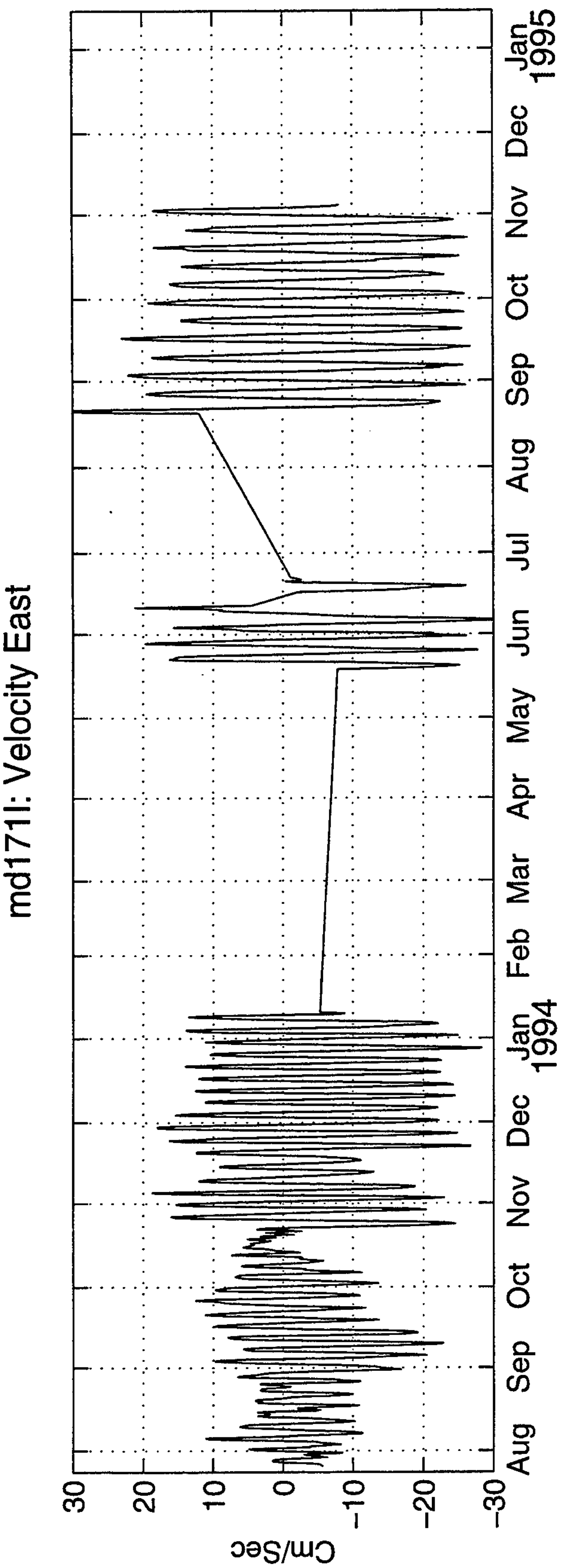


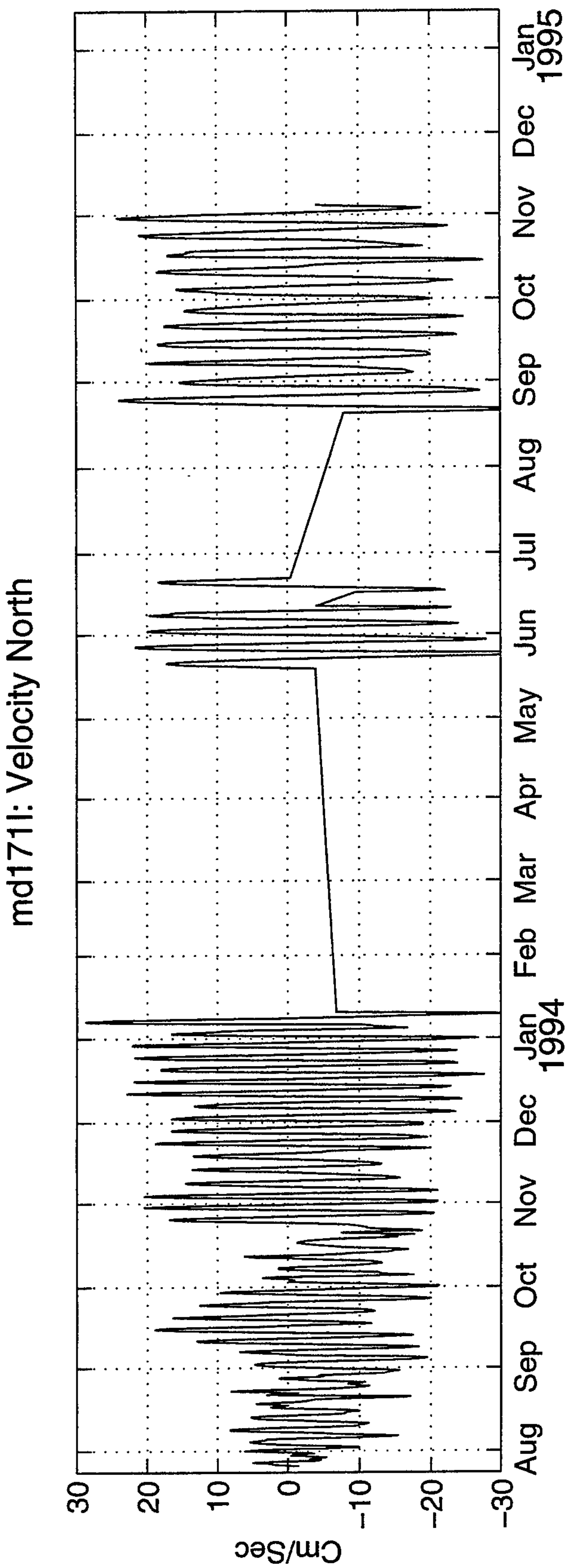
md171: Velocity North



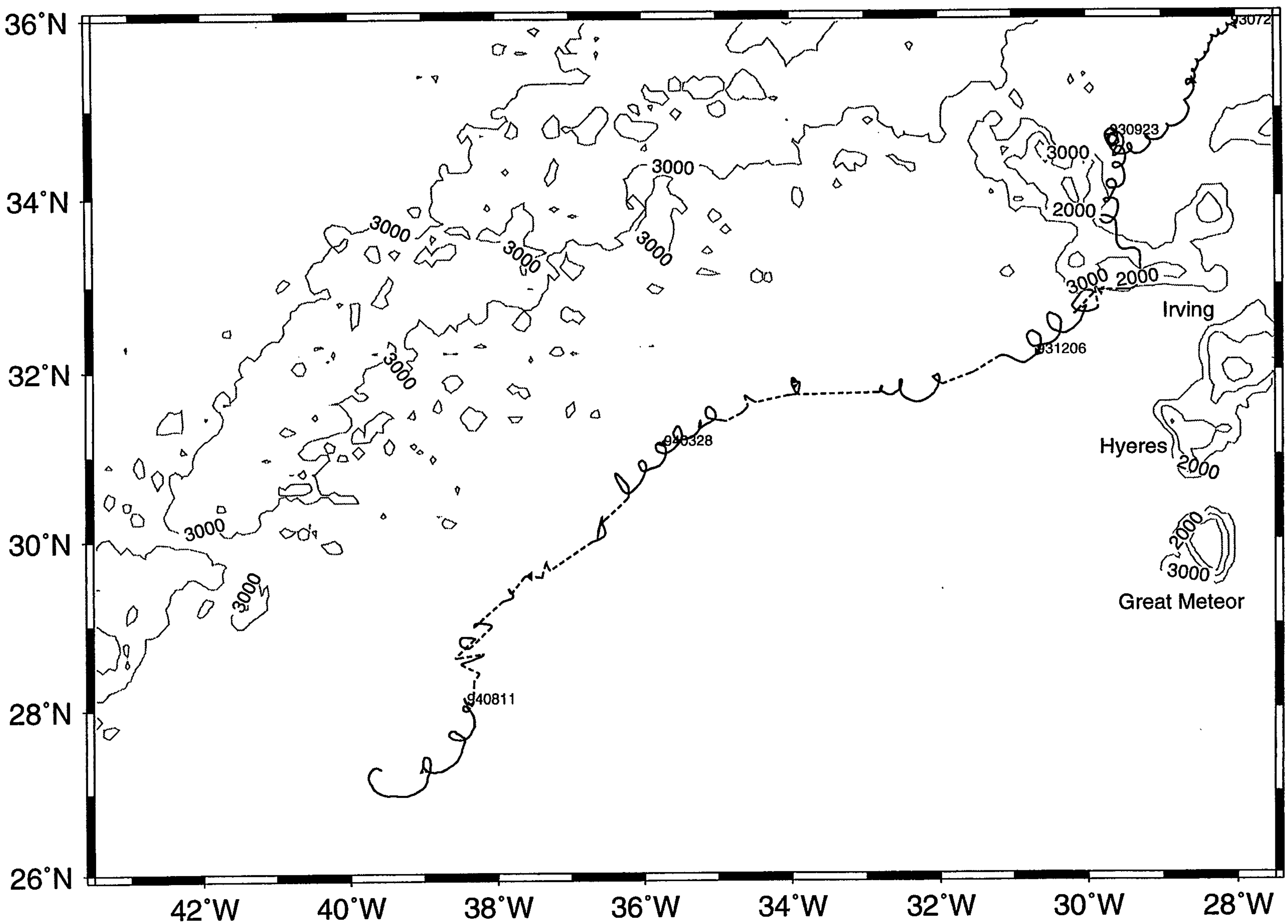
Meddy 1 Float 171 Interpolated

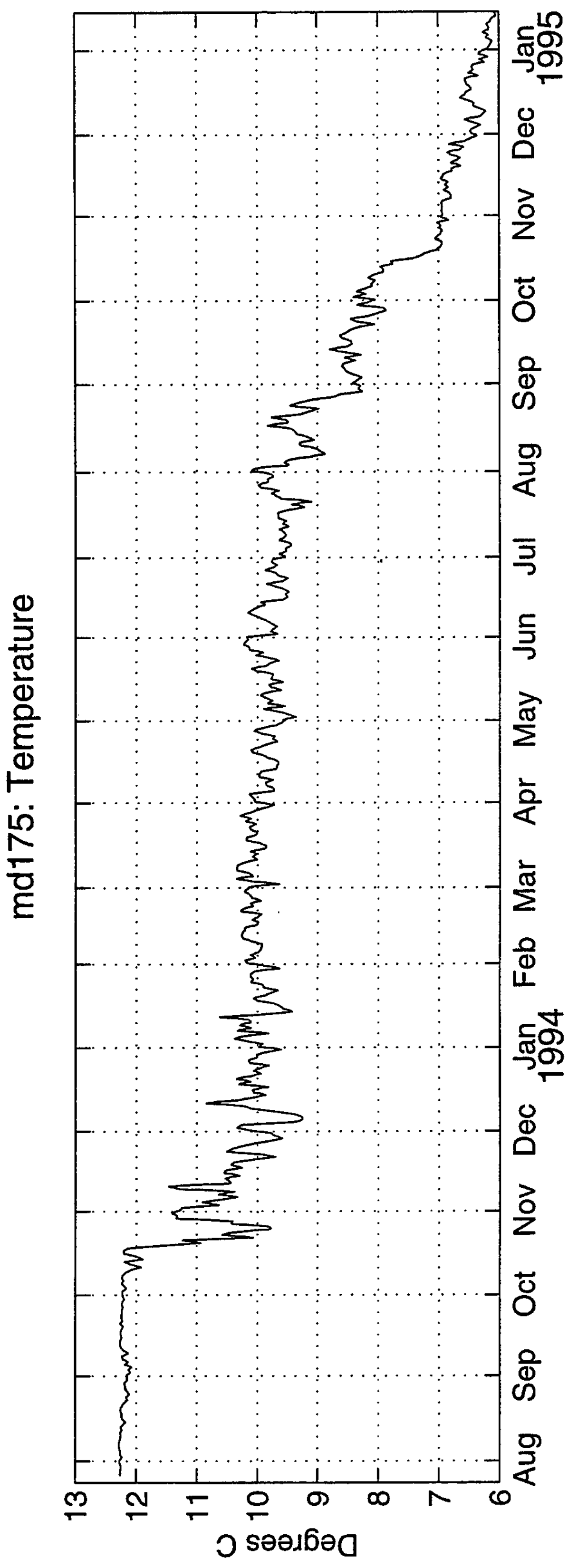


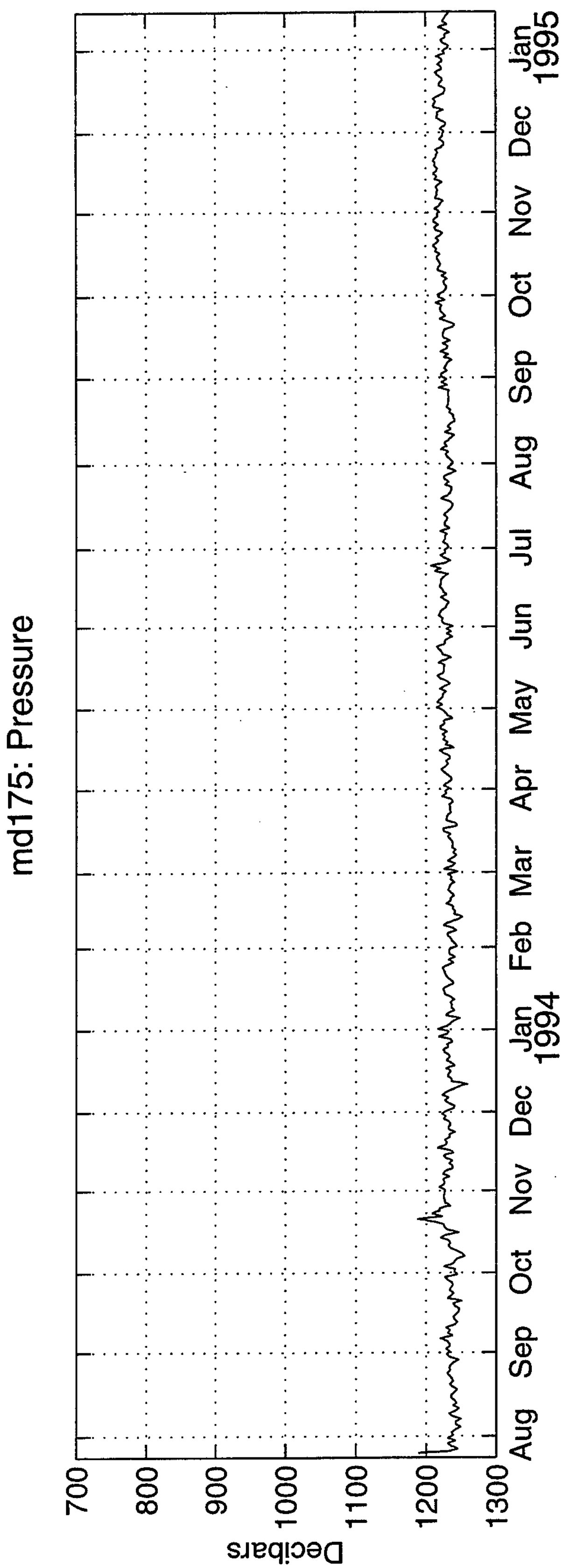

md171l: Velocity East
Cm/Sec
30
20
10
0
-10
-20
-30
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995


md171l: Velocity North
Cm/Sec
30
20
10
0
-10
-20
-30
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995

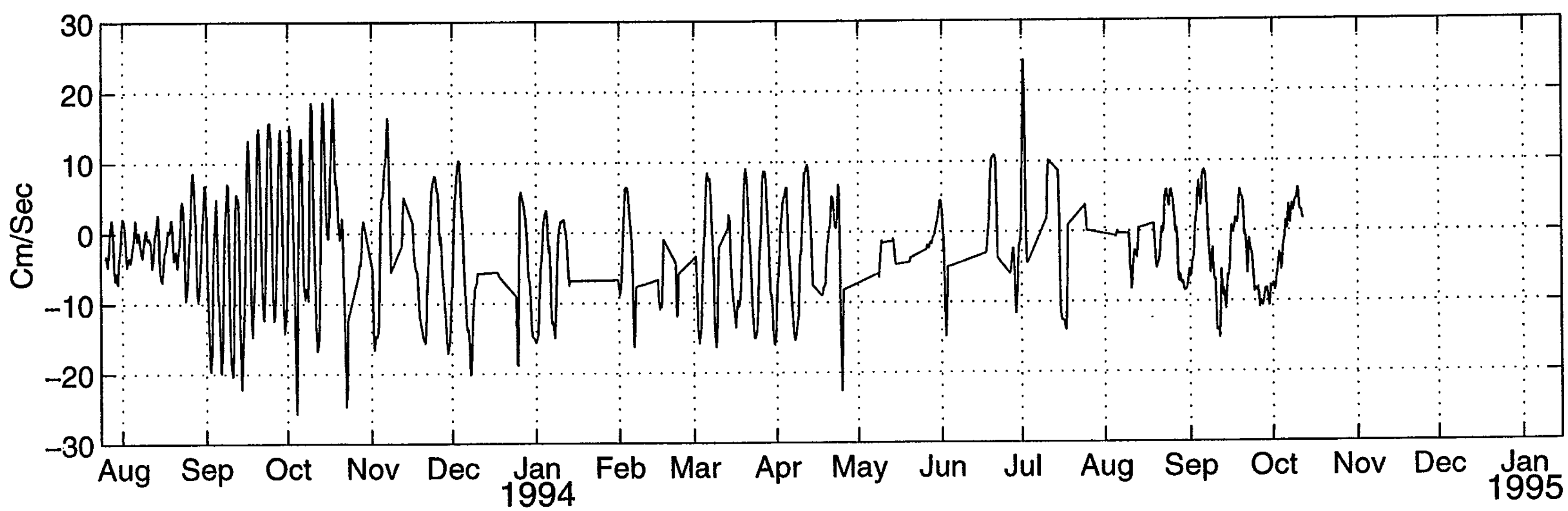
Meddy 1 Float 175



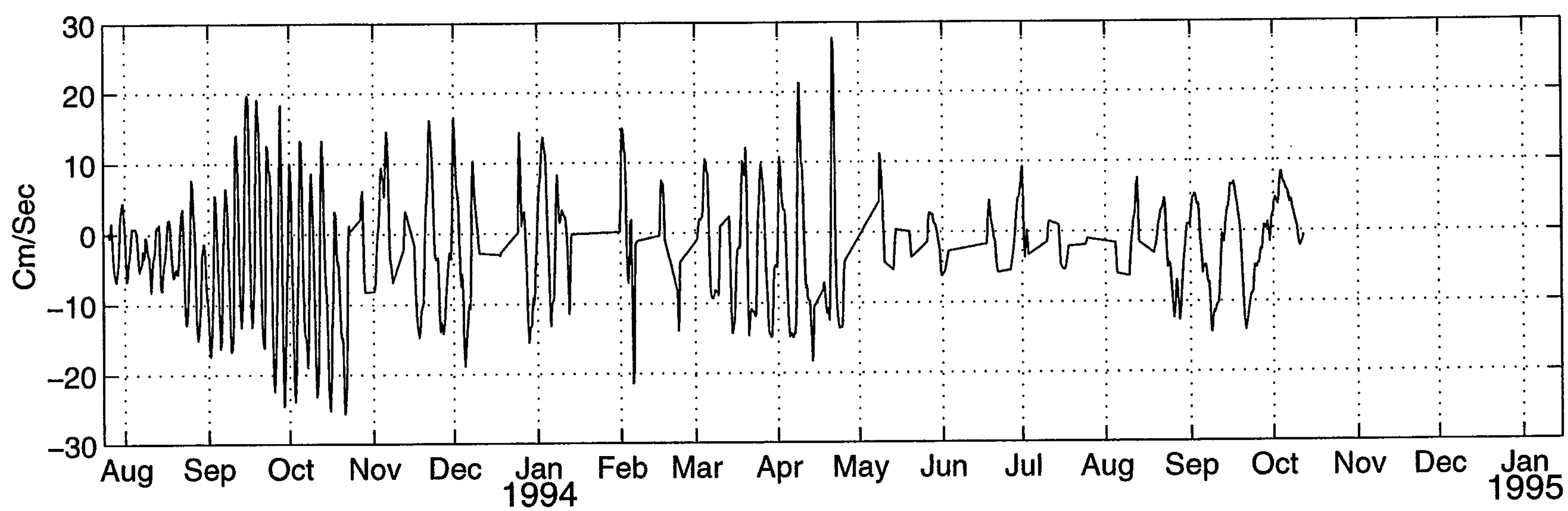

md175: Temperature
Degrees C
13
12
11
10
9
8
7
6
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995


md175: Pressure
Decibars
700
800
900
1000
1100
1200
1300
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995

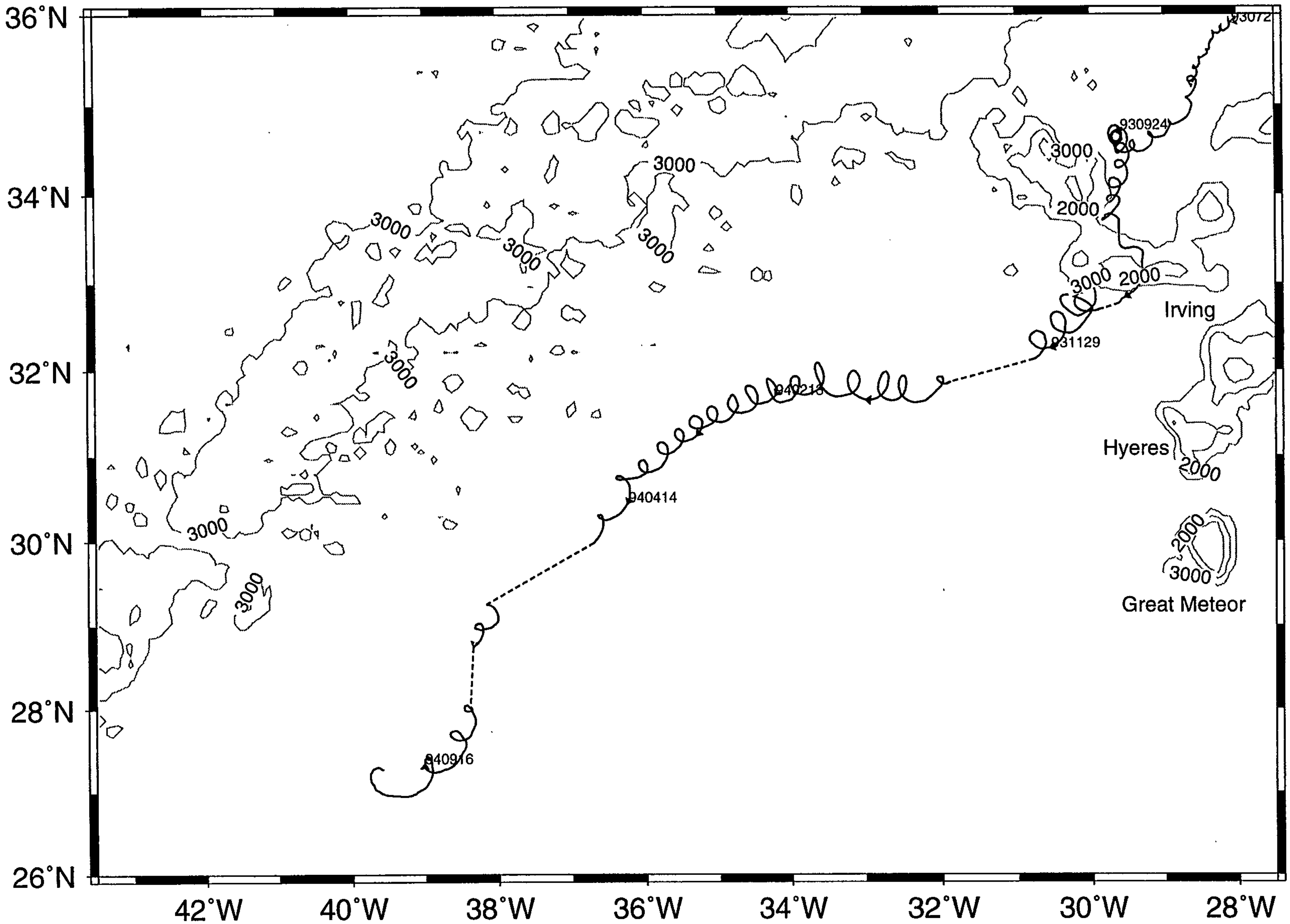
md175: Velocity East

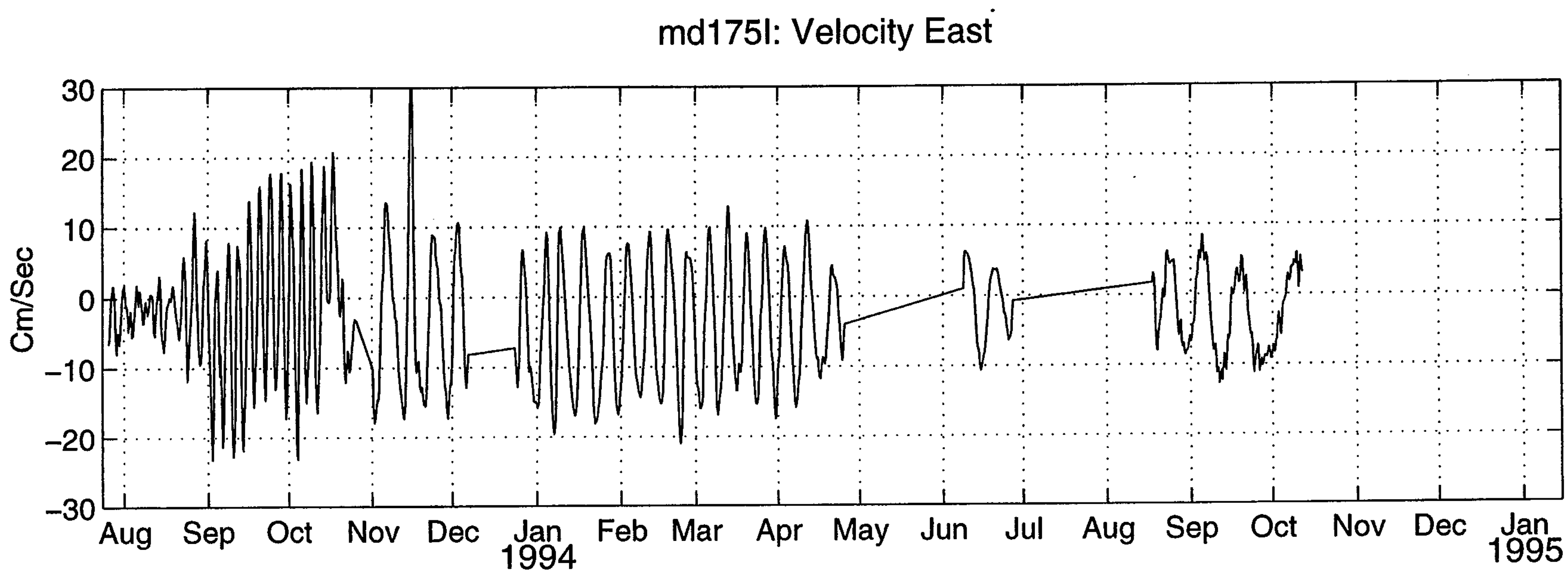


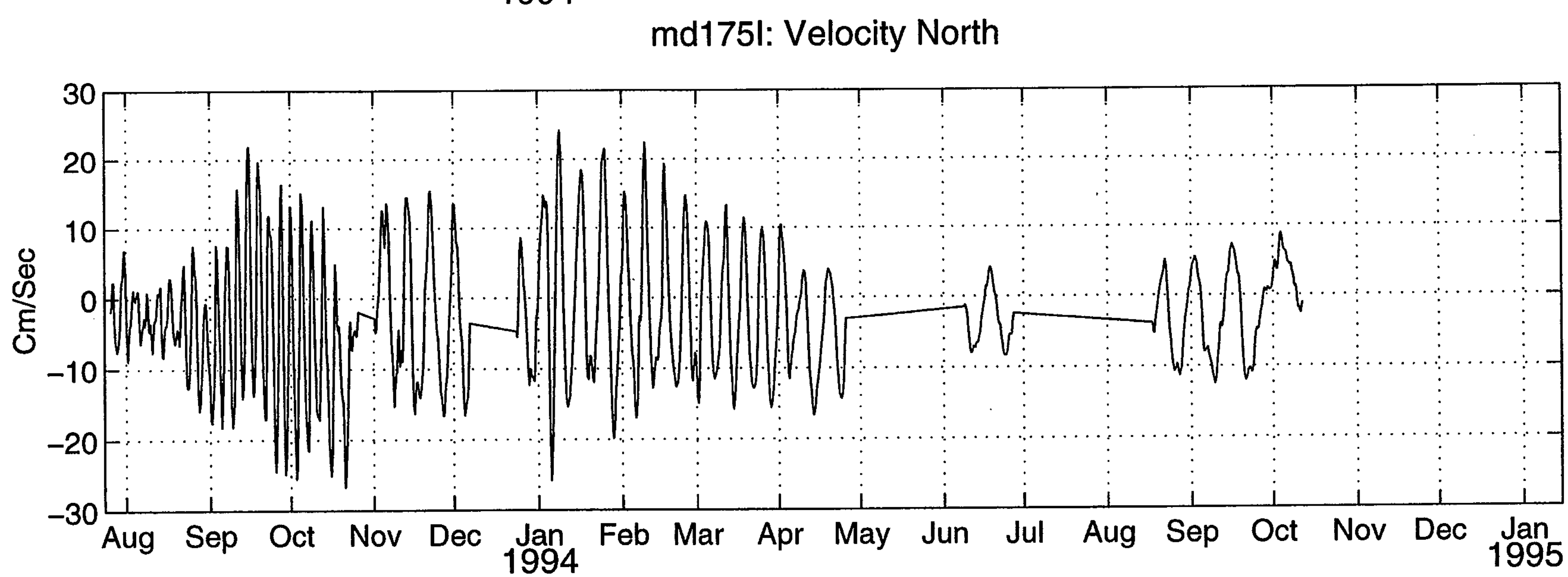
md175: Velocity North



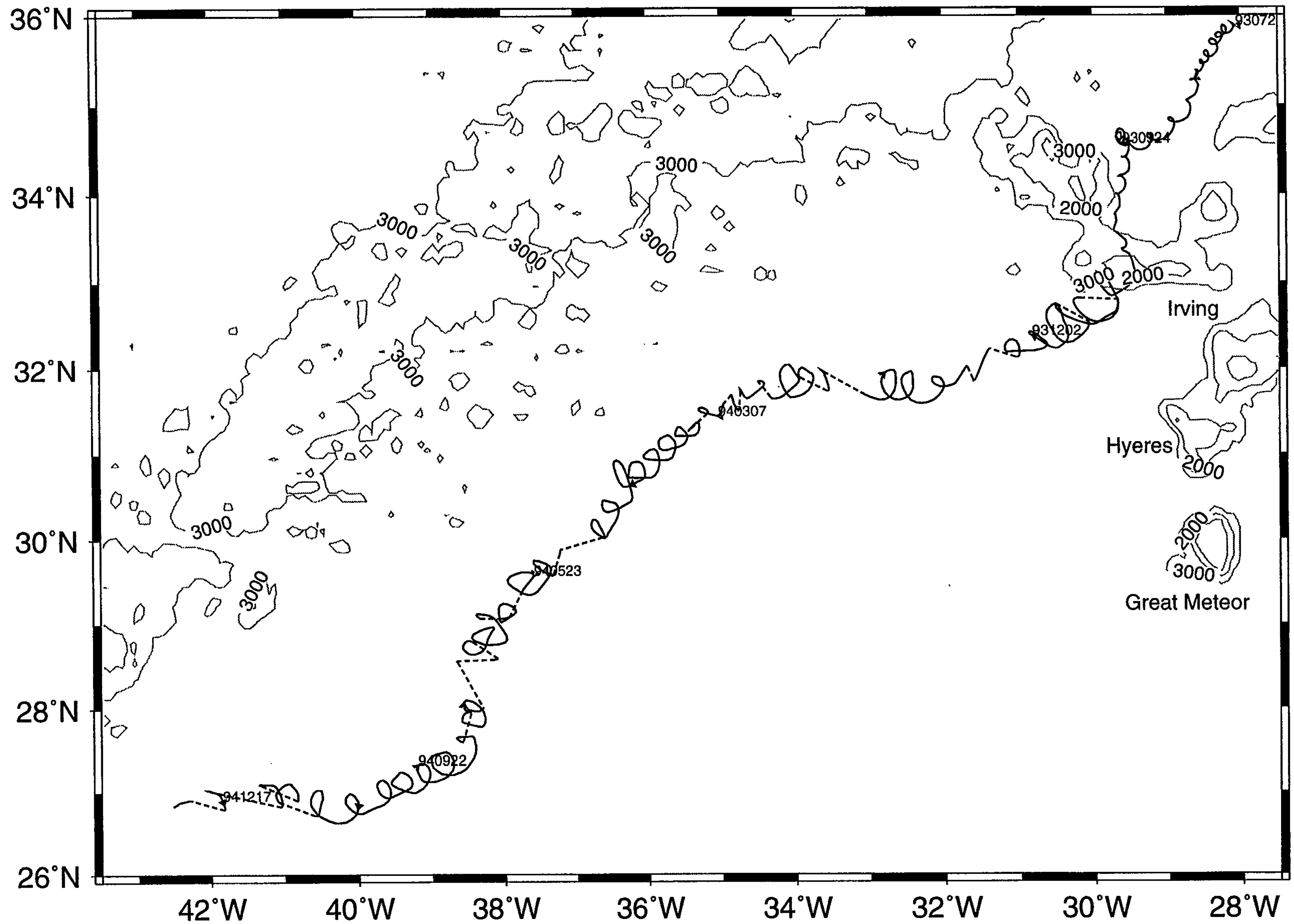
Meddy 1 Float 175 Interpolated



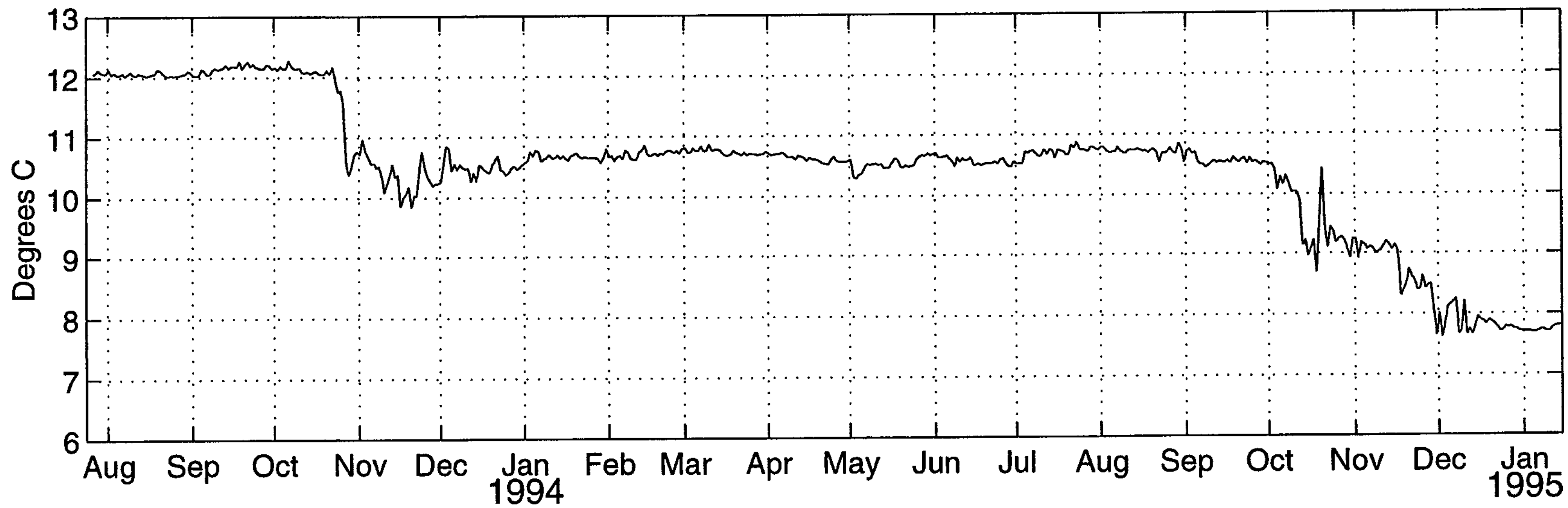

md175I: Velocity East
Cm/Sec
30
20
10
0
−10
−20
−30
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
1994
1995


md175I: Velocity North
Cm/Sec
30
20
10
0
−10
−20
−30
Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
1994
1995

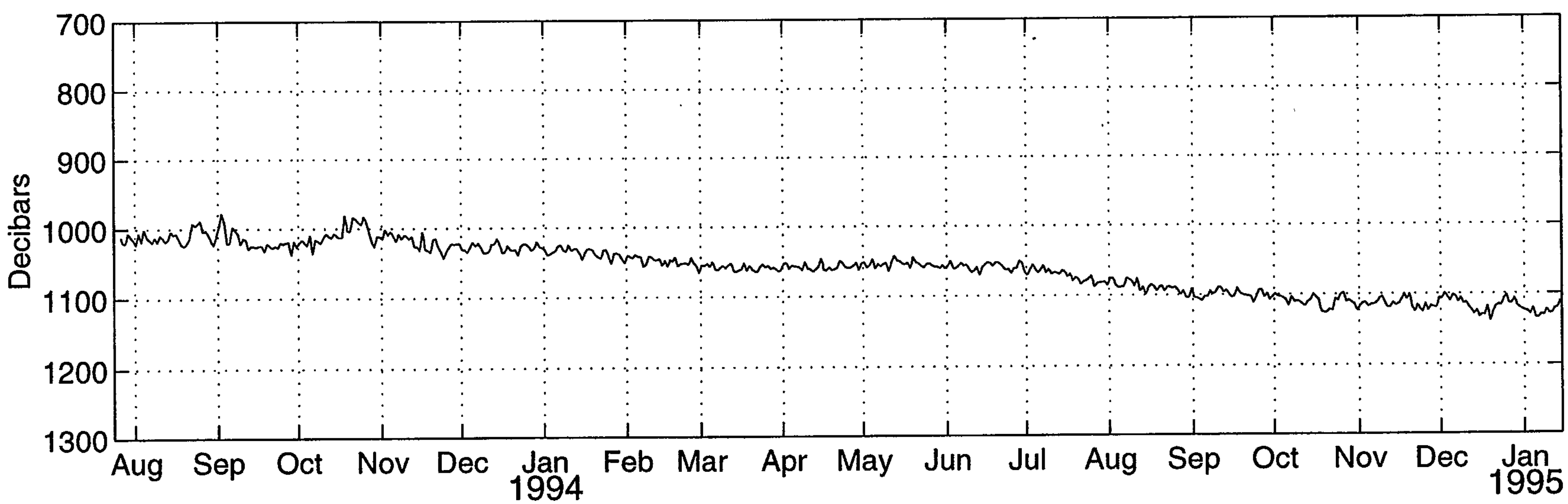
Meddy 1 Float 177



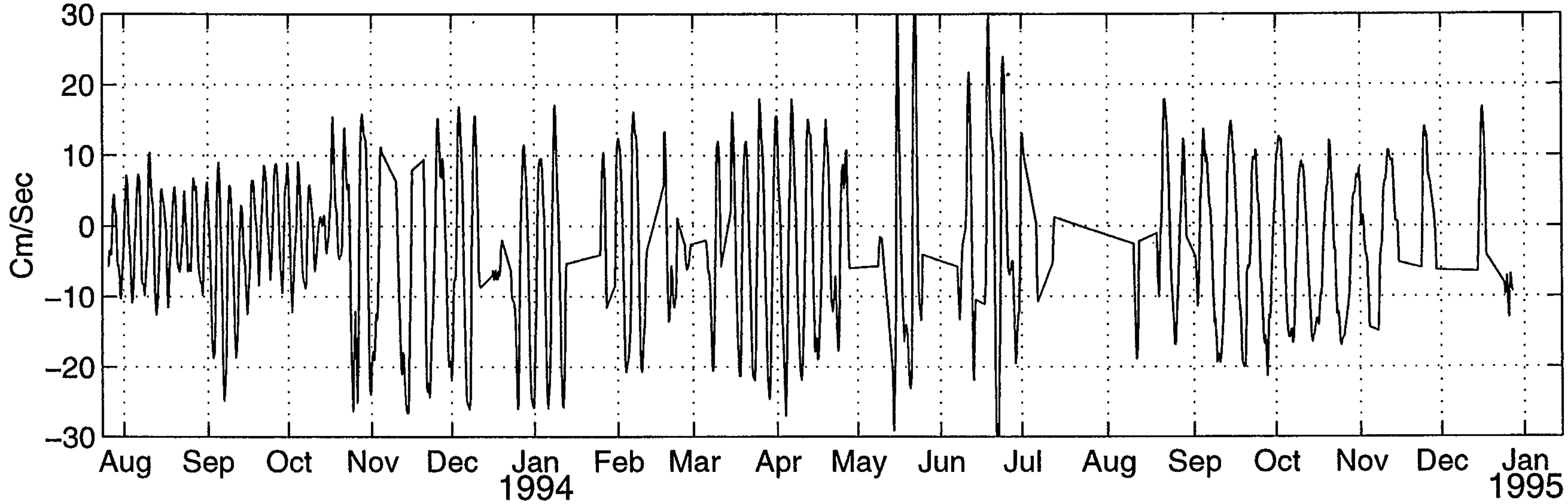
md177: Temperature



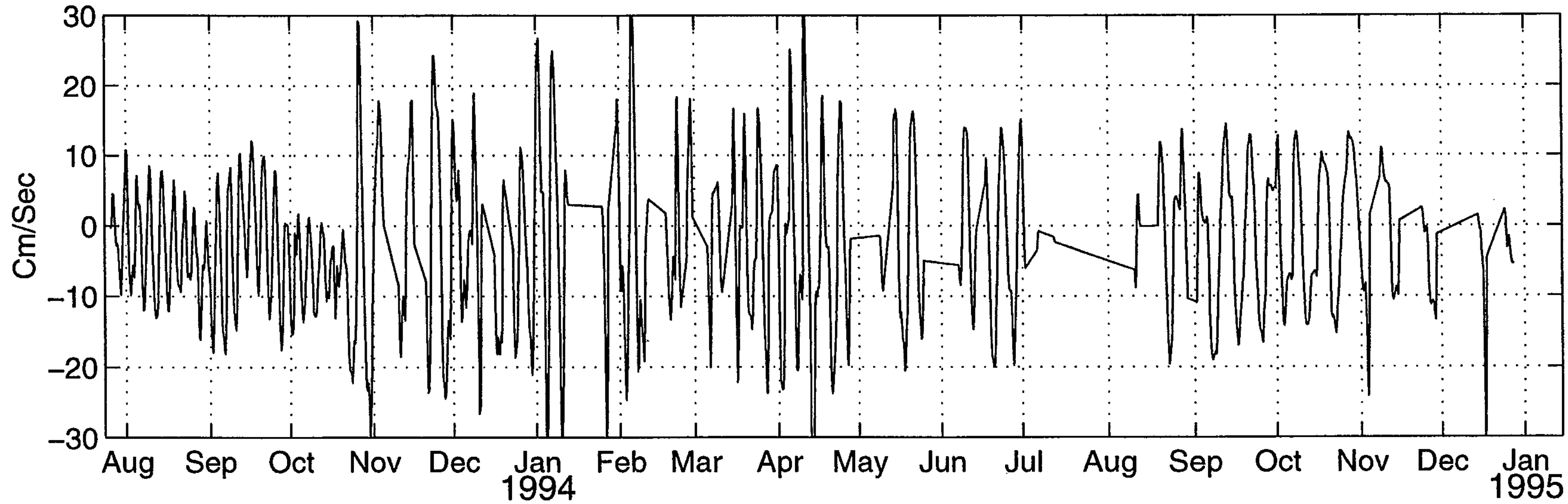
md177: Pressure



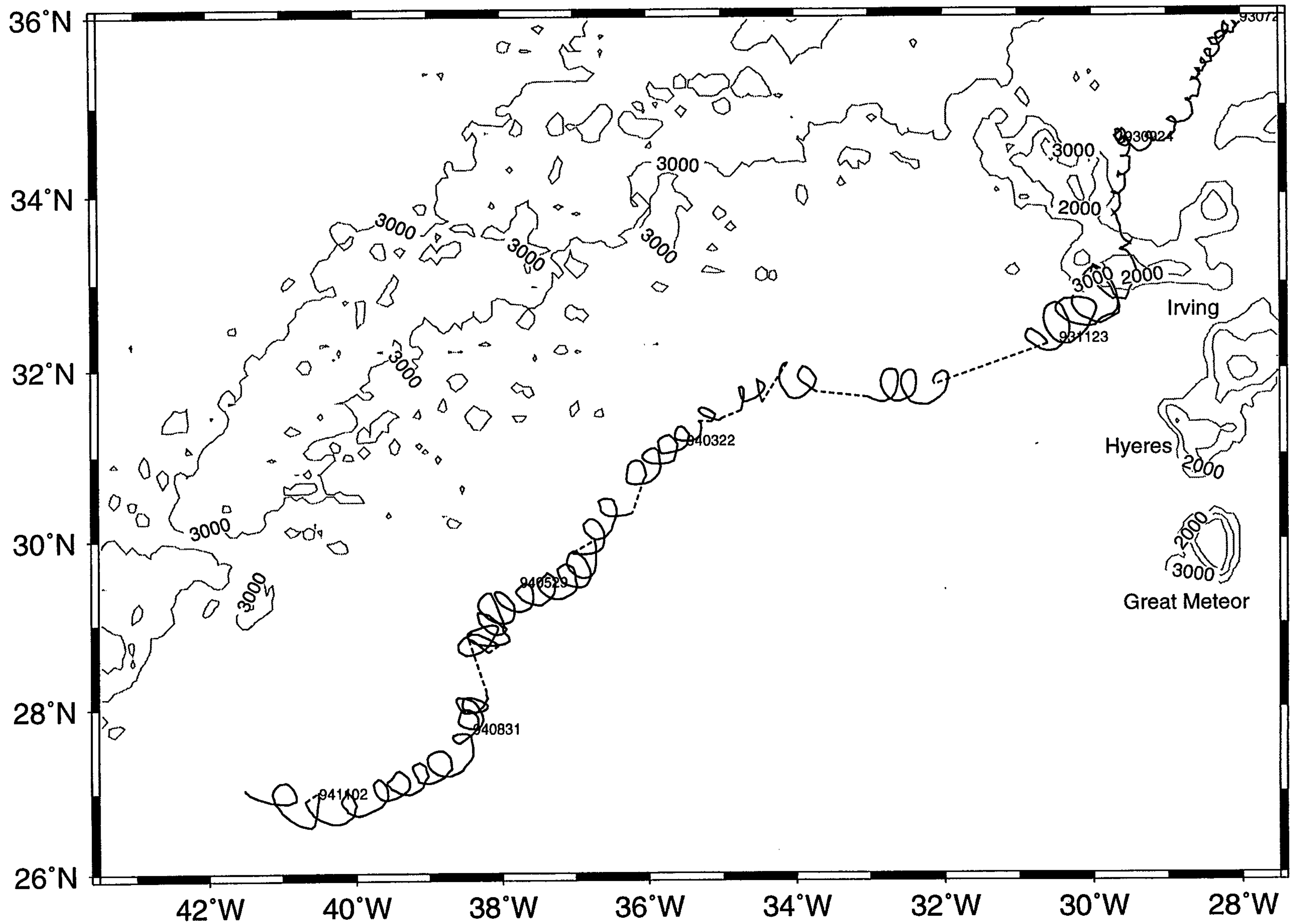
md177: Velocity East



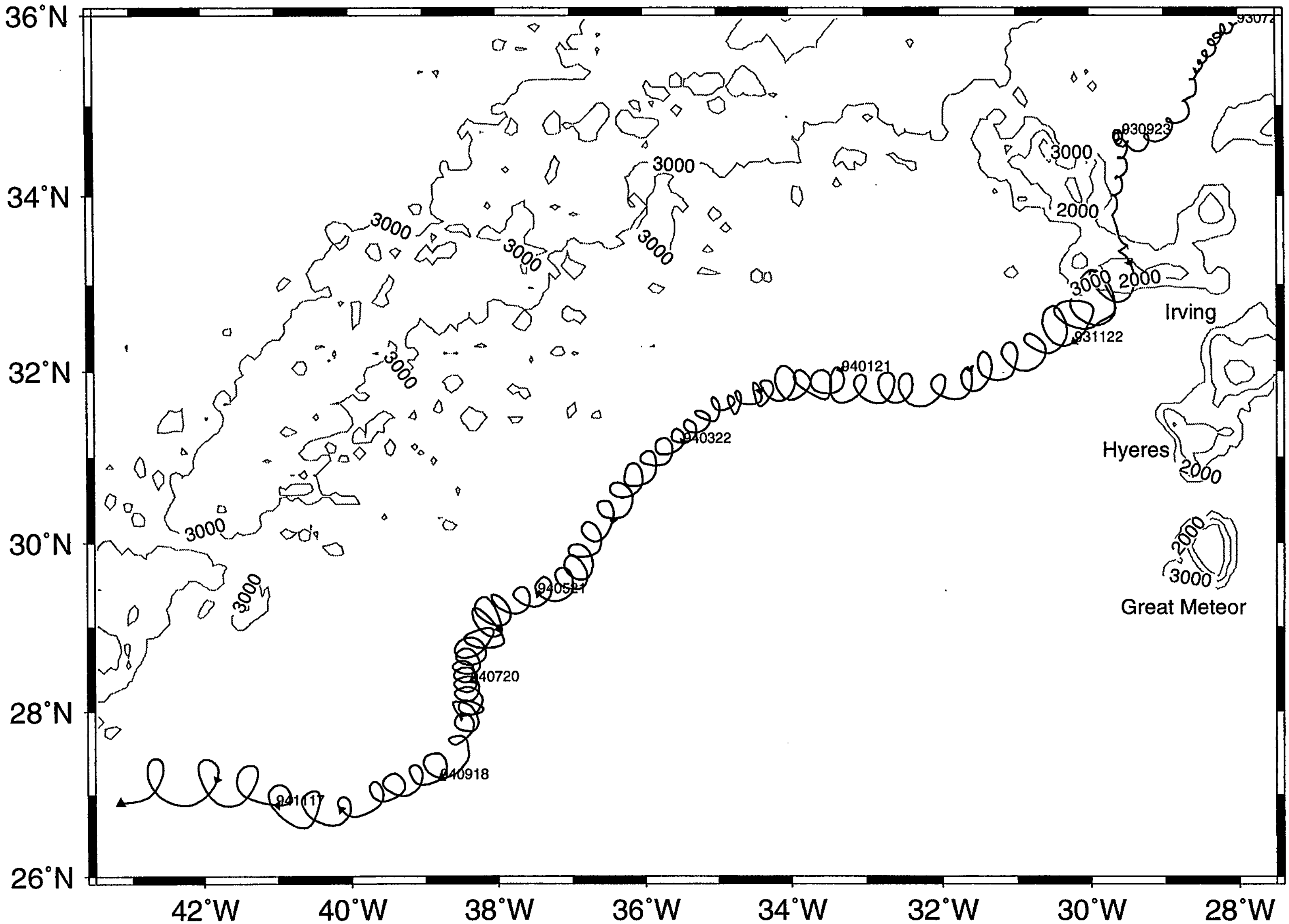
md177: Velocity North

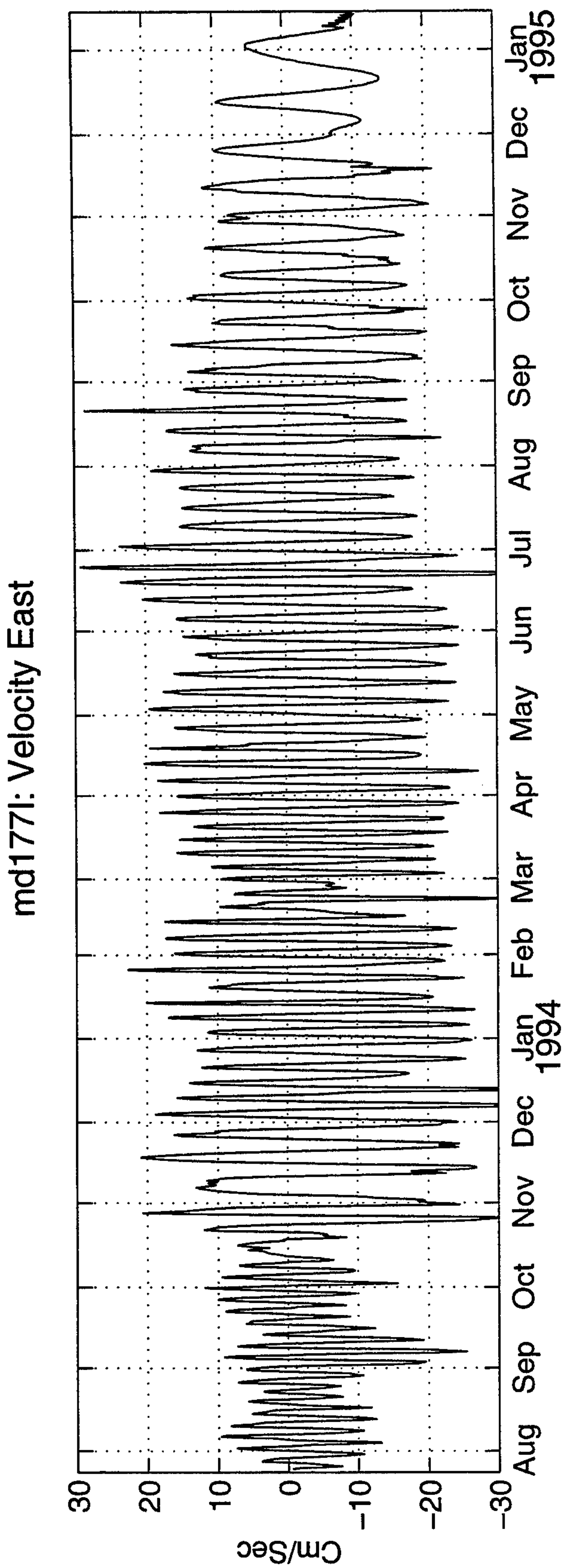


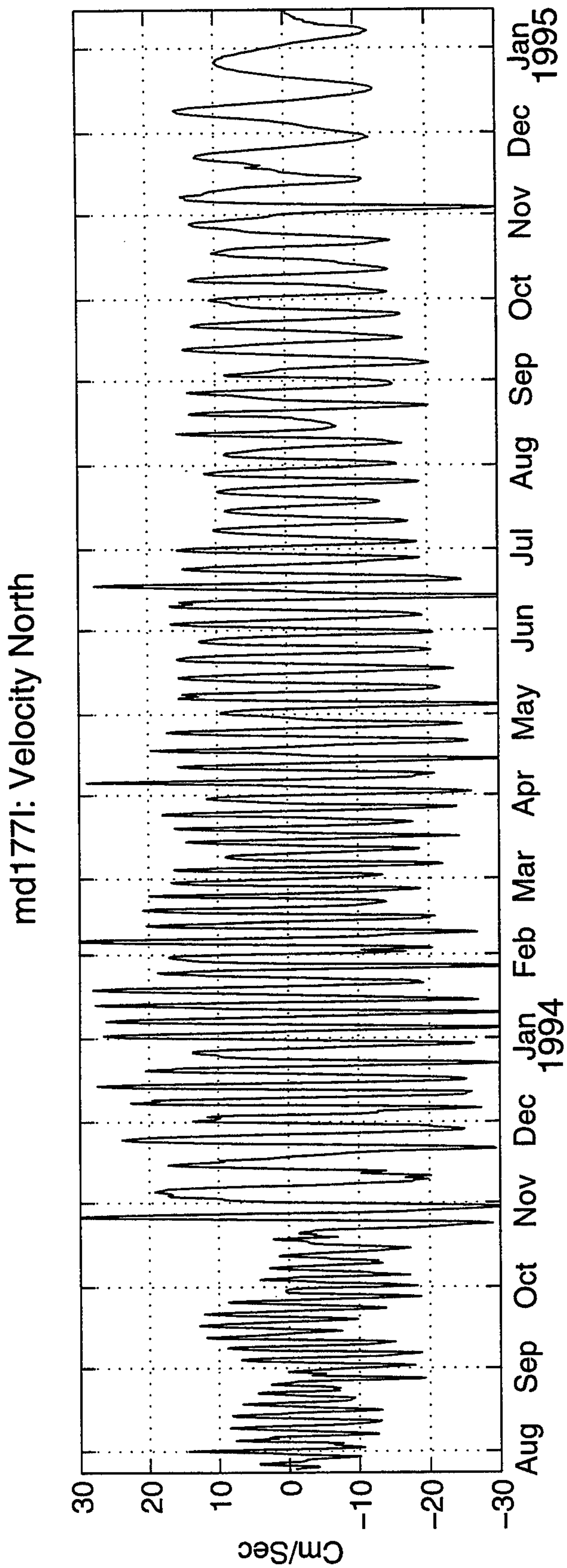
Meddy 1 Float 177 Interpolated



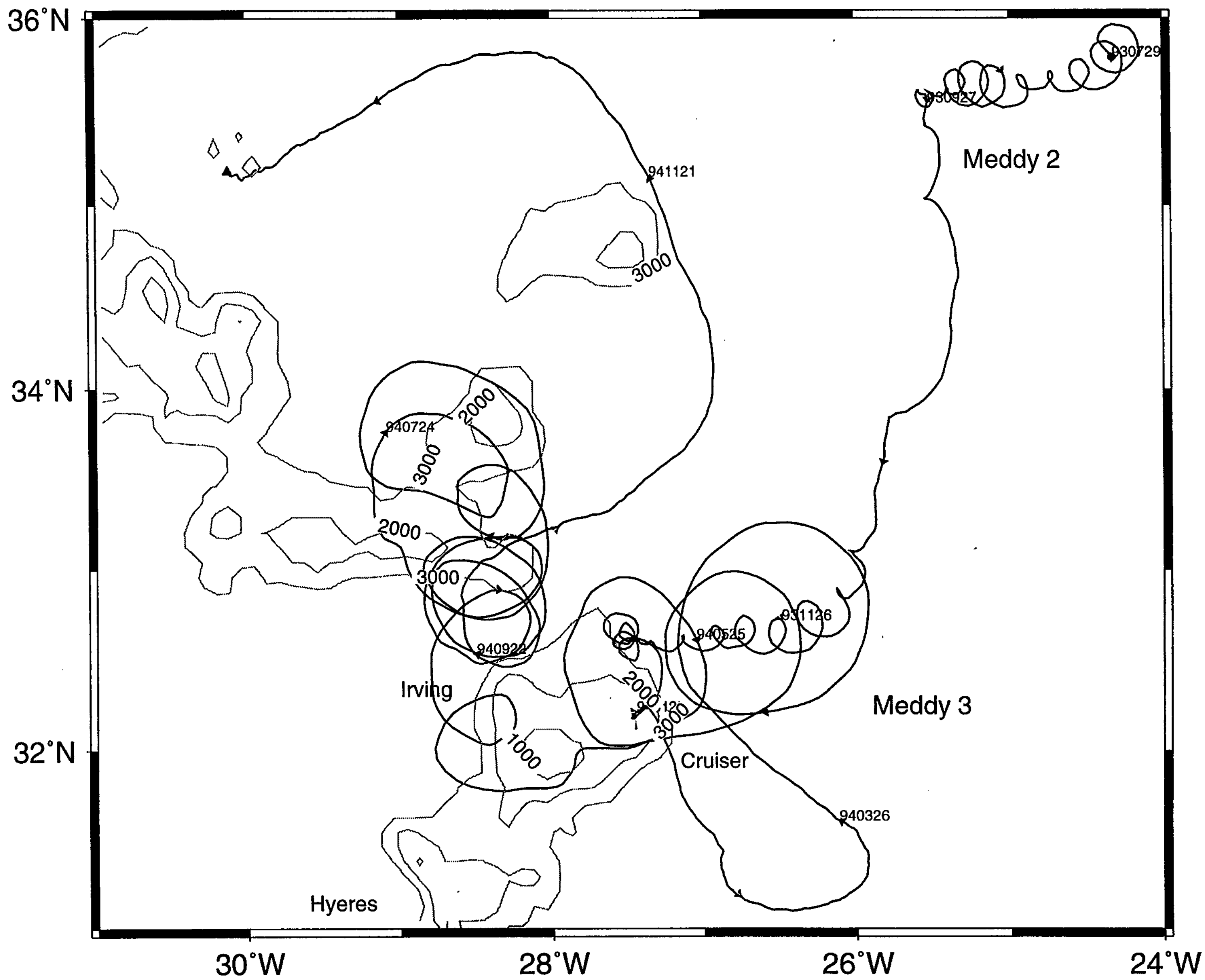
Meddy 1 Float 177 Subjective Interpolation



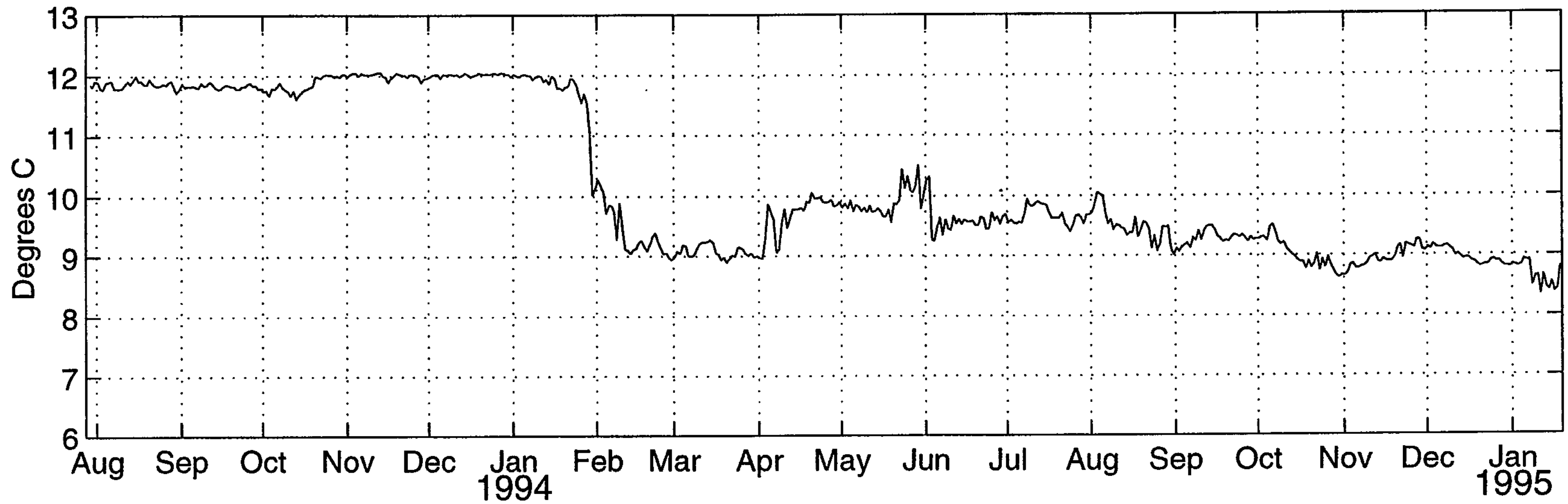

md177I: Velocity East
Cm/Sec
30
20
10
0
−10
−20
−30
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995


md177I: Velocity North
Cm/Sec
30
20
10
0
−10
−20
−30
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995

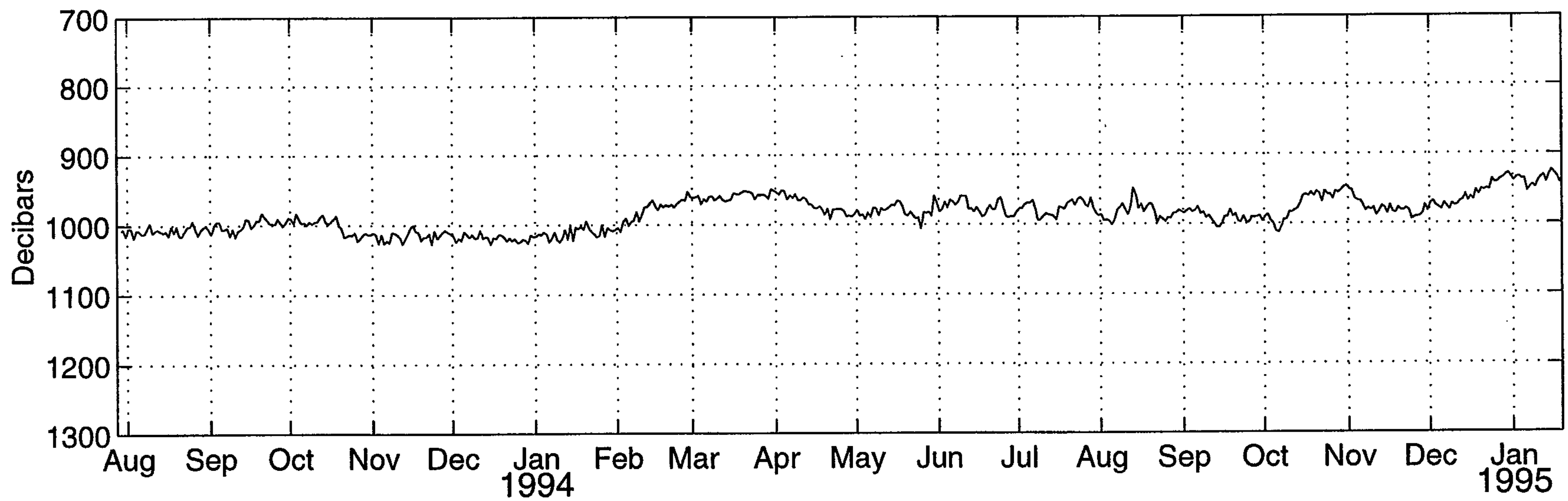
Meddy 2 and Meddy 3 Float 172

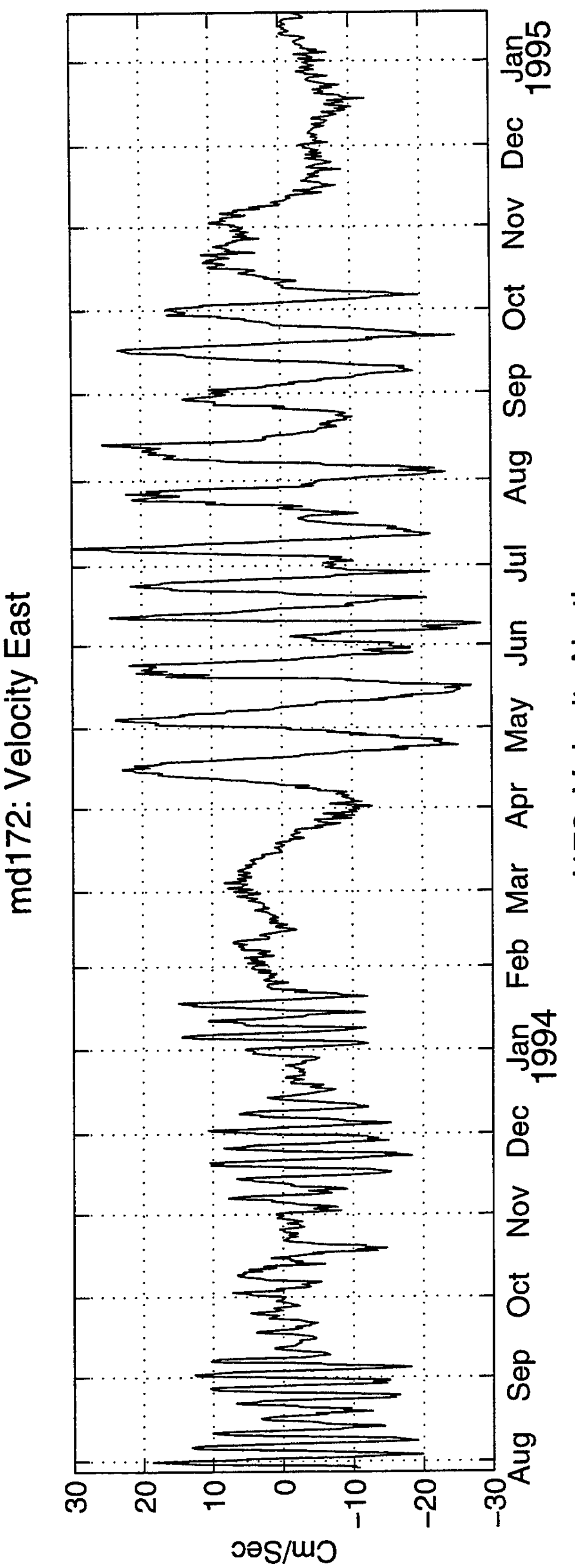


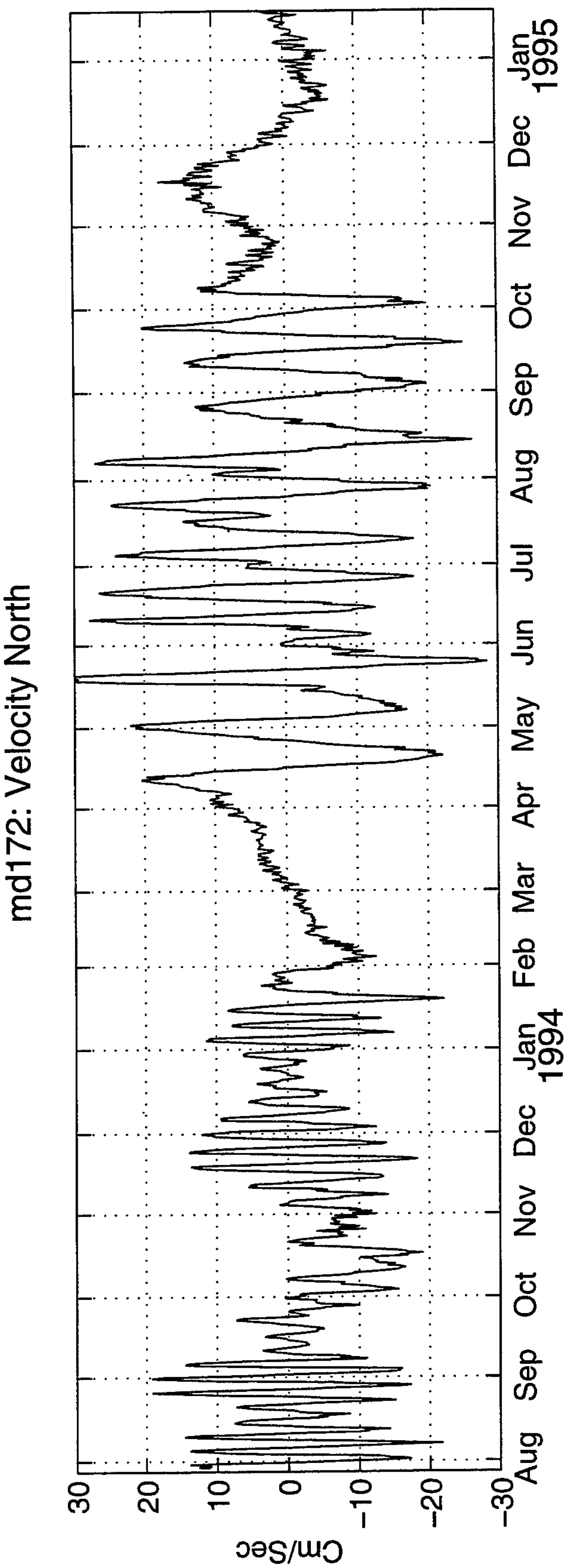
md172: Temperature



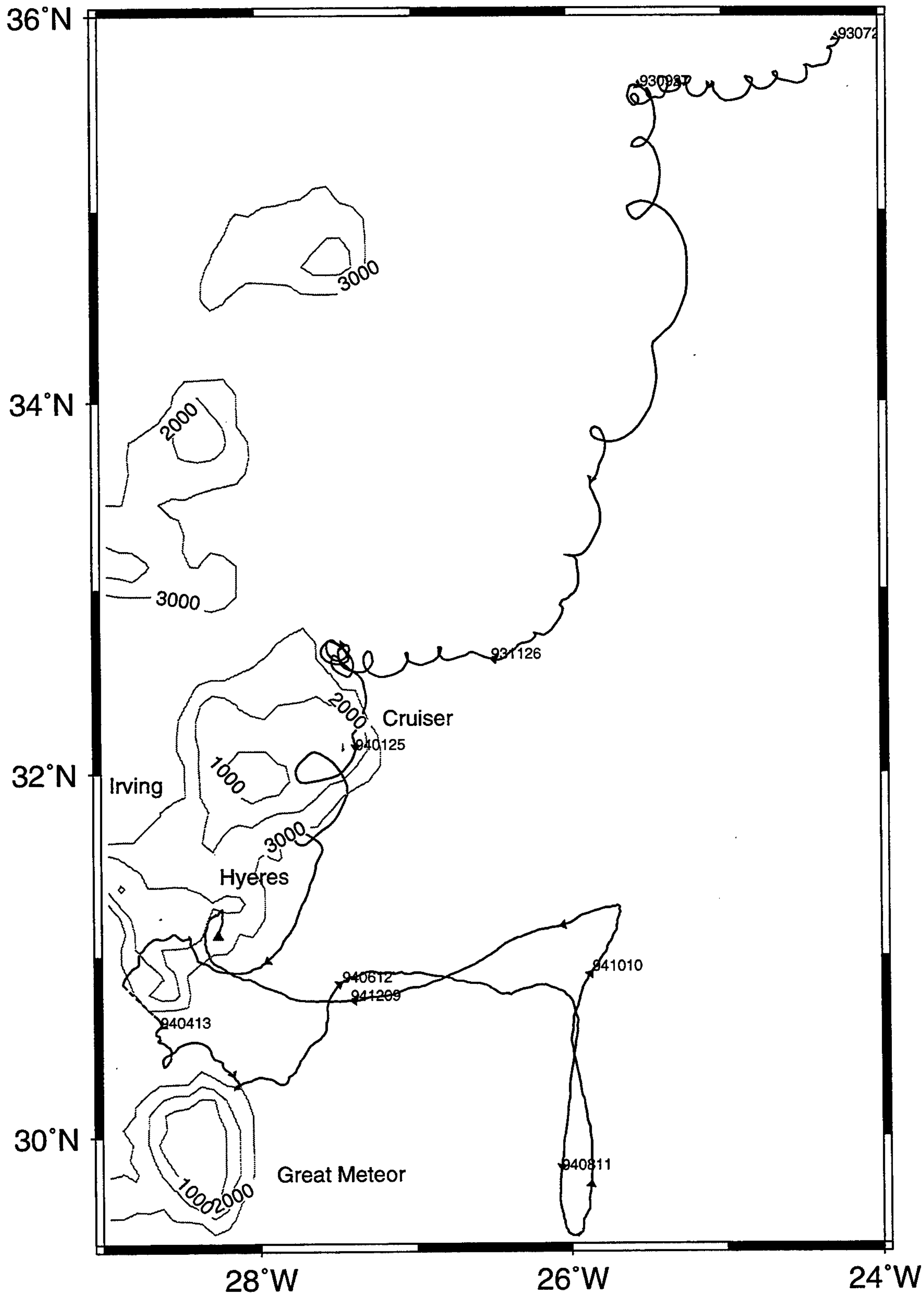
md172: Pressure



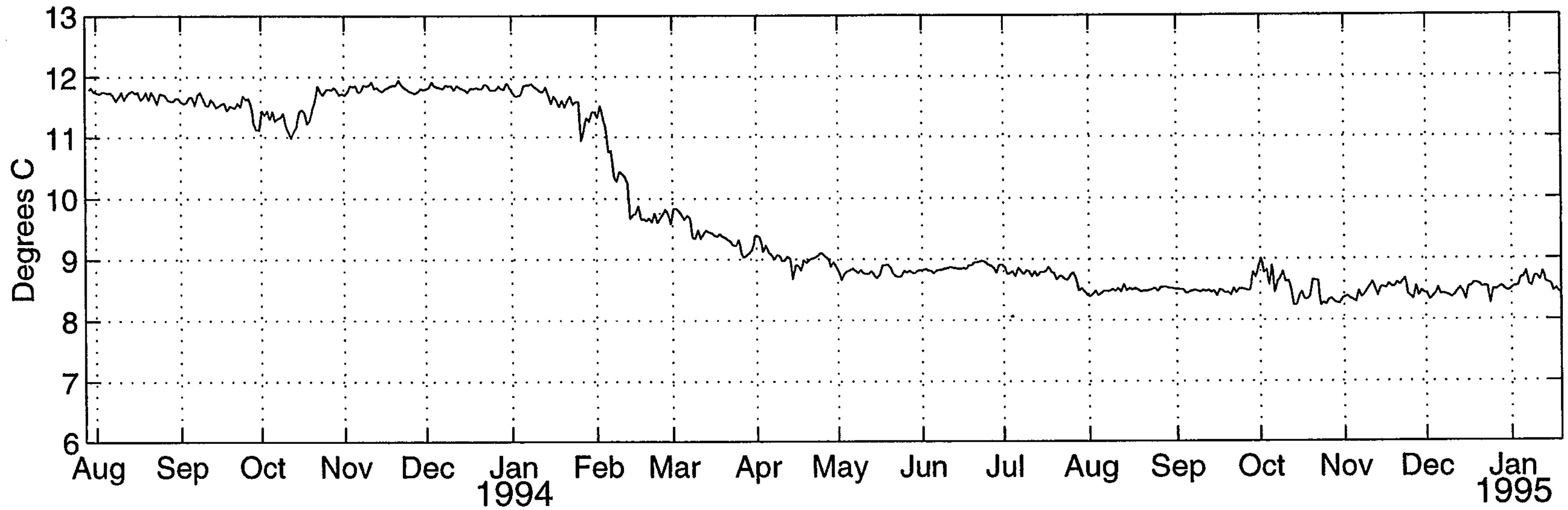

md172: Velocity East
Cm/Sec
30
20
10
0
−10
−20
−30
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995


md172: Velocity North
Cm/Sec
30
20
10
0
−10
−20
−30
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995

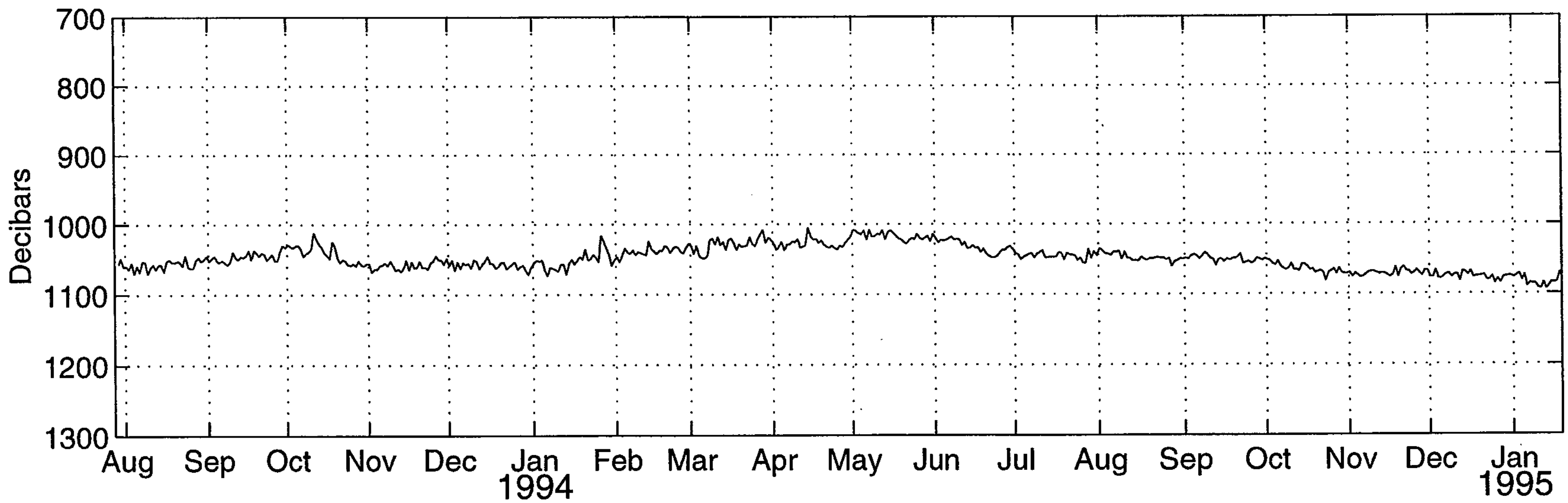
Meddy 2 Float 174

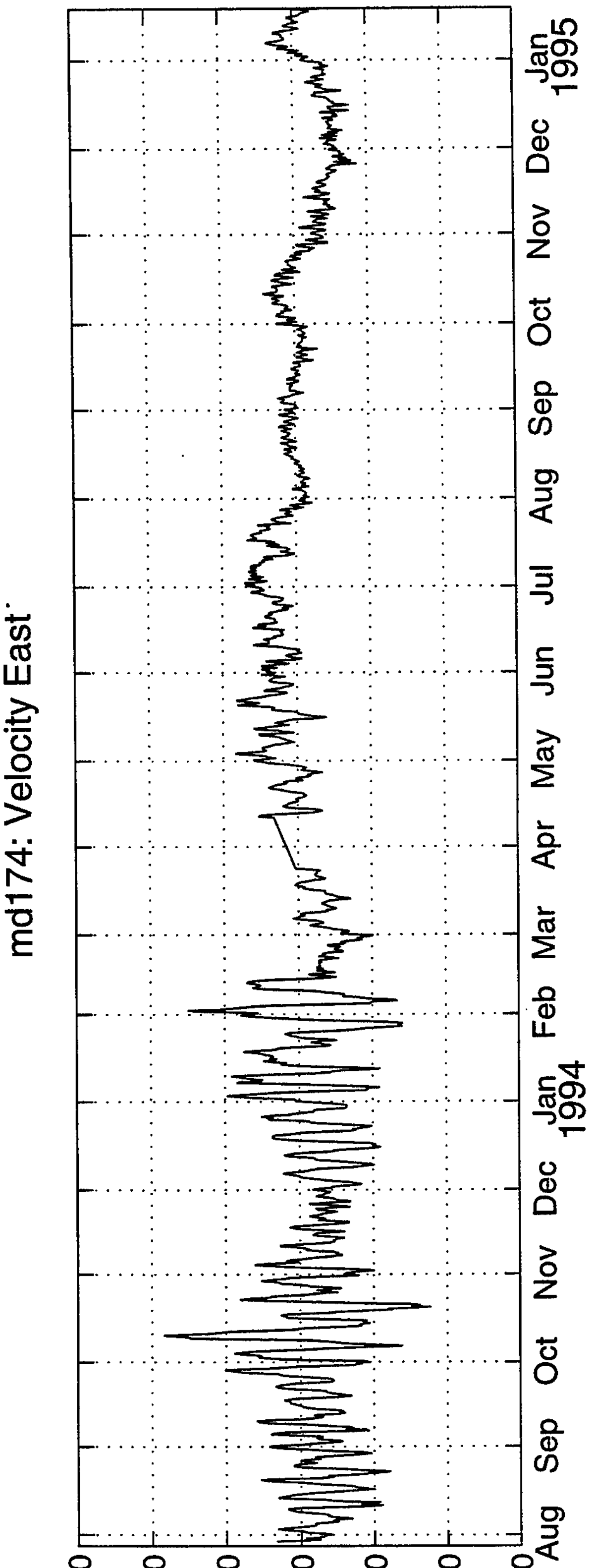


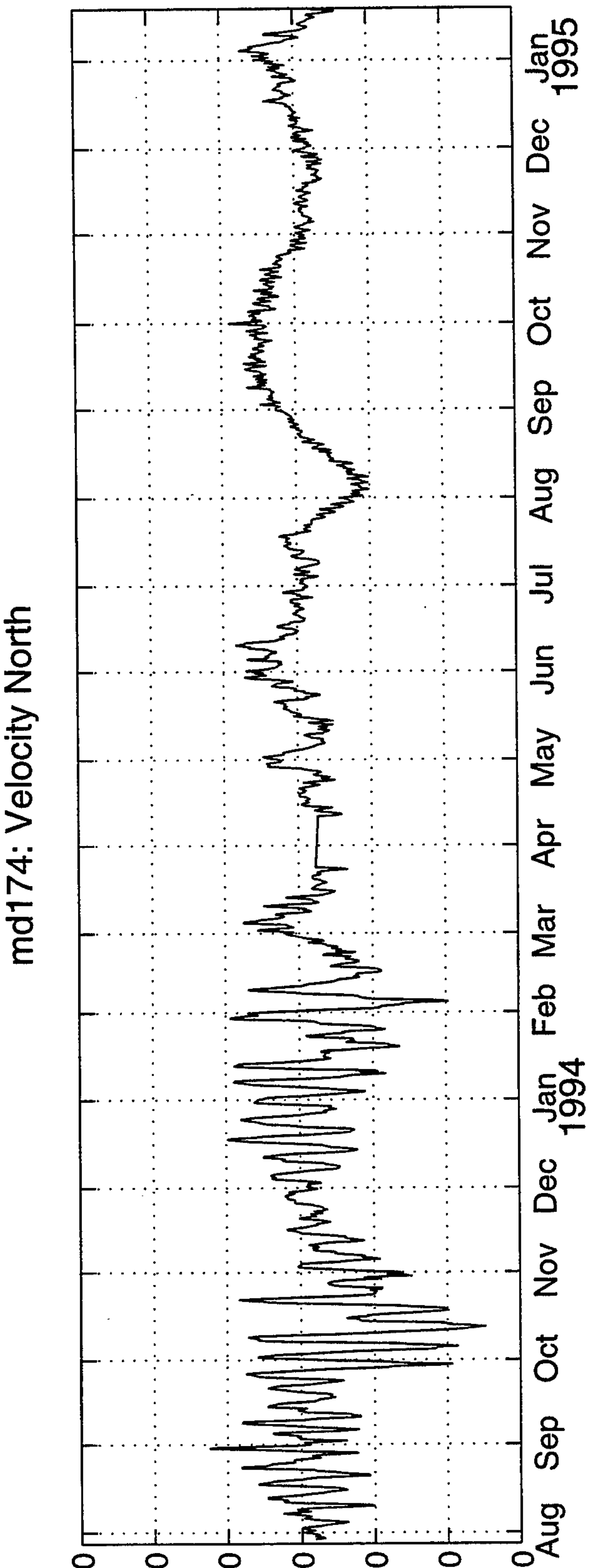
md174: Temperature



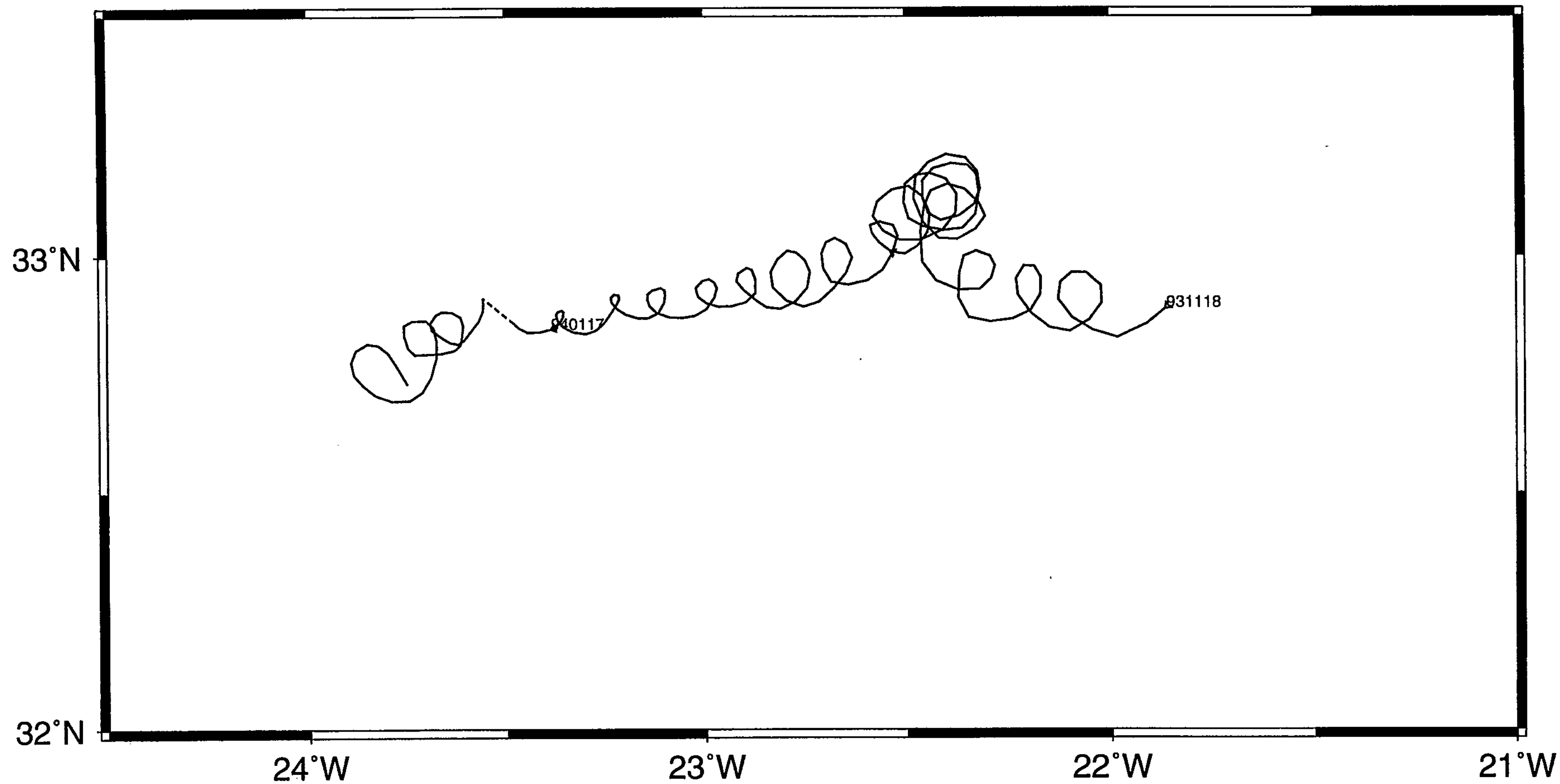
md174: Pressure



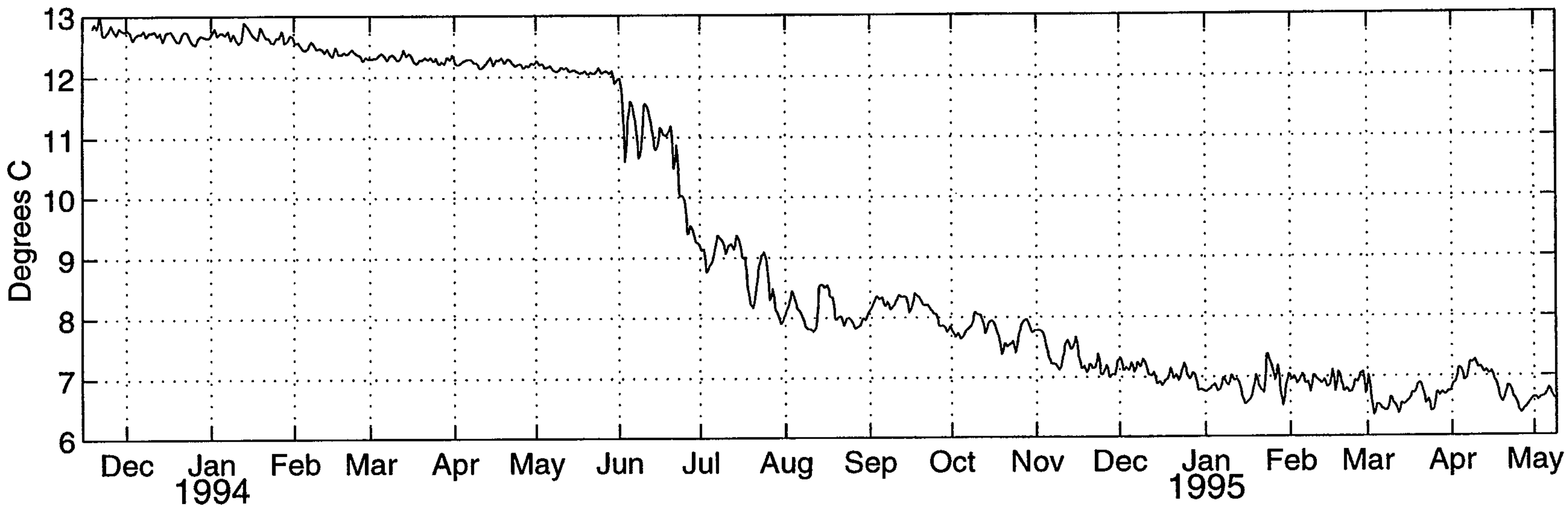

md174: Velocity East
Cm/Sec
30
20
10
0
−10
−20
−30
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995


md174: Velocity North
Cm/Sec
30
20
10
0
−10
−20
−30
Aug
Sep
Oct
Nov
Dec
Jan
1994
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995

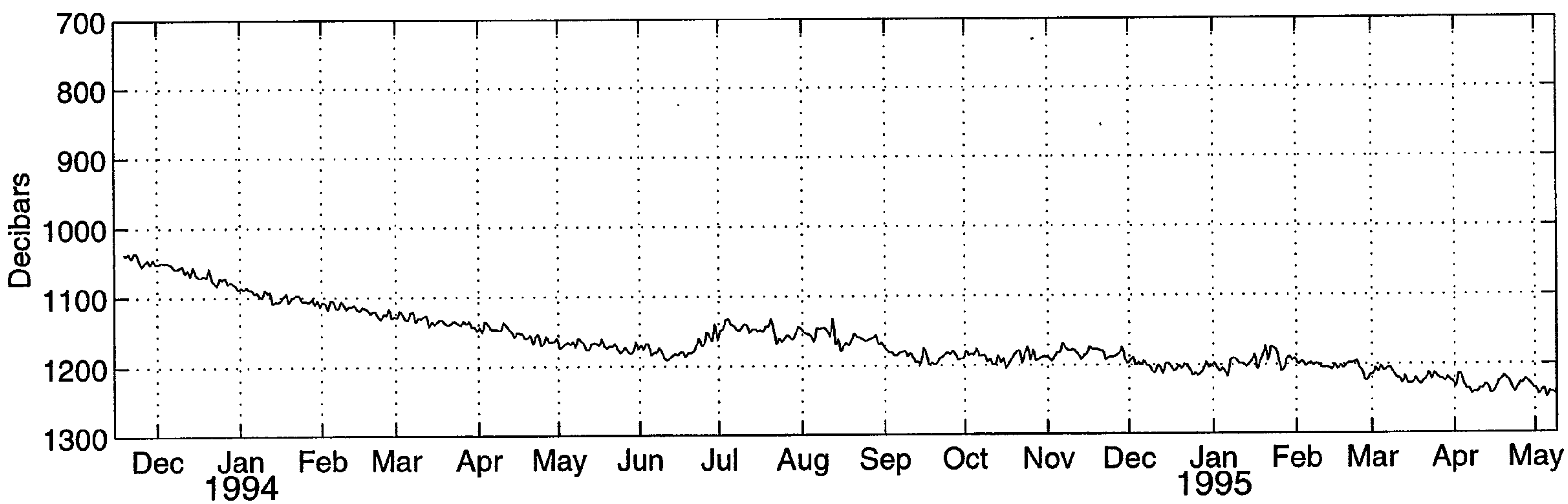
Meddy 3 Float 168



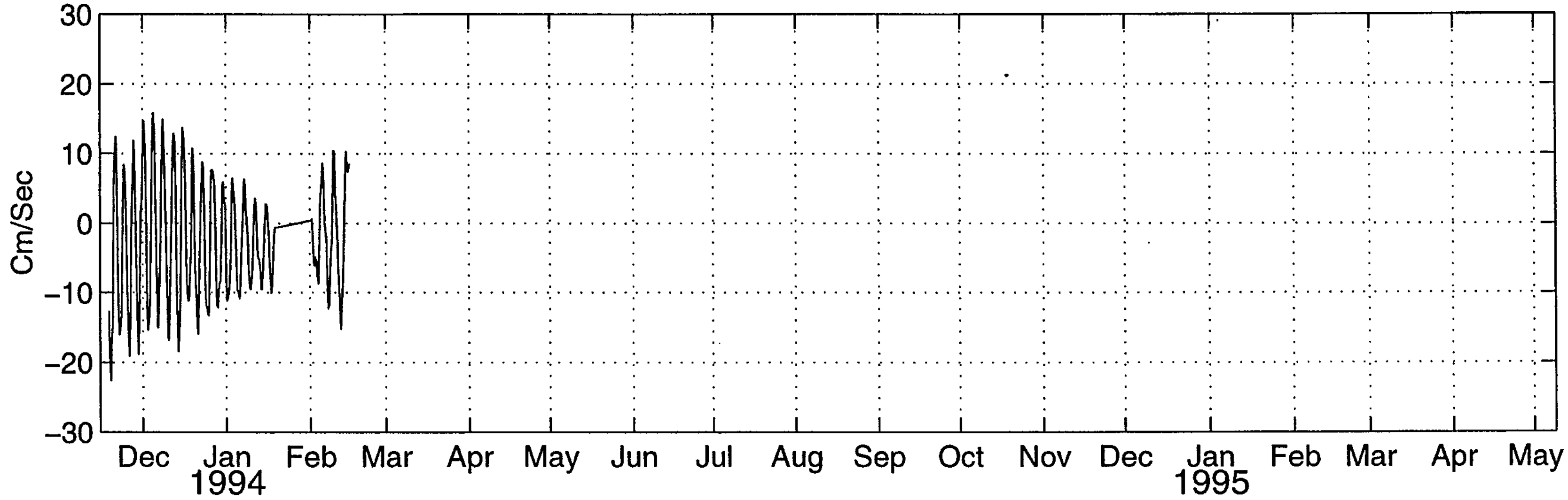
md168: Temperature



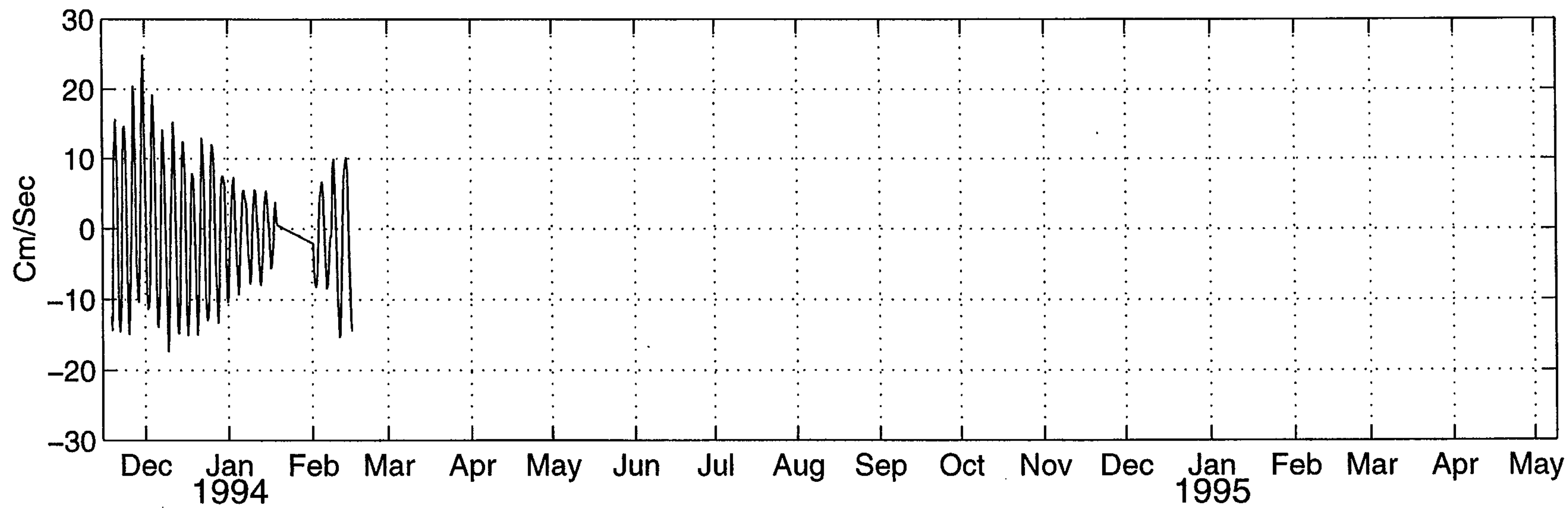
md168: Pressure



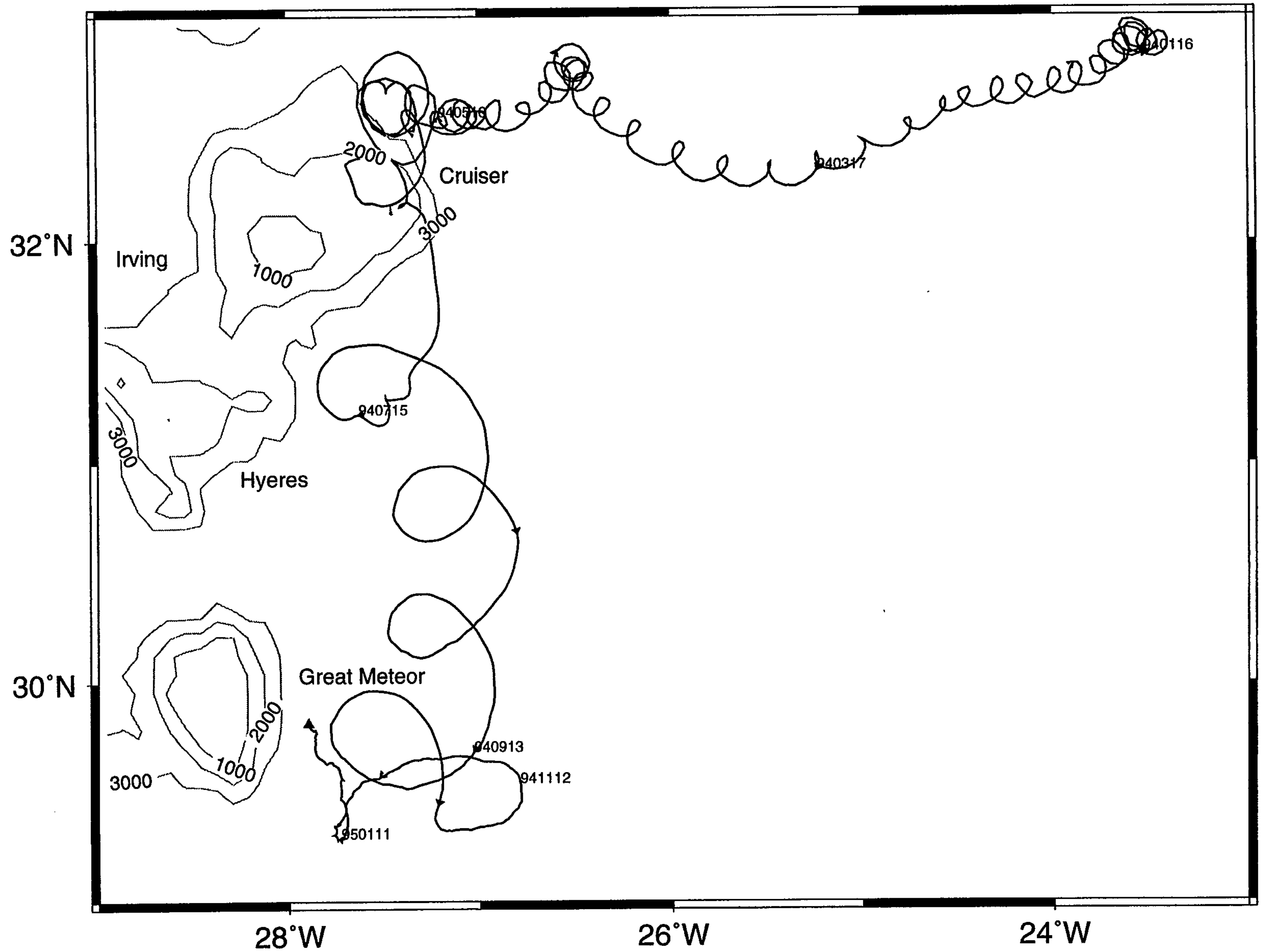
md168: Velocity East



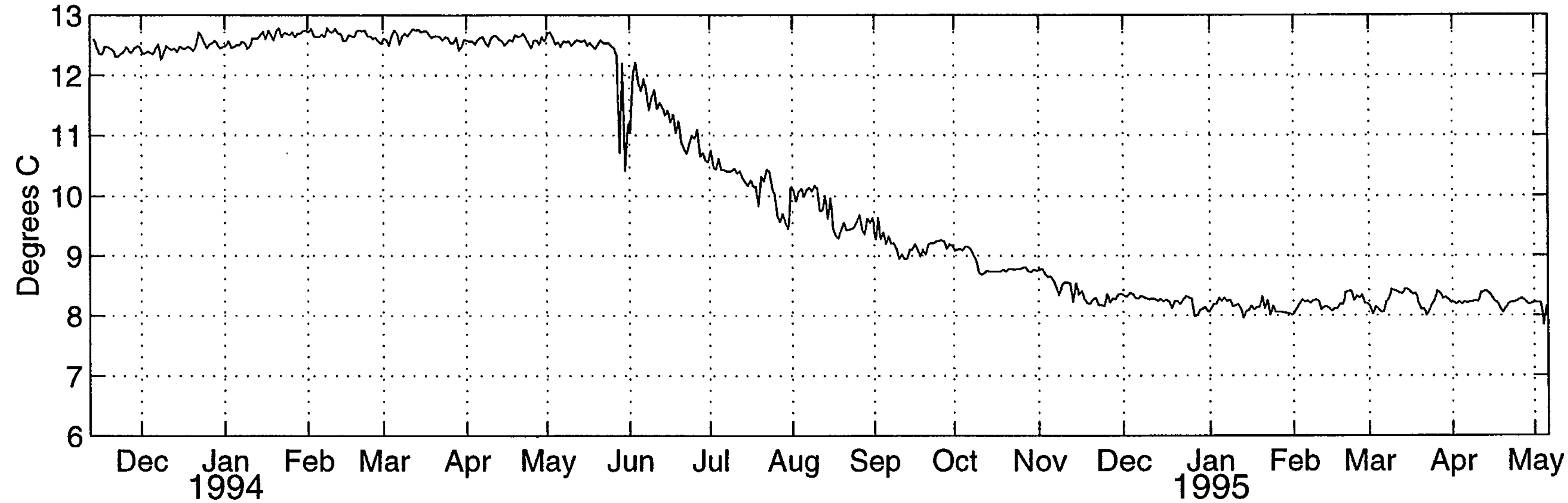
md168: Velocity North



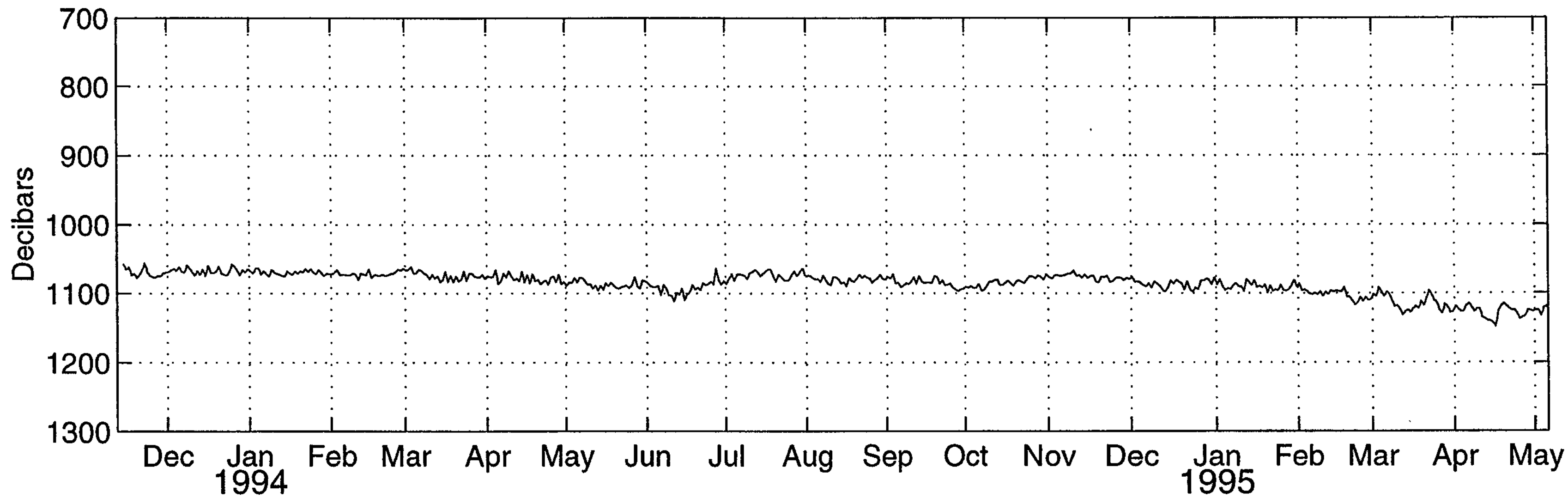
Meddy 3 Float 173



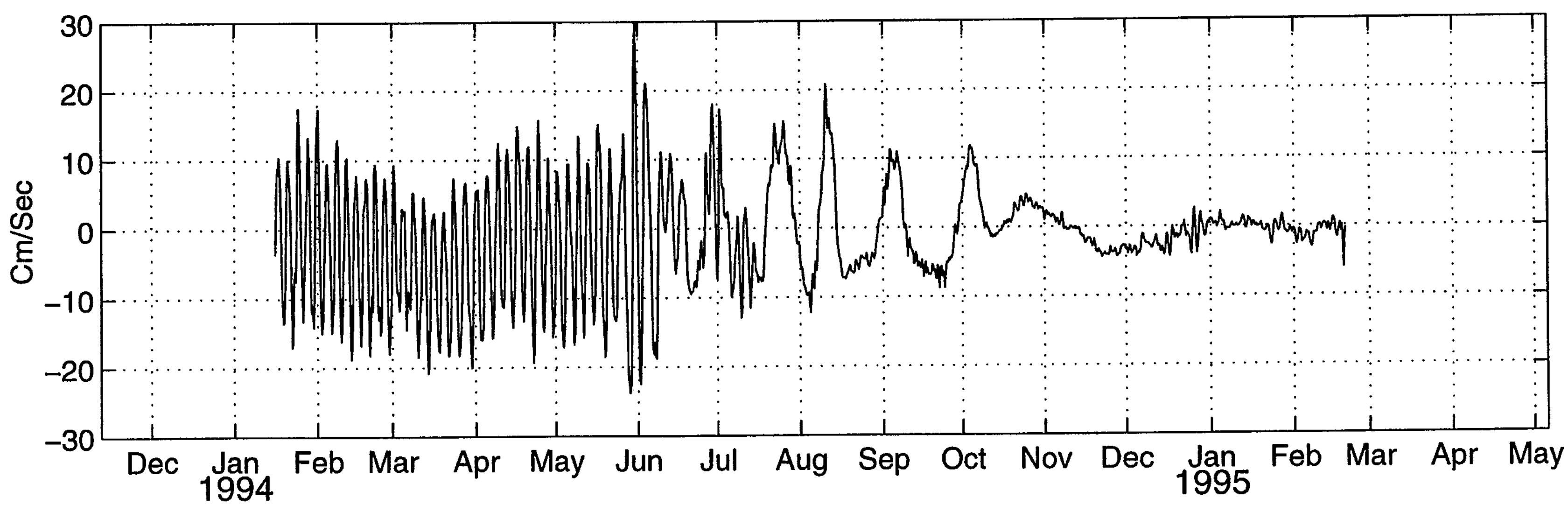
md173: Temperature



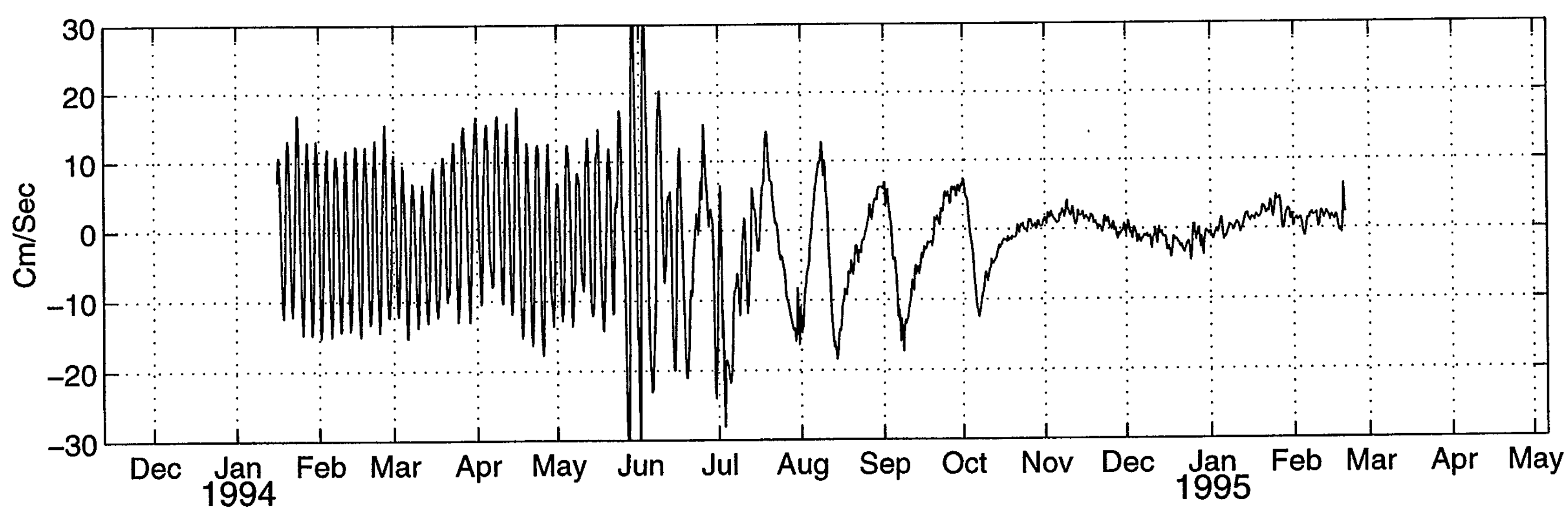
md173: Pressure



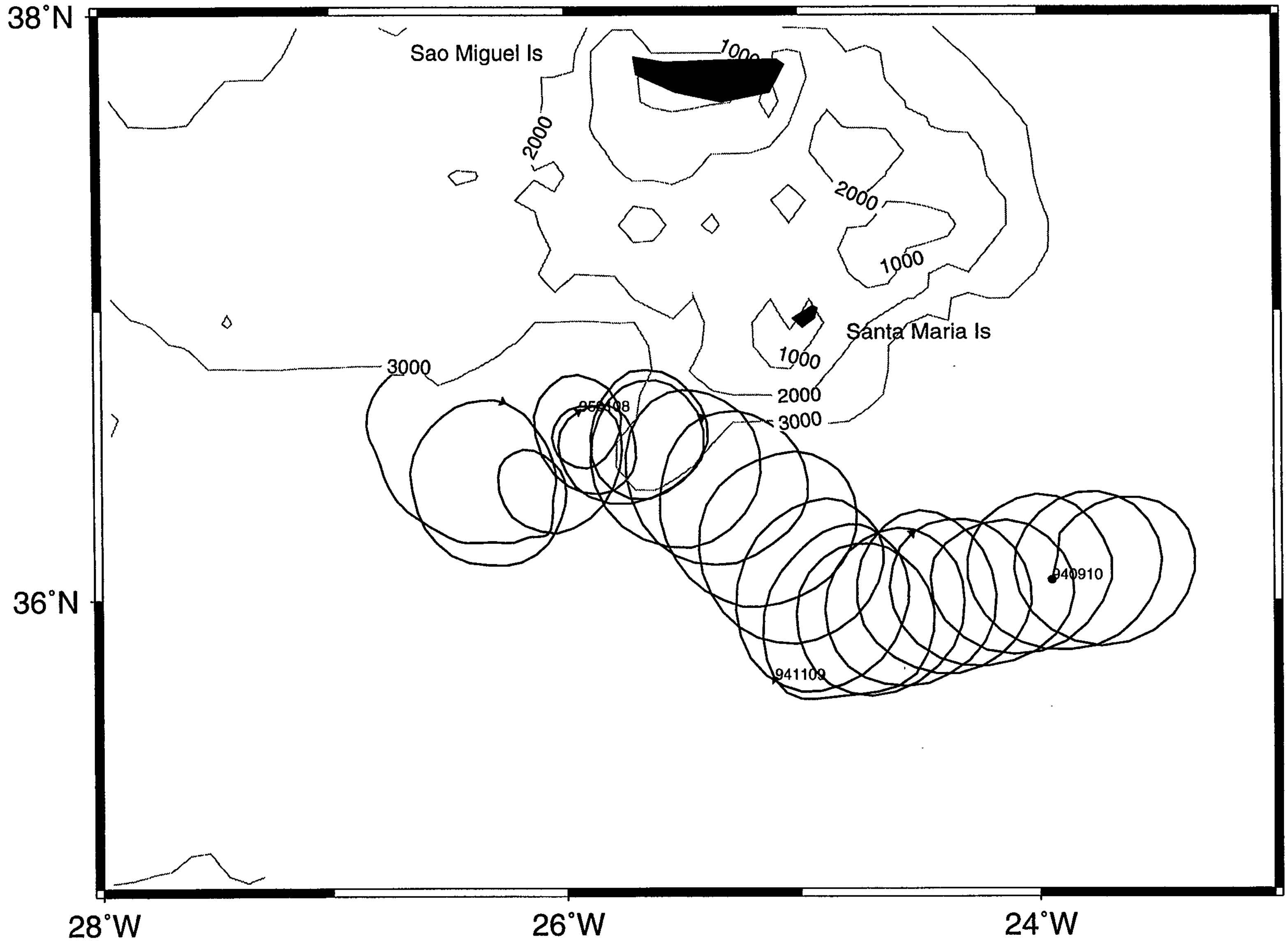
md173: Velocity East

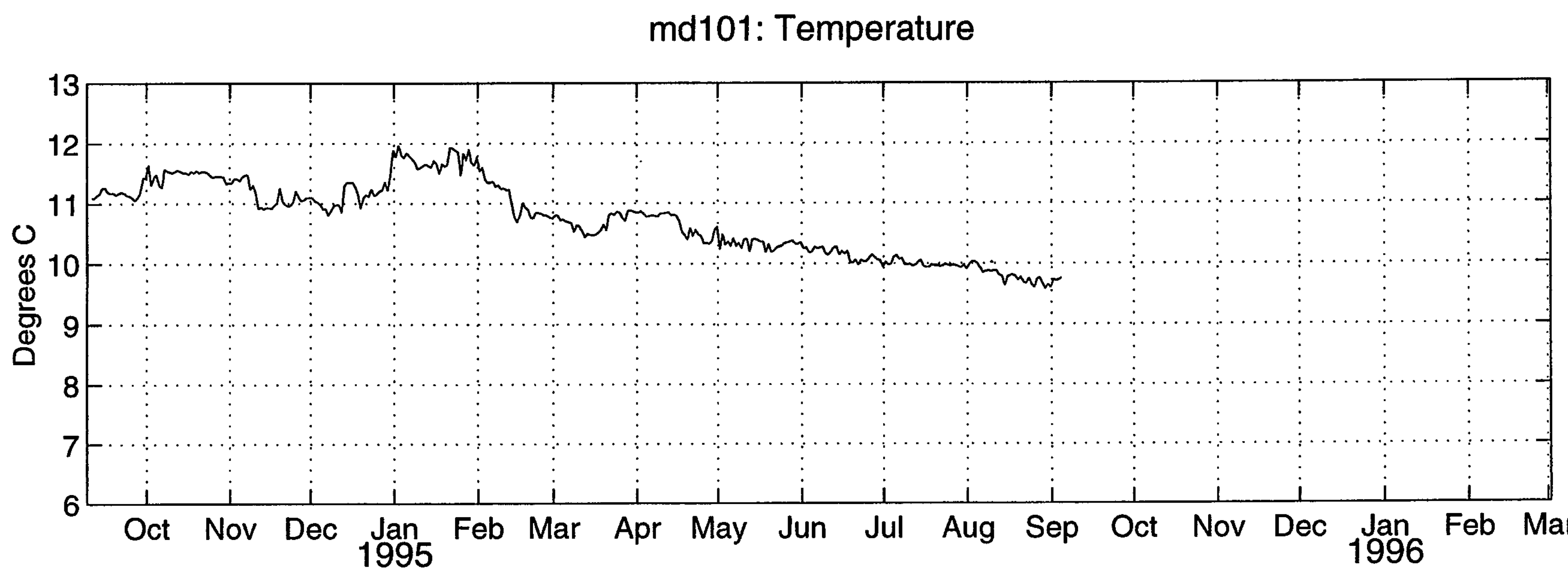


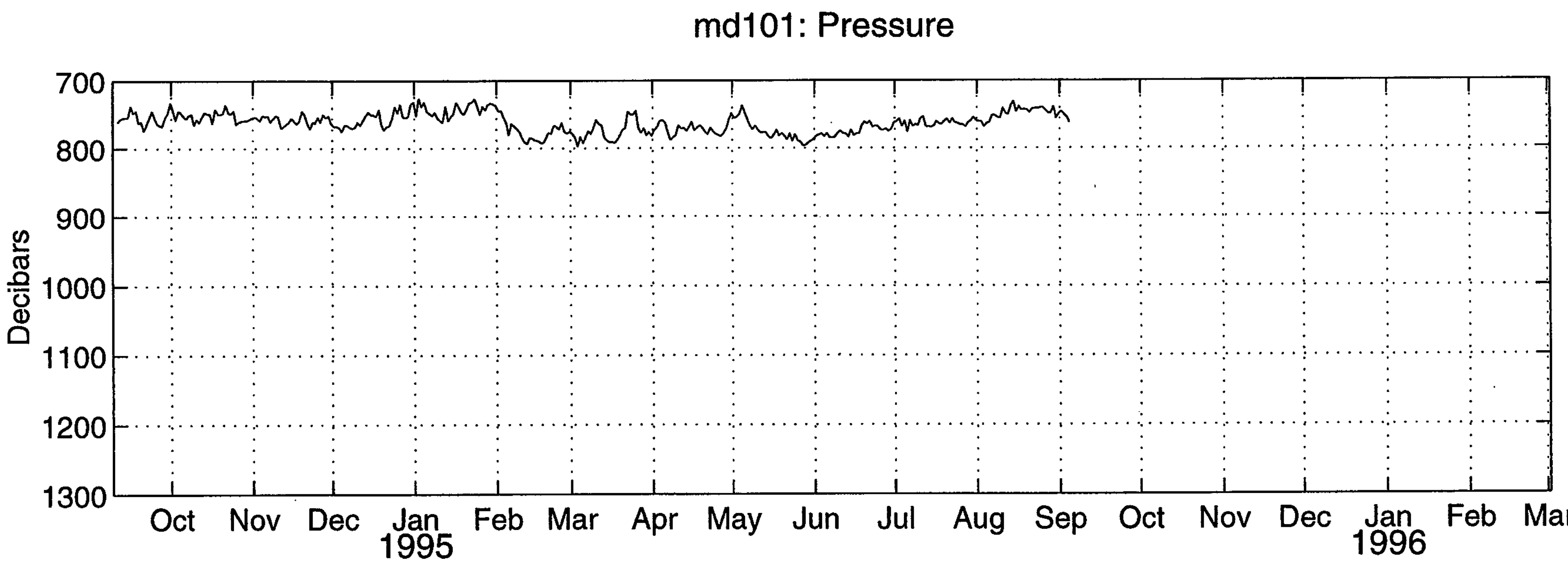
md173: Velocity North



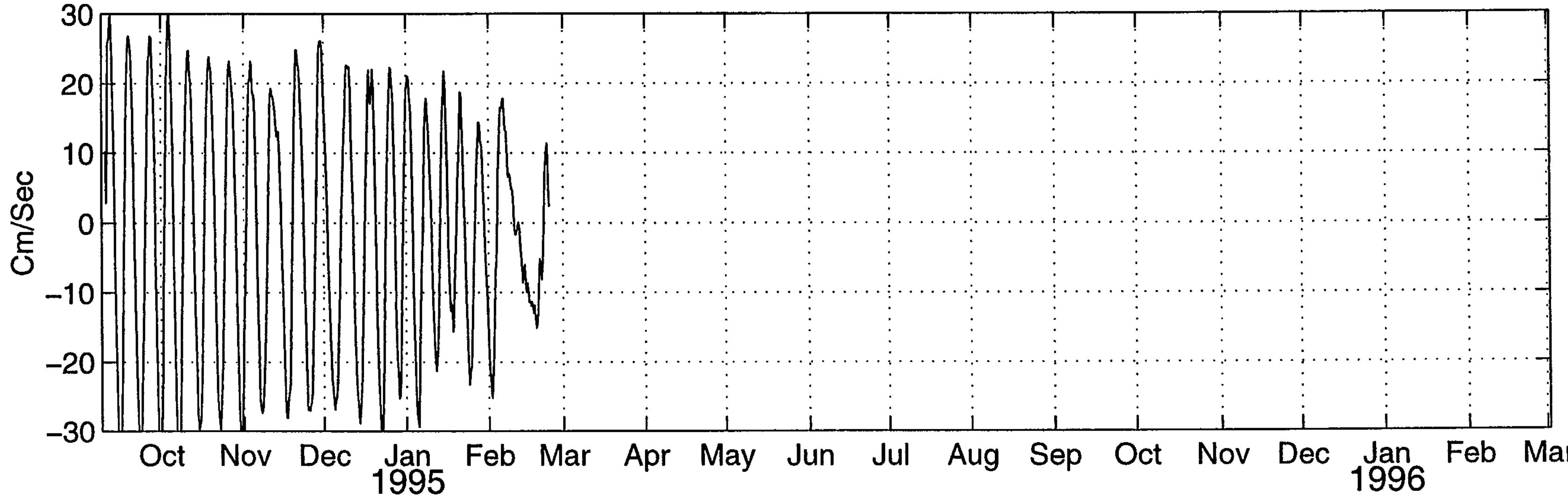
Meddy 4 Float 101



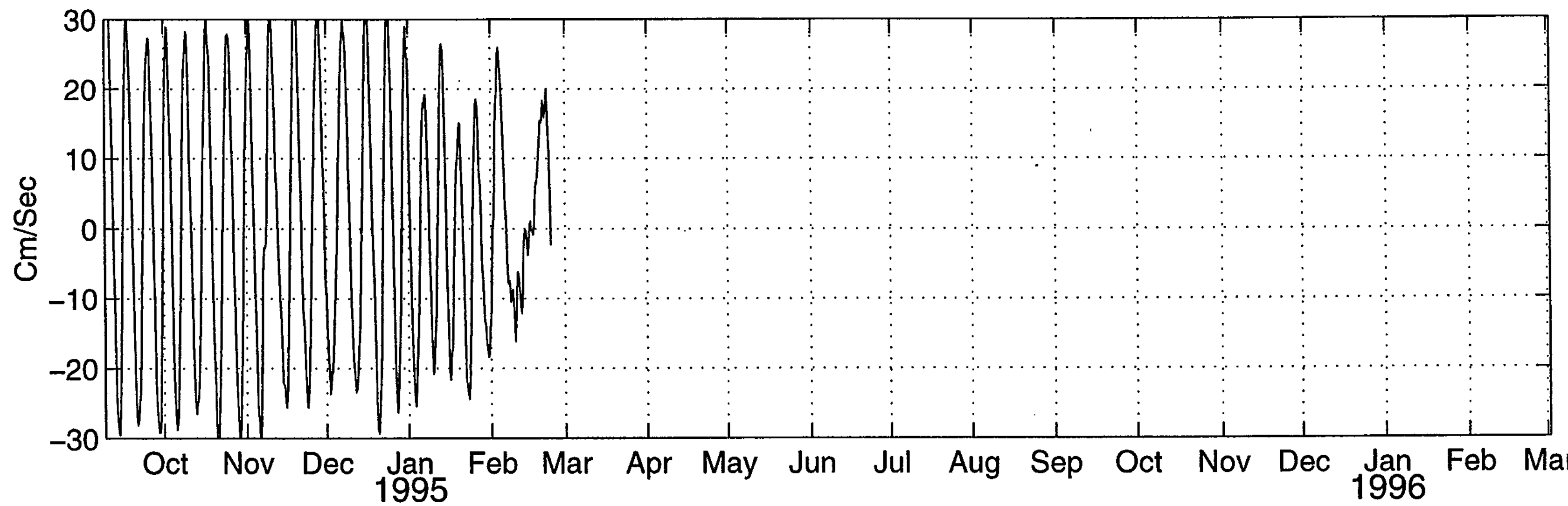

md101: Temperature
Degrees C
13
12
11
10
9
8
7
6
Oct
Nov
Dec
Jan
1995
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1996
Feb
Mar

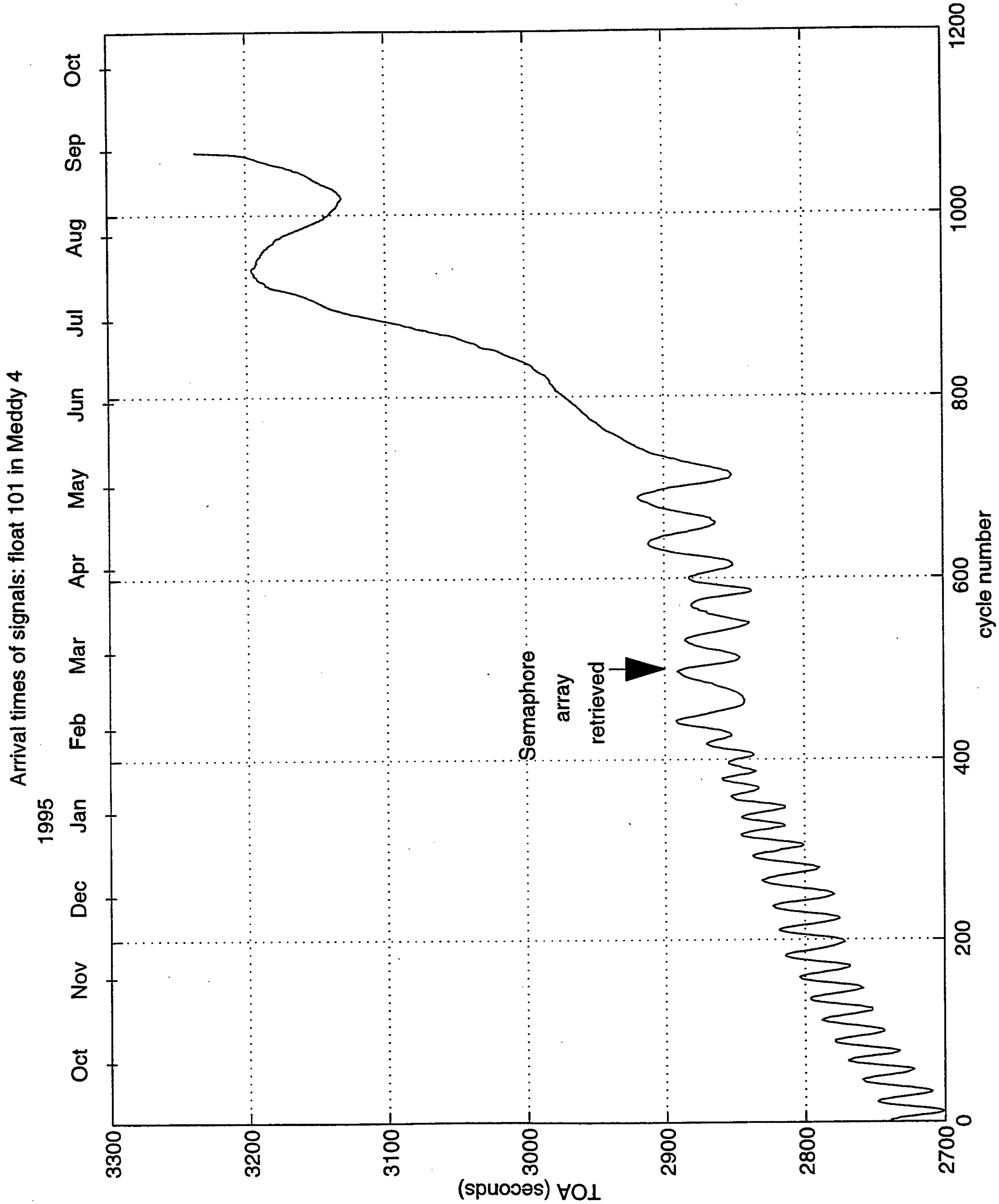

md101: Pressure
Decibars
700
800
900
1000
1100
1200
1300
Oct
Nov
Dec
Jan
1995
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1996
Feb
Mar

md101: Velocity East



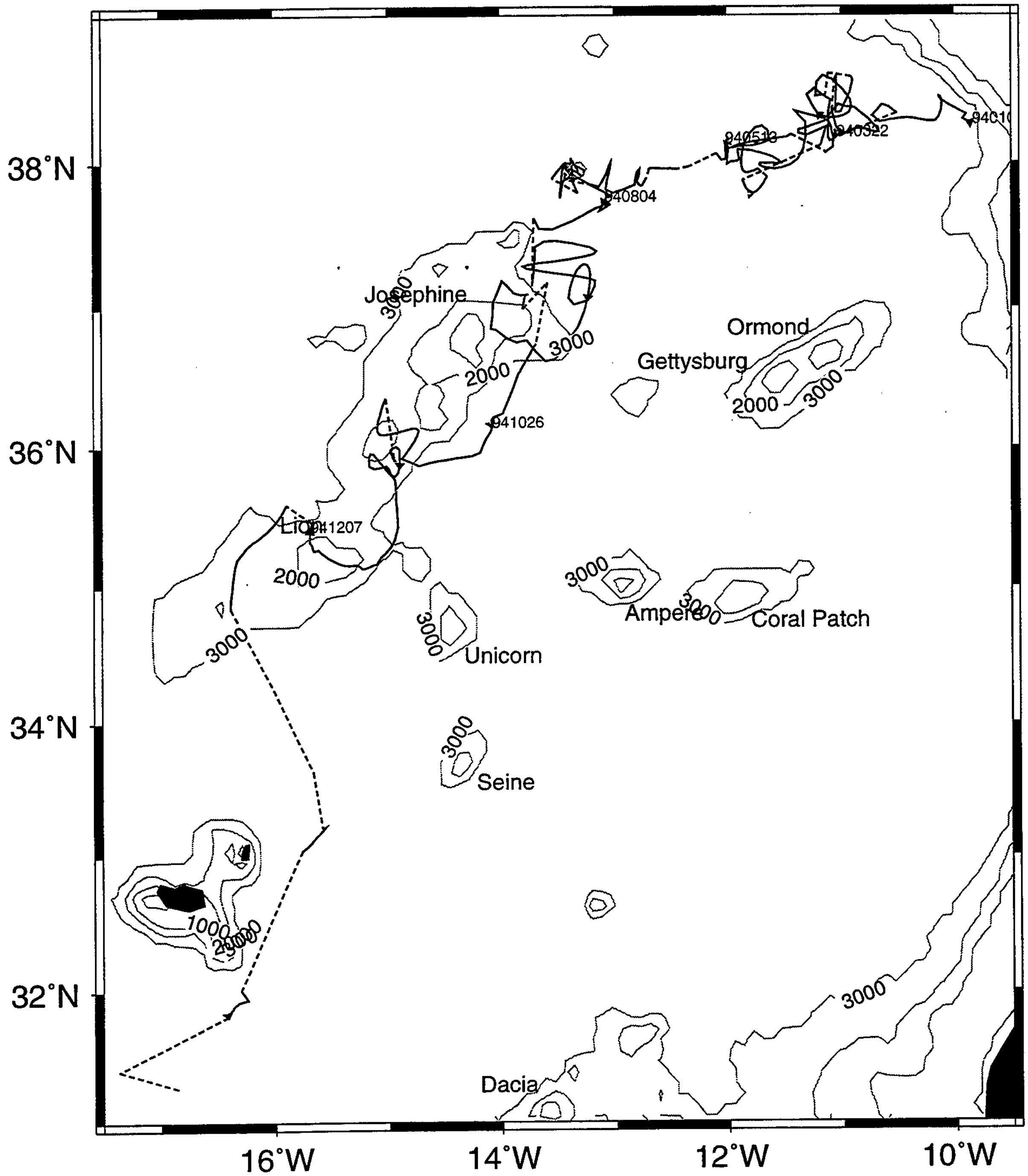
md101: Velocity North

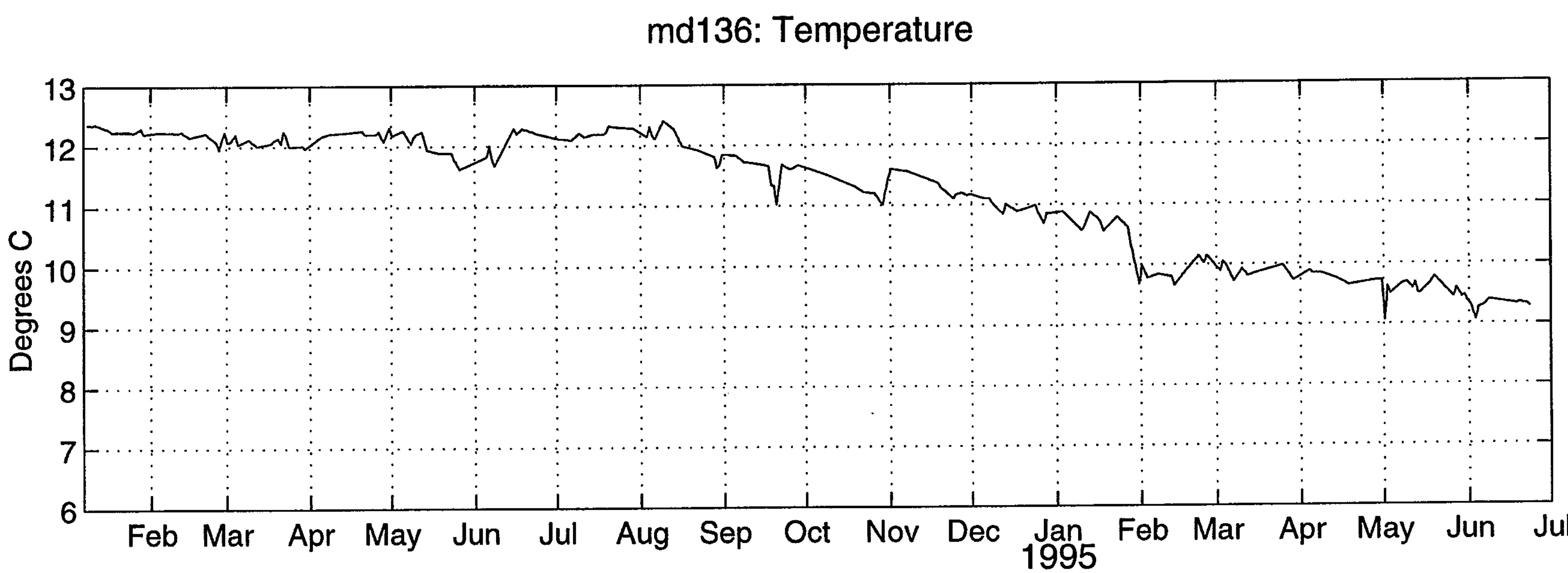




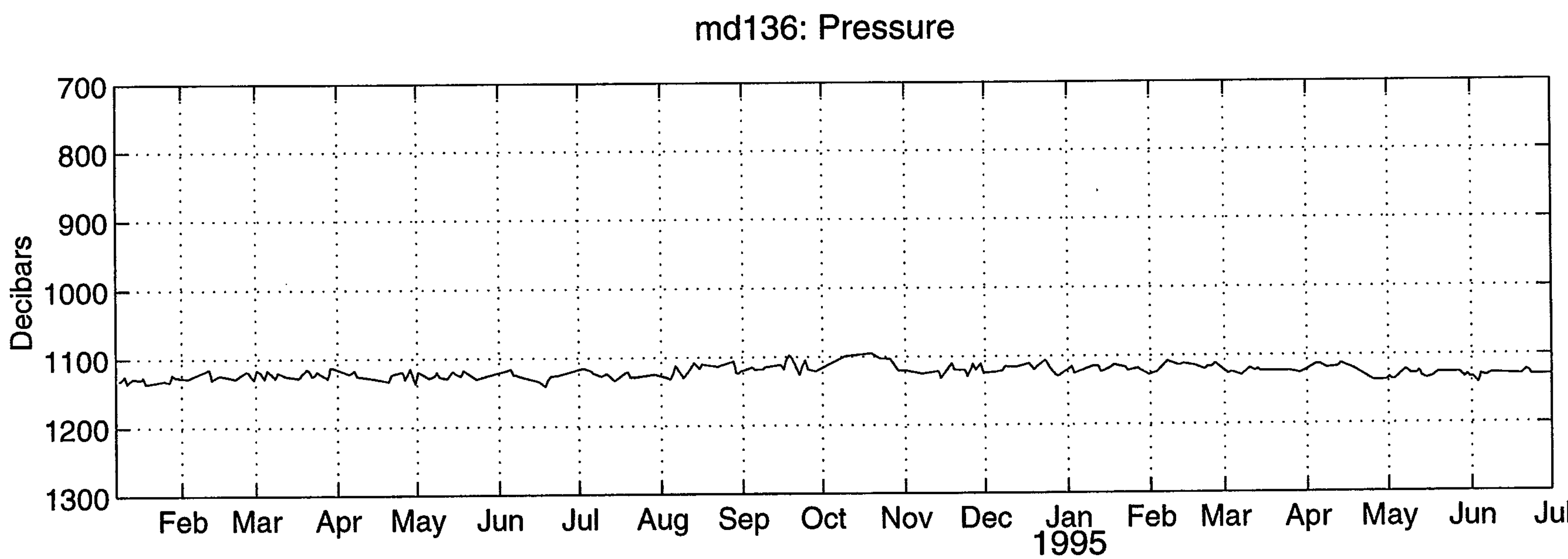
Arrival times of signals: float 101 in Meddy 4
1995
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
3300
3200
3100
3000
2900
2800
2700
TOA (seconds)
0
200
400
600
800
1000
1200
cycle number
Semaphore
array
retrieved

Meddy 5 Float 136

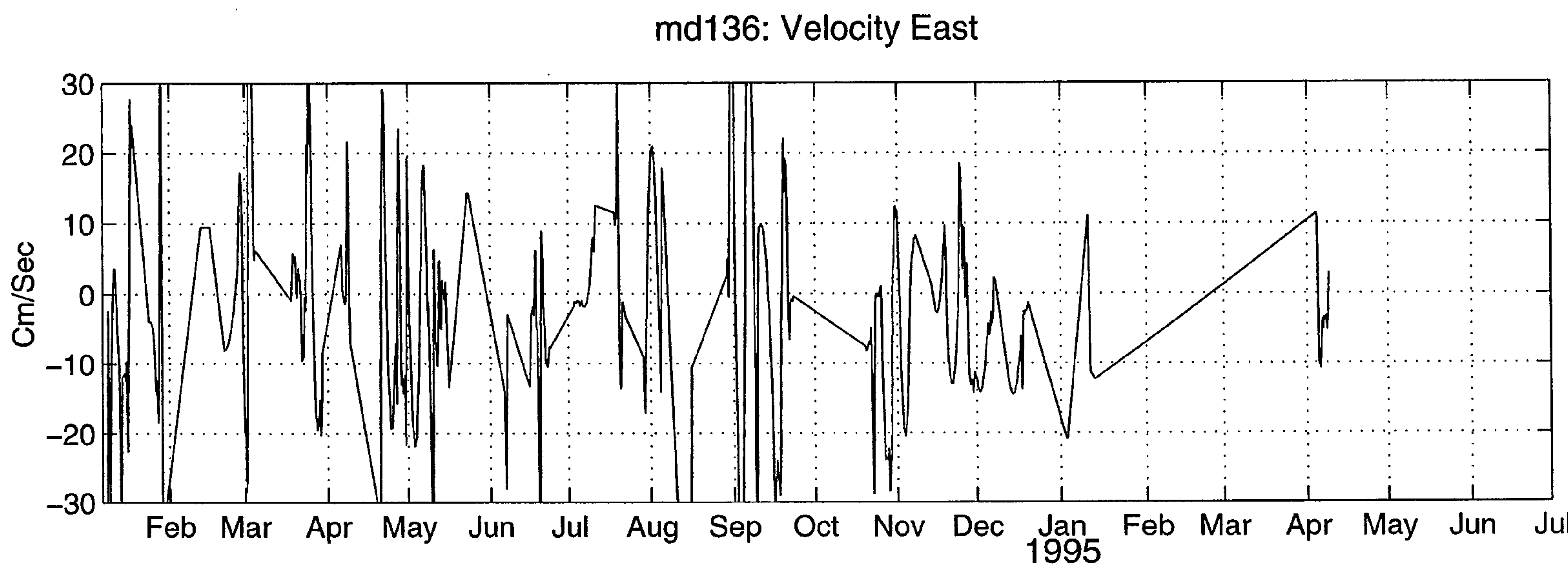


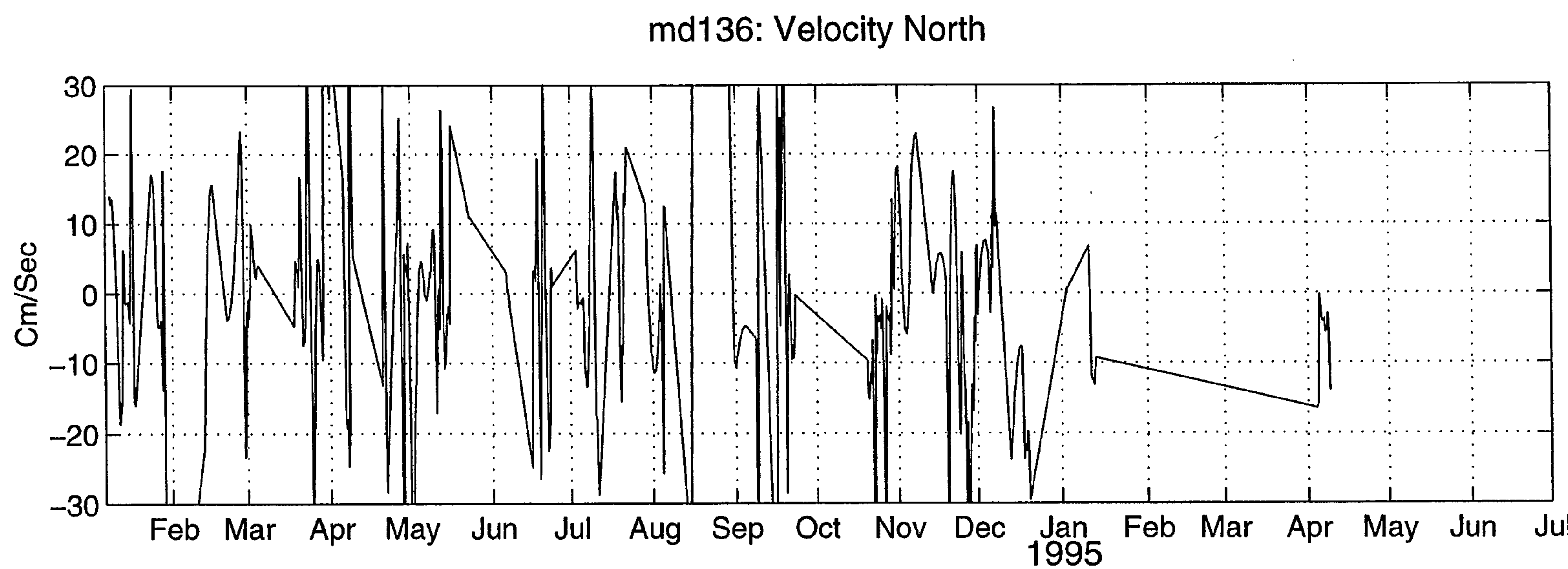


md136: Temperature
Degrees C
13
12
11
10
9
8
7
6
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995
Feb
Mar
Apr
May
Jun
Jul

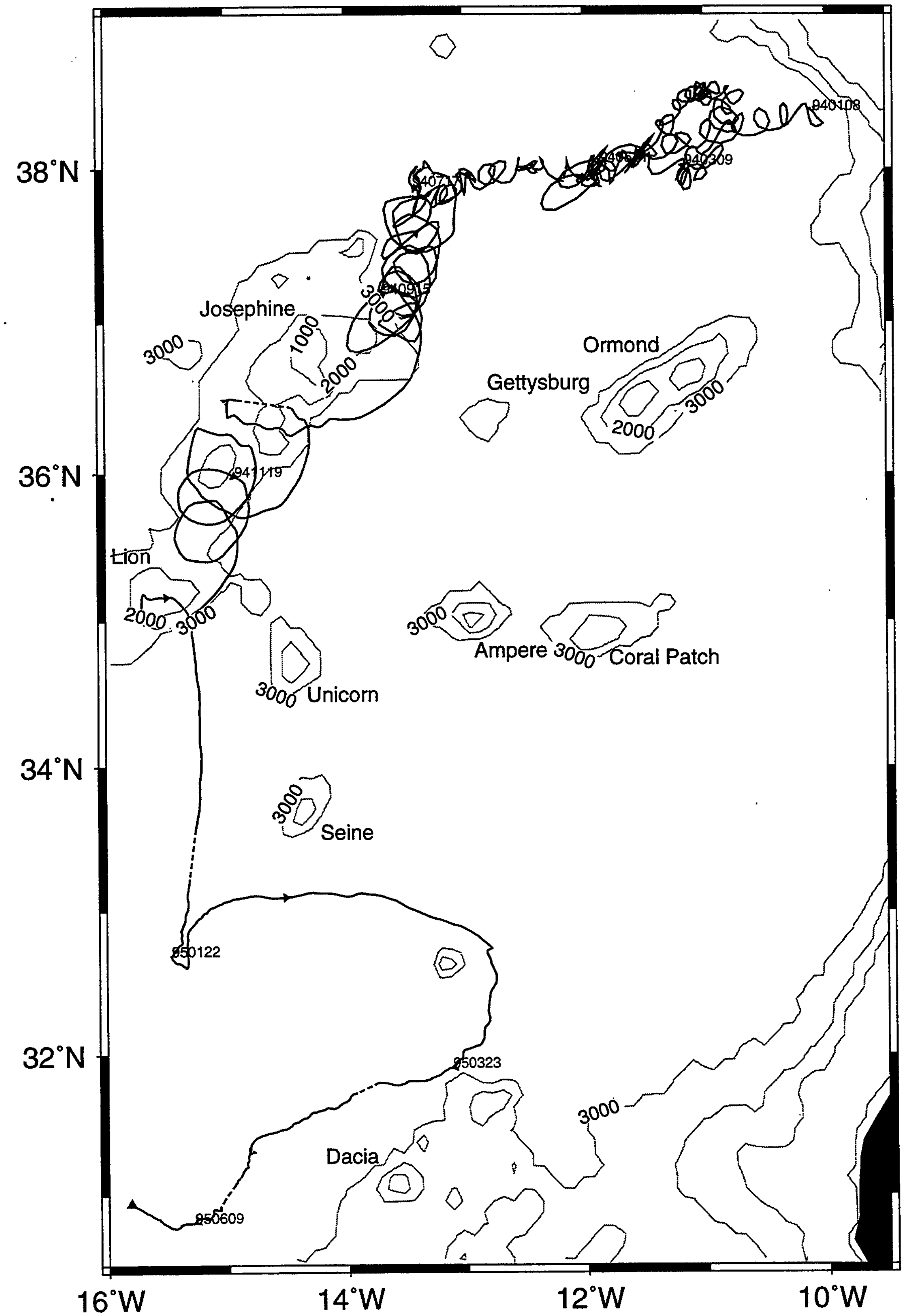


md136: Pressure
Decibars
700
800
900
1000
1100
1200
1300
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995
Feb
Mar
Apr
May
Jun
Jul

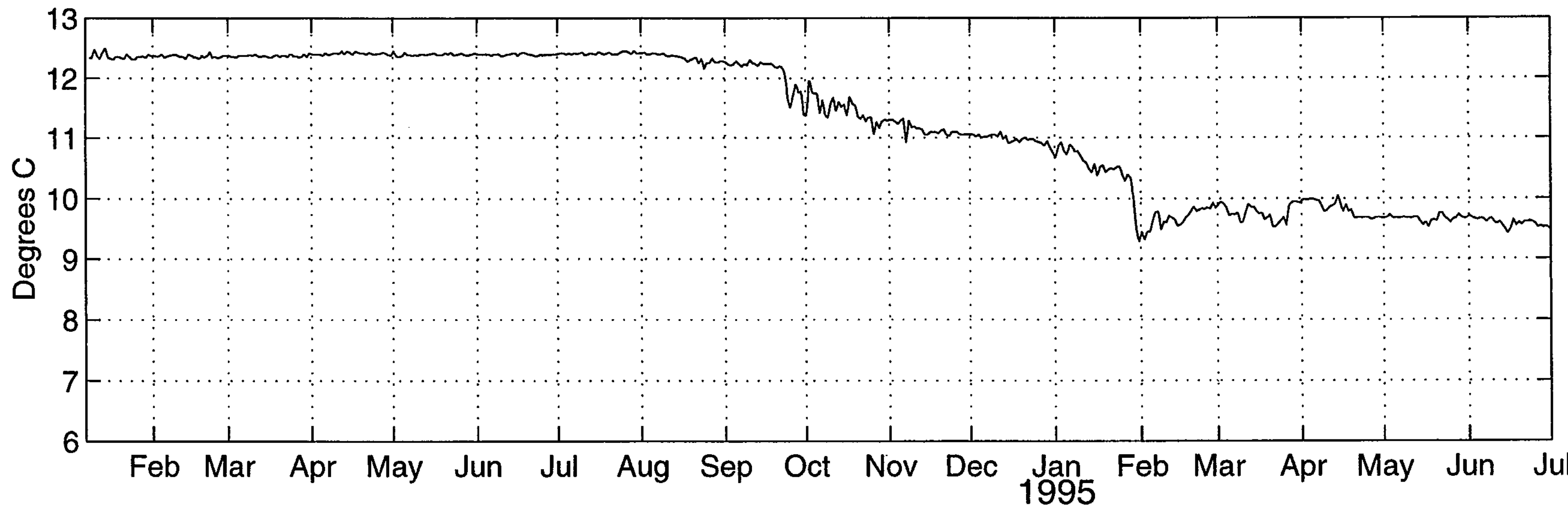

md136: Velocity East
Cm/Sec
30
20
10
0
−10
−20
−30
Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul
1995


md136: Velocity North
Cm/Sec
30
20
10
0
−10
−20
−30
Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul
1995

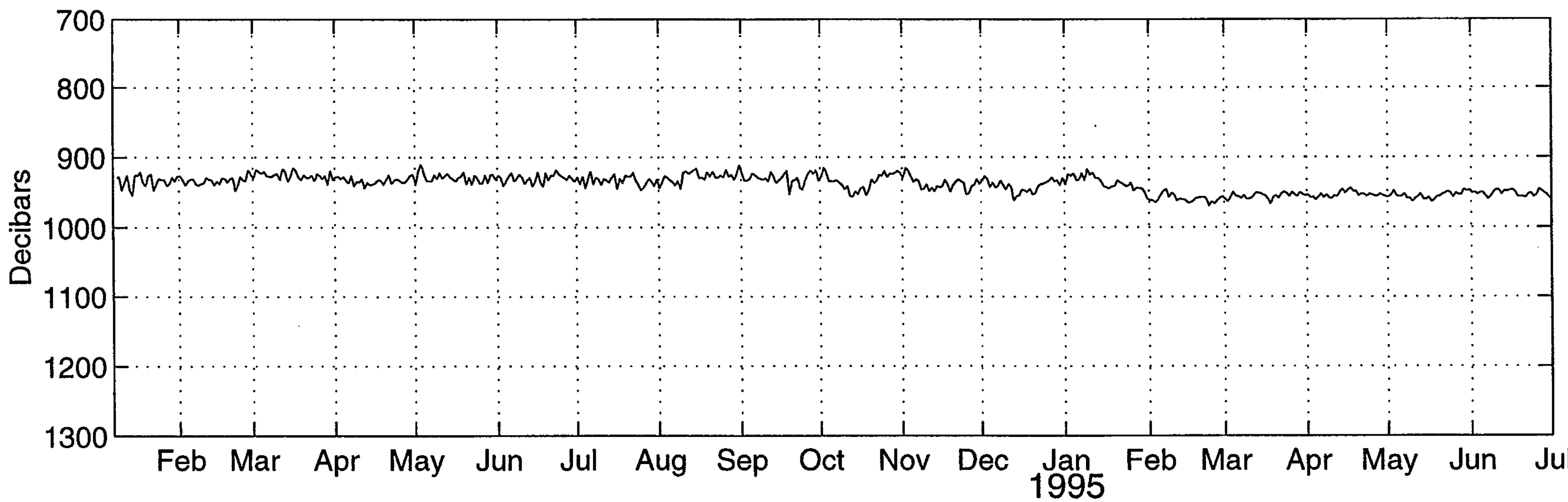
Meddy 5 Float 137

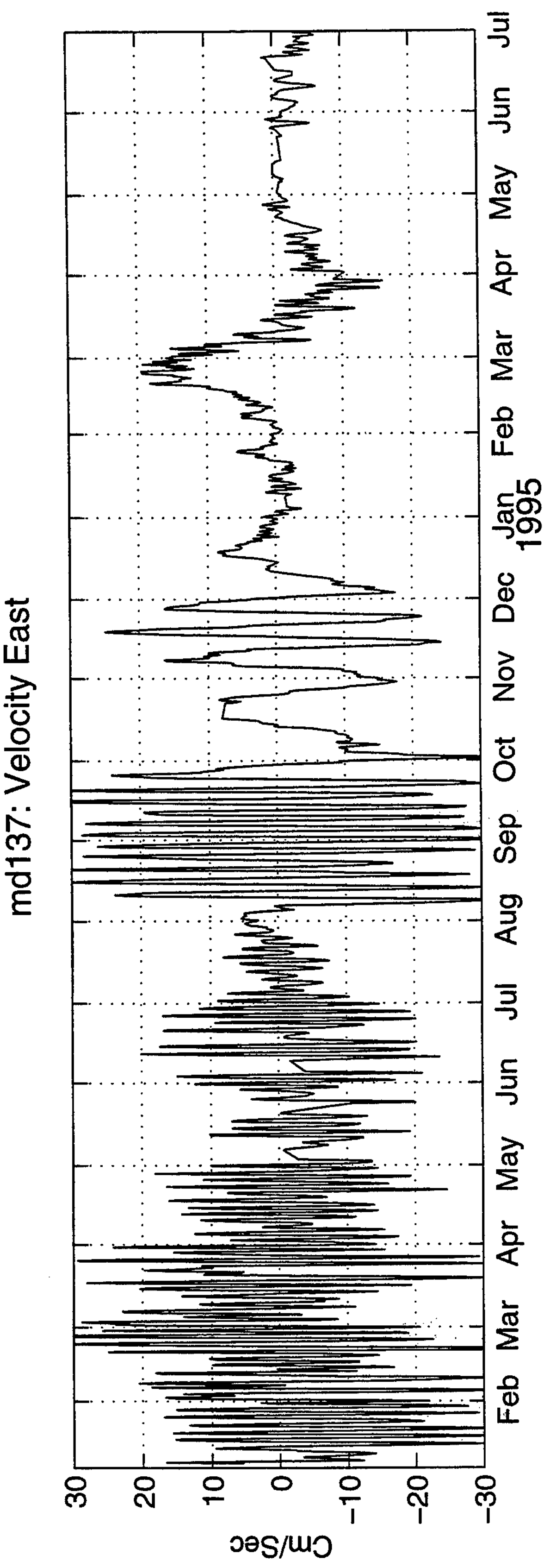


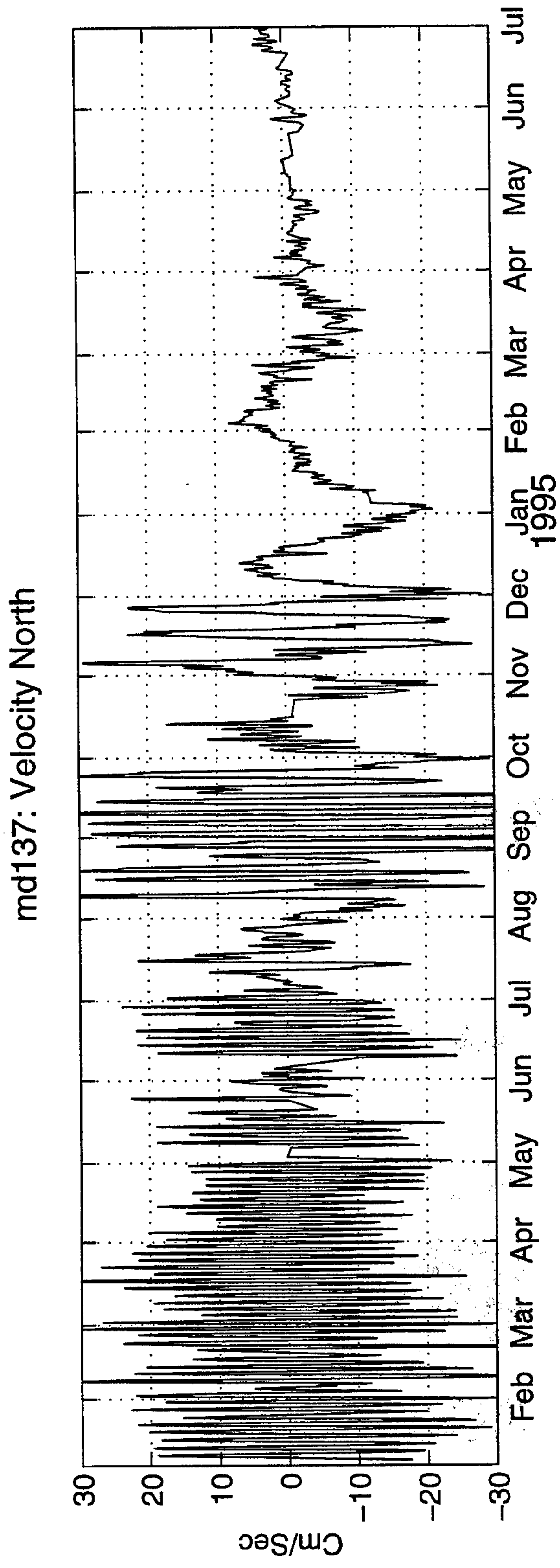
md137: Temperature



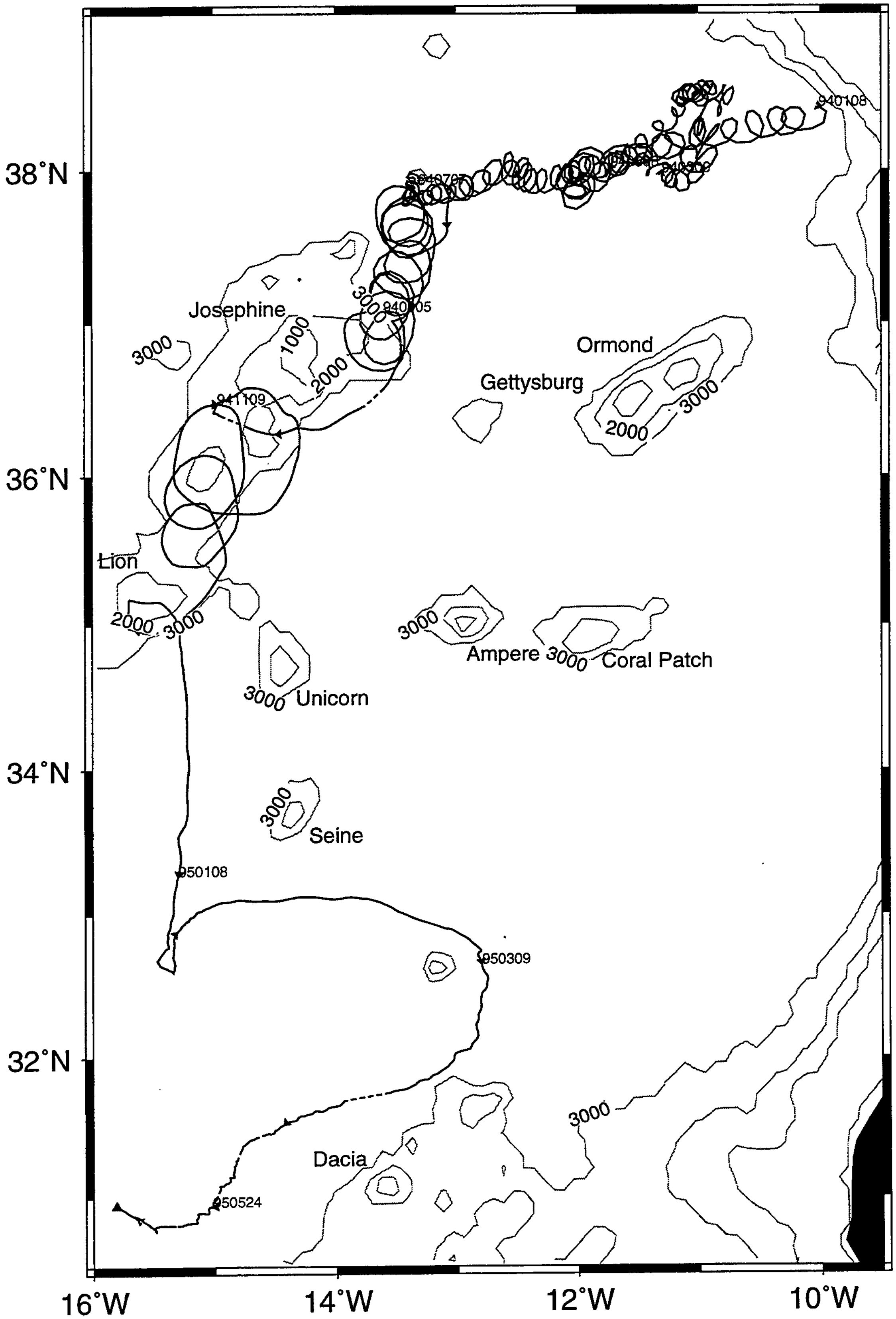
md137: Pressure



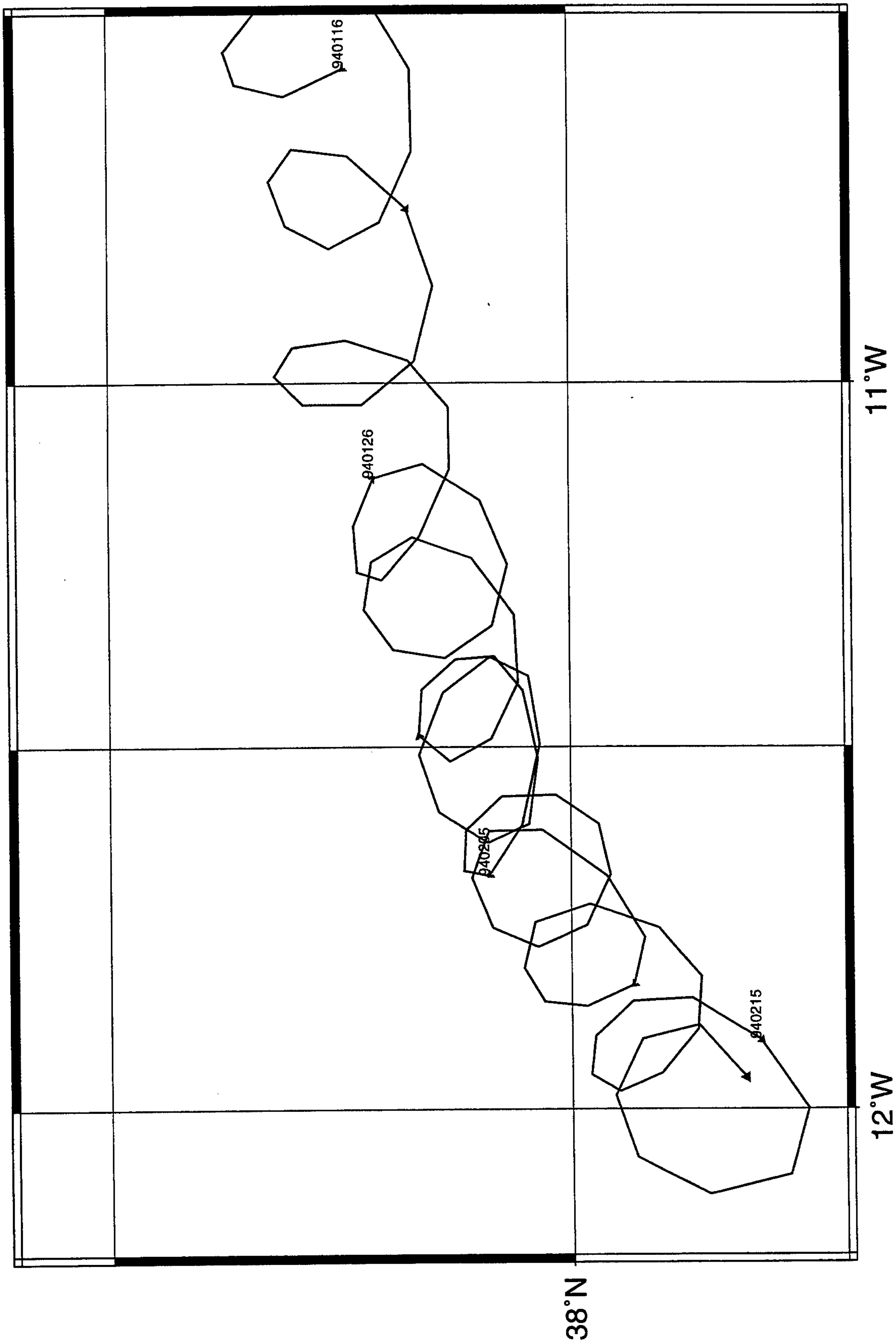

md137: Velocity East
Cm/Sec
30
20
10
0
−10
−20
−30
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995
Feb
Mar
Apr
May
Jun
Jul


md137: Velocity North
Cm/Sec
30
20
10
0
−10
−20
−30
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995
Feb
Mar
Apr
May
Jun
Jul

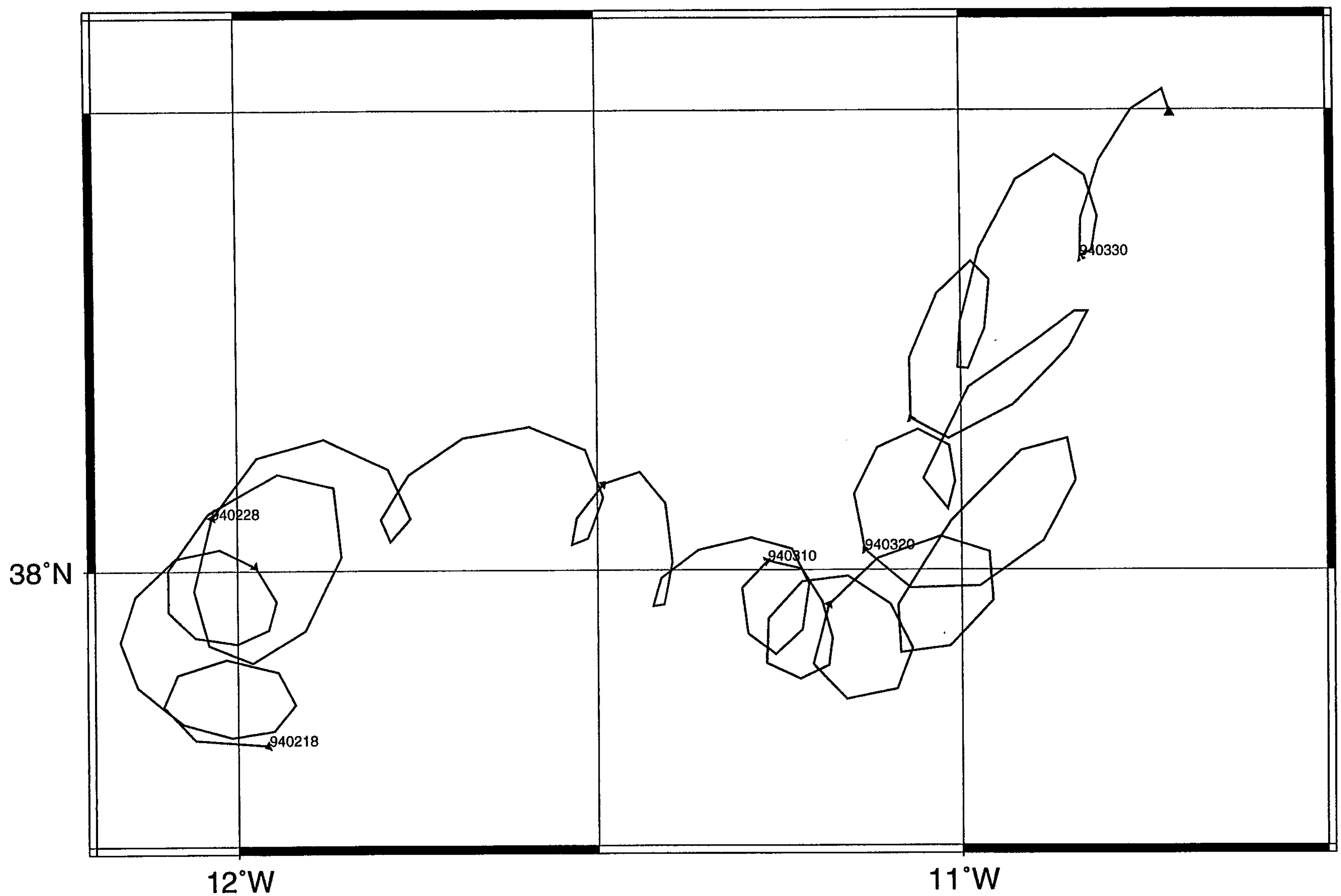
Meddy 5 Float 137 Interpolated



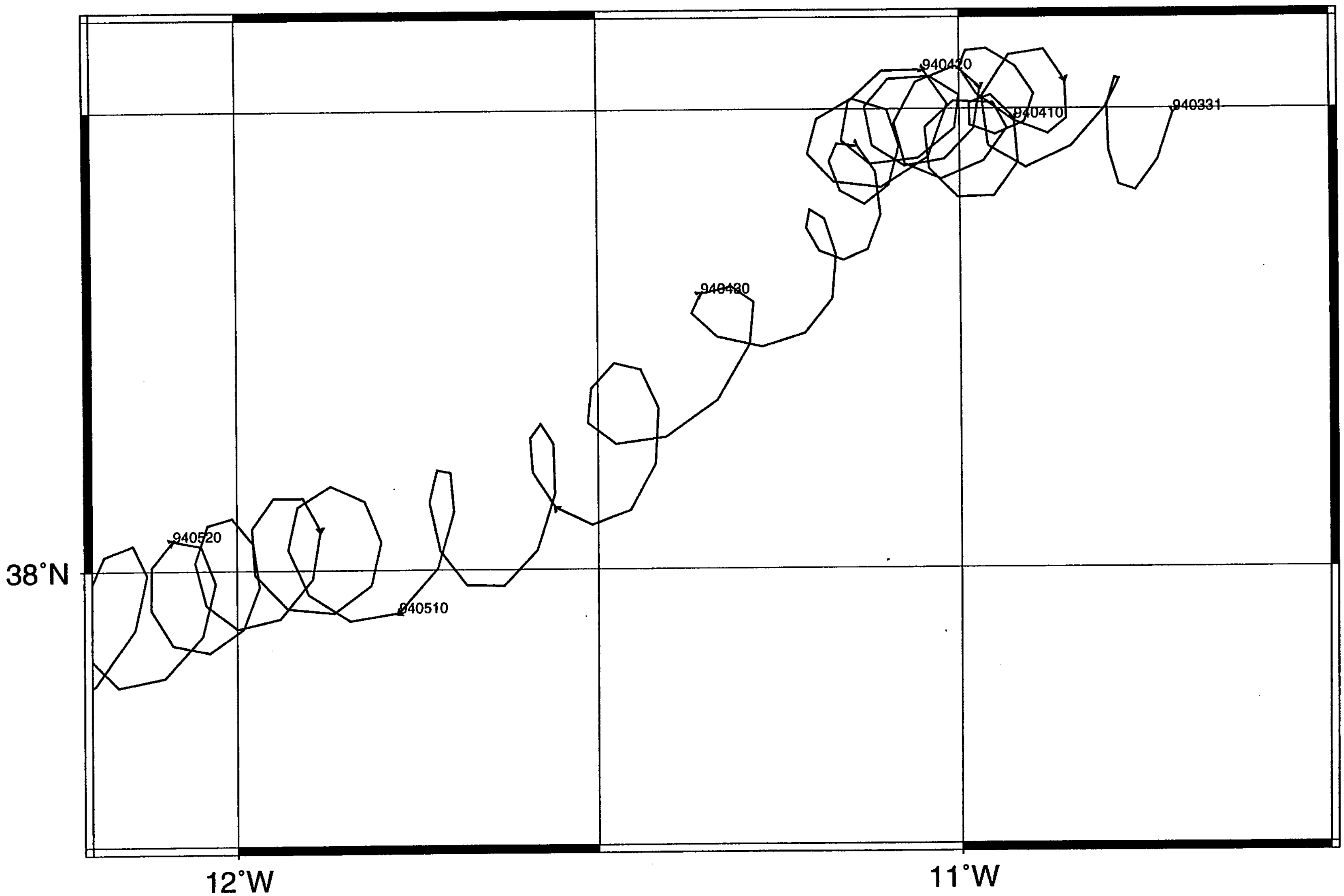
Meddy 5 Float 137 interpolated

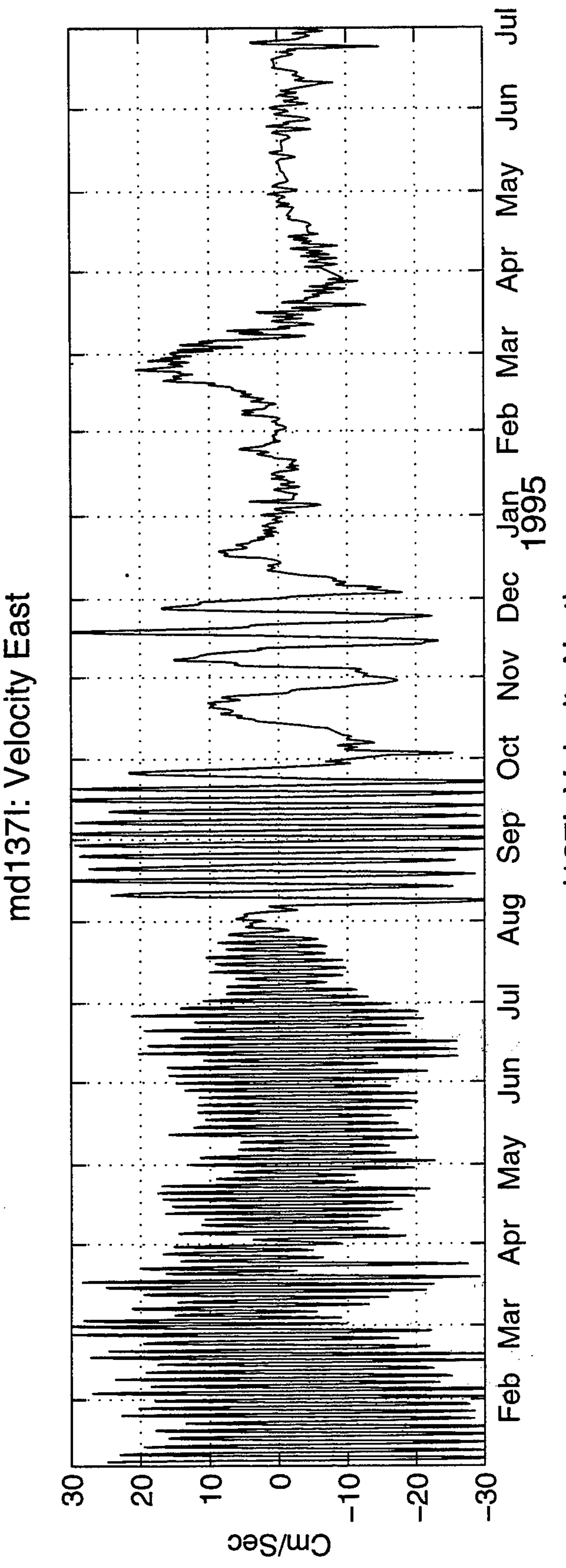


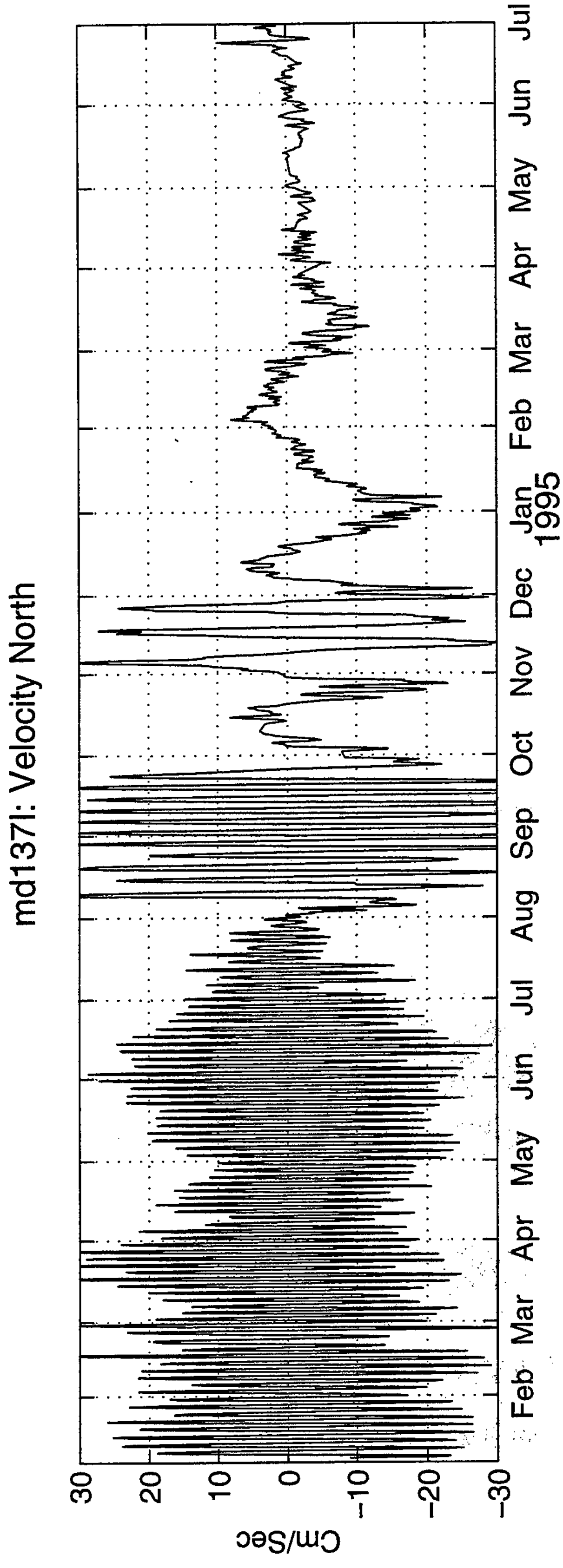
Meddy 5 Float 137 interpolated



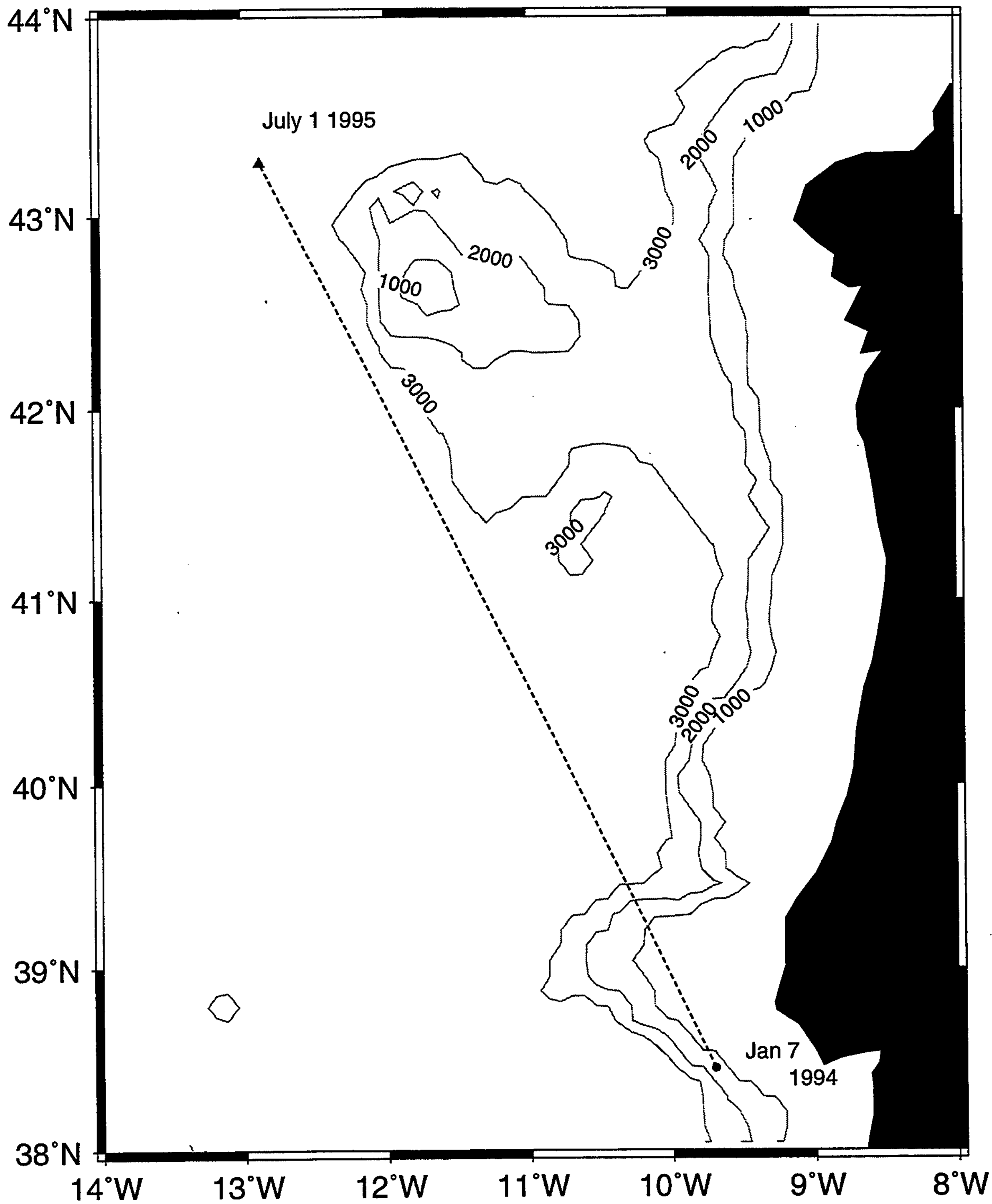
Meddy 5 Float 137 interpolated



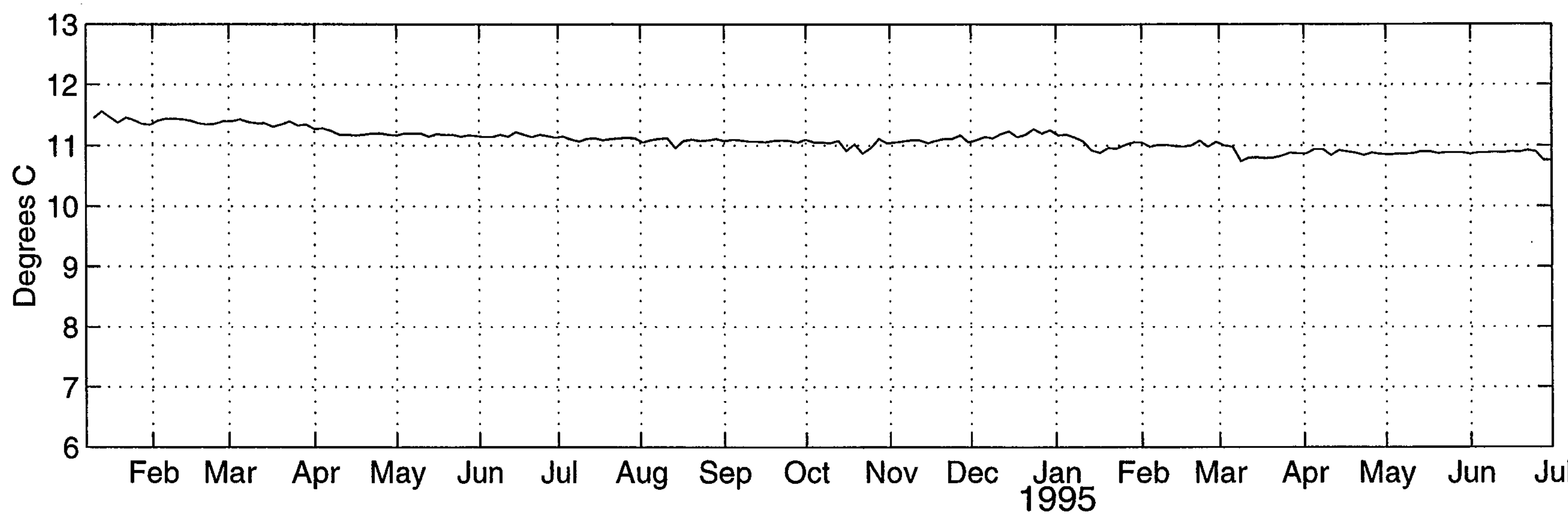

md137l: Velocity East
Cm/Sec
30
20
10
0
−10
−20
−30
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995
Feb
Mar
Apr
May
Jun
Jul


md137l: Velocity North
Cm/Sec
30
20
10
0
−10
−20
−30
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
1995
Feb
Mar
Apr
May
Jun
Jul

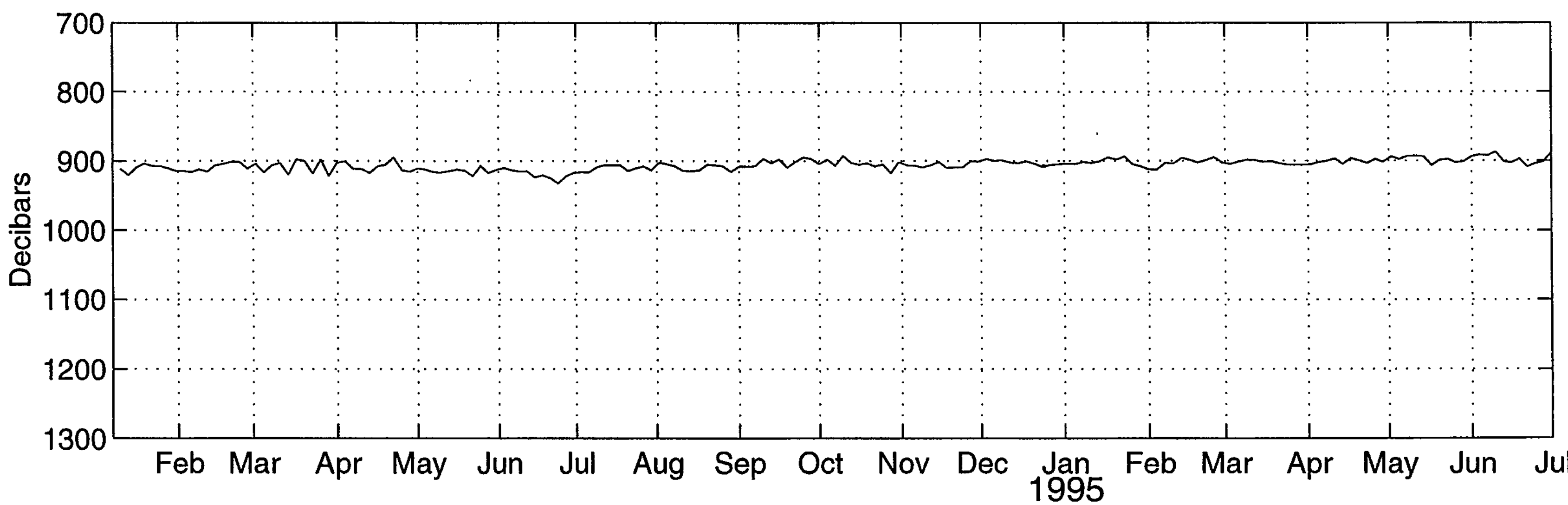
Meddy 5 Float 113 Displacement



md113: Temperature



md113: Pressure



DOCUMENT LIBRARY

Distribution List for Technical Report Exchange – July 1998

University of California, San Diego
SIO Library 0175C
9500 Gilman Drive
La Jolla, CA 92093-0175

Hancock Library of Biology & Oceanography
Alan Hancock Laboratory
University of Southern California
University Park
Los Angeles, CA 90089-0371

Gifts & Exchanges
Library
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, NS, B2Y 4A2, CANADA

NOAA/EDIS Miami Library Center
4301 Rickenbacker Causeway
Miami, FL 33149

Research Library
U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Marine Resources Information Center
Building E38-320
MIT
Cambridge, MA 02139

Library
Lamont-Doherty Geological Observatory
Columbia University
Palisades, NY 10964

Library
Serials Department
Oregon State University
Corvallis, OR 97331

Pell Marine Science Library
University of Rhode Island
Narragansett Bay Campus
Narragansett, RI 02882

Working Collection
Texas A&M University
Dept. of Oceanography
College Station, TX 77843

Fisheries-Oceanography Library
151 Oceanography Teaching Bldg.
University of Washington
Seattle, WA 98195

Library
R.S.M.A.S.
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149

Maury Oceanographic Library
Naval Oceanographic Office
Building 1003 South
1002 Balch Blvd.
Stennis Space Center, MS, 39522-5001

Library
Institute of Ocean Sciences
P.O. Box 6000
Sidney, B.C. V8L 4B2
CANADA

National Oceanographic Library
Southampton Oceanography Centre
European Way
Southampton SO14 3ZH
UK

The Librarian
CSIRO Marine Laboratories
G.P.O. Box 1538
Hobart, Tasmania
AUSTRALIA 7001

Library
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead
Merseyside L43 7 RA
UNITED KINGDOM

IFREMER
Centre de Brest
Service Documentation - Publications
BP 70 29280 PLOUZANE
FRANCE

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. WHOI-99-05	2.	3. Recipient's Accession No.

4. Title and Subtitle RAFOS Float Trajectories in Meddies During the Semaphore Experiment, 1993-1995	5. Report Date April 1999
	6.
7. Author(s) P.L. Richardson C.M. Wooding	8. Performing Organization Rept. No. WHOI-99-05
9. Performing Organization Name and Address Woods Hole Oceanographic Institution Woods Hole, Massachusetts 02543	10. Project/Task/Work Unit No.
	11. Contract(C) or Grant(G) No. (C) OCE 93-01234 (G)
12. Sponsoring Organization Name and Address National Science Foundation	13. Type of Report & Period Covered Technical Report
	14.

15. Supplementary Notes

This report should be cited as: Woods Hole Oceanog. Inst. Tech. Rept., WHOI-99-05.

16. Abstract (Limit: 200 words)

As part of the Semaphore Experiment four Meddies (Mediterranean Water Eddies) were discovered in the Canary Basin and tracked with freely drifting RAFOS floats. An additional Meddy was discovered off Lisbon by Pingree (1995) and also tracked with RAFOS floats. One large and energetic Meddy, discovered 1700 km west of Cape St. Vincent, Portugal, set a distance and speed record as it translated another 1700 km southwestward at 3.9 cm/sec during 1.5 years. This Meddy traveled 57% of the distance from Cape St. Vincent toward the spot McDowell and Rossby (1978) found a possible Meddy north of the Dominican Republic. Four Meddies collided with tall seamounts which seemed to disrupt the normal swirl velocity perhaps fatally in three cases. One Meddy appeared to bifurcate when it collided with seamounts. This report describes the float trajectories in the Meddies and summarizes the main results.

17. Document Analysis a. Descriptors

meddies

RAFOS floats

semaphore

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Approved for public release; distribution unlimited.	UNCLASSIFIED	94
	20. Security Class (This Page)	22. Price

(See ANSI-Z39.18) *See Instructions on Reverse* OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce