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Hypoxia in the York River, 1991

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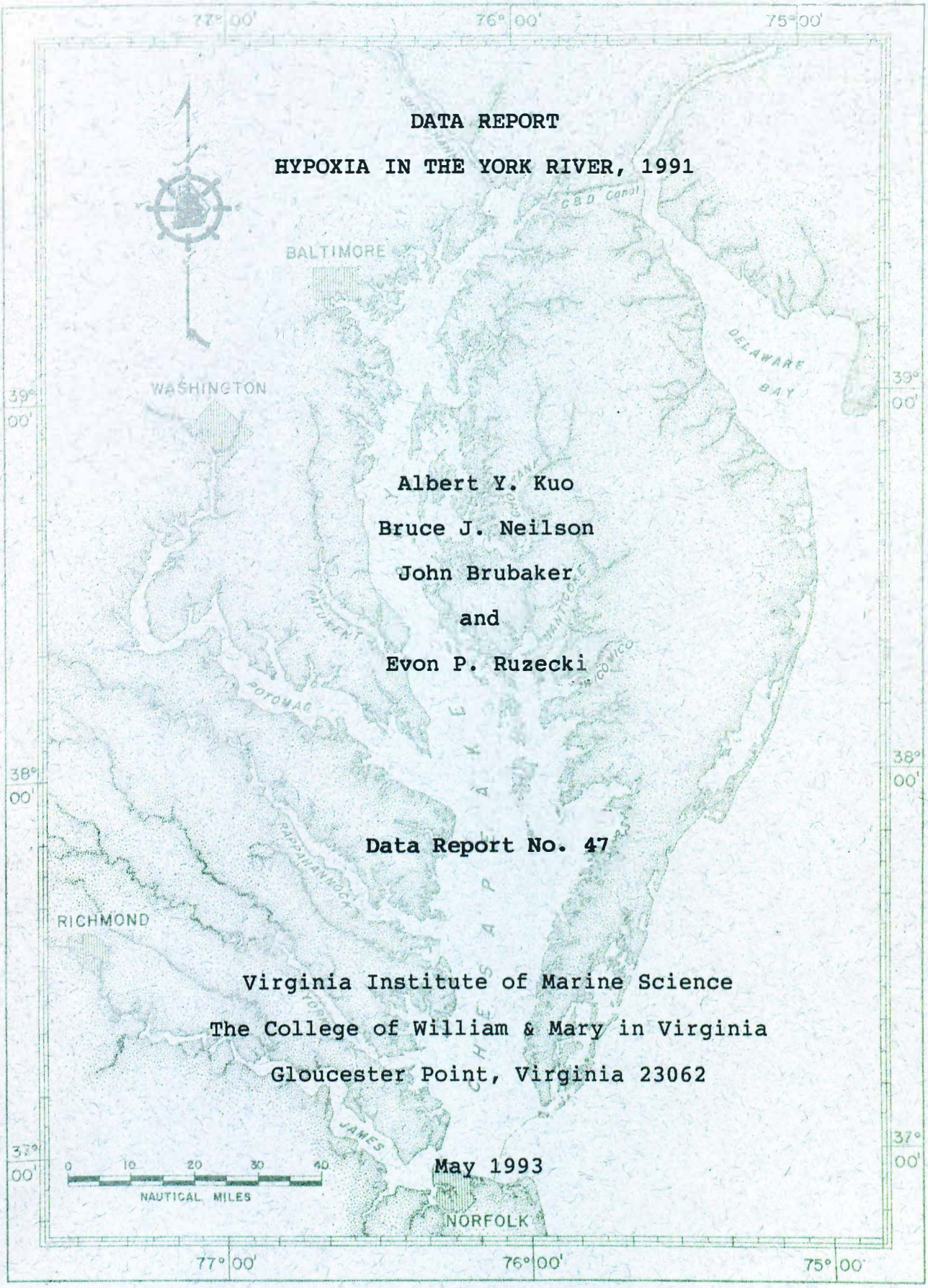
DATA REPORT

HYPOXIA IN THE YORK RIVER, 1991



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Bruce J. Neilson

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and

Evon P. Ruzecki

Data Report No. 47

Virginia Institute of Marine Science

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INTRODUCTION

One of the most important measures of water quality is the dissolved oxygen (DO) concentration. Oxygen is required by virtually all aqautic organisms, certainly all of the commercially important species. When the available oxygen is low, a condition termed hypoxia, organisms may be stressed. The stress is greater still when all of the dissolved oxygen is depleted, a condition called anoxia. Because DO is so important to marine animals, it is important to understand the processes which control its distribution.

The waters in estuaries usually exhibit vertical density differences and, as a consequence, the heavier bottom waters are separated from the atmosphere by the lighter surface layer. The end result is that the inflow of "new" oxygen into the bottom waters is small. During summer periods more oxygen is consumed by animals and by the decomposition of organic matter than is brought in, and bottom waters become hypoxic or anoxic.

Within the mainstem of Chesapeake Bay, the DO of bottom waters generally decreases as one moves up the Bay and away from the Bay mouth. A question of interest to water quality engineers is whether the dissolved oxygen regime in the major tributaries of Chesapeake Bay [the James, York, and Rappahannock rivers] is controlled by the quality of water

entering from Chesapeake Bay, by processes occurring within the tributaries, or by some combination of these and other processes. The intent of the work presented in this report is to describe the interactions between the Chesapeake Bay and the York River, especially as they affect dissolved oxygen levels in the York River.

This data report describes field studies conducted during the summer of 1991 by the Virginia Institute of Marine Science (VIMS) when both the physical environment and the dissolved oxygen regime were monitored, with the objective of better understanding how physical transport processes affect DO. The 1991 data sets will be presented here. Analysis and interpretation of the data is the subject of other scientific reports.

I. MEASUREMENTS AT MOORED STATIONS

A. Introduction

Often oceanographic instruments are deployed on moorings so that measurements can be made at short intervals (e.g. every fifteen minutes or half an hour) for some longer period of time, (e.g., two weeks). Modern instruments include microprocessors to control the sensors, record the observations, and perform other tasks. Deployment times can be limited by a number of factors including battery life, the amount of data that can be stored, and fouling of the instruments.

Mooring locations are selected to provide the most appropriate and useful data sets. Often hazards due to vessel traffic dictate that nearby stations be used in place of the optimal site, say near the side of the navigational channel instead of in the center.

In the following sections the sampling stations and the deployments will be described. Next the instruments used and other particulars will be specified for the measurement of current speeds and directions and for the measurements of temperature, salinity, and dissolved oxygen.

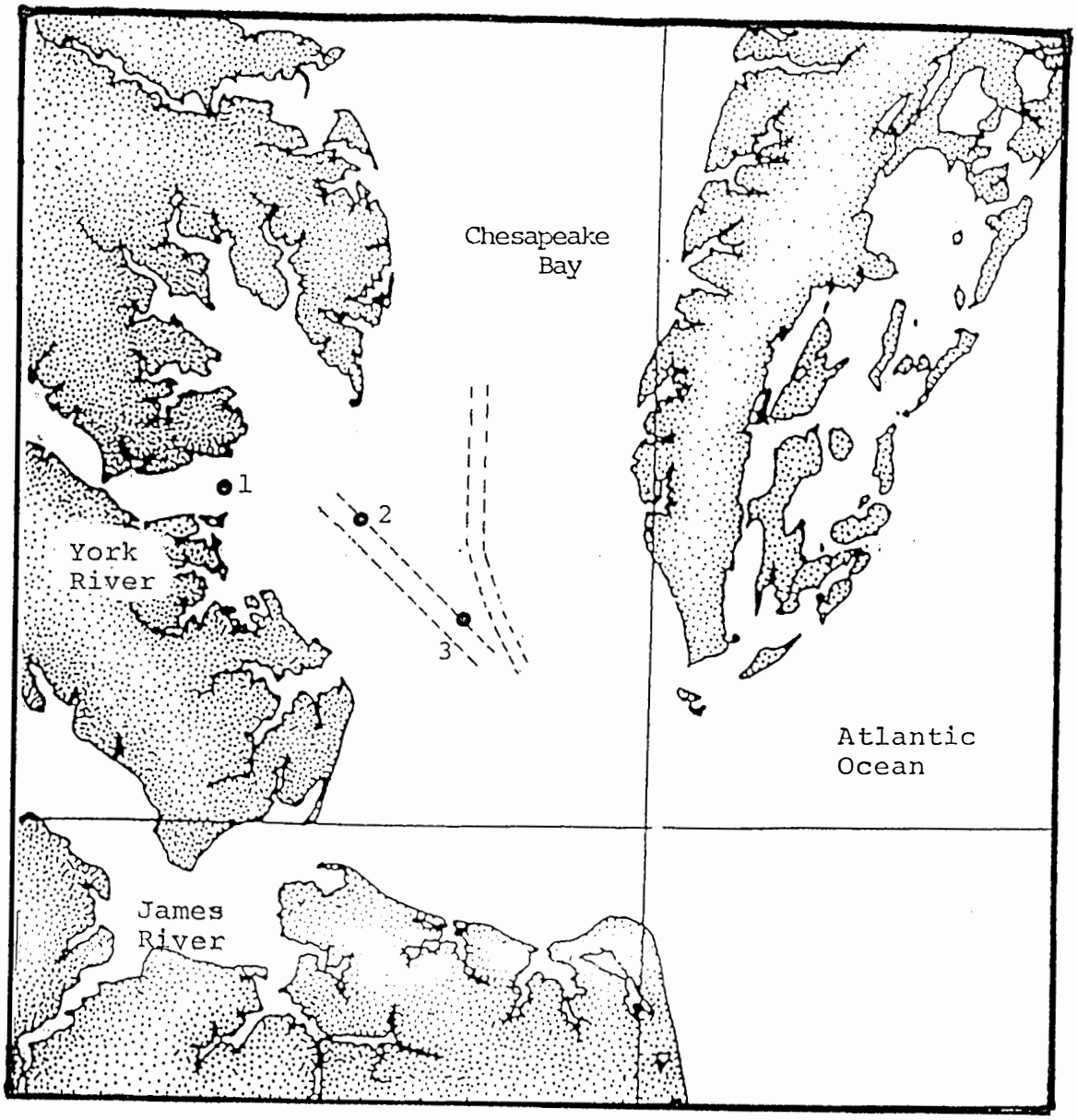
B. Description of Stations and Deployments

Earlier studies showed that dissolved oxygen conditions differed greatly among the Virginia tributaries and

suggested that physical transport processes were a primary factor causing these differences (Kuo and Neilson, 1987). Subsequent work suggested that the transport of bottom waters from Chesapeake Bay into the tributaries varied with the lunar cycle (Ruzecki, 1990). In order to document the movement of Chesapeake Bay bottom waters into the York River, two primary moorings were identified: The Tue Marsh station was located along the transect at the mouth of the river and the "N16" station was located near the end of the York River Entrance Channel (see Figure I-1). Currents were measured at several depths at both moorings. Water temperature and salinity were measured concurrently by some meters. Dissolved oxygen concentrations, along with salinity and temperature, were monitored in the bottom waters at both sites.

Additional measurements of dissolved oxygen, temperature and salinity were made in conjunction with two other programs. A buoy fabricated for the Chesapeake Bay Program (CBP) of the U.S. Environmental Protection Agency (EPA) was moored near VIMS' buoy (Tue Marsh station) at the mouth of the York River. The temperature, salinity, and DO sensors were located at a water depth of 11 meters. Readings were telemetered back to VIMS.

The Environmental Monitoring and Assessment Program (EMAP) of EPA also monitored dissolved oxygen concentrations as one measure of ecosystem health. Instantaneous readings



KEY TO STATIONS

(1) Tue Marsh Station	EPA Telemetering Buoy Hydrolab DataSonde 1 S4 Current Meters
(2) York River Entrance Channel (near Buoy N16)	Hydrolab Datasonde 1 S4 Current Meters
(3) York River Entrance Channel (near Buoy N8)	EMAP Hydrolab Datasonde 3

Figure I-1. Location of moored sampling stations.

were taken at most of their stations, with longer term monitoring at a subset of those stations. During the summer of 1991 VIMS staff maintained an "EMAP" station located near the York River Entrance Channel (Fig. I-1). Temperature, salinity, and dissolved oxygen were measured at 15 minute intervals using a Hydrolab Datasonde 3.

The results of current measurements will be described in the following section and those for temperature, salinity, and dissolved oxygen in the subsequent section.

C. Current Measurements

Current velocities were measured at two stations, one at the buoy across the channel from Tue Marshes light, and the other at Buoy #N16 in the York River Entrance Channel (Fig. I-1). Four current meters were deployed at Tue Marshes station at the depths of 1.5m, 6.0m, 10.0m, and 18.5m. Three current meters were deployed at Buoy #N16 station at the depths of 1.5m, 6.0m and 10.3m. All velocities were measured every half hour. The half-hourly average velocity vectors are presented as stickplots in Appendix I-1. These vectors were adjusted from magnetic north to true north by the annual local magnetic variation. Extraneous data were identified by visual inspection of stickplots of currents. Files of current readings were edited for elimination of identified extraneous data before further analyses.

The currents observed were primarily along distinct ebb and flow axes. Because of irregular channel topography, these axes can vary with location and depth, and are not necessarily opposing. In order to determine the major axis of flow at given location-depth, it was necessary to find the principal axis along which the longitudinal component is maximized. This axis was determined for each location-depth as follows:

$$PA = 0.5 * \tan^{-1} [2\overline{uv}/(\overline{v^2} - \overline{u^2})]$$

where

PA is the principal axis relative to true north,

u is the east-west component of a velocity vector,

v is the north-south component of a velocity vector,

overbars indicate averaging over all data.

The data points were then split into two groups by a line perpendicular to the principal axis. Ebb and flood axes were then determined by calculating the average vector direction for each group of data respectively. The angles of principal, ebb, and flood axes are presented in Table I-1. The relationship between these axes and the observed currents are evident in the scatterplots (Appendix I-2). Superposed on these are two dashed lines showing flood and ebb axes, and a solid line showing the principal axis.

Current velocities were resolved into longitudinal and transverse components relative to the principal axis for all data at each location-depth. The longitudinal components are strongly influenced by semidiurnal tides, which can be seen in the time-series component plots (Appendix I-3). The tidal fluctuations are less discernable in the time-series plots of the traverse components (Appendix I-4). Tidal contributions to transverse currents are severely restricted in the river (Tue Marsh station). At the bay station, tidal contributions decrease with depth.

In order to study mean circulation it was necessary to remove the tidal variations from the data. One approach is to apply a low-pass filter, which removes variations with frequencies higher than a specified cutoff value. The low-pass filtering procedure used here involved the application of a frequency domain filter response function to the fast Fourier transformed data series. The filtered time series was recovered by an inverse FFT (Walters and Heston, 1981). The cut-off period for the filter was chosen to be 36 hours. The low pass filtered longitudinal components generally exhibits a seaward surface flow and a landward bottom flow (Appendix I-5). The average velocity components at each location-depth are also listed in Table I-1. Variations from this mean pattern and the variations of transverse components (Appendix I-6) are largely the result of meteorological forcing caused especially by the wind. The

Table I-1. Summary of available current data.

STAT/ DEPTH	CALEN. DATES	DEPLOY #	# OBS	A X E S PRIN	EBB	FLOOD	AVG LONG cm/s	VEL TRAN cm/s
TUE	05/29-06/29	2	1497	74	70	258	-0.1	1.5
MARSHES	07/02-07/11	3	438	77	76	259	1.0	0.6
1.5 M	07/12-07/23	4	535	71	69	255	4.5	1.1
	07/24-08/10	5	830	72	70	255	1.5	0.5
	08/12-09/07	6	1239	75	74	256	2.7	0.4
	09/09-09/22	7	602	73	71	256	3.1	0.8
TOTALS/AVGS:		ALL	5141	74	71	257	1.8	0.9
TUE	05/29-07/02	2	1634	77	80	252	3.3	-1.6
MARSHES	07/02-07/12	3	478	78	80	255	2.4	-1.2
6.0 M	07/12-07/24	4	573	80	80	260	-0.7	-0.3
	07/24-08/12	5	904	80	82	258	2.0	-0.9
	08/12-09/09	6	1349	82	84	260	0.1	-1.0
	09/09-09/23	7	665	82	82	262	-0.6	-0.2
TOTALS/AVGS:		ALL	5603	79	81	257	1.4	-1.0
TUE	05/29-07/02	2	1635	74	76	252	2.1	-0.4
MARSHES	07/02-07/12	3	479	73	78	247	3.1	-2.2
10.0 M	07/12-07/24	4	573	75	78	253	-4.6	-1.0
	07/24-08/12	5	904	74	77	249	2.2	-1.9
	08/12-09/09	6	1349	75	79	251	-1.5	-1.4
	09/09-09/23	7	666	76	77	255	-3.6	-0.5
TOTALS/AVGS:		ALL	5606	74	77	252	0.0	-1.1
TUE	05/29-06/29	2	1485	74	74	254	-3.4	-0.2
MARSHES	07/02-07/11	3	435	72	71	253	-1.7	0.1
18.5 M	07/12-07/24	4	553	70	72	250	-7.8	0.3
	07/24-08/10	5	813	72	72	252	-1.1	0.0
	08/12-09/06	6	1198	67	69	245	-3.1	0.5
	09/09-09/21	7	577	66	66	246	-5.7	0.5
TOTALS/AVGS:		ALL	5061	70	71	250	-3.6	-0.1
YORK	05/29-07/02	2	*					
ENTRANCE	07/02-07/11	3	449	129	131	295	0.0	-1.5
CHANNEL	07/12-07/23	4	545	130	137	298	2.6	0.4
1.5 M	07/24-08/11	5	856	128	132	296	-0.6	-0.1
	08/12-09/01	6	983	125	130	295	0.1	0.9
	09/09-09/18	7	**					
TOTALS/AVGS:		ALL	2833	127	123	312	0.3	0.1
YORK	05/29-07/02	2	*					
ENTRANCE	07/02-07/12	3	470	23	23	203	1.1	-0.5
CHANNEL	07/12-07/24	4	573	129	130	304	-1.6	0.1
6.0 M	07/24-08/12	5	914	132	133	307	-3.2	-0.3
	08/12-09/09	6	1338	129	131	304	-3.8	0.0
	09/09-09/20	7	515	128	127	304	-4.6	-1.2
TOTALS/AVGS:		ALL	3810	132	132	306	-3.9	-0.2
YORK	05/29-07/02	2	*					
ENTRANCE	07/02-07/11	3	410	122	114	307	-1.7	-1.5
CHANNEL	07/12-07/23	4	527	120	119	298	-5.3	-1.2
10.3 M	07/24-08/10	5	830	129	123	316	-1.1	-1.6
	08/12-09/06	6	1177	123	123	297	-2.7	-0.7
	09/09-09/18	7	455	122	118	293	-4.8	-2.5
TOTALS/AVGS:		ALL	3399	124	130	300	-2.9	-1.4

NOTES: * Current meters failed to activate.
** Current meter was destroyed by tugboat.

wind data measured at VIMS are presented graphically in Appendix I-7. For reference, the data from tide gauge station at Gloucester Point are presented in Appendix I-8.

D. Measurements of Temperature, Salinity, and Dissolved Oxygen

Water temperature, salinity, and dissolved oxygen concentration were measured at three locations, with measurements at two depths at the Tue Marsh station. The sensors for the telemetering buoy (EPA-Chesapeake Bay Program) were located at a depth of 11 meters. Observations were made beginning in mid-July and continued through mid-September (Appendix I-9). Gaps in the data are the result of problems with the sensors or problems with data transmission or receipt. Sensors were cleaned during each visit.

A Hydrolab Datasonde 1, equipped with temperature, conductivity, and pressure sensors, was deployed with the current meters at the buoy across the channel from the Tue Marshes light. The meter was located about two meters off the bottom at a water depth of 17 meters. Observations began at the beginning of May and continued through late September (Table I-2 & Appendix I-9).

A Hydrolab Datasonde 1, also equipped with temperature, conductivity, and pressure sensors, was deployed with current meters at Buoy #N16 along the York River Entrance

Channel. The meter was located one meter above the river bottom at a water depth of 10.3 meters. The deployment began in early May and continued through late September (Table I-2 & Appendix I-9).

The Hydrolab Datasonde 3, deployed at the EMAP station one mile north (at 60°) near Buoy "N8" along the York River Entrance Channel, was equipped with temperature, conductivity, pH and depth sensors. The meter was deployed about one meter above the bottom at a depth of 10m beginning in mid-July and continuing through late September (Table I-2 & Appendix I-9).

Prior to each deployment, the membranes on the oxygen sensors were replaced, the Hydrolab datasonde was allowed to equilibrate over night, and the unit was calibrated. Post-deployment calibrations were conducted as well. In addition water samples were collected at the stations; samples were analyzed for dissolved oxygen using Winkler titrations, and salinities were determined in the laboratory using a salinometer calibrated with Copenhagen water.

Table I - 2. Summary of available dissolved oxygen data*

STATION and DEPTH, Calendar Dates for deployment/retrieval

TUE MARSHES - 11 meters (Telemetering buoy)

07/17-09/23

TUE MARSHES - 17 meters

05/01-05/16	07/12-07/24
05/16-05/29	07/24-08/01
05/29-06/13	08/01-08/12
06/13-06/21	08/12-08/23
06/21-06/26	08/23-08/29
06/26-07/02	08/29-09/09
07/02-07/12	09/09-09/23

YORK RIVER ENTRANCE CHANNEL - BUOY #N16 - 10.3 meters

05/01-05/16	07/12-07/24
05/16-05/29	07/24-08/01
05/29-06/13	08/01-08/12
06/13-06/21	08/12-08/23
06/21-06/26	08/23-08/29
06/26-07/02	08/29-09/09
07/02-07/12	09/09-09/23

YORK RIVER ENTRANCE CHANNEL - One mile north (60^0) of buoy N8, York River Entrance Channel (EMAP) - 10 meters

07/12-07/18	08/23-08/29
07/18-07/24	08/29-09/06
07/24-08/01	09/06-09/13
08/01-08/16	09/13-09/23
08/16-08/23	

* Water temperature and salinity were measured concurrently with DO concentration.

II. SLACKWATER SURVEYS

The slackwater surveys were designed as supplement to the measurements at moored stations. Three surveys were conducted in early April, prior to the design of moored stations. Temperature and salinity were measured at stations along a transect from the southeast end of the York River Entrance Channel, running along the channel and river axis to Gloucester Point. The surveys were conducted to probe the density structure in the bay and the river adjacent to the river mouth. The results are presented as isotherms and isohalines in the longitudinal transect (Appendix II). While conducting the surveys, it was noted by the field crew that the slackwater phase of tide did not propagate progressively along the transect from the bay into the river. No sampling sequence may be developed to follow the same phase of tide at all stations. Therefore, the surveys were conducted with sampling time only approximating time of slackwater in this general area.

The summer slackwater survey was designed to coincide with the event of strong vertical oscillation of interface separating bottom hypoxic water from surface water. This objective requires daily monitoring of time series data from telemetry buoy. Because of strategic difficulty, only one such survey was conducted and the results are included in Appendix II.

III. MEASUREMENTS OF CURRENT PROFILES

A. Introduction

Conditions in Chesapeake Bay and its tributary estuaries are a function of local processes, but are also strongly dependent upon exchange processes between the Bay and the tributaries. A comprehensive description of the flow field at regions of the Bay near tributary entrances is fundamental to understanding the modes of exchange and controls on them. However, the varied and interacting influences, including tidal flows, bottom topography, gravitational circulation, and wind stress, may be expected to produce a spatially complex and time varying flow field that is not at all straightforward to measure and characterize.

To complement the current measurements based on moored instruments (Section I) and drogue tracking (Section IV), our field program in summer 1991 included a preliminary experiment to map the spatial structure of the flow field near the mouth of the York River with a relatively new tool based on acoustic remote sensing, the acoustic Doppler current profiler (ADCP). As deployed in this study, the ADCP is capable of determining the vertical profile of current speed and direction beneath a vessel underway. Thus by repeatedly traversing a sampling trackline, information on spatial structure of the flow and its temporal evolution

can be acquired. The objectives of this component of the 1991 field program were: 1) to acquire preliminary information on the characteristics of the flow field in the vicinity of York Spit, including length scales in the spatial structure and a sampling of temporal variability on tidal time scales (i.e. changes over a few hours, but not an entire tidal cycle in this first trial), and 2) to assess the operational capabilities and constraints of the towed ADCP system with respect to this type of current mapping study in order to design a subsequent, more comprehensive investigation.

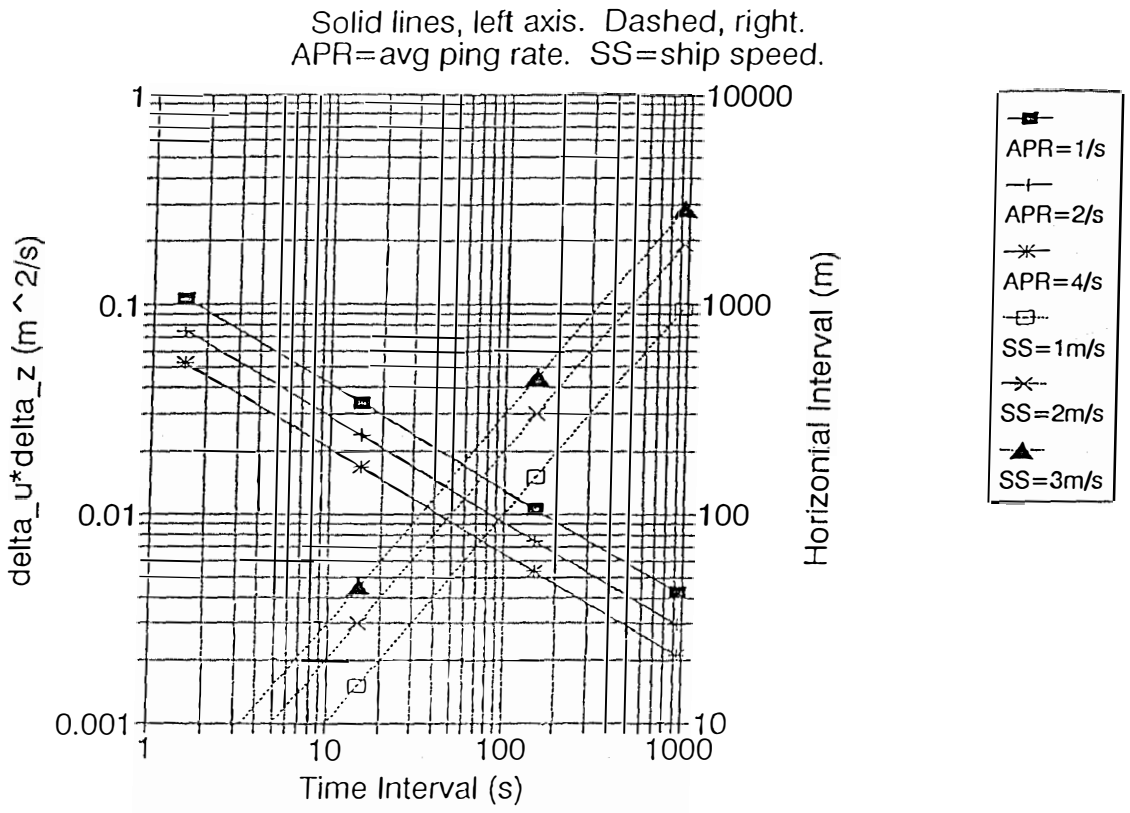
B. Instrumentation

Currents were measured with an acoustic Doppler current profiler, or ADCP, deployed from the R/V Langley. The unit operated by the Division of Physical Oceanography at VIMS, model DR-1200 manufactured by RD Instruments, transmits sound pulses at 1.2MHz in four narrow beams, each pointing downward through the water column at an angle of 30^{o} off vertical and arranged in azimuth at 90d intervals so that one beam is directed forward, one to starboard, one aft, and one to port. The ADCP is mounted in a catamaran vehicle and towed alongside the research vessel, out of range of wake influence. In addition to the profile of currents at a series of levels within the water column, the ADCP can determine its own velocity relative to the bottom. With

this "bottom tracking" data, the raw water velocity values measured from the moving vessel can be corrected for vessel motion so that they represent absolute currents over the ground.

Depth cells were spaced at 1m vertical intervals and the pulse length was set at 1m as well. The ADCP was programmed to transmit sets of four pings, average the resulting current data and send it to the on-board computer, which accumulated this input over a 30-s interval for further averaging, screen display, and recording to disk. Typically, the 30-s ensemble average included 11 of the 4-ping averages, or a total of 44 pings, yielding an average ping rate of 1.4 pings/s. According to Figure III-1, the corresponding product $\delta u \delta z$, where δu is the velocity uncertainty and δz is the vertical depth cell length, is approximately $0.02 m^2/s$. As noted, δz = 1m; therefore δu = 0.02m/s. Figure III-1 also indicates that the horizontal averaging interval corresponding to a time interval of 30-s is 60 to 90m at ship speeds of 2 to 3m/s (approximately 4 to 6 knots).

Navigation data from a Loran-C receiver aboard the Langley were input to the computer controlling the ADCP, with position and current data integrated into the same data file. ADCP setup and sampling were under control of RD Instruments' Data Acquistion Software, version 2.48, which called a user exit routine written by John Posenau of VIMS to read the Loran data.



With $\delta z = 1$ m (usual vertical bin length), velocity uncertainty δu can be read directly on the left axis.

Example: $\delta z = 1$ m with 1 ping/s. For 40 s average, $\delta u = 0.02$ m/s, and at ship speed of 2 m/s, horizontal interval is 80 m. Increasing ping rate to 4 pings/s would give $\delta u = 0.01$ m/s.

Figure III-1. Relationship among operating characteristics for 1.2 MHz acoustic Doppler current profiler with beams 30° off vertical.

C. Observations

The current mapping study was conducted on 15 August 1991 in the vicinity of York Spit in the Chesapeake Bay, Figure III-2. A triangular sampling trackline was defined by the points labelled A, B, and C. Three counter-clockwise circuits around the triangle were executed at the following times (Eastern Standard Time), where XYn denotes the n-th transect along the leg connecting points X and Y:

AB1	0842 - 0912
BC1	0921 - 1007
CA1	1012 - 1048
AB2	1055 - 1127
BC2	1128 - 1218
CA2	1222 - 1304
AB3	1306 - 1336
BC3	1337 - 1422
CA3	1424 - 1509

Relevant NOS tidal current predictions for this date were:

	Near A	Near C
Slack before flood	0734	0844
Maximum flood	1155	1207
Slack before ebb	1606	1547

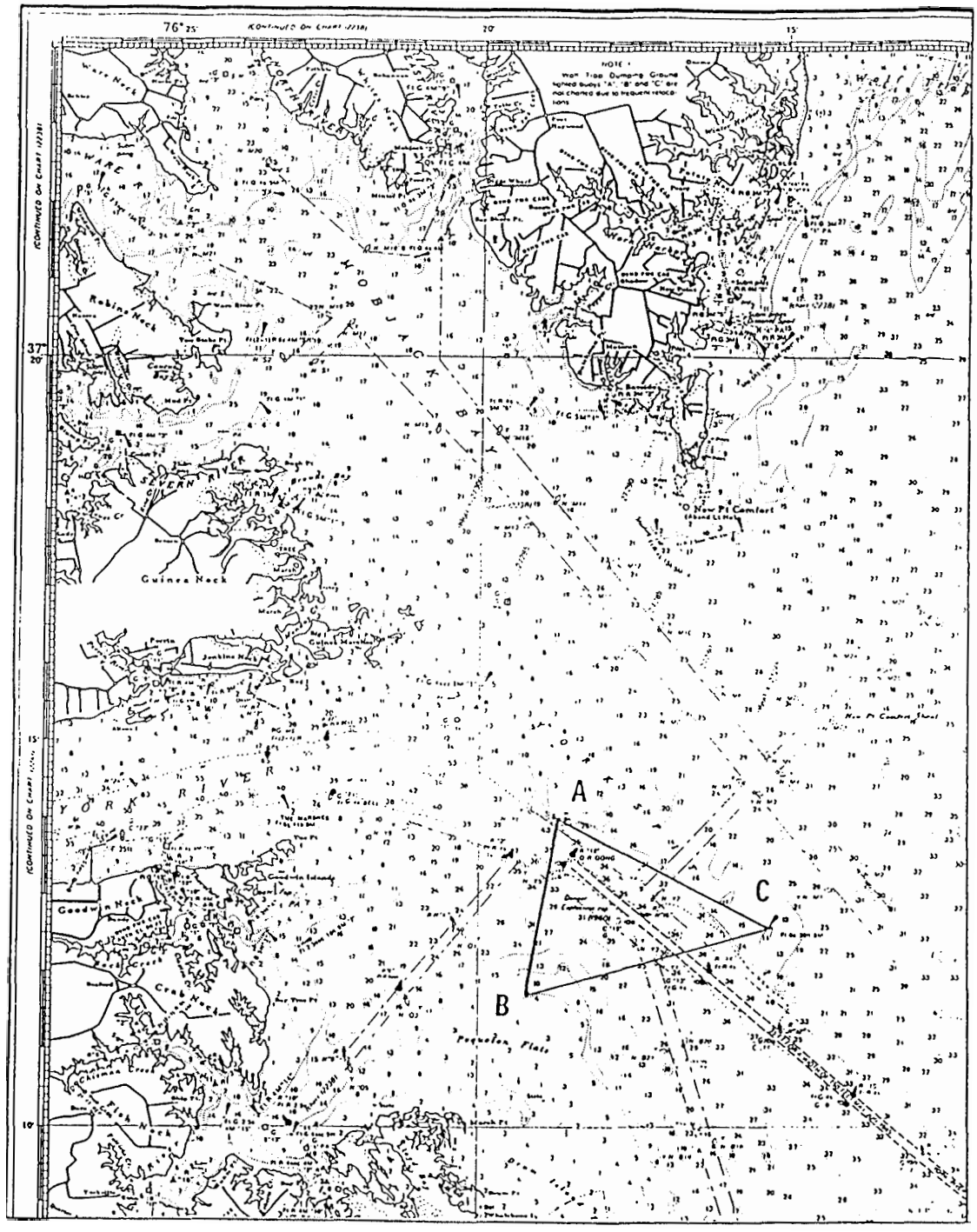


Figure III-2 The triangular sampling line for the towed ADCP, in the York Spit area of Chesapeake Bay near the mouth of the York River.

D. Results

For each transect along a leg of the triangle, the measured currents are presented in Appendix III as contour plots, one for current speed and one for direction, over the vertical slice sampled by the ADCP. Note that in order to avoid some gridding problems, different but equivalent numerical ranges have been used to express direction so that, for example, flow to the west is indicated in the plot for Leg BC1 as 270^{o} and in the plot for Leg CA1 as -90^{o}.

Significant variability is evident in both the horizontal and vertical structure of the flow field, and further analysis and interpretation of these results is underway. Spatial resolution capabilites of the towed ADCP appear to be well suited to important length scales in this flow environment. Temporal resolution is limited by the time required to cover the desired sampling pattern. In this study, one "lap" required approximately two hours, which is probably near the maximum useful time interval for repeat sampling in a tidal flow.

IV. DROGUE STUDIES

A. Introduction

A series of drogue experiments was initiated in the summer of 1991 to examine the movement of bottom water between Chesapeake Bay and the York River. The study is based on a conceptual model which considers dissolved oxygen depletion with time as a function of both water column and benthic demand and allows for oxygen renewal through vertical (downward) diffusion (Kuo and Neilson, 1987). Assuming oxygen demands and vertical diffusion are constant along the path of a water parcel, the DO content of the water will be a function of the time it takes to traverse the distance between the Bay mouth (where it is assumed that the water is well oxygenated) to the receiving tributary. Preliminary calculations show that, using predicted tidal currents, a given parcel of water will take from seven to fifteen days to reach the York and from 12 to 25 days to reach the Rappahannock. The time successive water parcels require to traverse these distances is a function of predicted flood or ebb dominance of bottom water at the Bay mouth with differences in residence time in the Bay of successive parcels moving into the York reaching seven days. The model therefore predicts abrupt changes in the DO content of bottom water entering this tributary.

The path a water parcel takes in its movement is of

prime importance. Drogue experiments were initiated to determine the path of bottom water entering the York and examine changes, if any, in the physical characteristics (temperature, salinity, and density) of this water as it moves. The experiments also afforded an opportunity to instruct students of the School of Marine Science enrolled in Introduction to Physical Oceanography (MS 501) in the use of various types of oceanographic equipment and data collection techniques. To this end, three experiments (October 1, 3, and 10) were conducted in conjunction with a class cruise.

B. Materials

To conduct these experiments, a device was needed which would serve as a Lagrangian marker for bottom water. The device must remain coupled to the bottom water, allow for tracking of its motion, and avoid bottom obstructions. It also had to have sufficient buoyancy to eventually support an instrument package used to measure and record water temperature, conductivity, pressure, and DO and had to remain near, but not at, the bottom of the water column.

A drogue designed to meet these requirements and be deployed from a small (20 foot) outboard powered research vessel was developed at VIMS. It consists of three intersecting vertical heart-shaped panels with hard plastic floats at the top and ballast at the bottom apex. The six

panel segments are interconnected with tilted radial panels which serve to provide lift to aid in tracking upward movement of the water. Ballast was adjusted to give the drogue approximately 500gm of positive buoyancy and a 600gm flexible weighted tail (a length of garden hose with a lead slug at the bottom) is attached at the apex of the drogue giving the device 100gm of negative buoyancy. When placed in the water, the drogue sinks until the lower end of the tail rests on the bottom. Without the tail, the drogue weighs approximately 35kg (77 lb) in air. Floats and ballast are separated vertically by 1.5m thus allowing the drogue to maintain a vertical orientation with an integrated center of pressure approximately 1.3m above the bottom apex. With a one meter long tail, the drogue appeared to be coupled with water that is moving 2m above the bottom because of curvature of the tail. Construction is of bent PVC pipe frame (with holes to allow flooding) attached to a central aluminum pipe. Panels are of rip-stop nylon sewn between the PVC pipe. The drogue has a height and width of 2m as shown in Figure IV-1.

A 1/10 scale model of the drogue was tested in the VIMS flume with water speeds from 10 to 20cm s^{-1}. Tests showed the center of the drogue remained approximately 20cm from the bottom. It negotiated over obstructions (cement blocks) and up a ramp (to simulate an upward slope) placed on the bottom while maintaining a vertical orientation.

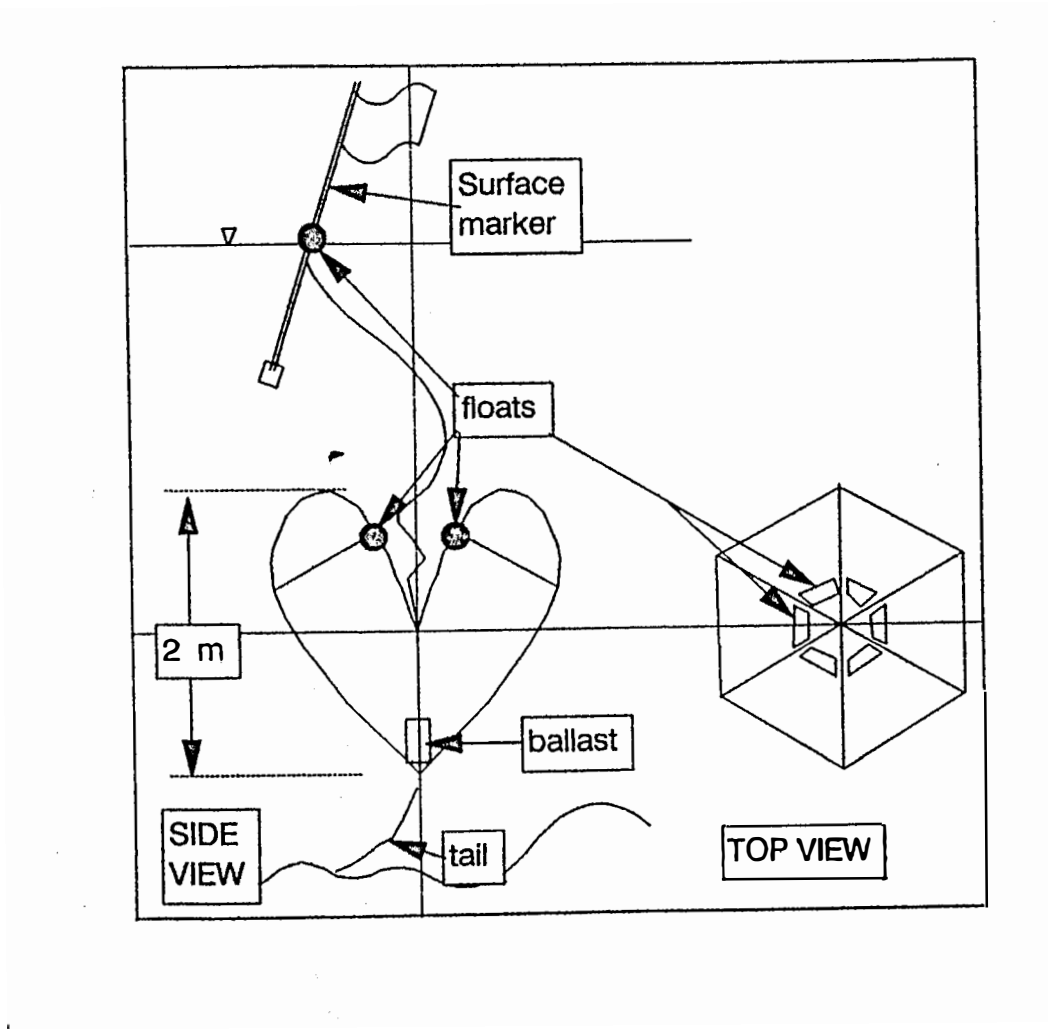


Figure IV-1. Drogue used to measure bottom water advection. Side view (left) shows heart-shaped cross section; top view (right) shows arrangement of three intersecting panels. Weighted tail provides added ballast to keep the system negatively buoyant.

For field use, a 70m tether (of 1/4 inch nylon line) connected the drogue to a surface float made from a weighted bamboo pole with a central float (10cm hard plastic sphere) and a 30 x 30cm flag on top (Fig. IV-1). Initial field tests using SCUBA divers showed the drogue moved with bottom water near the mouth of Chesapeake Bay and maintained a vertical orientation with just the lower end of the tail in contact with the bottom.

C. Methods

1. Field

In order to examine the excursion of bottom water towards and into the mouth of the York, four drogue sets were made in the York River Entrance Channel (YREC) of Chesapeake Bay (between York Spit Light and the York mouth) and one set at the mouth of the York River (across the channel from Tue Marsh Light). Sets were timed to coincide with predicted slack water before flood tide (SBF) in the YREC. Drogue sets were on 15 August, 19 September, and 1, 3 and 10 October. All sets were initially planned for the YREC but unfavorable wind conditions dictated an early termination of the 19 September set and relocation of the 3 October set to the mouth of the York. During each experiment, Loran C coordinates of the surface marker were determined at 10 minute intervals (checks of Loran coordinates at known locations in the study area were made

before and after each set) and a CTD casts was made at the marker every 20 minutes from a 20 ft outboard motor launch (Garvey). Instrument failure prevented the collection of CTD data during the September deployment. During the October experiments, a second vessel, the R/V Langley, was employed to make periodic CTD and current measurements along transects normal to the expected drogue trajectories. The primary mission of R/V Langley was to conduct a class cruise for students enrolled in the School of Marine Science course: Introduction to Physical Oceanography (MS 501). The purpose of the cruises was to instruct students in the deployment and use of oceanographic instruments and various techniques used to obtain oceanographic and meteorological data. Instruments used included water sampling bottles, CTD, S-4 current meter (as a profiling instrument), Acoustic Doppler Current Profiler (ADCP), and meteorological instruments. As these were instructional exercises and students were learning to deploy and operate the instruments, not all data obtained was of sufficient quality for scientific use; however, data from the CTD and ADCP were of acceptable quality and are included in this report. Note that the ADCP data is discussed in Section III of this report.

2. Data Processing

All data obtained from CTD casts were processed to provide sequential listings of pressure, depth, temperature,

salinity, and the density parameter σ (where, when ρ is density in kg m^{-3}, $\sigma = \rho - 1000$) using internationally accepted UNESCO processing routines. Loran C data (as time delays) was converted to latitude and longitude and thence to meters west and north of the bay mouth (taken as 37.000°N, 76.000°W).

D. Results

Results of these experiments are presented, by date, in appendices IV-1 through IV-5. Graphic, rather than tabular results are provided because of the large volume of the latter. Tabular results are on file at VIMS.

Movement of the drogue during all sets is summarized in Figure IV-2 which shows starting and ending times for each set. Each drogue track is annotated with tick marks indicating drogue position at ten minute intervals. Grid lines in this figure are 500m apart. Overlying tracks on a chart of the study area shows the drogue generally remained in natural channels except during the 15 August experiment when the drogue moved northward during the flooding tide and crossed over York Spit. During this excursion, the drogue, while remaining 2m above the bottom, changed elevation from a starting depth of 9m, descended to 10.5m and then moved vertically to 3.5m below the surface in less than an hour (see Appendix IV-1). Temperature at the drogue changed lessthan .02°C while salinity decreased by less than .05psu from its deepest to it shallowest positions.

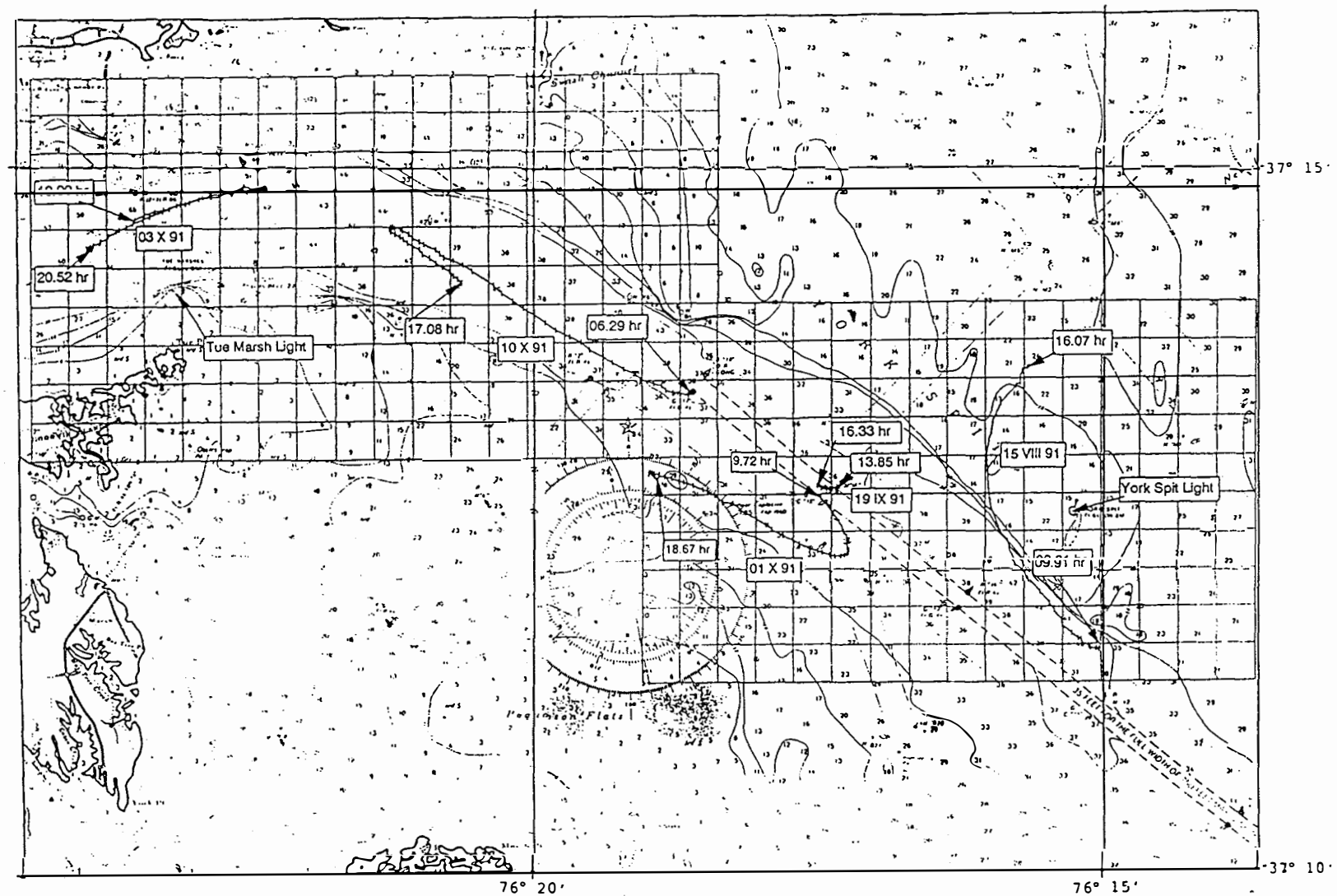


Figure IV-2. Section of NOAA chart #12238, Chesapeake Bay (Mobjack Bay and York River Entrance) showing drogue tracks during five sets in August, September and October 1991. Dates and starting-ending time of each set are indicated. Tick marks along drogue track indicate positions at 10 minute intervals. Overlying grid has 1/2 km squares.

Cruise tracks of R/V Langley during the October experiments are shown in Figure IV-3 with CTD stations indicated by squares.

Graphic results from each drogue experiment are found in individual appendices (IV-1 through IV-5). The first figure in each appendix gives an enlarged view of the drogue track on a 500 by 500m grid with tick marks indicating successive 10 minute positions. Next, contour plots of depth and time variations of isotherms, isohalines and isopycnals along the drogue track are presented. For the October cruises, results of the R/V Langley CTD casts are presented as plots of similar isopleth variations (of temperature, salinity and density) for depth vs distance normal to the drogue track. Contour plots are followed by two types of parameter vs depth plots for temperature, salinity, and density. The first in each of these series is a composite of all values of the parameter vs depth obtained for the experiment. It indicates the variability of the parameter at drogue level during the experiment. The same data is then presented in expanded fashion where each successive plot is offset by .05 unit to allow easier comparison of changes in vertical structure with time. Finally, values of drogue depth and temperature, salinity, and density at the drogue level are shown as time series.

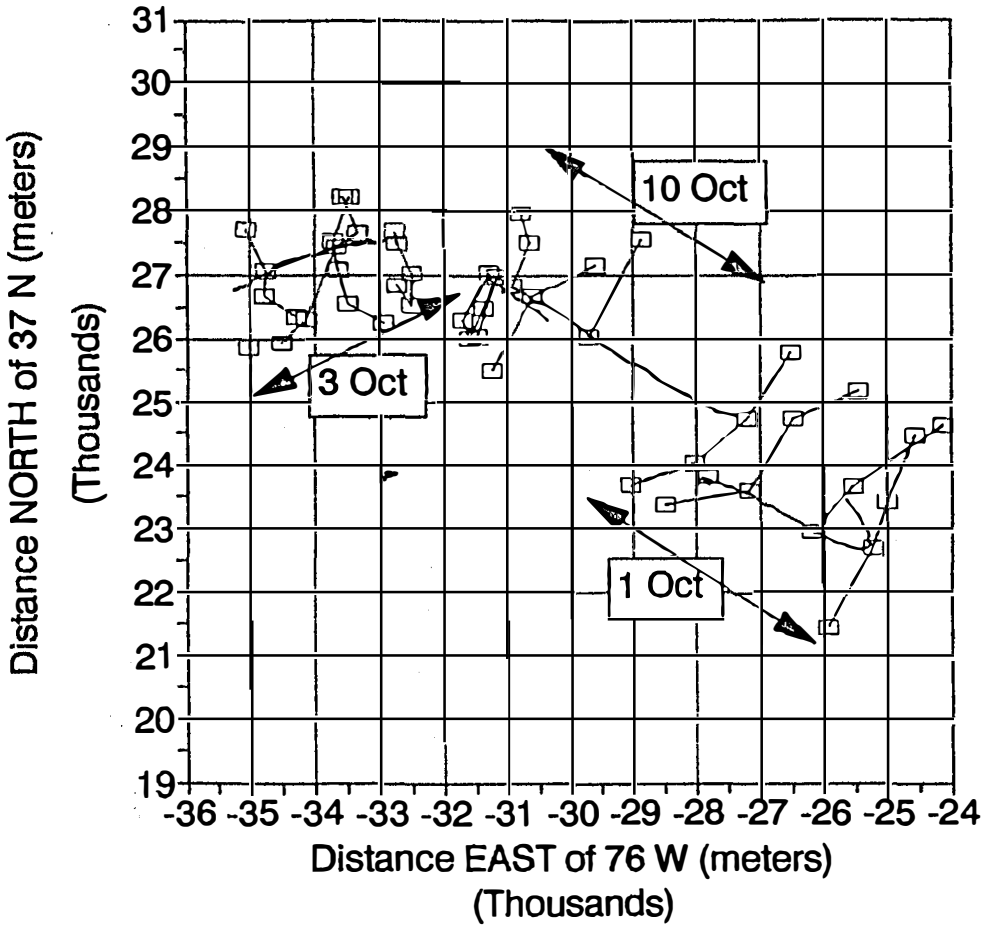


Figure IV-3. Transects and stations occupied by R/V Langley (dashed lines and open squares) across drogue trajectories during October 1991.

REFERENCES

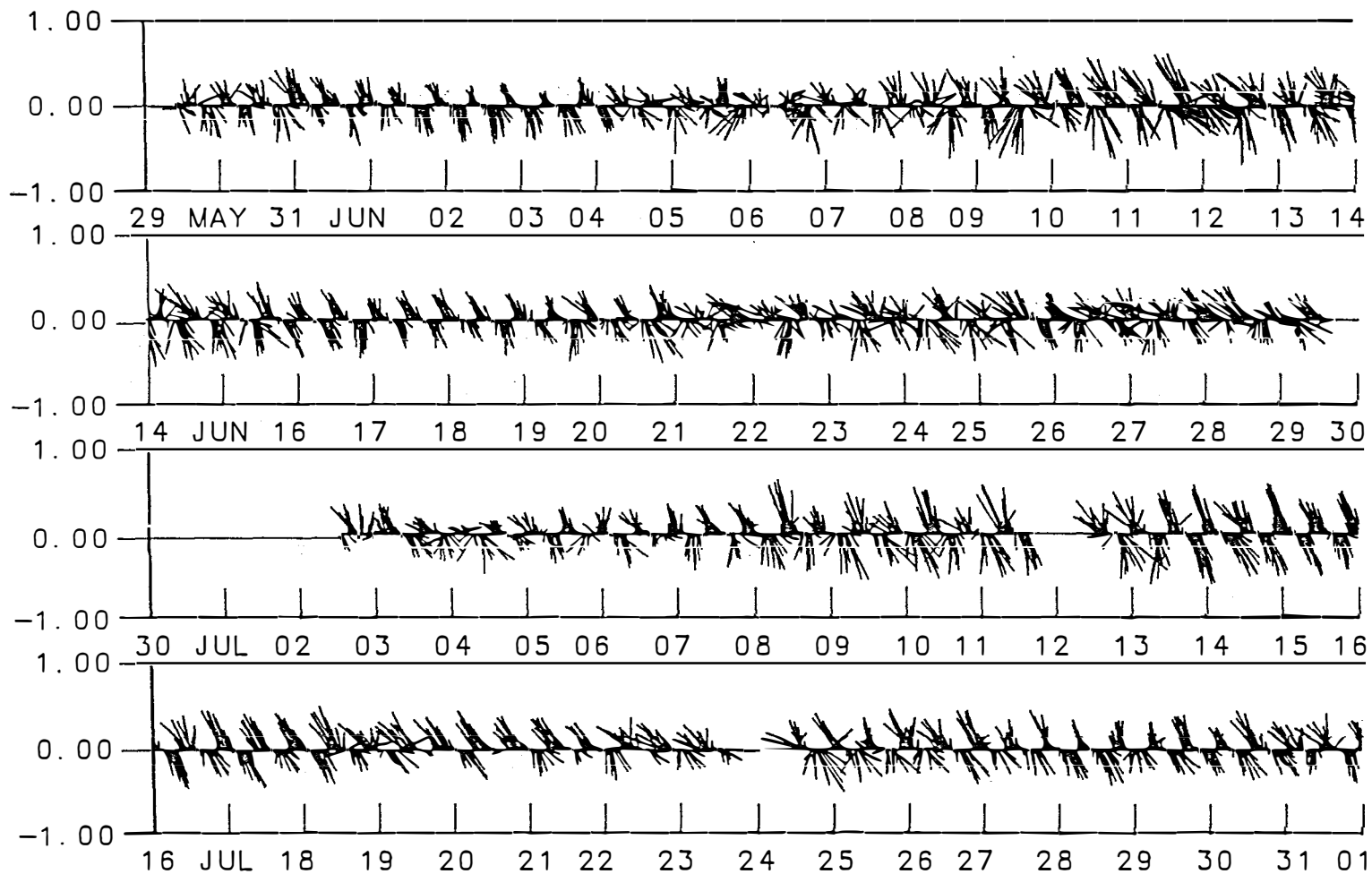
Kuo, A. Y, and B. J. Neilson, 1987. Hypoxia and Salinity in Virginia Estuaries. Estuaries, Vol. 10, No. 4, pp 277-283.

Ruzecki, Evon P., 1990. Bottom Water Advection and Potential for Dissolved Oxygen Depletion in Chesapeake Bay. Unpublished manuscript, VIMS.

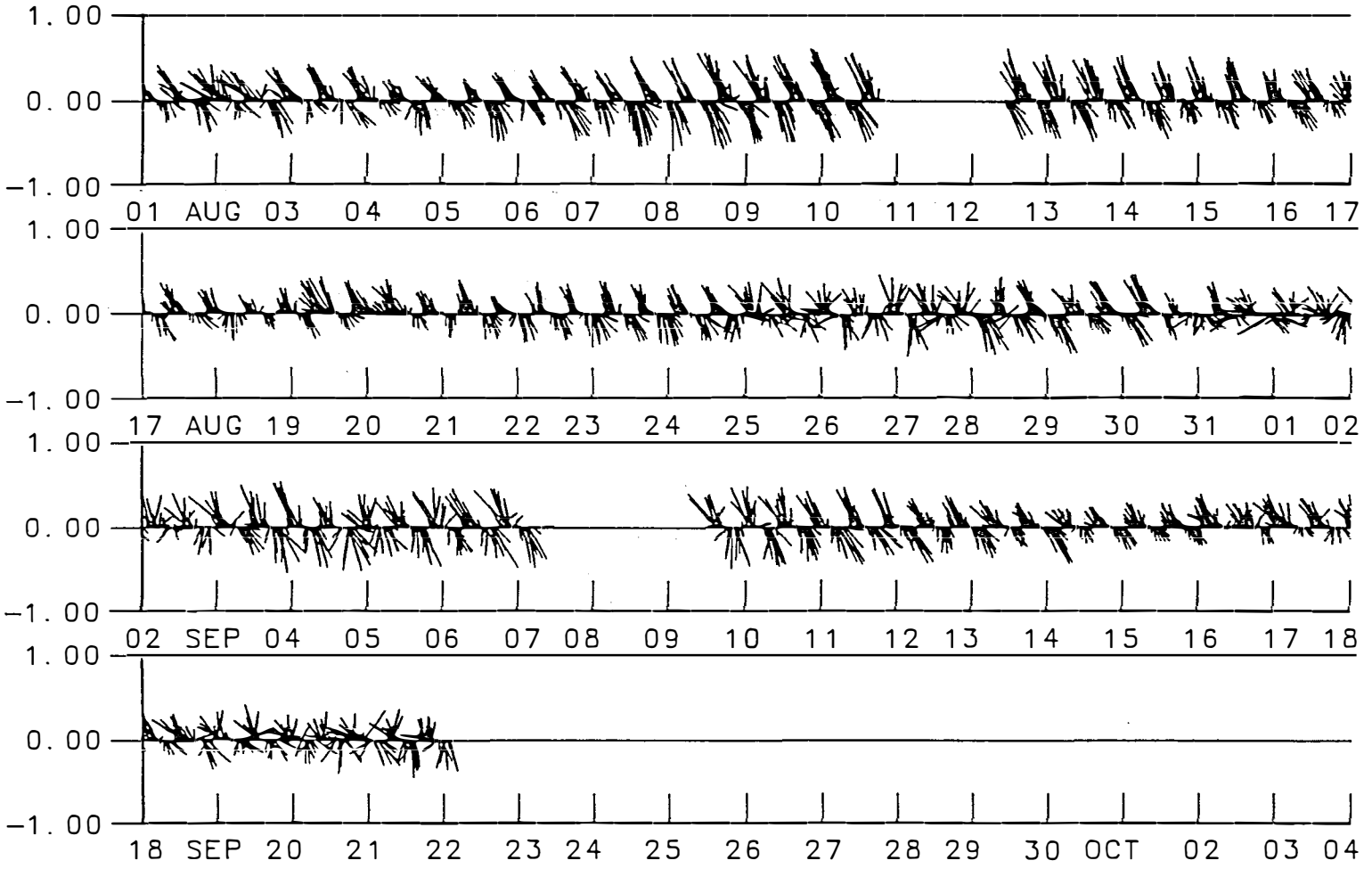
Walters, R. A. and C. Heston, 1981. Removing Tidal Period Variations from Time-Series Data Using Low-Pass Digital Filters. J. of Physical Oceanography, Vol 12, pp 112-115.

Appendix I-1

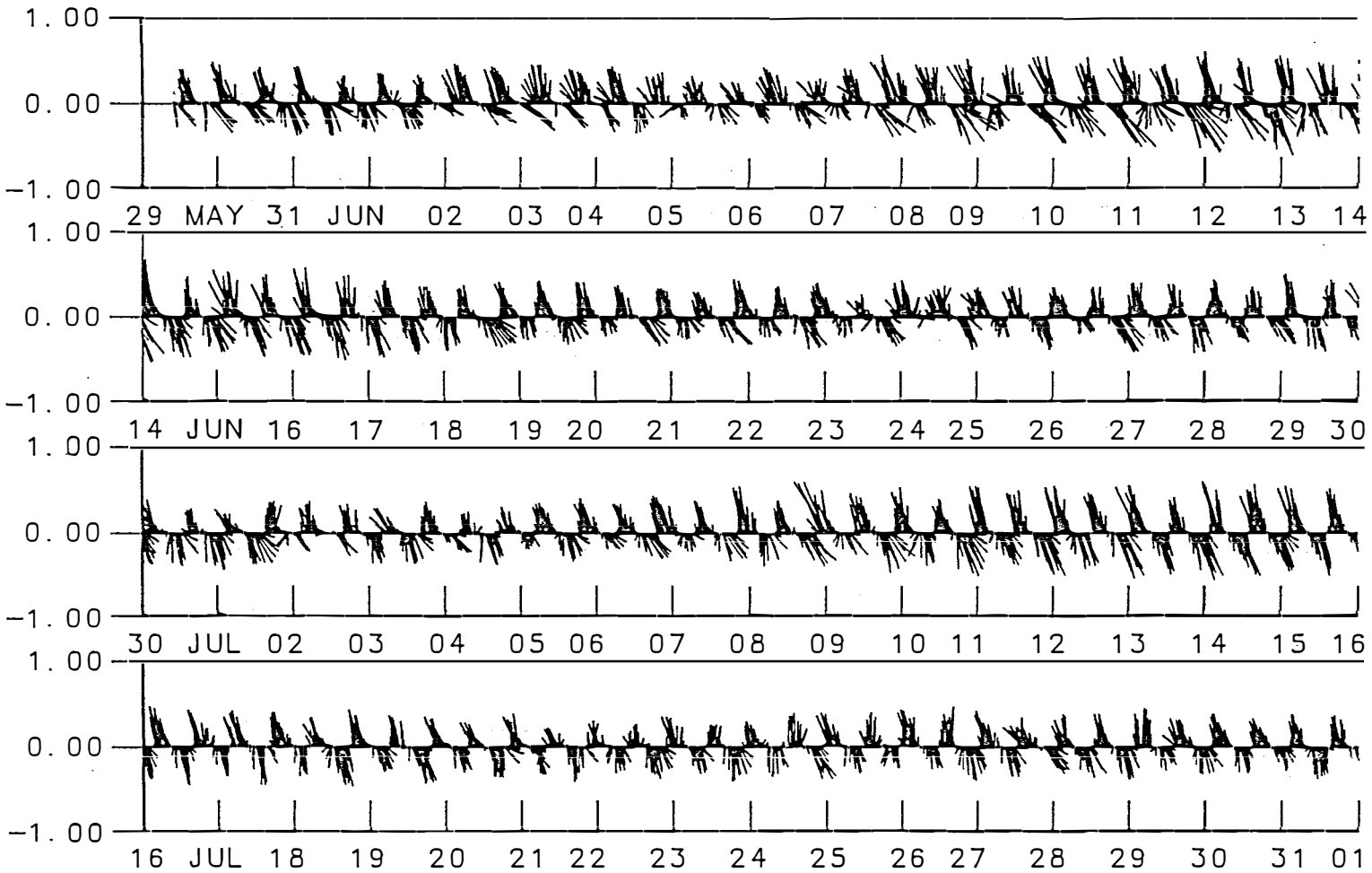
Stickplots of Currents



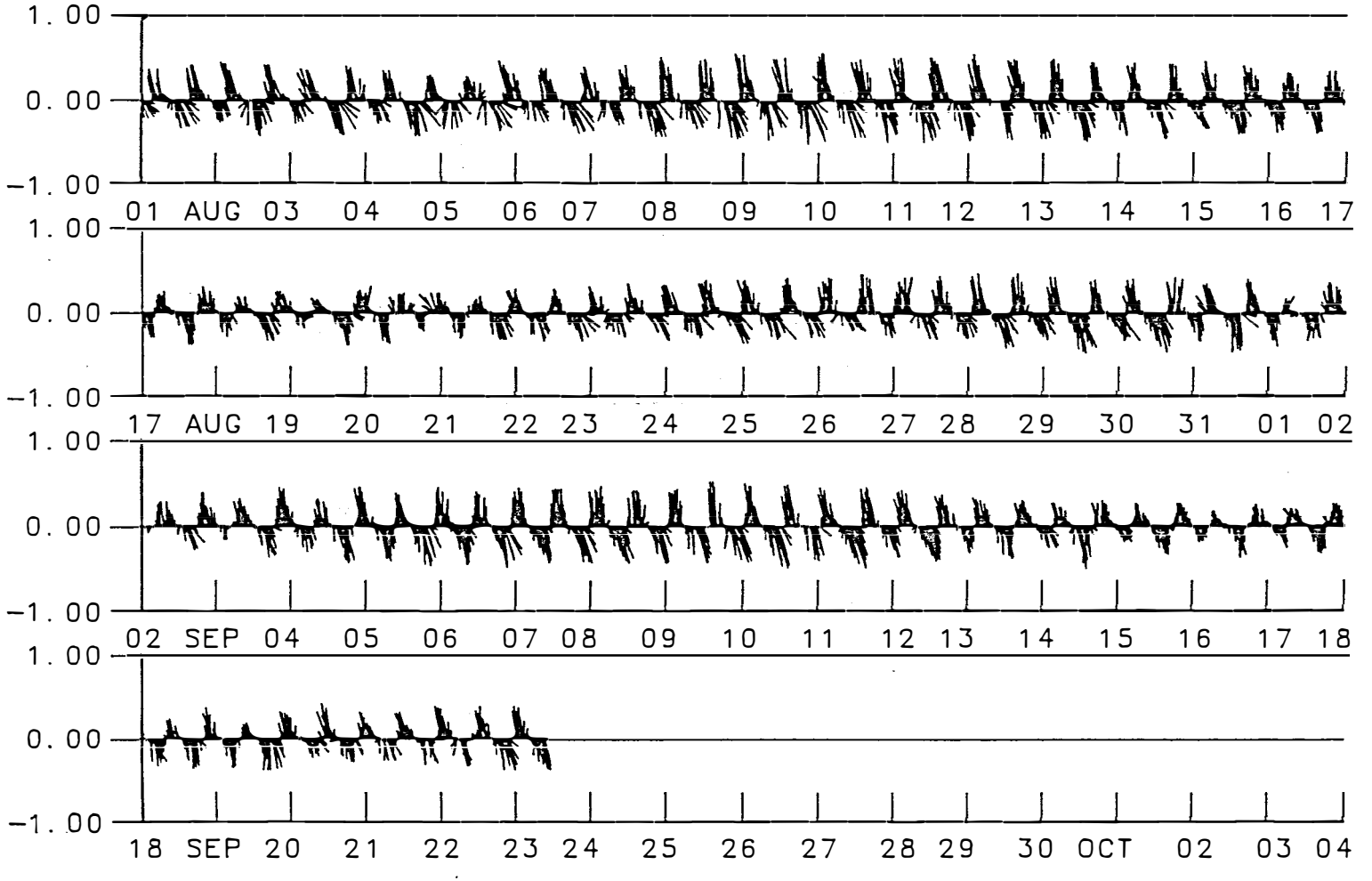
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.5 M
VECTORS ARE IN M/SEC, POSITIVE Y-AXIS TO THE EAST



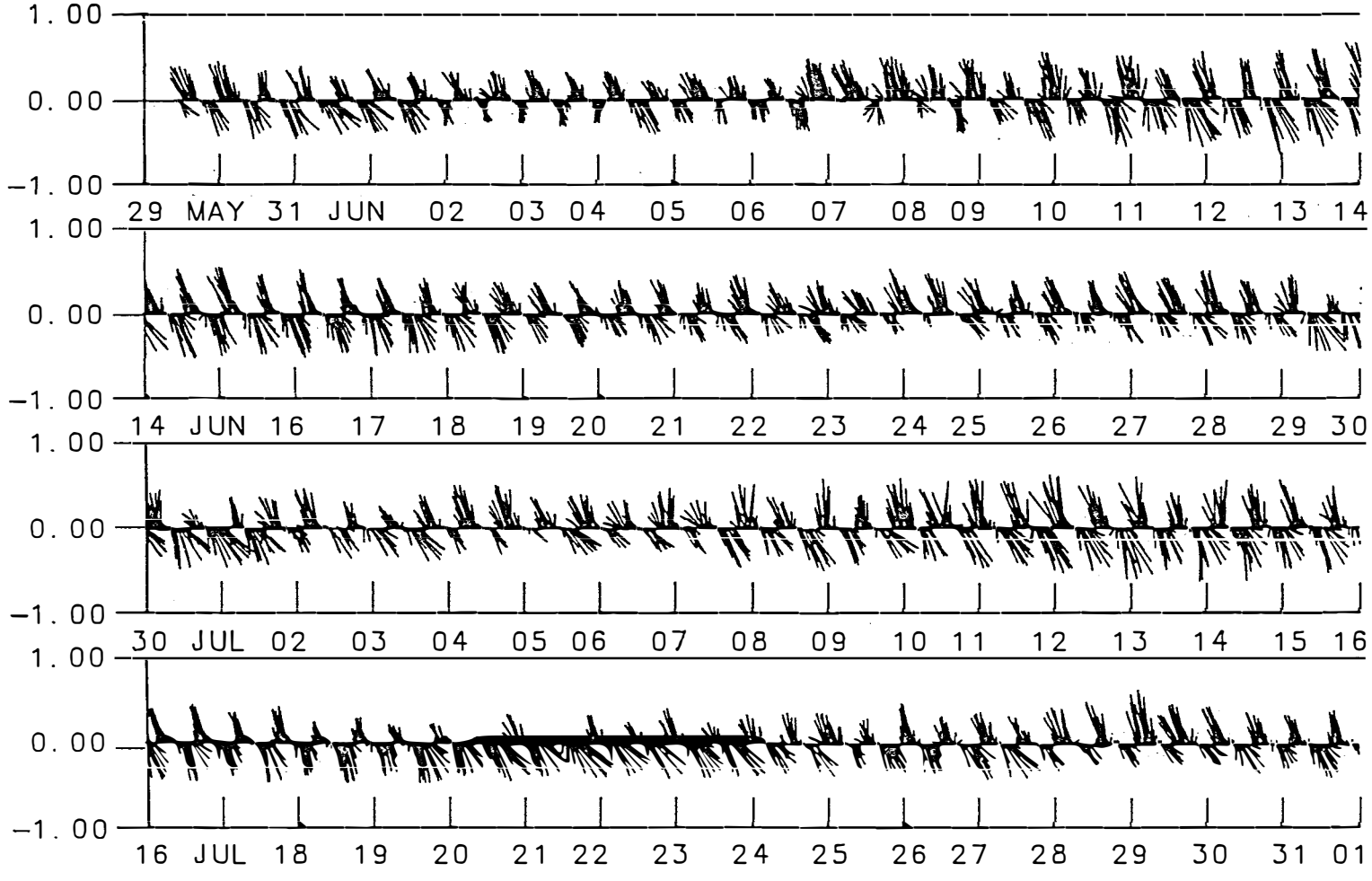
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES, DEPTH = 1.5 M
VECTORS ARE IN M/SEC, POSITIVE Y-AXIS TO THE EAST



1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 6 M
VECTORS ARE IN M/SEC, POSITIVE Y-AXIS TO THE EAST



1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 6 M
VECTORS ARE IN M/SEC, POSITIVE Y-AXIS TO THE EAST



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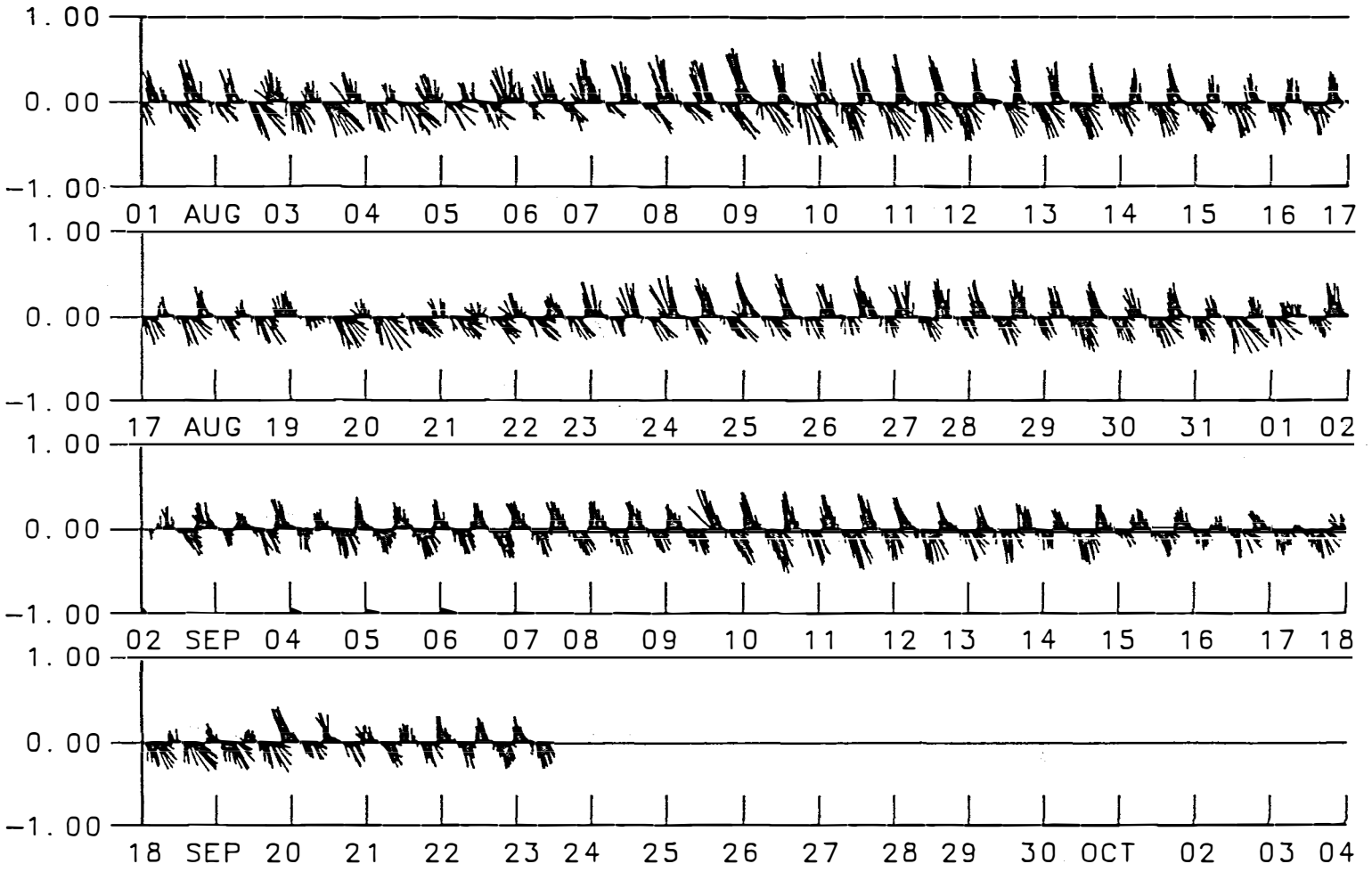
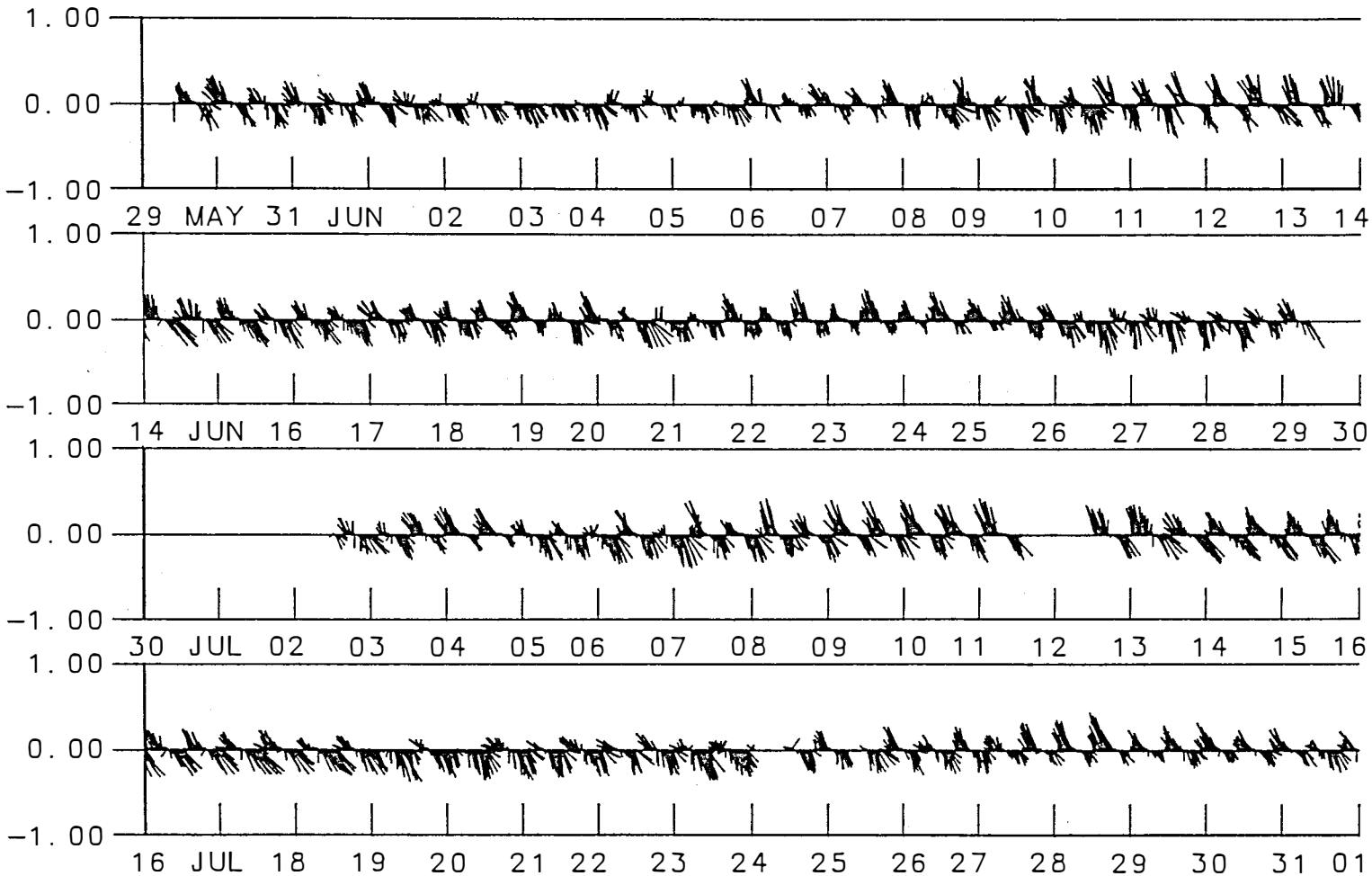
VECTORS ARE IN M/SEC, POSITIVE Y-AXIS TO THE EAST



1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 10 M
VECTORS ARE IN M/SEC, POSITIVE Y-AXIS TO THE EAST



1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
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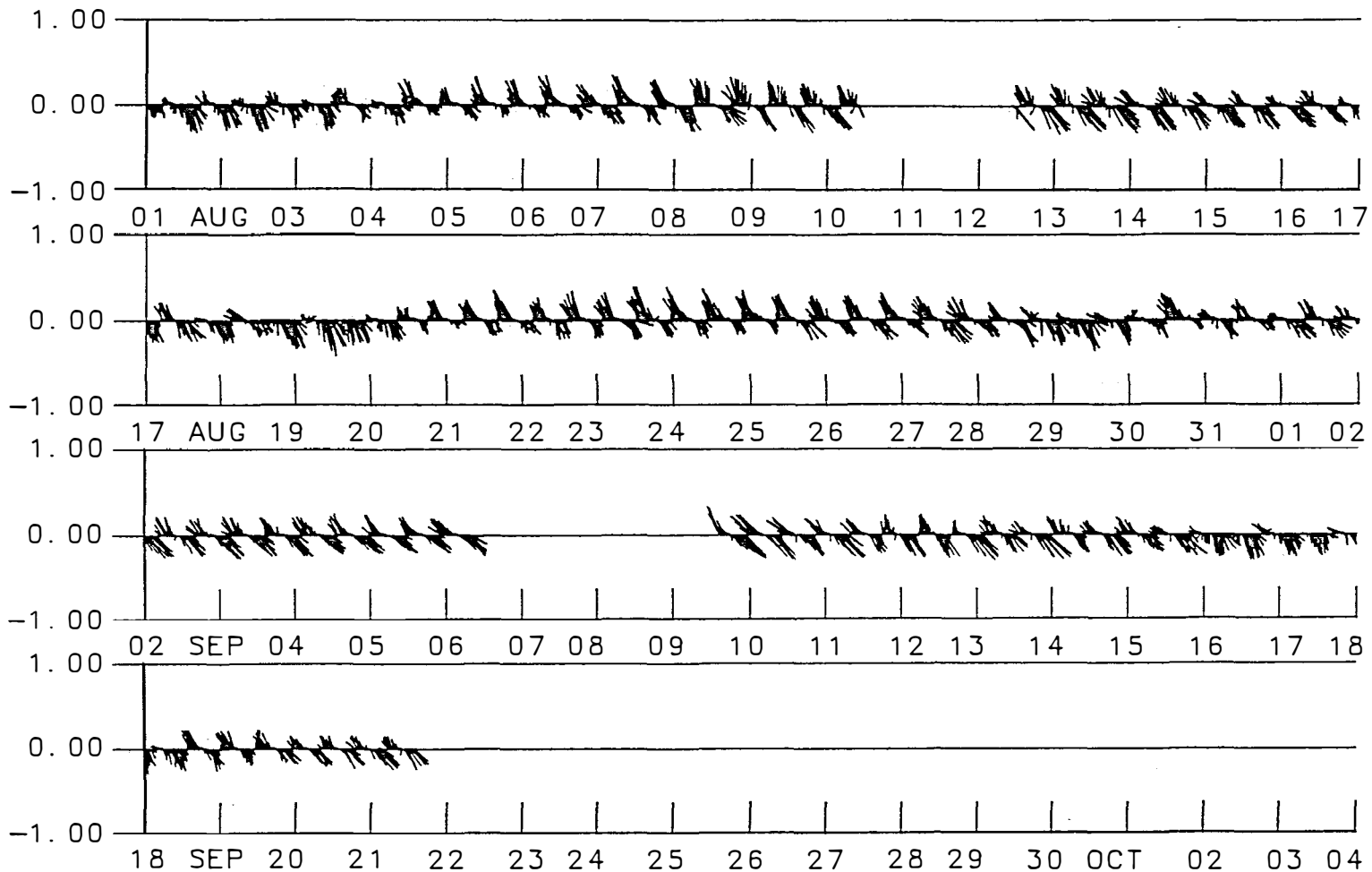
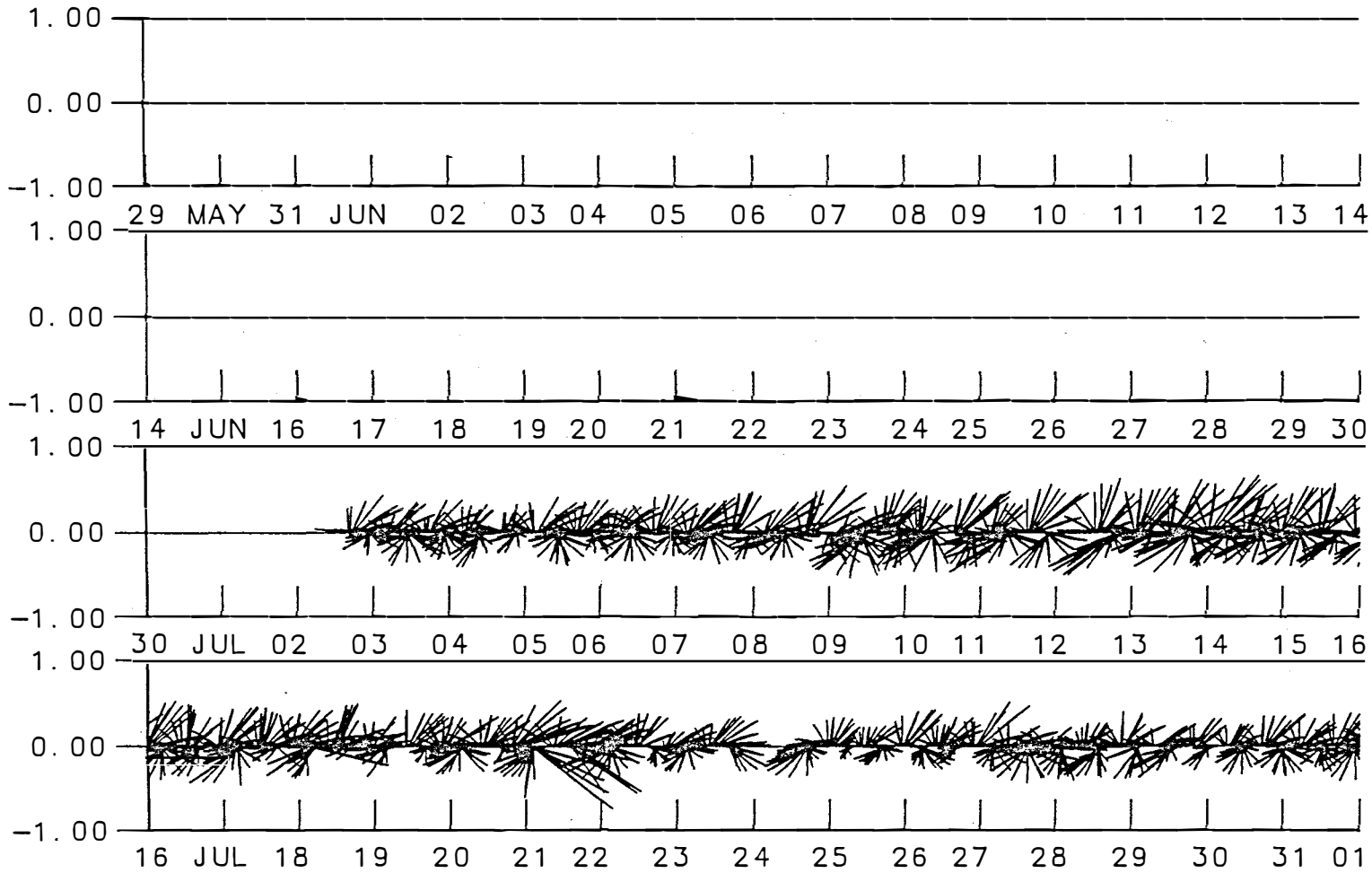
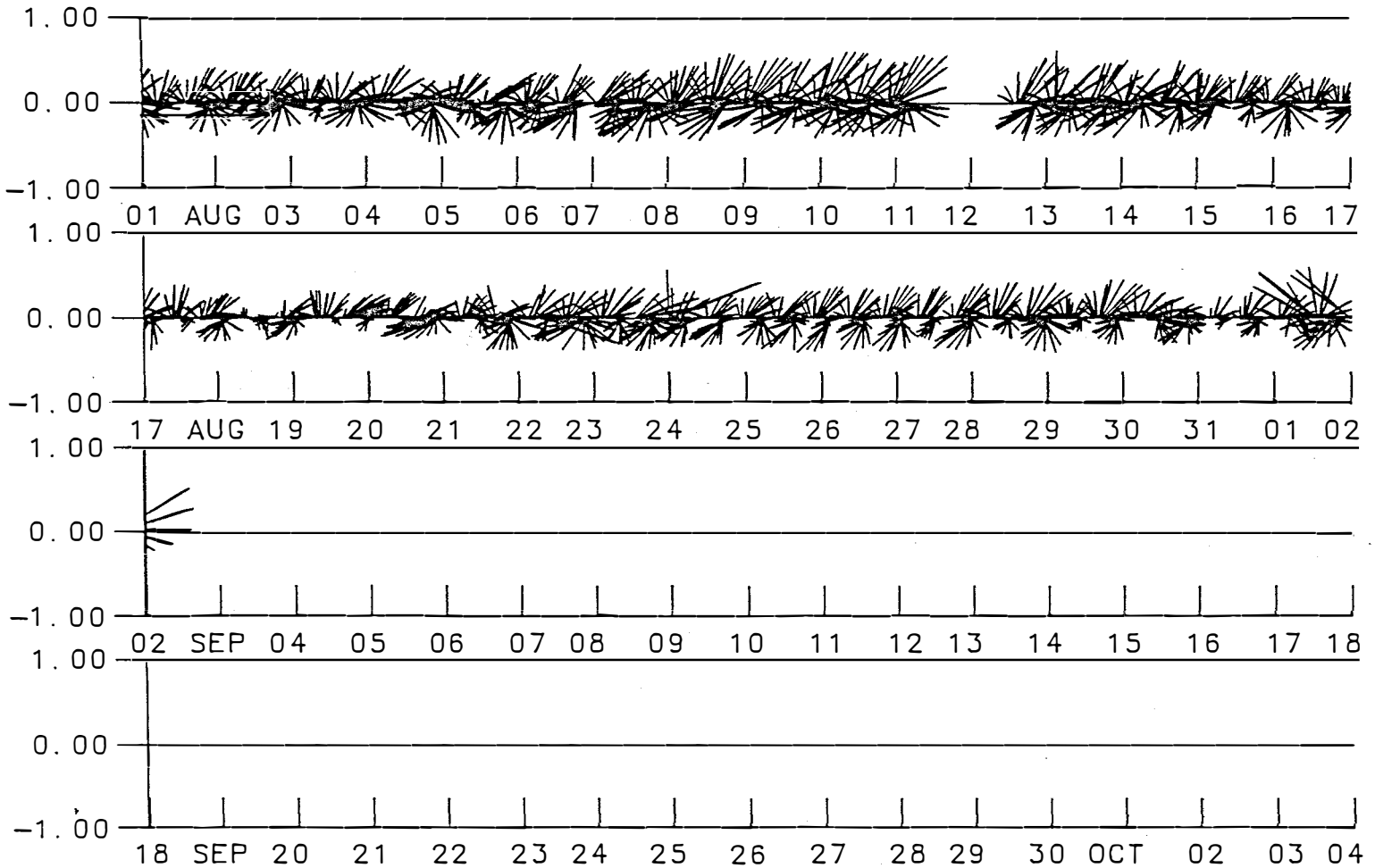


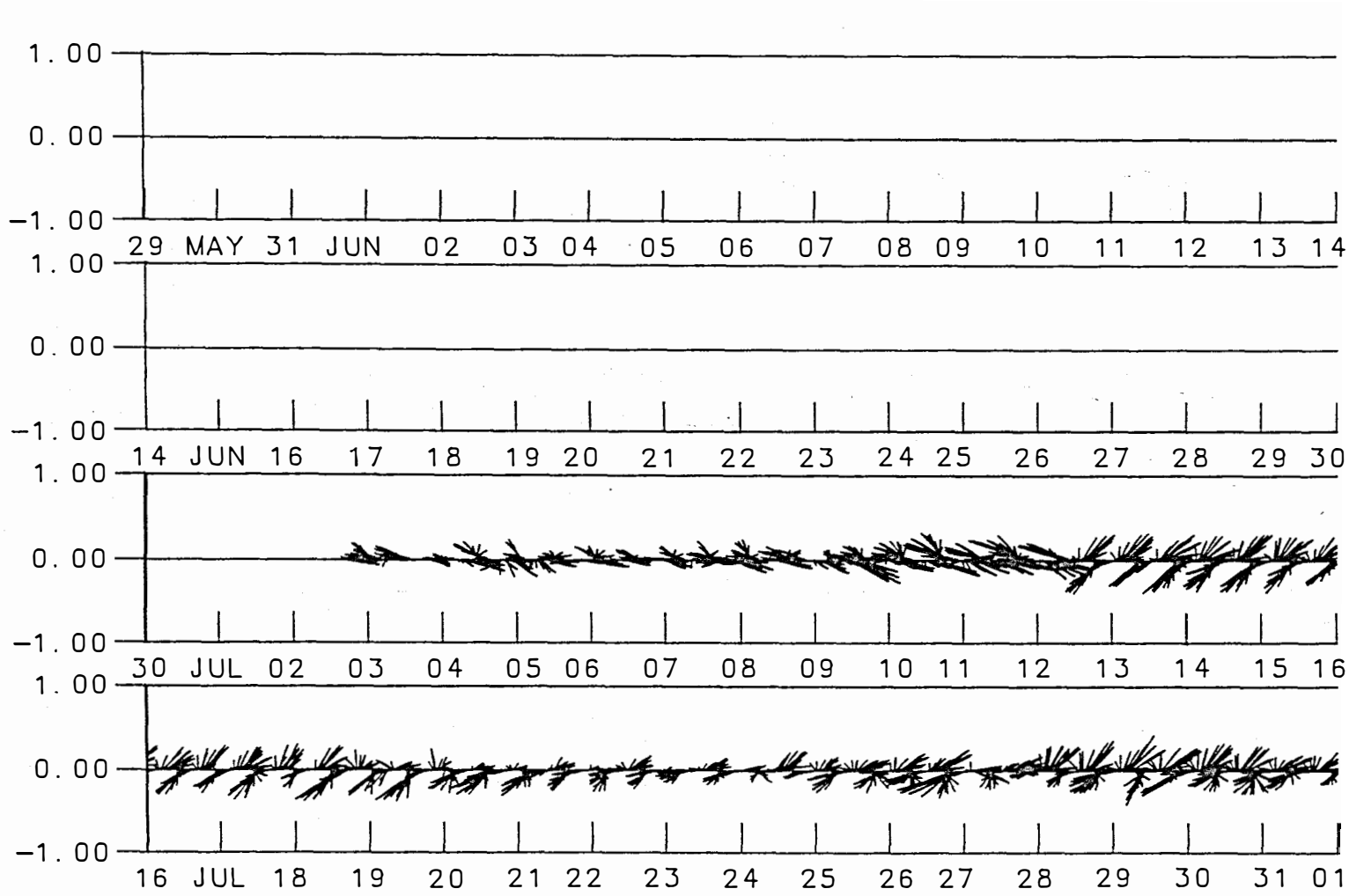
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
VECTORS ARE IN M/SEC, POSITIVE Y-AXIS TO THE EAST



1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
VECTORS ARE IN M/SEC, POSITIVE Y-AXIS TO THE EAST



1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
VECTORS ARE IN M/SEC, POSITIVE Y-AXIS TO THE EAST



1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 6 M
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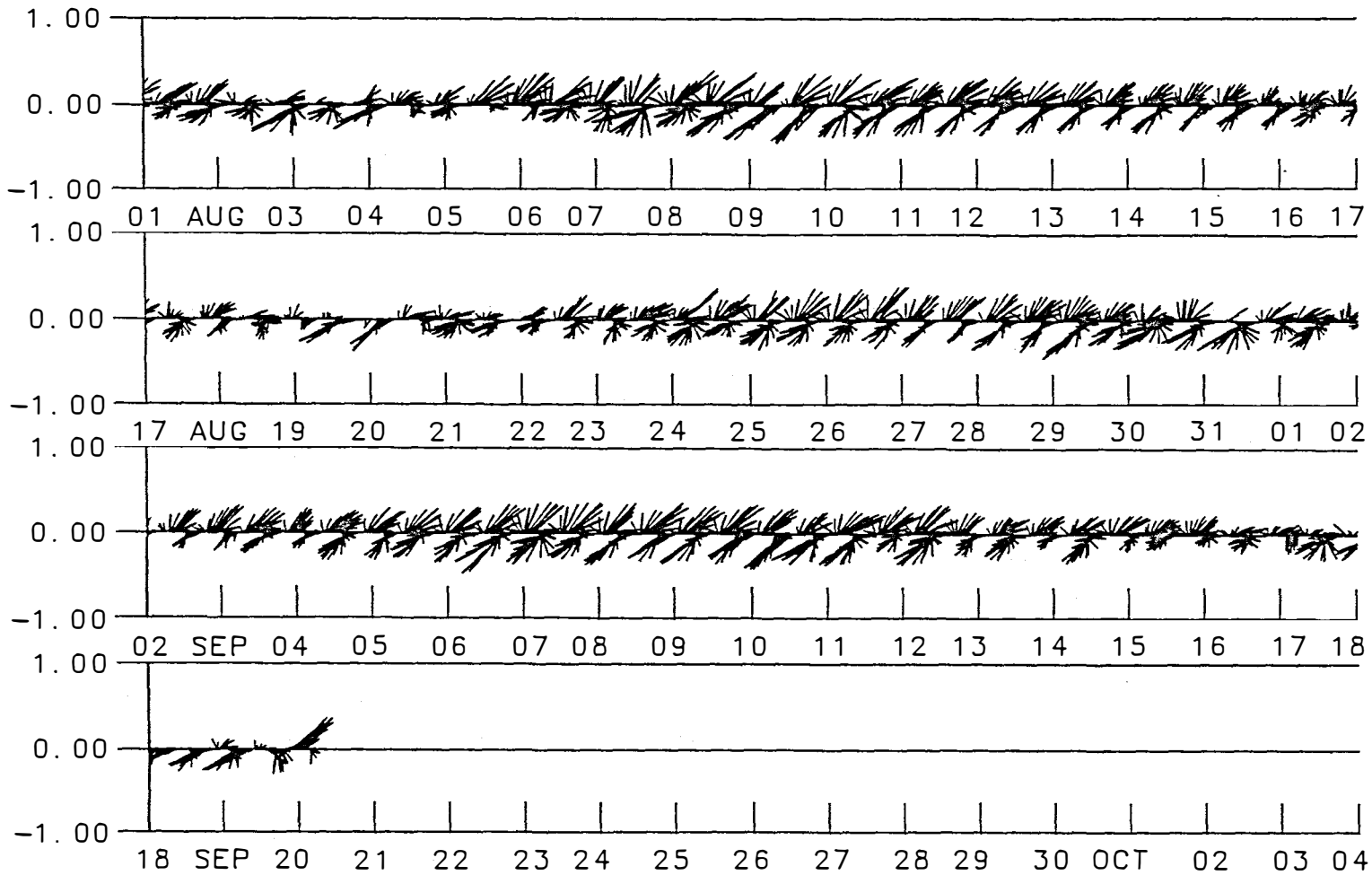

1991 YORK RIVER SUMMER SURVEY
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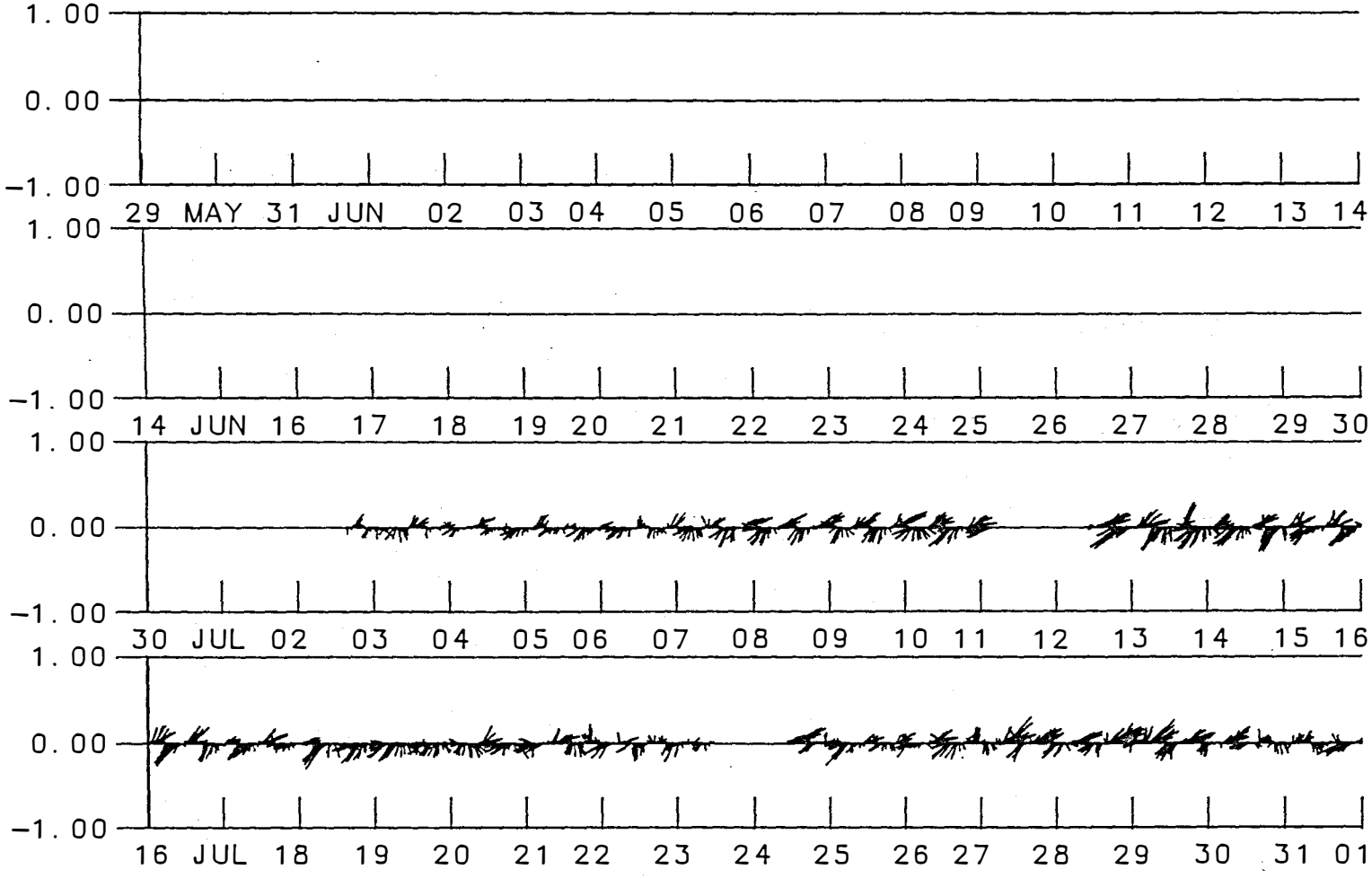

1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 10.3 M
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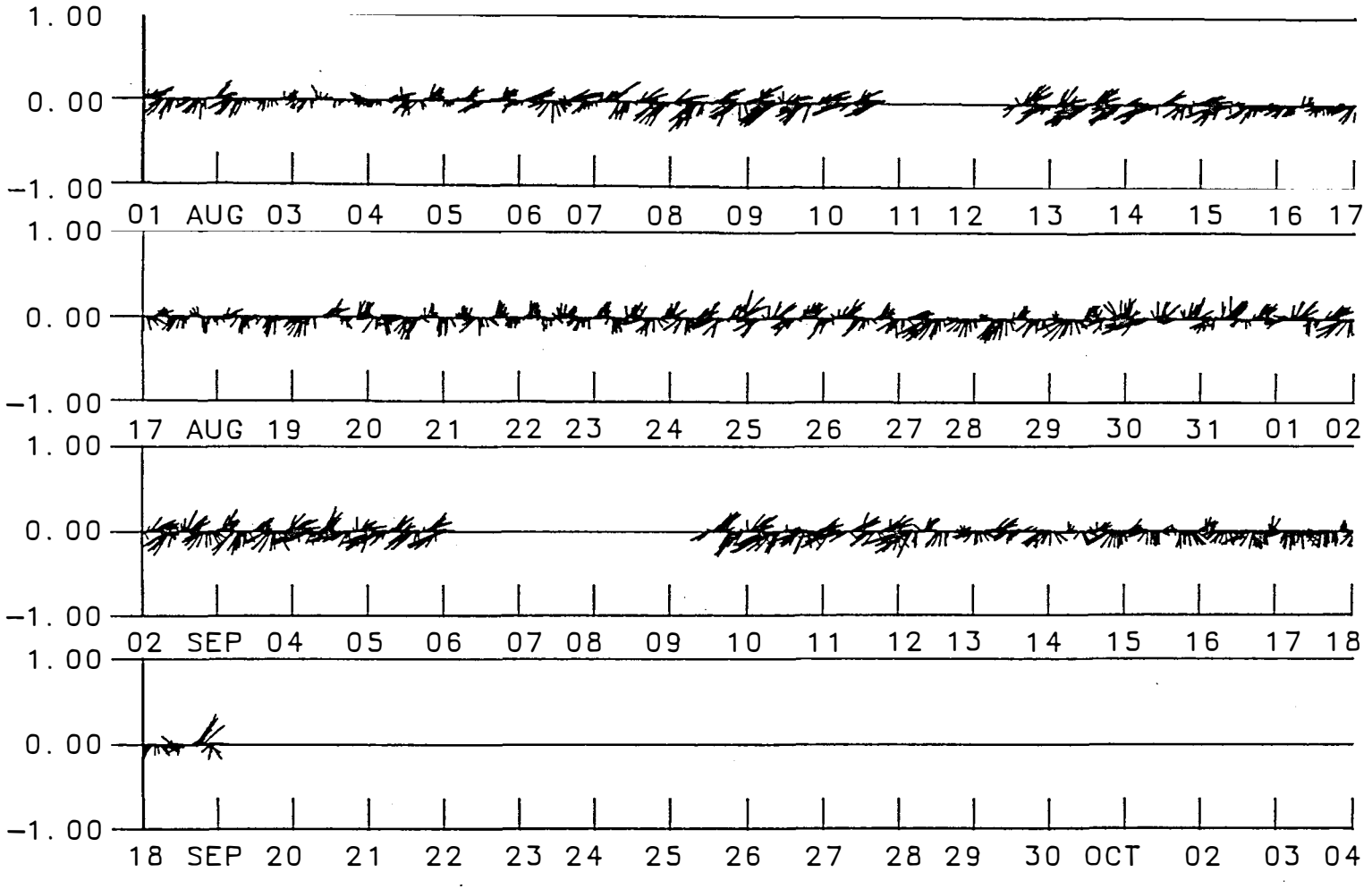
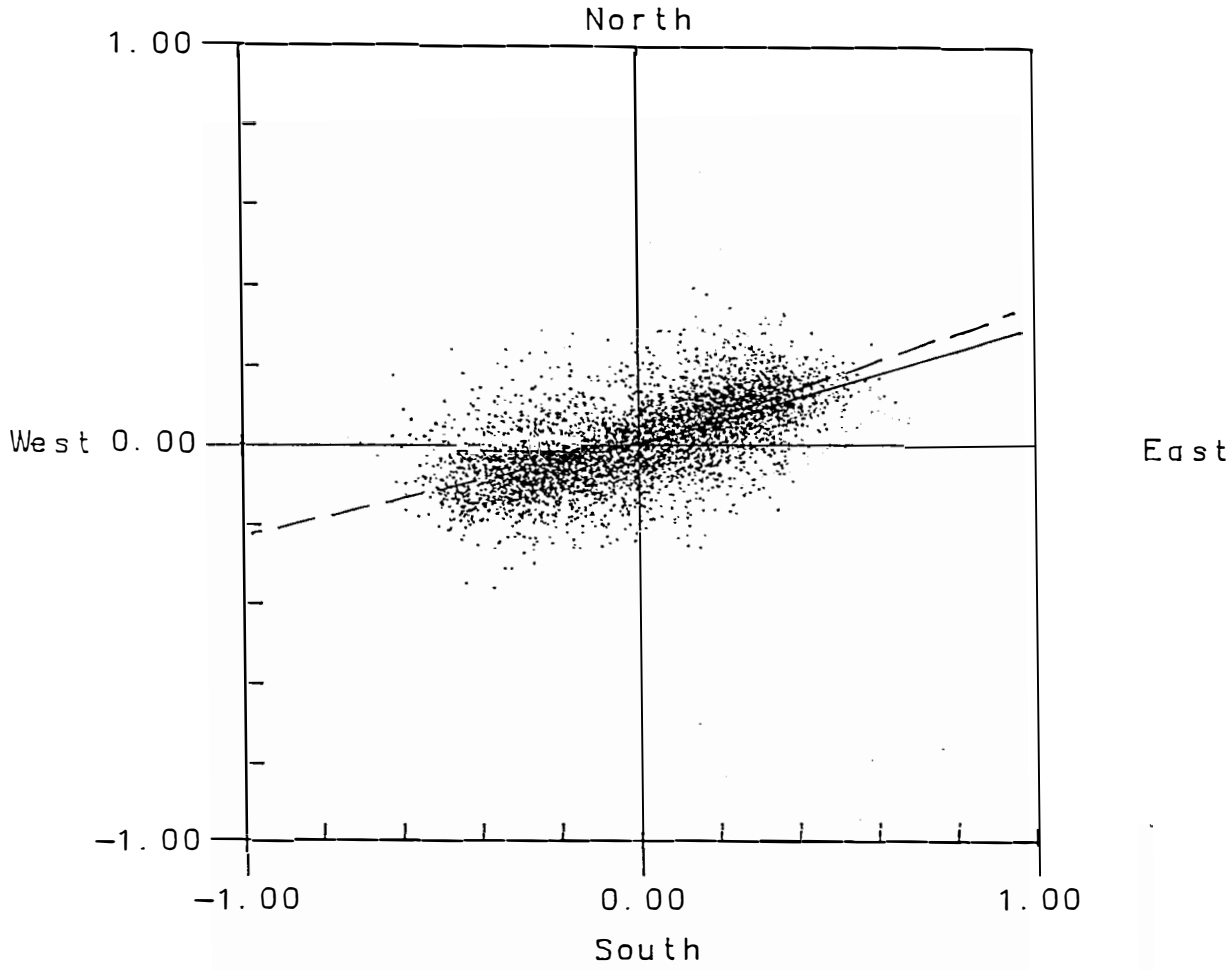


1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 10.3 M
VECTORS ARE IN M/SEC, POSITIVE Y-AXIS TO THE EAST

Appendix I-2

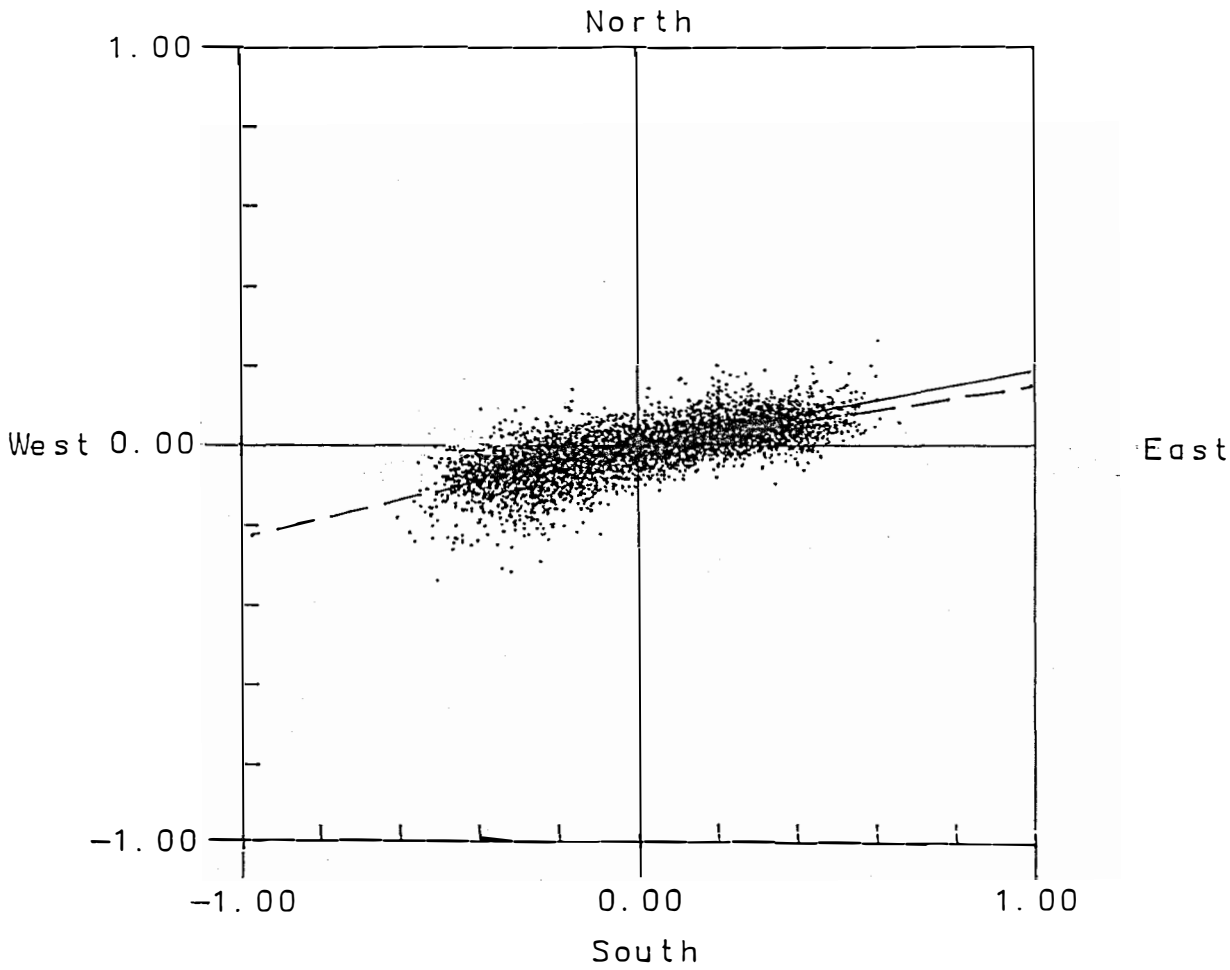
Scatterplots of Currents

(solid line is principal axis,
dashed lines are flood and ebb axes)



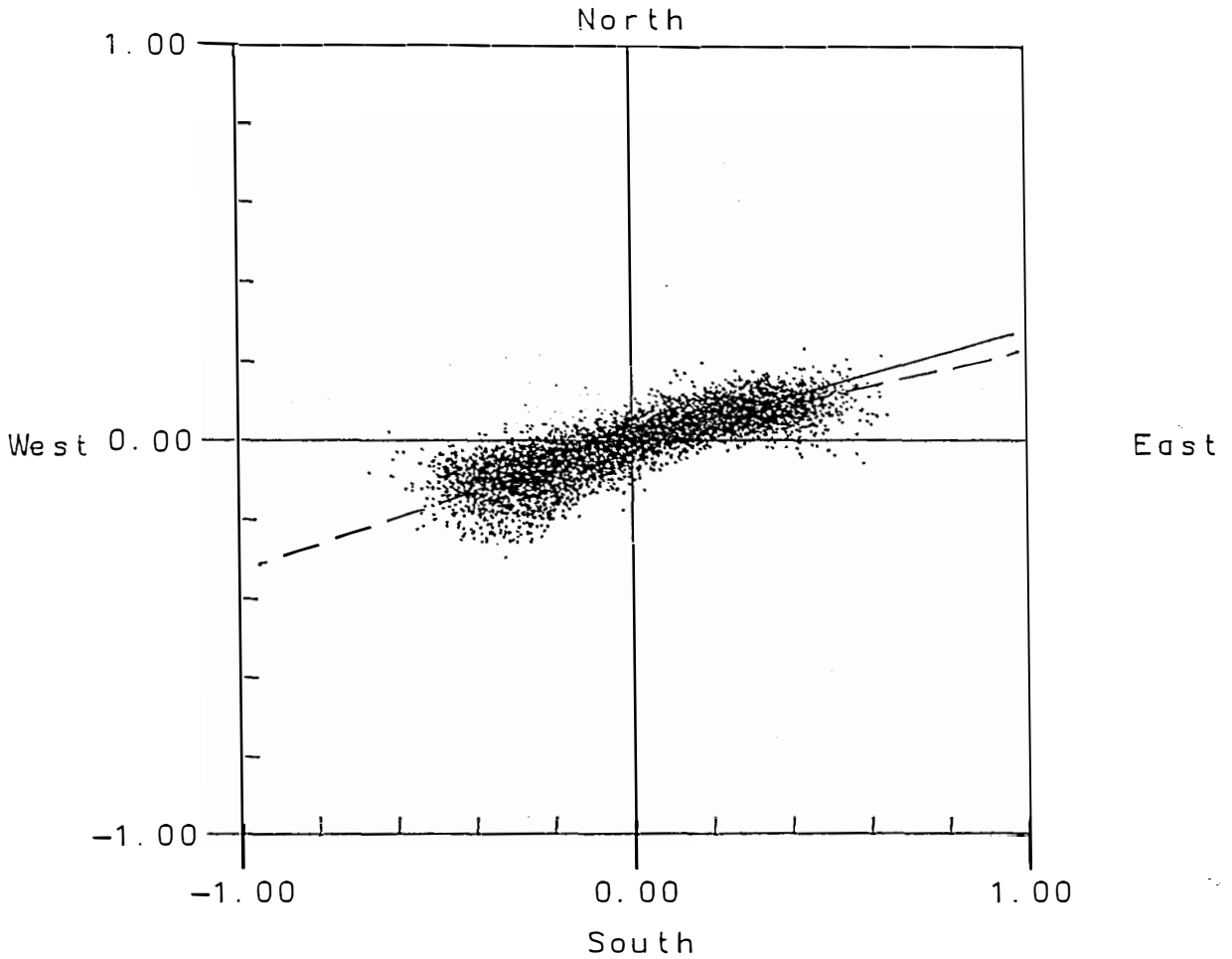
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.5 M
29 MAY, 1991 – 24 SEP, 1991 5141 OBSERVATIONS

PRINCIPAL AXIS	EBB	FLOOD
74.	71.	257.



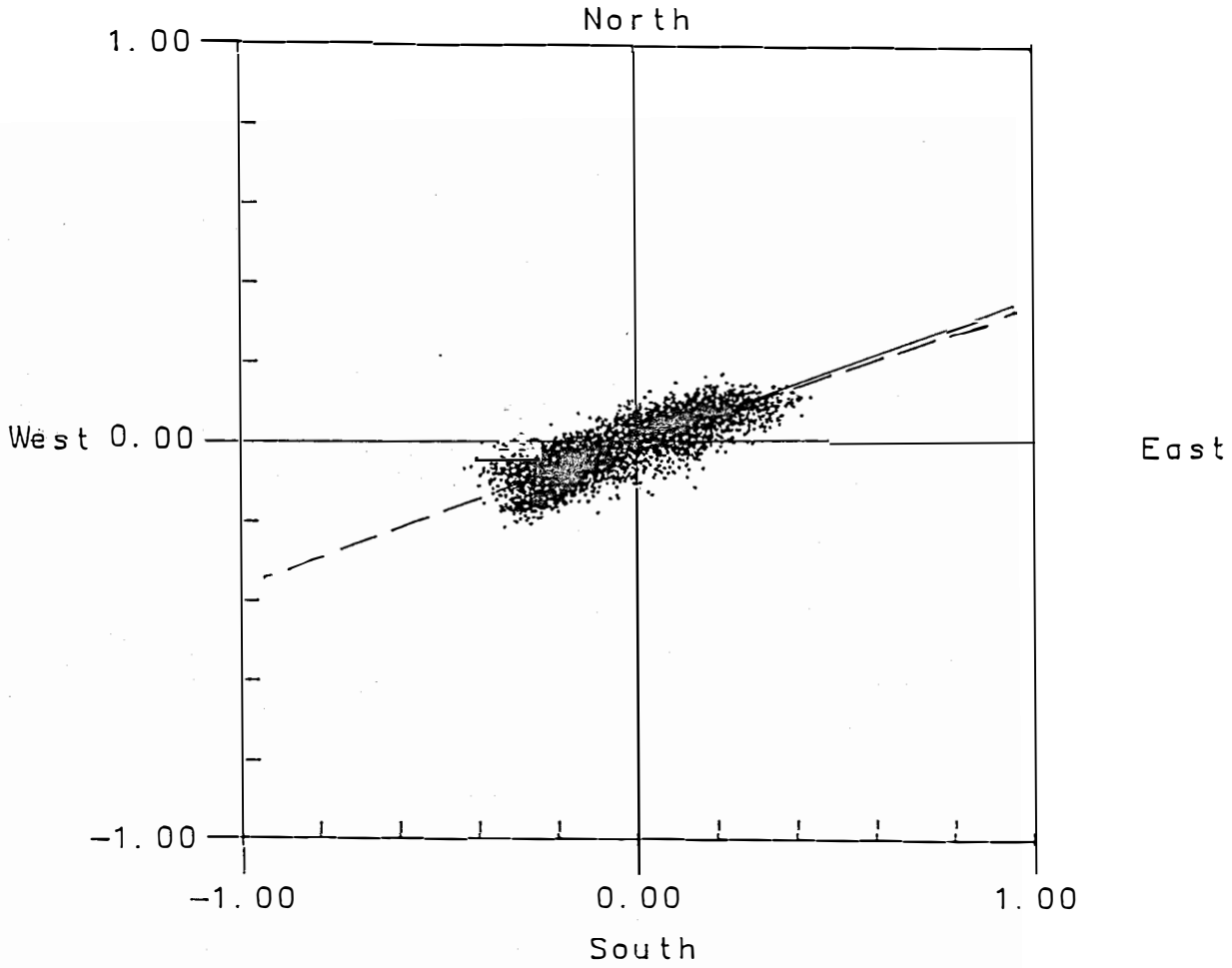
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 6 M
29 MAY, 1991 – 24 SEP, 1991 5603 OBSERVATIONS

PRINCIPAL AXIS	EBB	FLOOD
79.	81.	257.



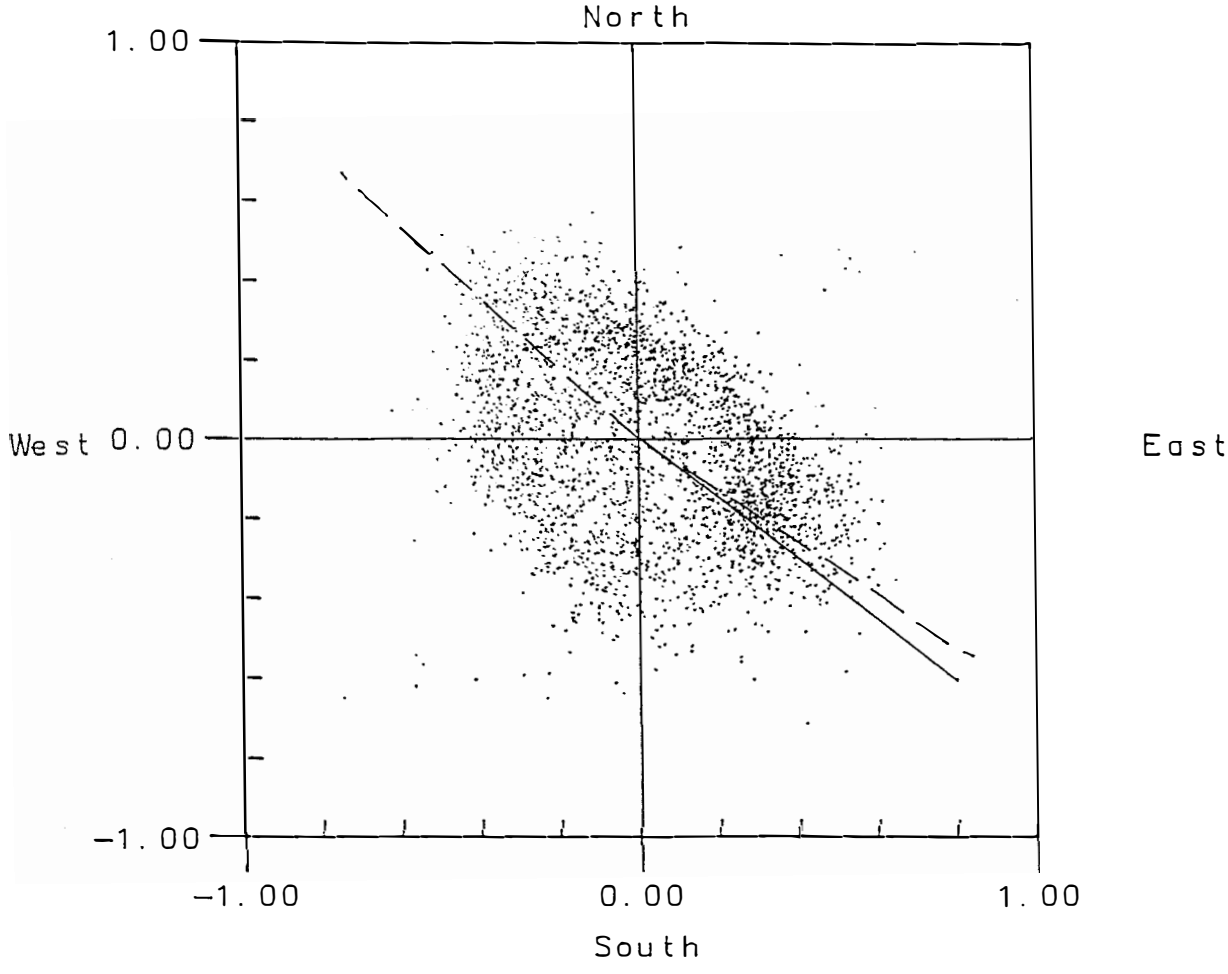
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 10 M
29 MAY, 1991 – 24 SEP, 1991 5606 OBSERVATIONS

PRINCIPAL AXIS	EBB	FLOOD
74.	77.	252.



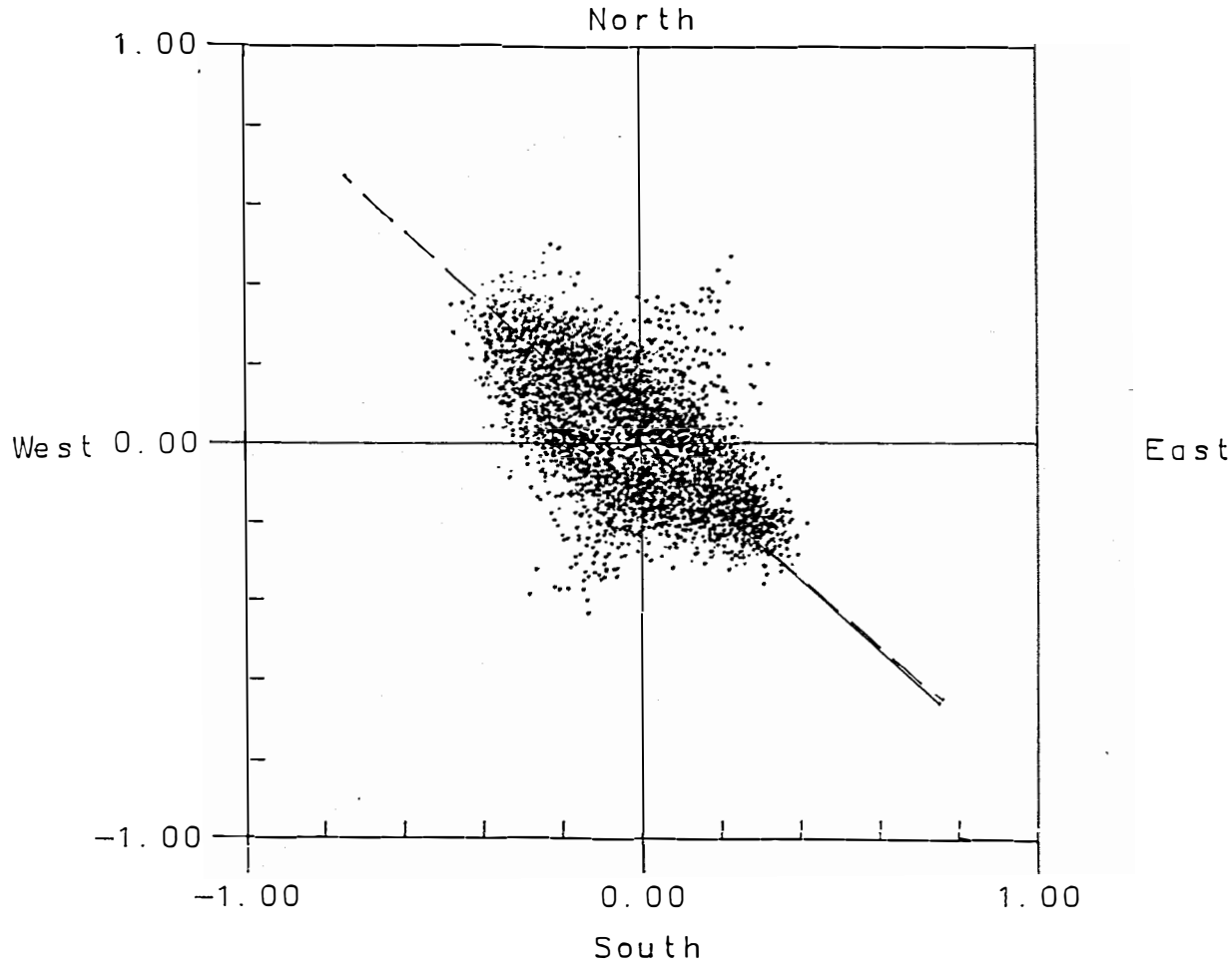
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
29 MAY, 1991 – 24 SEP, 1991 5061 OBSERVATIONS

PRINCIPAL AXIS	EBB	FLOOD
70.	71.	250.



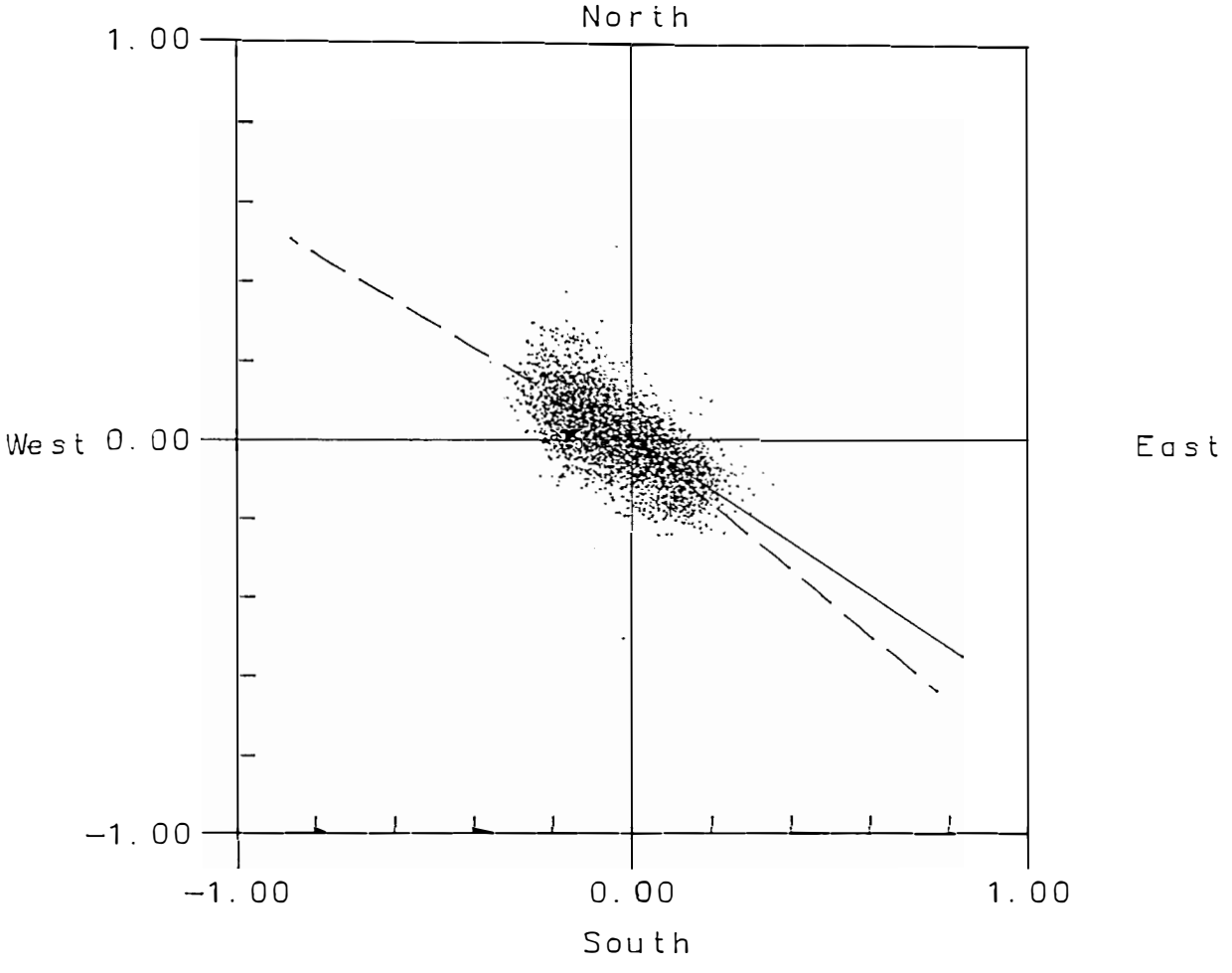
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
29 MAY, 1991 – 24 SEP, 1991 2833 OBSERVATIONS

PRINCIPAL AXIS	EBB	FLOOD
127.	123.	312.



1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 6 M
29 MAY, 1991 – 24 SEP, 1991 3810 OBSERVATIONS

PRINCIPAL AXIS	EBB	FLOOD
132.	131.	312.



1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 10.3 M
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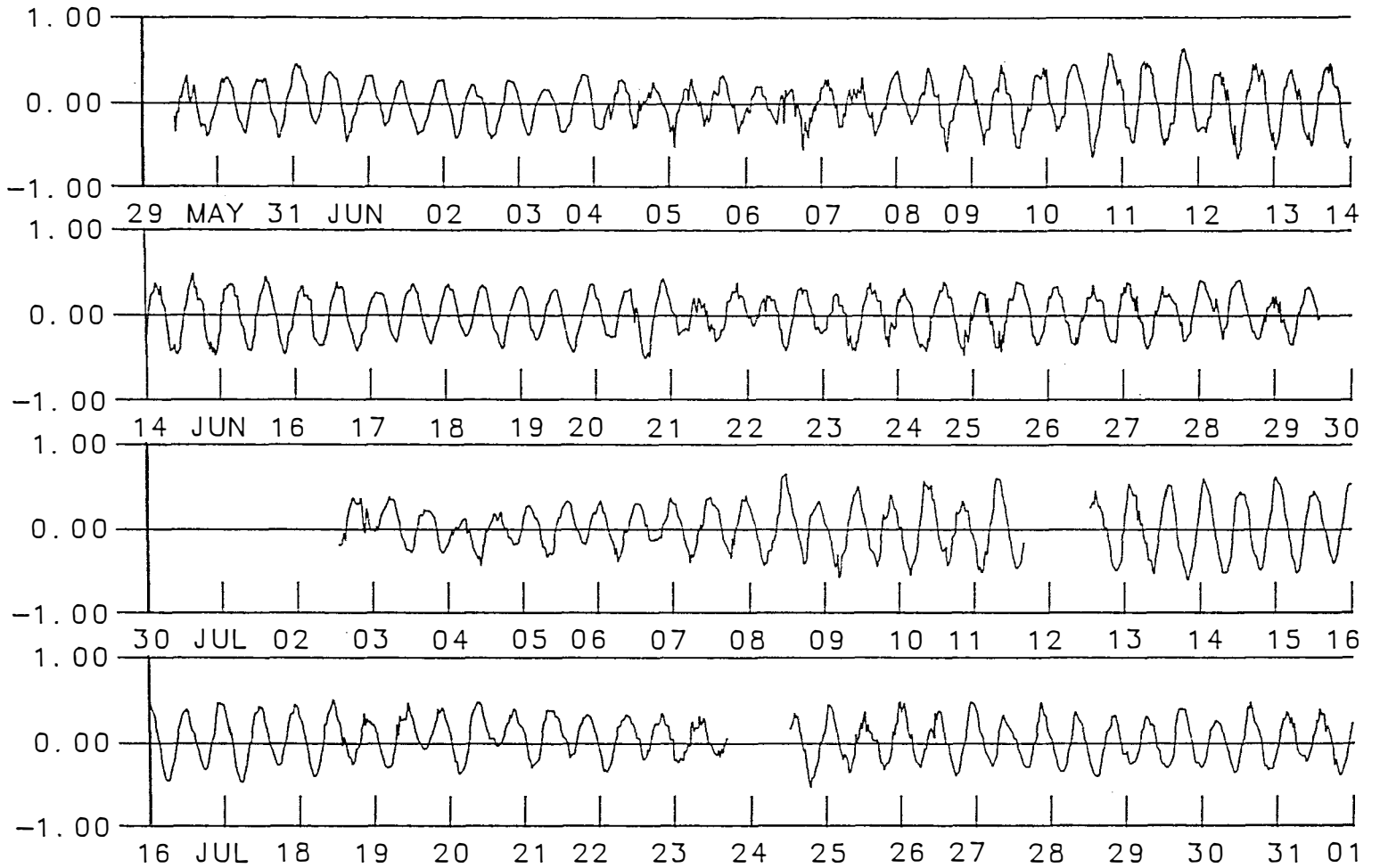
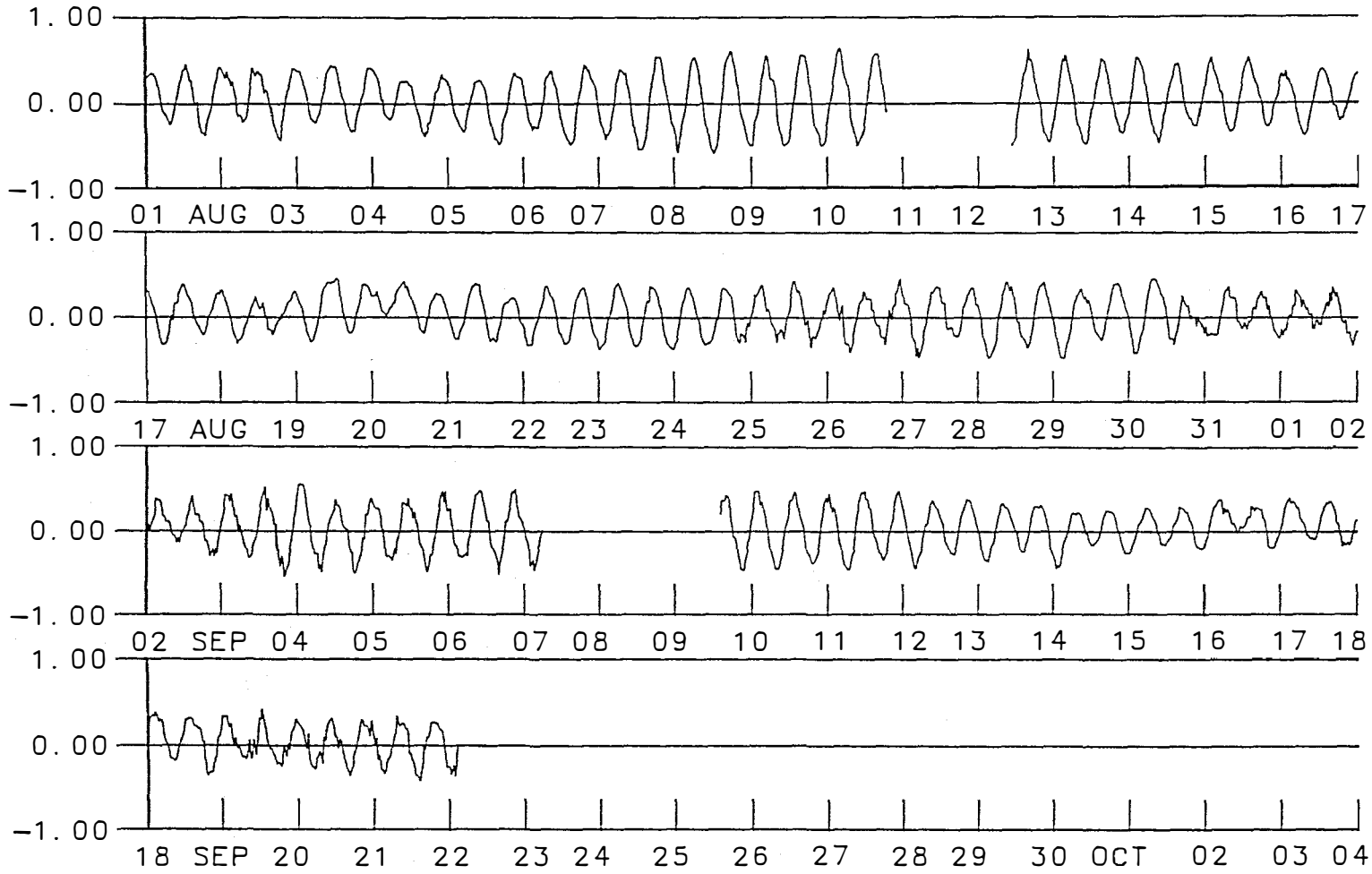
PRINCIPAL AXIS	EBB	FLOOD
124.	130.	300.

Appendix I-3

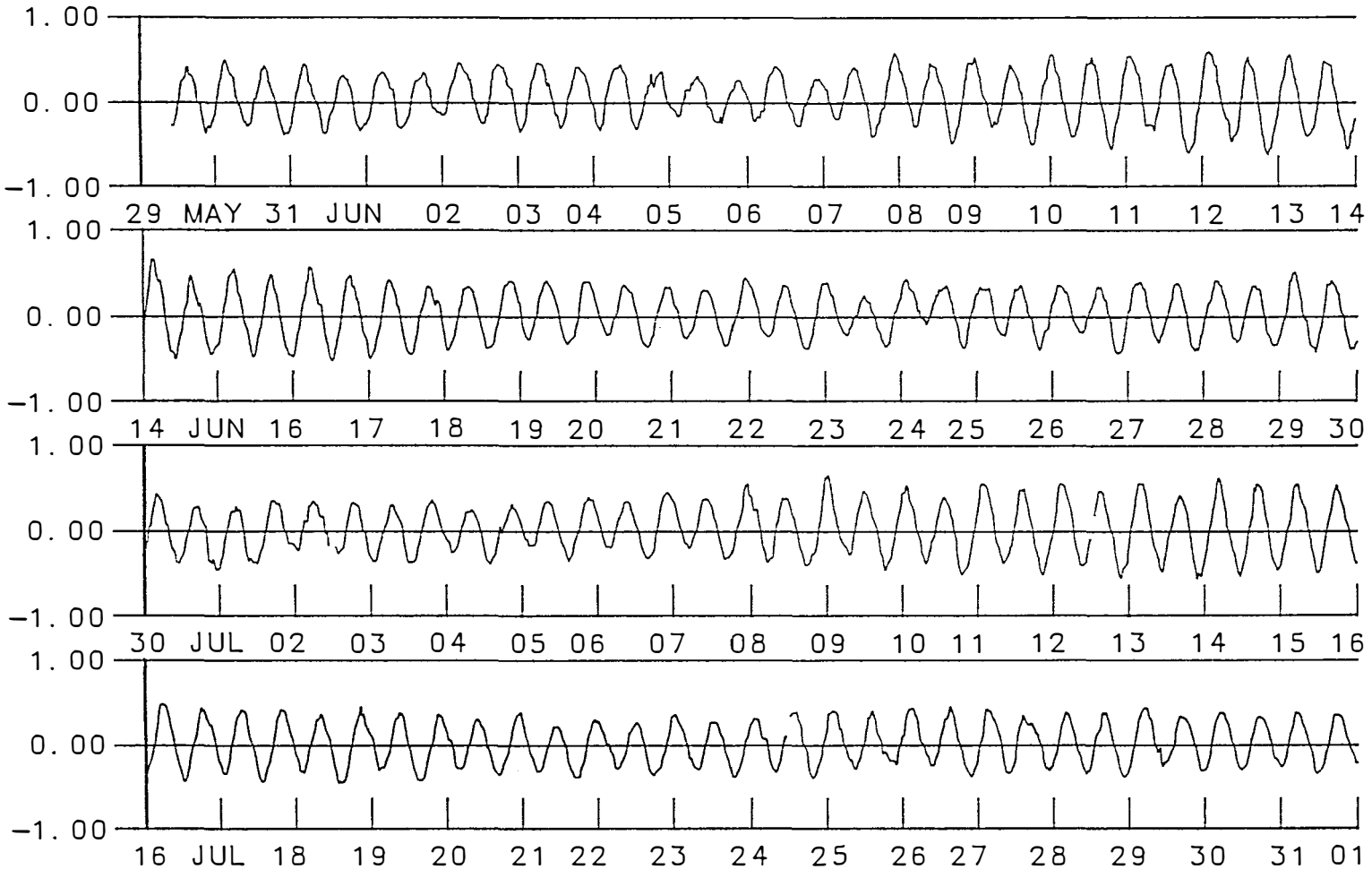
Longitudinal Components of Currents



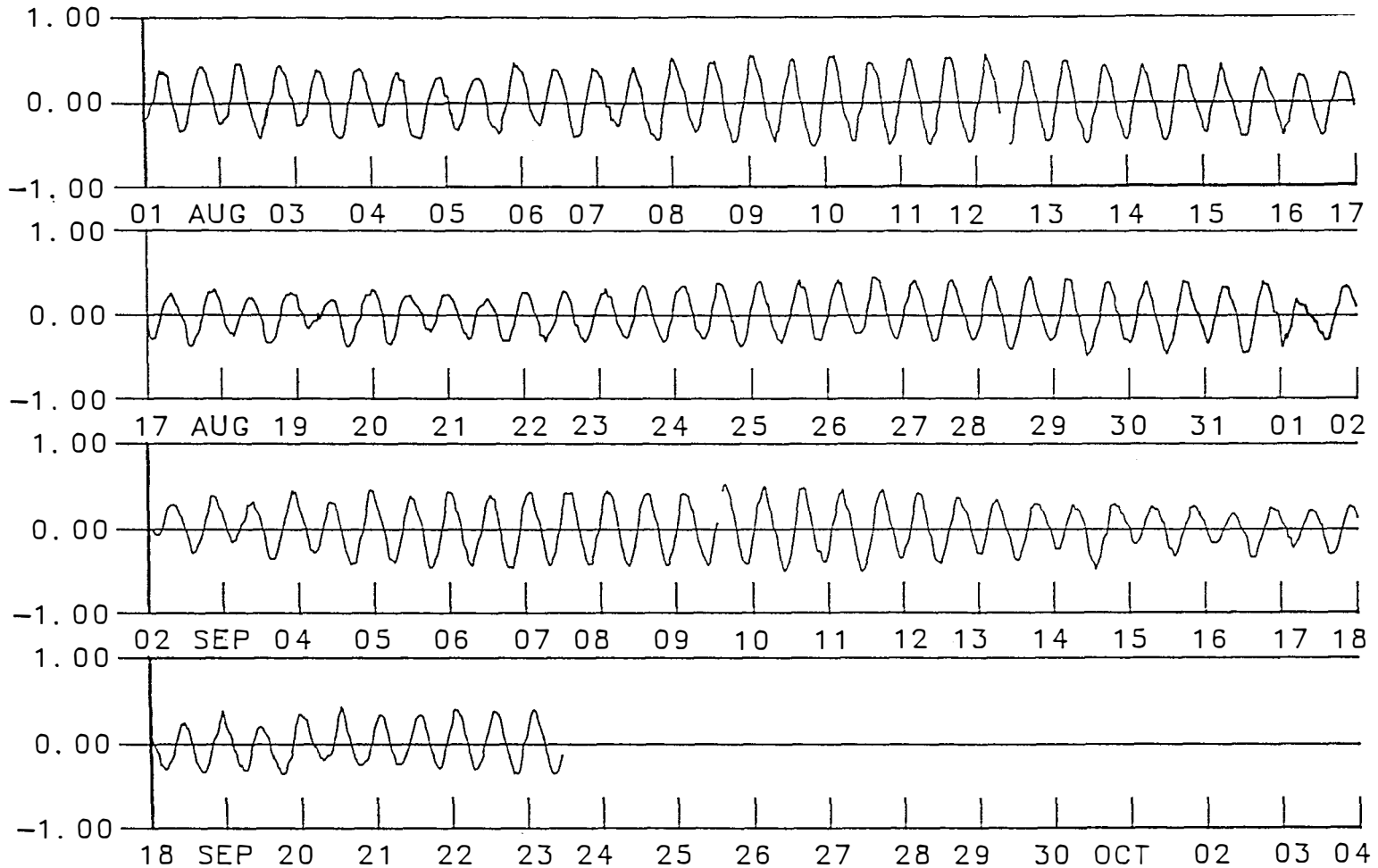
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



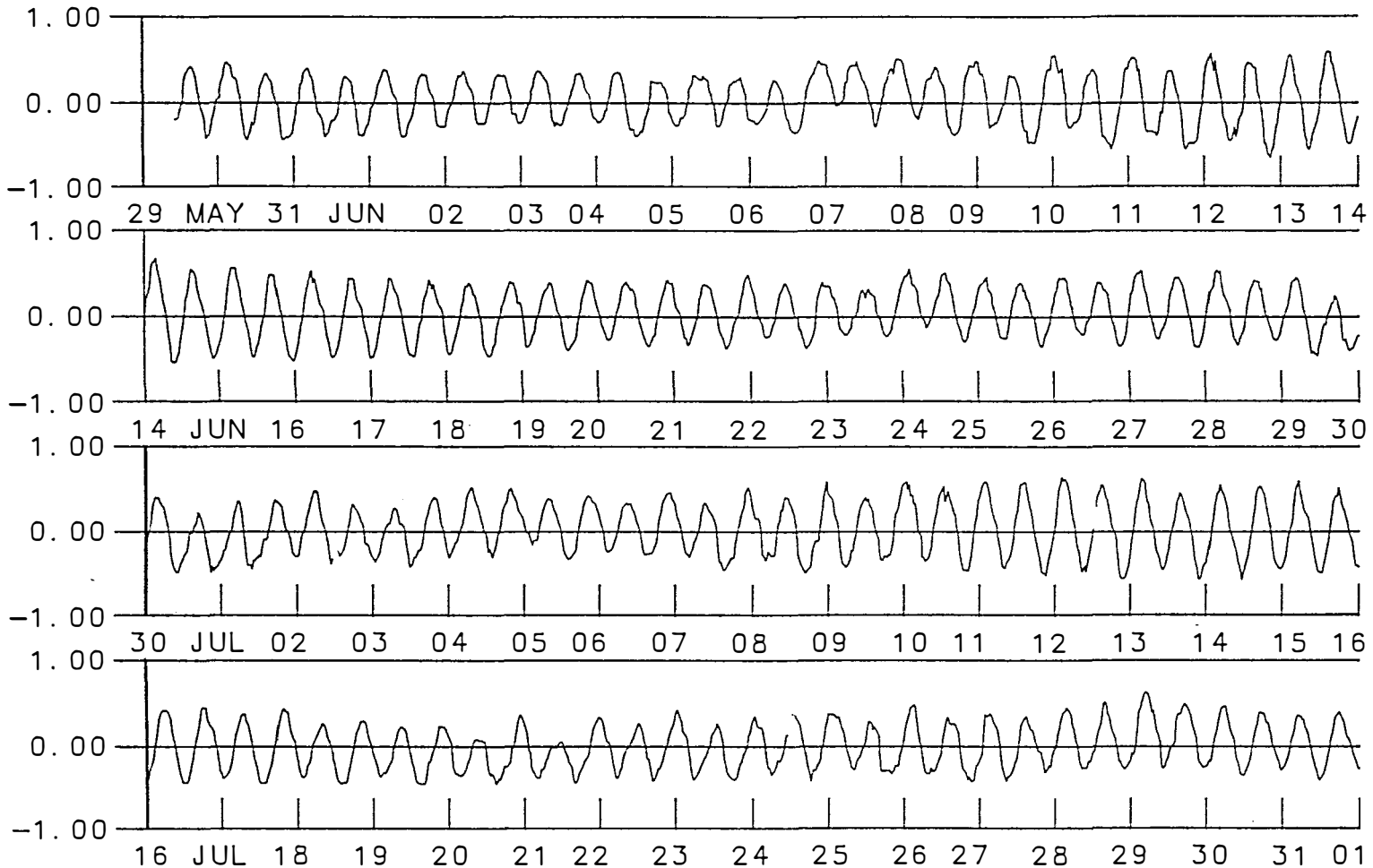
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



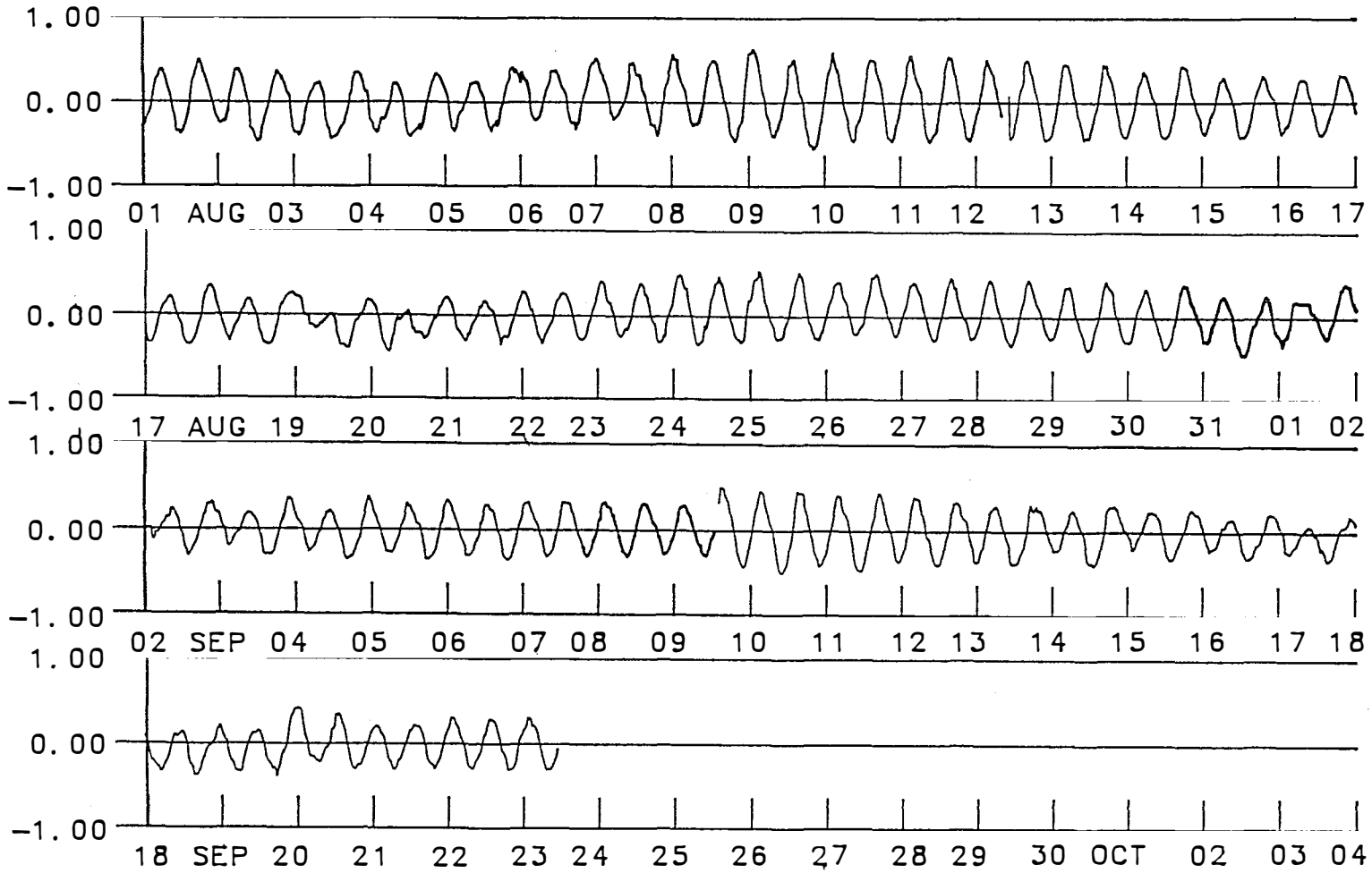
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 6 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



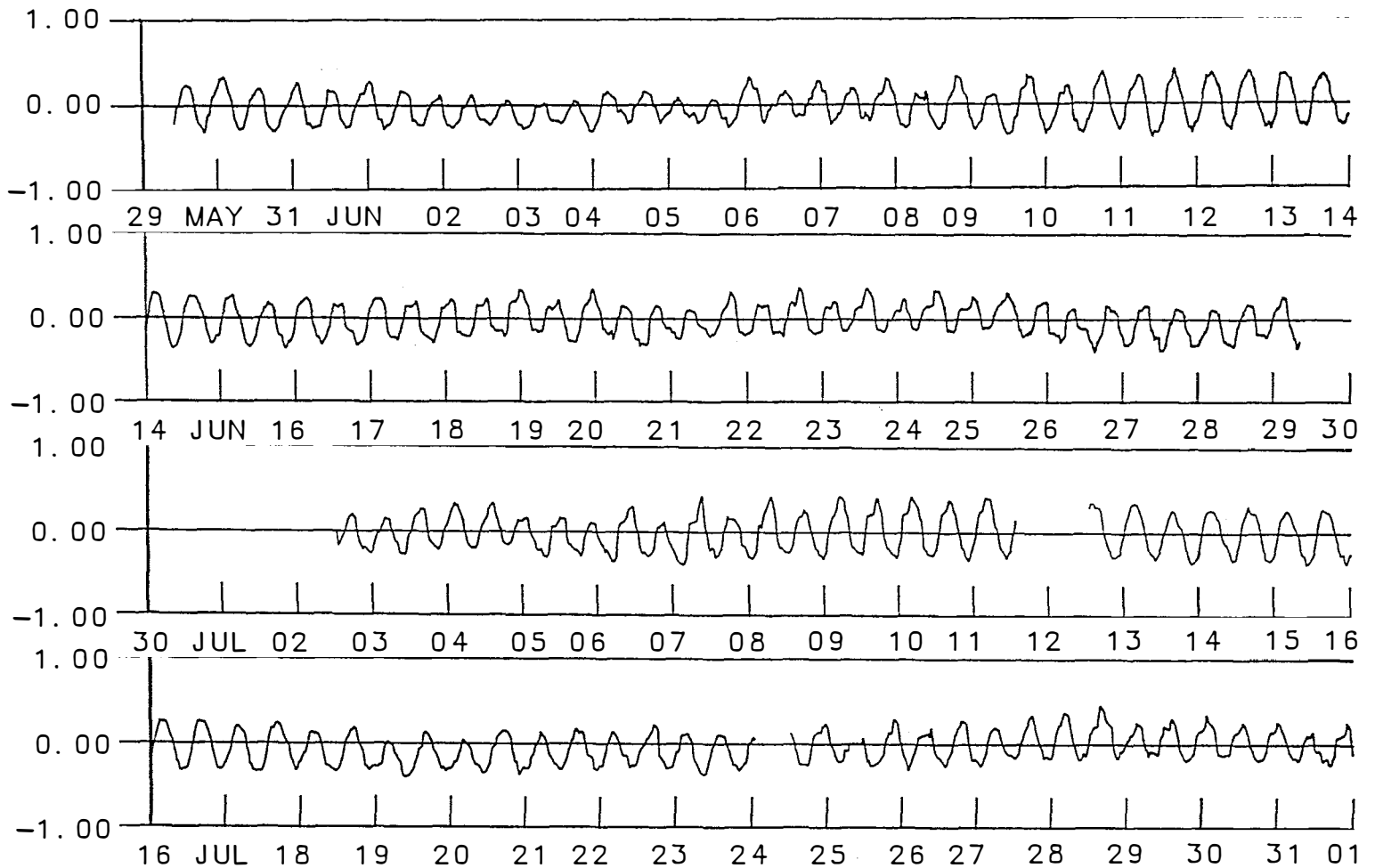
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 6 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



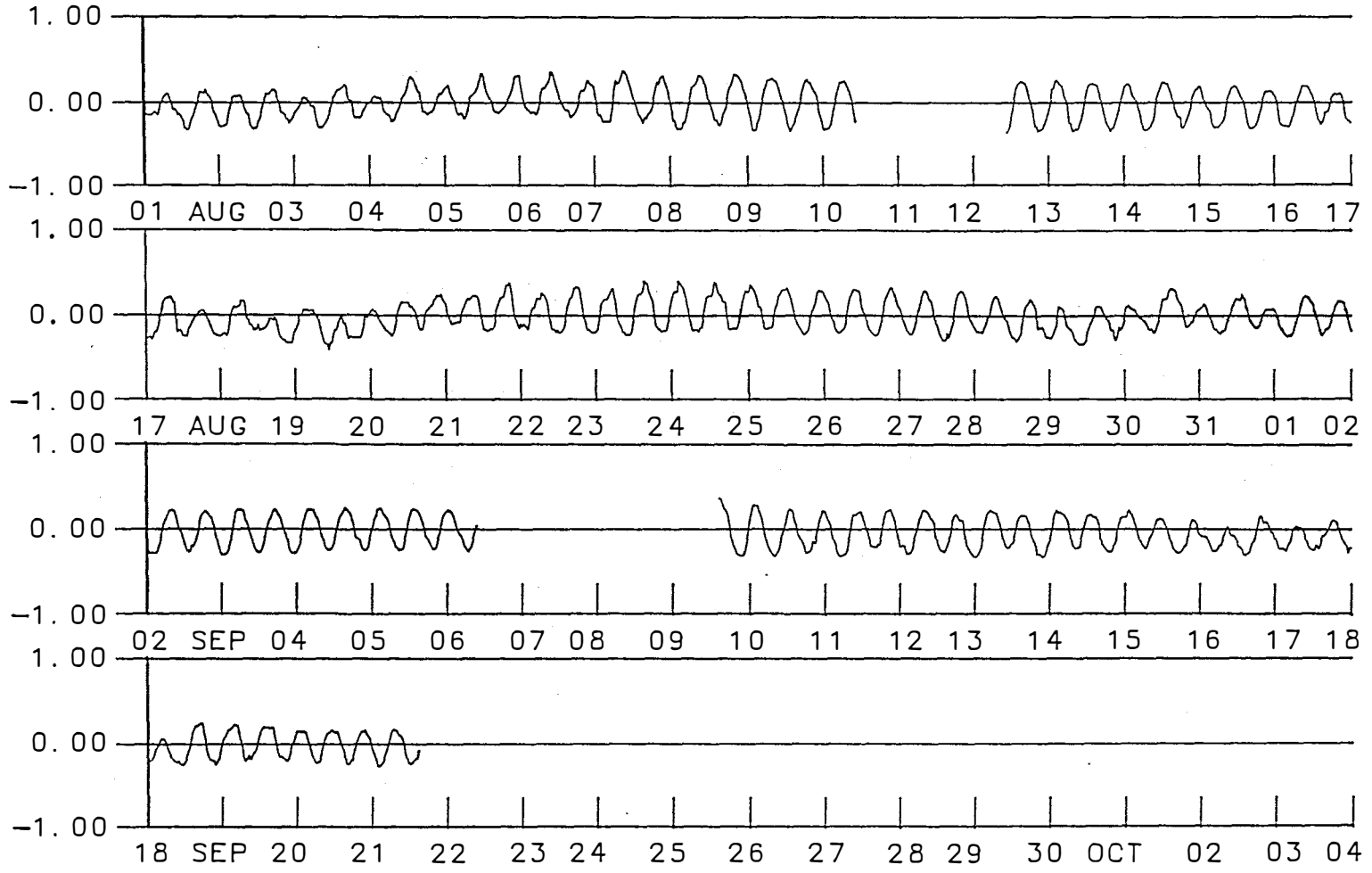
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 10 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



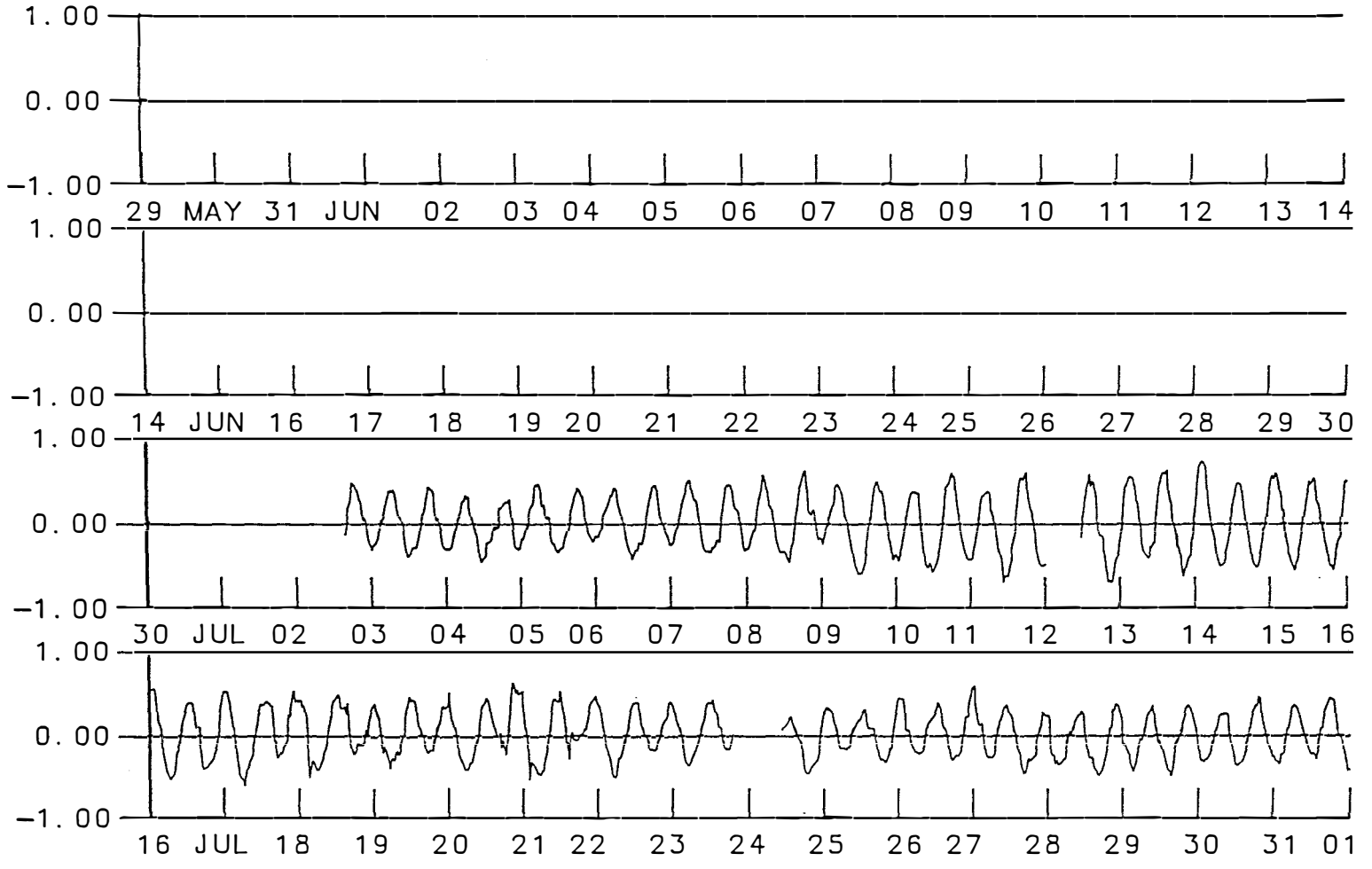
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.0 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



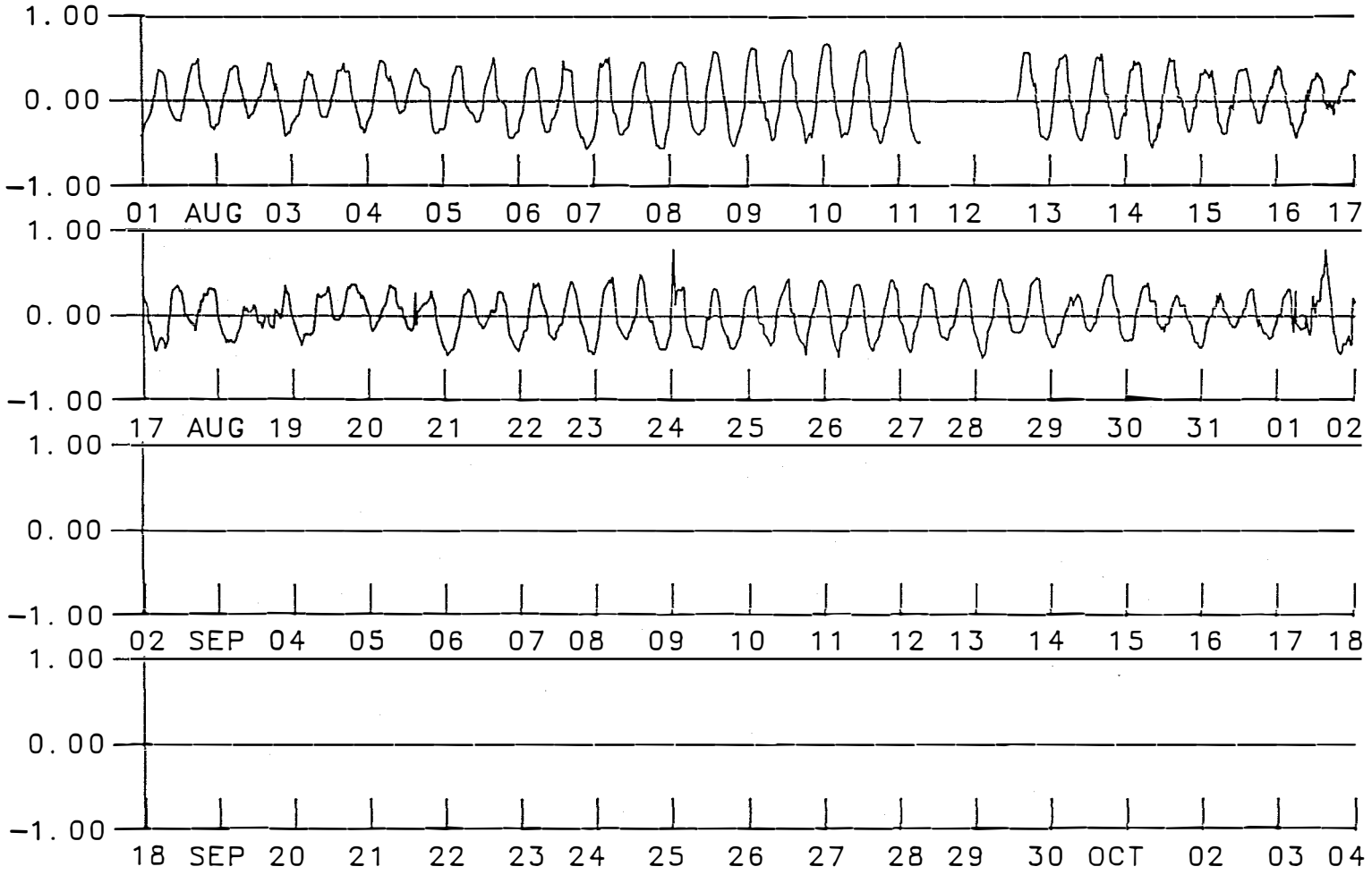
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



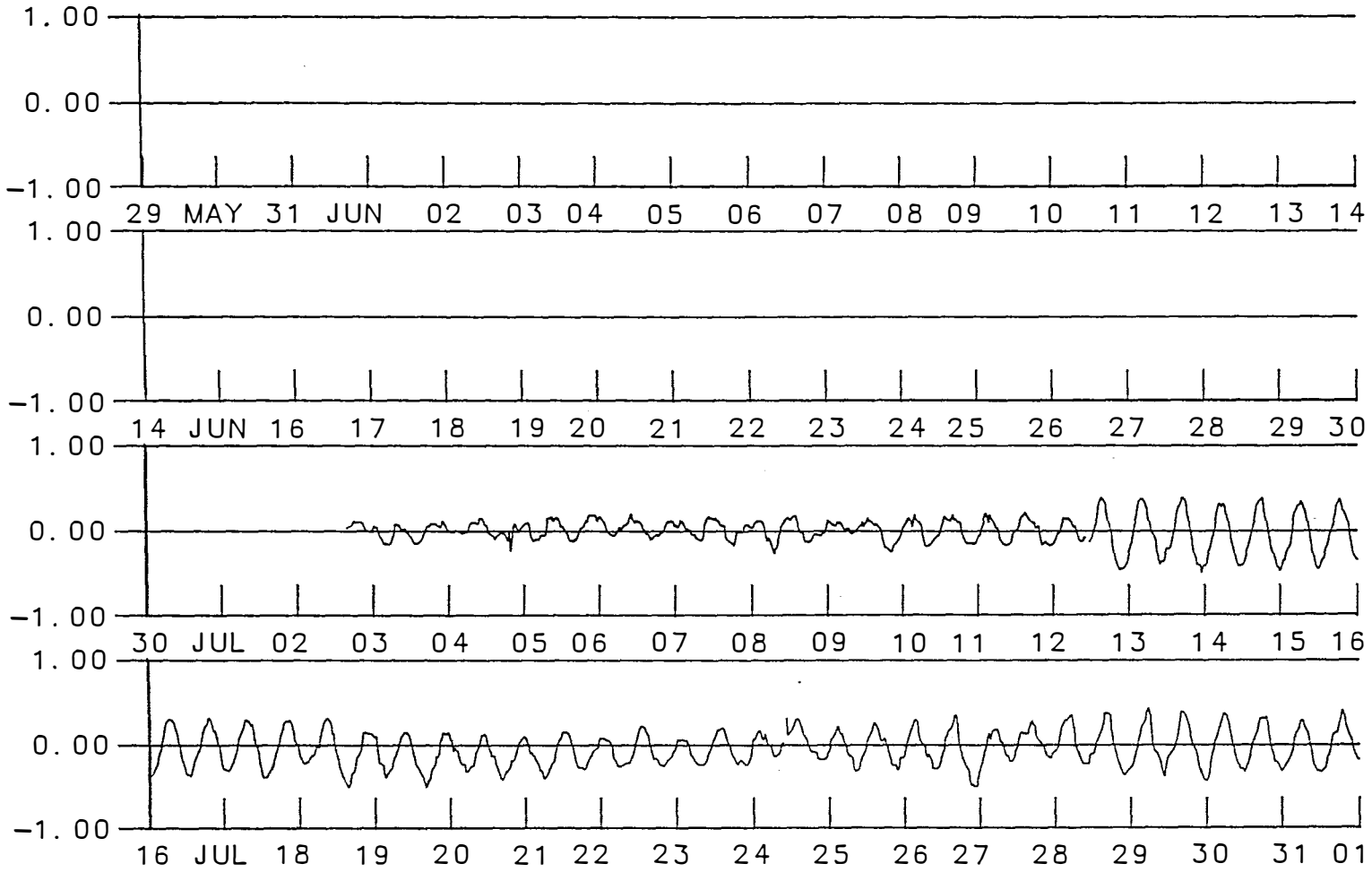
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



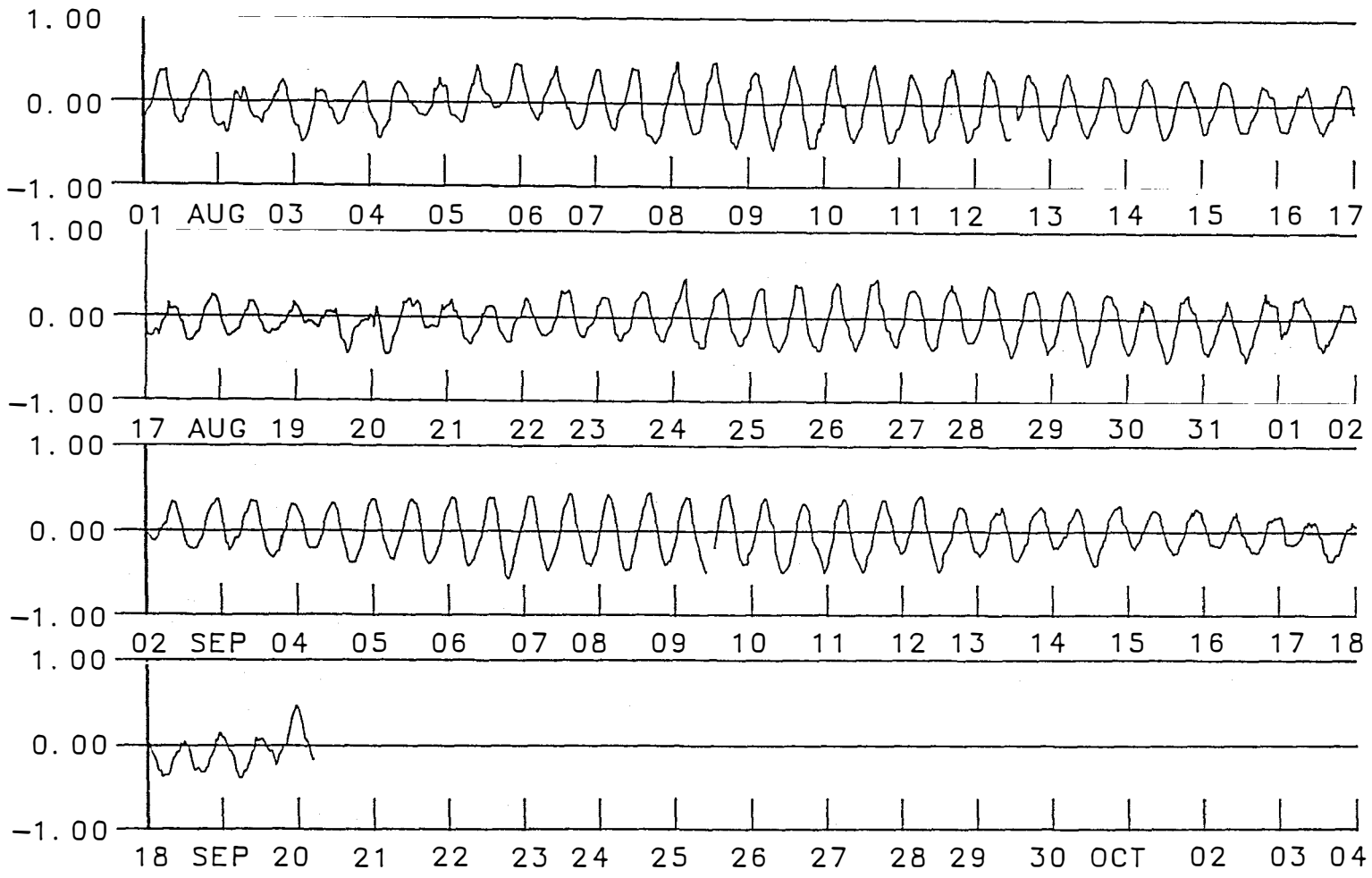
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



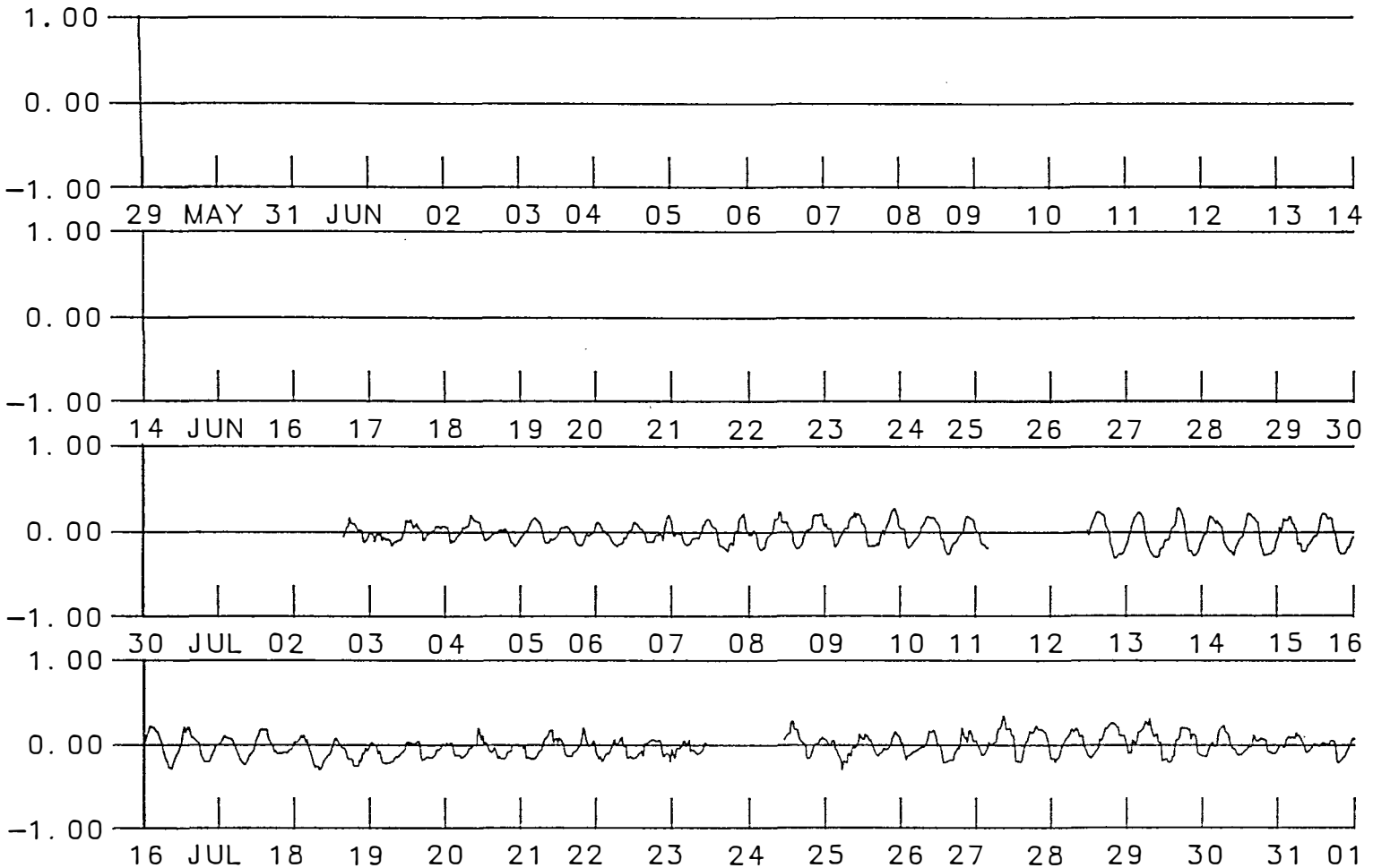
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



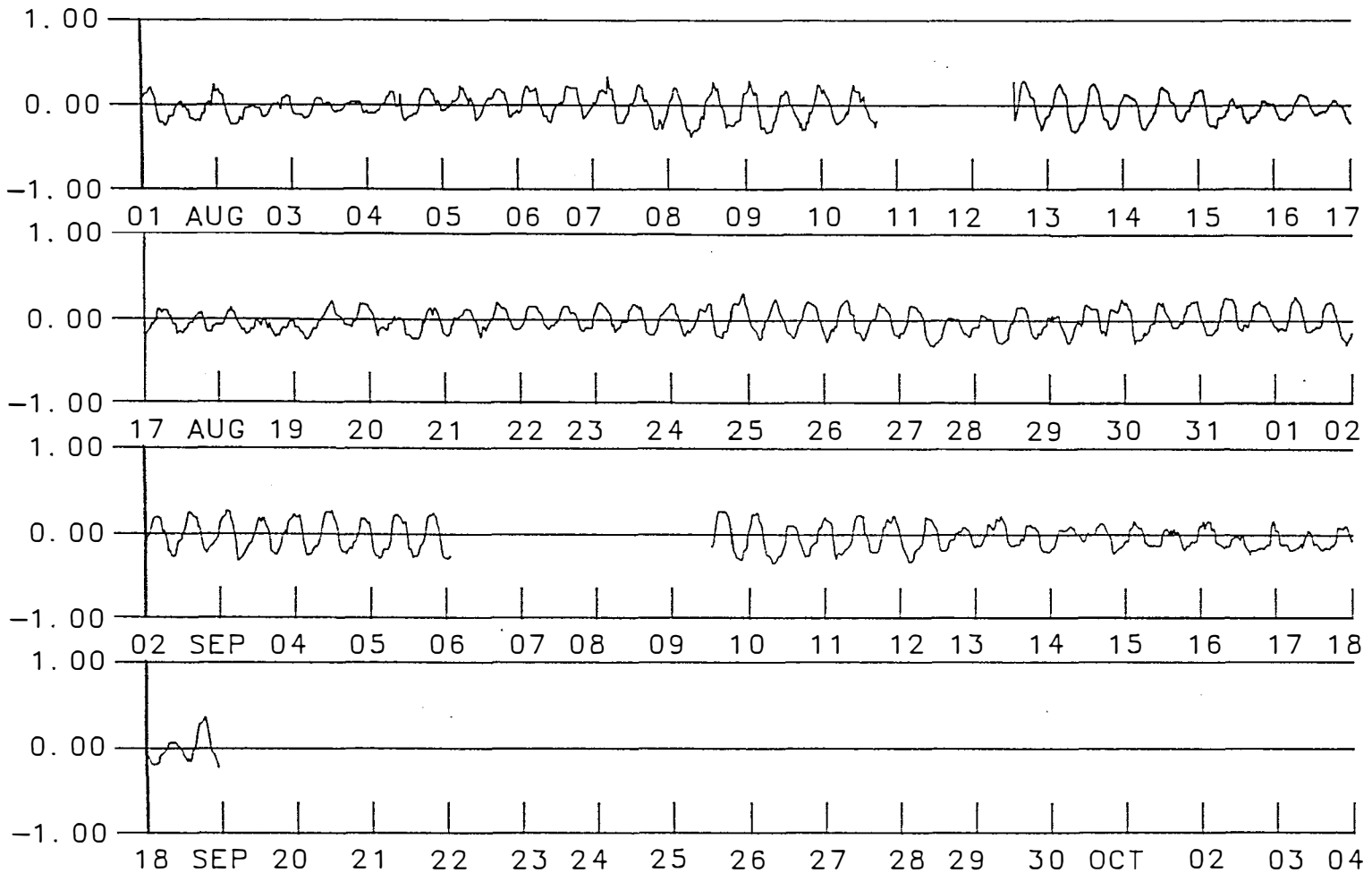
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 6 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 6 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



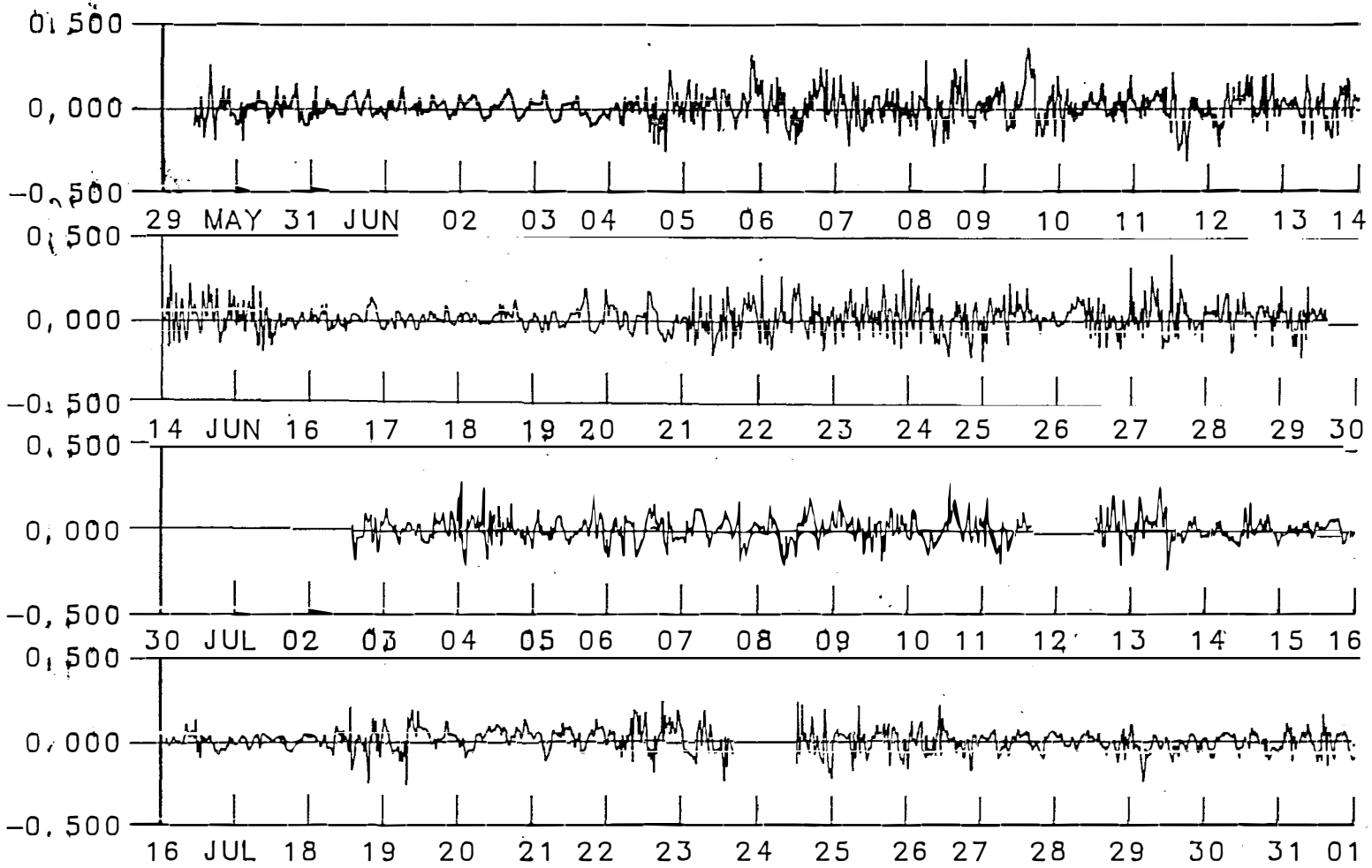
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 10.3 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB



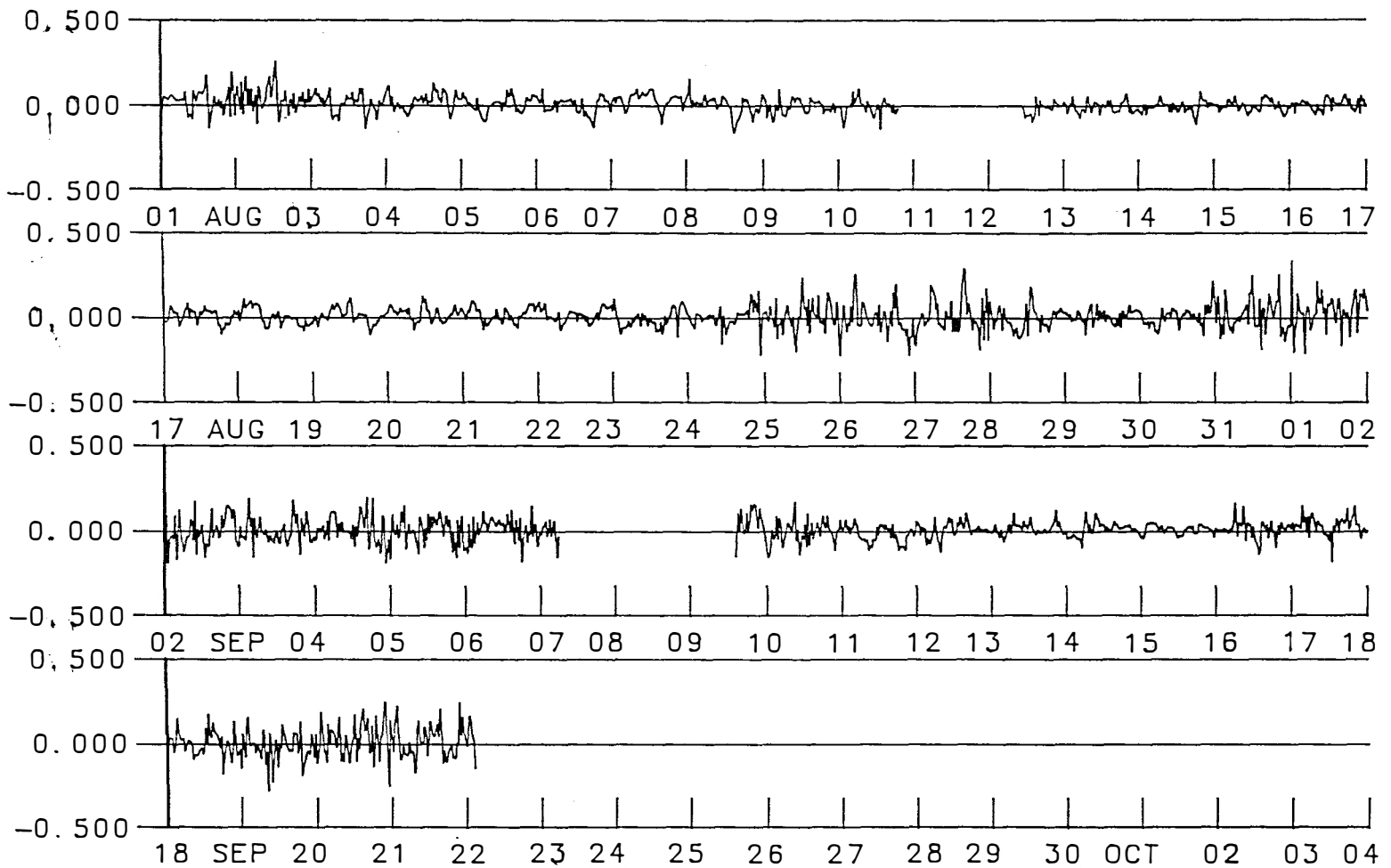
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 10.3 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB

Appendix I-4

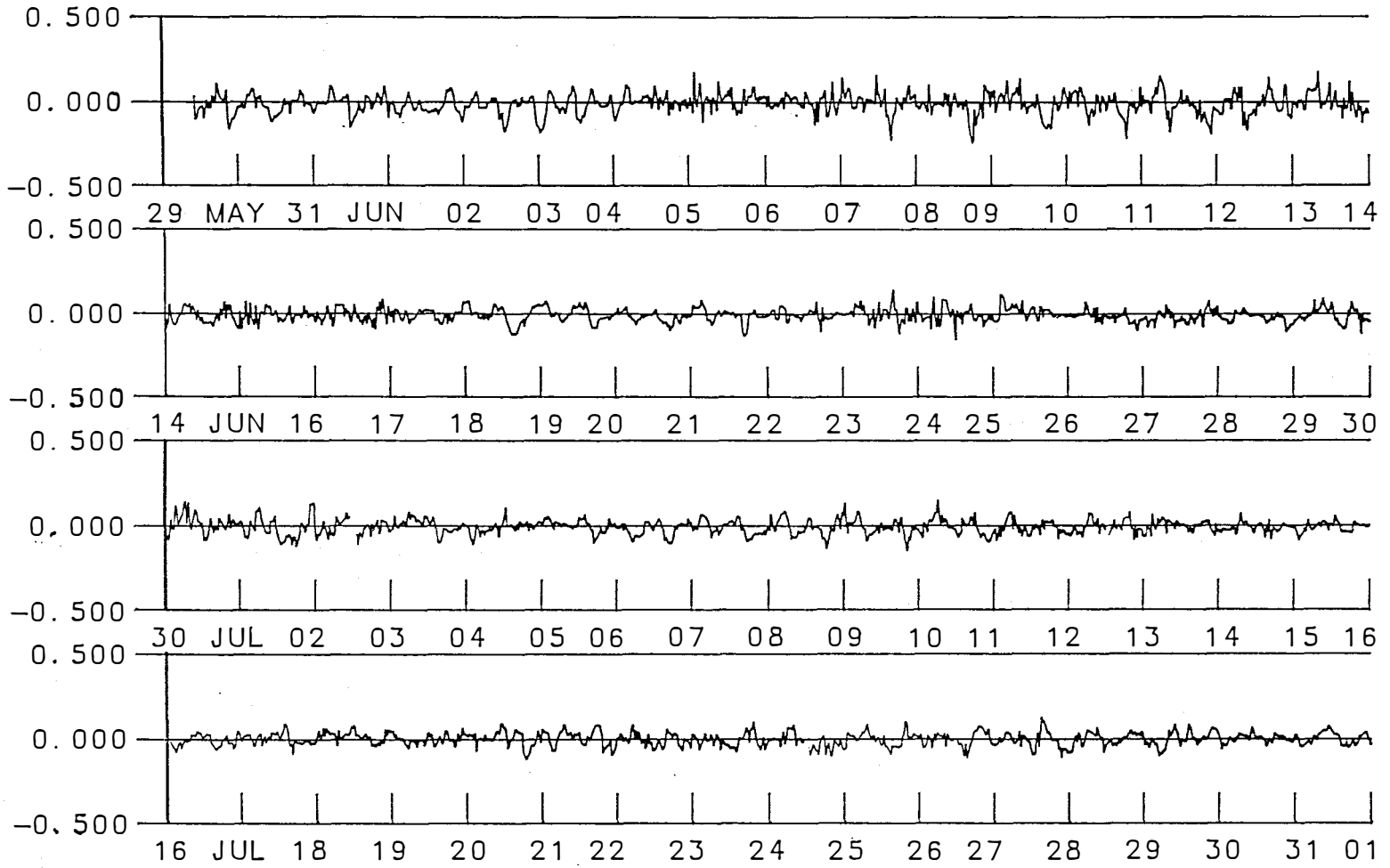
Transverse Component of Currents



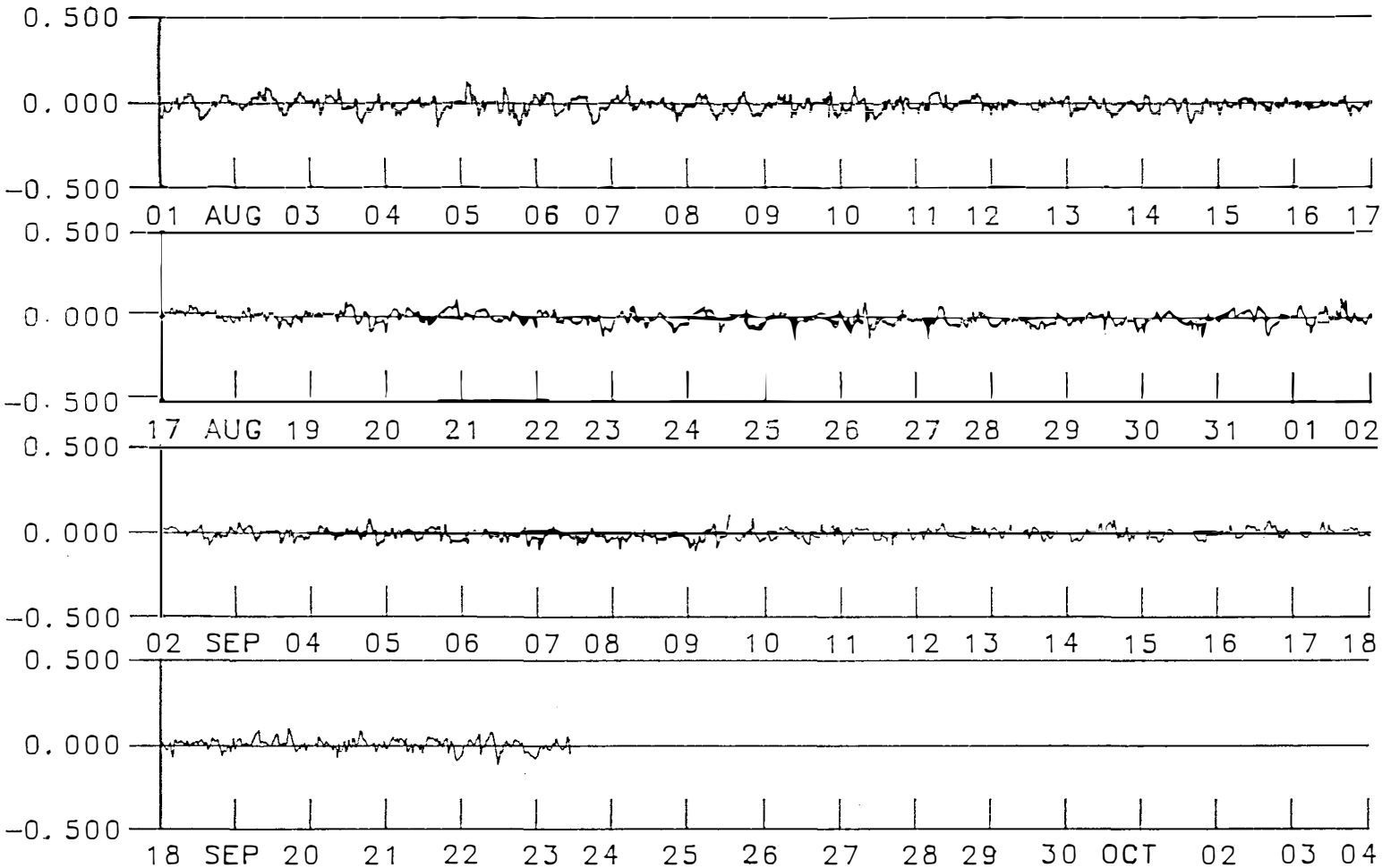
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



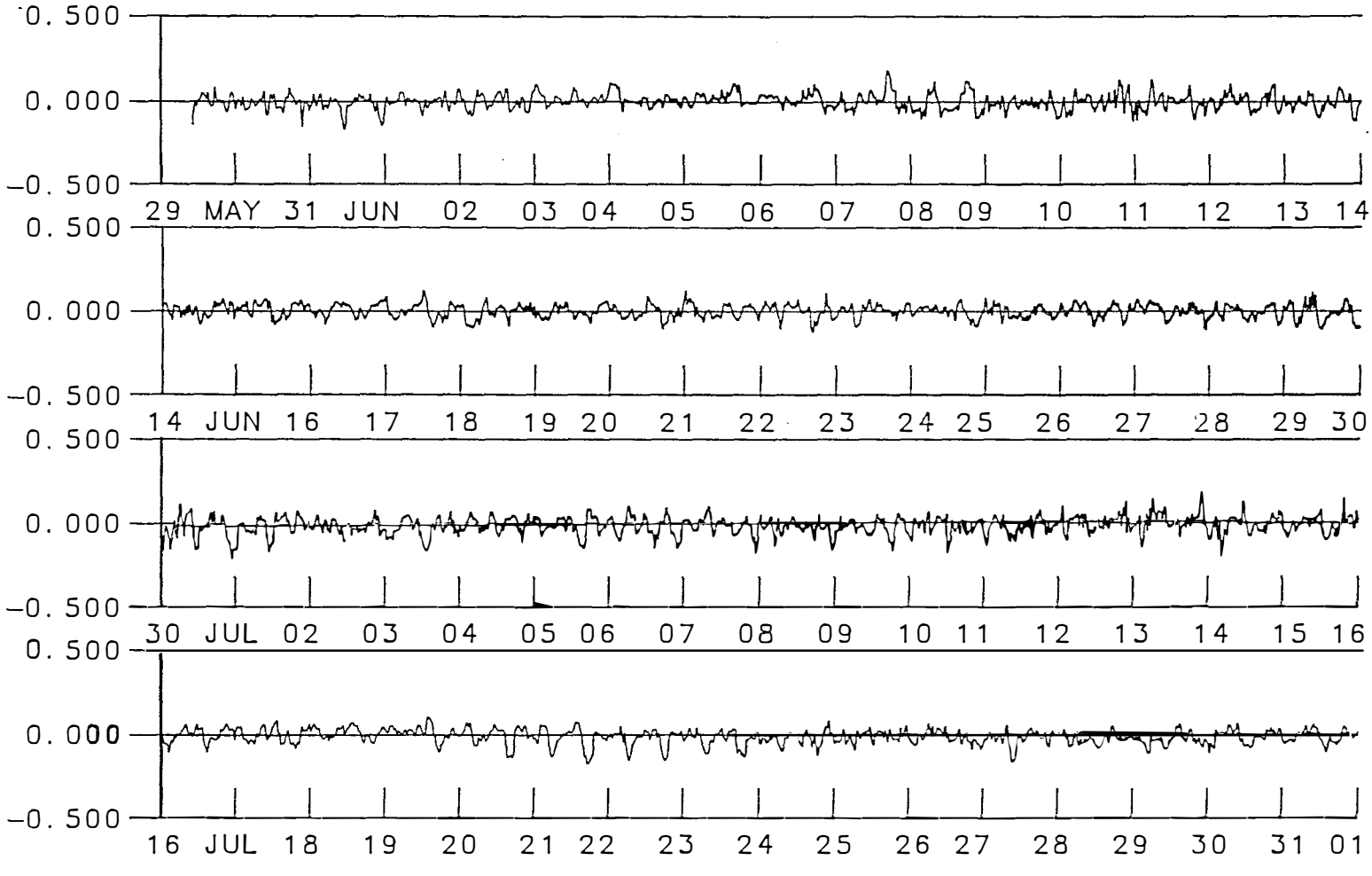
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



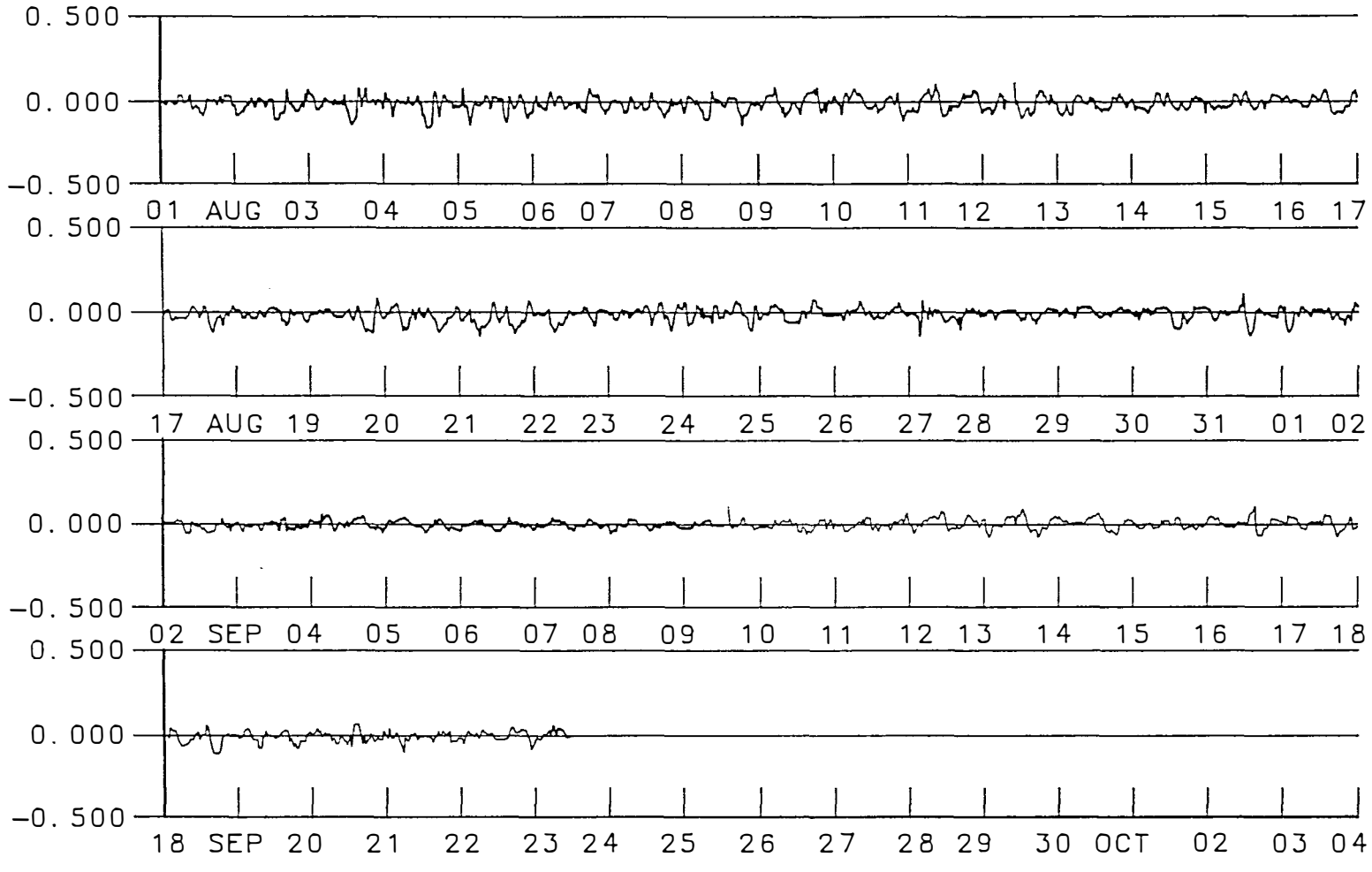
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 6 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



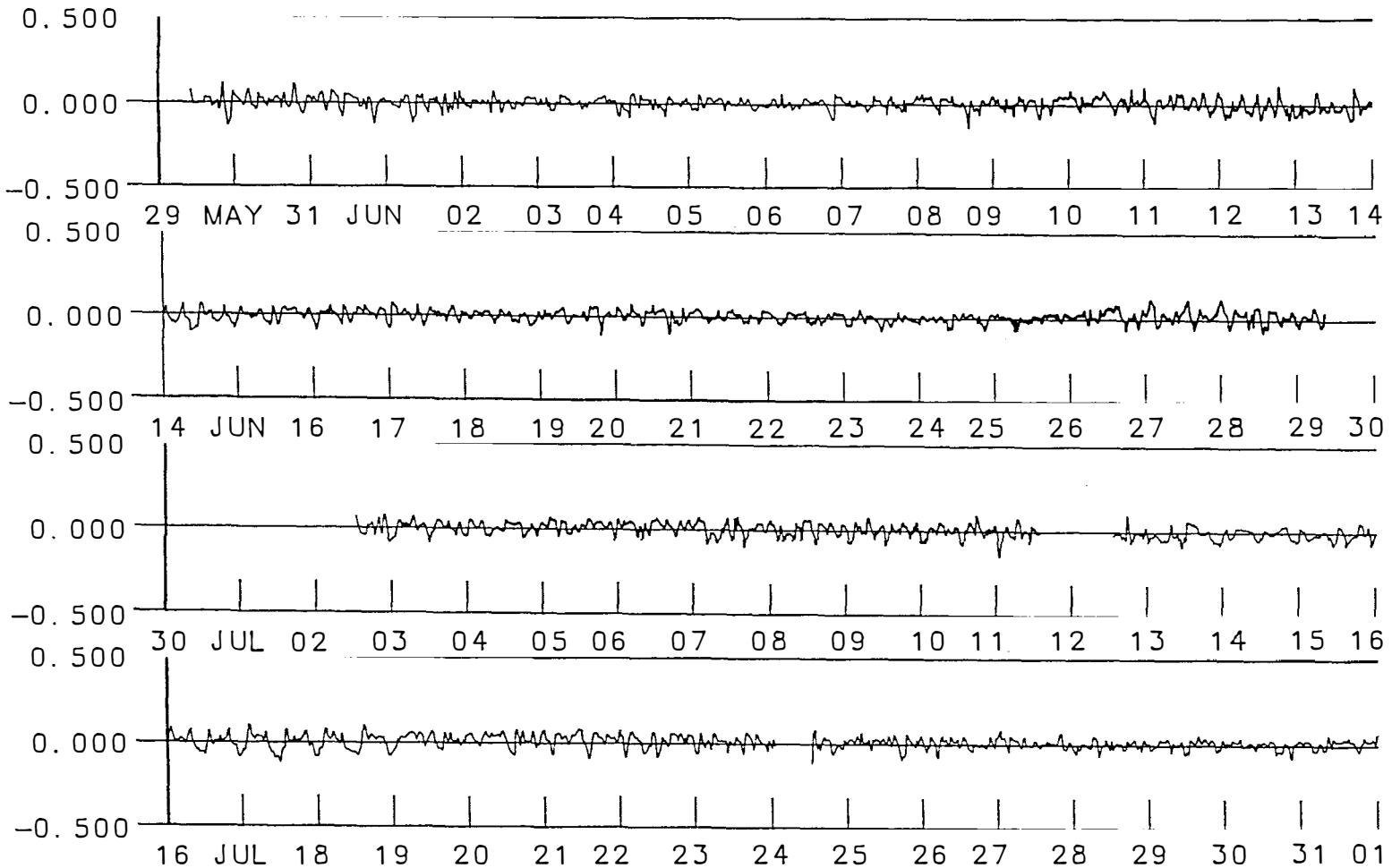
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 6 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



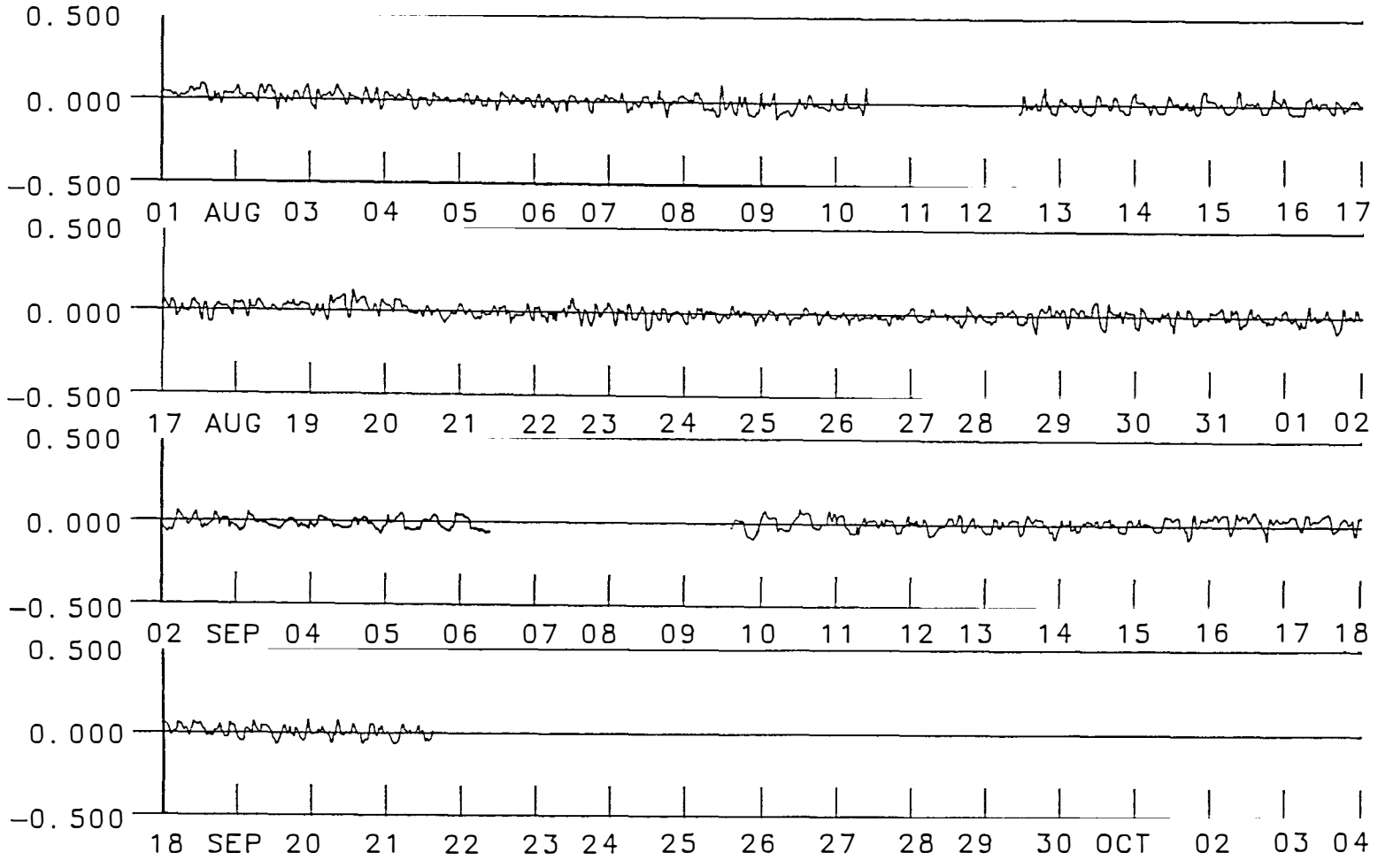
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 10 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



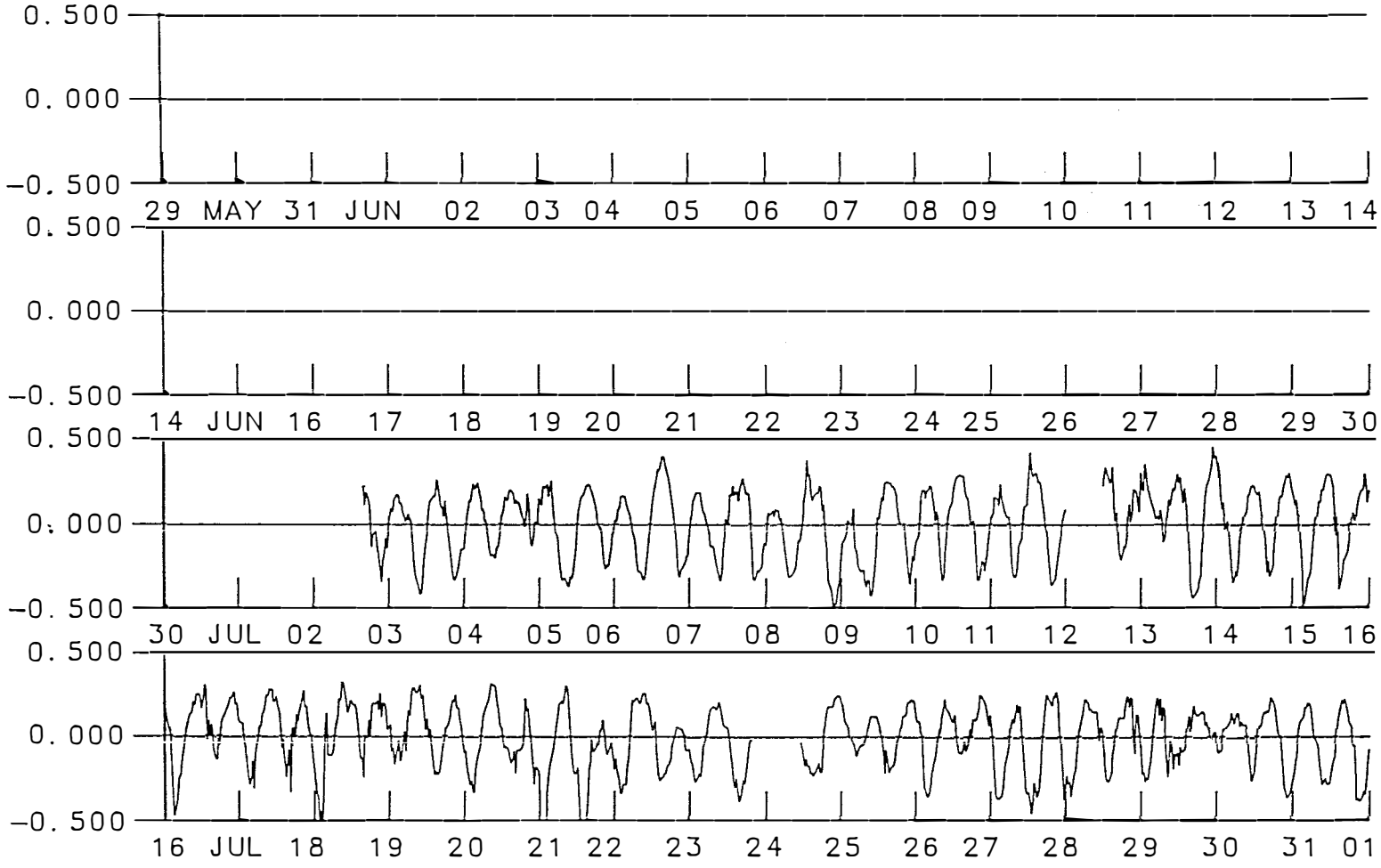
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 10 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



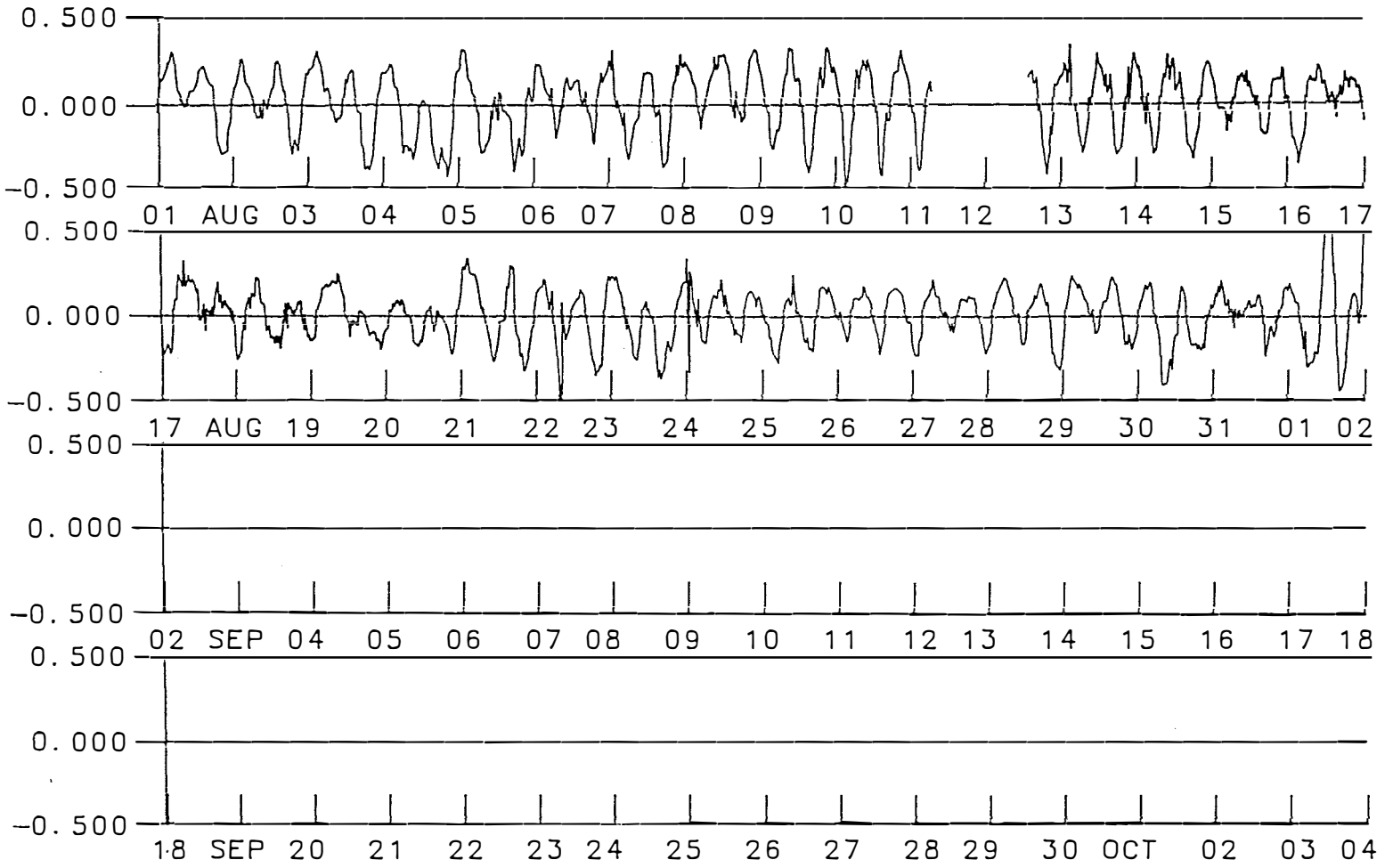
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



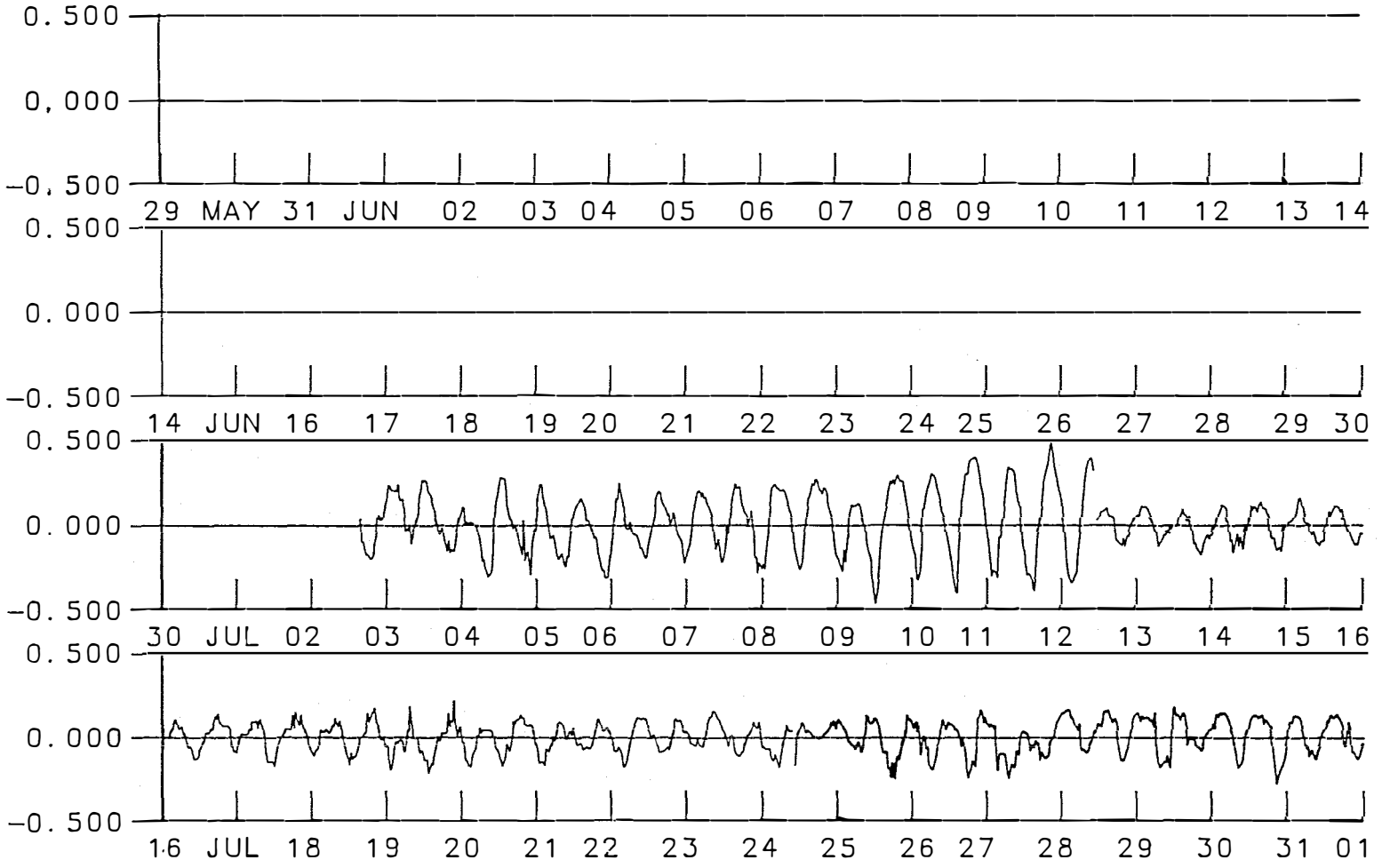
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



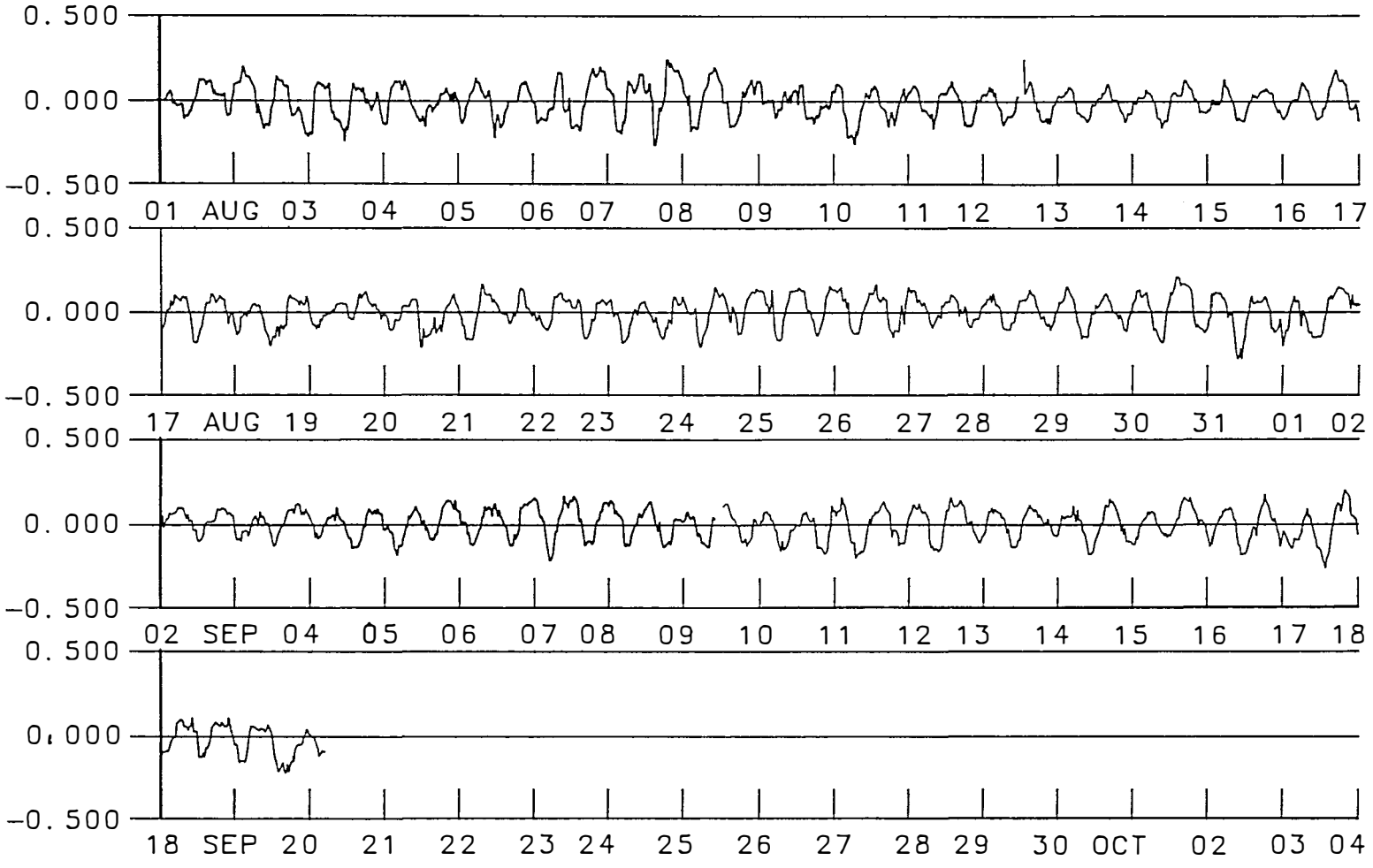
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



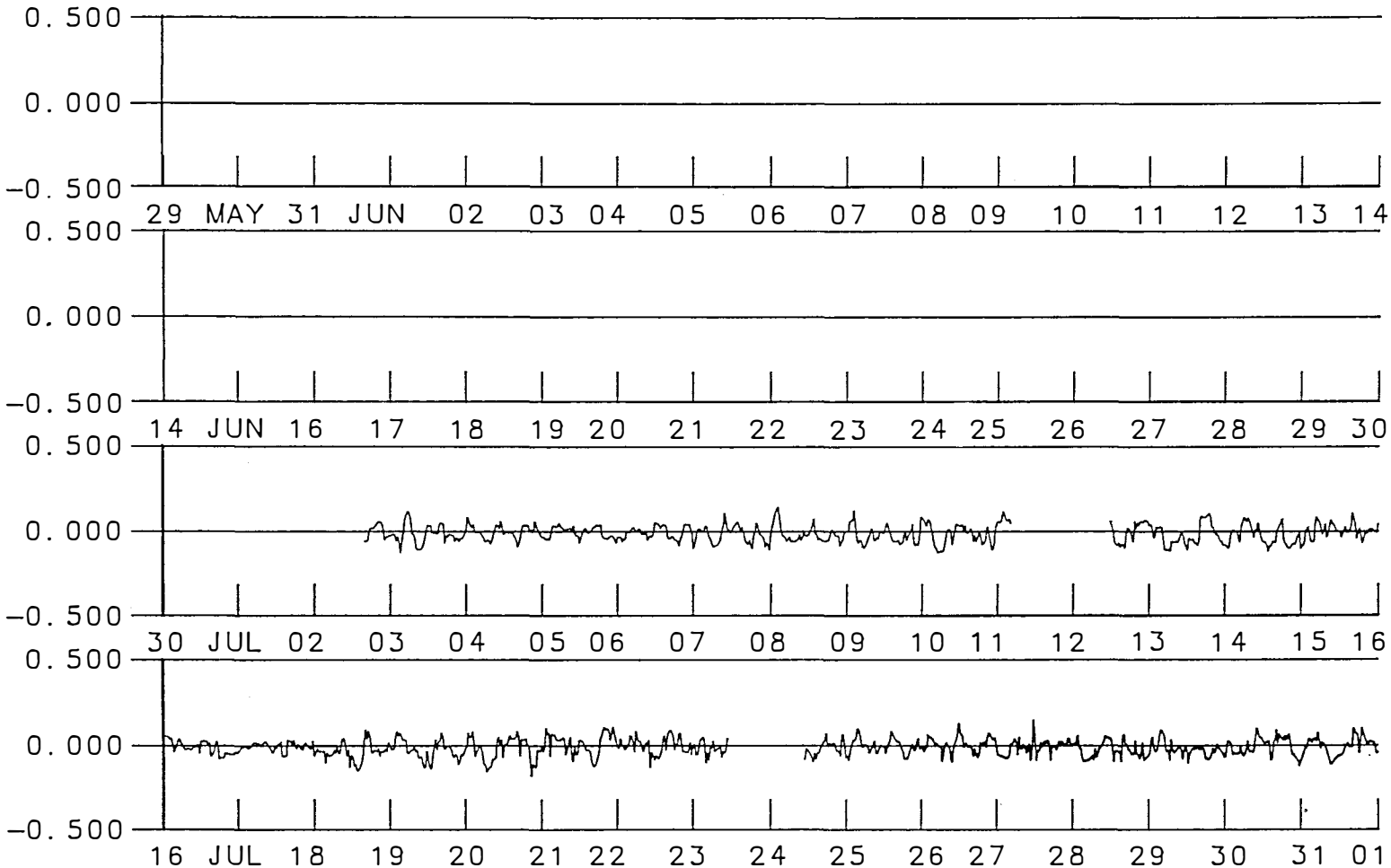
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



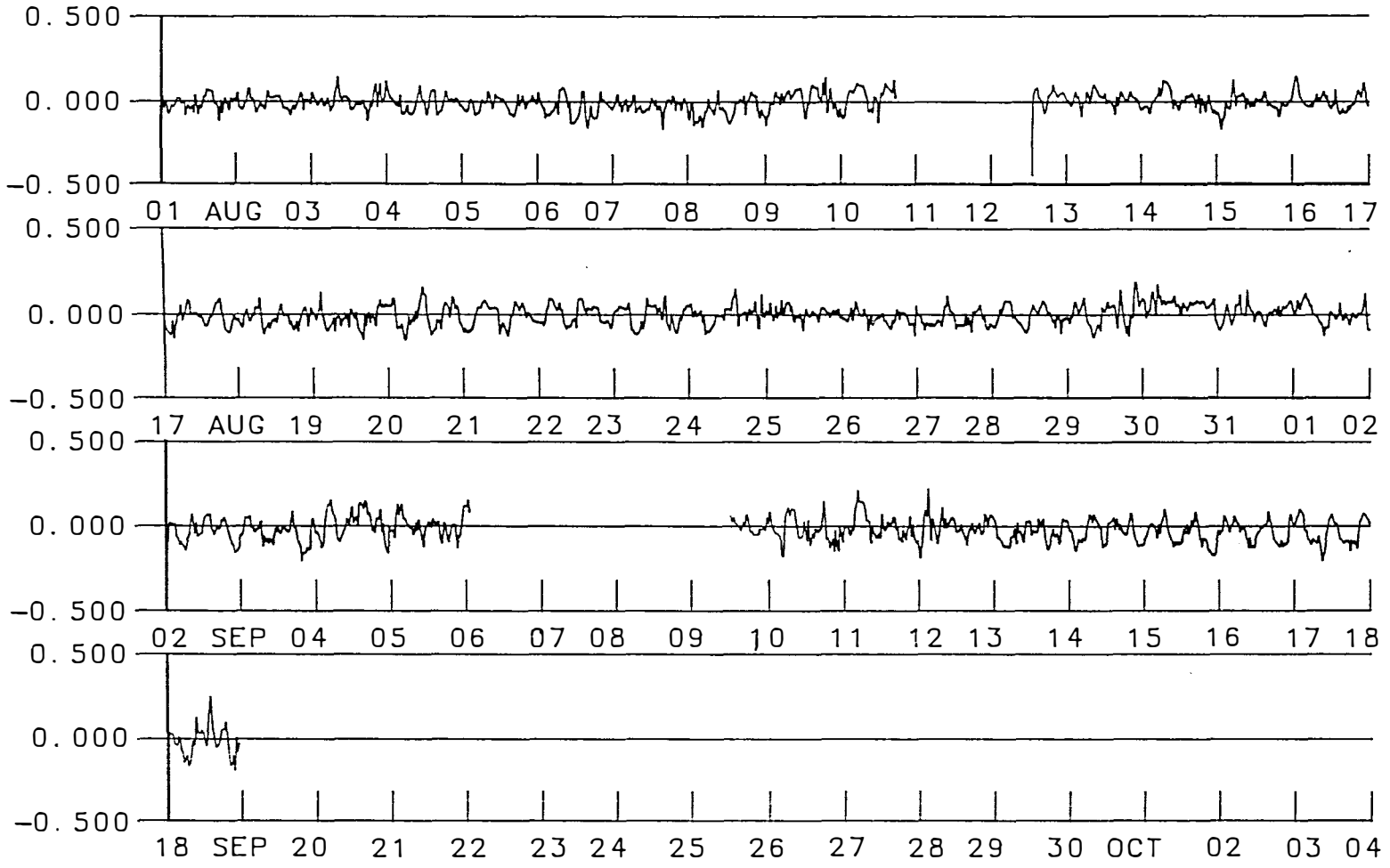
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 6 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 6 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



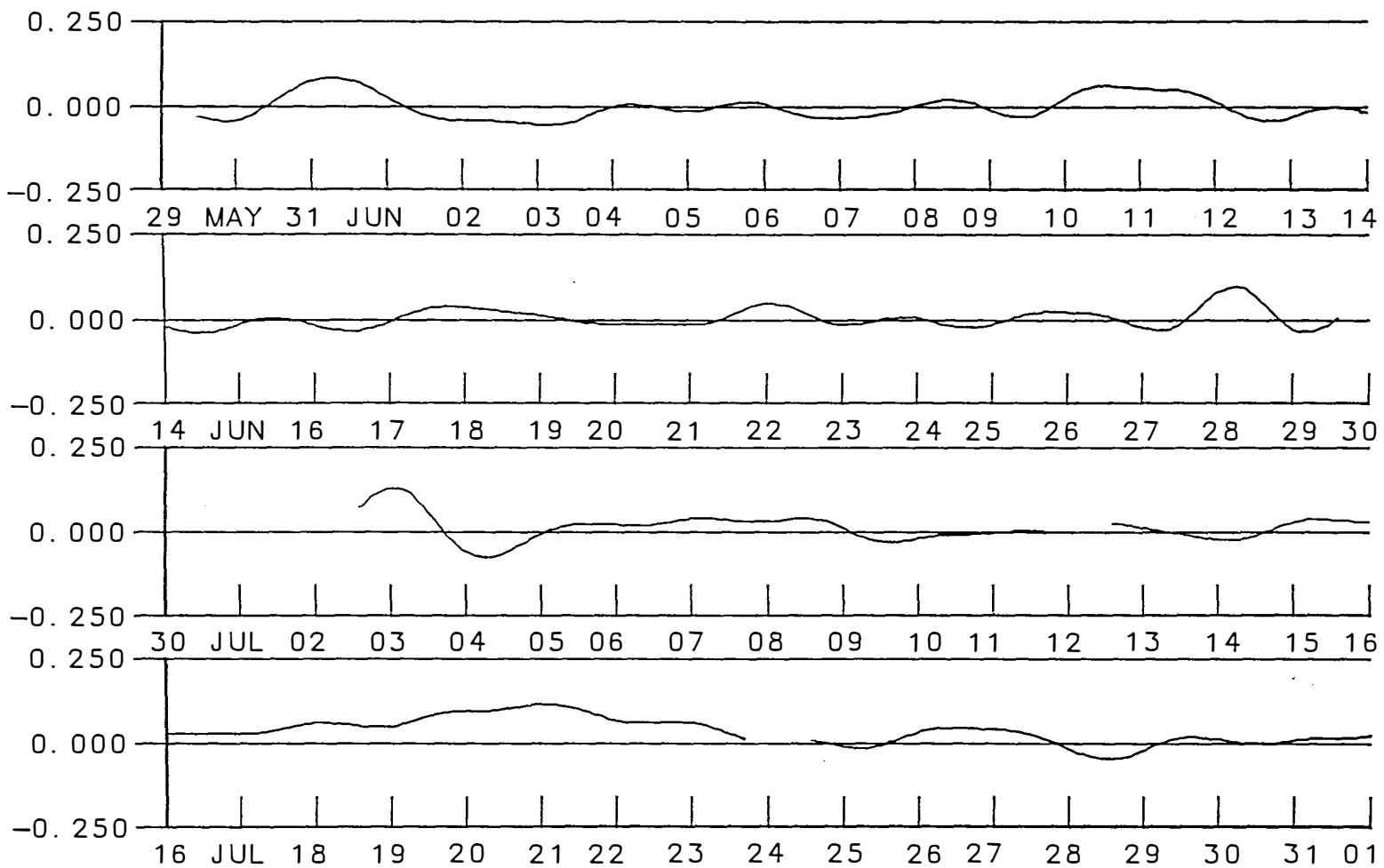
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 10.3 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.



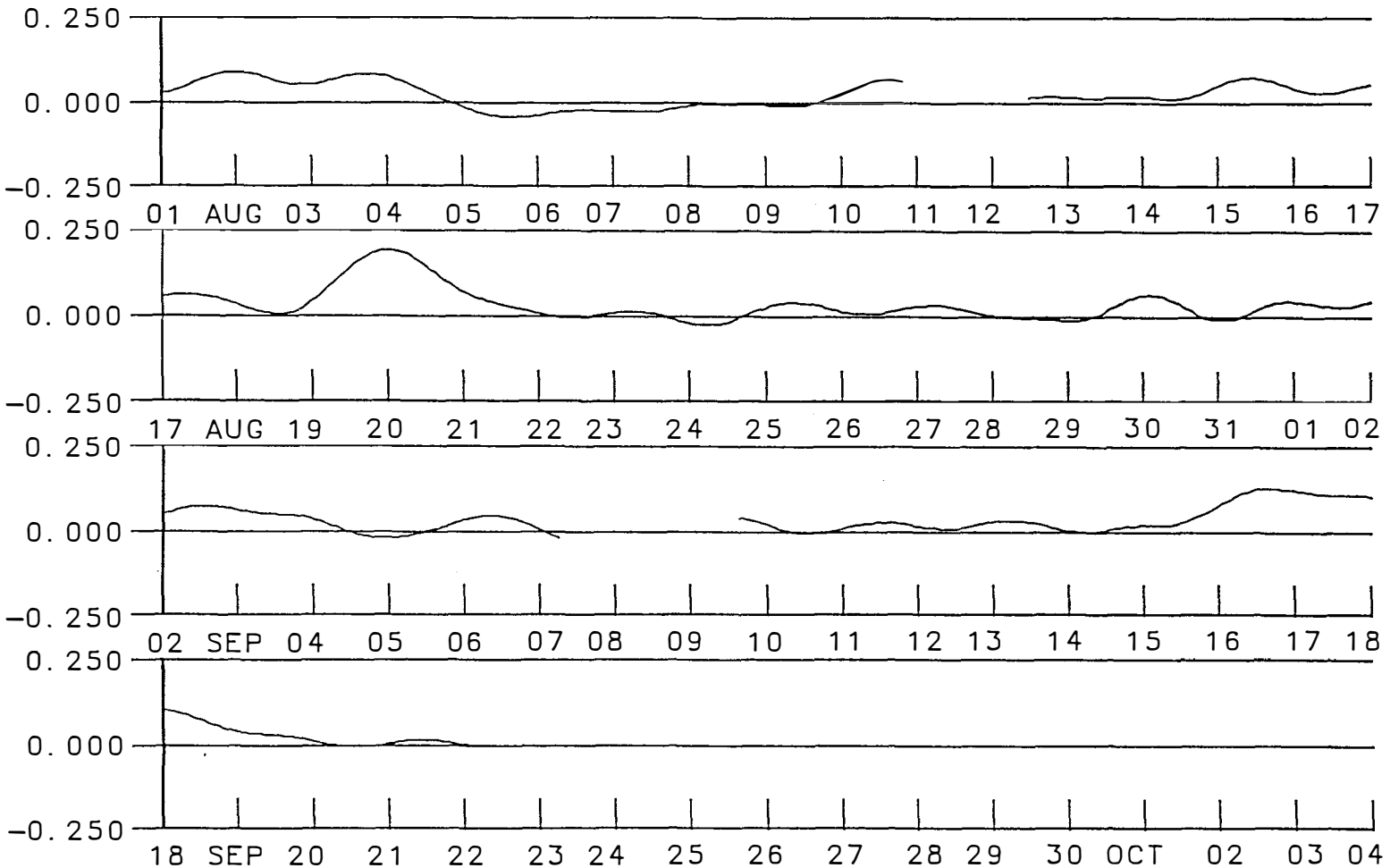
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 10.3 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.

Appendix I-5

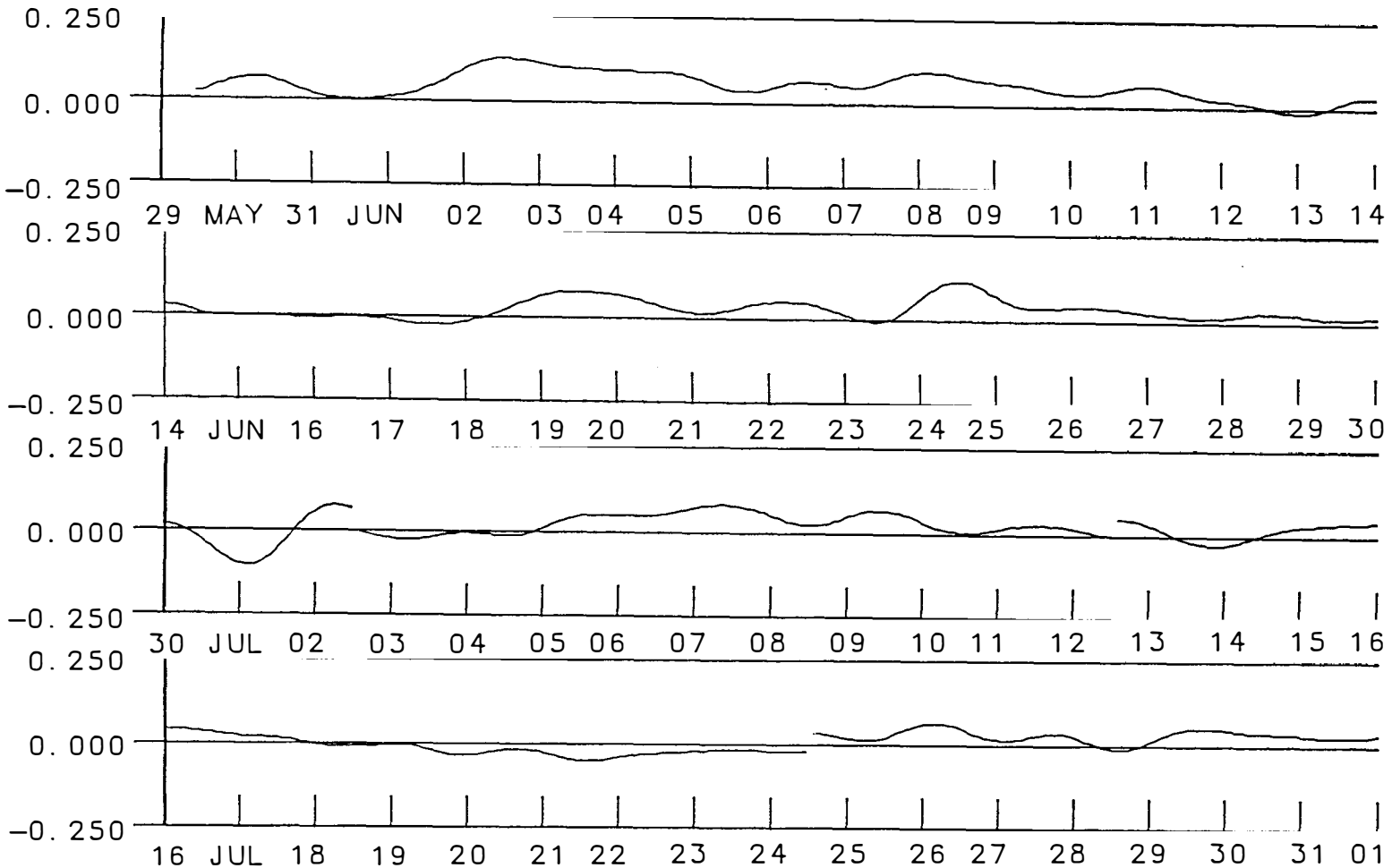
Low-Pass Filtered Longitudinal Components of Currents



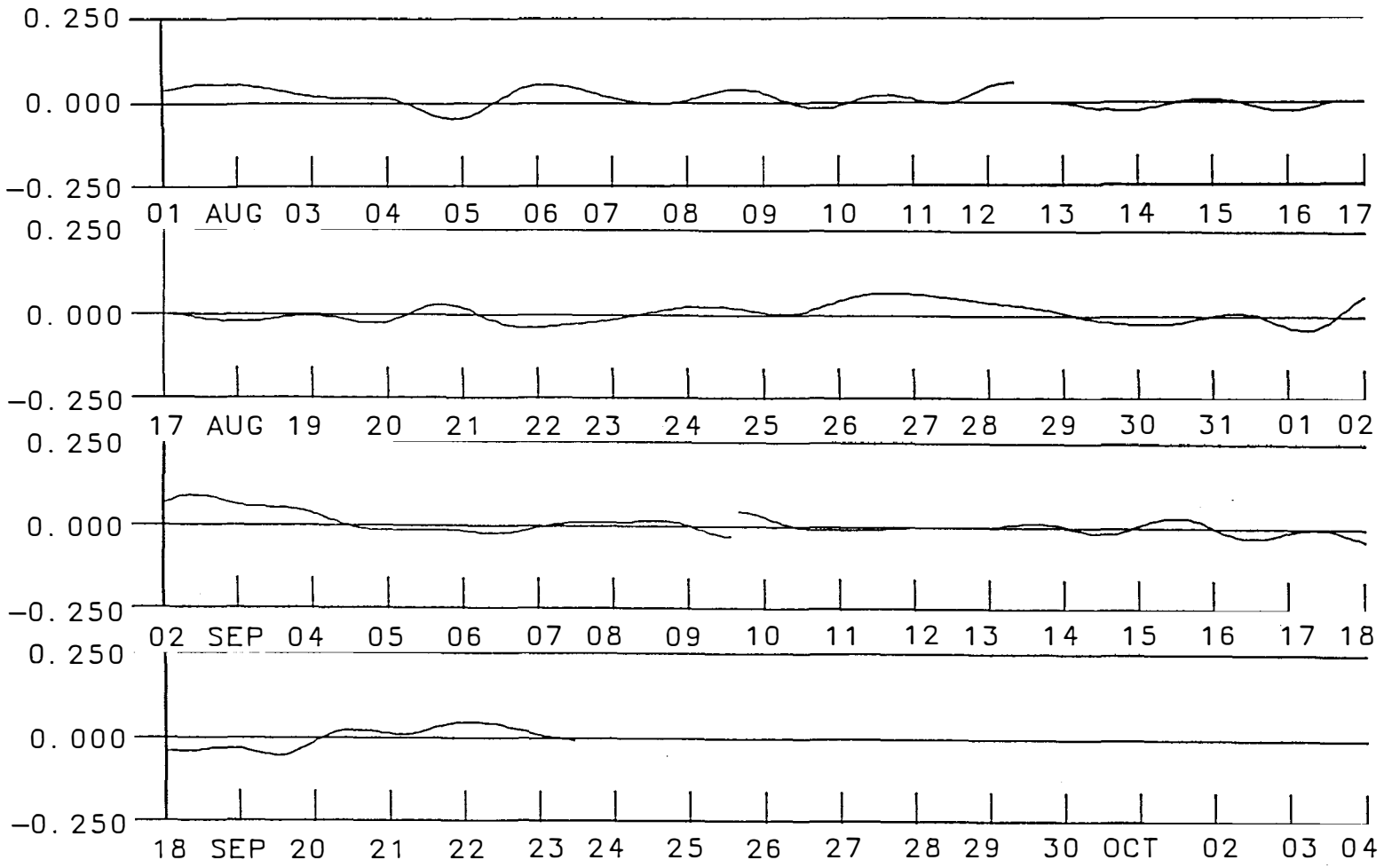
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



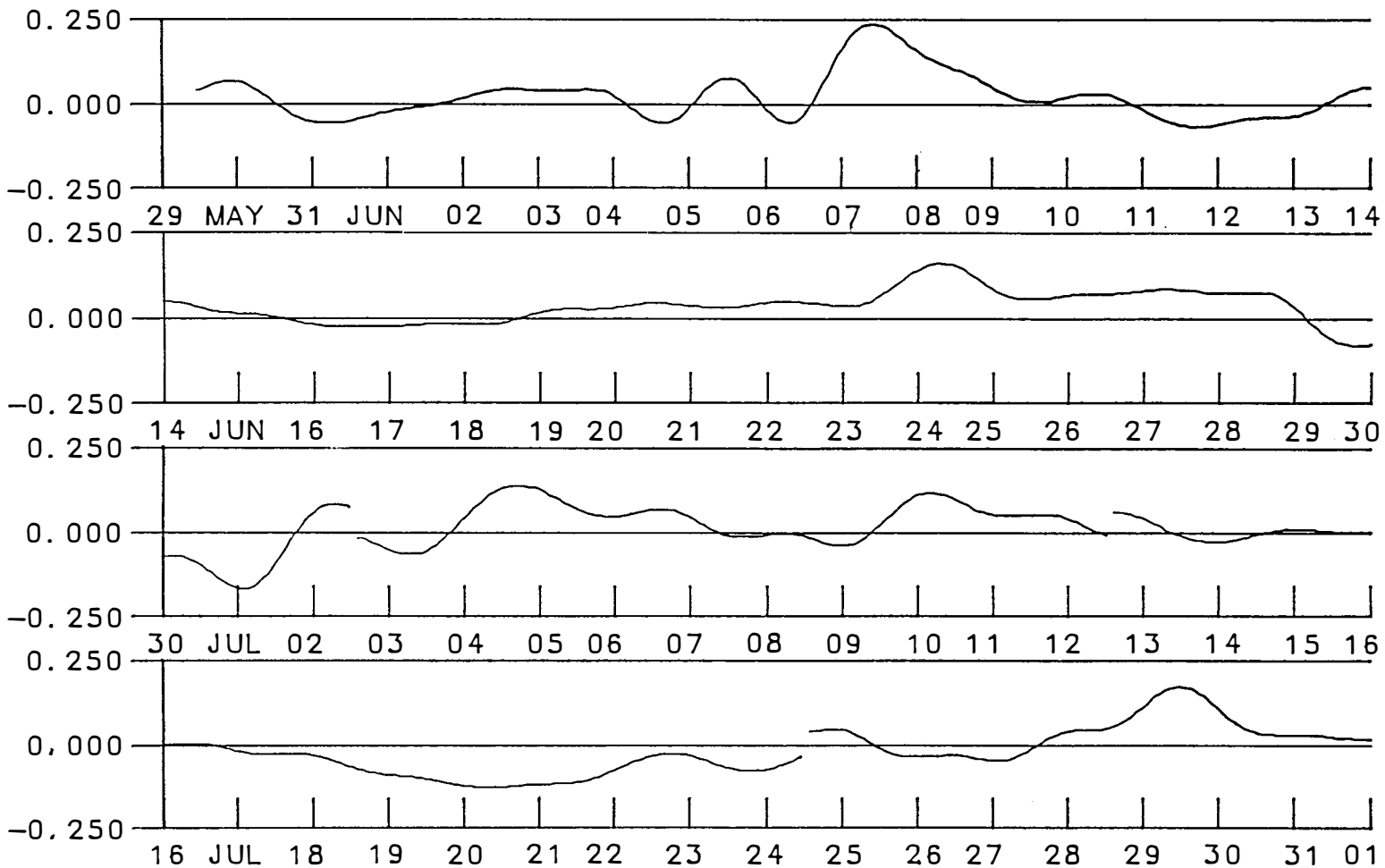
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



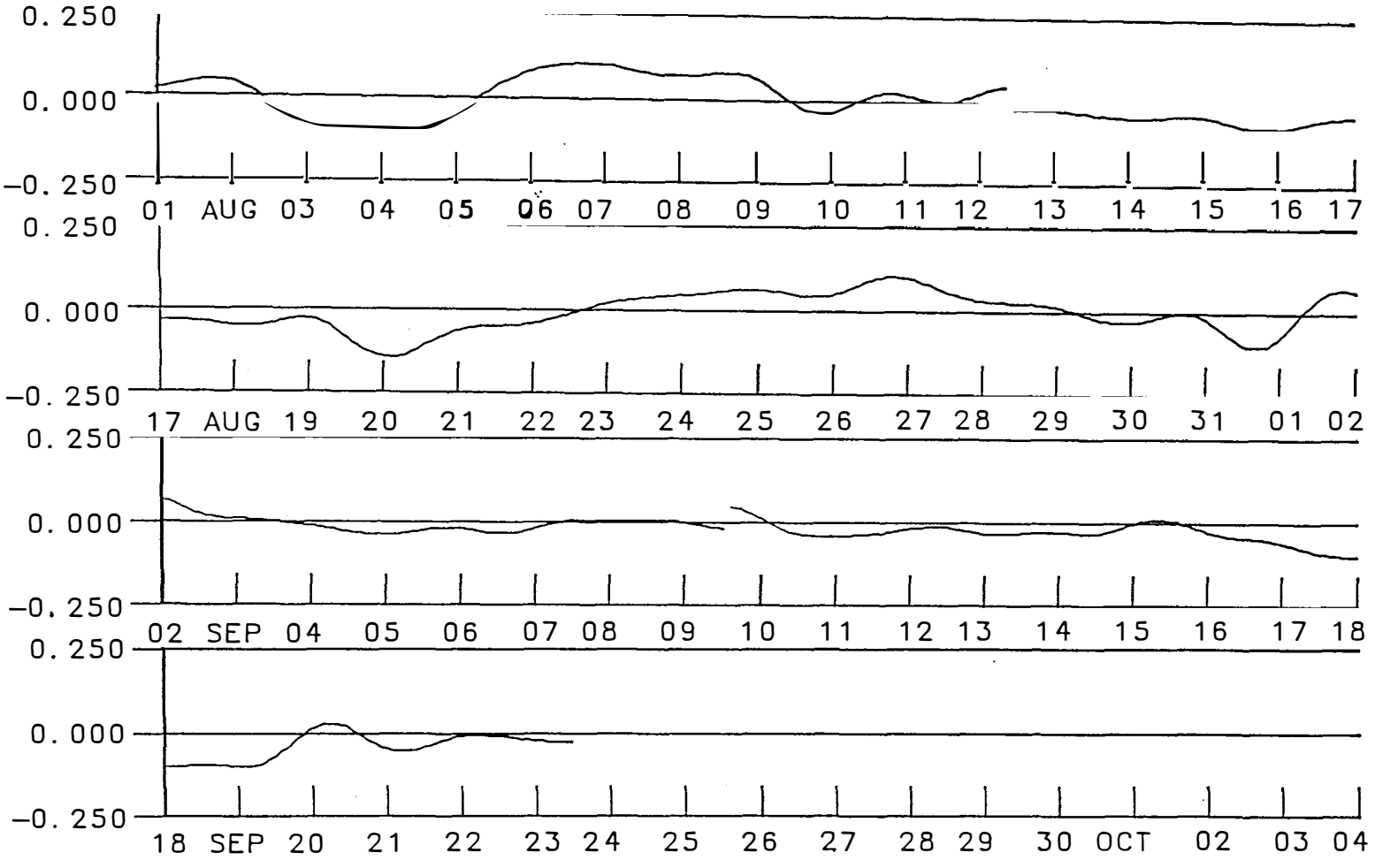
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = .6 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



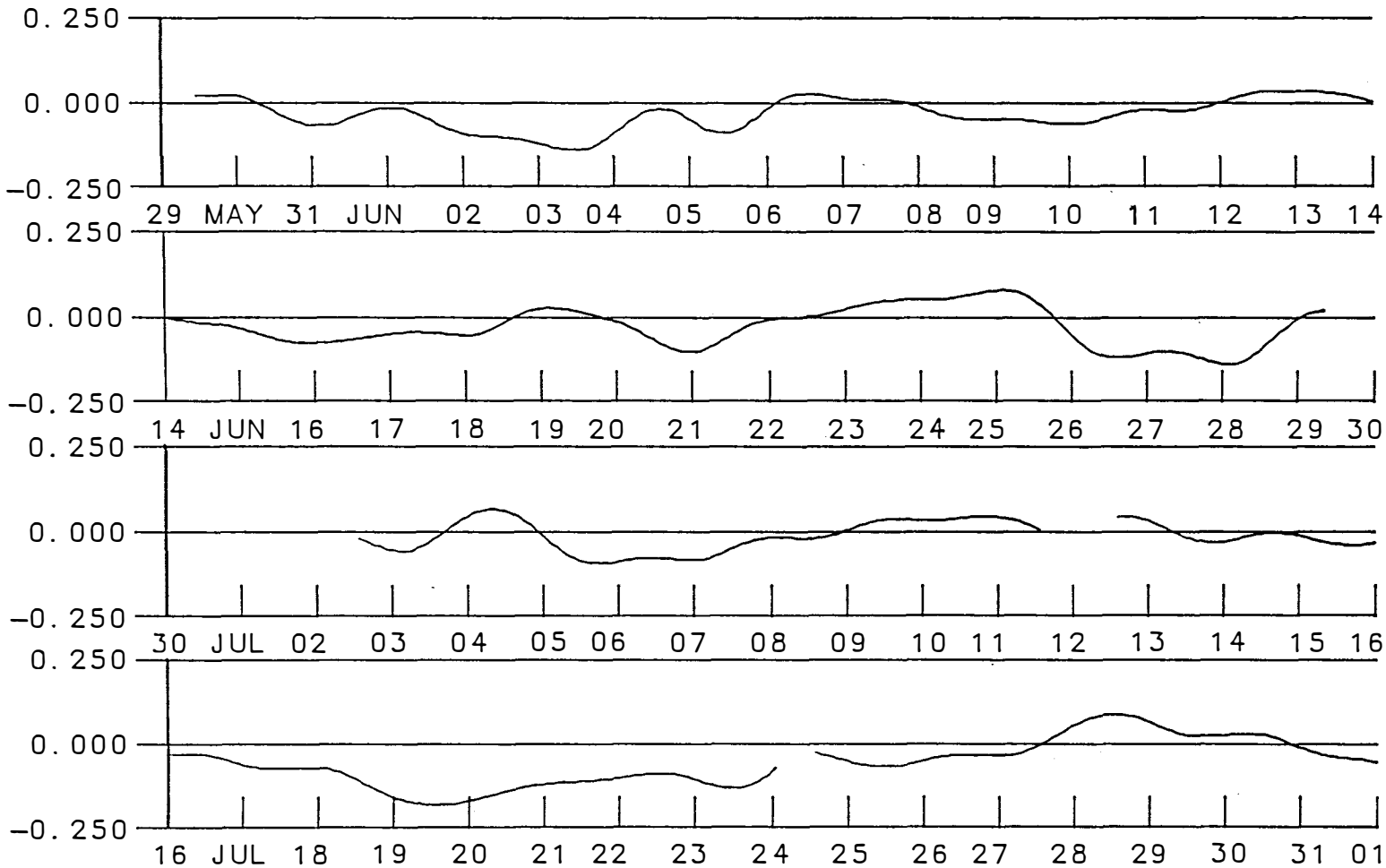
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = .6 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



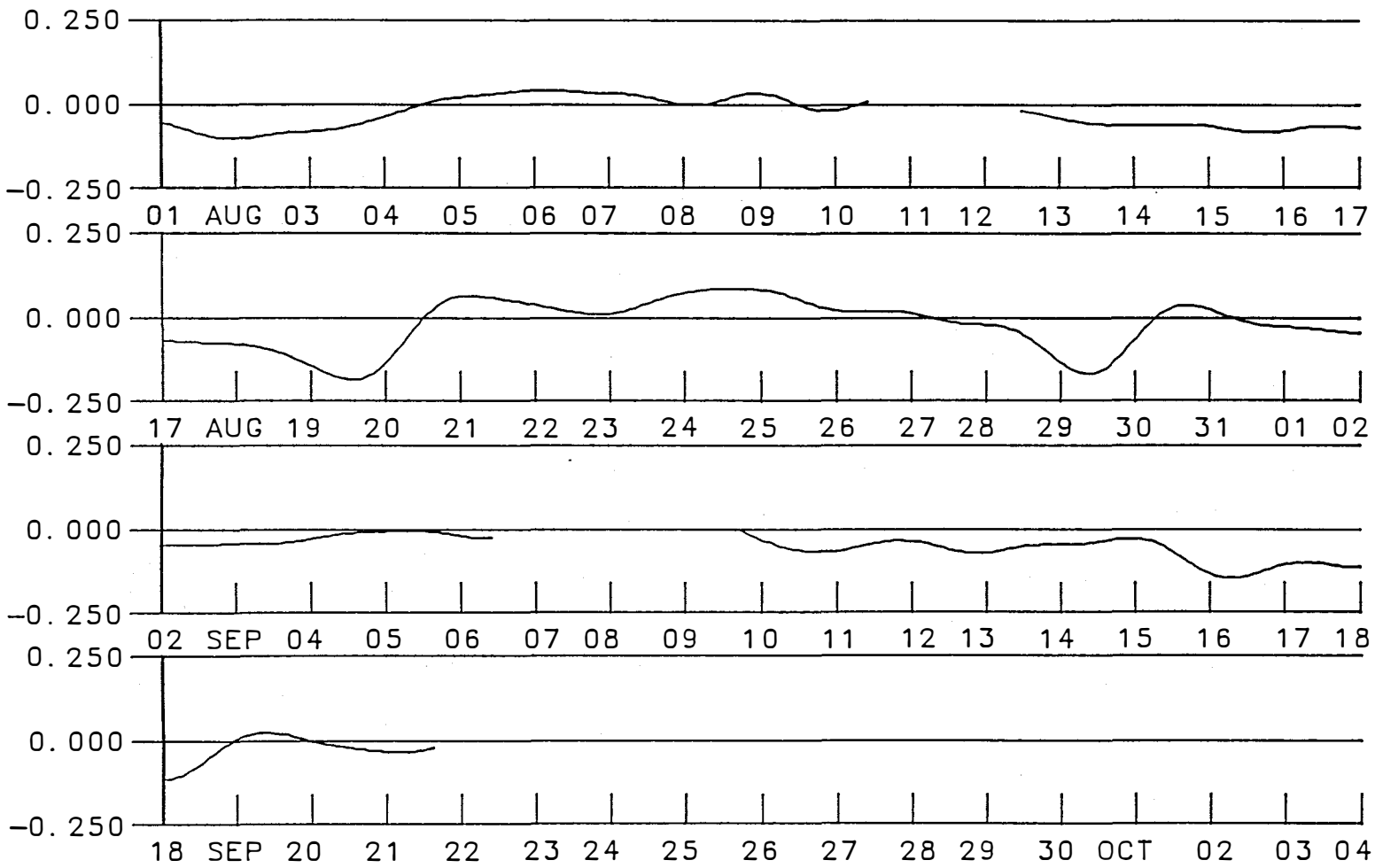
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.0 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



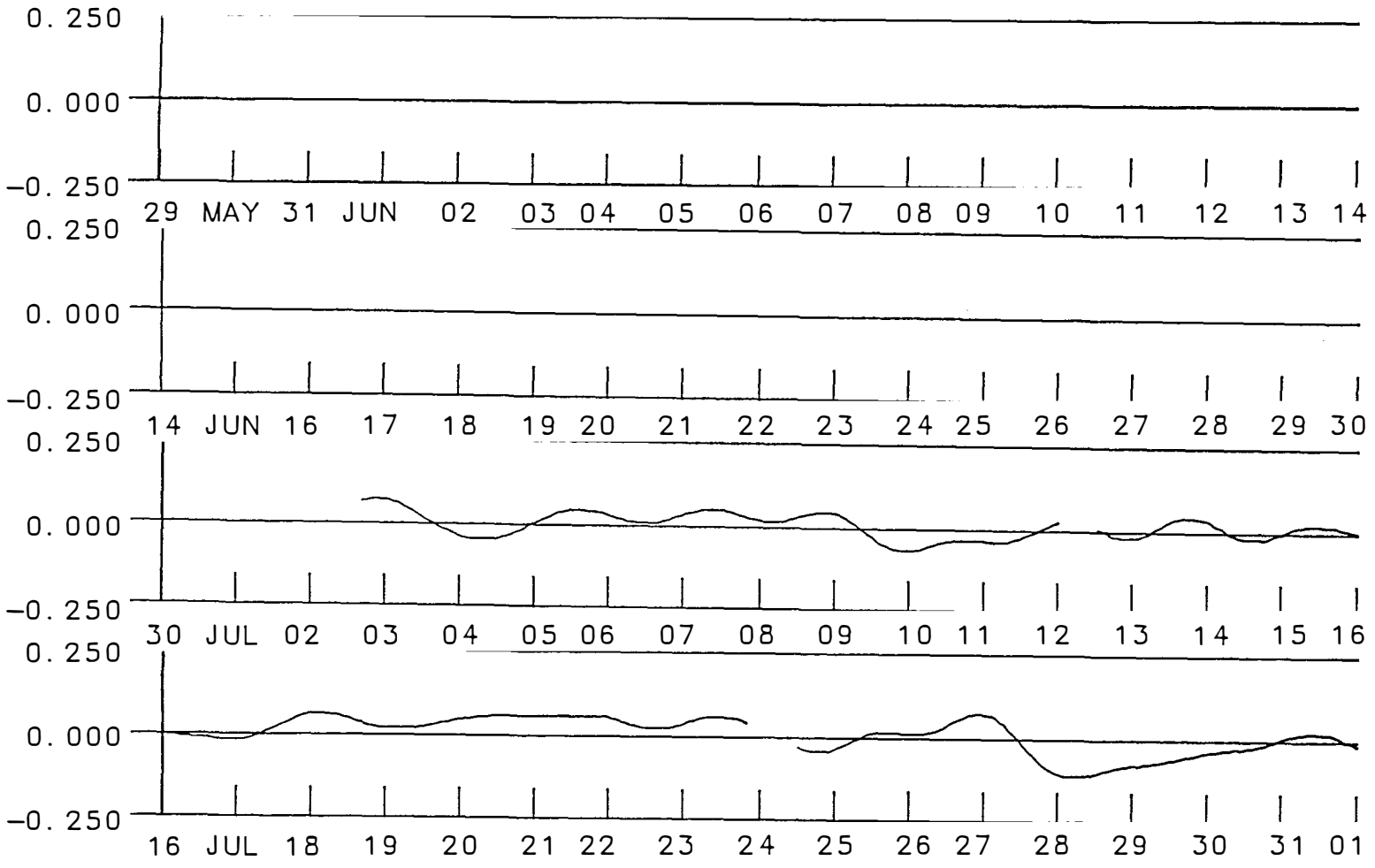
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.0 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



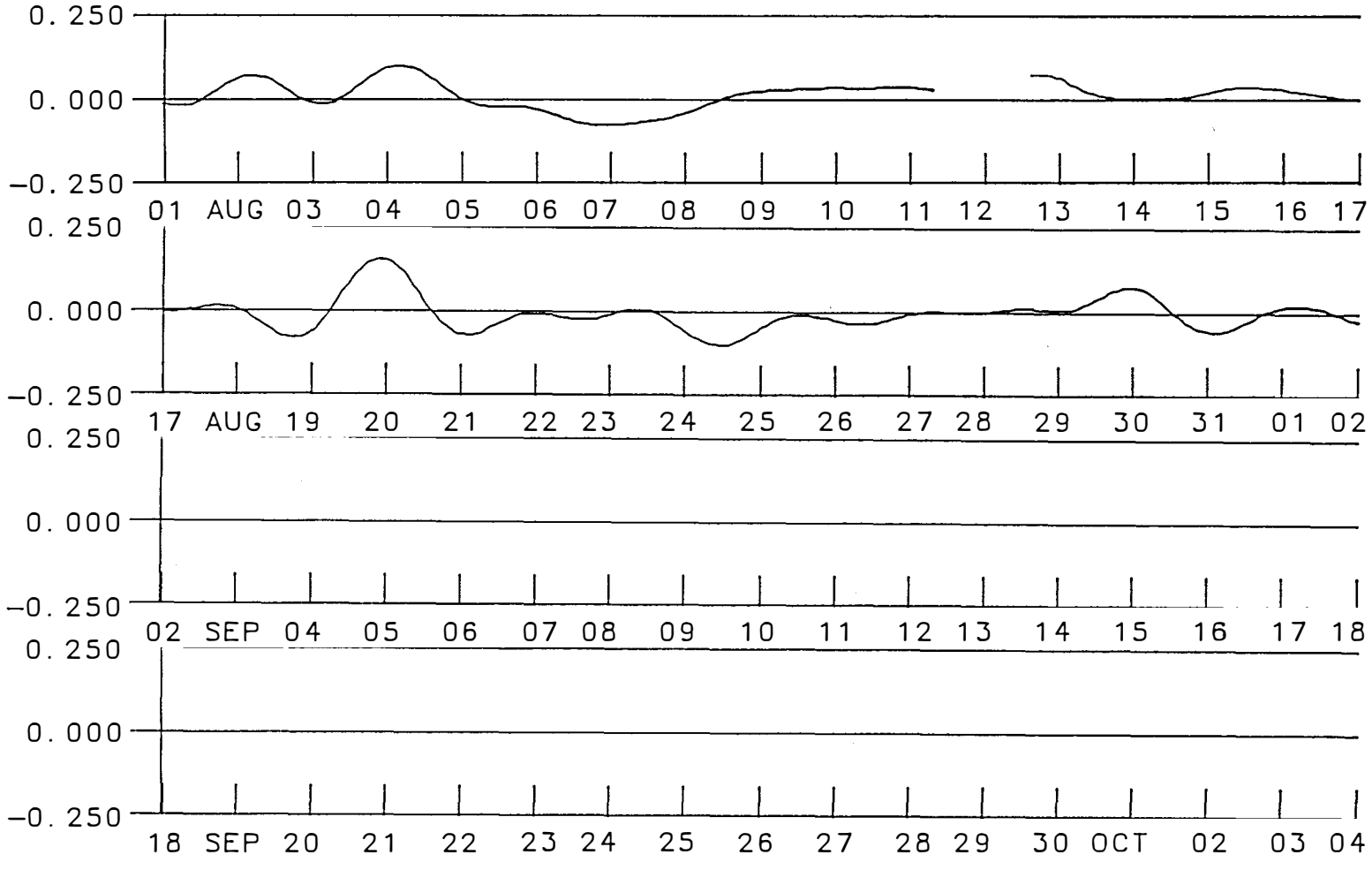
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



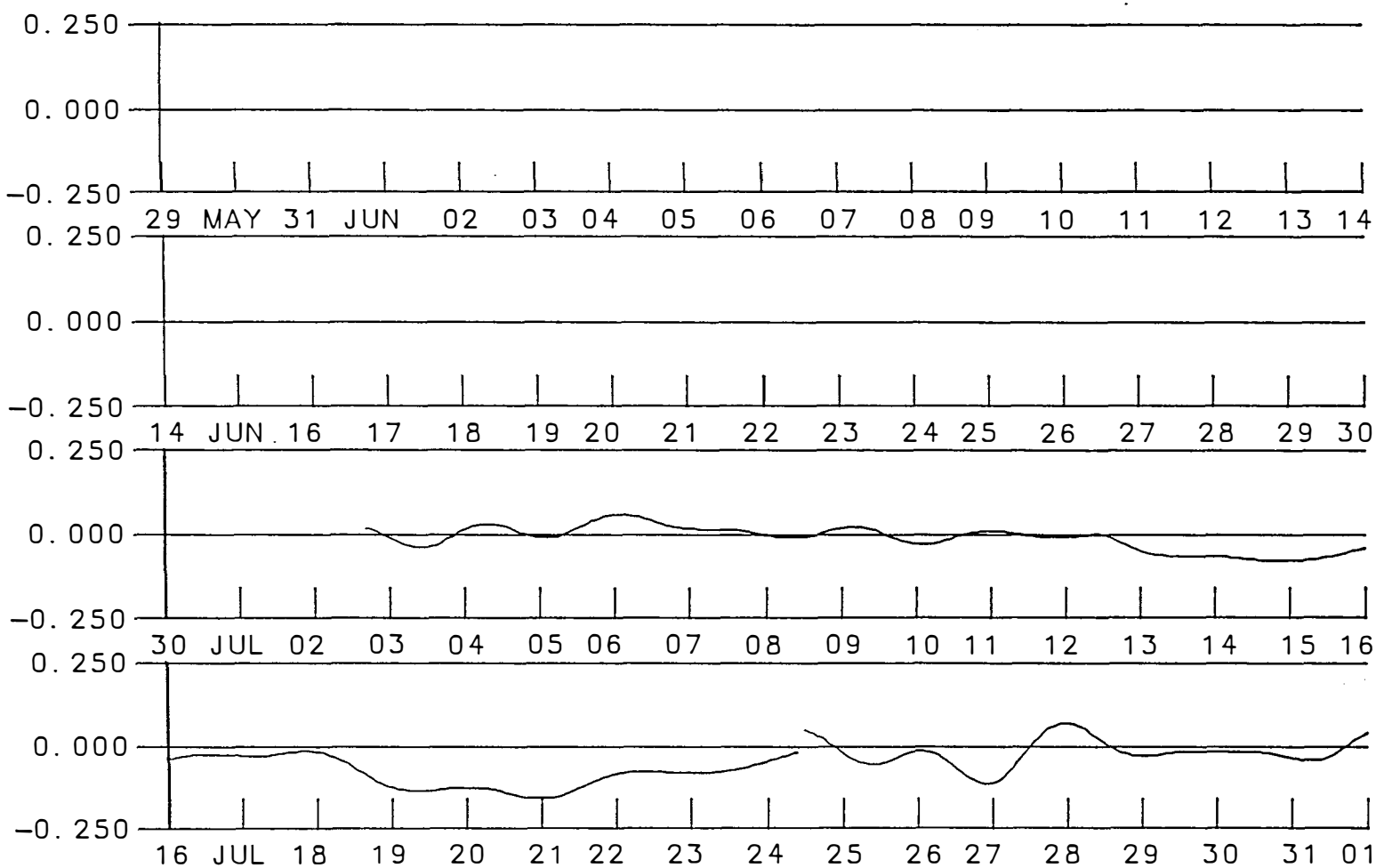
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



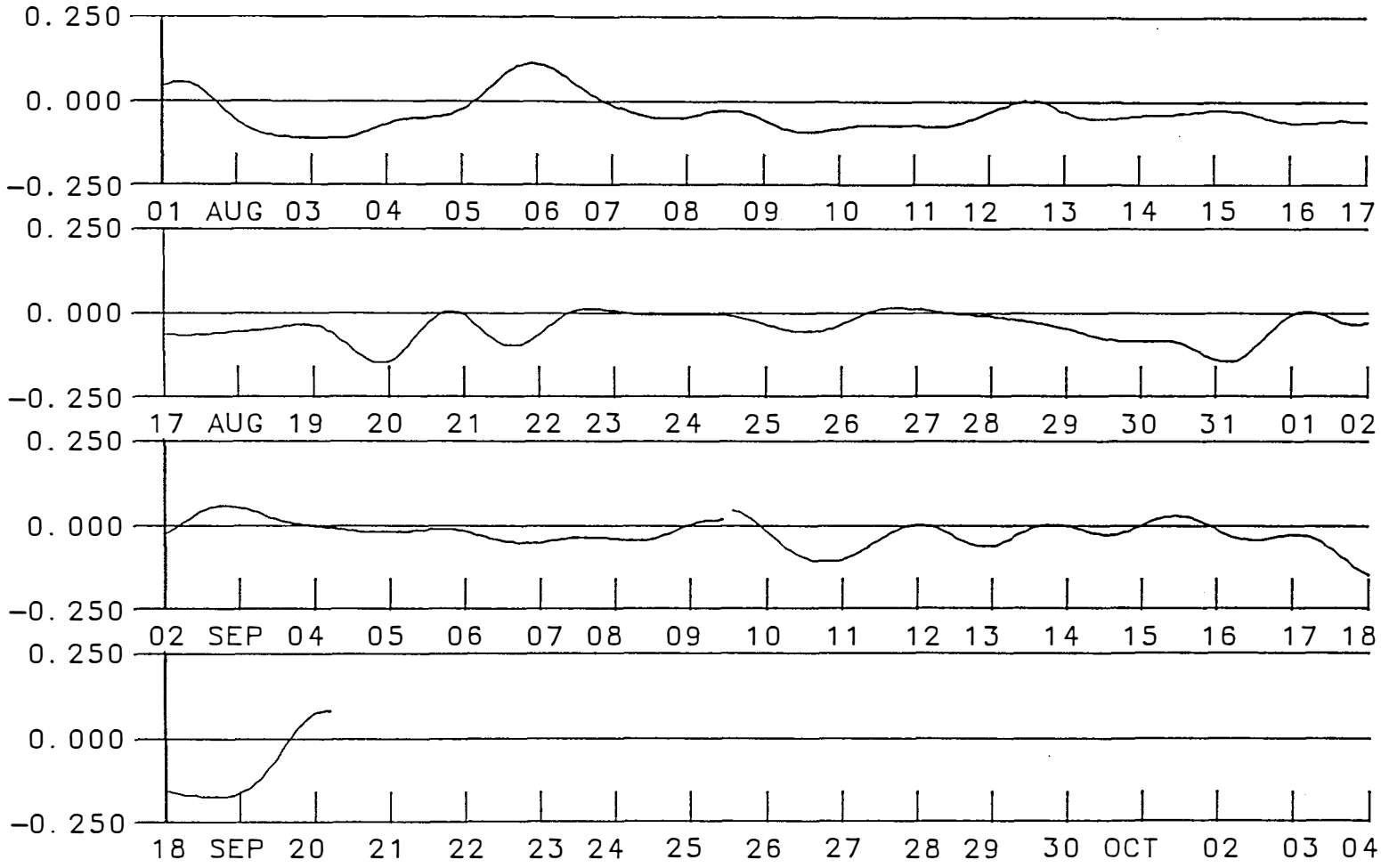
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



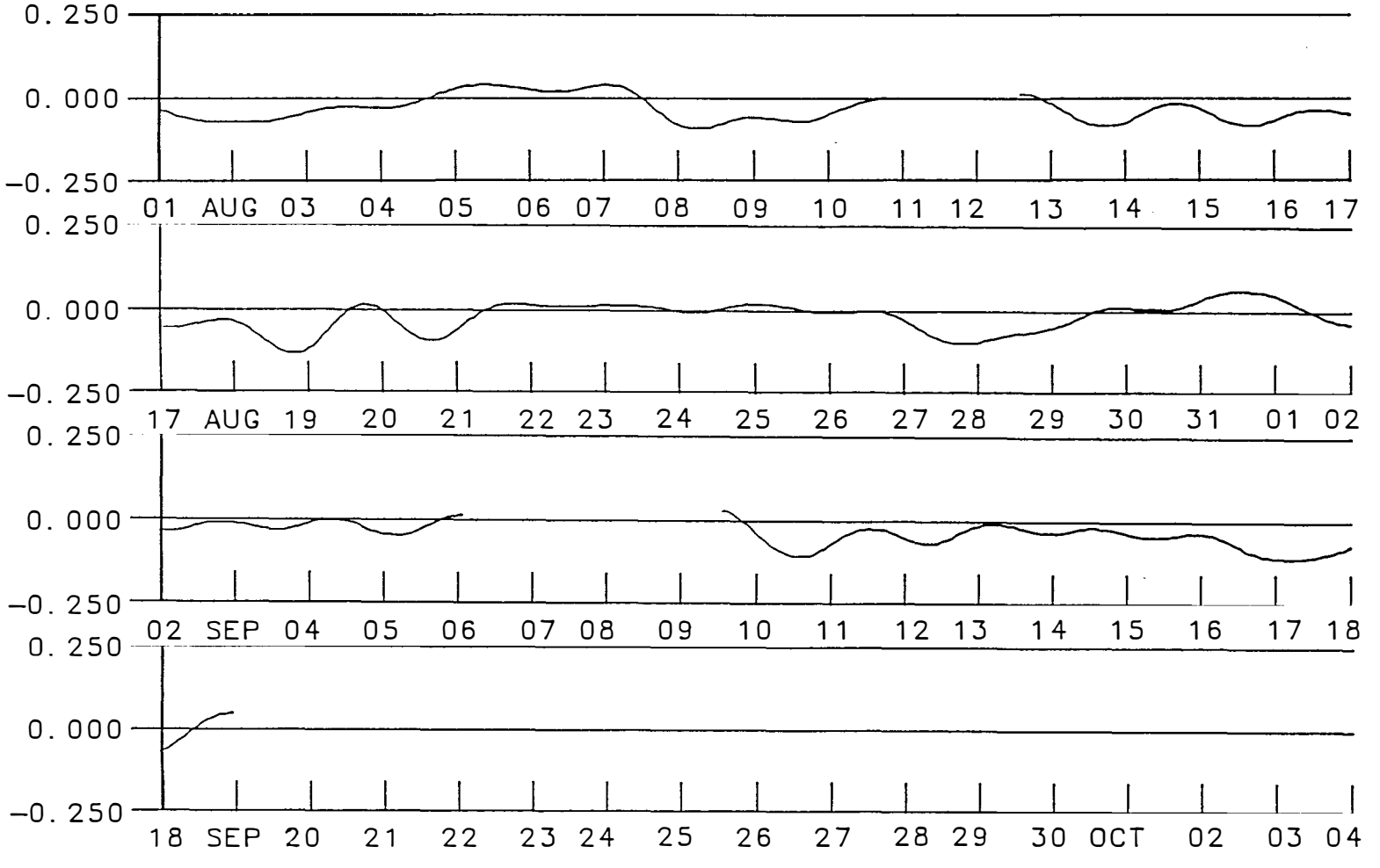
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = .6 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



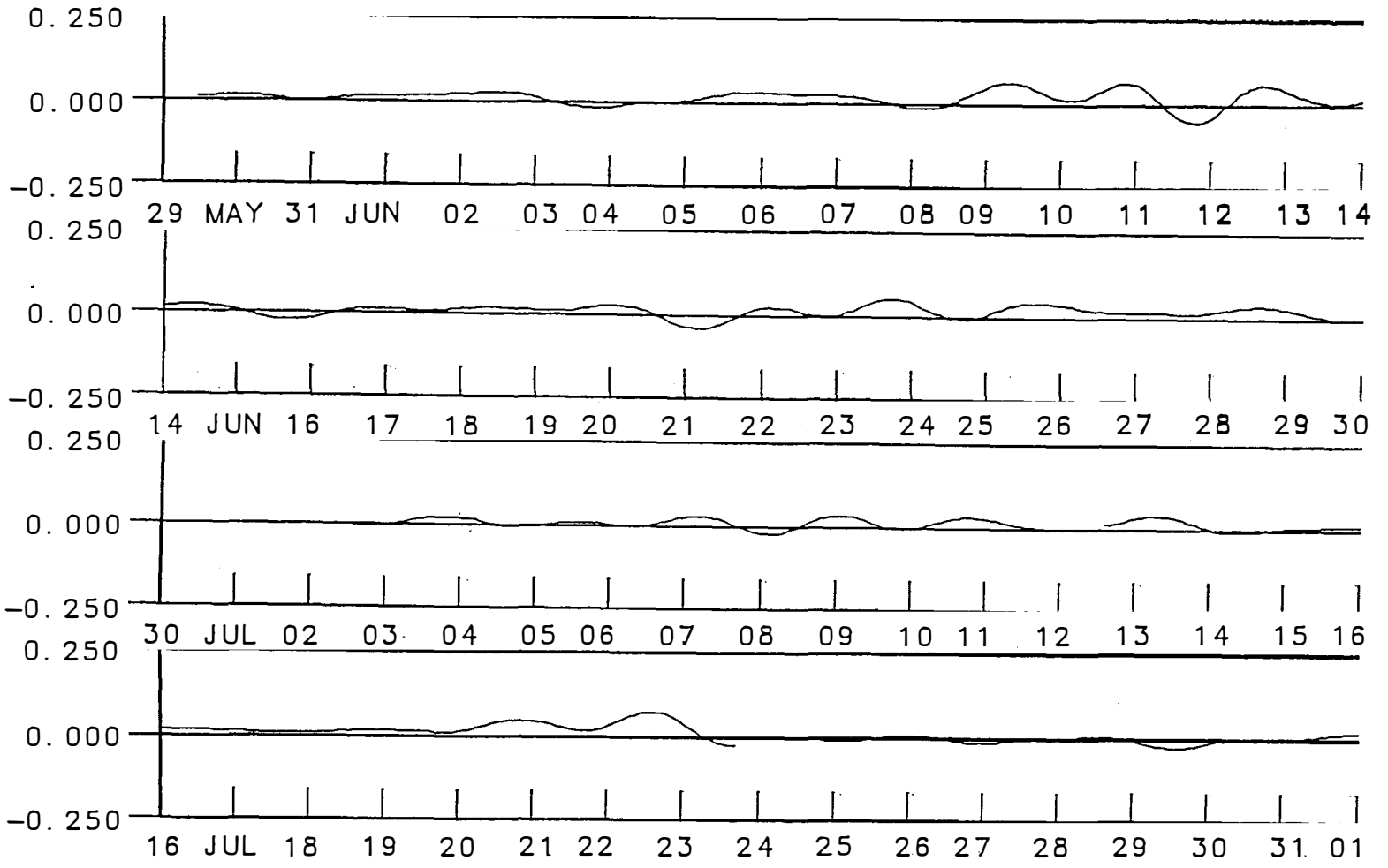
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 6 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS



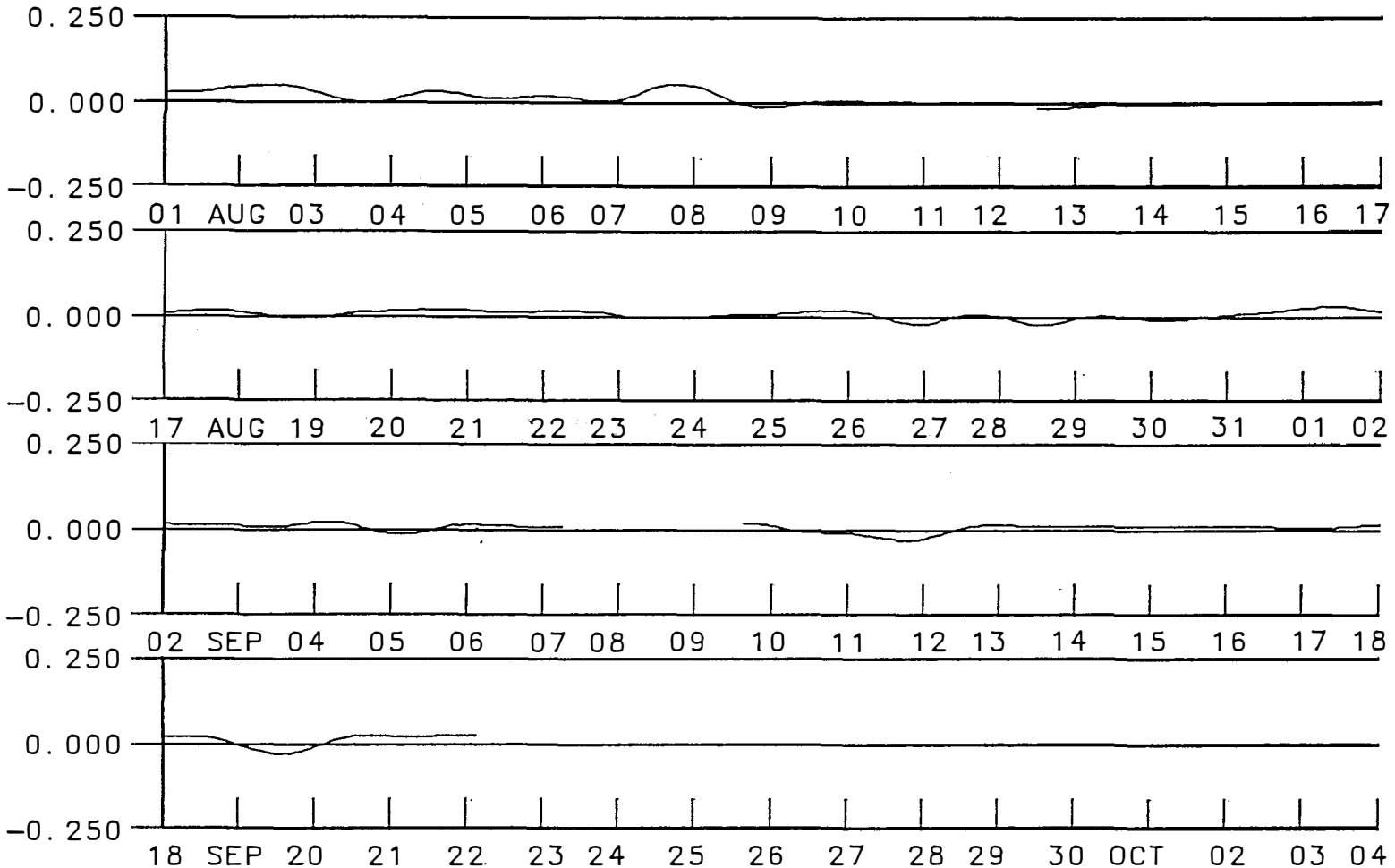
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 10.3 M
LONGITUDINAL COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB
CUT OFF PERIOD FOR FILTER = 36 HOURS

Appendix I-6

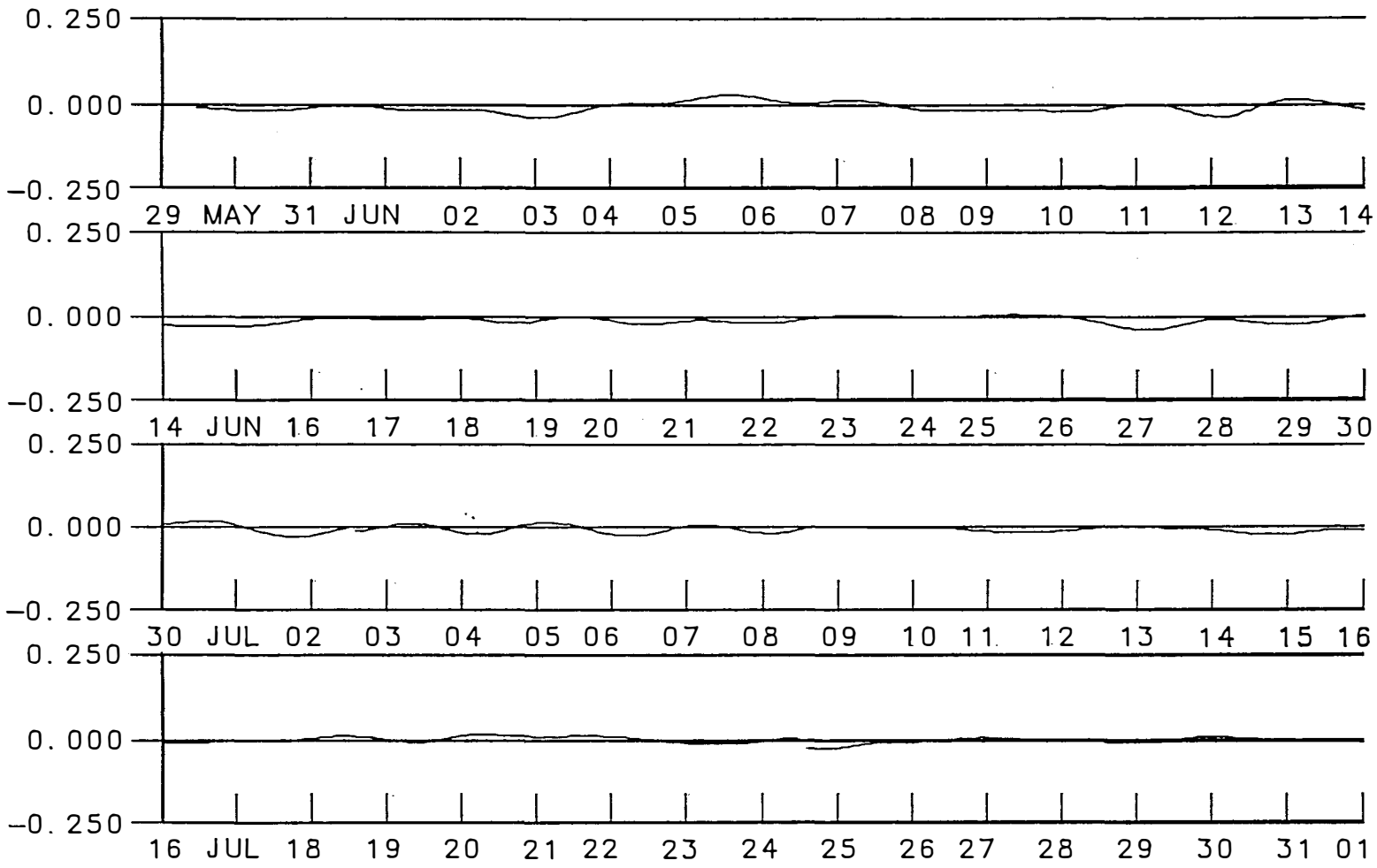
Low-Pass Filtered Transverse Components of Currents



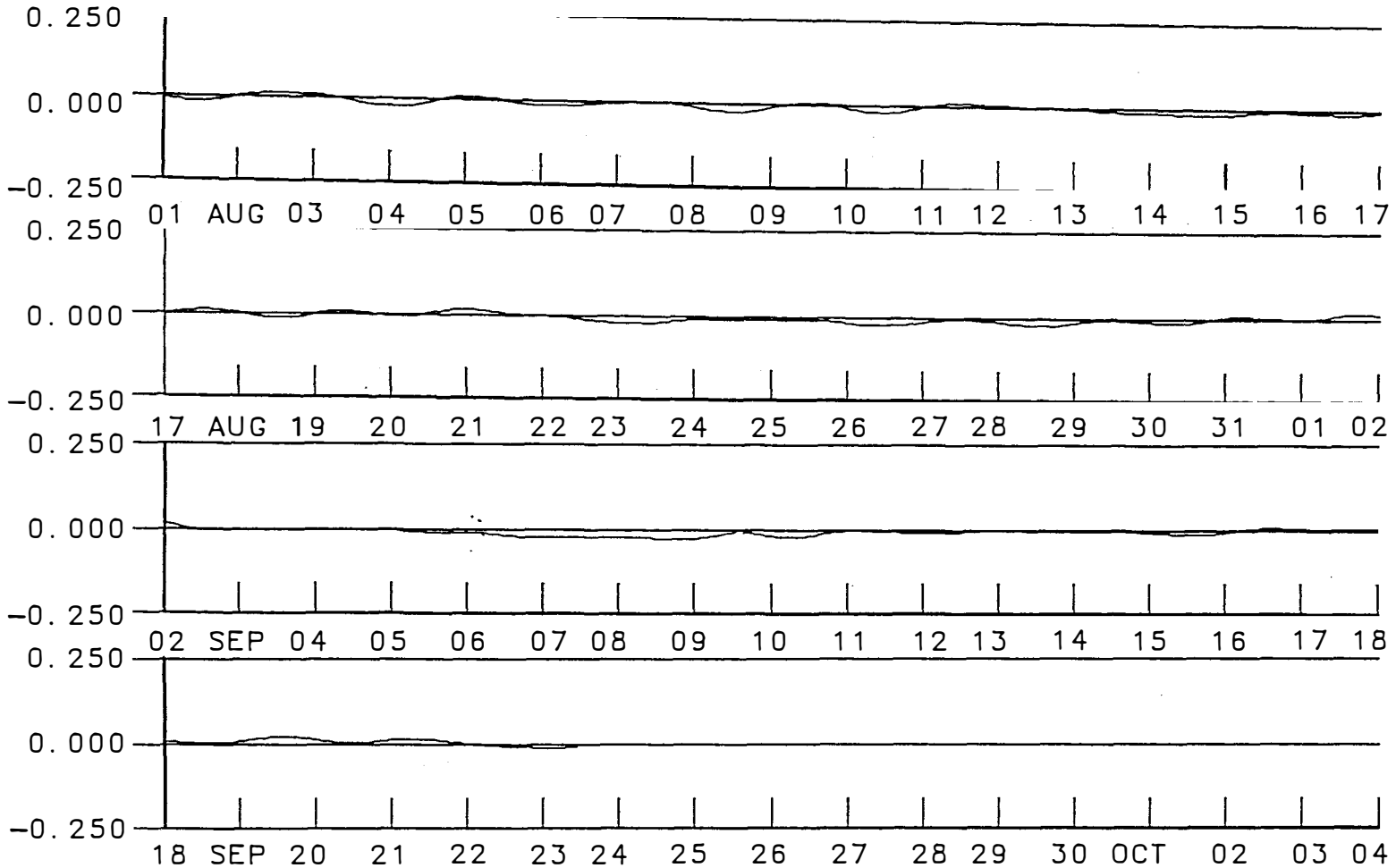
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



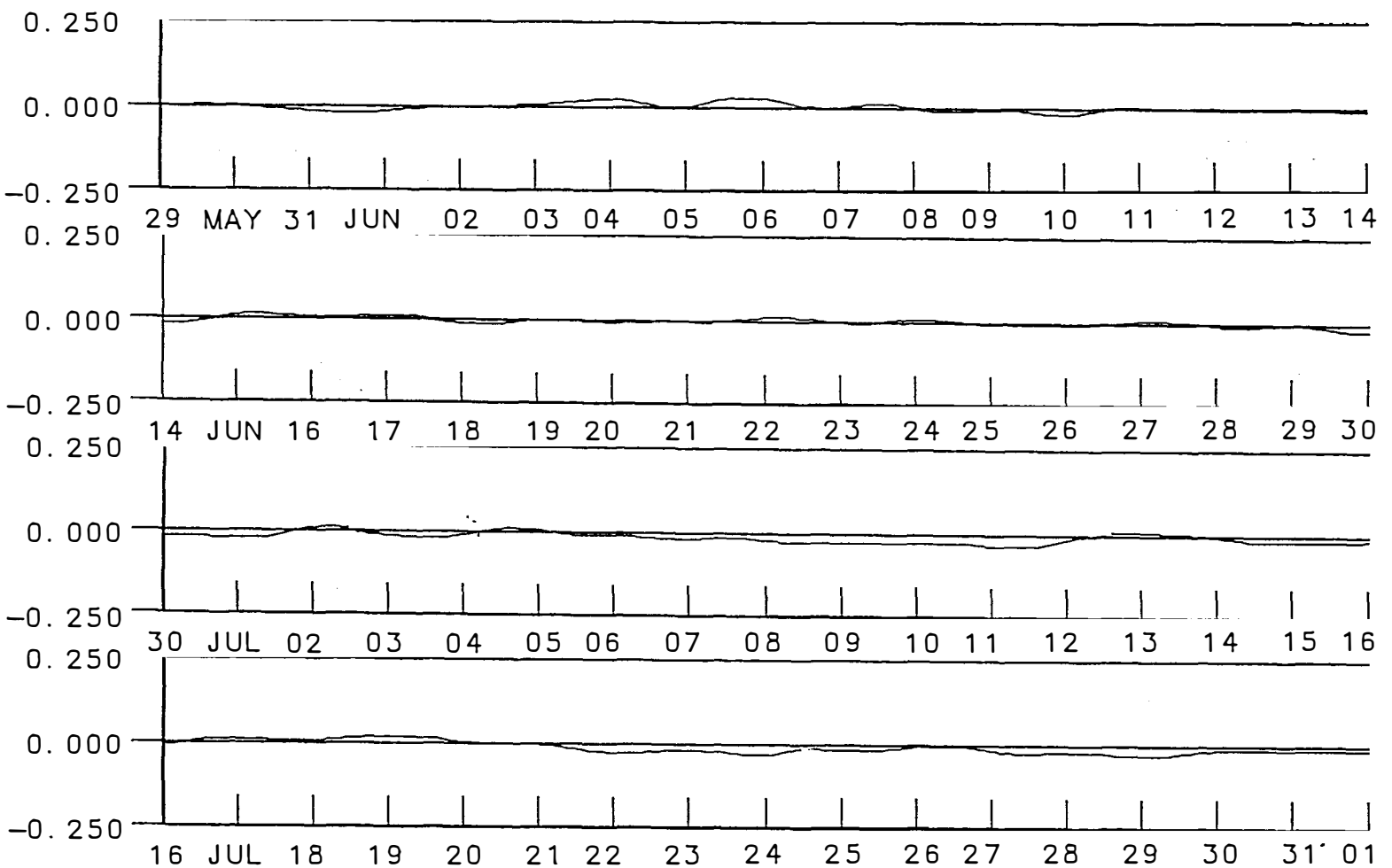
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



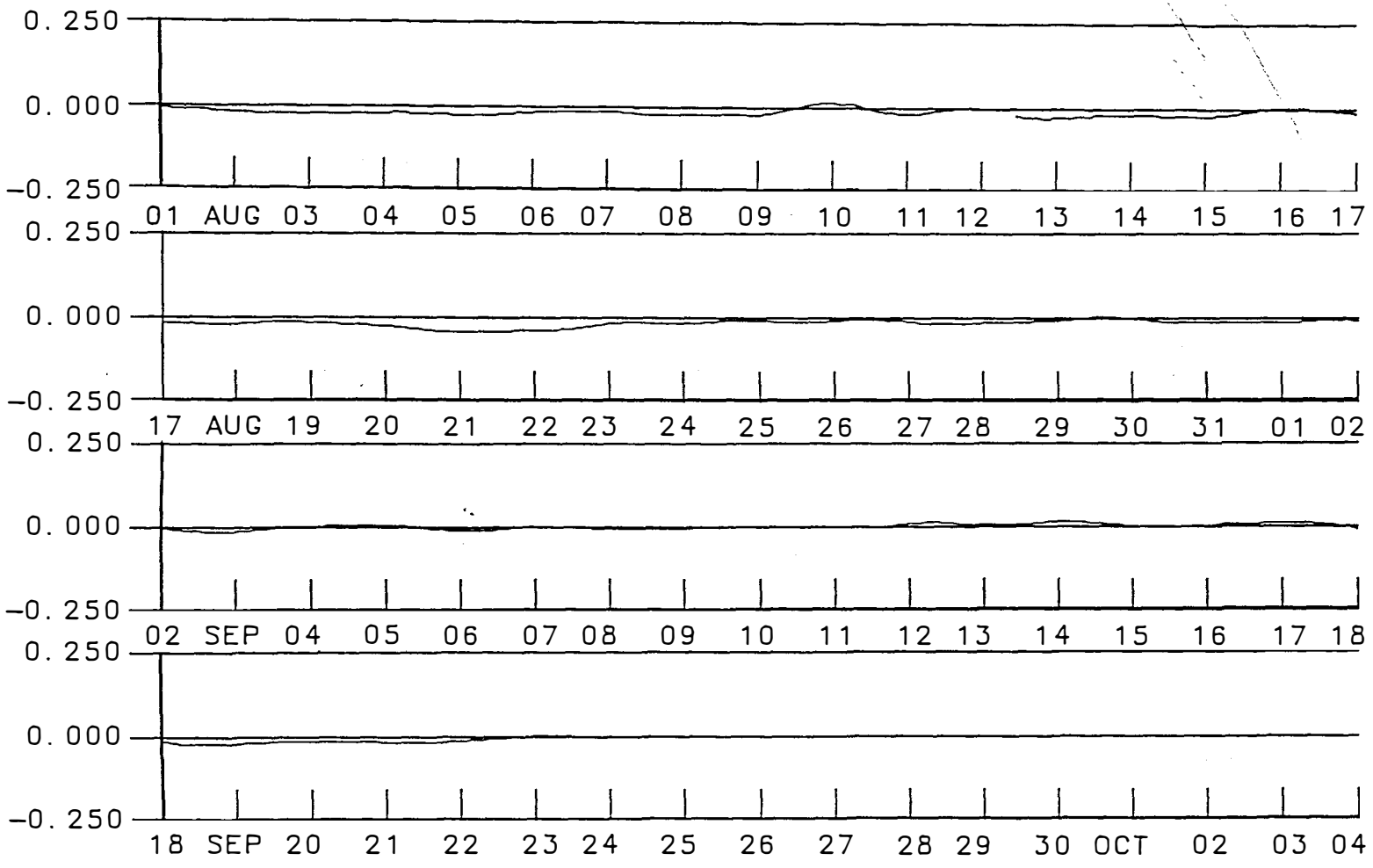
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 6 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



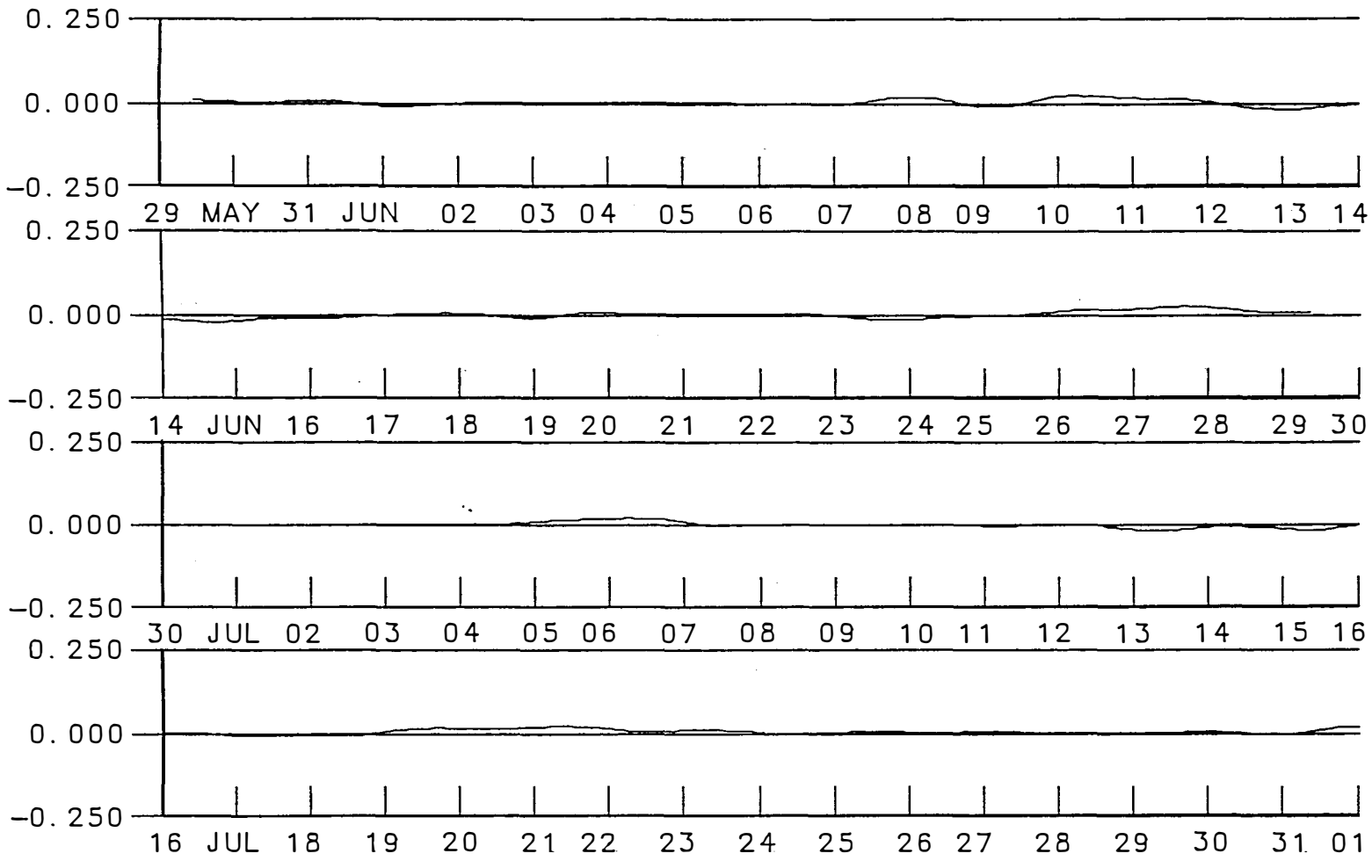
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 6 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



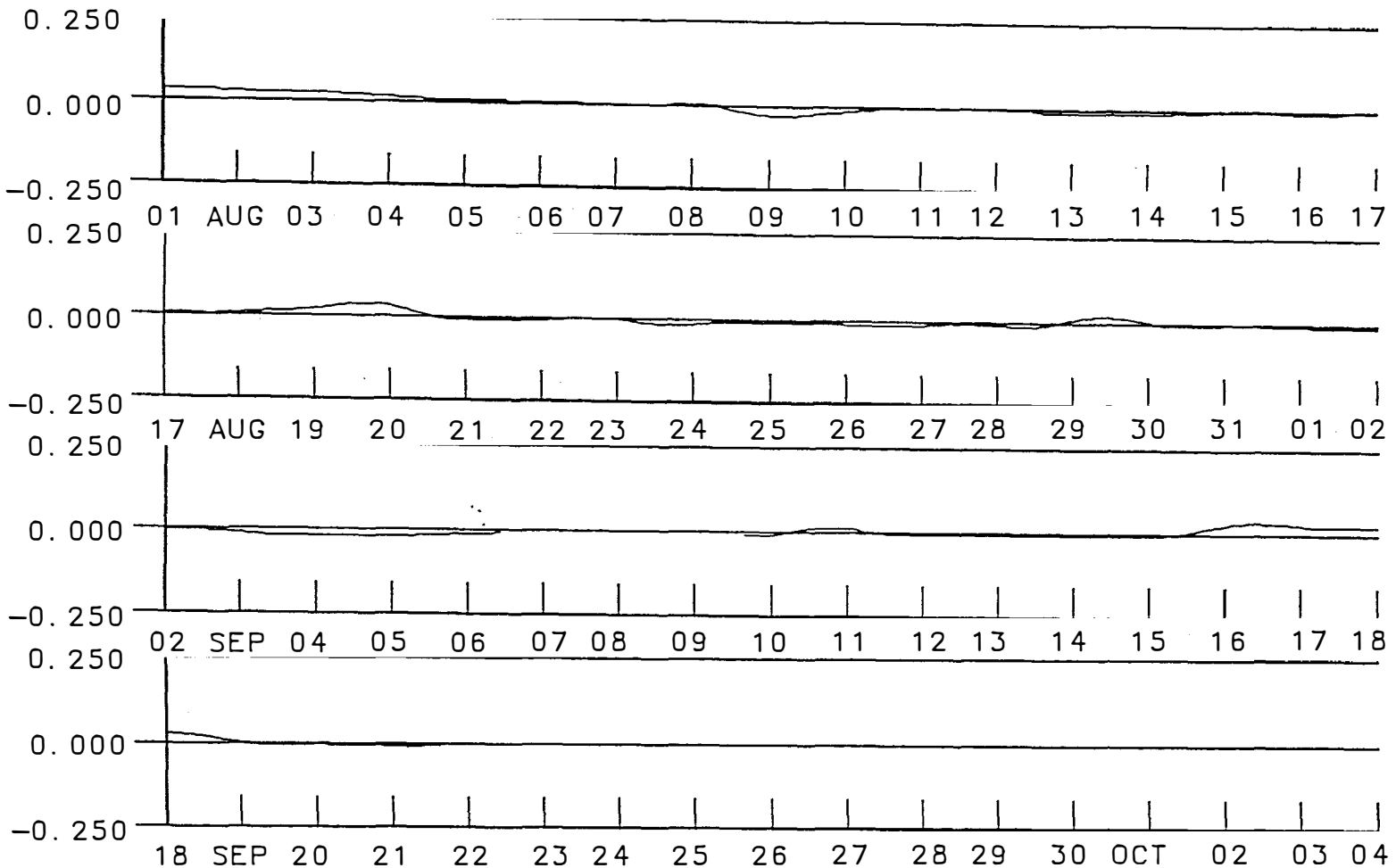
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 10 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



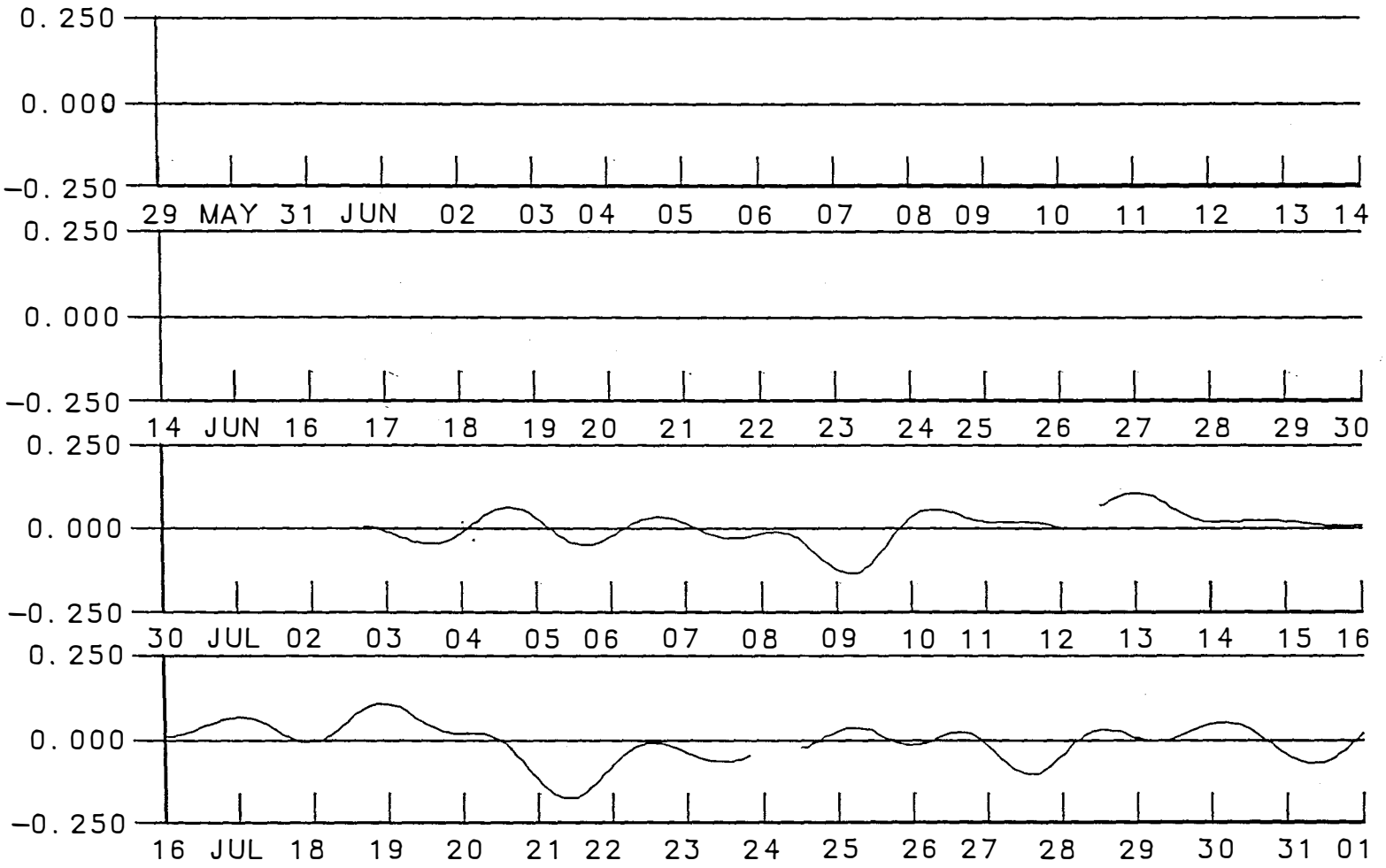
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 1.0 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



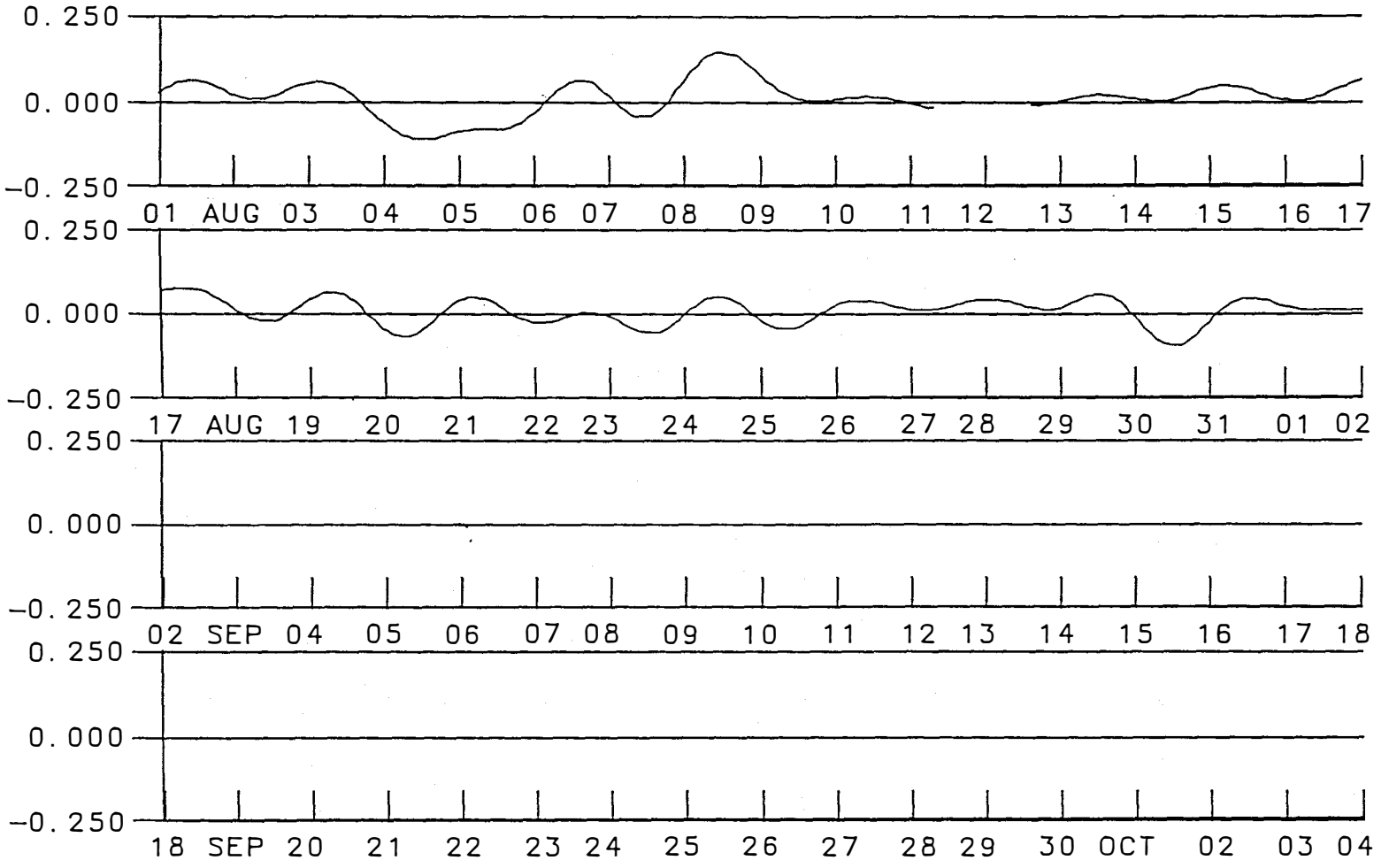
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



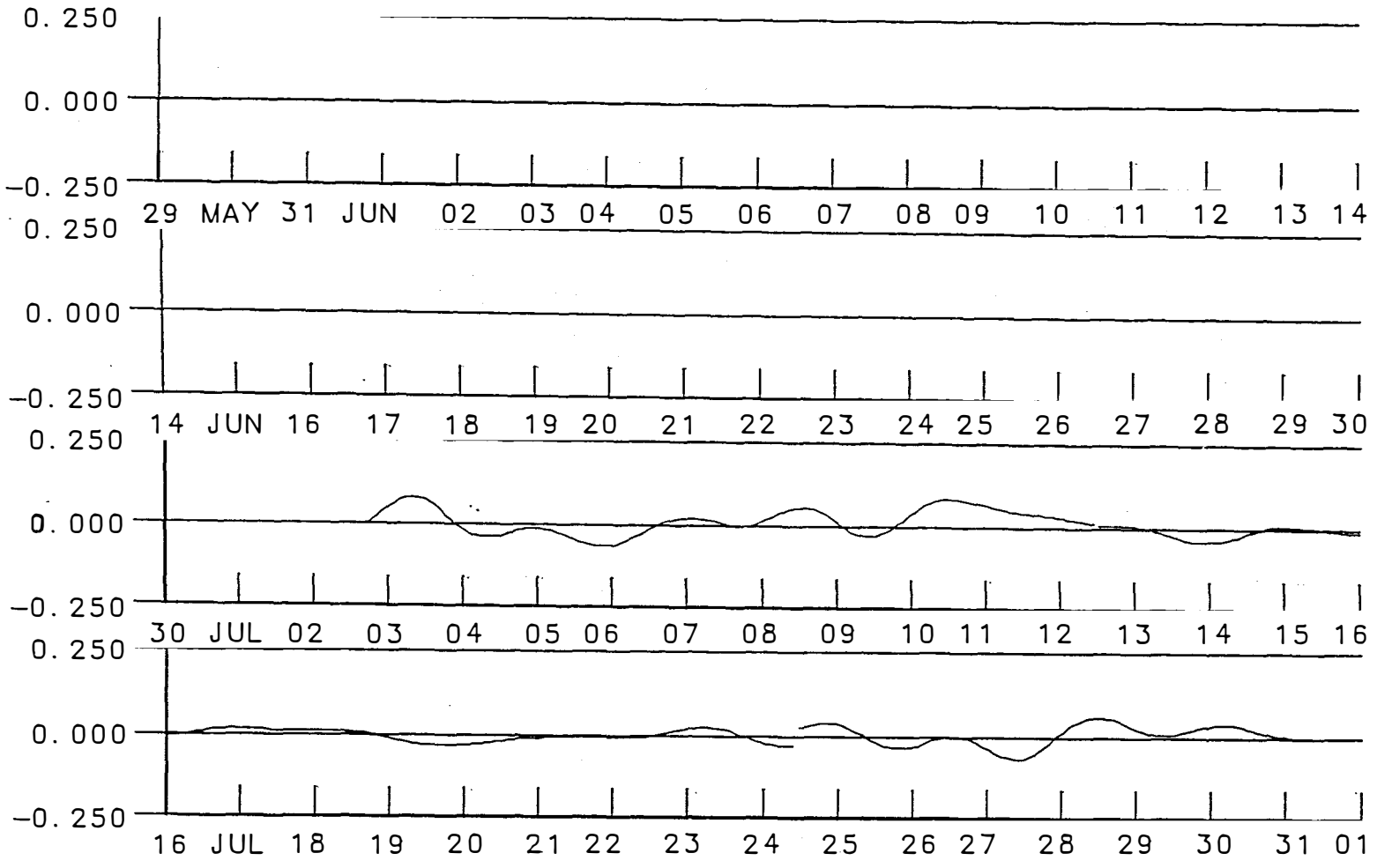
1991 YORK RIVER SUMMER SURVEY
TUE MARSHES DEPTH = 18.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



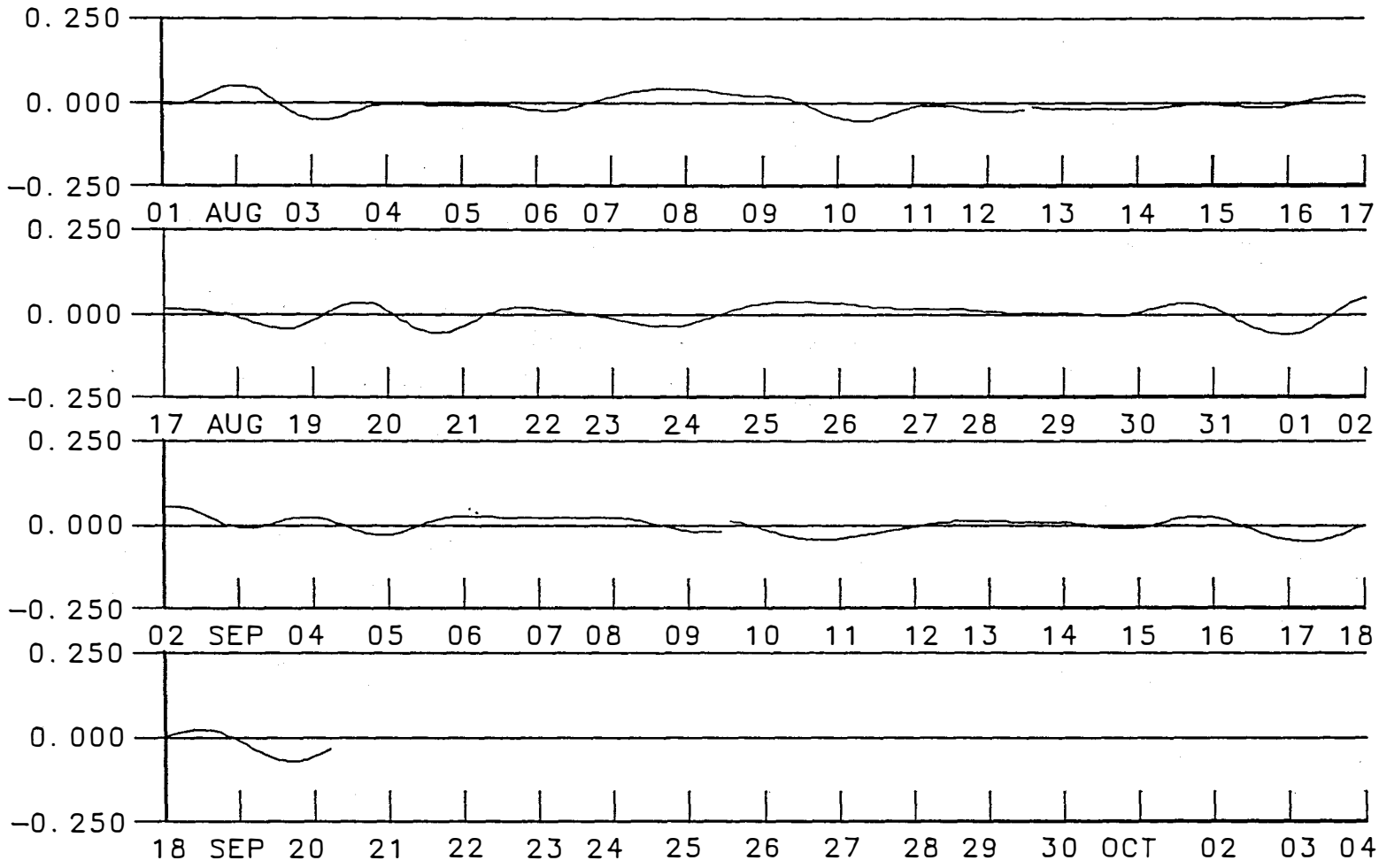
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



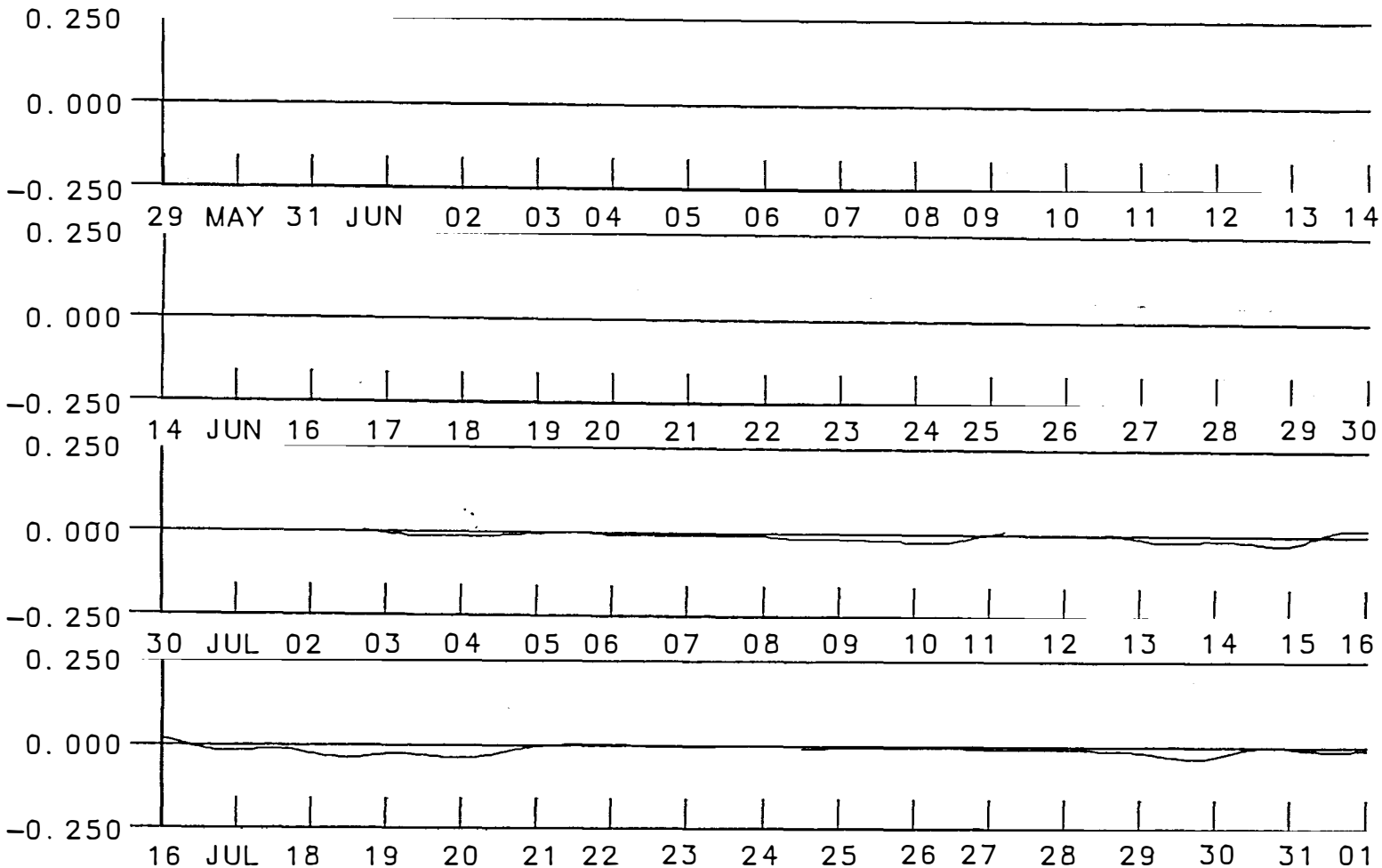
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 1.5 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



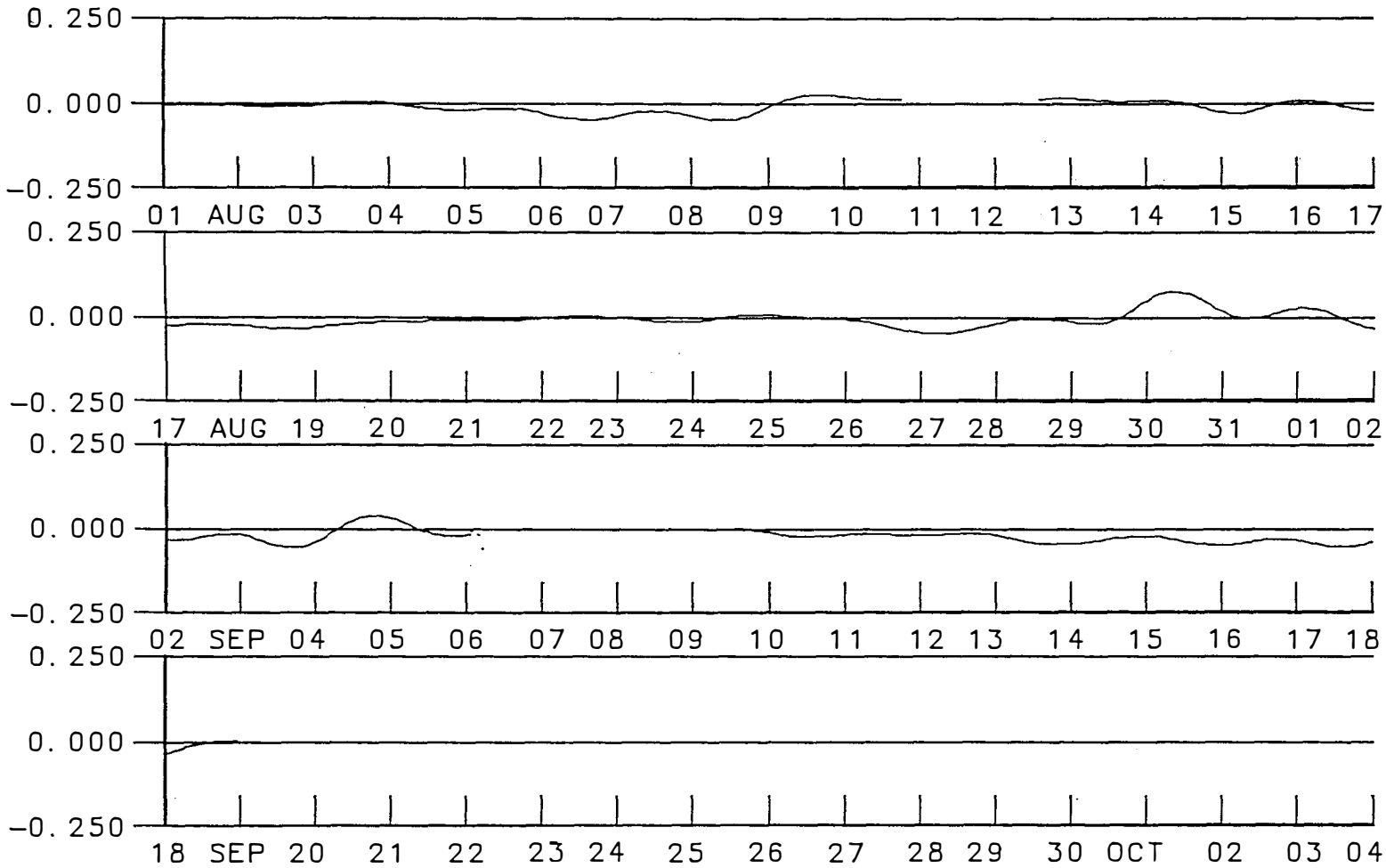
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 6 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 6 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



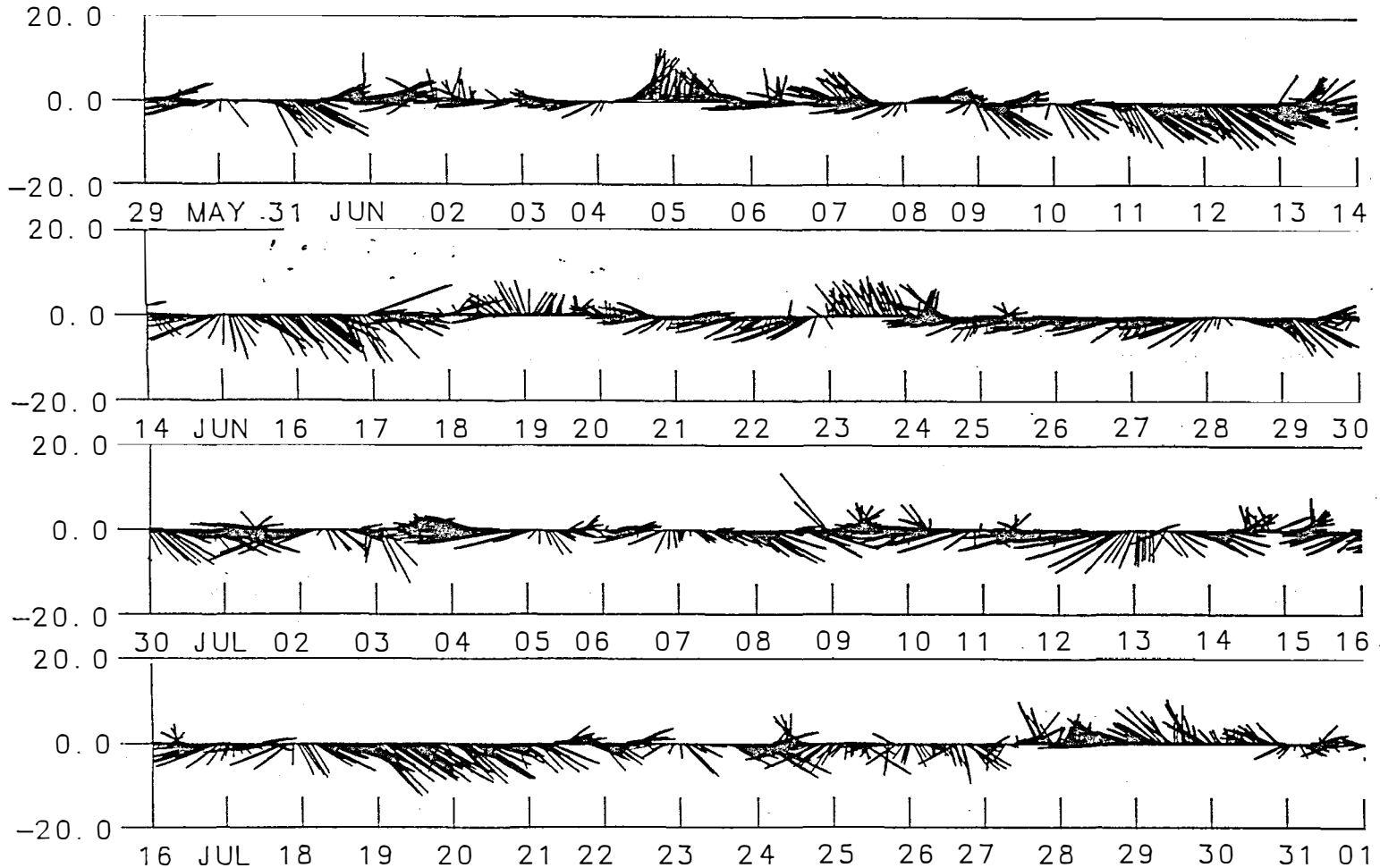
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 10.3 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS



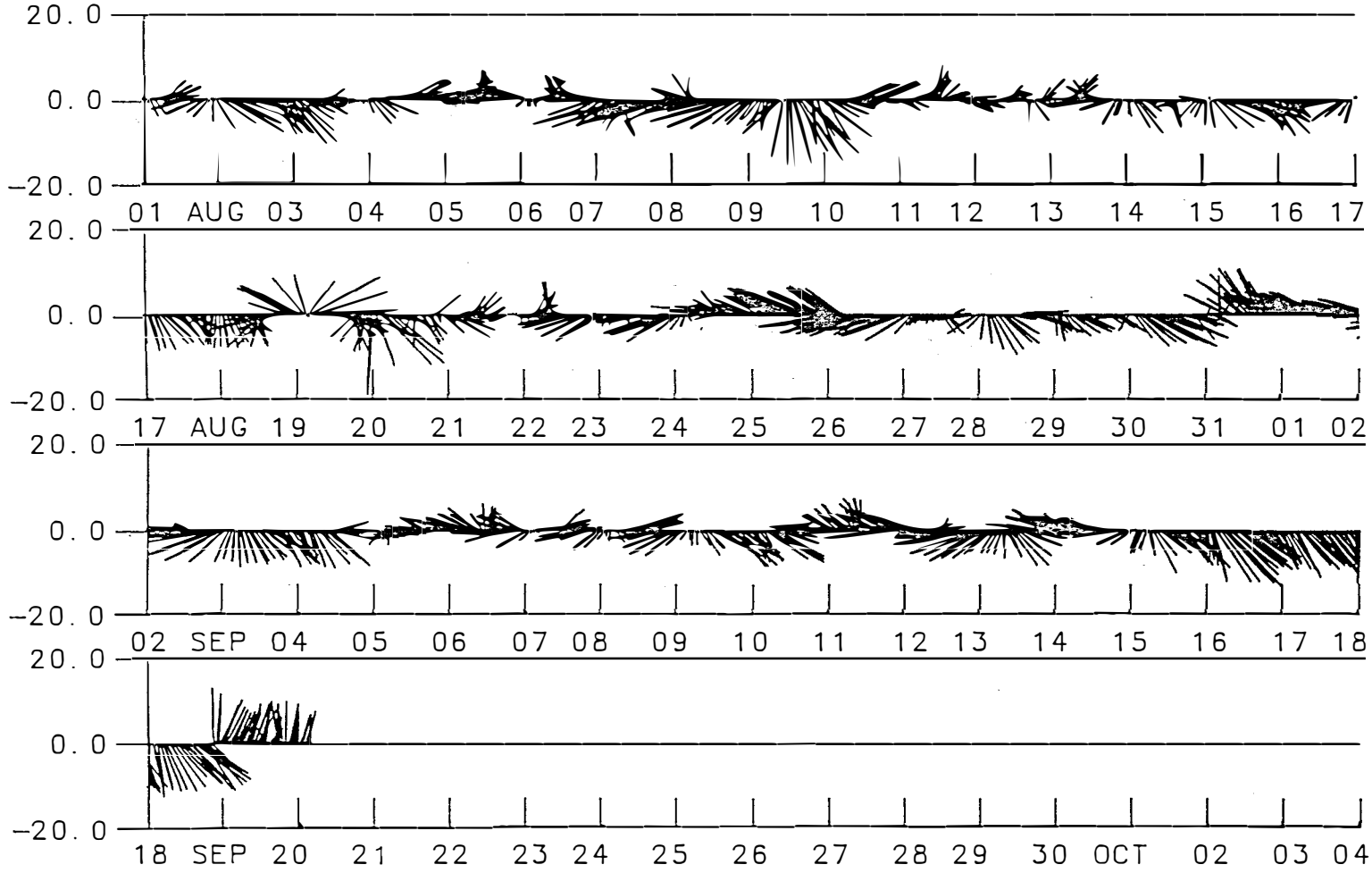
1991 YORK RIVER SUMMER SURVEY
YORK ENTRANCE CHANNEL DEPTH = 10.3 M
TRANSVERSE COMPONENTS (M/S)
POSITIVE Y AXIS IS EBB MINUS 90 DEG.
CUT OFF PERIOD FOR FILTER = 36 HOURS

Appendix I-7

Stickplots of Wind at Gloucester Point



1991 YORK RIVER SUMMER SURVEY
MEASUREMENTS FROM VIMS ANEMOMETER (GLOUCESTER PT.)
VECTORS ARE IN KNOTS, POSITIVE Y-AXIS TO THE WEST

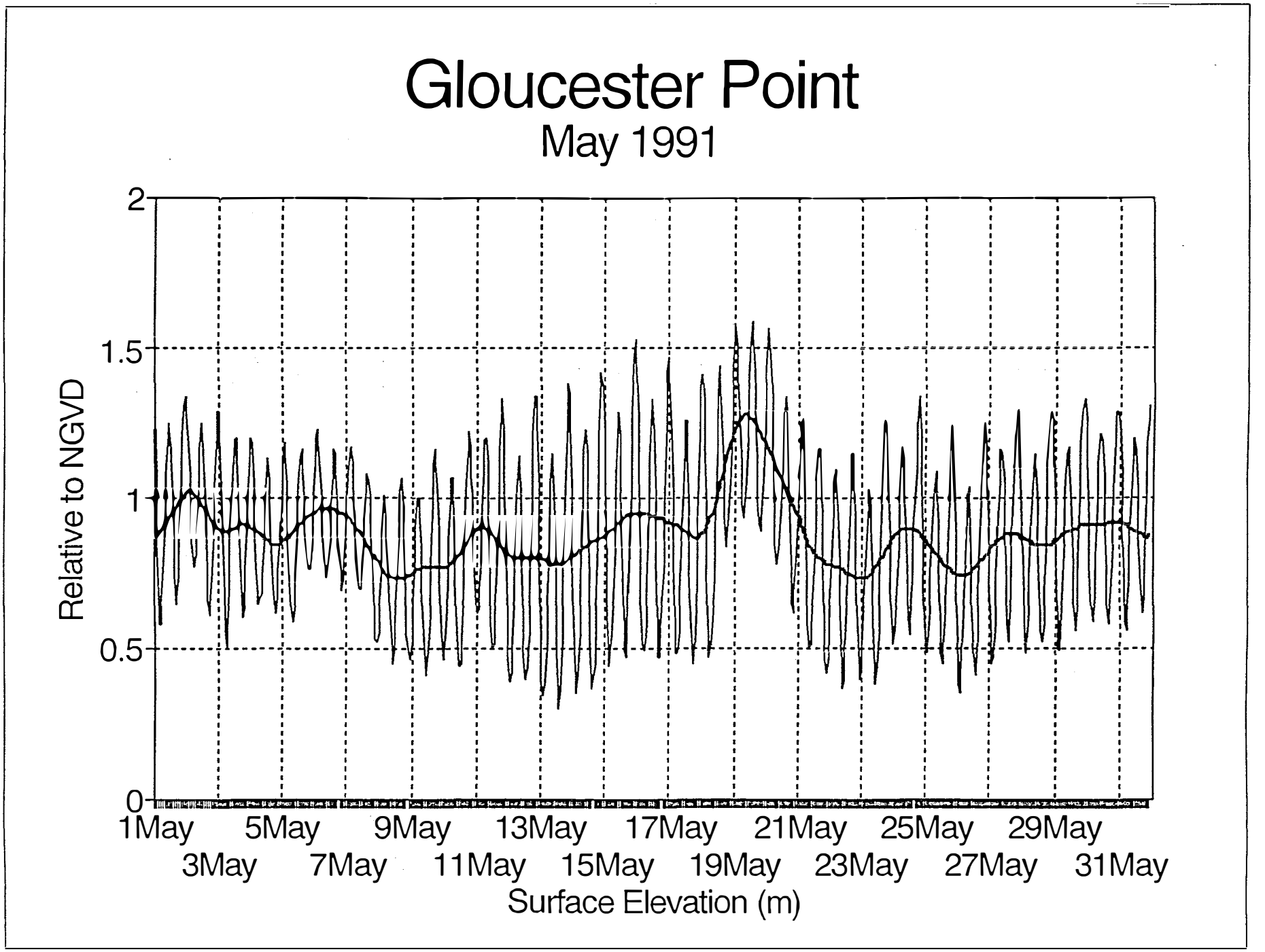


1991 YORK RIVER SUMMER SURVEY
MEASUREMENTS FROM VIMS ANEMOMETER (GLOUCESTER PT.)
VECTORS ARE IN KNOTS, POSITIVE Y-AXIS TO THE WEST

Appendix I-8

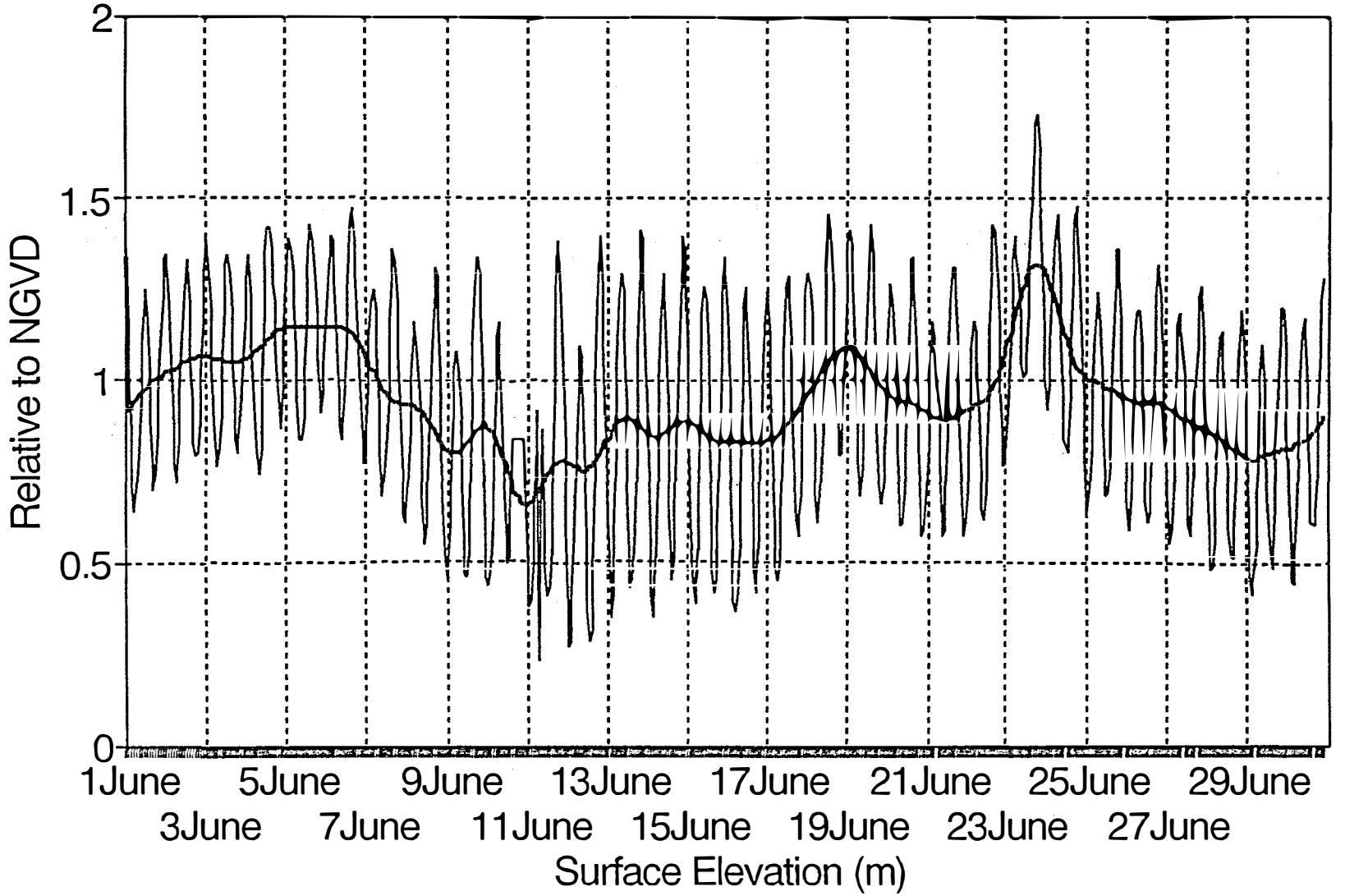
Observed and Low-Pass Filtered (heavy line)
Surface Elevation
at Gloucester Point, Virginia

(NGVD = National Geodetic Vertical Datum)


Gloucester Point
May 1991
2
1.5
1
0.5
0
Relative to NGVD
1May
3May
5May
7May
9May
11May
13May
15May
17May
19May
21May
23May
25May
27May
29May
31May
Surface Elevation (m)

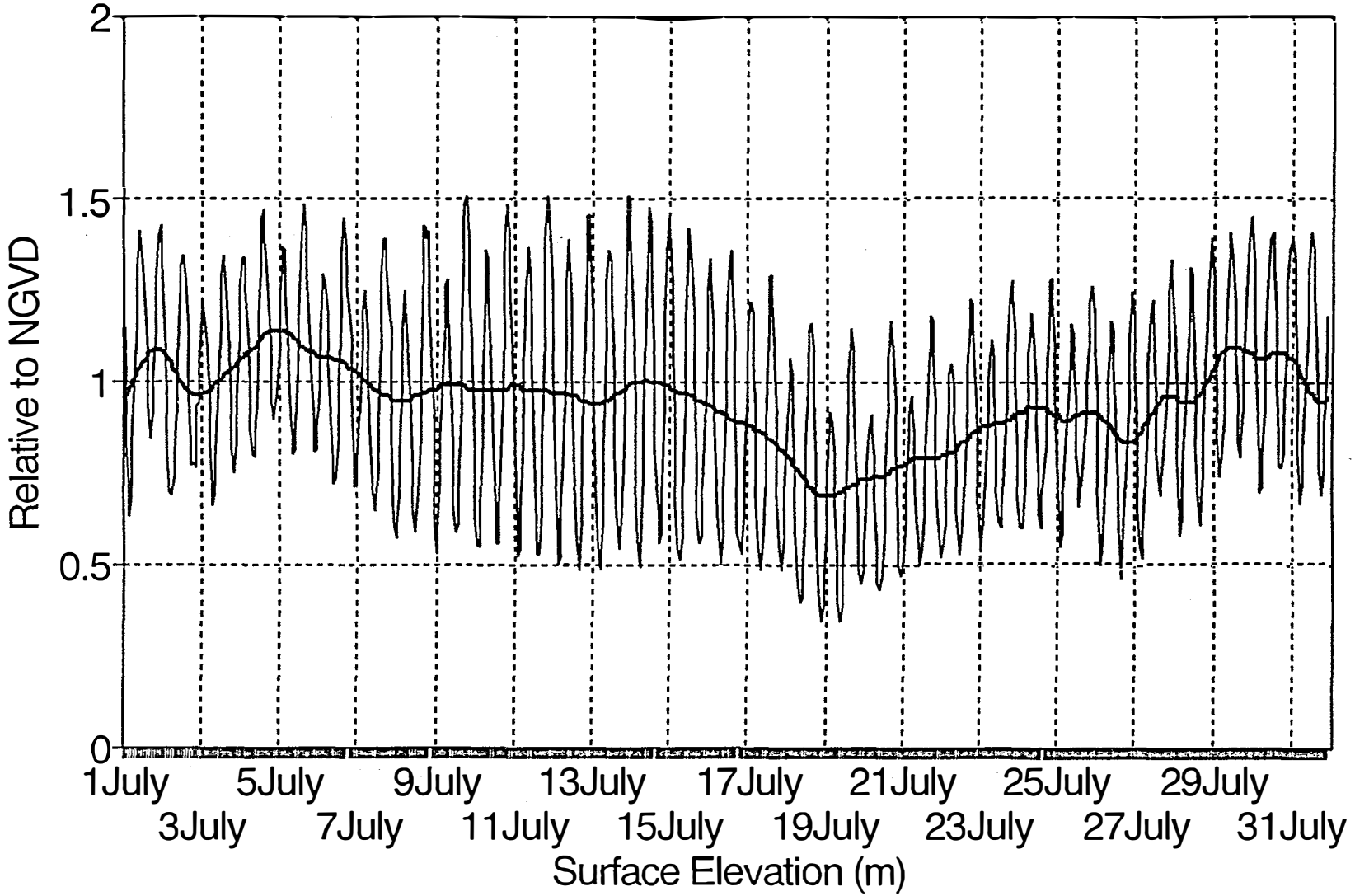
Gloucester Point

June 1991



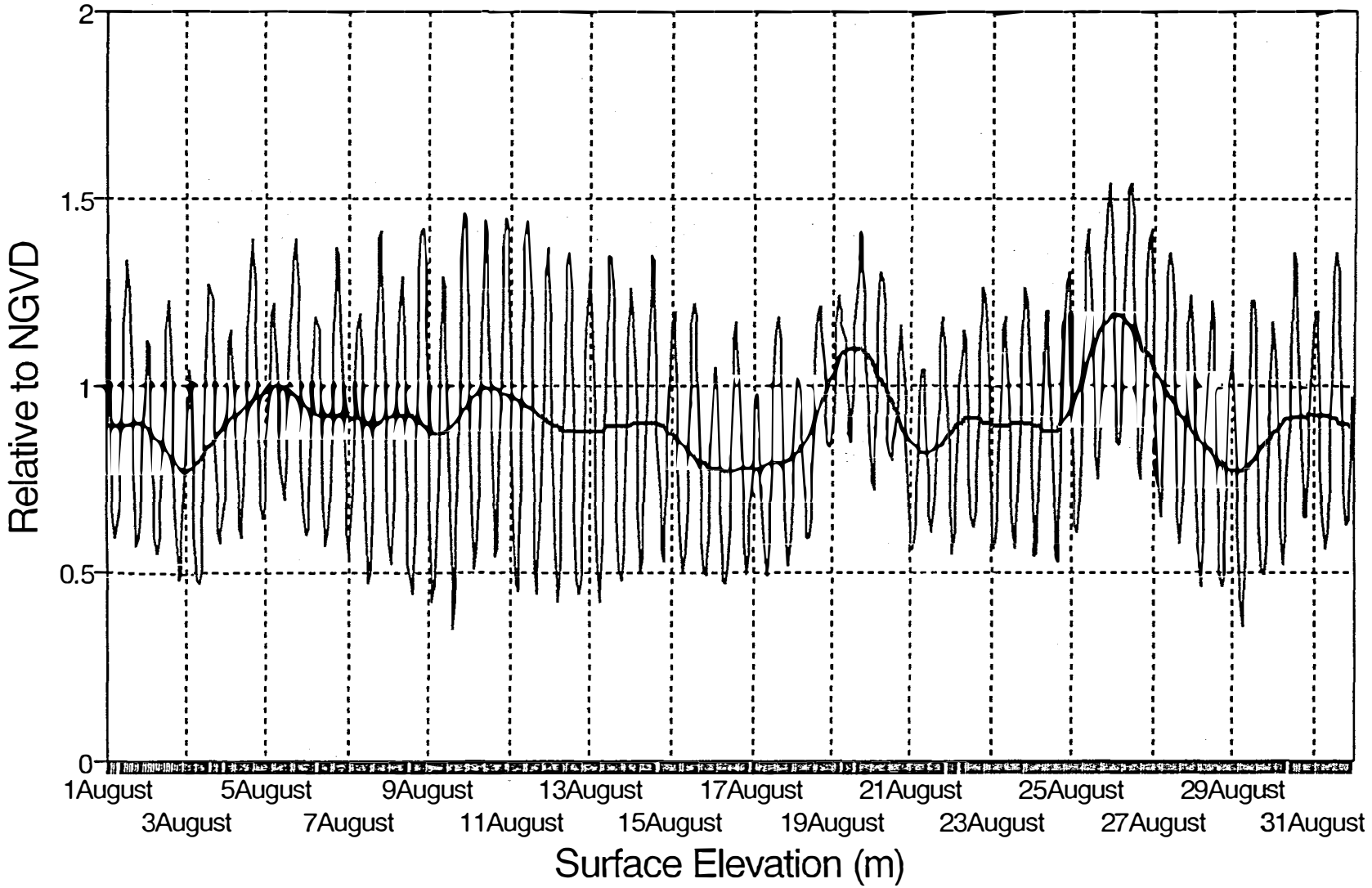
Gloucester Point

July 1991



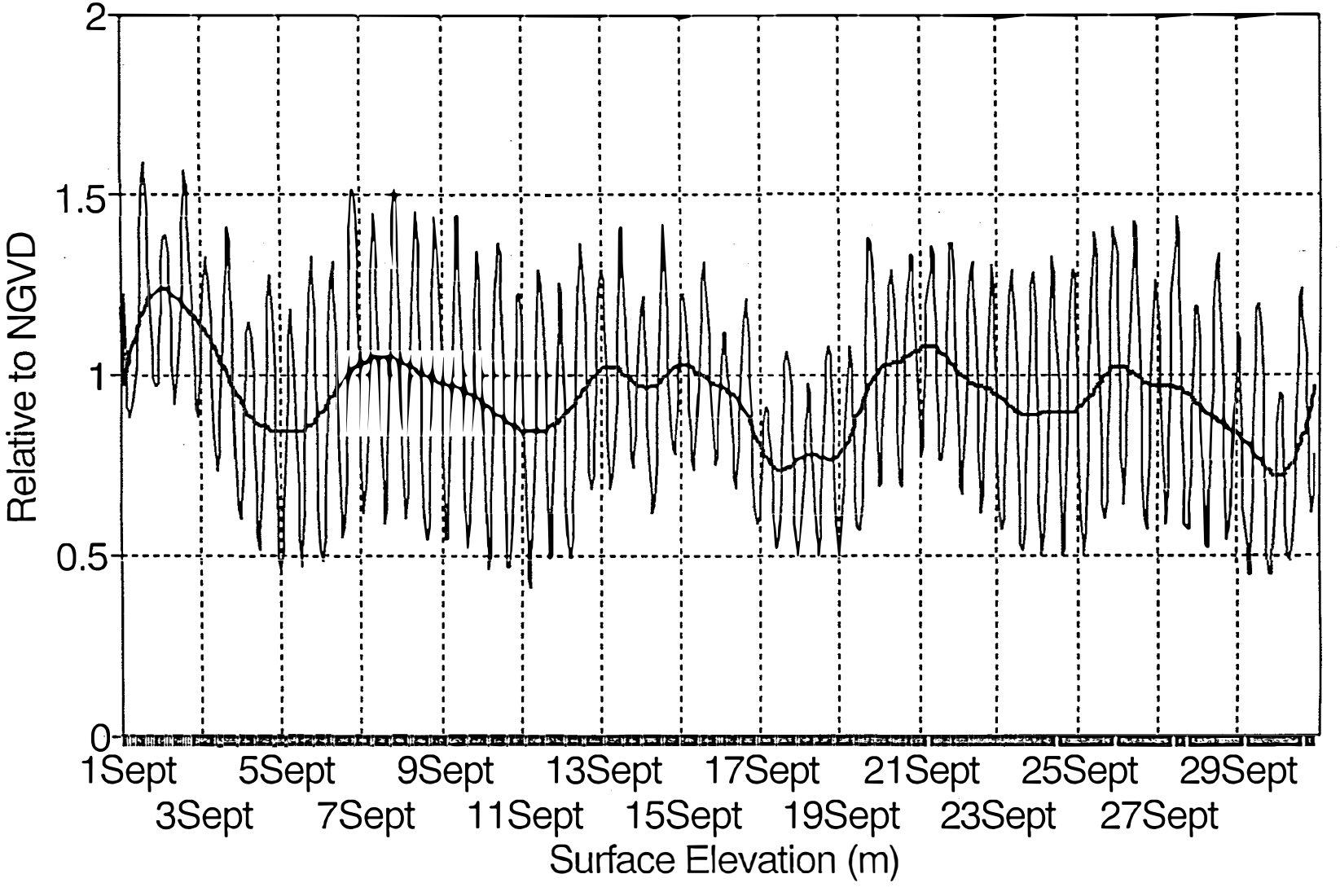
Gloucester Point

August 1991



Gloucester Point

September 1991



Appendix I-9

Temperature, Salinity and Dissolved Oxygen Measurements

(1) Tue Marsh Station (EPA Telemetering Buoy; 11m) from July to Sept.;

(2) Tue Marsh Station (VIMS Hydrolab Datasonde 1; 17m) from May to Sept.;

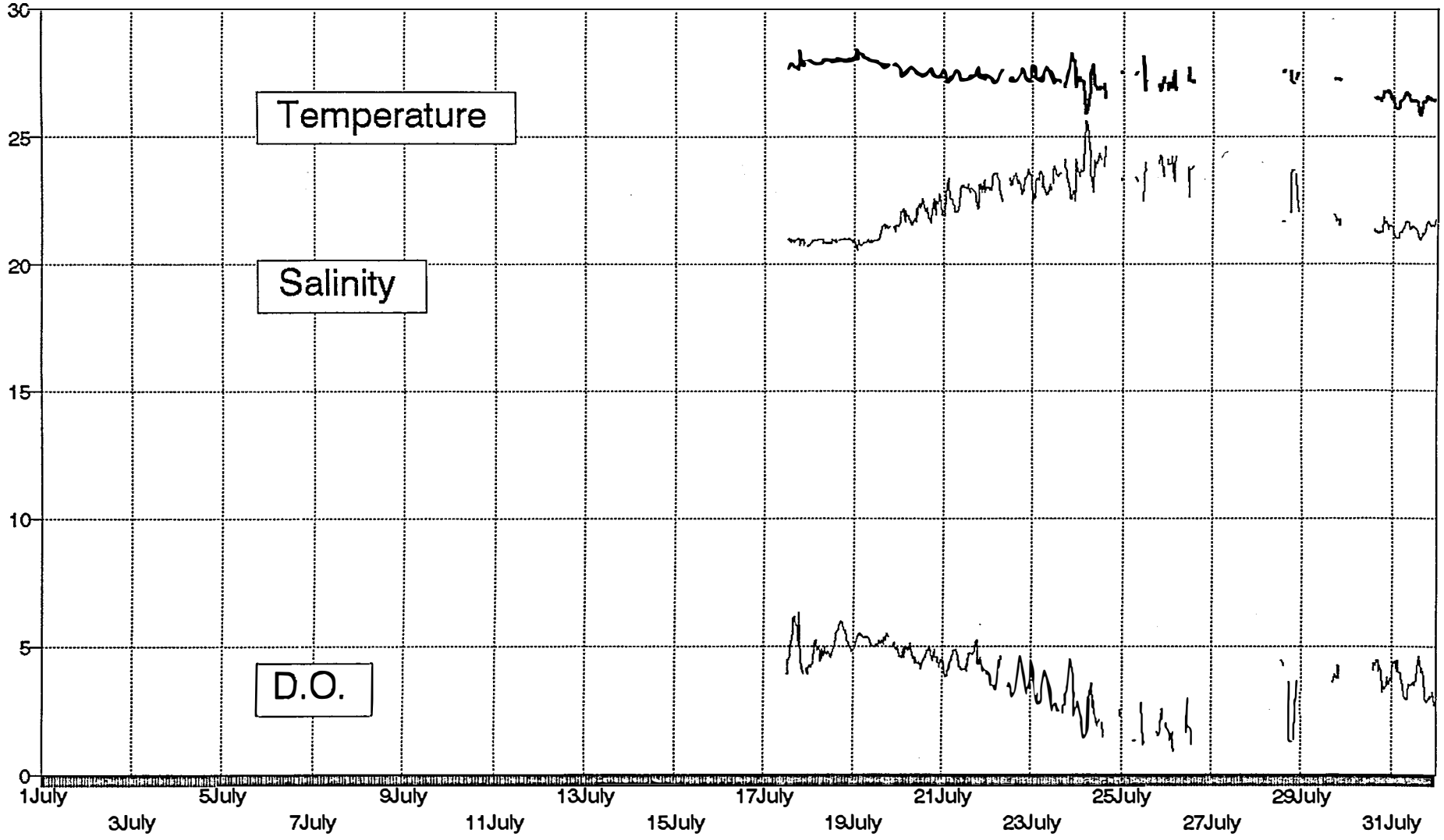
(3) York River Entrance Channel (near Buoy N16, VIMS Hydrolab Datasonde 1; 10m) from May to Sept.; and

(4) York River Entrance Channel (North of Buoy N8; EMAP Hydrolab Datasonde 3; 10m) from July to Sept.

(temperature is degree centigrade,
salinity in psu unit,
dissolved oxygen in milligrams per liter)

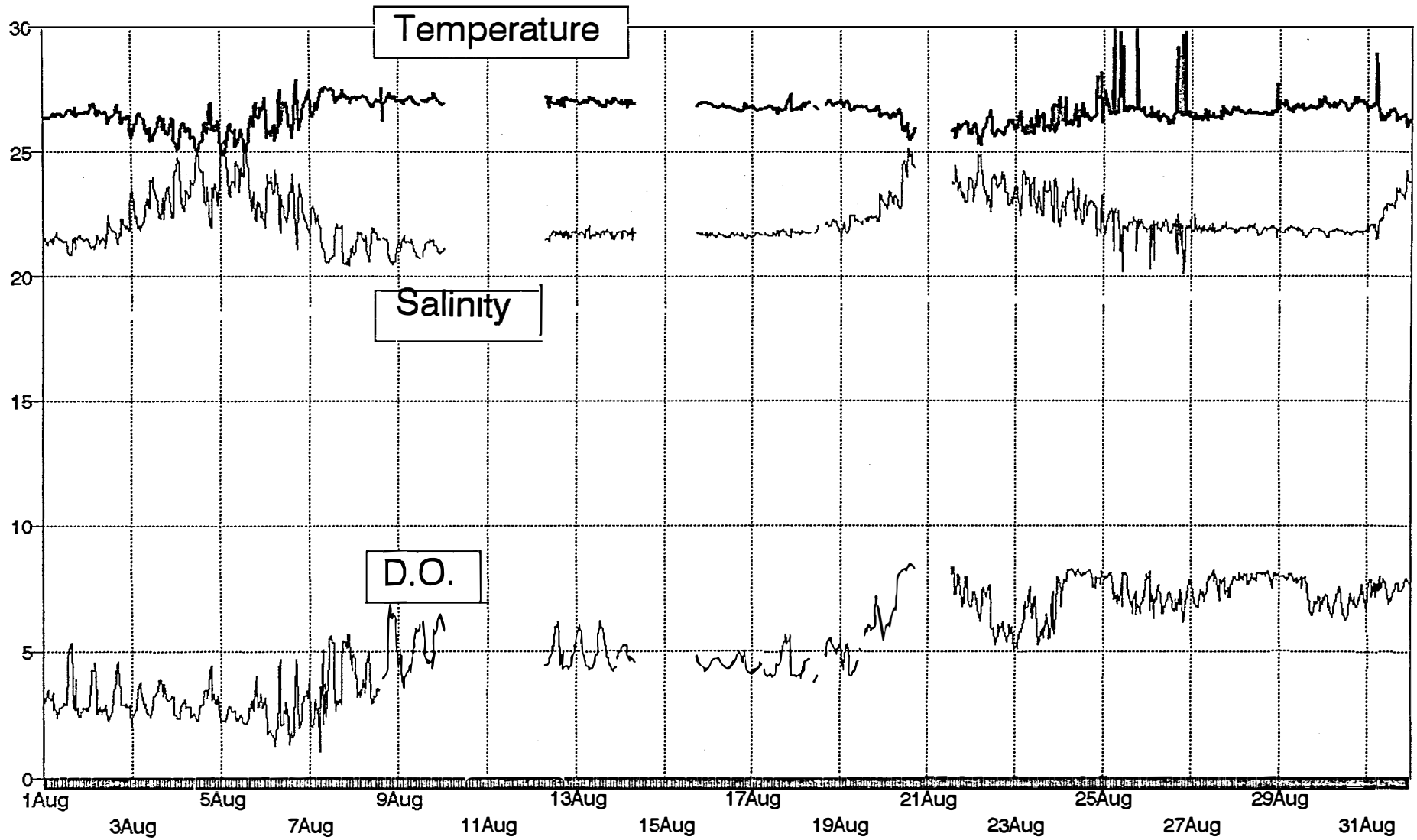
Tue Marsh Station - July 1991

EPA Telemetering Buoy - 11 m



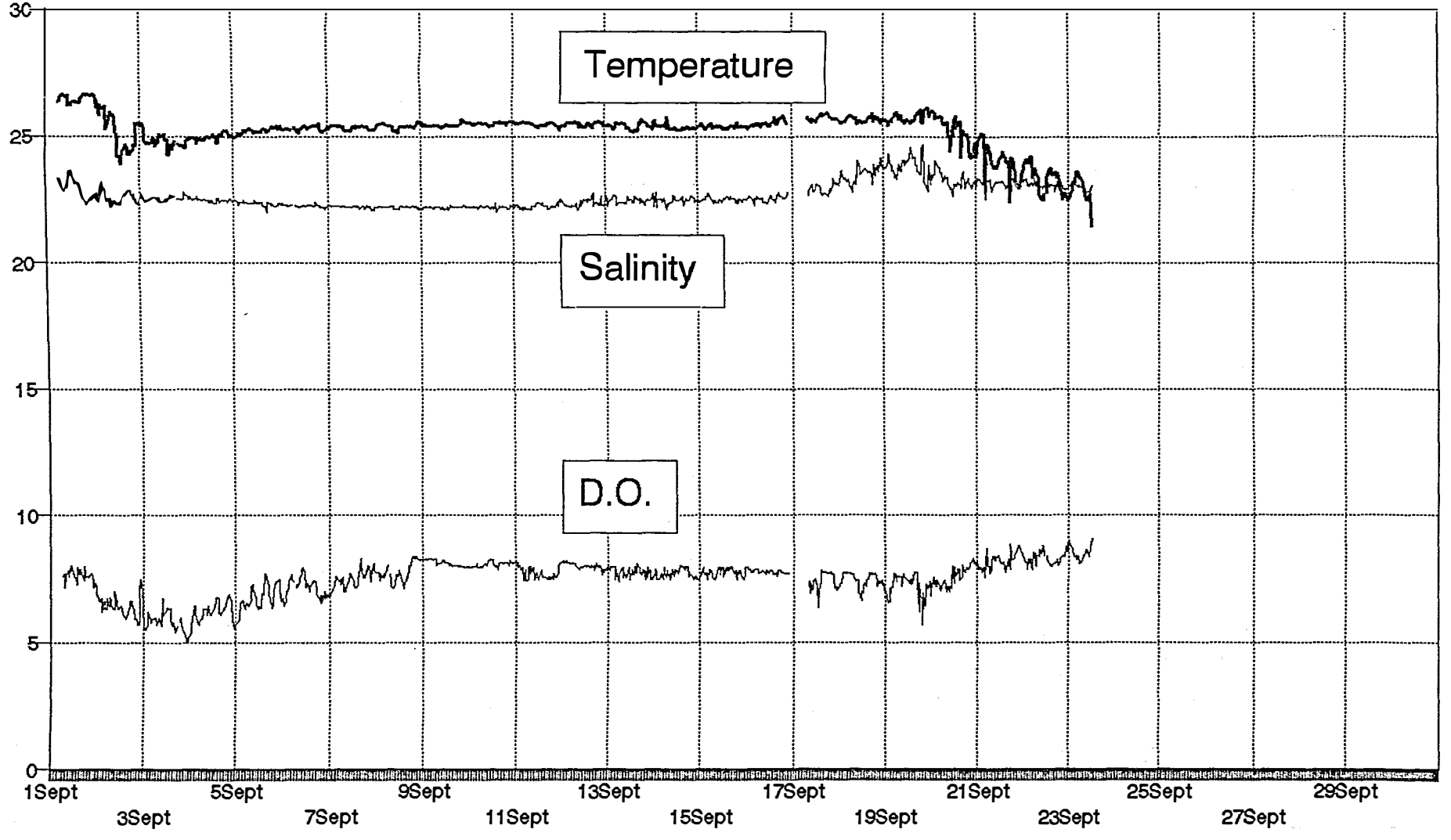
Tue Marsh Station - August 1991

EPA Telemetering Buoy - 11 m.



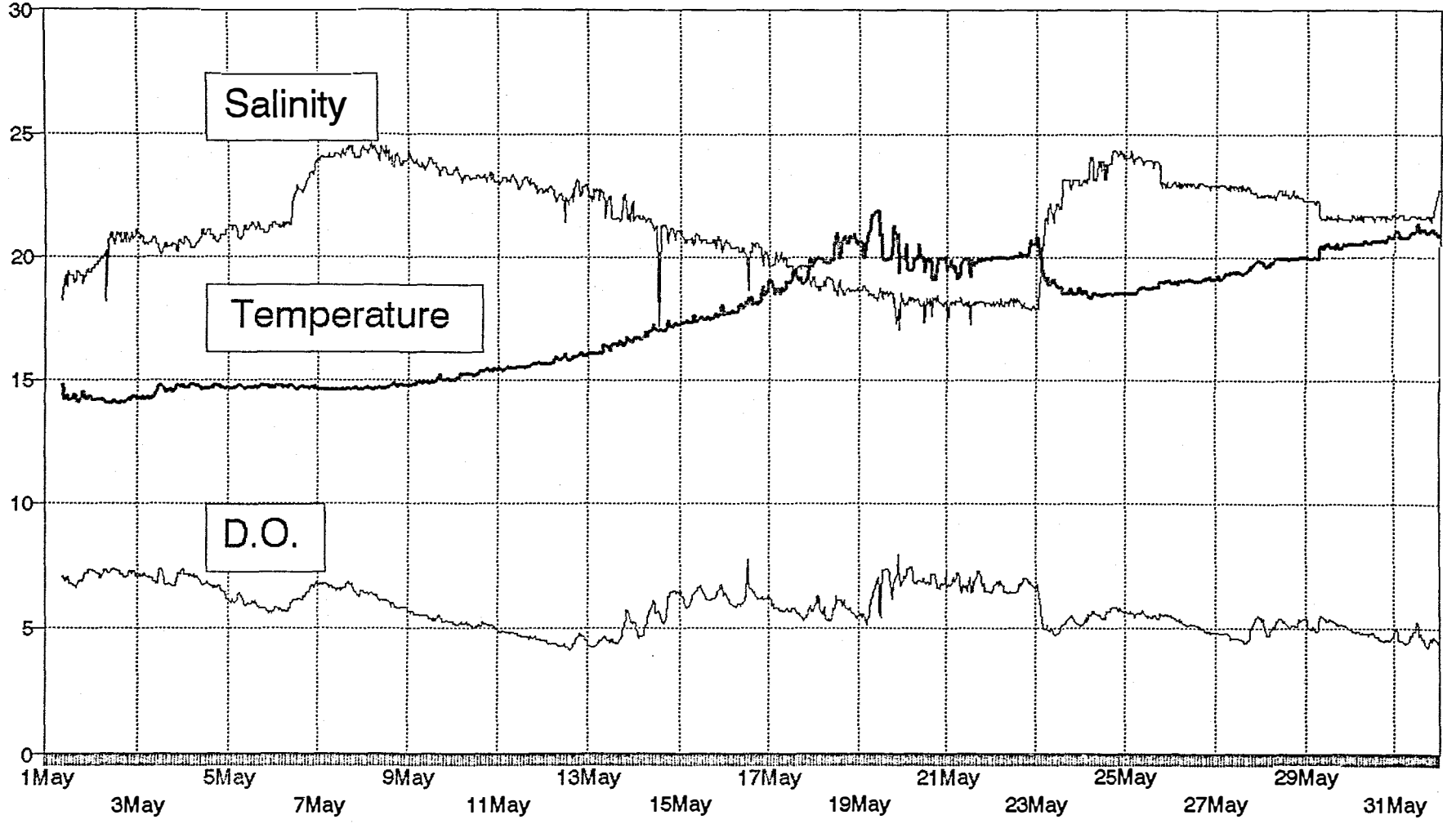
Tue Marsh Station - September 1991

EPA Telemetering Buoy - 11 m.



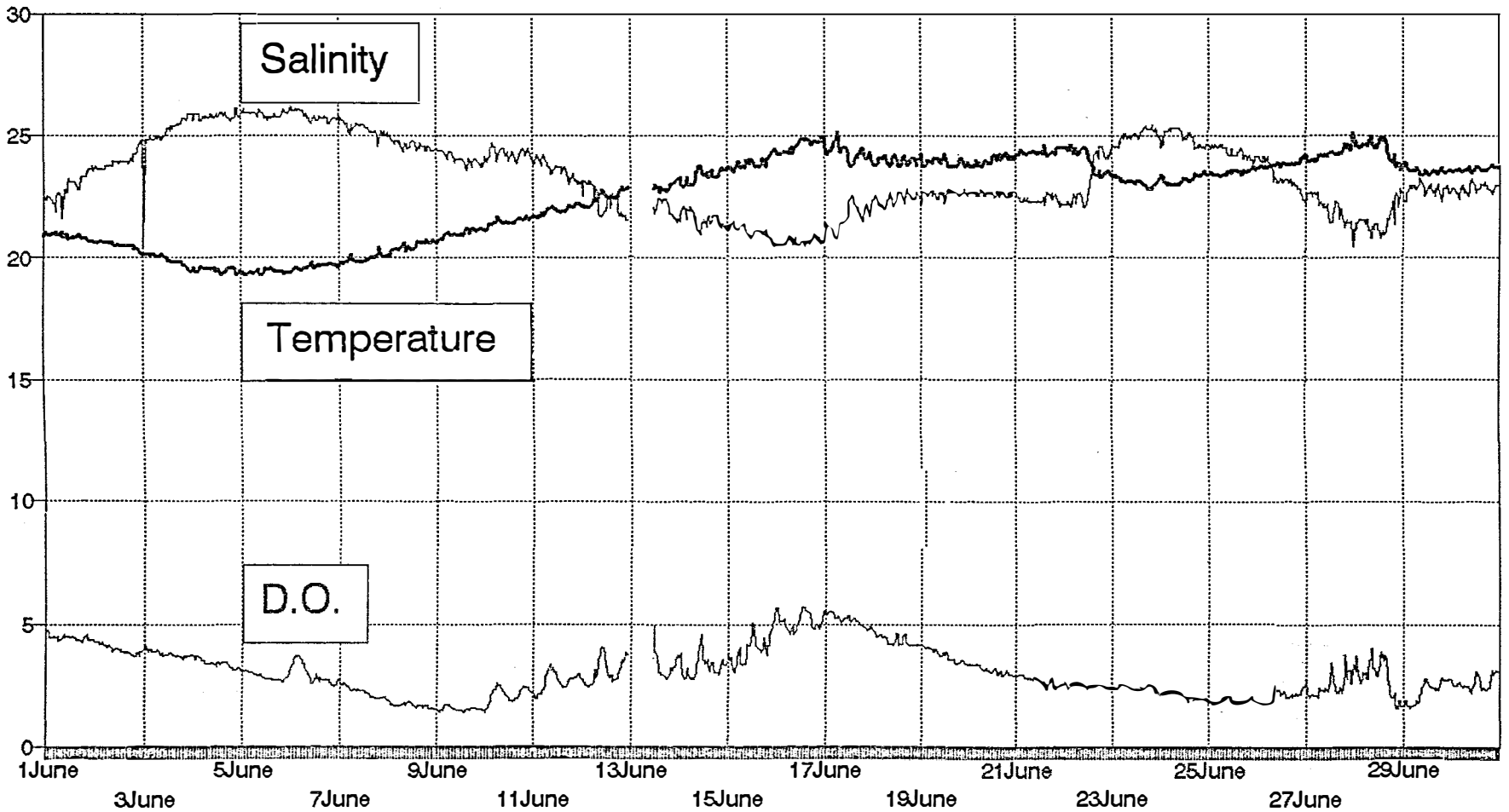
Tue Marsh Station - May 1991

VIMS Hydrolab Datasonde 1 - 17 m.



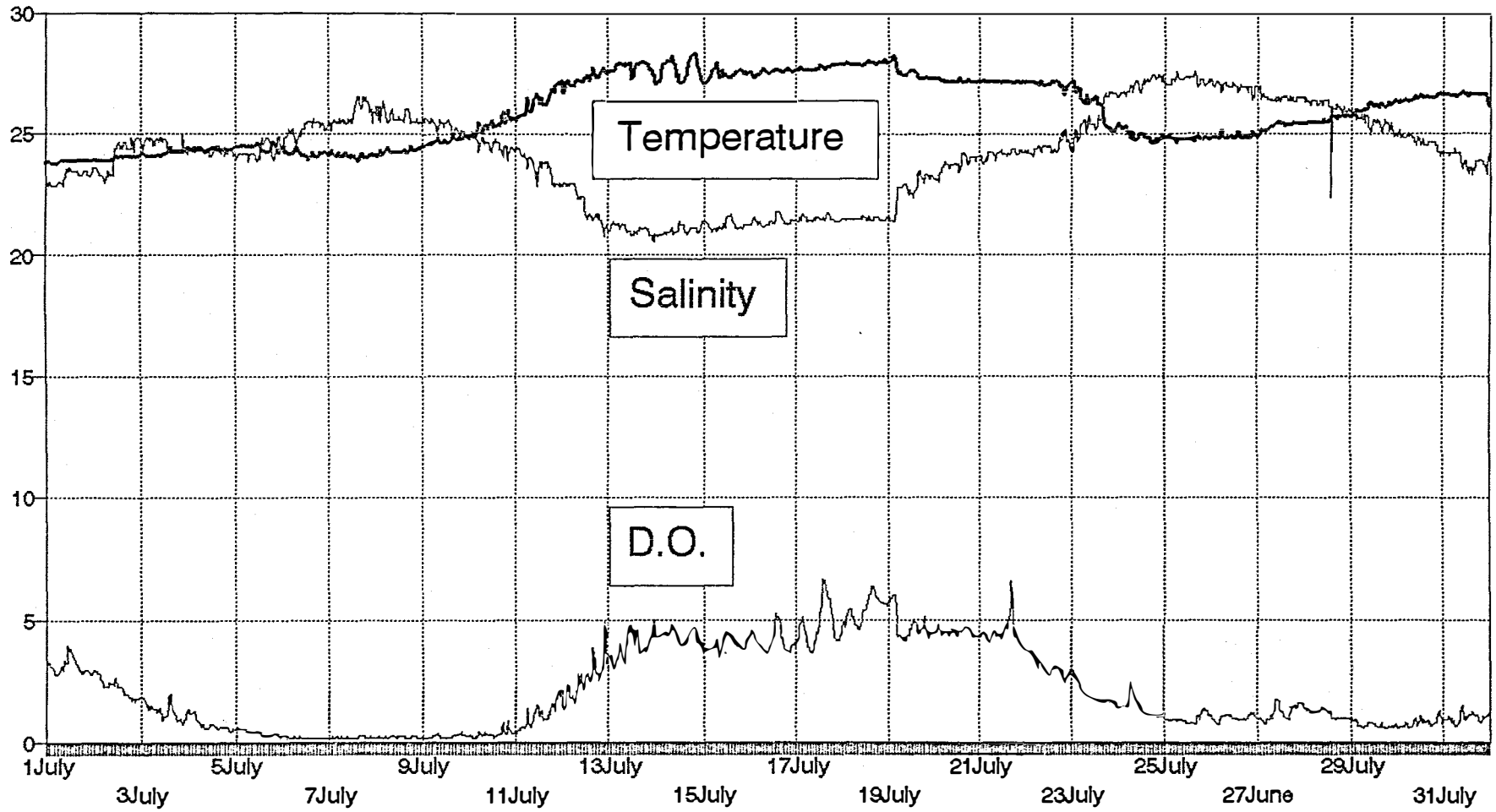
Tue Marsh Station - June 1991

VIMS Hydrolab Datasonde 1 - 17 m.



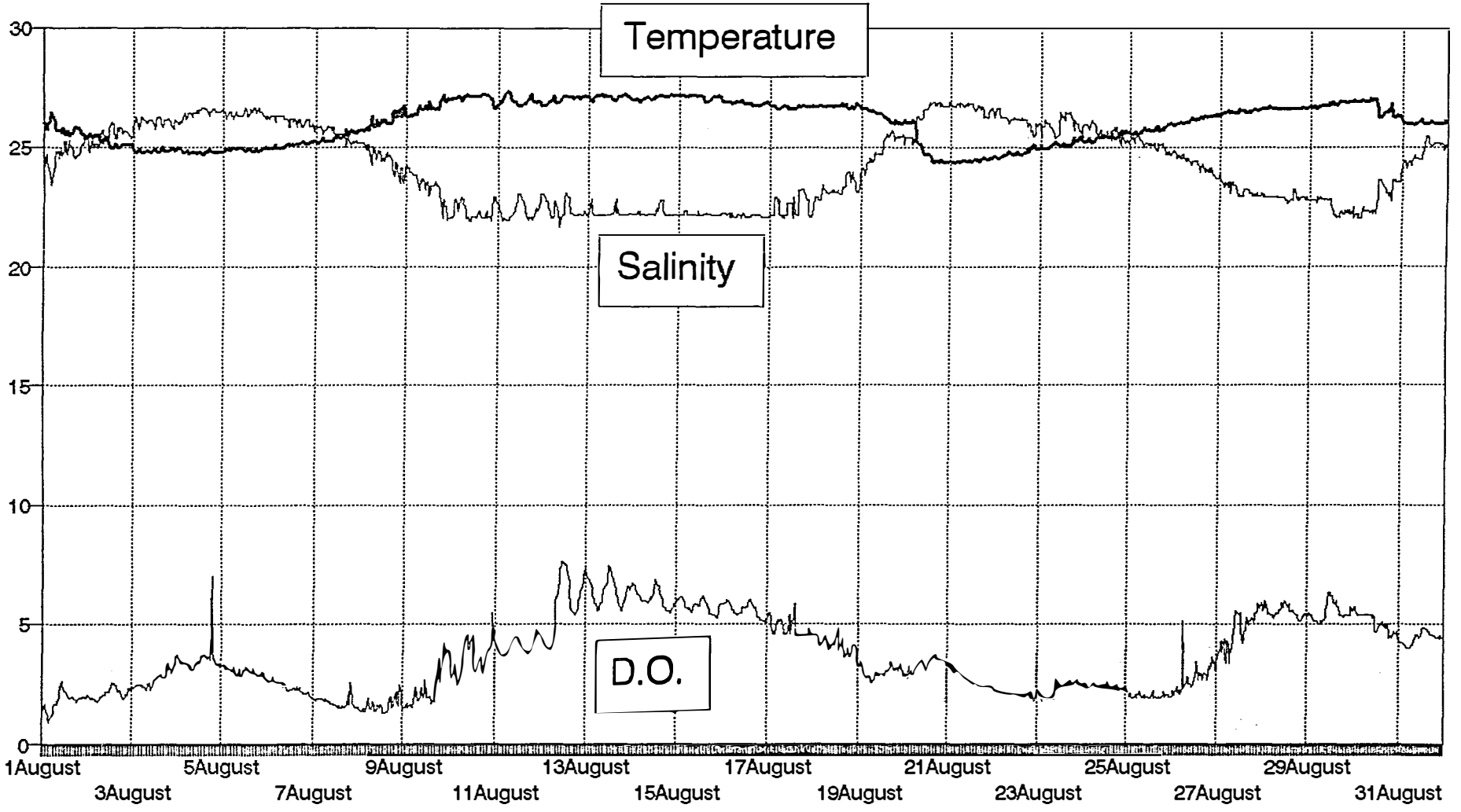
Tue Marsh Station - July 1991

VIMS Hydrolab Datasonde 1 - 17 m.



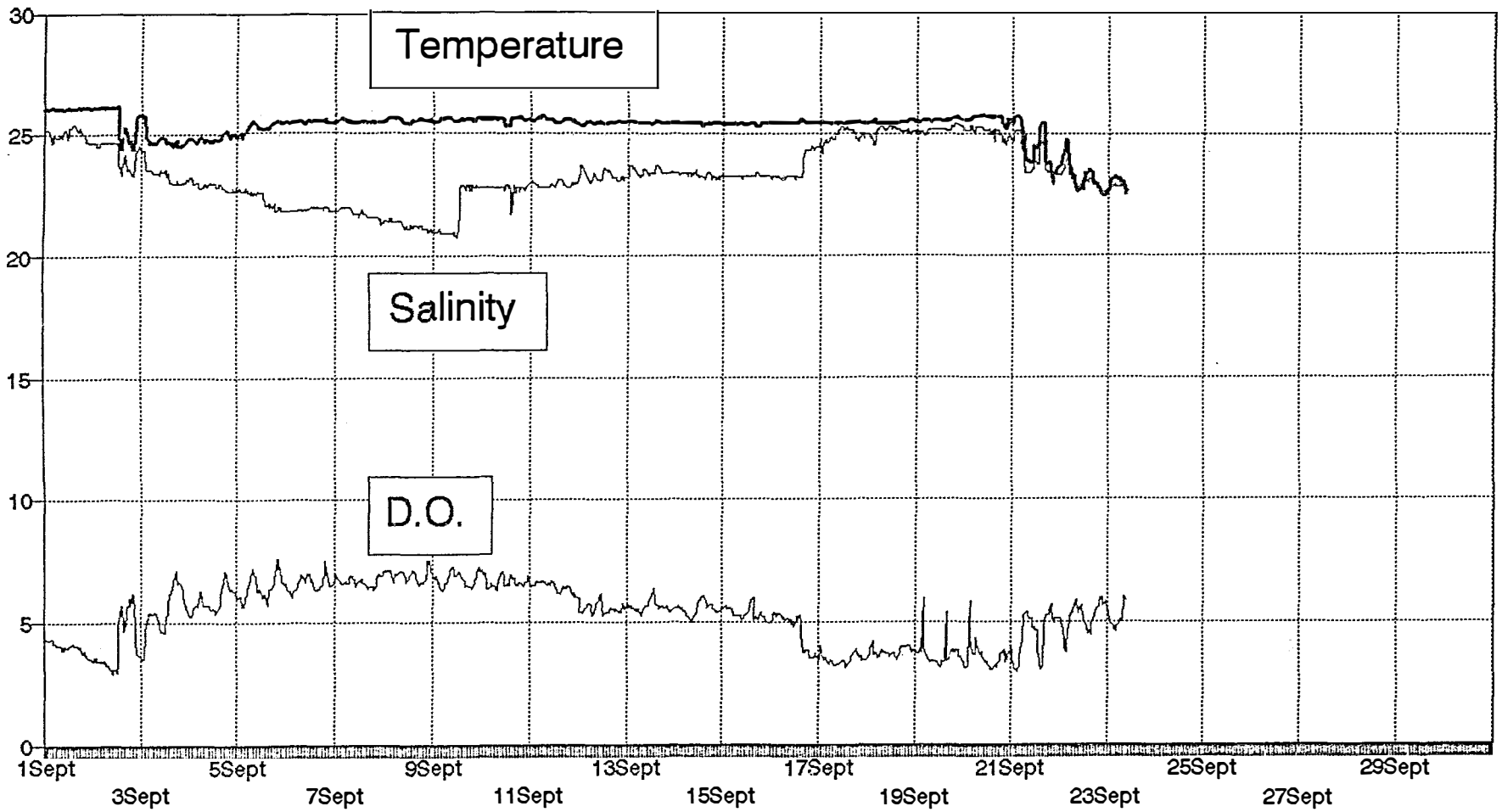
Tue Marsh Station - August 1991

VIMS Hydrolab Datasonde 1 - 17 m.



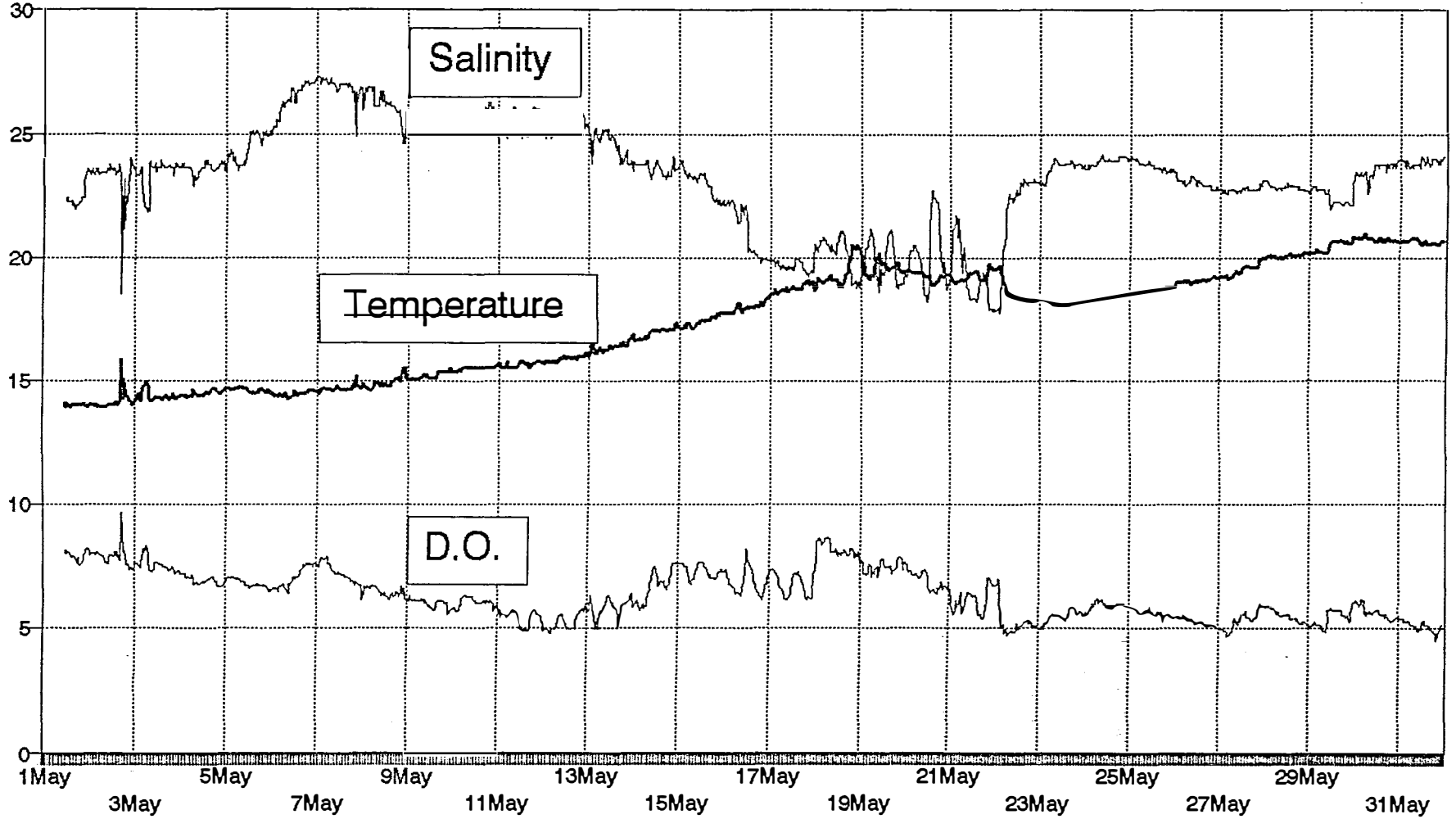
Tue Marsh Station - September 1991

VIMS Hydrolab Datasonde 1 - 17 m.



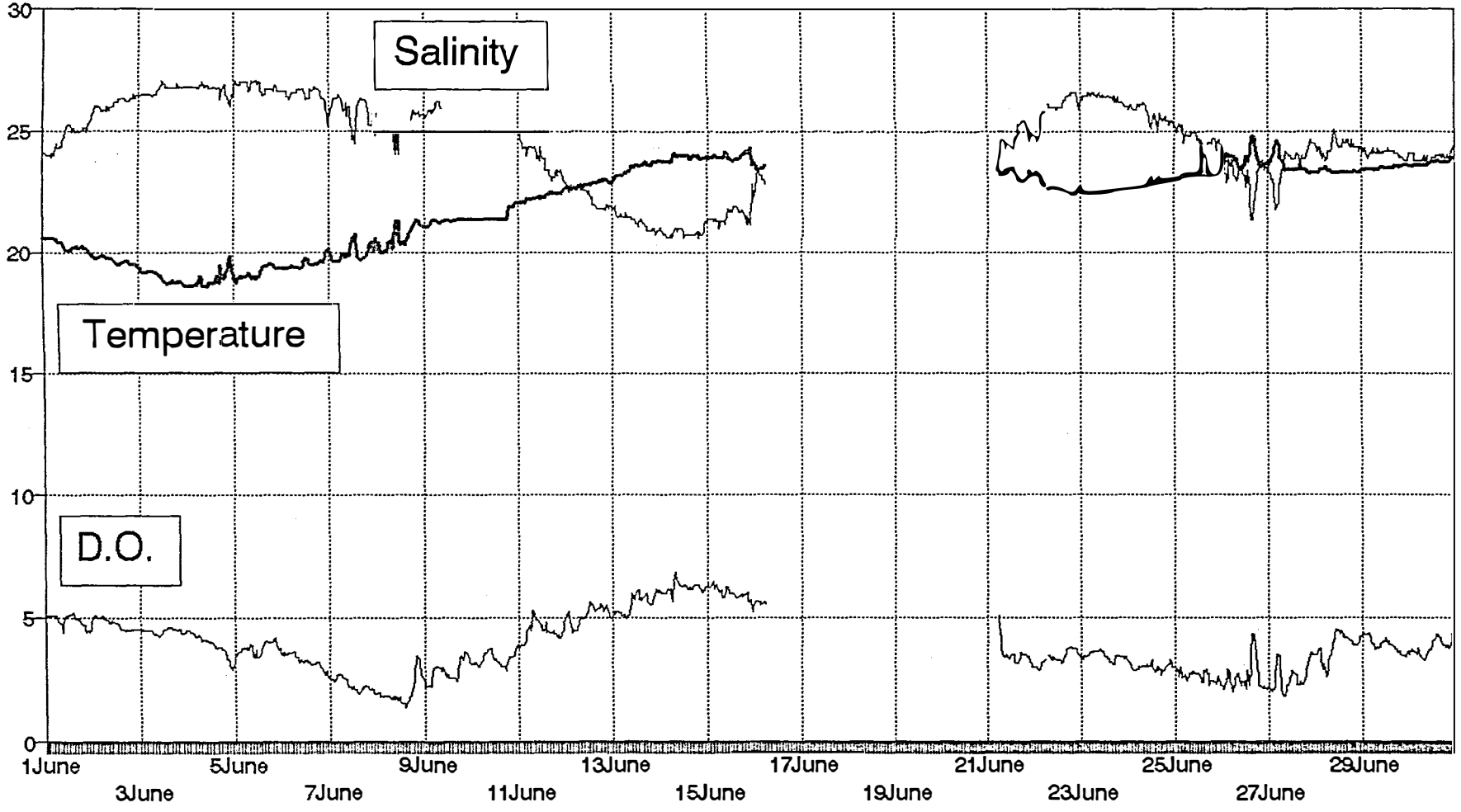
York R Ent Channel (#N16) - May 1991

VIMS Hydrolab Datsonde 1 - 10 m.



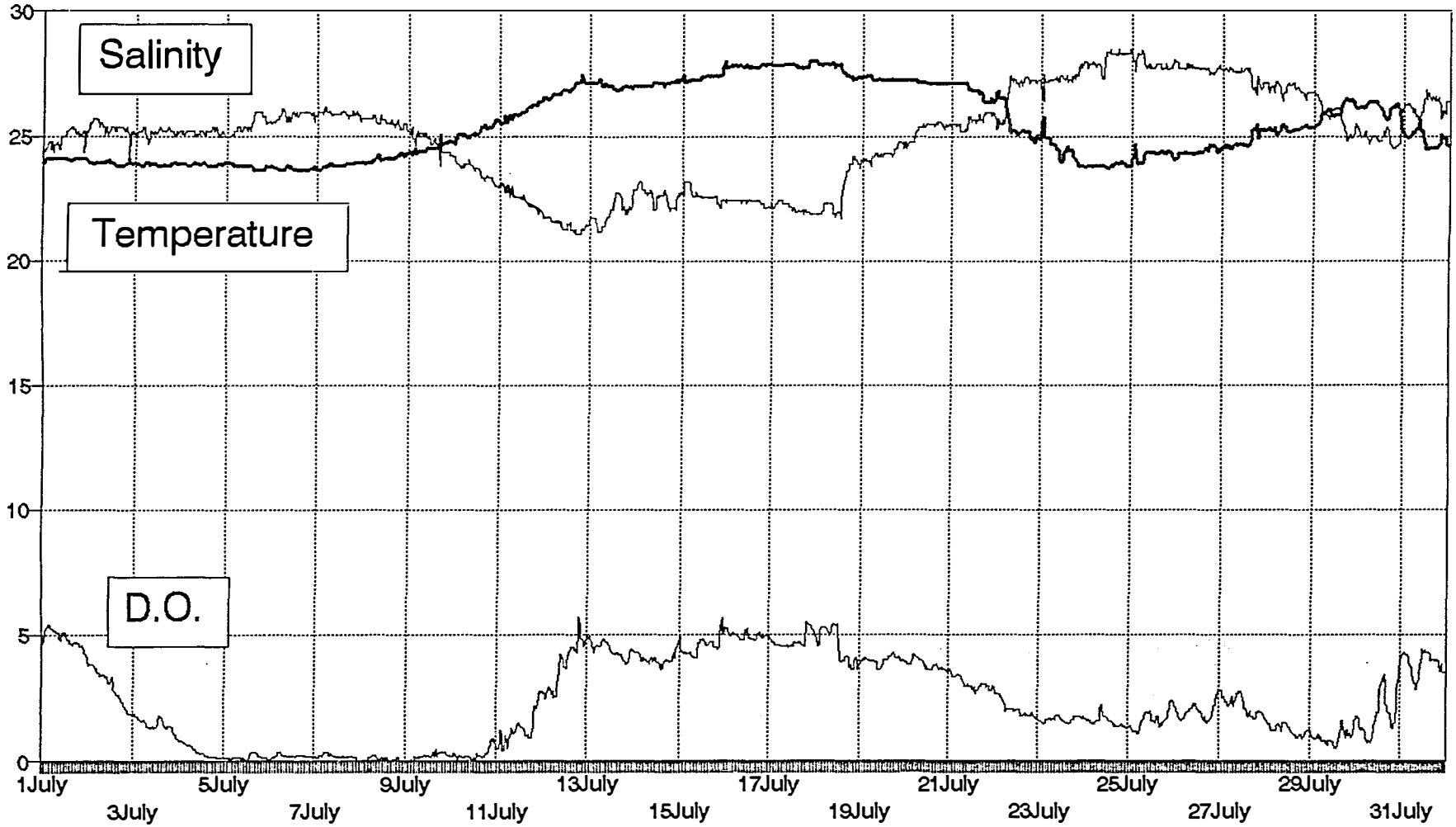
York R Entrance Channel - June 1991

VIMS Hydrolab Datasonde 1 - 10 m.



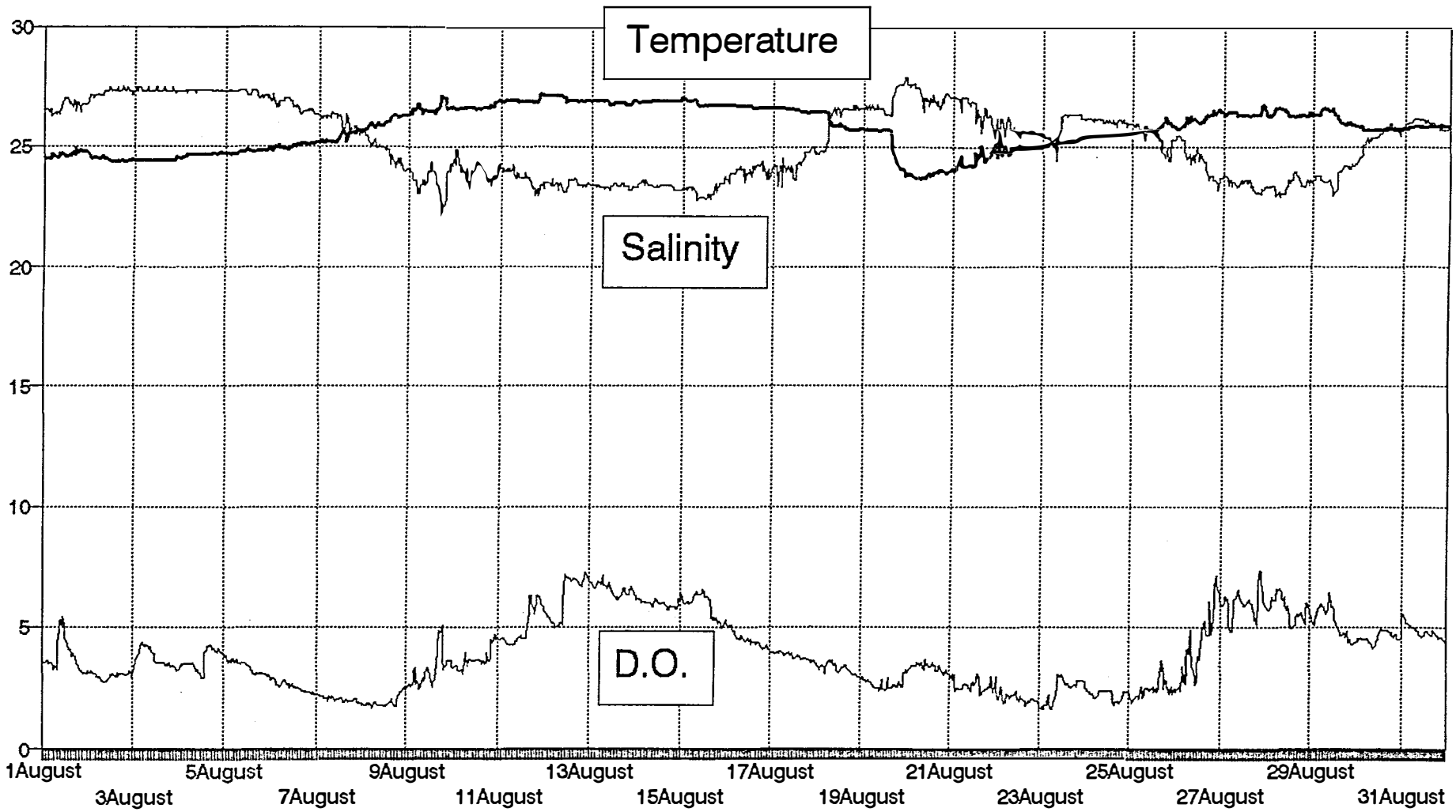
York R Entrance Channel - July 1991

VIMS Hydrolab Datasonde 1 - 10 m.



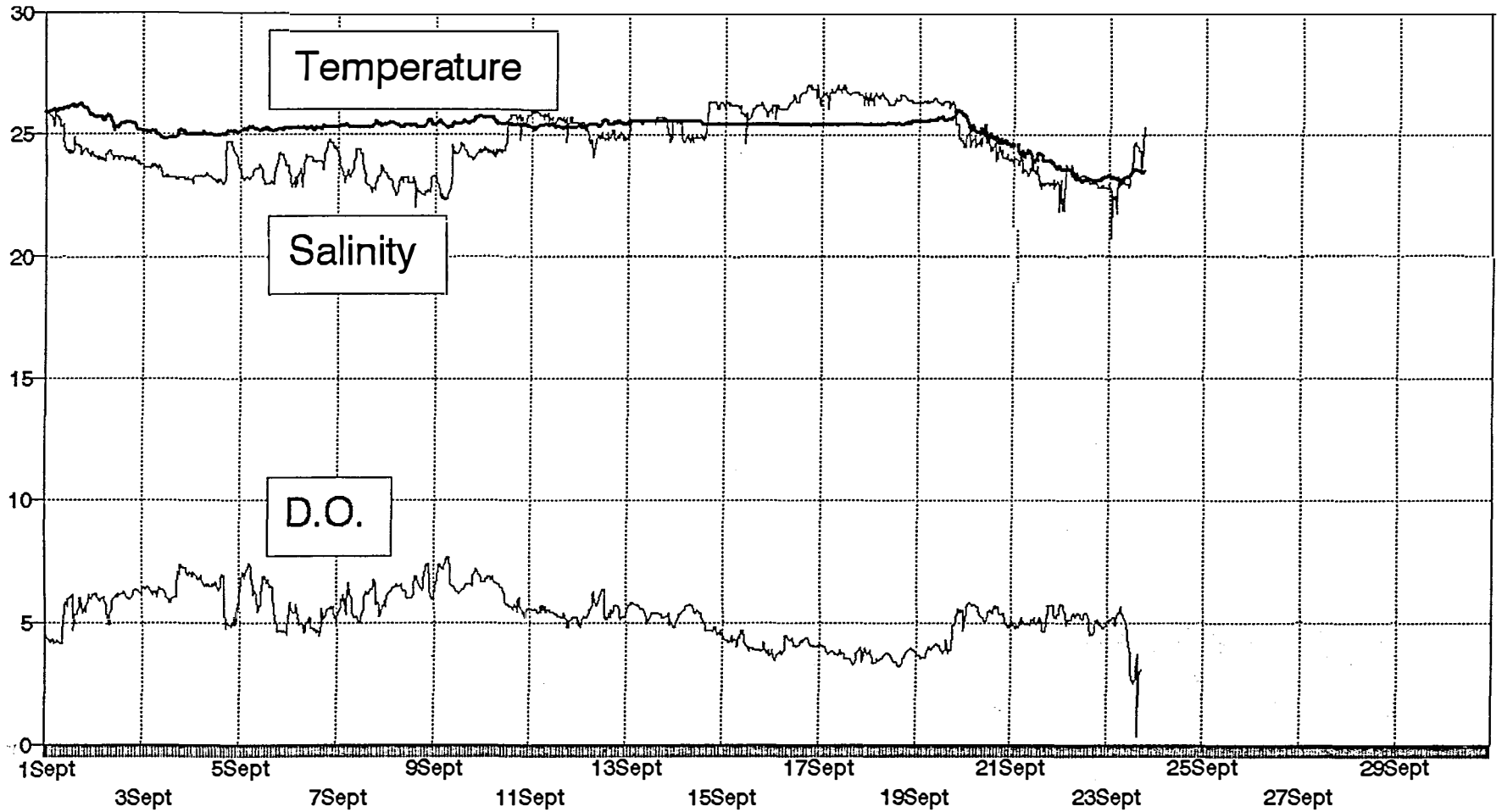
York R Ent Channel (#N16) - August 1991

VIMS Hydrolab Datasonde 1 - 10 m.



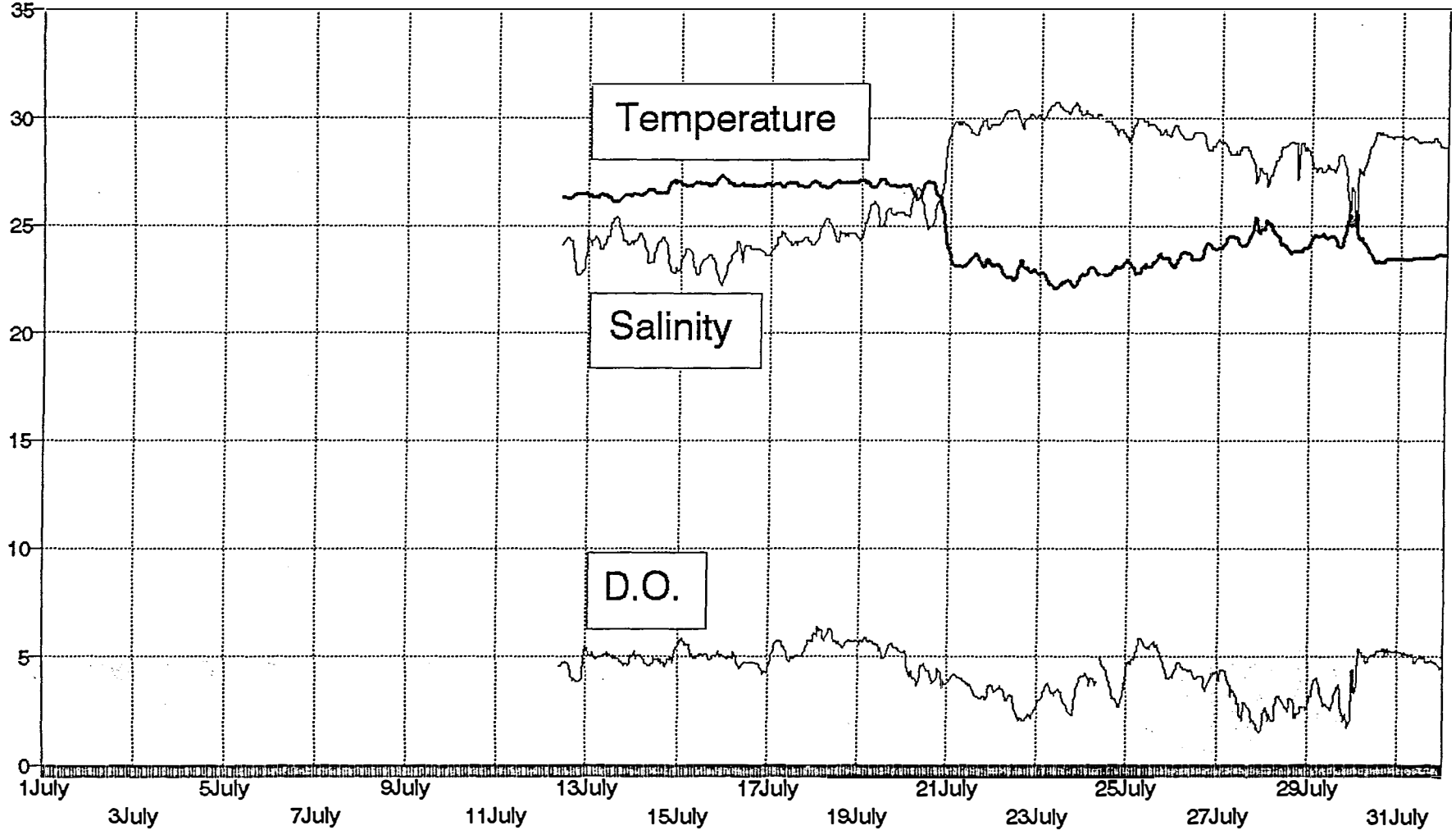
York R Ent Channel (#N16) - Sept 1991

VIMS Hydrolab Datasonde 1 - 10 m.



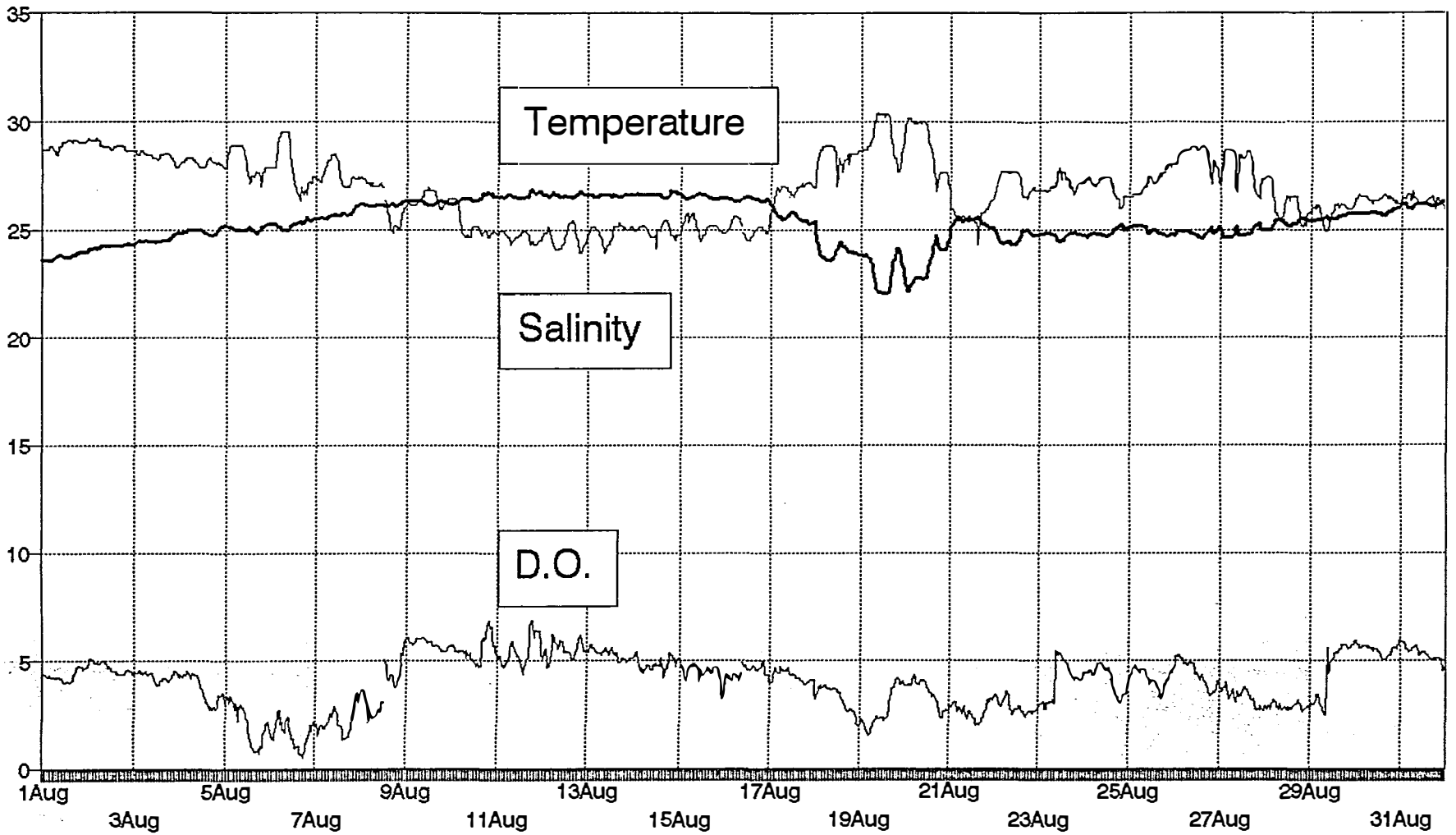
York R Ent Channel (#N8) - July 1991

EMAP Hydrolab Datasonde 3 - 10 m.



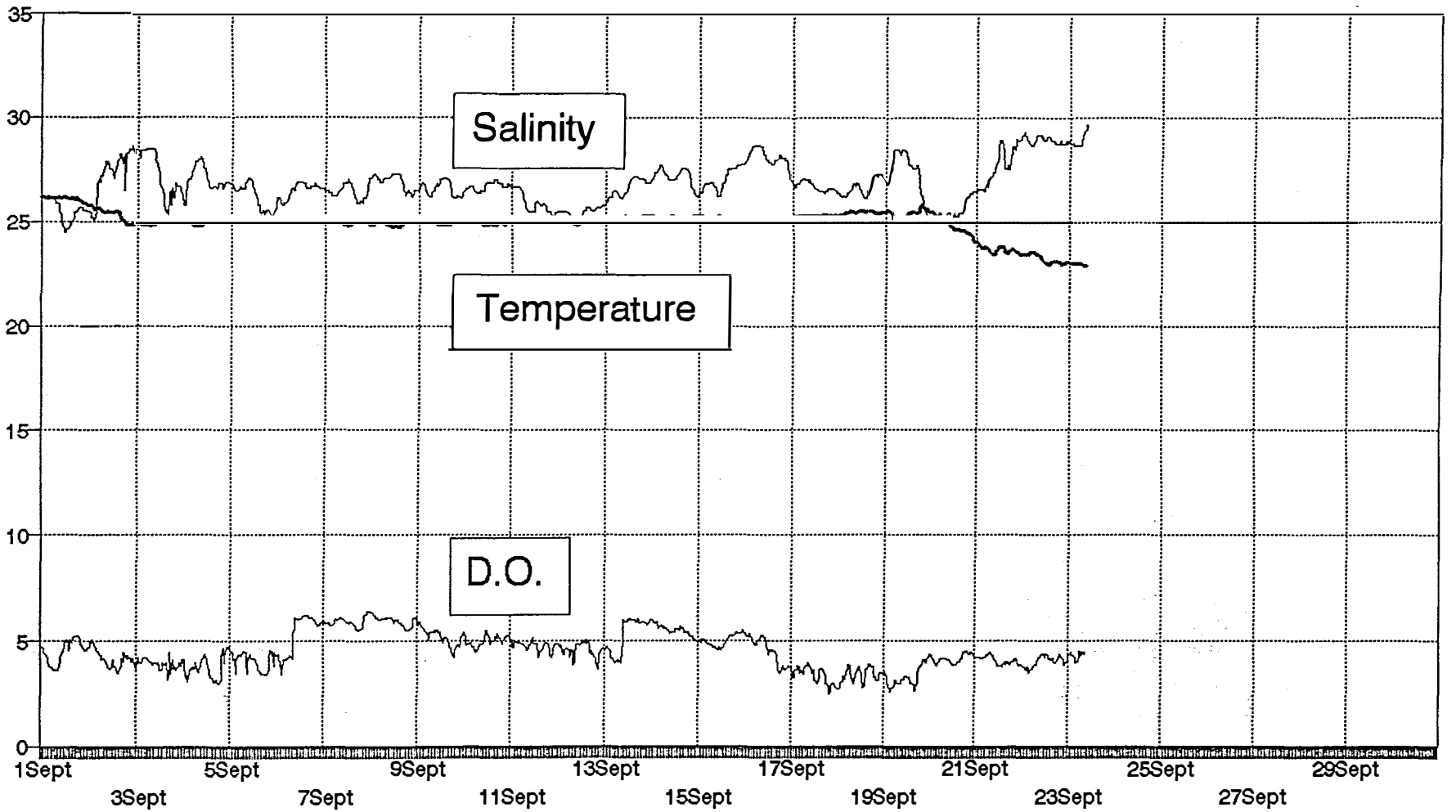
York R Ent Channel (#N8) - August 1991

EMAP Hydrolab Datasonde 3 - 10 m.



York R Ent Channel (#N8) - Sept 1991

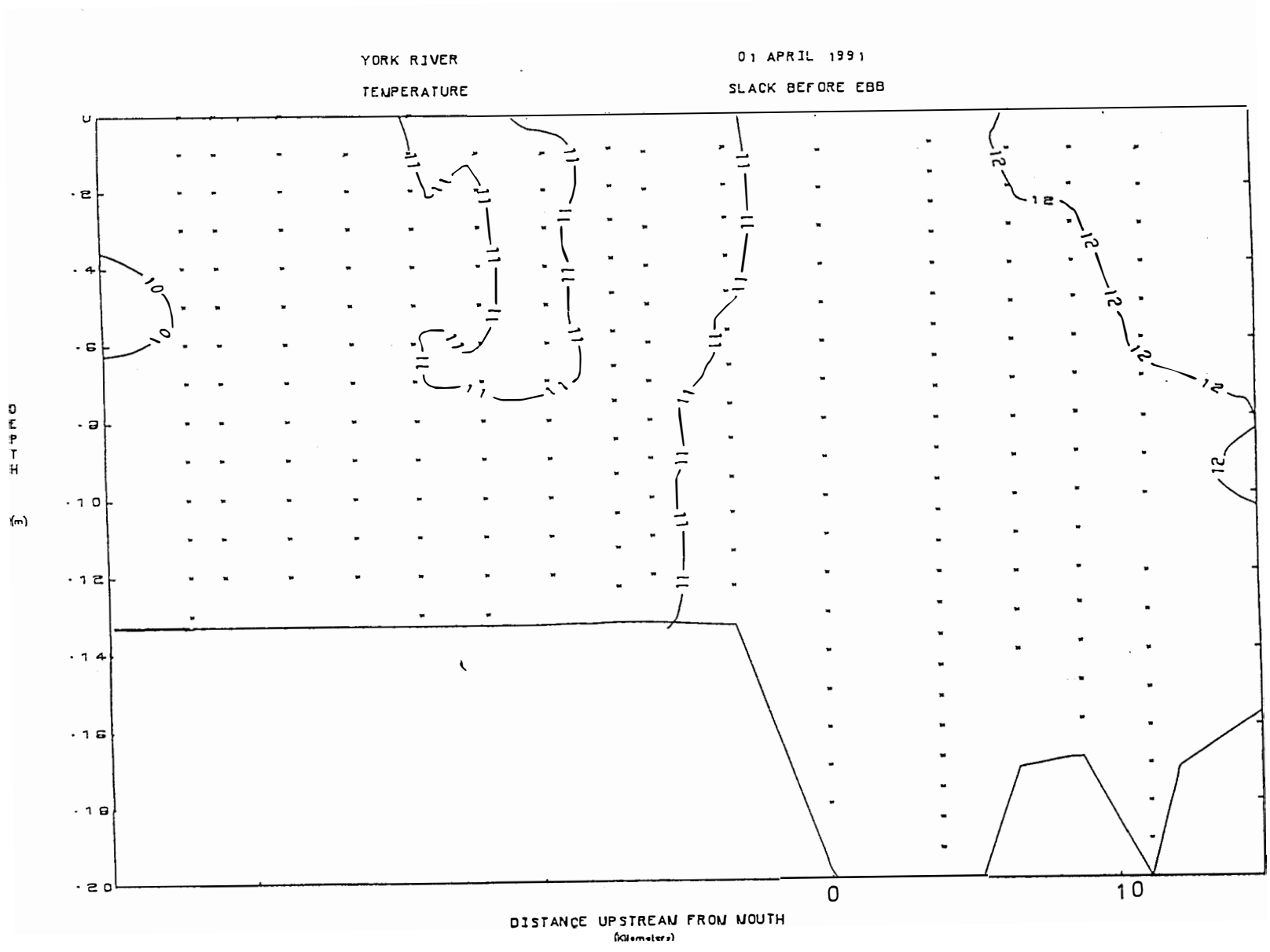
EMAP Hydrolab Datasonde 3 - 10 m.

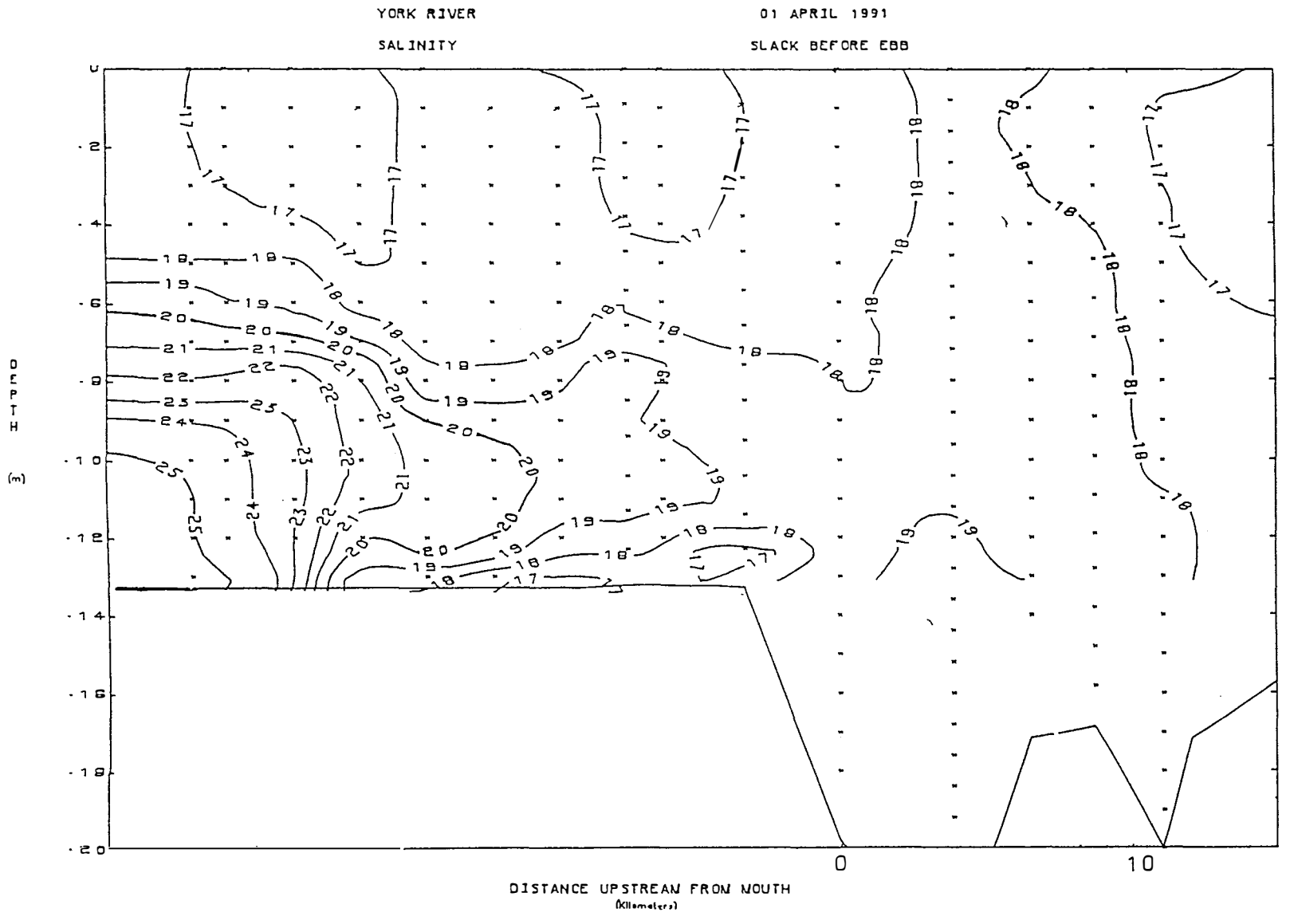


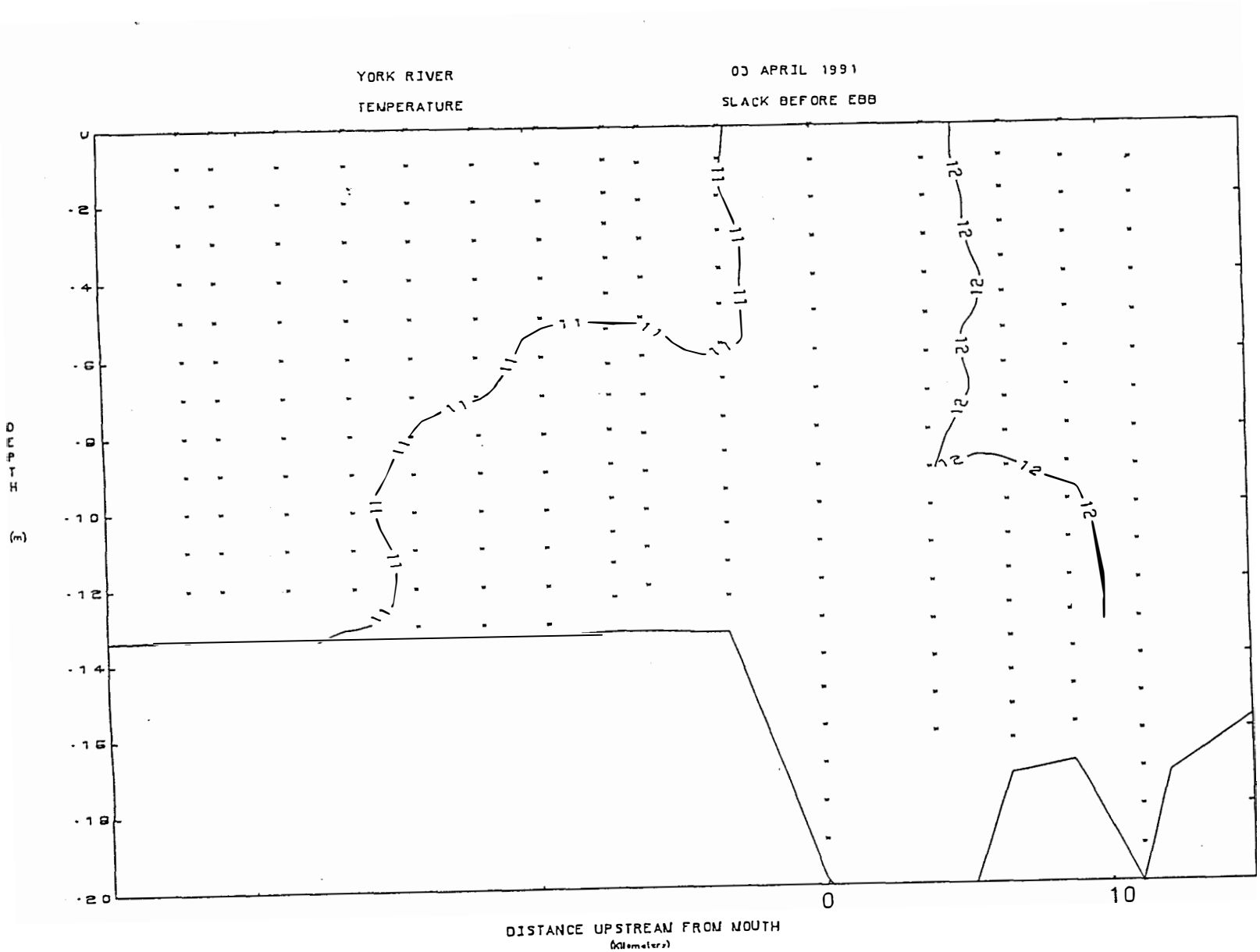
Appendix II

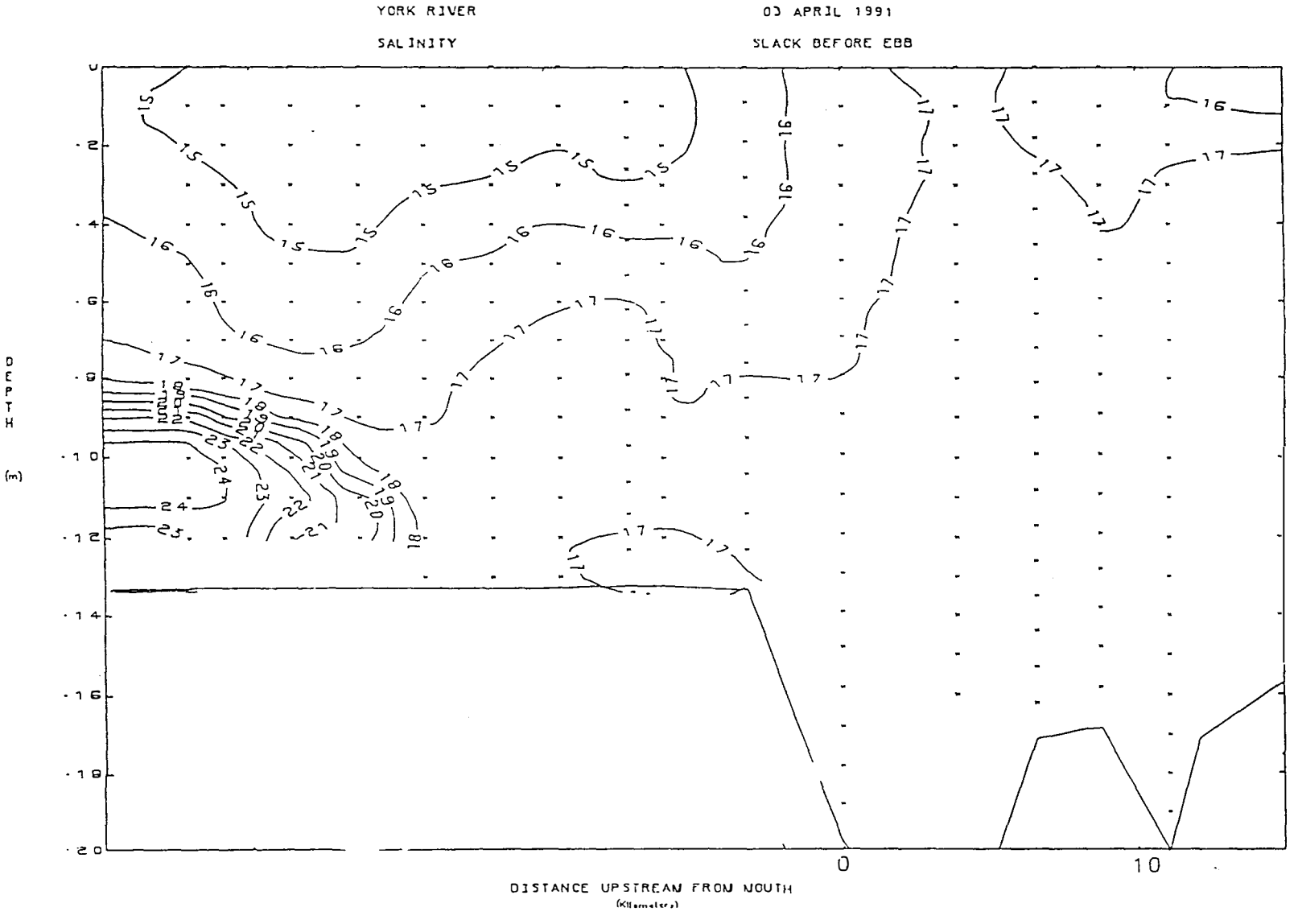
Results of Slackwater Surveys

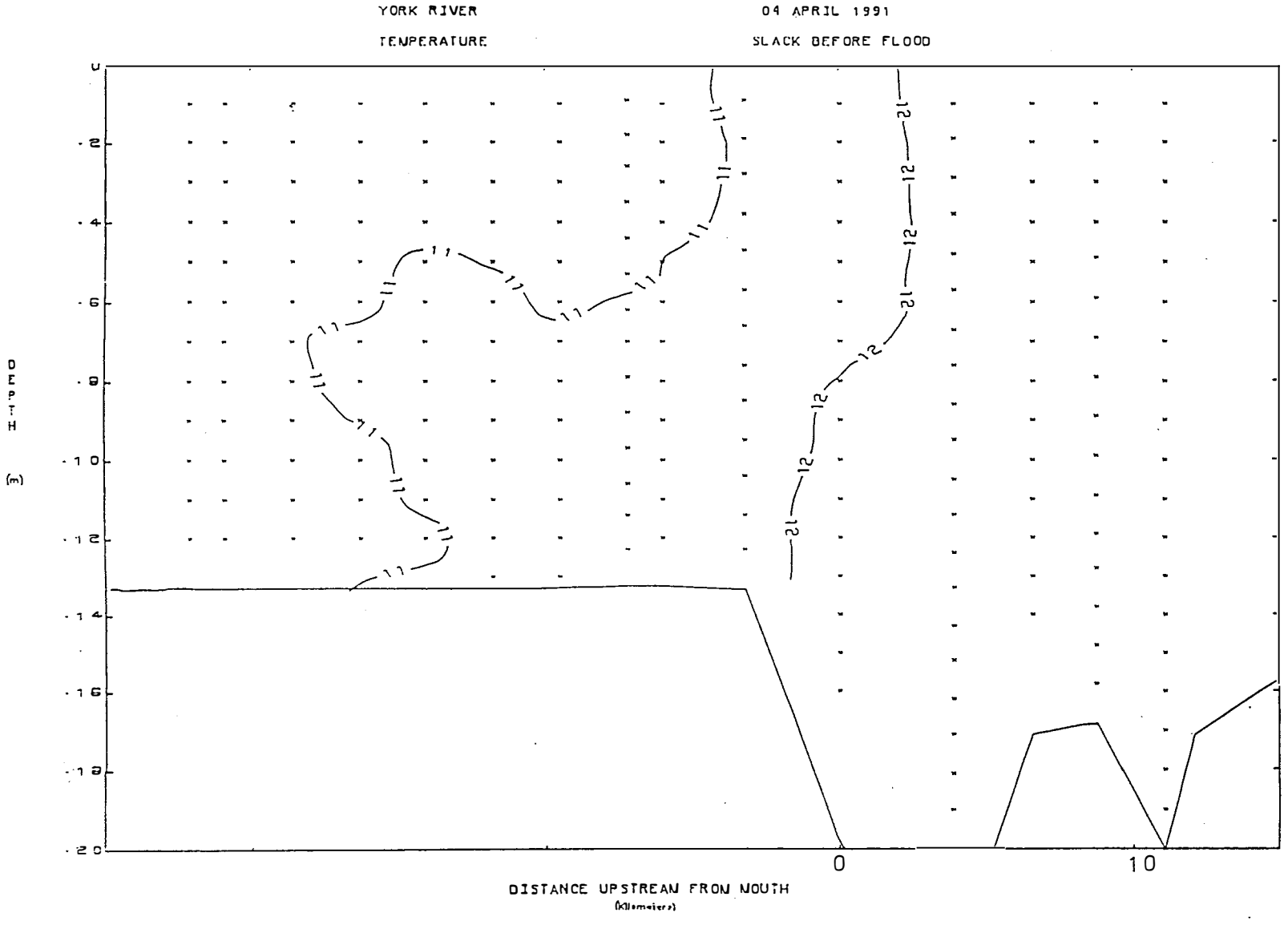
(temperature in degree centigrade,
salinity in SU1 unit,
dissolved oxygen in milligrams per liter)

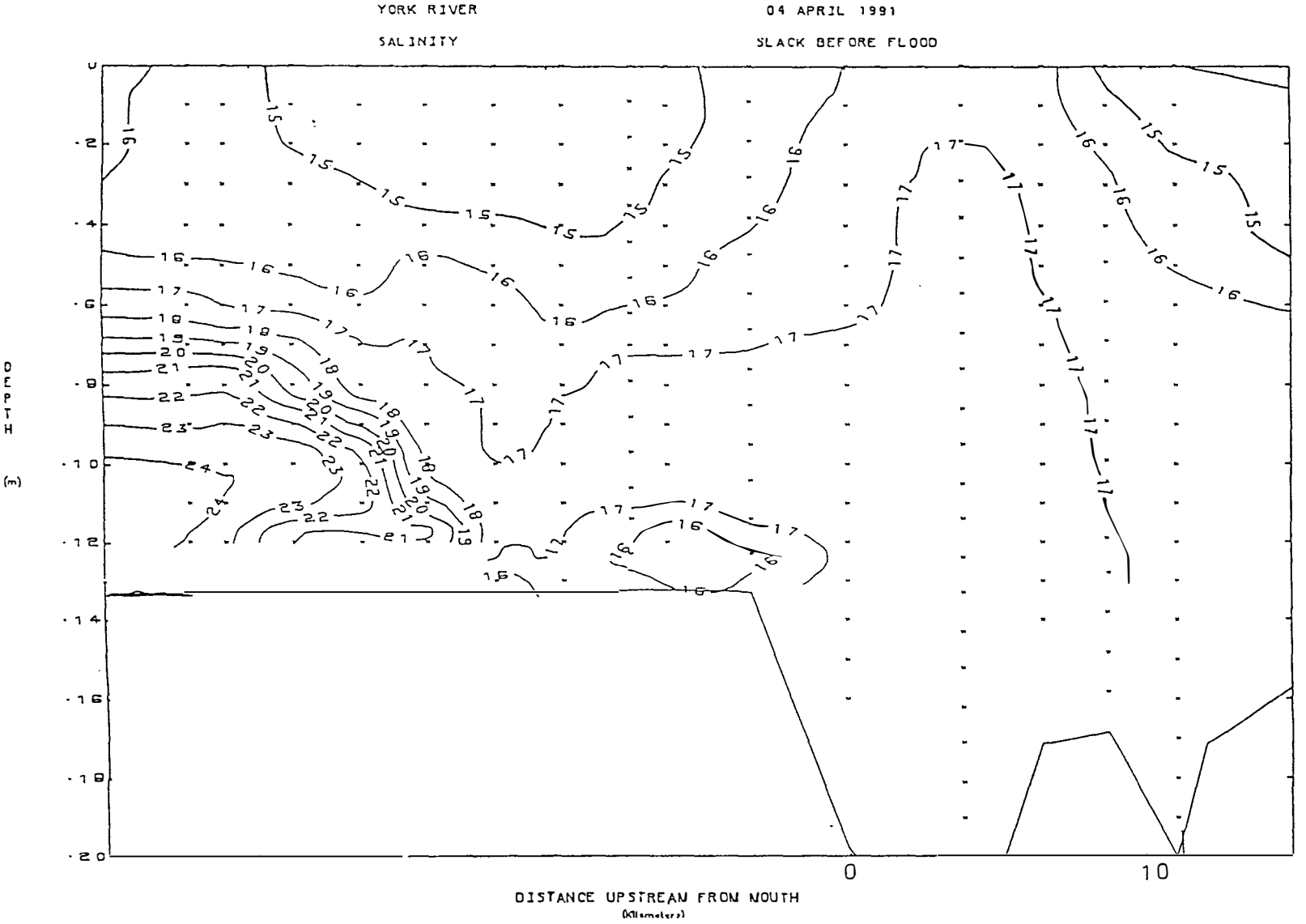

YORK RIVER
TEMPERATURE
01 APRIL 1991
SLACK BEFORE EBB
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
10
11
12
0
10
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

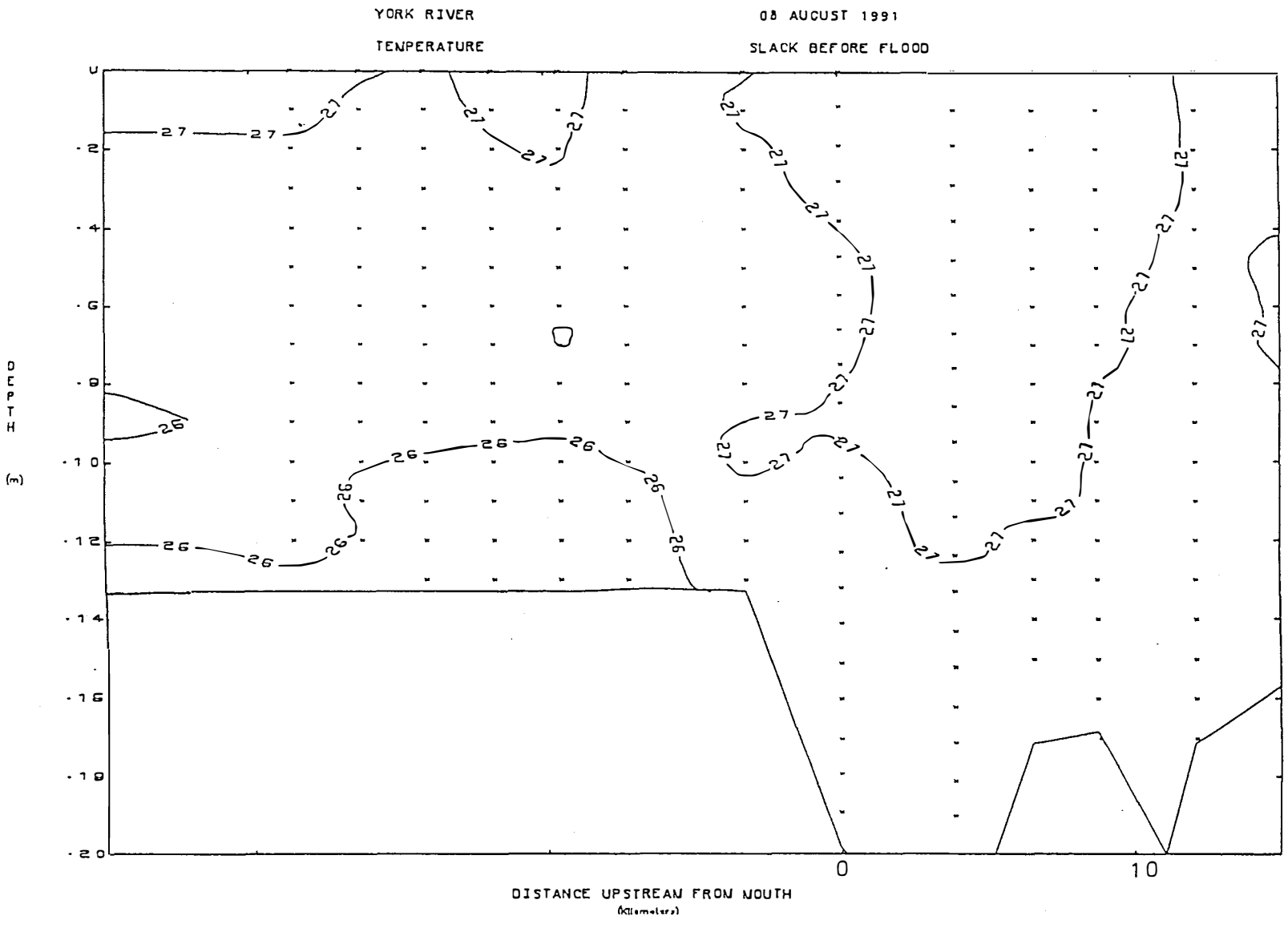

YORK RIVER
SALINITY
01 APRIL 1991
SLACK BEFORE EBB
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
0
10
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

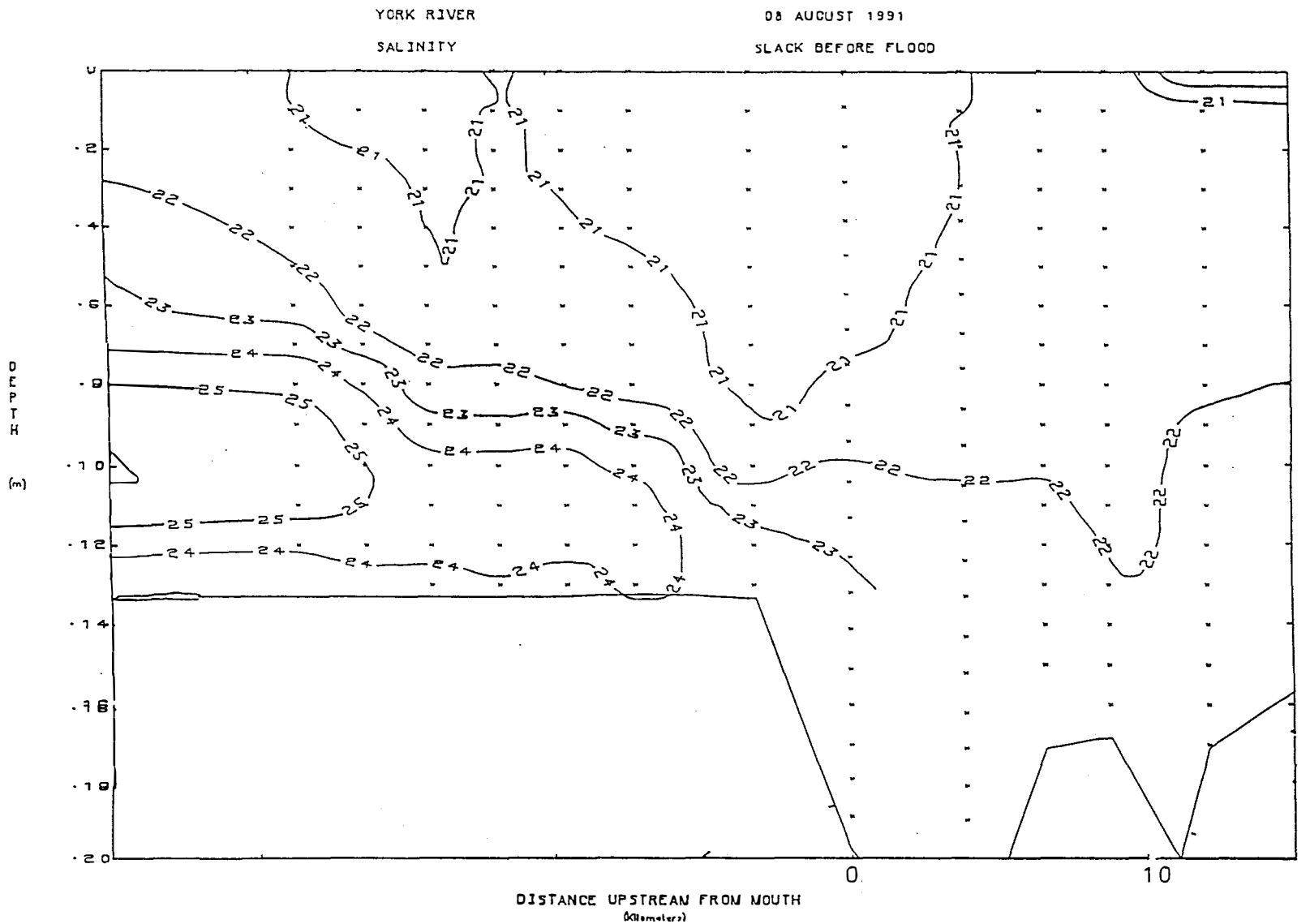

YORK RIVER
TEMPERATURE
03 APRIL 1991
SLACK BEFORE EBB
DEPTH (m)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
11
12
0
10
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

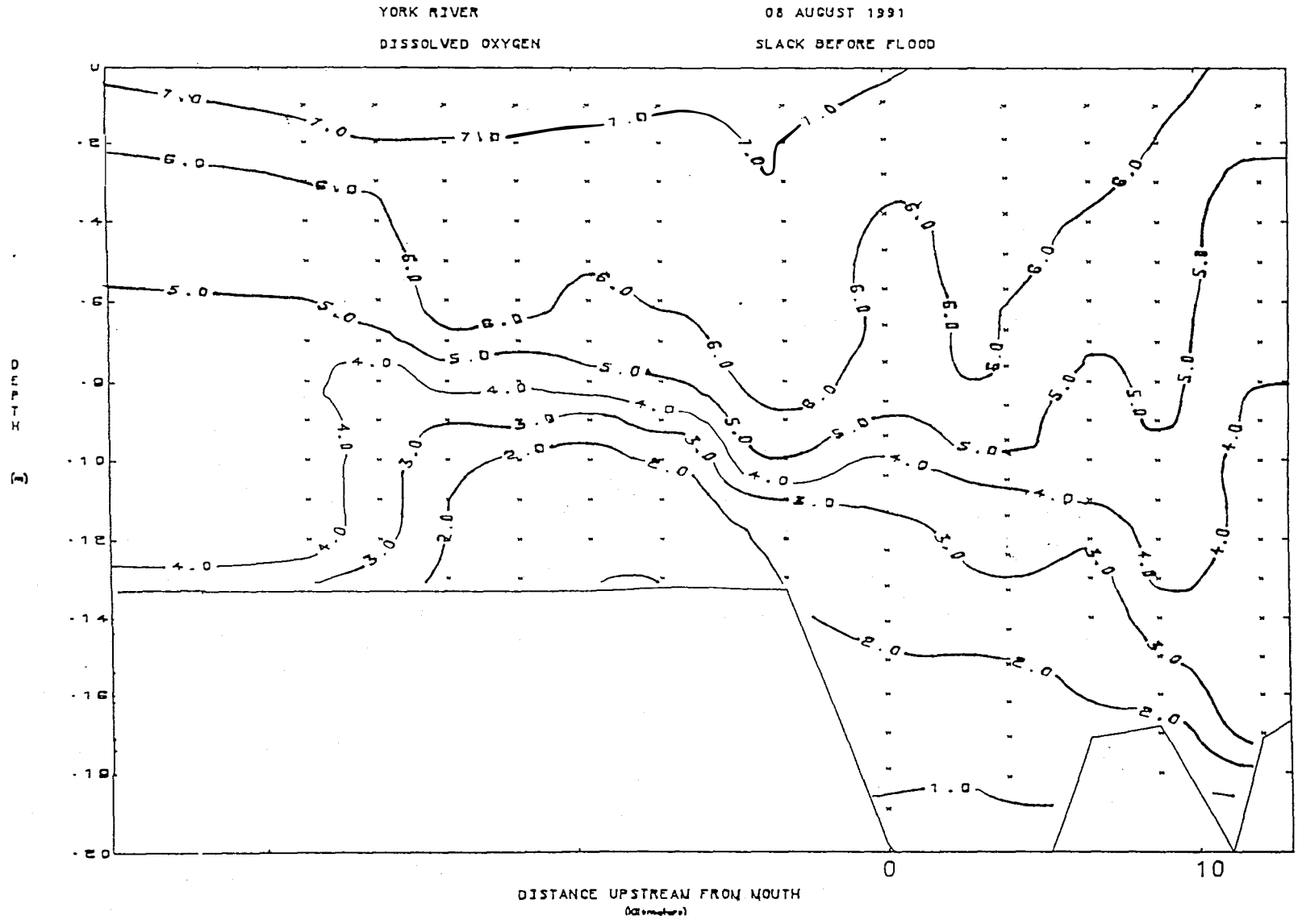

YORK RIVER
SALINITY
03 APRIL 1991
SLACK BEFORE EBB
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
0
10
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)


YORK RIVER
TEMPERATURE
04 APRIL 1991
SLACK BEFORE FLOOD
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
11
12
0
10
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)


YORK RIVER
SALINITY
04 APRIL 1991
SLACK BEFORE FLOOD
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
0
10
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

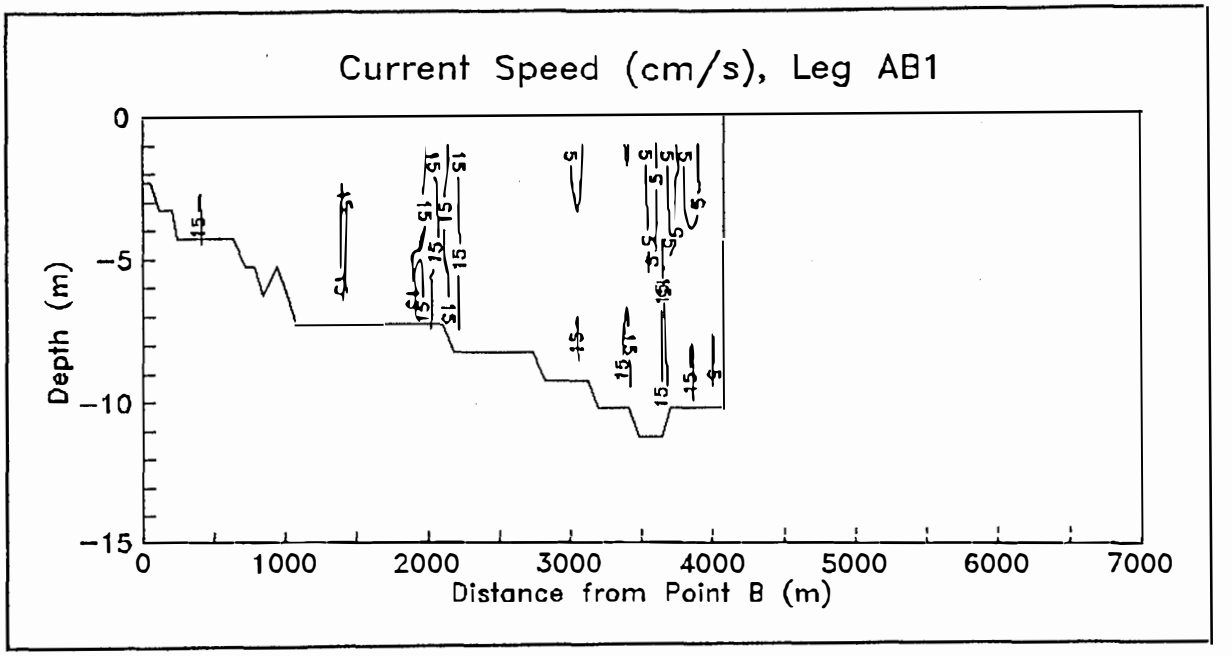

YORK RIVER
TEMPERATURE
08 AUGUST 1991
SLACK BEFORE FLOOD
DEPTH (m)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
27
26
0
10
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

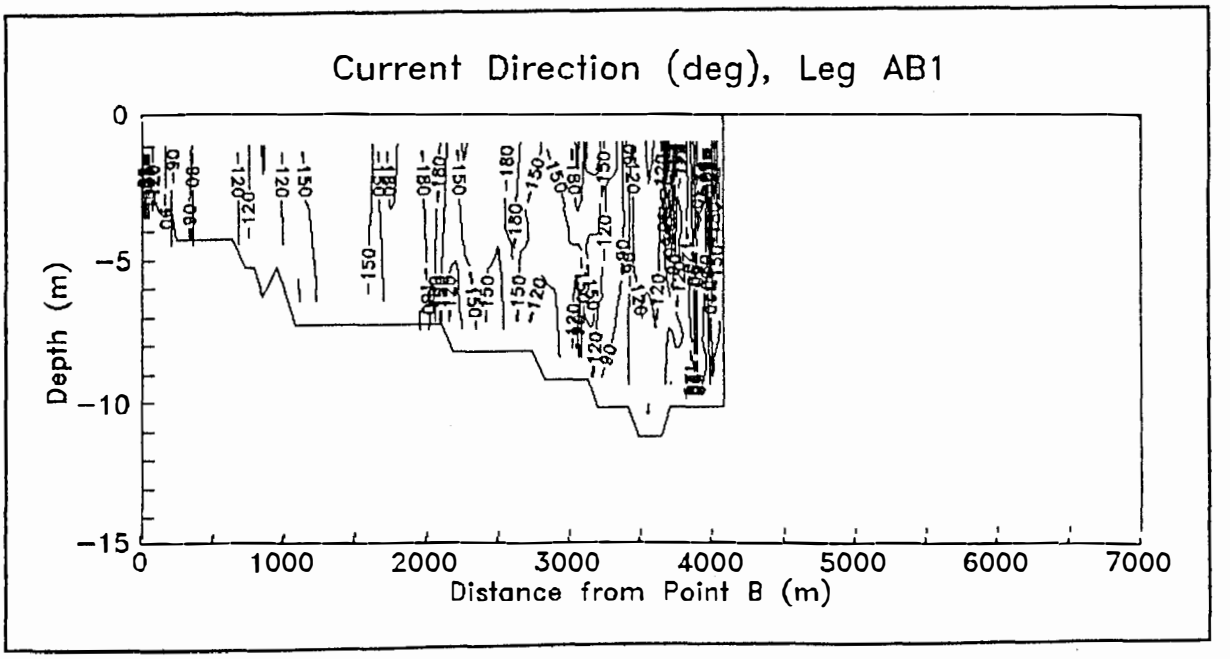

YORK RIVER
SALINITY
08 AUGUST 1991
SLACK BEFORE FLOOD
DEPTH (m)
0
2
4
6
8
10
12
14
16
18
20
0
10
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

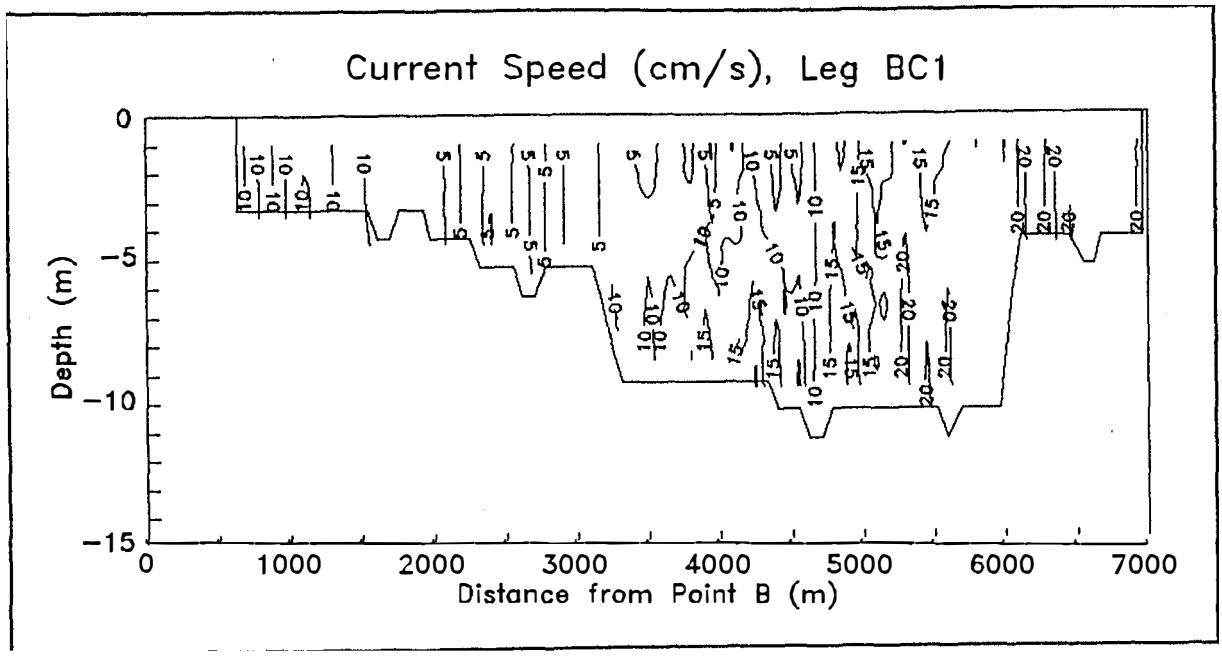

YORK RIVER
08 AUGUST 1991
DISSOLVED OXYGEN
SLACK BEFORE FLOOD
DEPTH (m)
0
10
DISTANCE UPSTREAM FROM MOUTH
(kilometers)

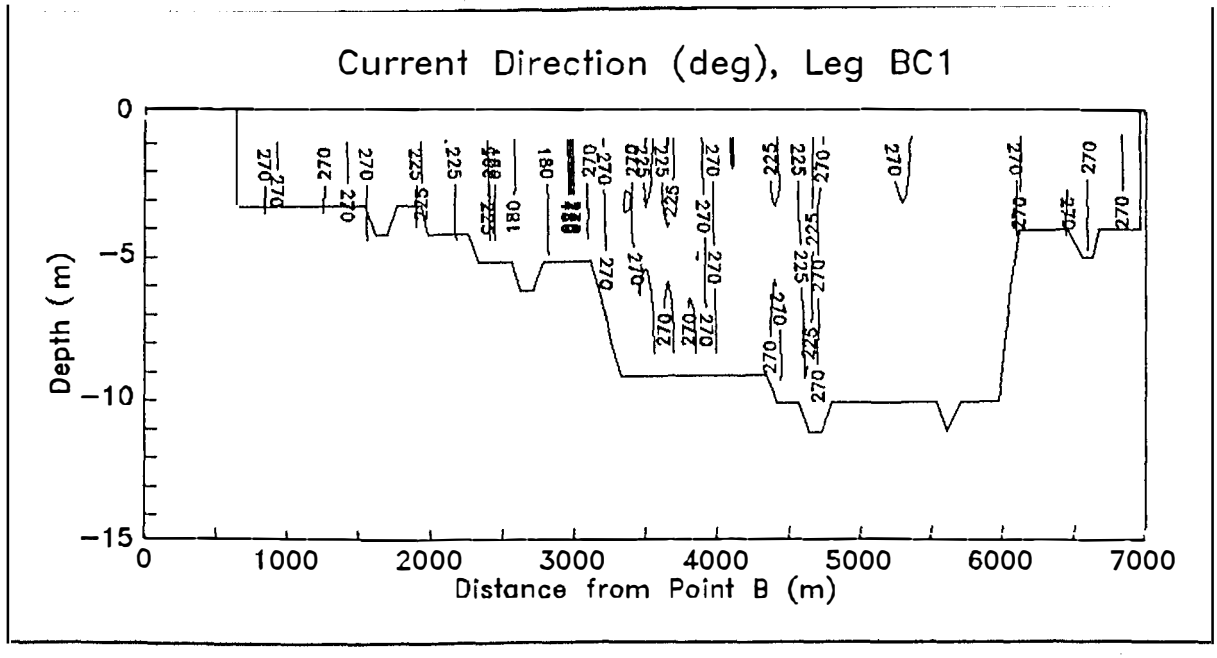
APPENDIX III

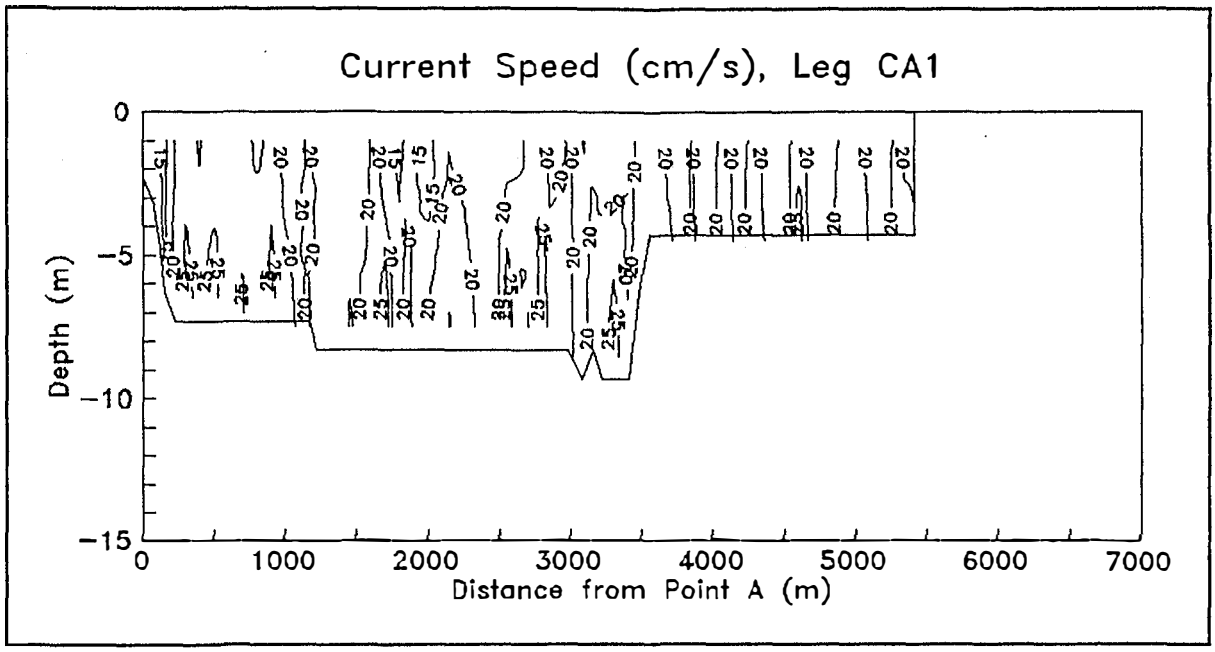
Current speed and direction contour plots for each transect along a leg of the sampling triangle on 15 August 1991. The complete triangle ABC was sampled three times. Notation of the form XYn in the plot labels refers to the n-th transect along the line connecting points X and Y.

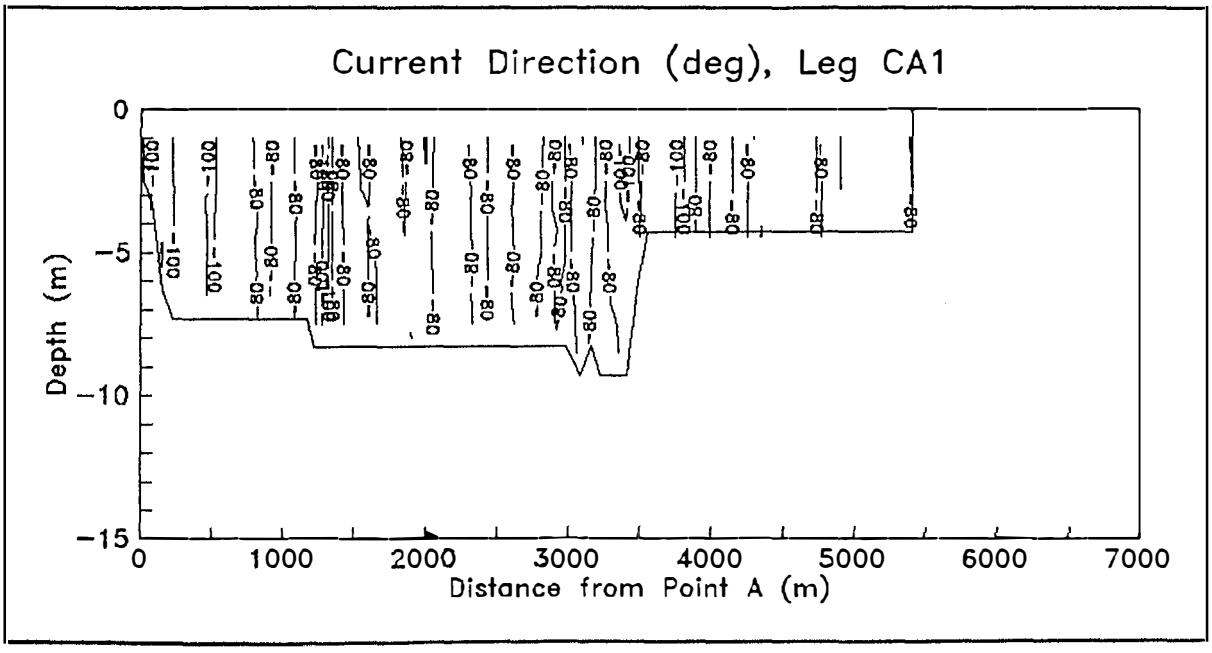

Current Speed (cm/s), Leg AB1
Depth (m)
0
-5
-10
-15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)

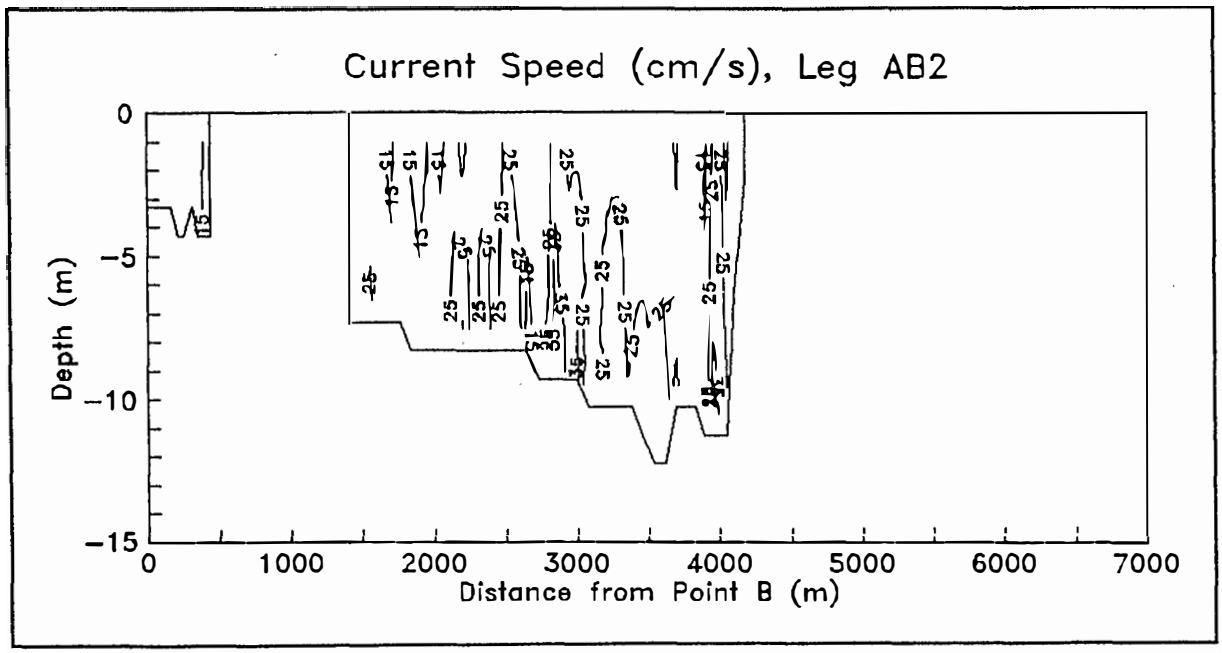

Current Direction (deg), Leg AB1
Depth (m)
0
-5
-10
-15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)

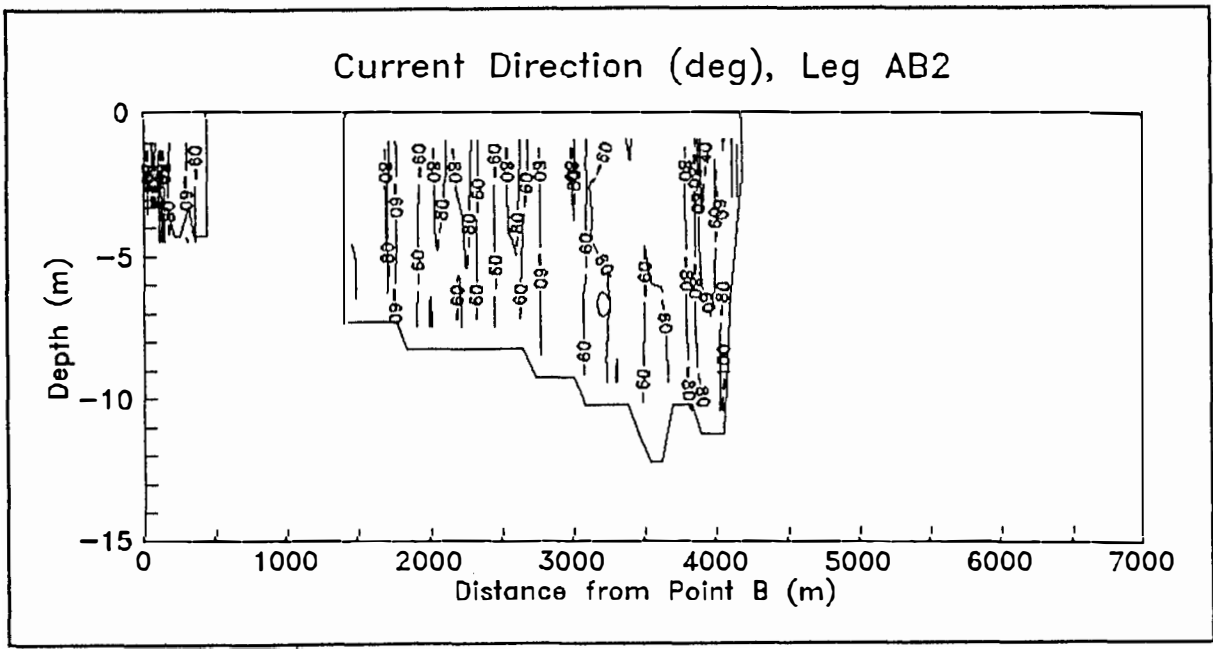

Current Speed (cm/s), Leg BC1
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)

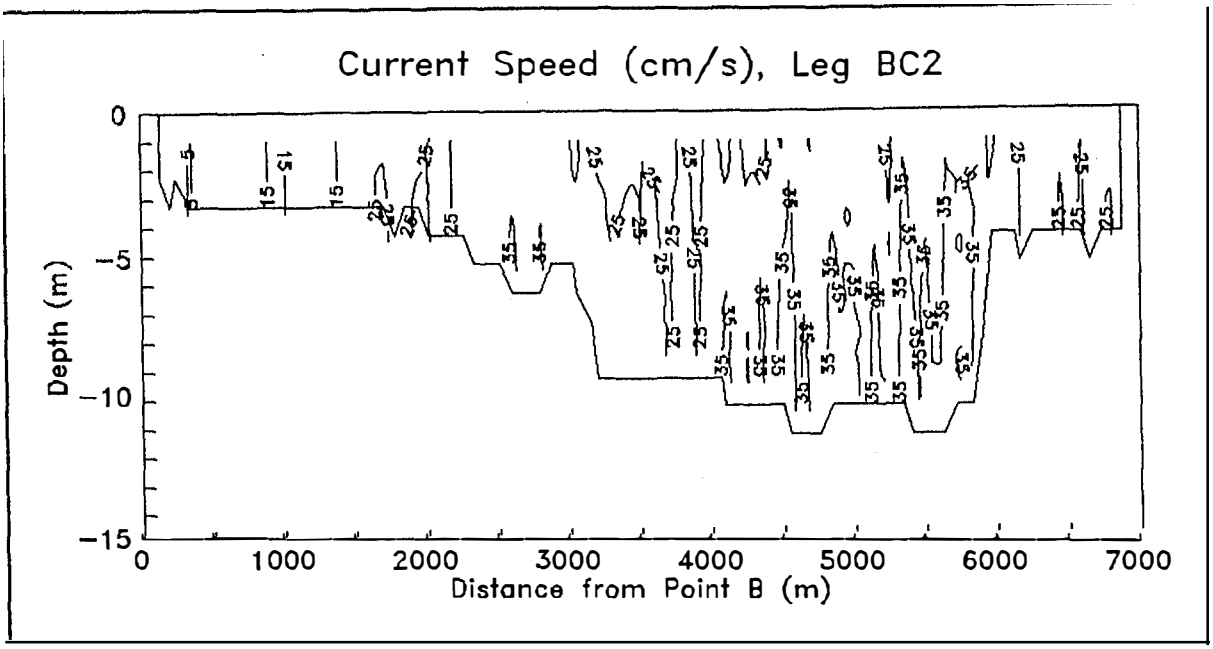

Current Direction (deg), Leg BC1
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)

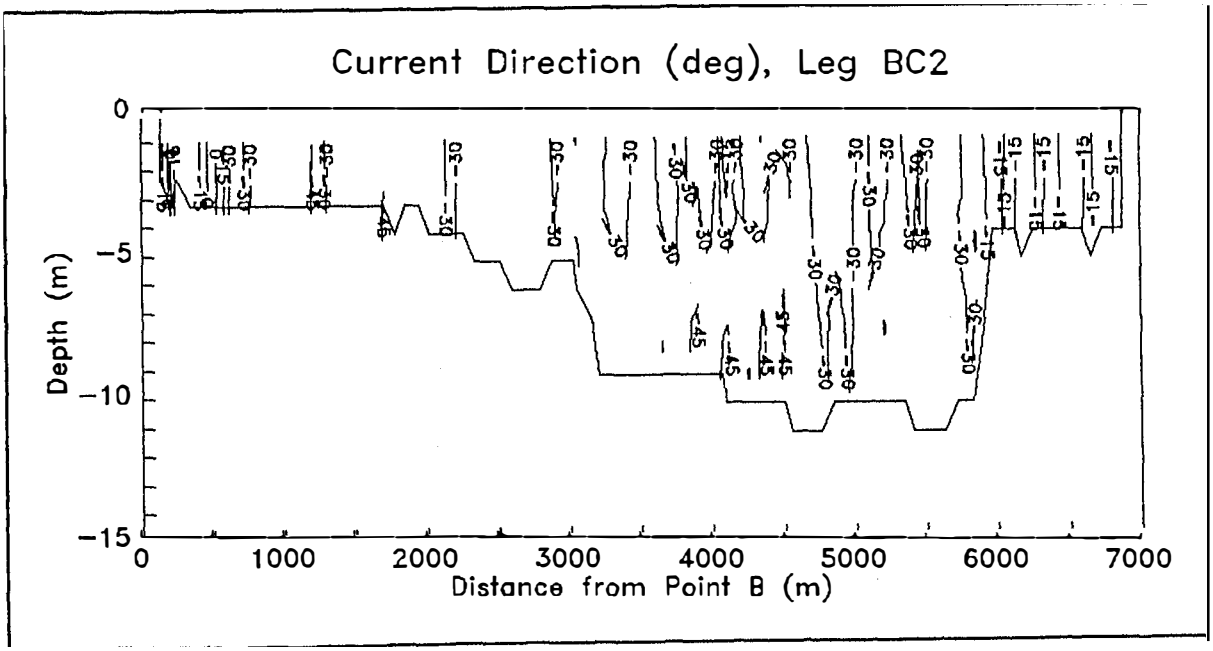

Current Speed (cm/s), Leg CA1
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point A (m)

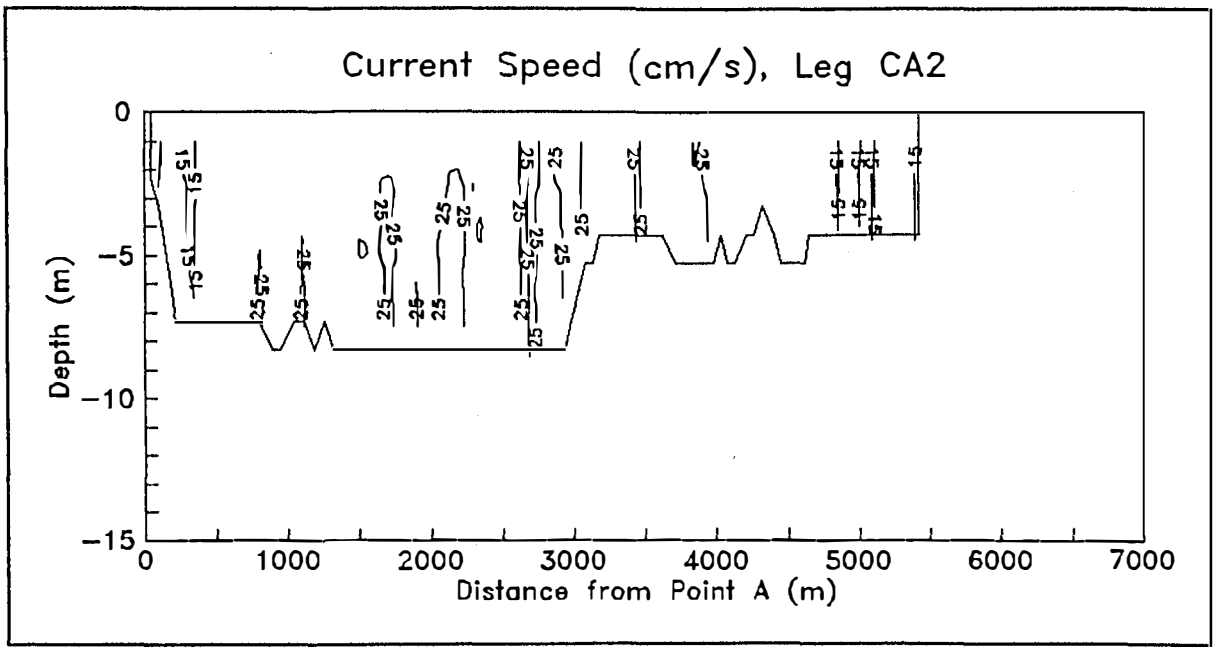

Current Direction (deg), Leg CA1
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point A (m)

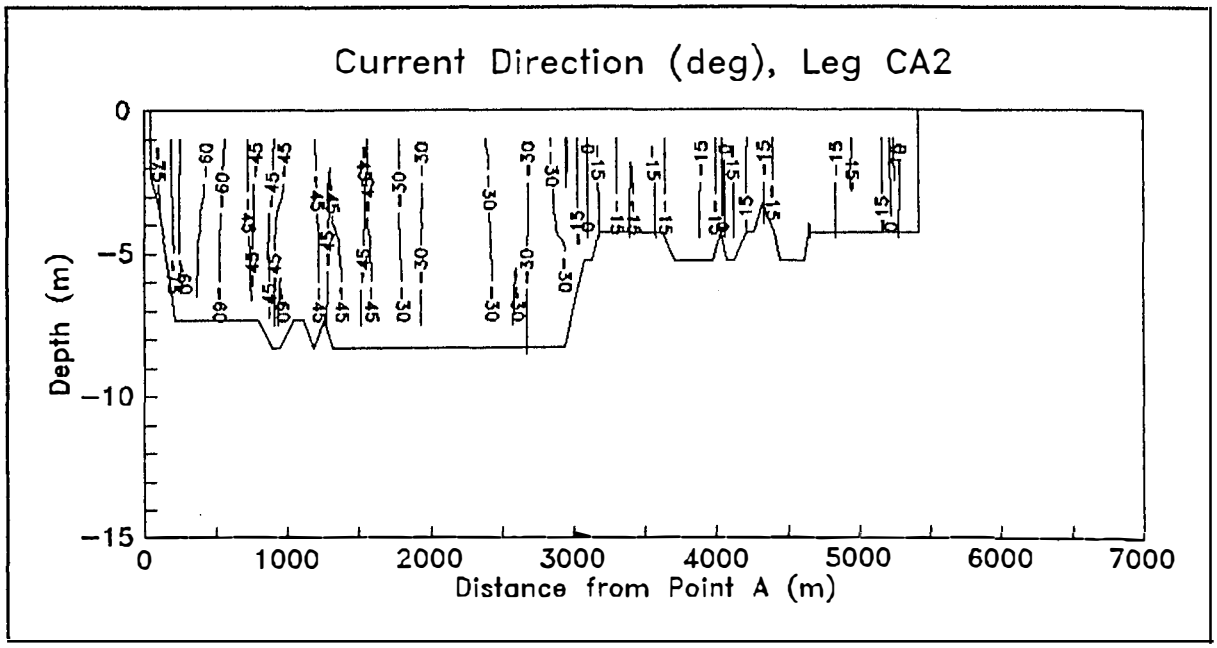

Current Speed (cm/s), Leg AB2
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)

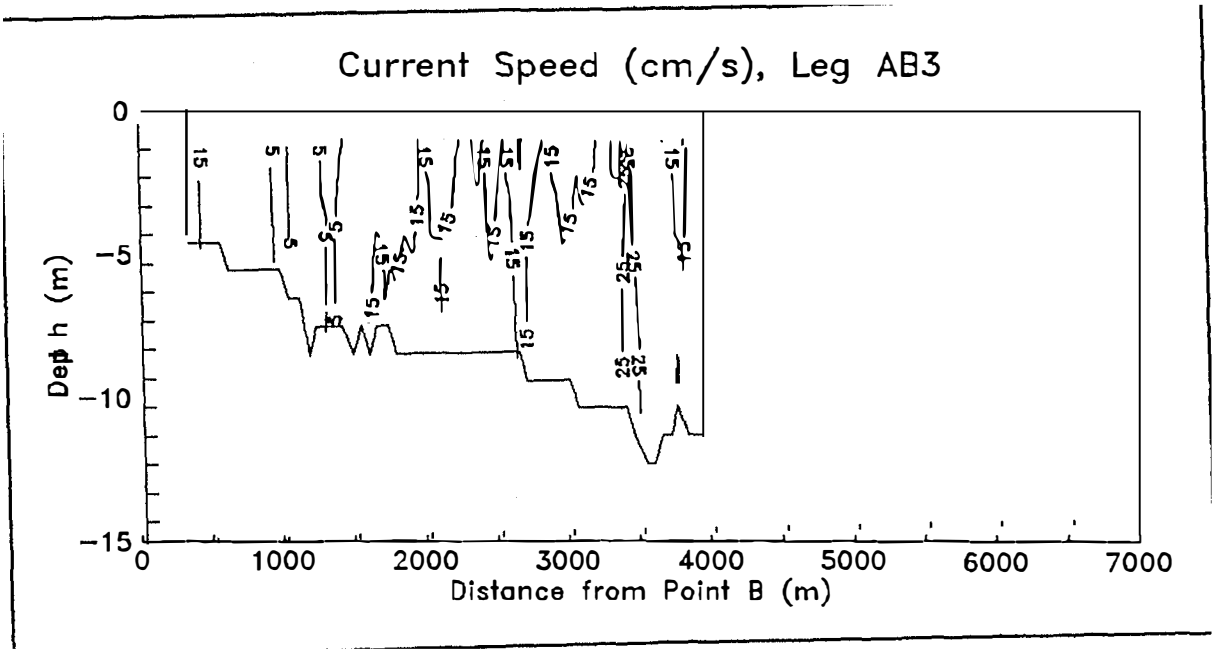

Current Direction (deg), Leg AB2
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)

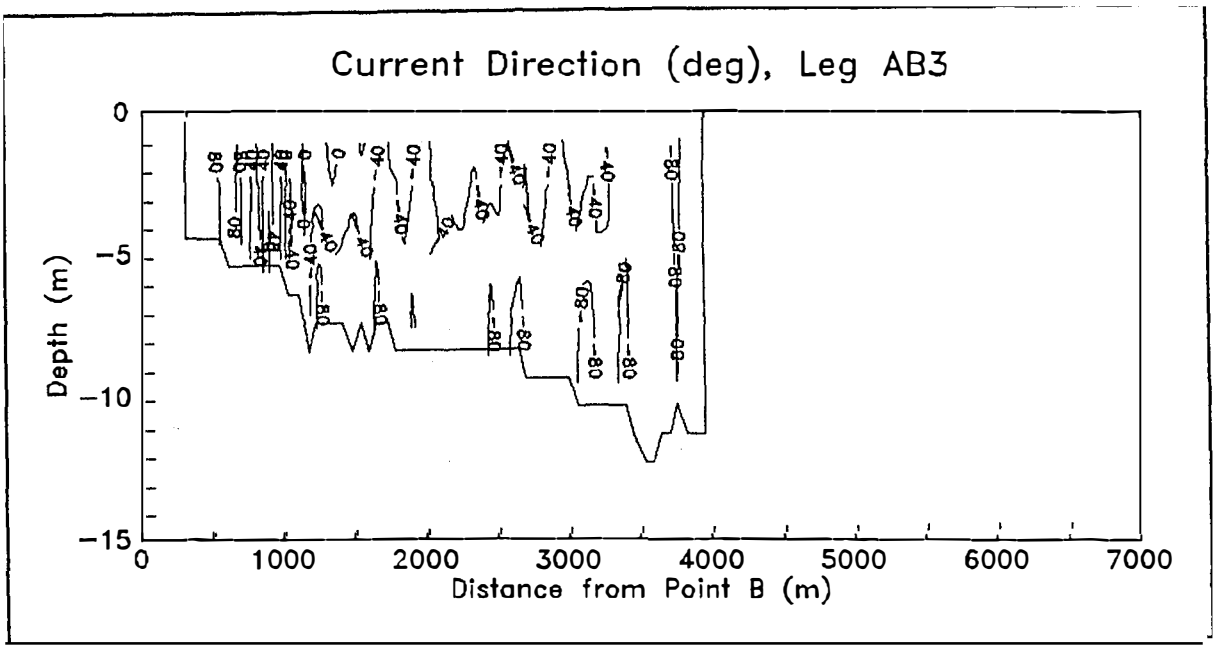

Current Speed (cm/s), Leg BC2
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)

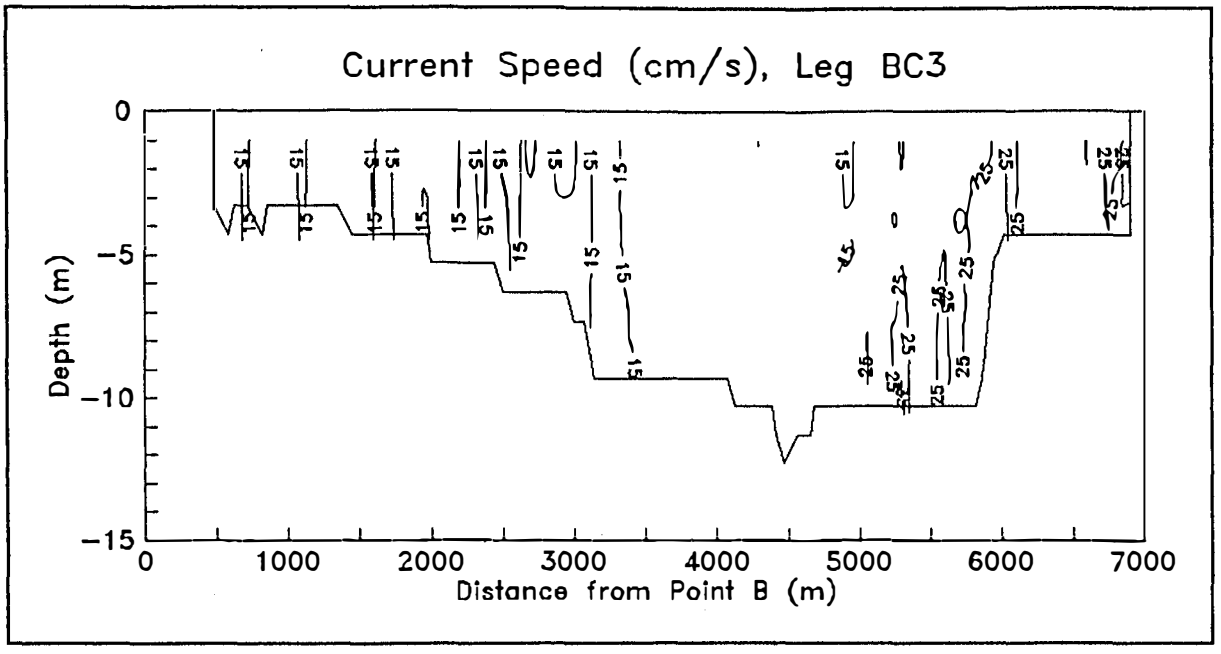

Current Direction (deg), Leg BC2
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)

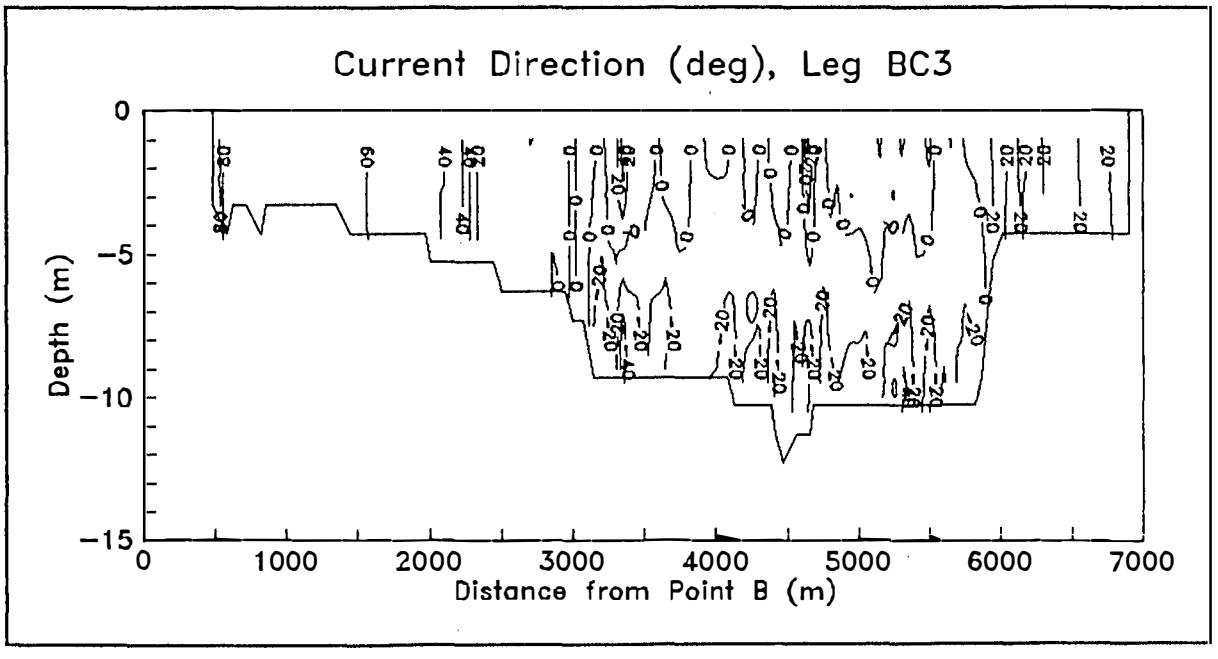

Current Speed (cm/s), Leg CA2
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point A (m)

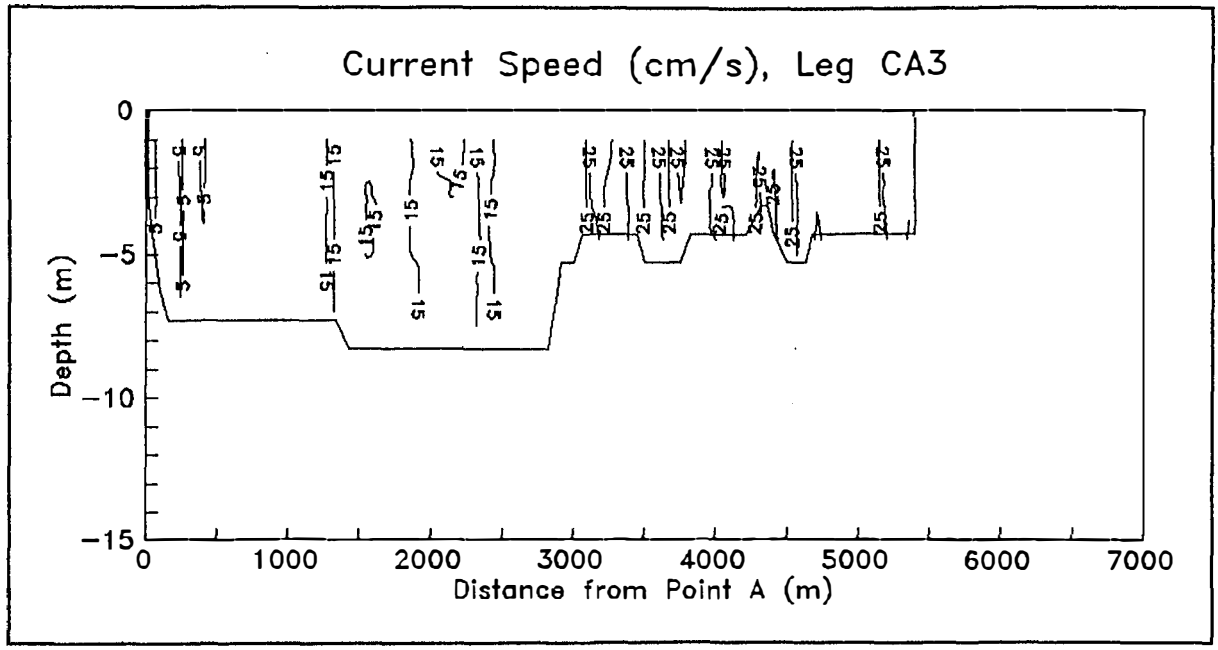

Current Direction (deg), Leg CA2
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point A (m)

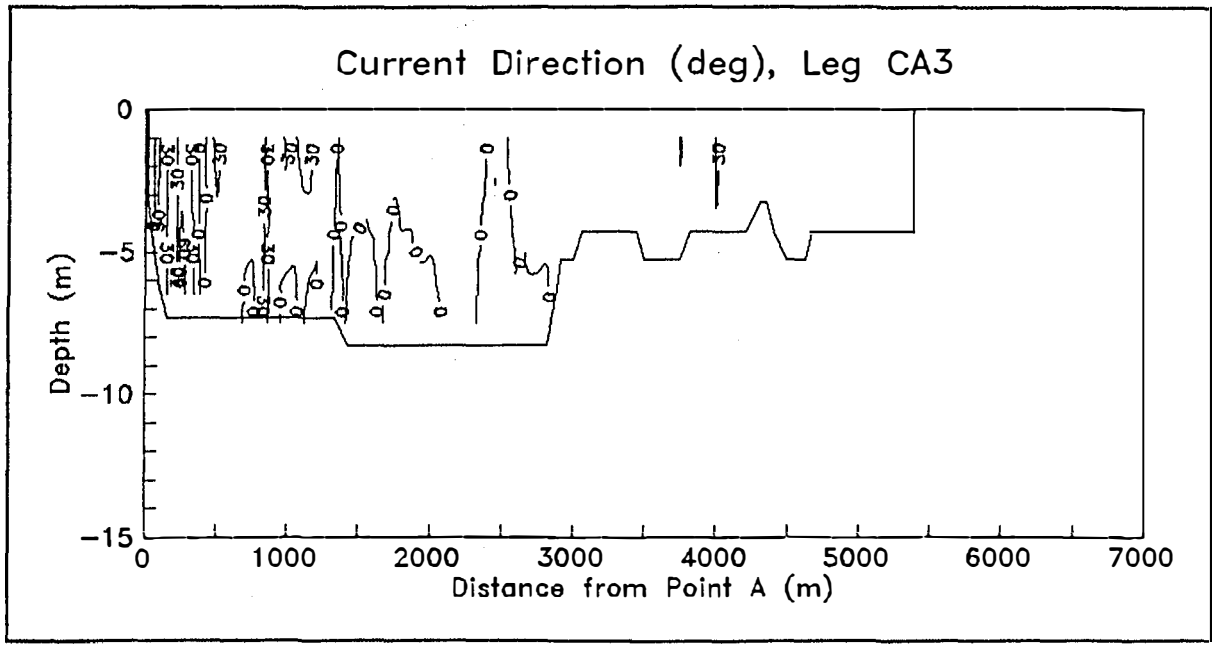

Current Speed (cm/s), Leg AB3
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)


Current Direction (deg), Leg AB3
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)


Current Speed (cm/s), Leg BC3
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)


Current Direction (deg), Leg BC3
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point B (m)


Current Speed (cm/s), Leg CA3
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point A (m)


Current Direction (deg), Leg CA3
Depth (m)
0
−5
−10
−15
0
1000
2000
3000
4000
5000
6000
7000
Distance from Point A (m)

APPENDIX IV-1

15 AUGUST 1991 DROGUE SET

This appendix consists of graphic presentations of data collected on 15 August 1991 as part of the drogue experiment on that date. The following are illustrated:

1. Drogue position as a function of time (IV-1-1).

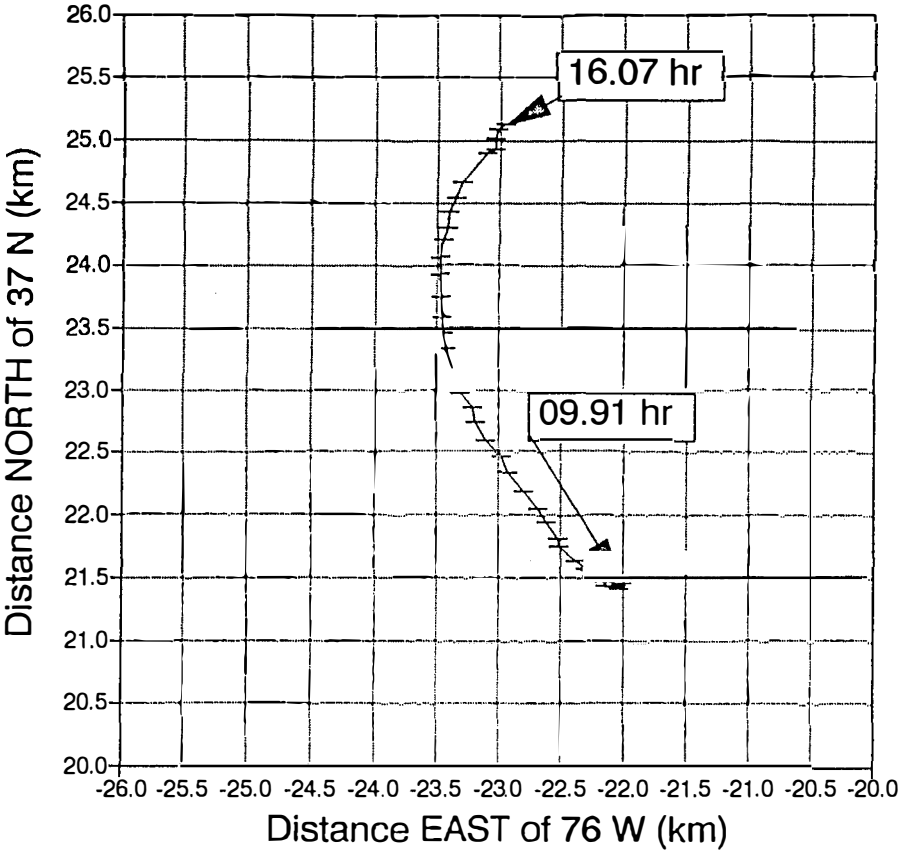
2. Vertical distributions of temperature, salinity, and density as functions of time along the drogue trajectory (IV-1-2).

3. Cluster plots of temperature, salinity, and density vs depth taken at 20 minute intervals along the drogue trajectory (IV-1-3 through IV-1-5).

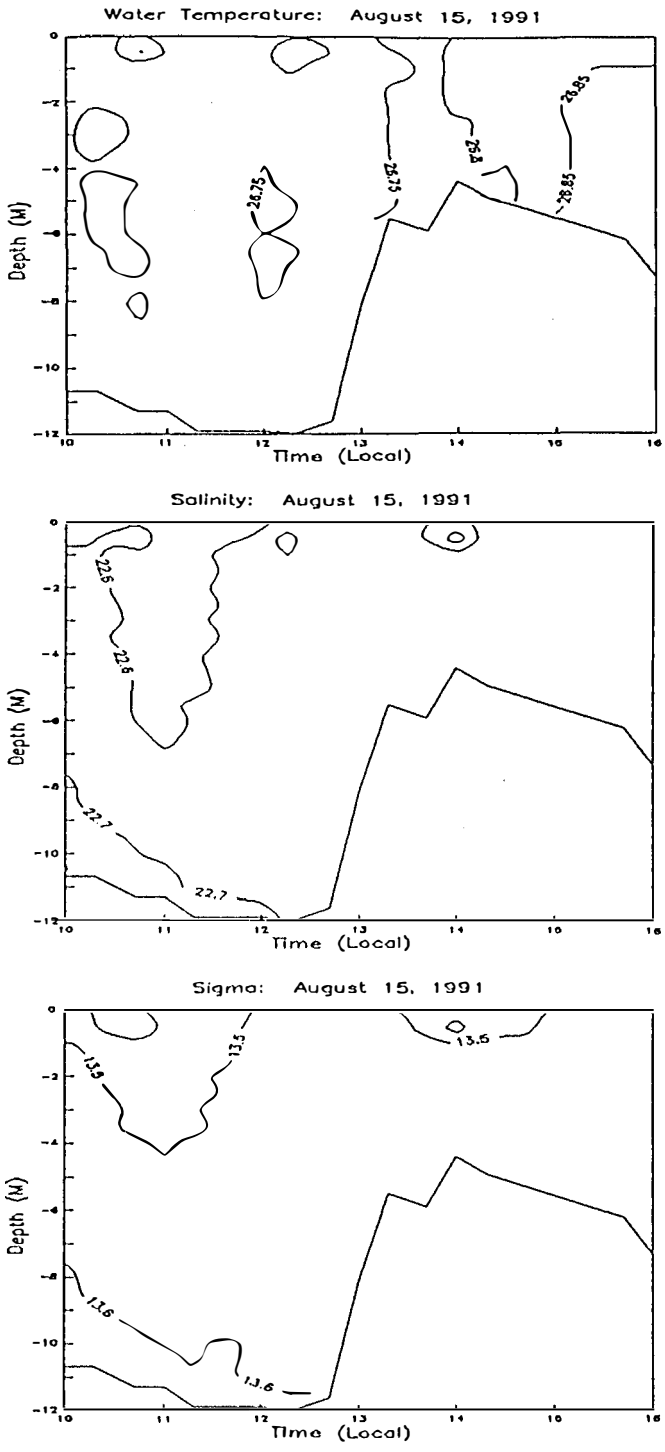
4. Individual plots of temperature, salinity, and density vs depth sequentially incremented by 0.05 parameter unit (IV-1-6 through IV-1-8).

5. Plots of drogue depth and temperature, salinity, and density at the drogue as functions of time (IV-1-9 and IV-1-10).

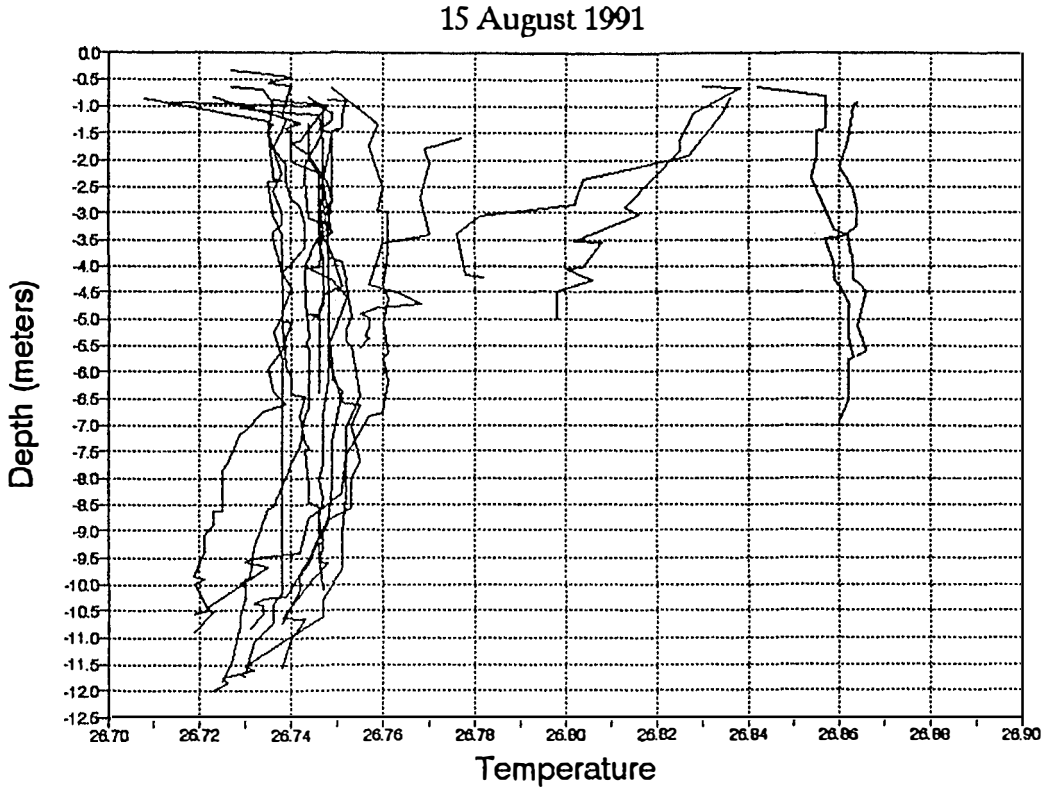
DROGUE TRACK ON 15 AUGUST 1991



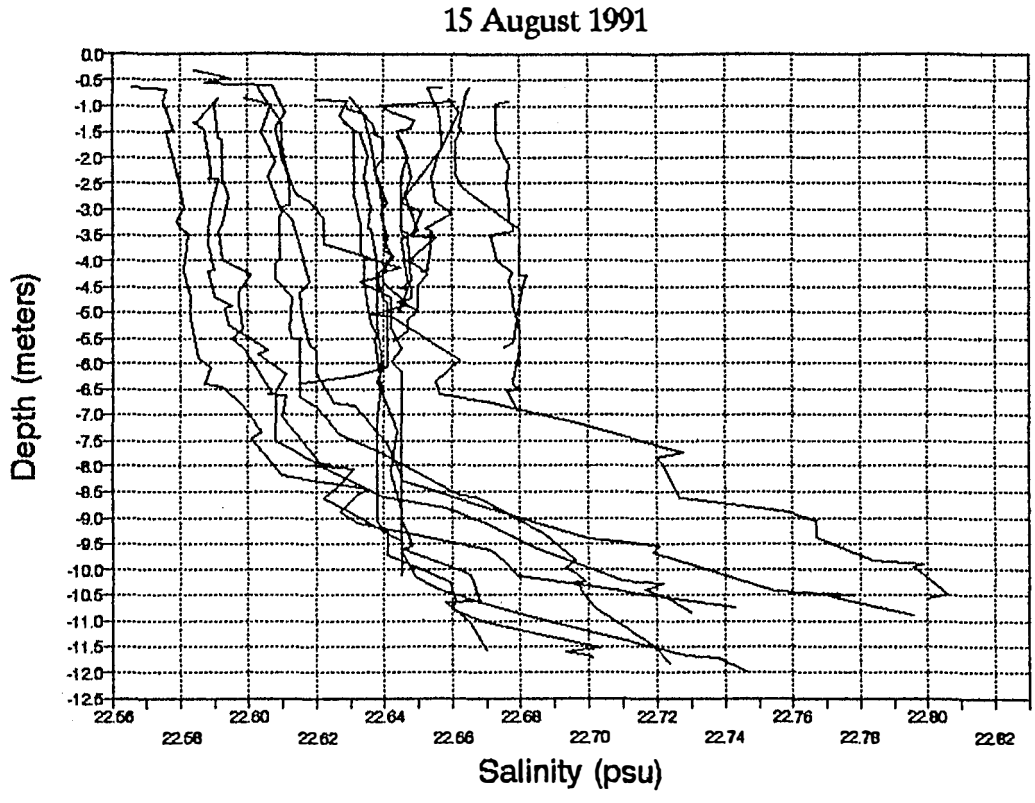
IV-1-1 Drogue track on 15 August 1991. Anticyclonic curvature starting 23 km north of the Bay mouth begins after the drogue moved 5 m upwards in 30 minutes while crossing York Spit (see Fig. IV-2).



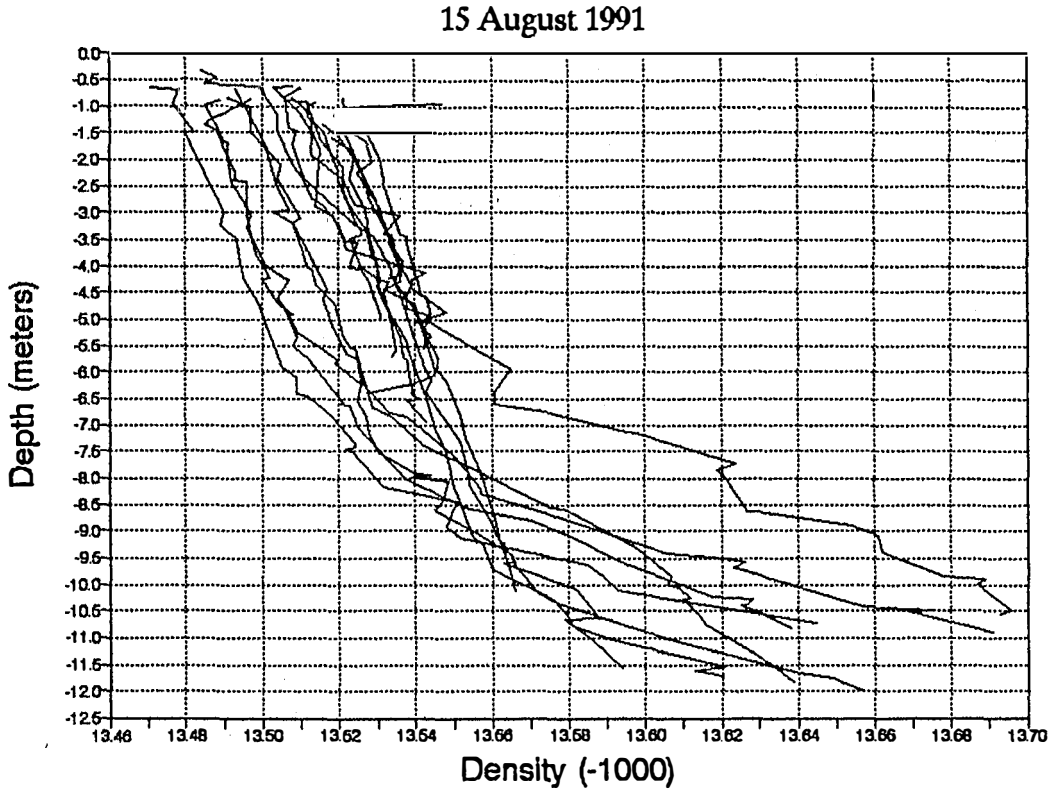
IV-1-2 Vertical structure of temperature, salinity, and density (σ) [top to bottom] as functions of time along the drogue trajectory.



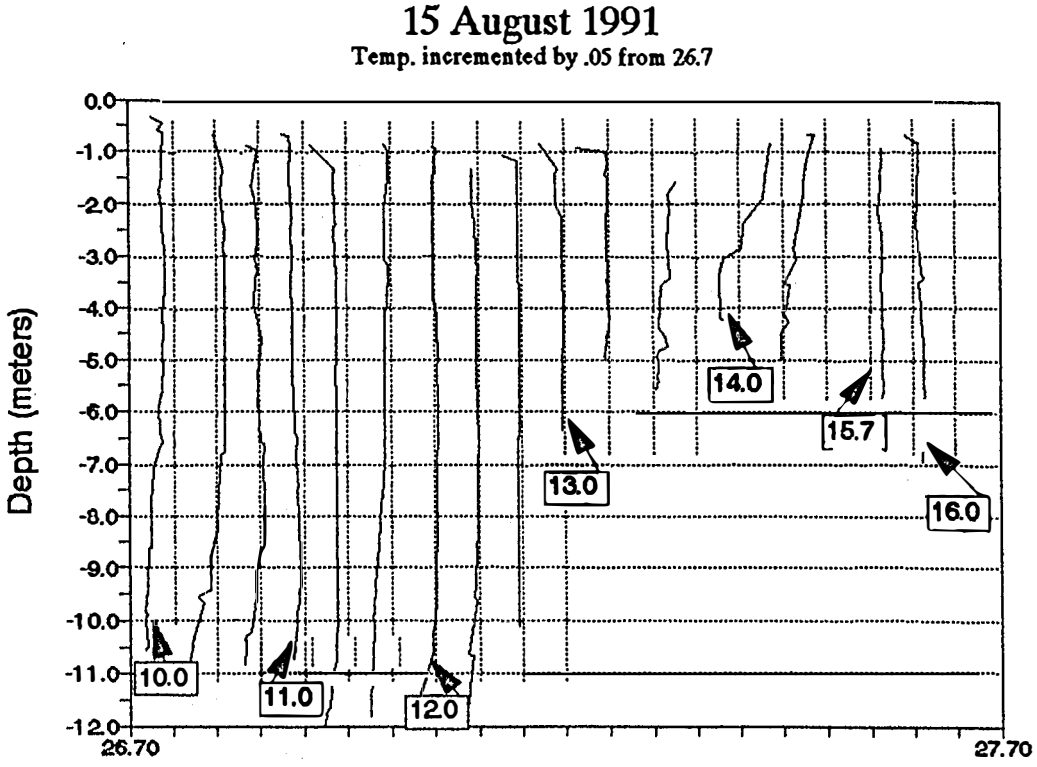
IV-1-3 Cluster plot of temperature with depth for stations sampled along drogue trajectory.



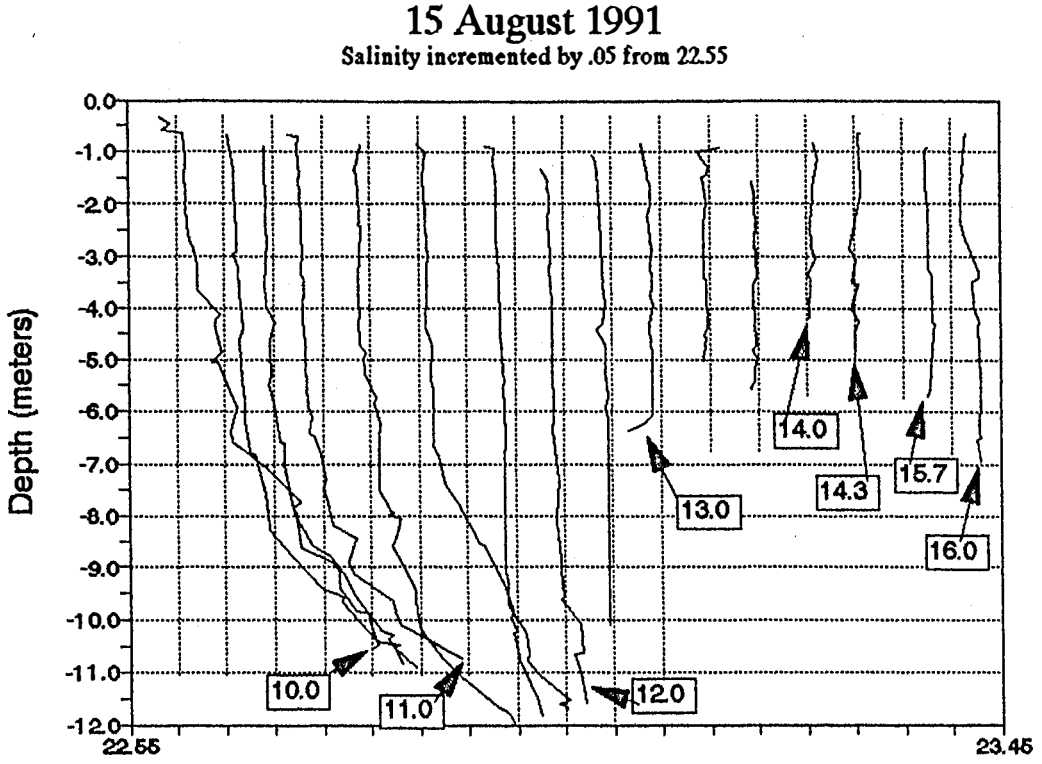
IV-1-4 Cluster plot of salinity with depth for stations sampled along drogue trajectory.



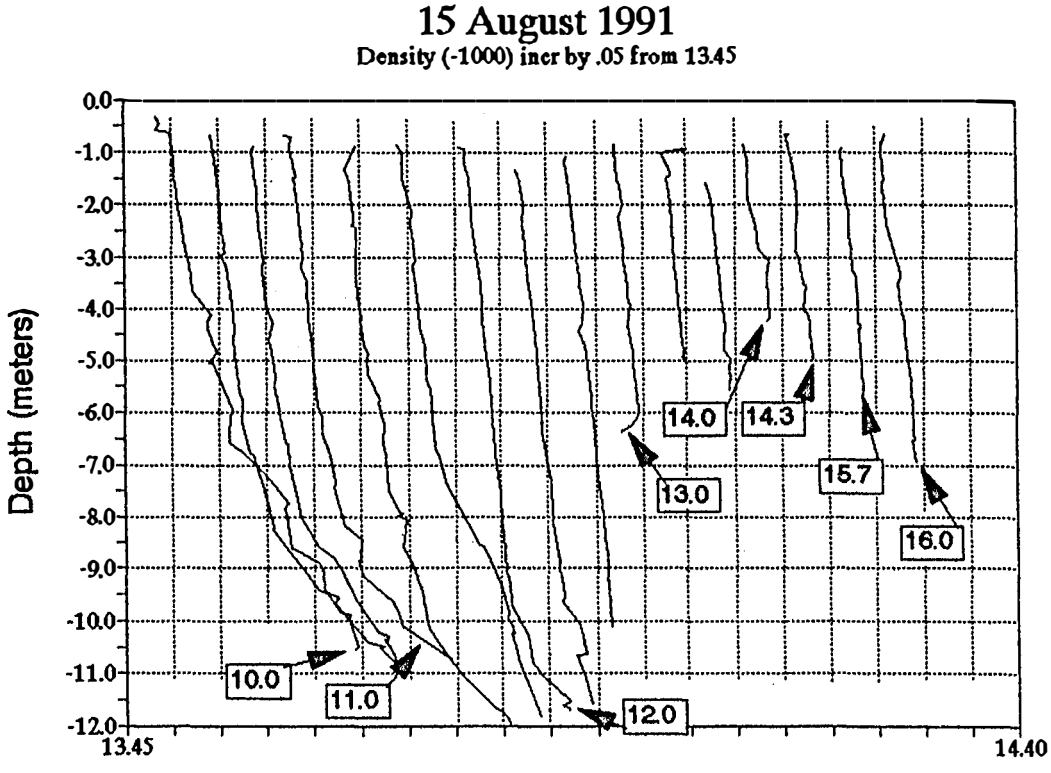
IV-1-5 Cluster plot of density with depth for stations sampled along drogue trajectory.



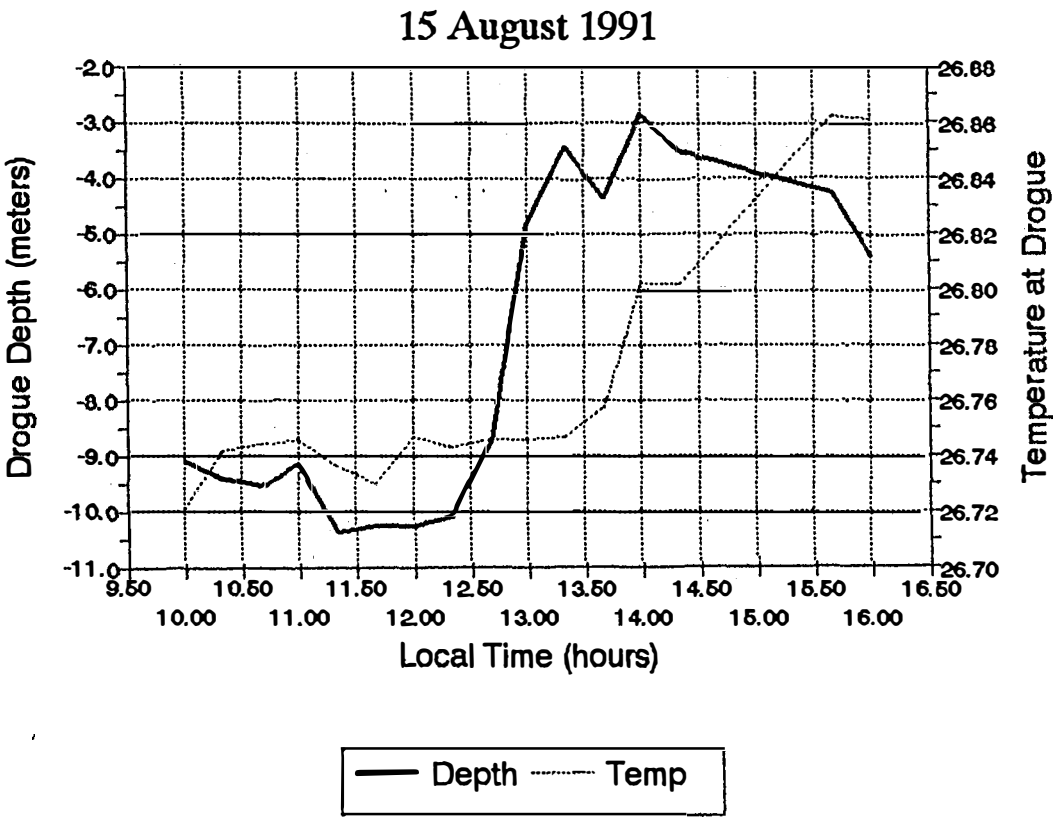
IV-1-6 Sequential plots of temperature with depth along drogue trajectory with offset of 0.05°C. Vertical lines associated with each plot indicate a temperature of 26.75°C.



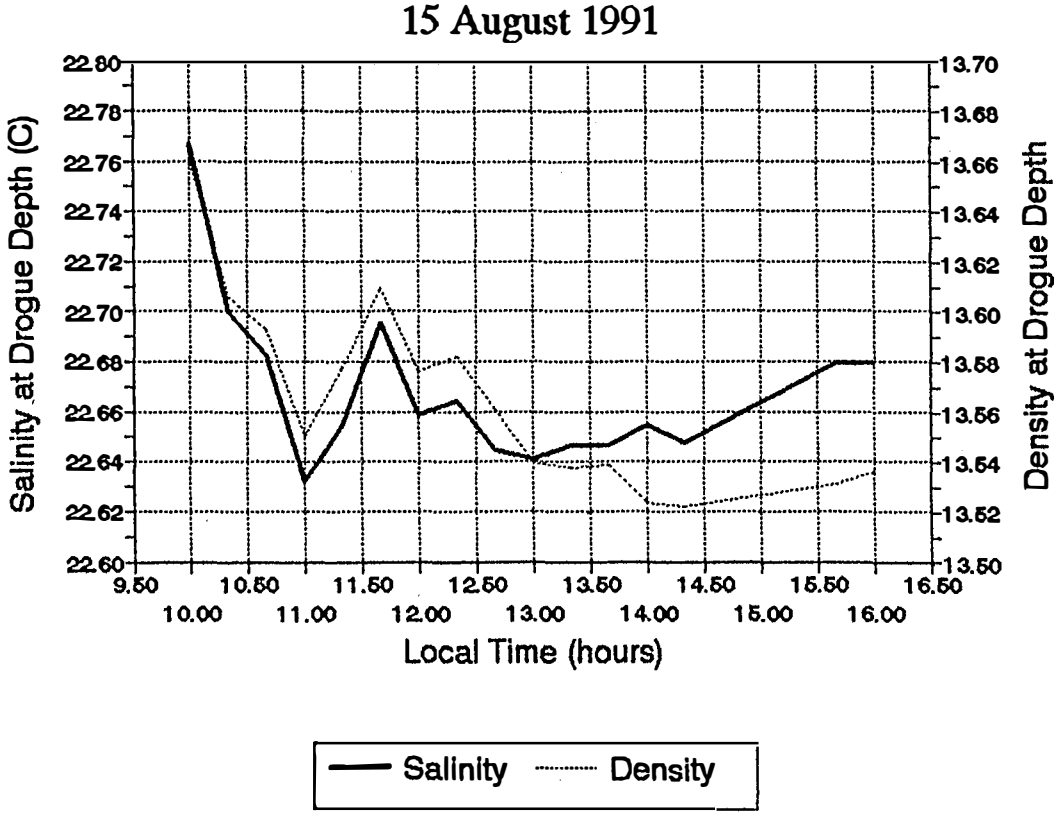
IV-1-7 Sequential plots of salinity with depth along drogue trajectory with offset of 0.05 psu. Vertical lines indicate salinity of 22.55 psu.



IV-1-8 Sequential plots of density with depth along drogue trajectory with offset of 0.05 kg m^{-3}. Vertical lines indicate density of 1013.45 kg m^{-3}.



IV-1-9 Temporal variations of drogue depth and temperature at drogue along its trajectory.



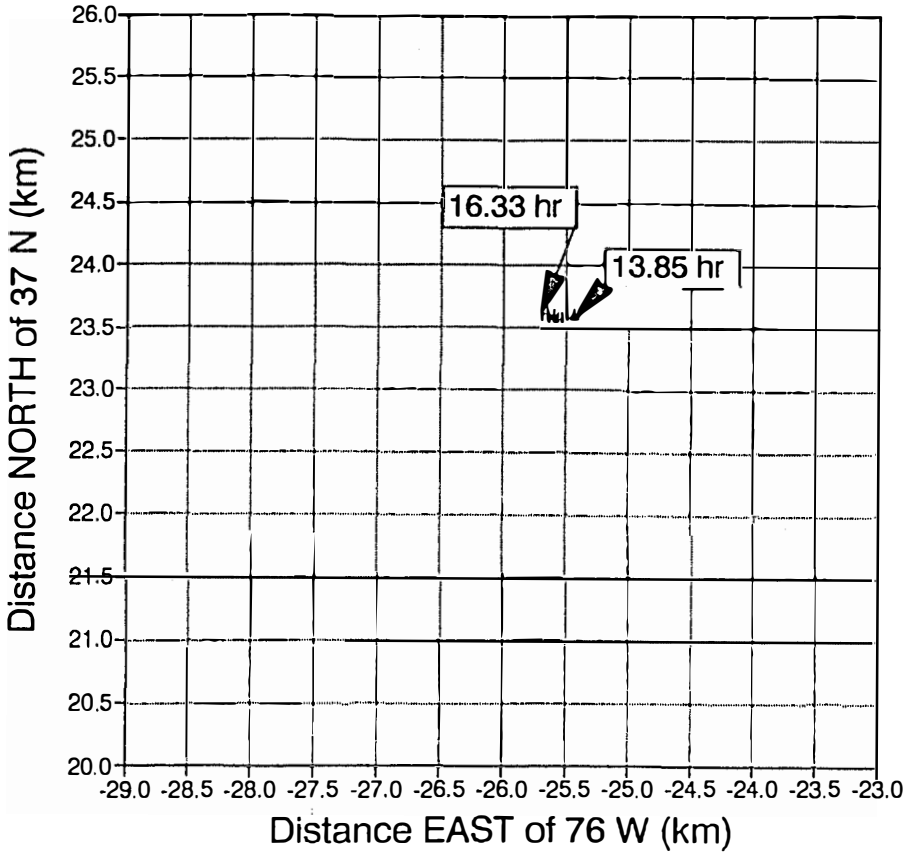
IV-1-10 Temporal variations of salinity and density at drogue depth along its trajectory.

APPENDIX IV-2

19 SEPTEMBER 1991 DROGUE SET

This appendix has only one figure which shows the trajectory of the drogue on 19 September 1991. CTD data was not obtained because of instrument malfunction and the experiment was terminated after less than three hours because of unfavorable wind conditions and heavy seas (for a 20 ft. vessel).

DROGUE TRACK ON 19 SEPTEMBER 1991



IV-2-1 Drogue track on 19 September 1991.

APPENDIX IV-3

1 OCTOBER 1991 DROGUE SET

This appendix consists of graphic presentations of data collected on 1 October 1991 as part of the drogue experiment on that date. The following are illustrated:

1. Drogue position as a function of time with transect stations occupied by R/V Langley (IV-3-1).

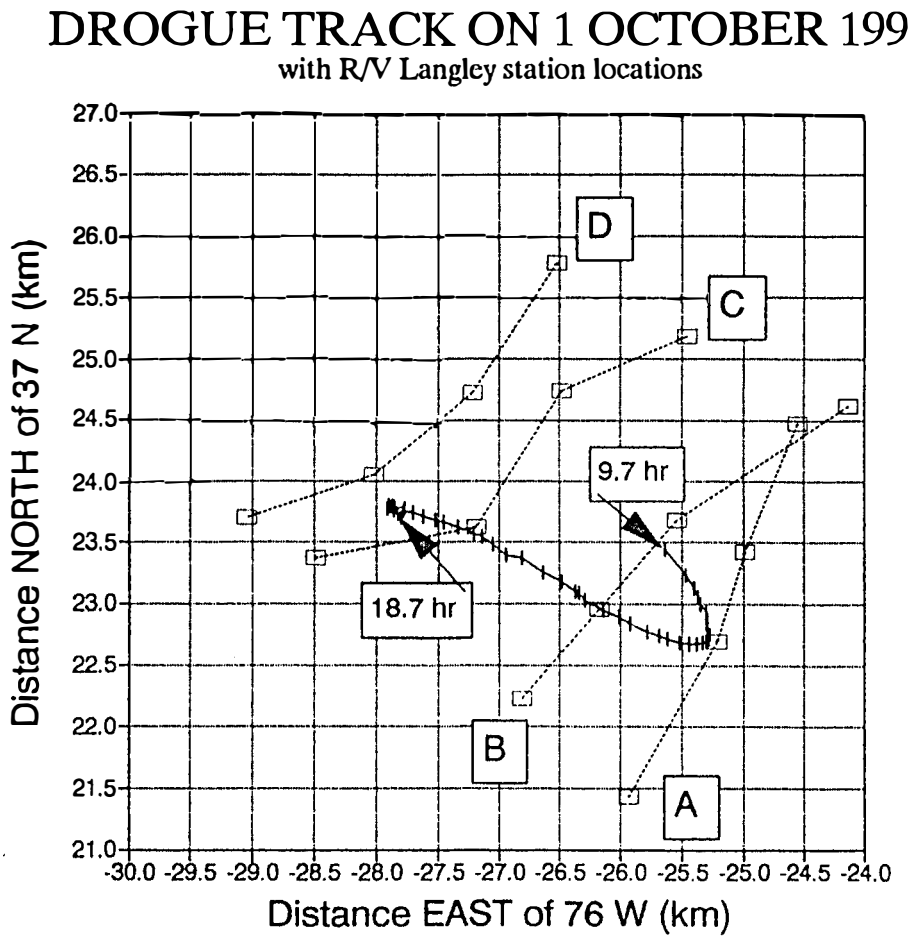
2. Vertical distributions of temperature, salinity, and density as functions of time along the drogue track (IV-3-2).

3. Temperature, salinity, and density as functions of depth and distance along the Langley transects (IV-3-3A through IV-3-3D).

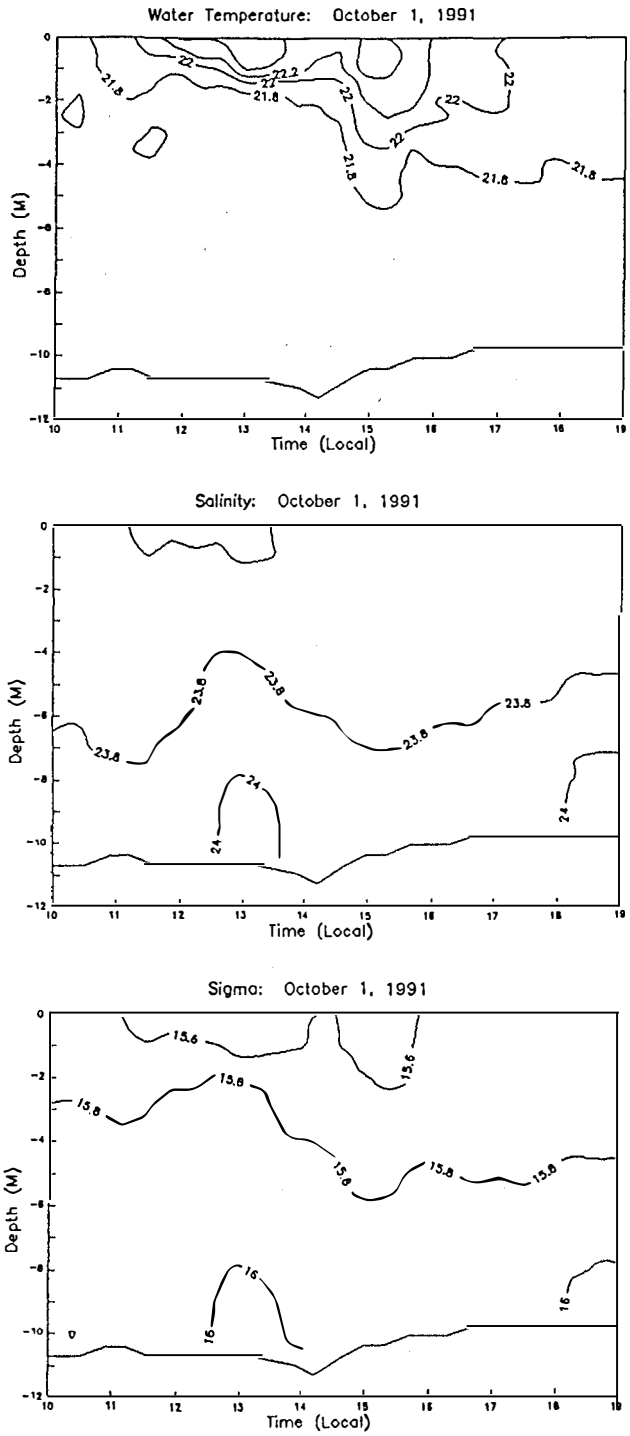
4. Cluster plots of temperature, salinity, and density vs depth at 20 minute intervals along the drogue trajectory (IV-3-4 through IV-3-6).

5. Individual plots of temperature, salinity, and density vs depth incremented by 0.05 parameter unit (IV-3-7 through IV-3-9).

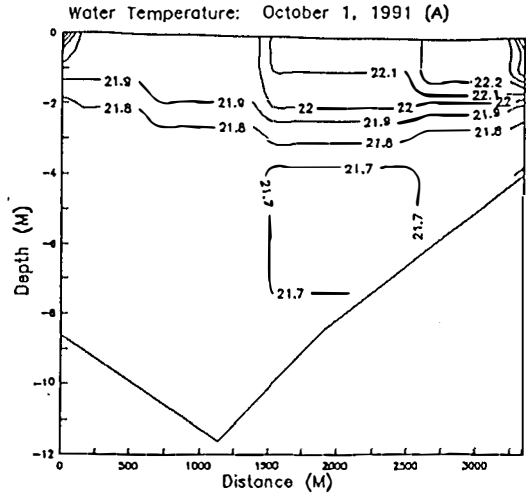
6. Plots of drogue depth and temperature, salinity, and density at the drogue as functions of time (IV-3-10 and IV-3-11).

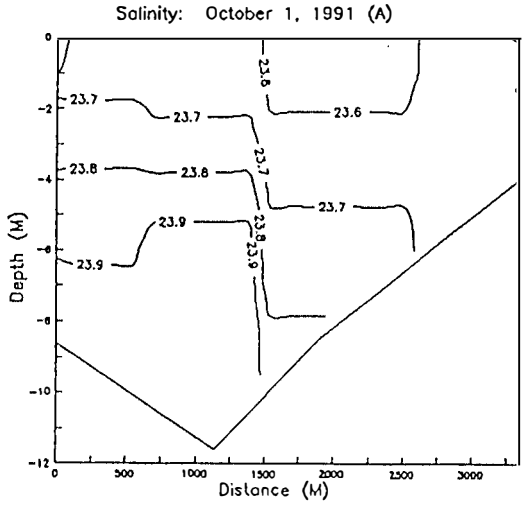


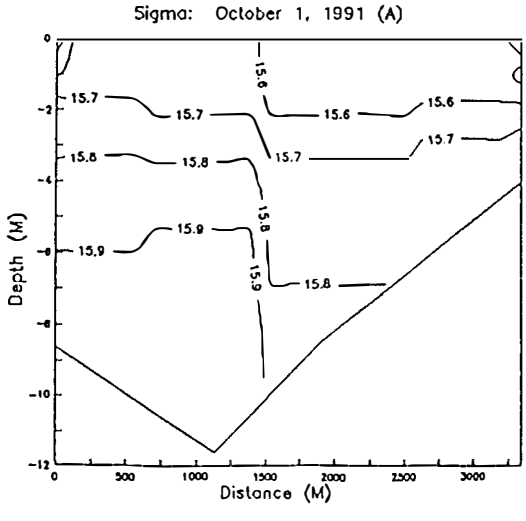
IV-3-1 Drogue track on 1 October 1991 (9.7 to 18.7 hr) with vertical tick marks indicating position at 10 minute intervals. Dashed lines and squares show transects with stations occupied by R/V Langley.



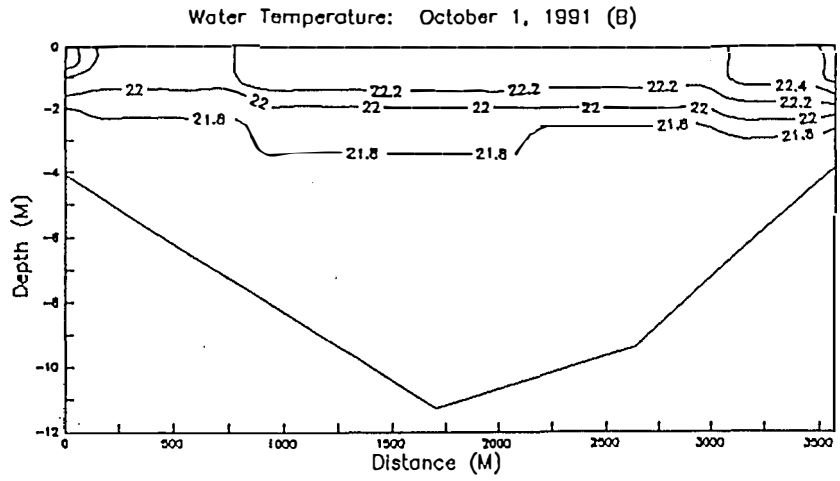
IV-3-2 Vertical structure of temperature, salinity, and density (σ) [top to bottom] as functions of time along the drogue trajectory.

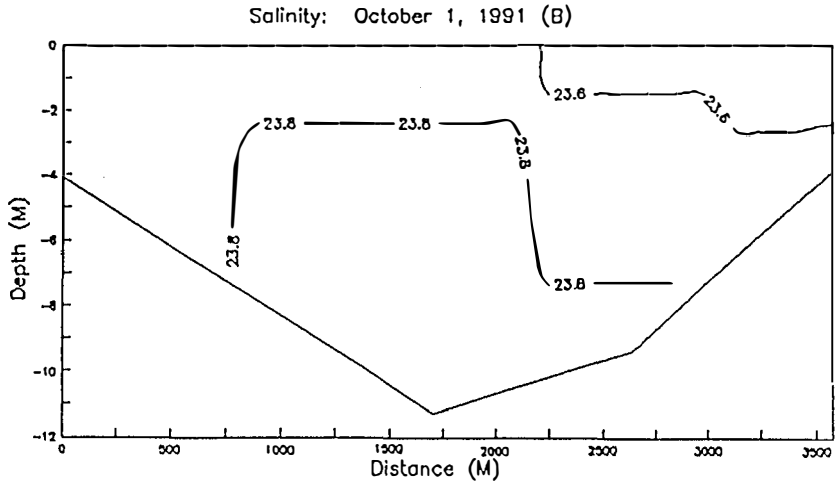


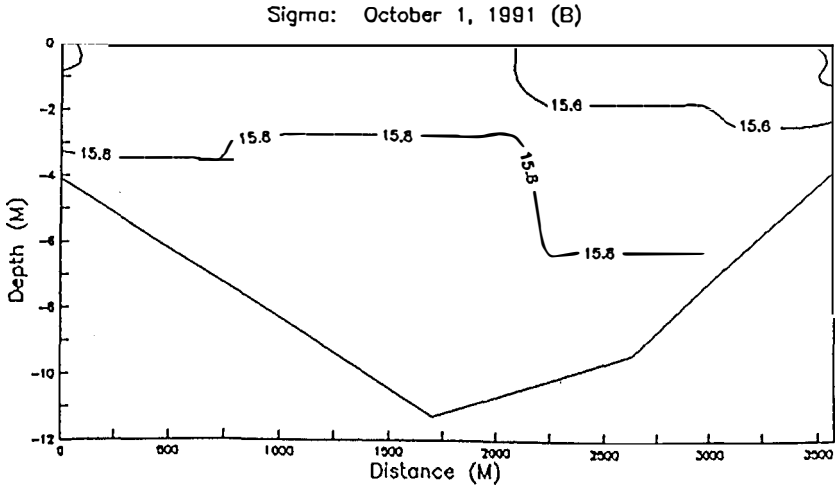




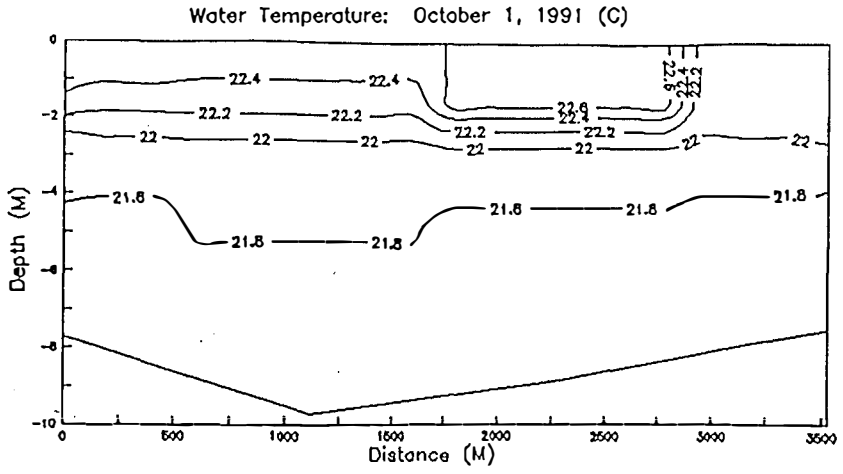
IV-3-3A Vertical structure of temperature, salinity, and density (top to bottom) along Langley transect A on 1 October 1991 (ref. IV-3-1). Viewer orientation is looking towards the Bay mouth (to the south-east).

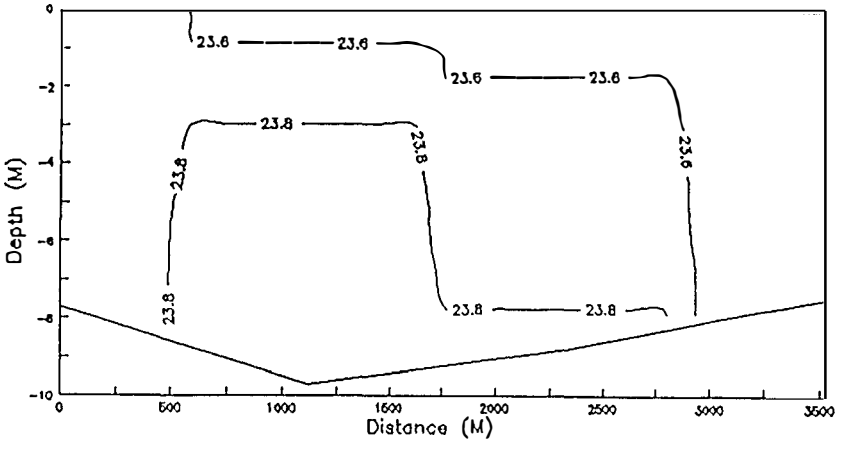


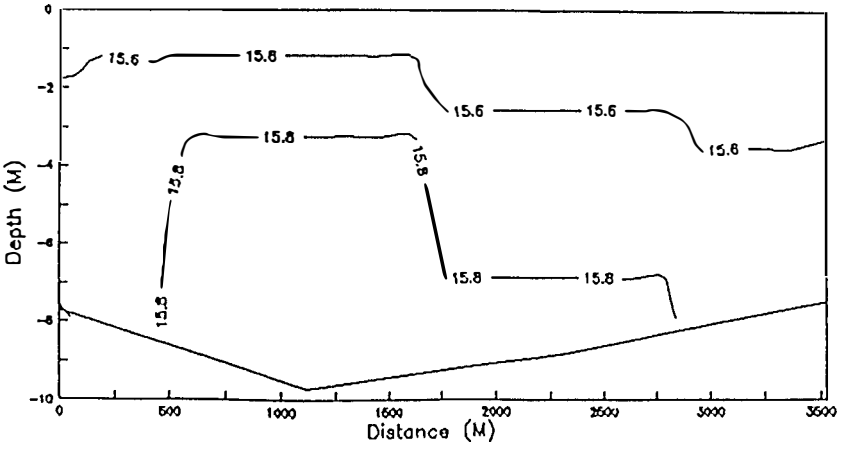




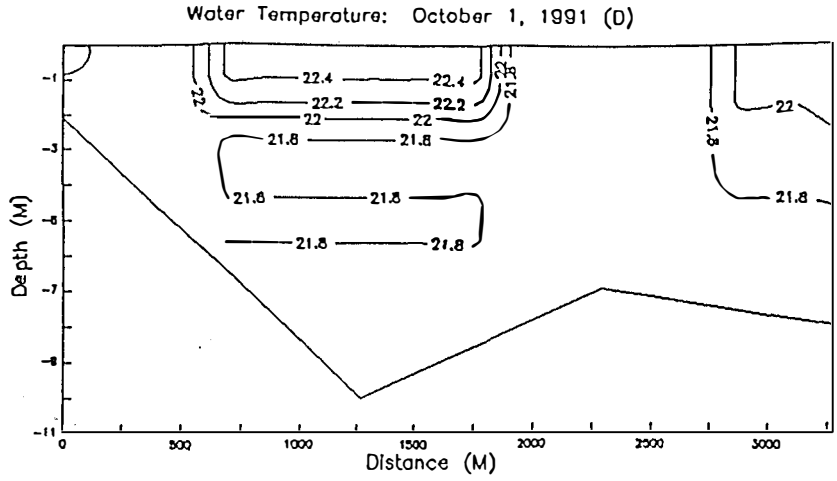
IV-3-3B Same as IV-3-3A except for transect B.

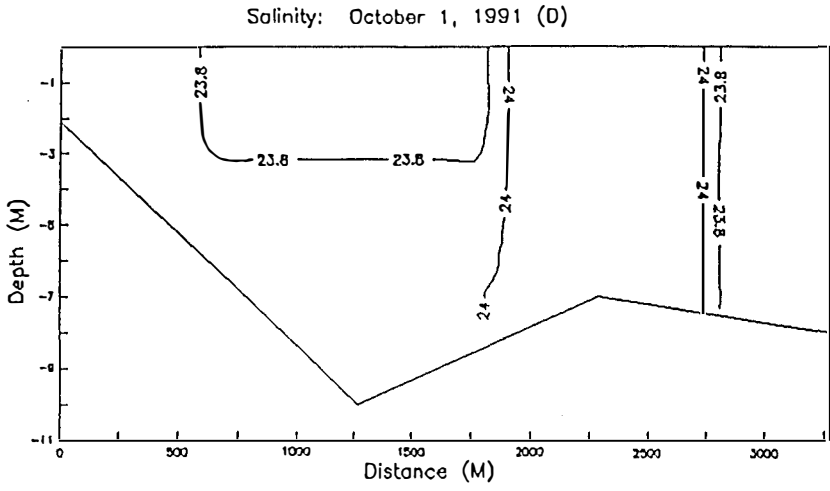


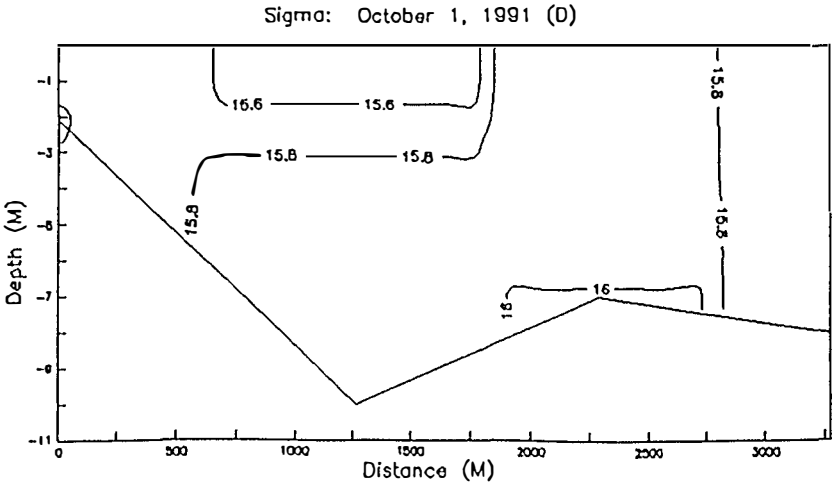




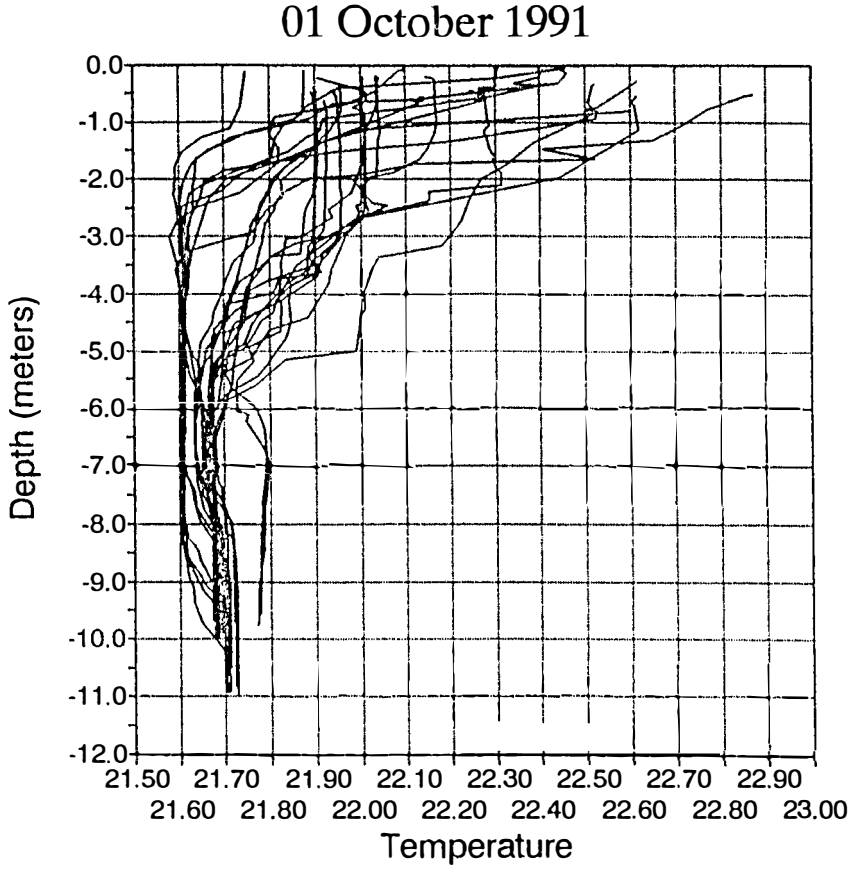
IV-3-3C Same as IV-3-3A except for transect C.



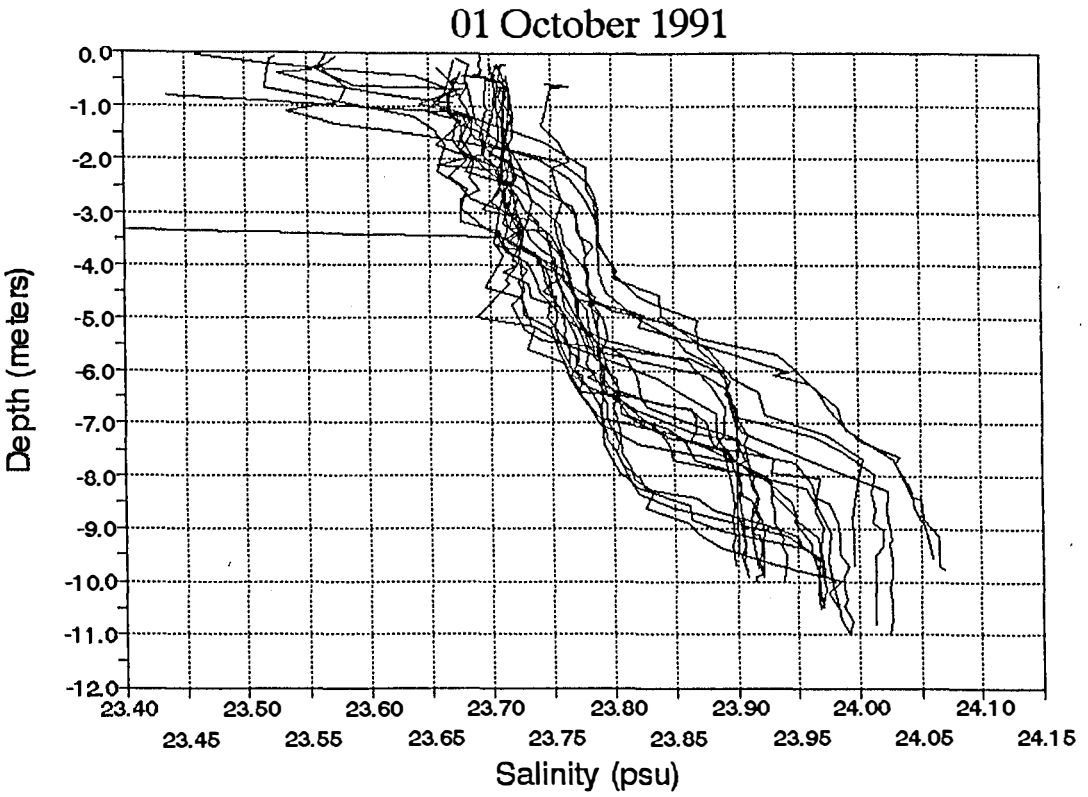




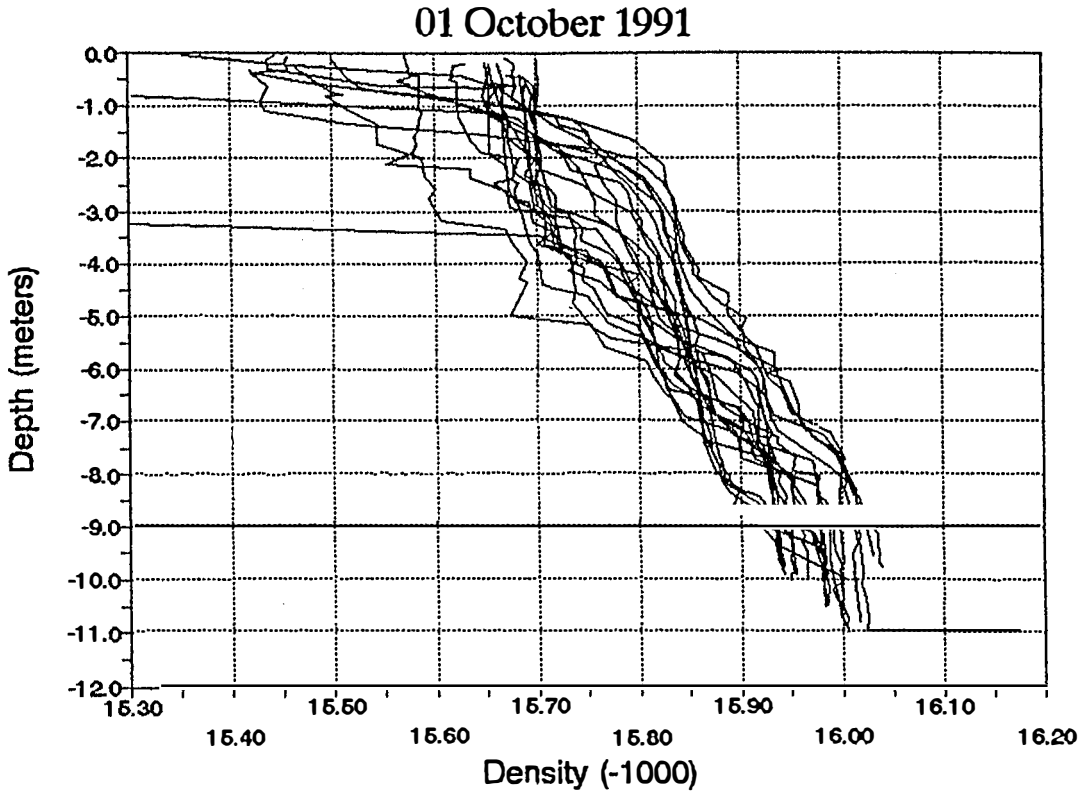
IV-3-3D Same as IV-3-3A except for transect D.



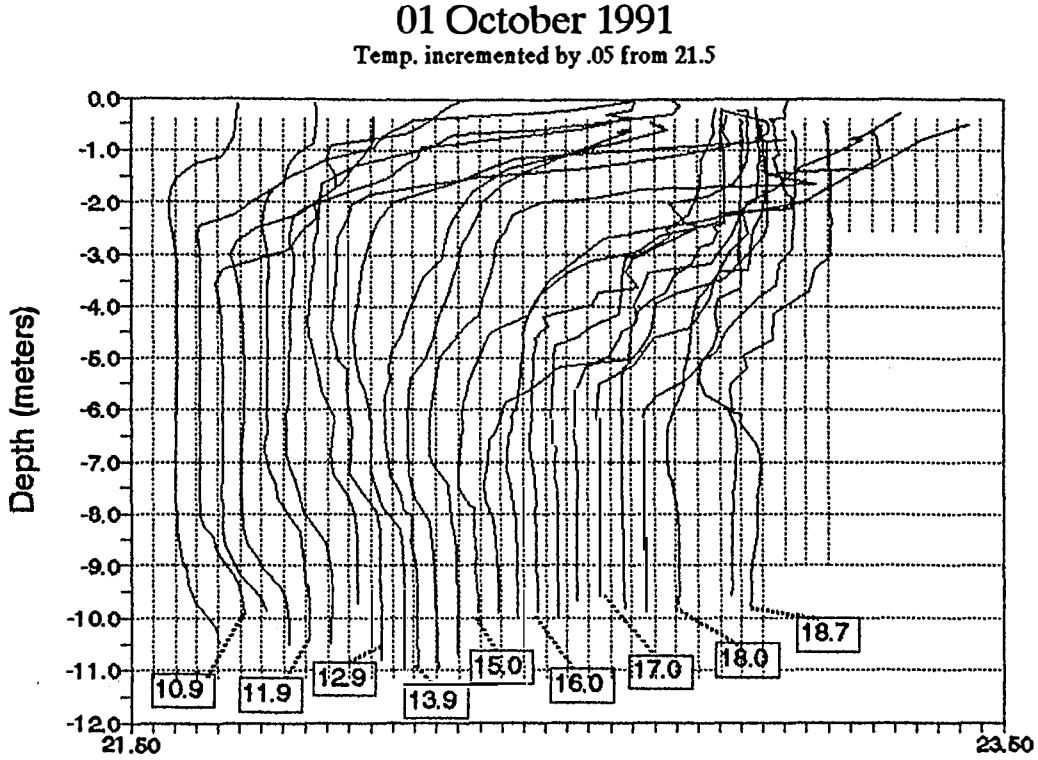
IV-3-4 Cluster plot of temperature with depth for stations sampled along drogue trajectory.



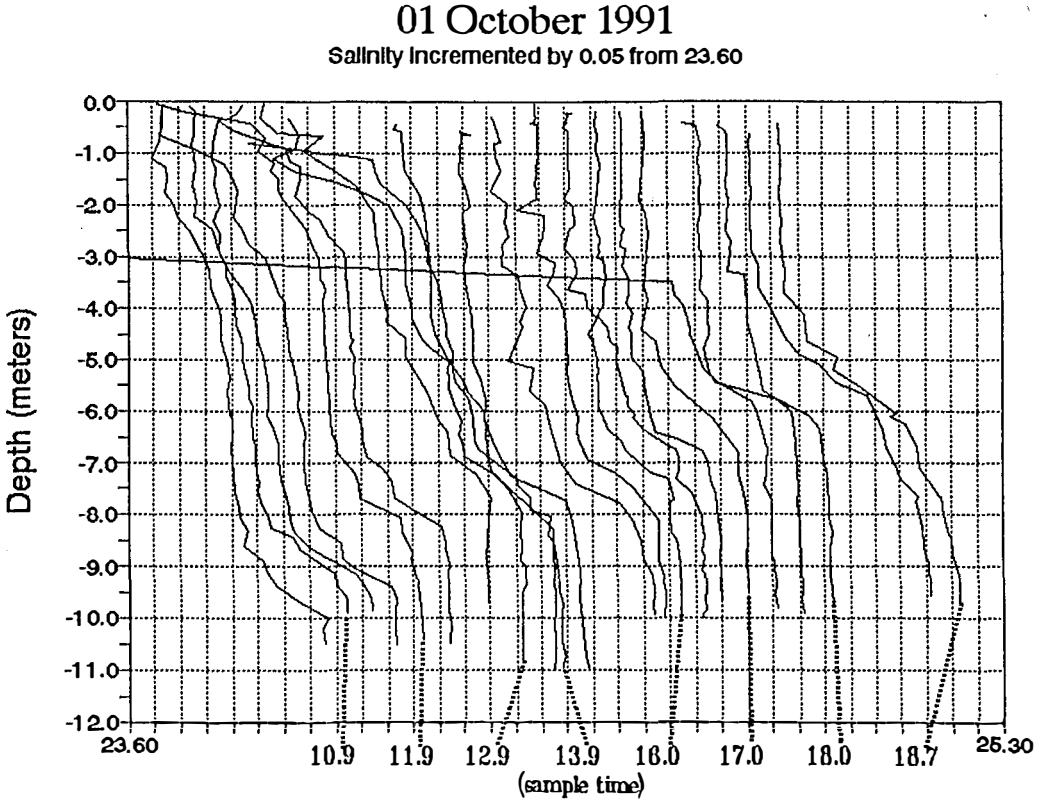
IV-3-5 Cluster plot of salinity with depth for stations sampled along drogue trajectory.



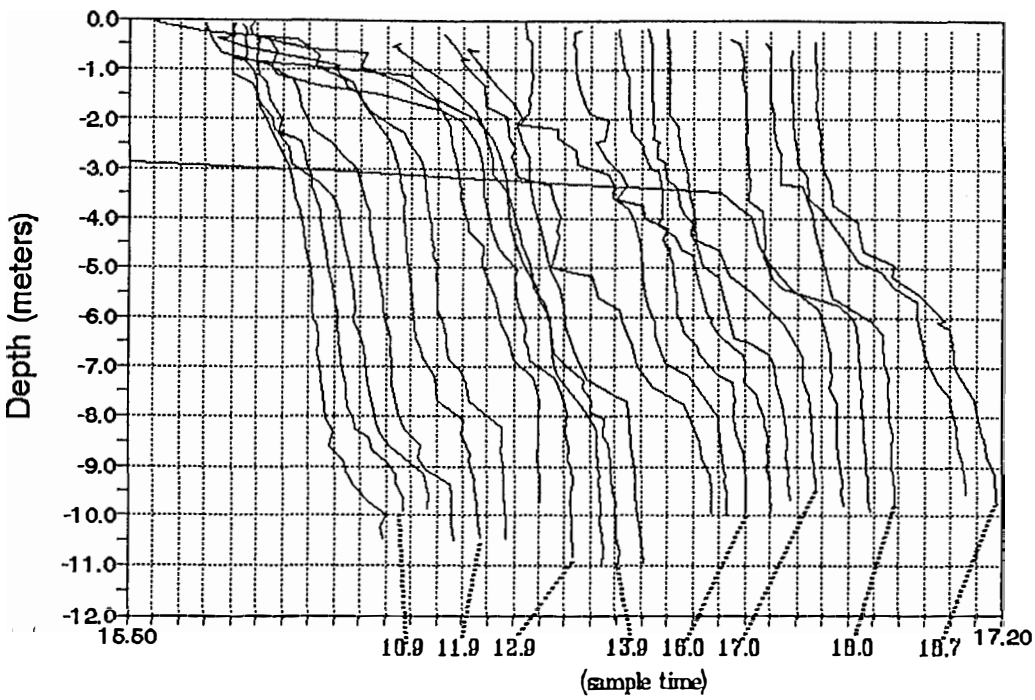
IV-3-6 Cluster plot of density with depth for stations sampled along drogue trajectory.



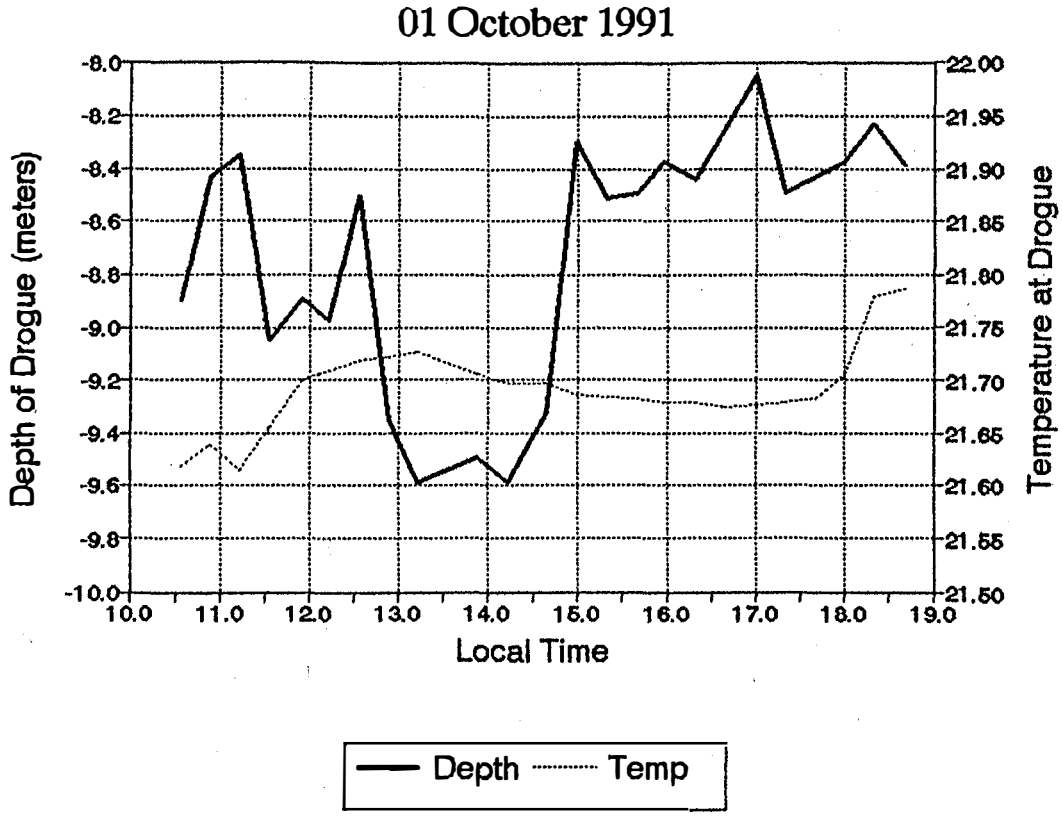
IV-3-7 Sequential plots of temperature with depth along drogue trajectory with offset of 0.05°C. Vertical lines associated with each plot indicate a temperature of 21.5°C.



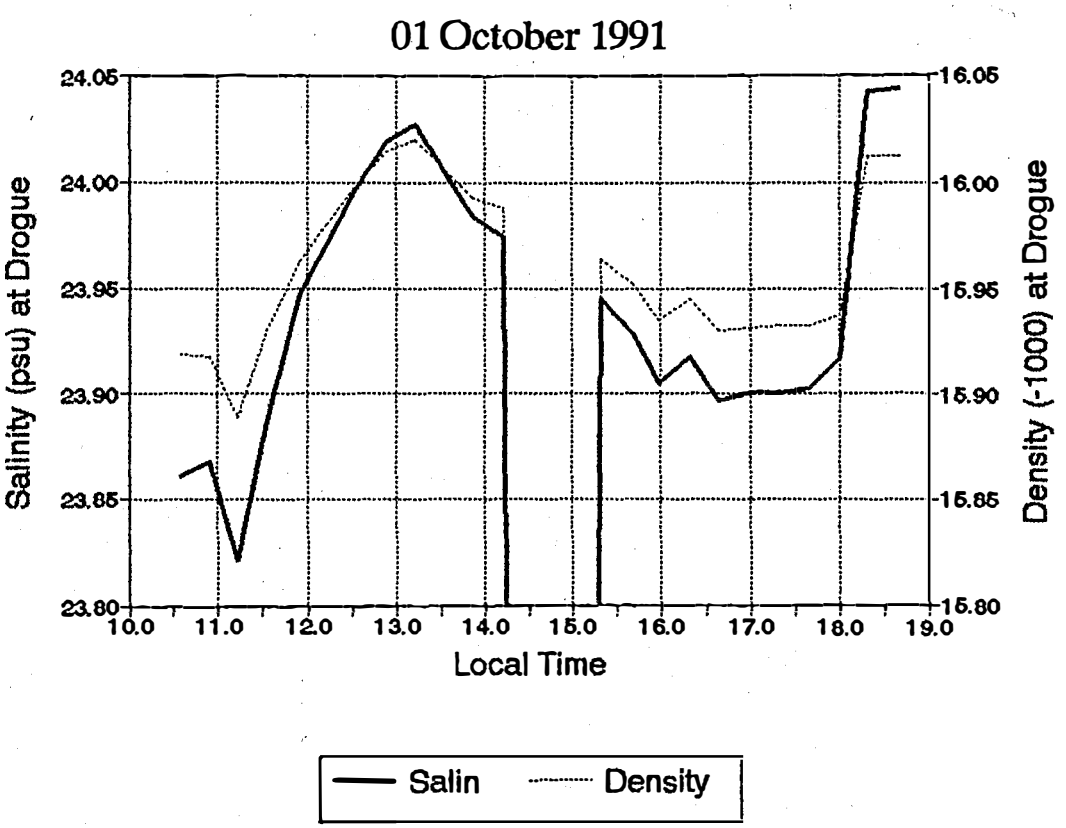
IV-3-8 Sequential plots of salinity with depth along drogue trajectory with offset of 0.05 psu. Vertical lines indicate salinity of 23.60 psu.



IV-3-9 Sequential plots of density with depth along drogue trajectory with offset of 0.05 kg m^{-3}.



IV-3-10 Temporal variations of drogue depth and temperature at drogue along its trajectory.



IV-3-11 Temporal variations of salinity and density at drogue depth along its trajectory. (Note that conductivity sensor may have malfunctioned between 14.3 and 15.3 hr.)

APPENDIX IV-4

3 OCTOBER 1991 DROGUE SET

This appendix consists of graphic presentations of data collected on 3 October 1991 as part of the drogue experiment on that date. The following are illustrated:

1. Drogue position as a function of time with transect stations occupied by R/V Langley (IV-4-1).

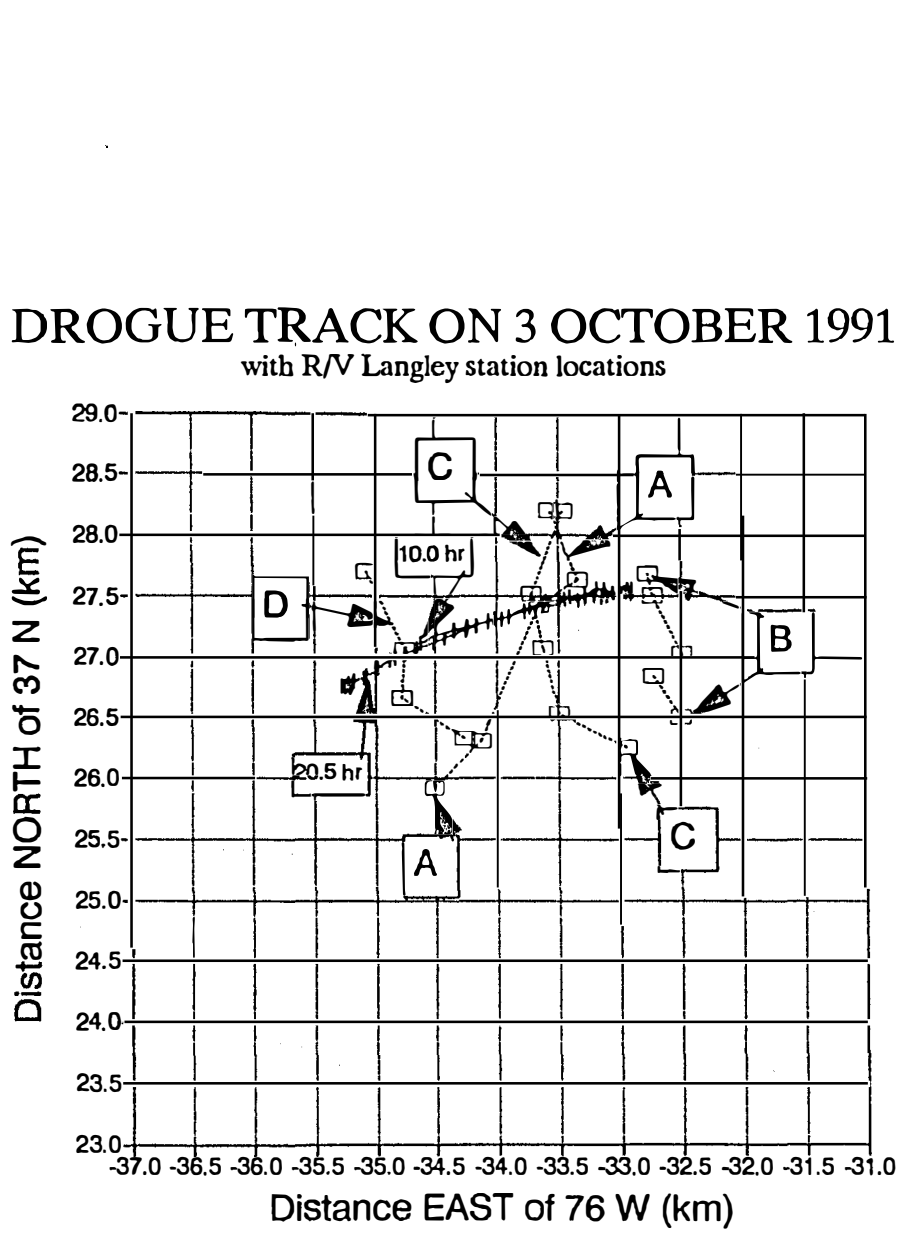
2. Vertical distributions of temperature, salinity, and density as functions of time along the drogue track (IV-4-2).

3. Temperature, salinity, and density as functions of depth and distance along the Langley transects (IV-4-3A through IV-4-3D).

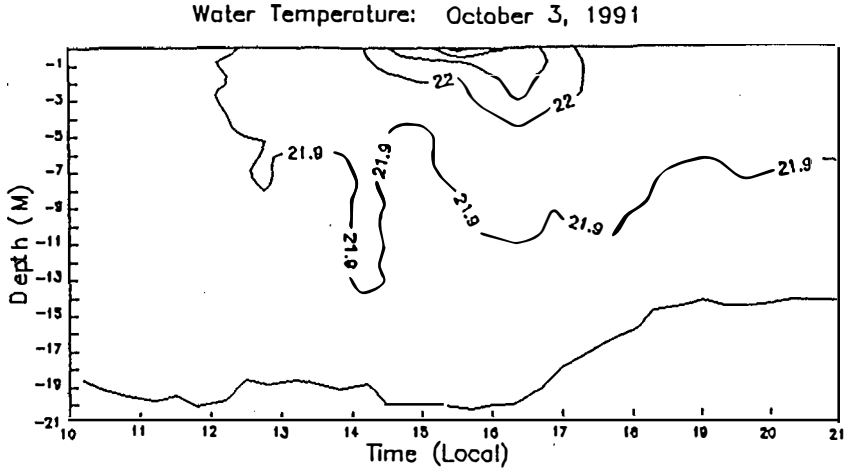
4. Cluster plots of temperature, salinity, and density vs depth at 20 minute intervals along the drogue trajectory (IV-4-4 through IV-4-6).

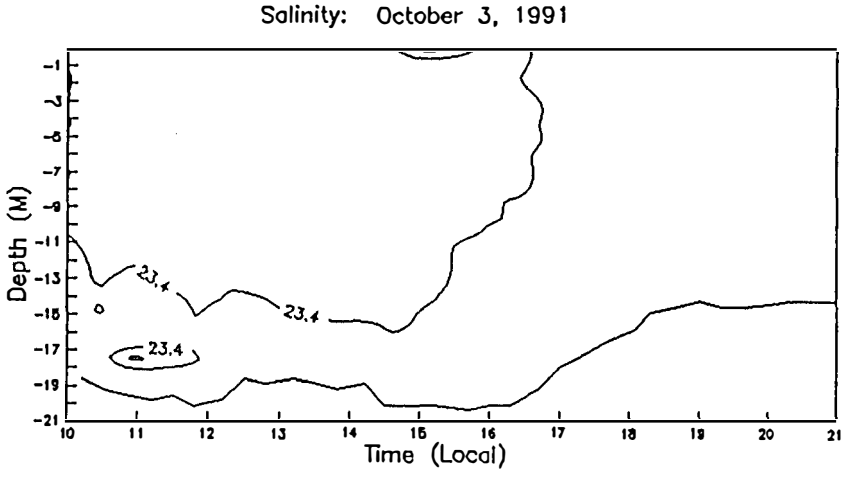
5. Individual plots of temperature, salinity , and density vs depth incremented by 0.05 parameter unit (IV-4-7 through IV-4-9).

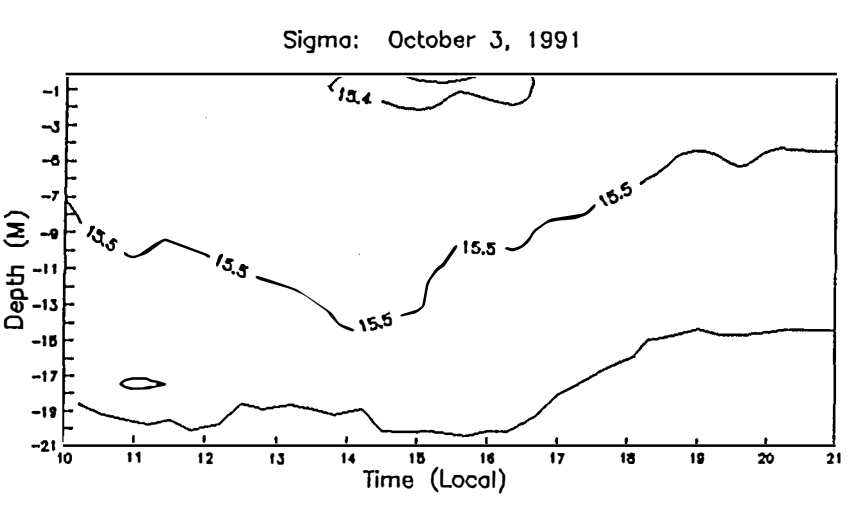
6. Plots of drogue depth and temperature, salinity, and density at the drogue as functions of time (IV-4-10 and IV-4-11).



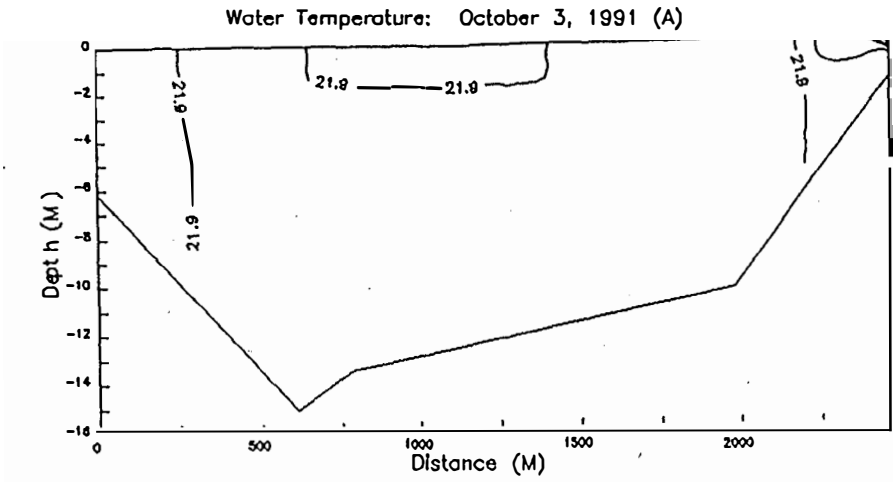
IV-4-1 Drogue track on 3 October 1991 (10.00 to 20.52 hr) with vertical tick marks indicating position at 10 minute intervals. Dashed lines and squares show transects with stations occupied by R/V Langley.

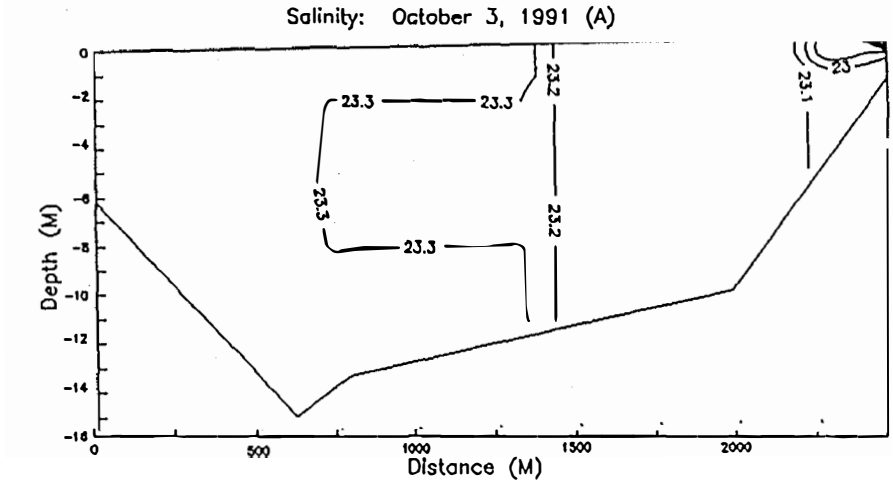


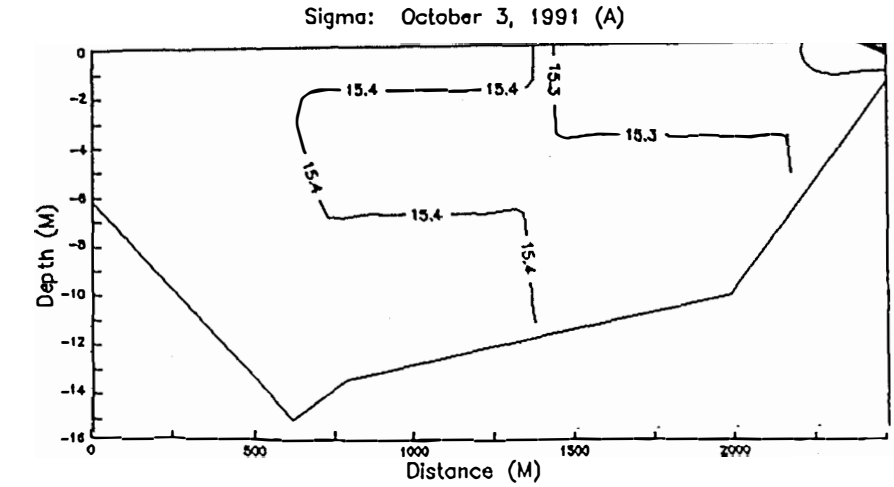




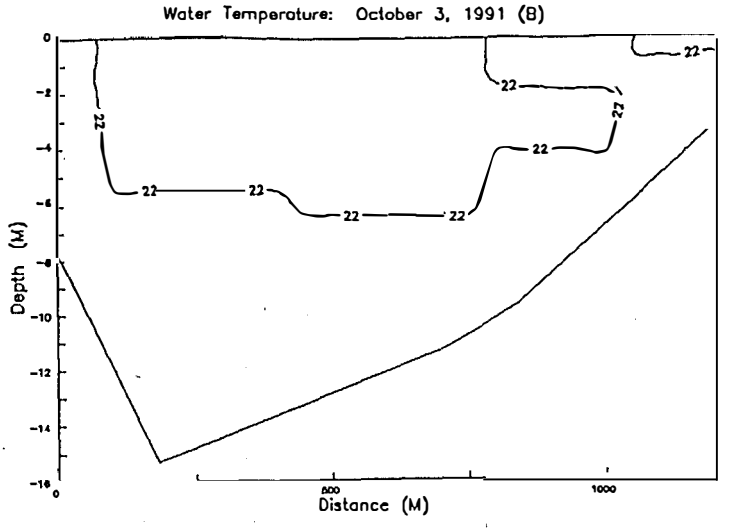
IV-4-2 Vertical structure of temperature, salinity, and density (σ) [top to bottom] as functions of time along the drogue trajectory.



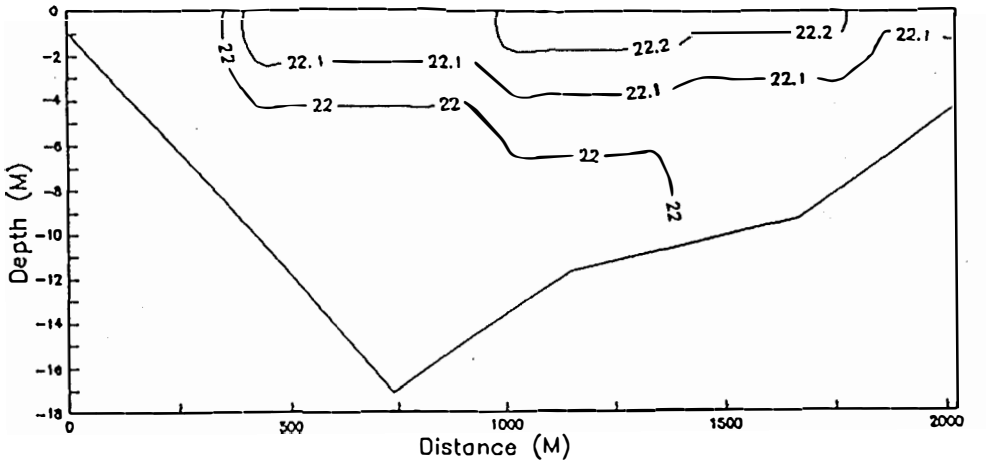




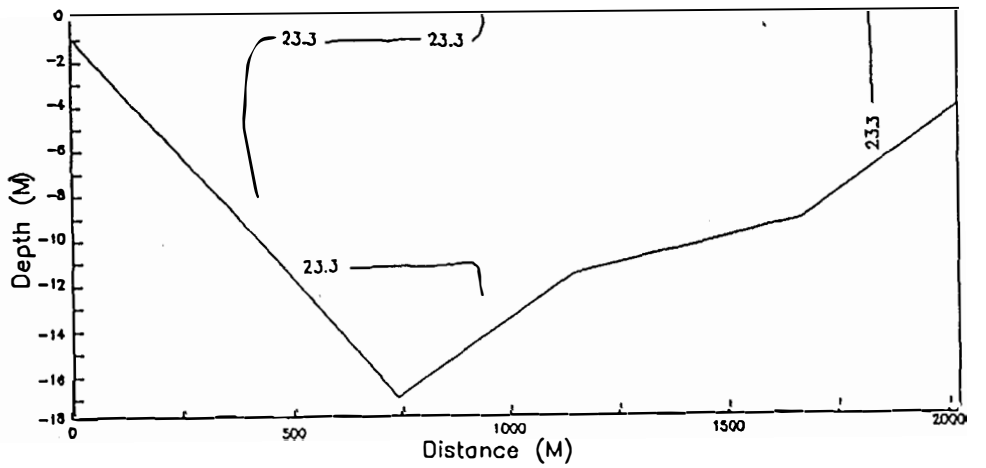
IV-4-3A Vertical structure of temperature, salinity, and density (top to bottom) along Langley transect A on 1 October 1991 (ref. IV-4-1). Viewer orientation is looking out of the York mouth (to the East).


Water Temperature: October 3, 1991 (B)
Depth (M)
Distance (M)
22
22
22

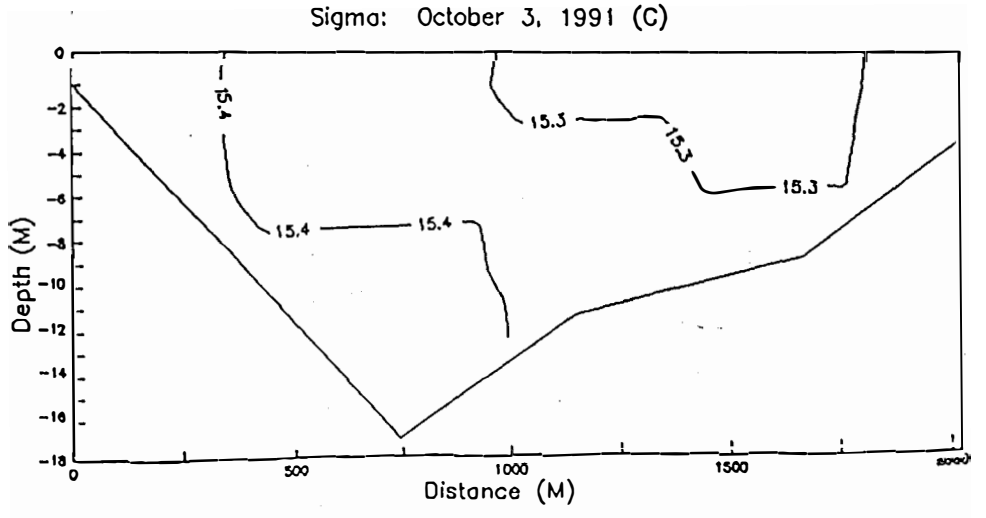
Water Temperature: October 3, 1991 (C)



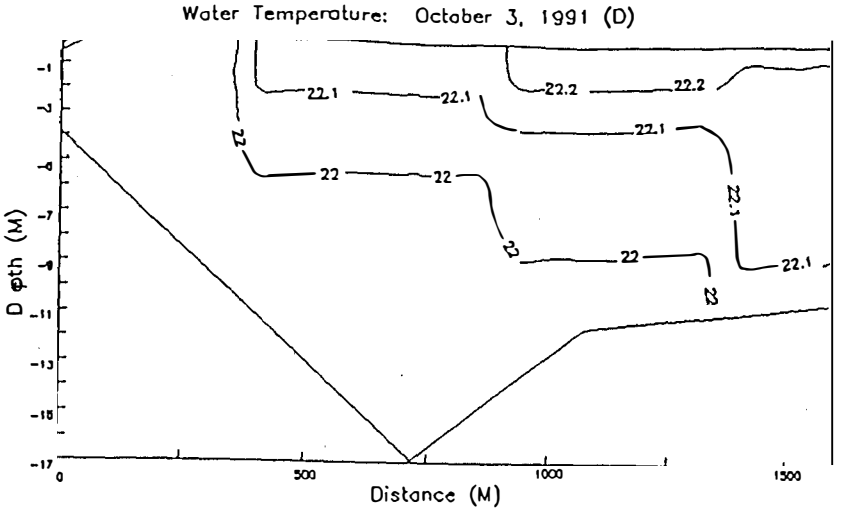
Salinity: October 3, 1991 (C)

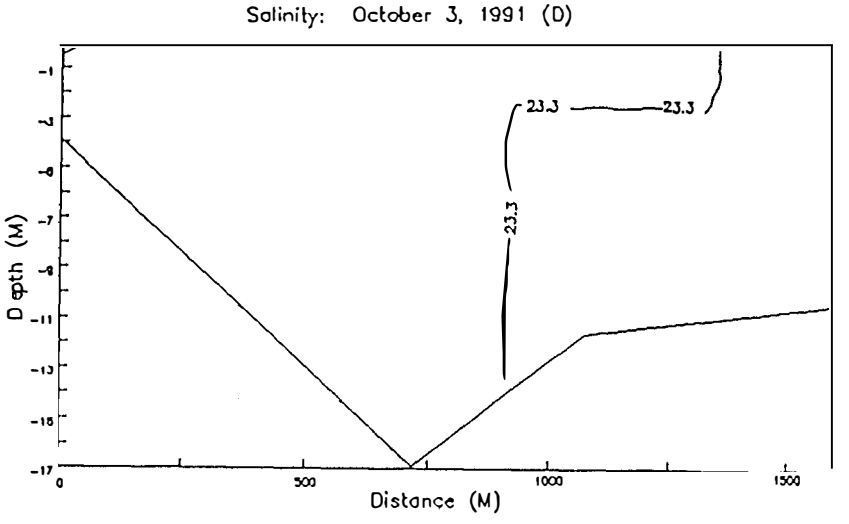


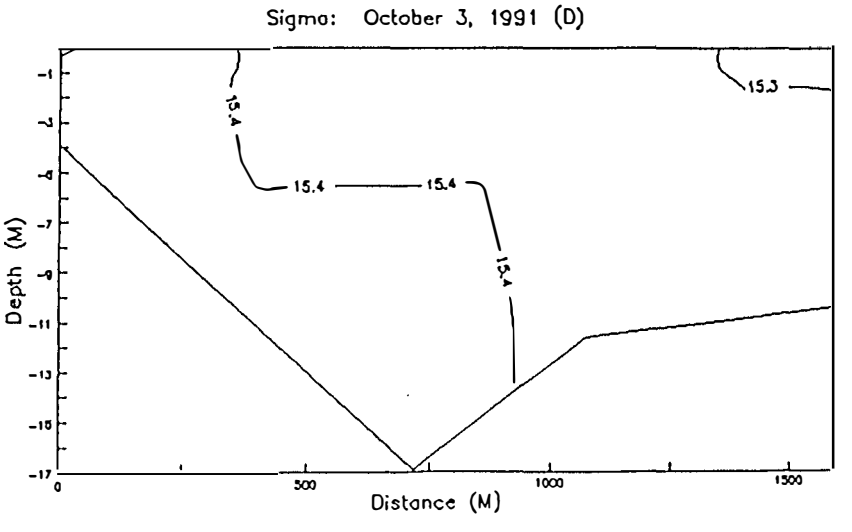
Sigma: October 3, 1991 (C)



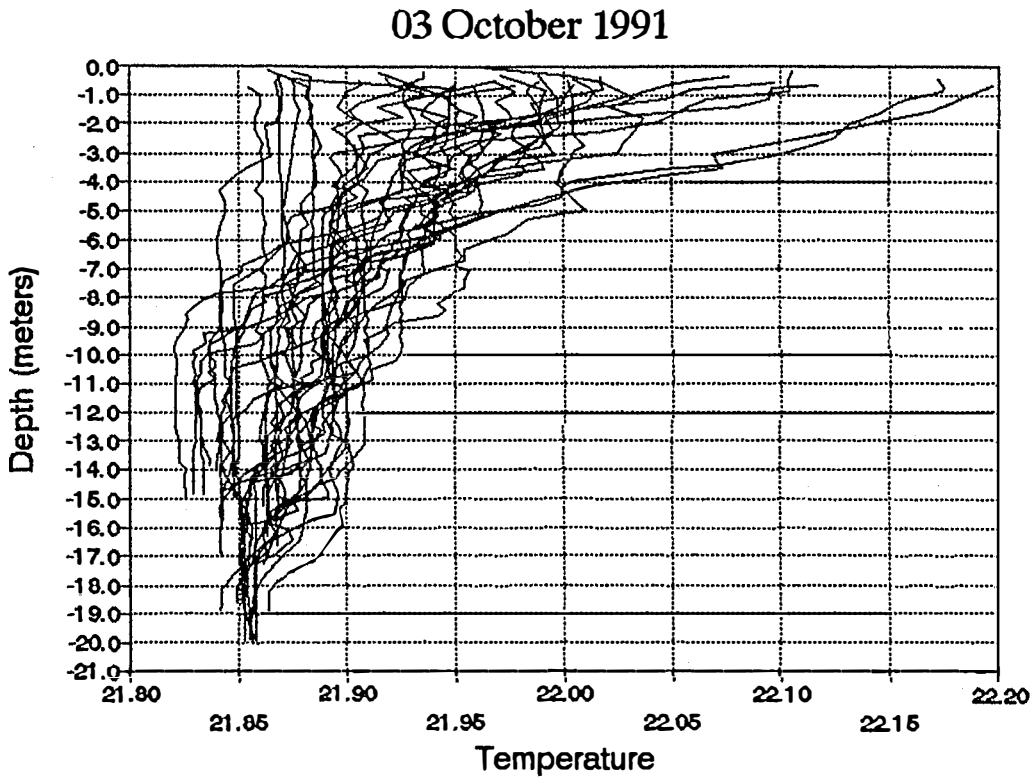
IV-4-3C Same as IV-4-3A except for transect C.



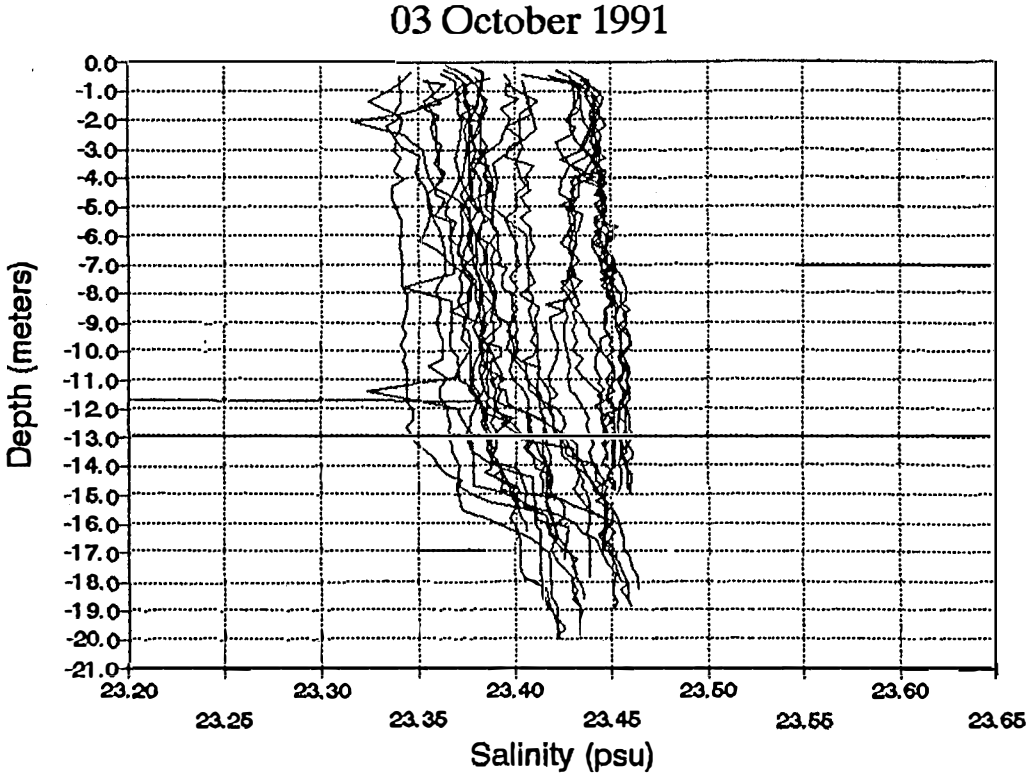




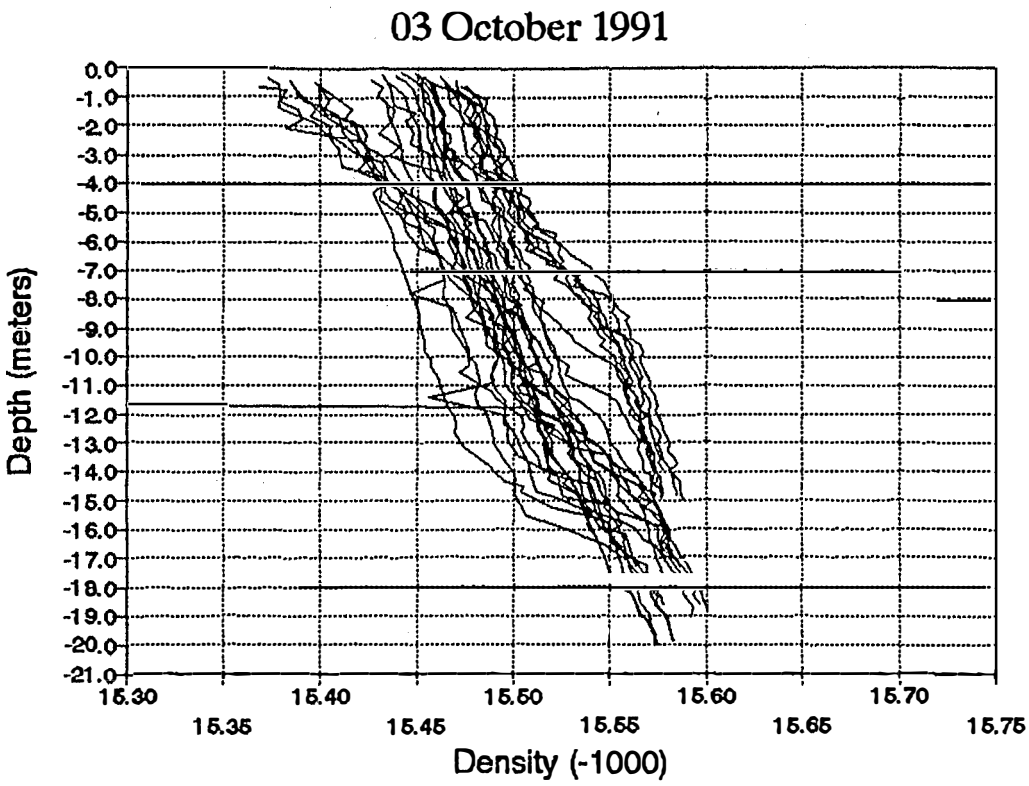
IV-4-3D Same as IV-4-3A except for transect D.



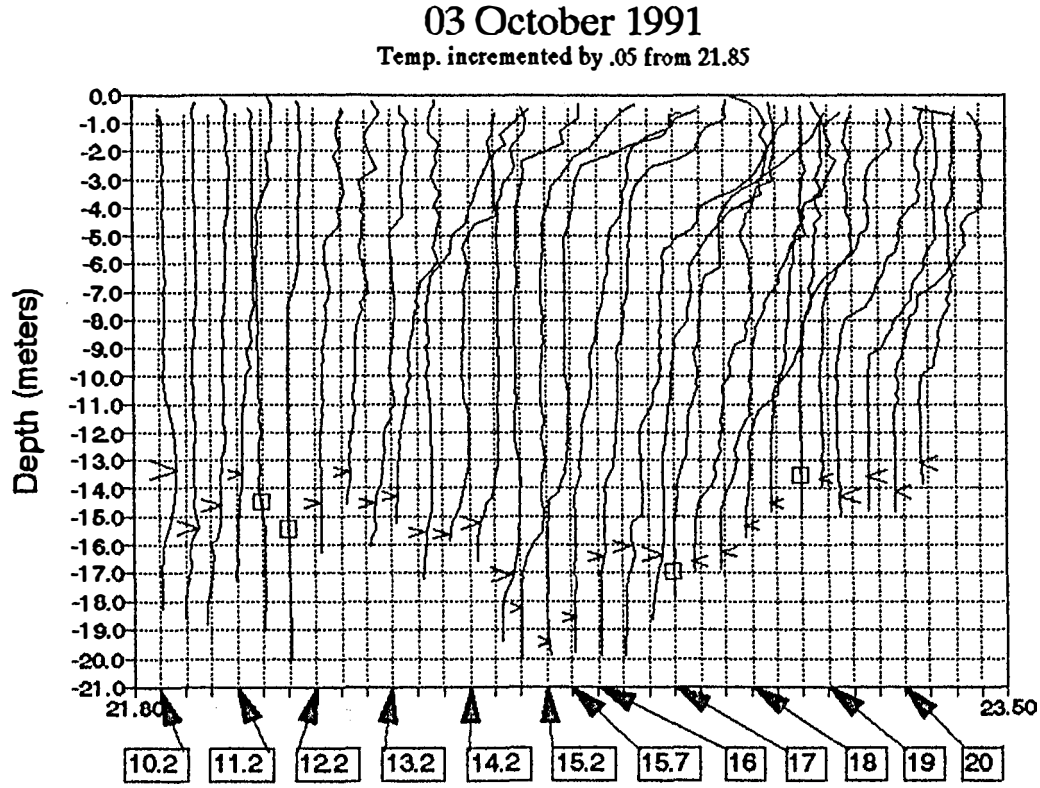
IV-4-4 Cluster plot of temperature with depth for stations sampled along drogue trajectory.



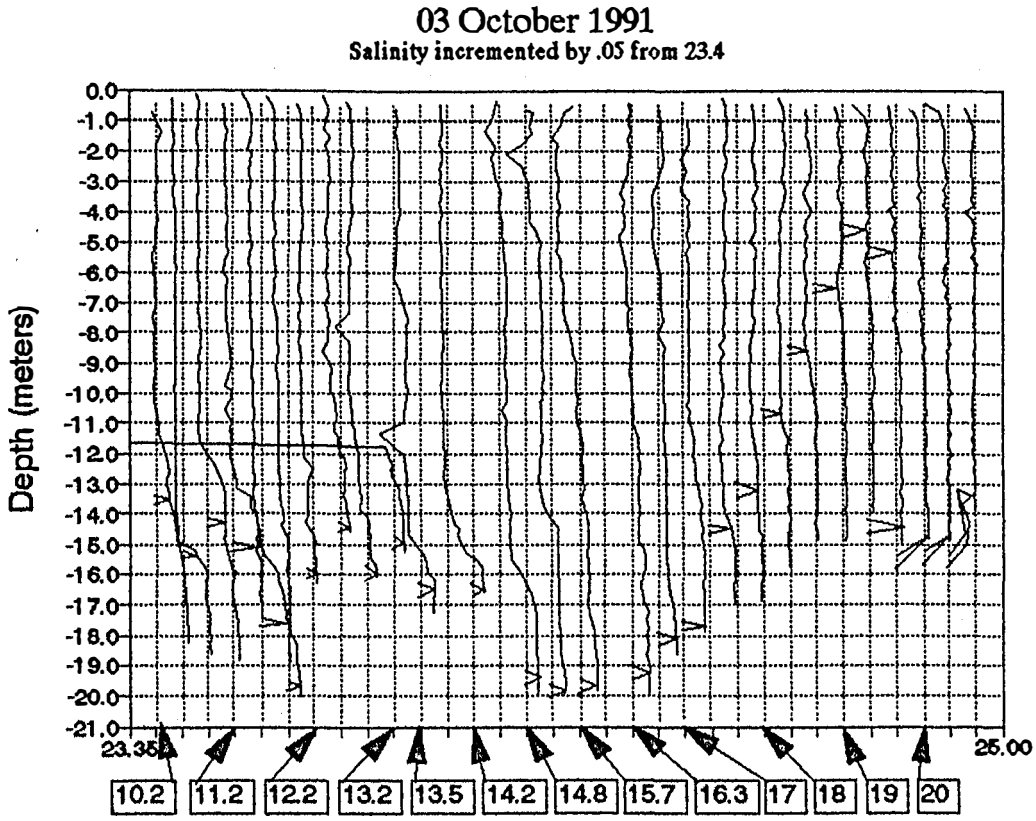
IV-4-5 Cluster plot of salinity with depth for stations sampled along drogue trajectory.



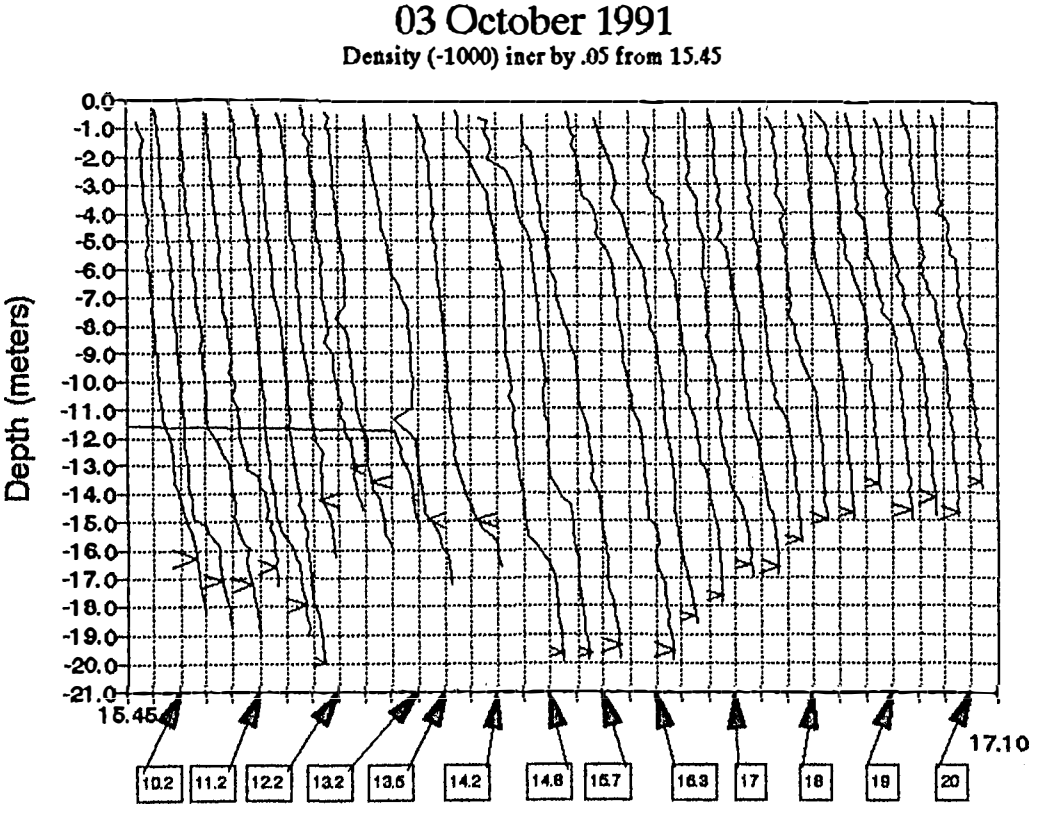
IV-4-6 Cluster plot of density with depth for stations sampled along drogue trajectory.



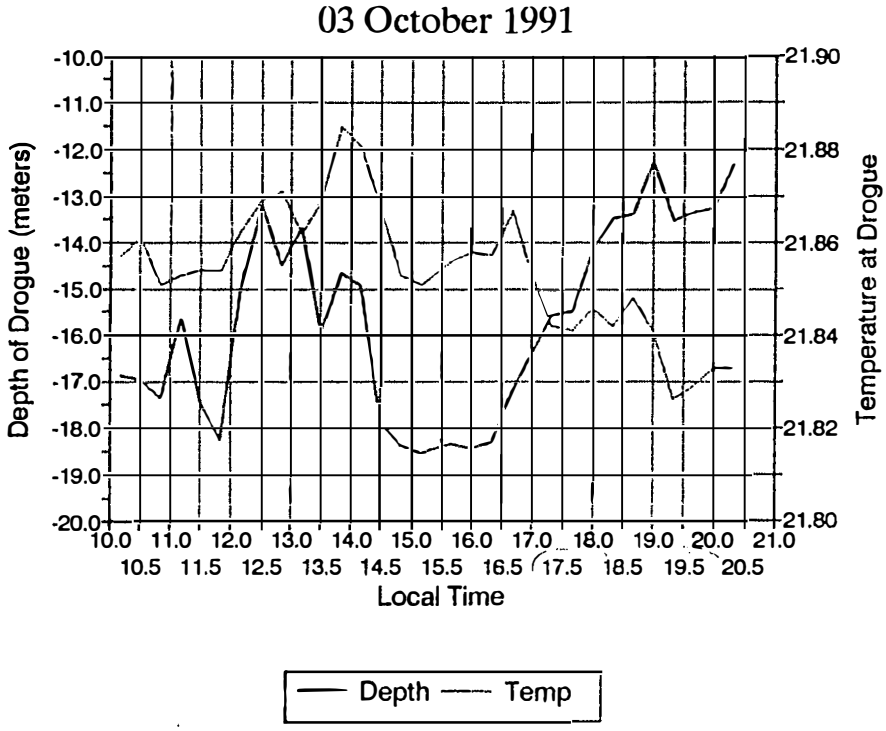
IV-4-7 Sequential plots of temperature with depth along drogue trajectory with offset of 0.05°C. Vertical lines associated with each plot indicate a temperature of 21.80°C.



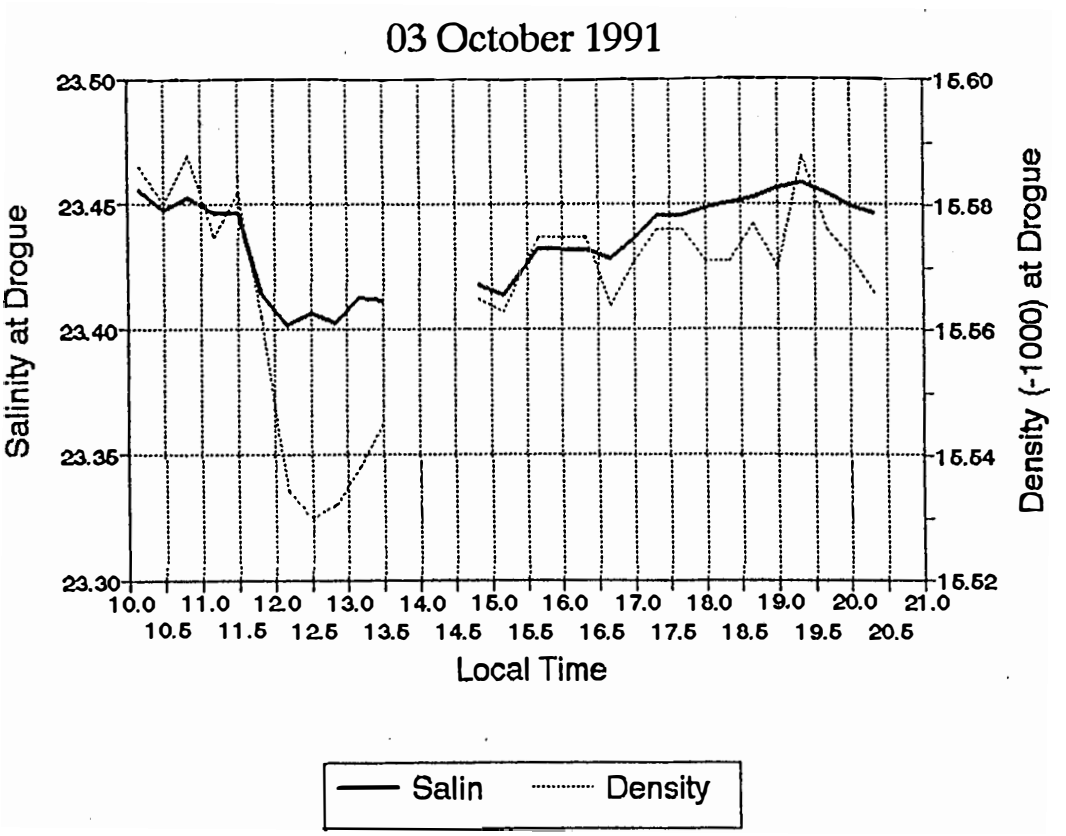
IV-4-8 Sequential plots of salinity with depth along drogue trajectory with offset of 0.05 psu. Vertical lines indicate salinity of 23.40 psu.



IV-4-9 Sequential plots of density with depth along drogue trajectory with offset of 0.05 kg m^{-3}. Vertical lines with arrows pointing to plots indicate a density of 1015.55 kg m^{-3}.



IV-4-10 Temporal variations of drogue depth and temperature at drogue along its trajectory.



IV-4-11 Temporal variations of salinity and density at drogue depth along its trajectory. (Note that conductivity sensor may have malfunctioned between 13.5 and 14.7 hr.)

APPENDIX IV-5

10 OCTOBER 1991 DROGUE SET

This appendix consists of graphic presentations of data collected on 10 October 1991 as part of the drogue experiment on that date. The following are illustrated:

1. Drogue position as a function of time with transect stations occupied by R/V Langley (IV-5-1).

2. Vertical distributions of temperature, salinity, and density as functions of time along the drogue track (IV-5-2).

3. Temperature, salinity, and density as functions of depth and distance along the Langley transects (IV-5-3A through IV-5-3C).

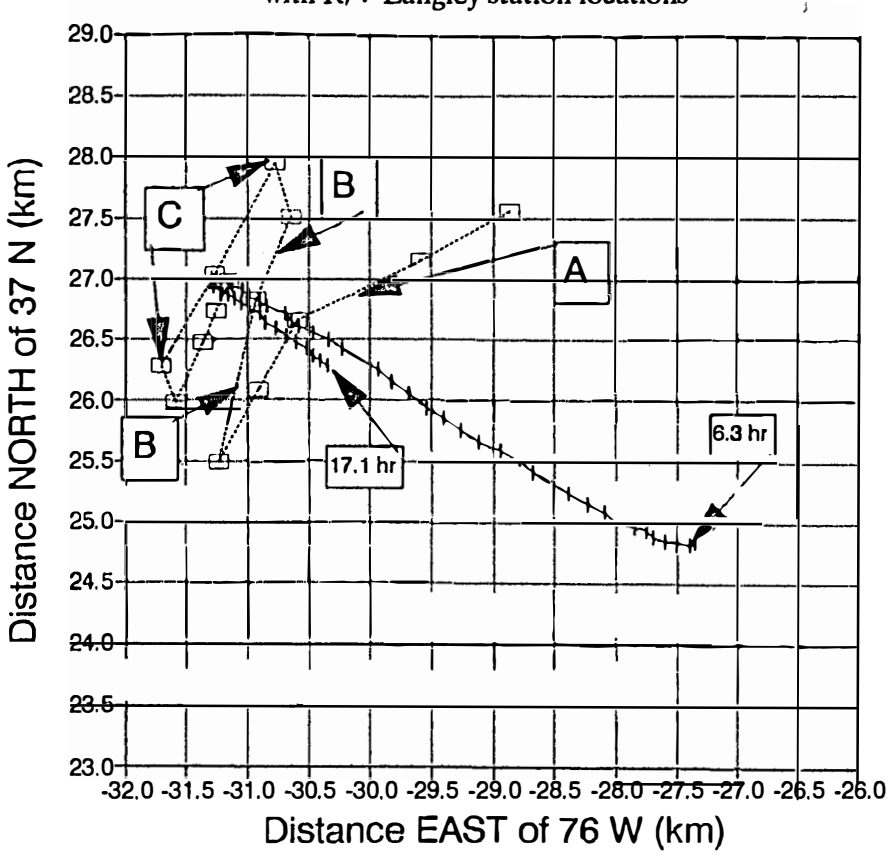
4. Cluster plots of temperature, salinity, and density vs depth at 20 minute intervals along the drogue trajectory (IV-5-4 through IV-5-6).

5. Individual plots of temperature, salinity, and density vs depth incremented by 0.05 parameter unit (IV-5-7 through IV-5-9).

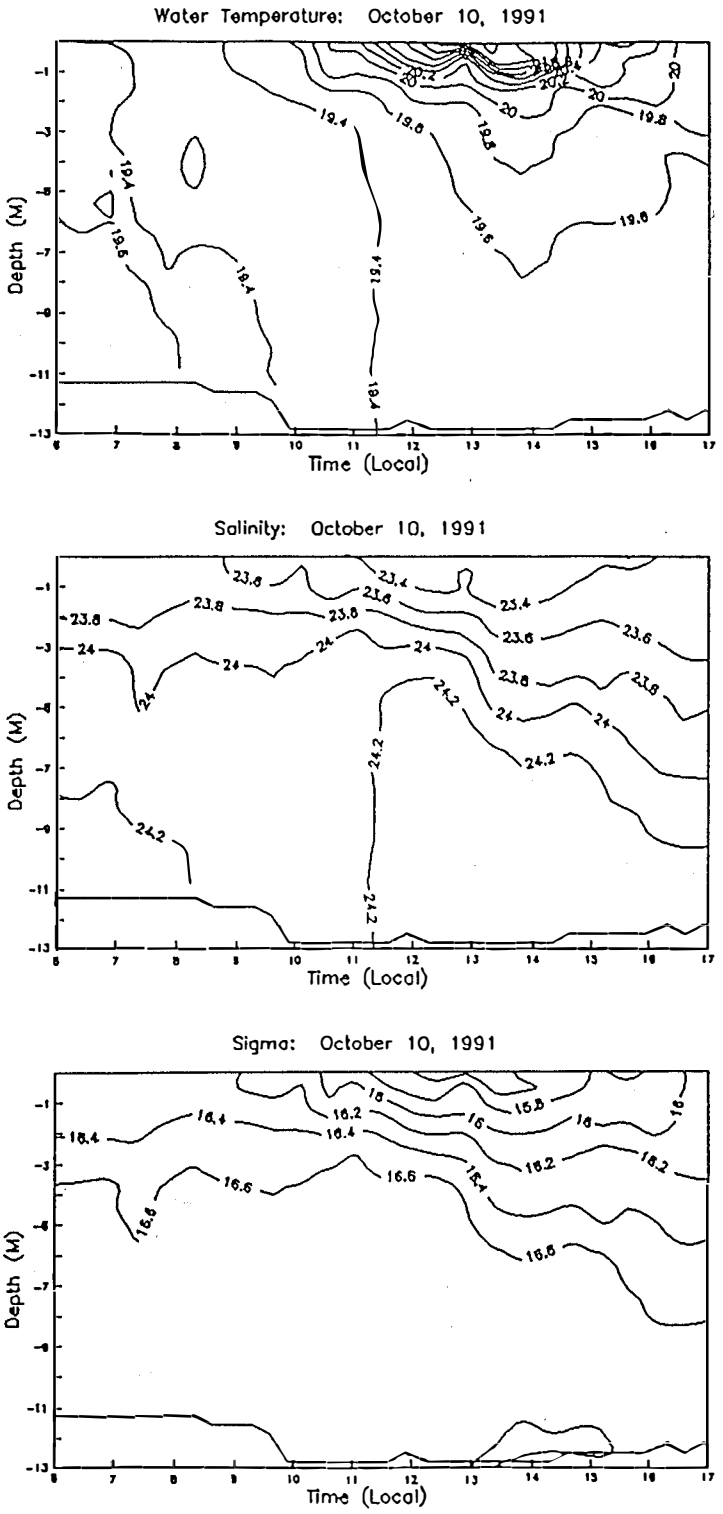
6. Plots of drogue depth and temperature, salinity, and density at the drogue as functions of time (IV-5-10 and IV-5-11).

DROGUE TRACK ON 10 OCTOBER 1991

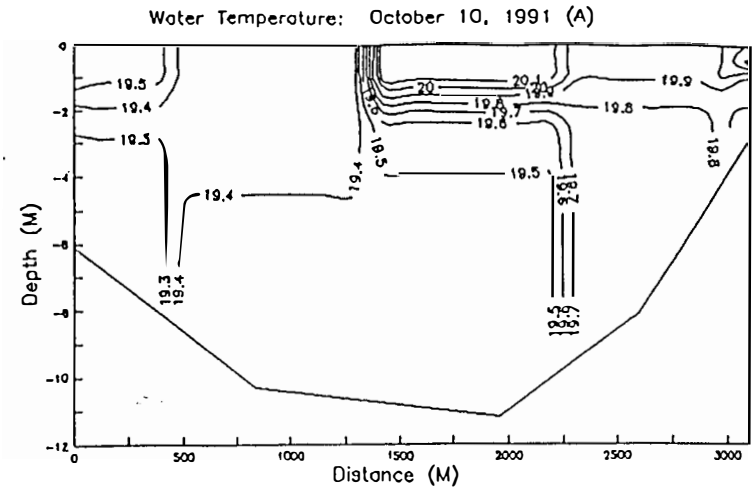
with R/V Langley station locations

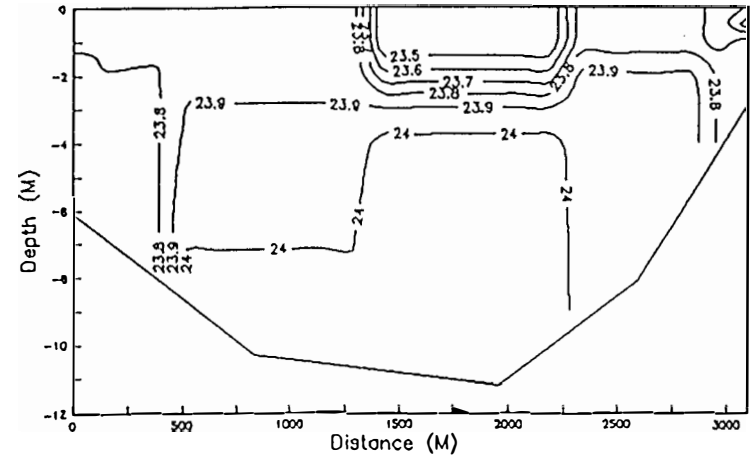


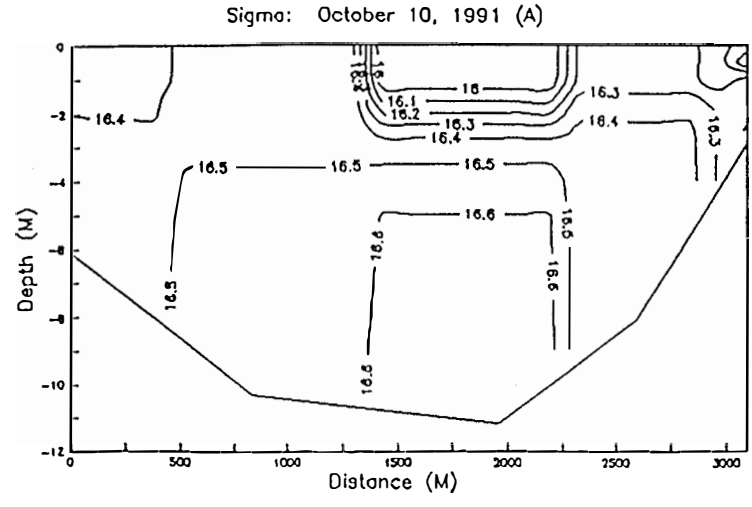
IV-5-1 Drogue track on 10 October 1991 (6.29 to 17.08 hr) with vertical tick marks indicating position at 10 minute intervals. Dashed lines and squares show transects with stations occupied by R/V Langley.



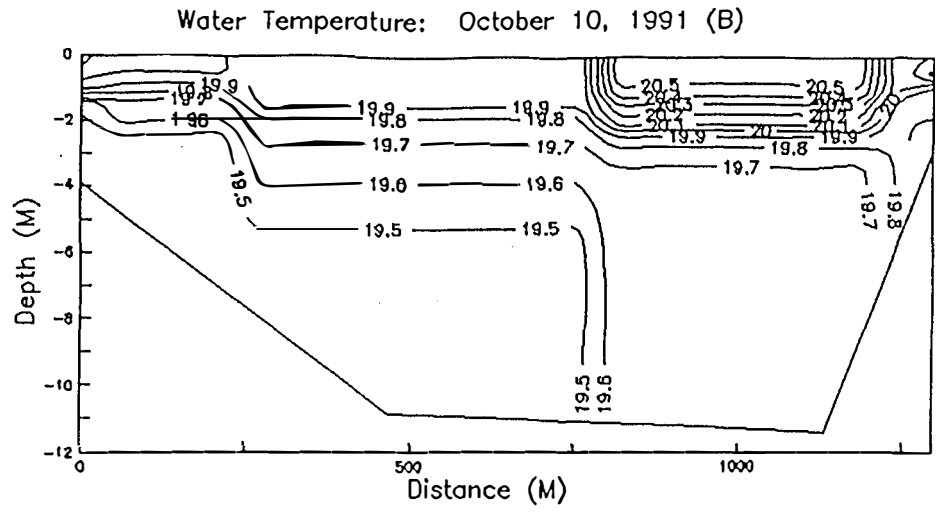
IV-5-2 Vertical structure of temperature, salinity, and density (σ) [top to bottom] as functions of time along the drogue trajectory.

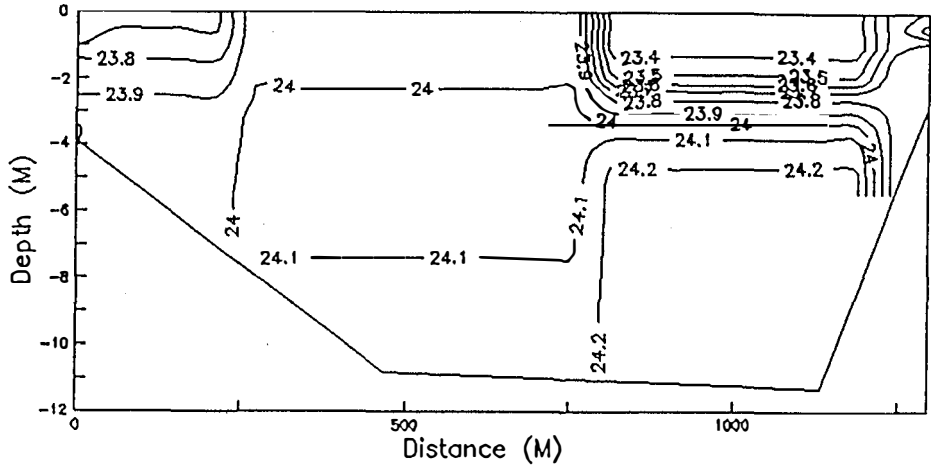


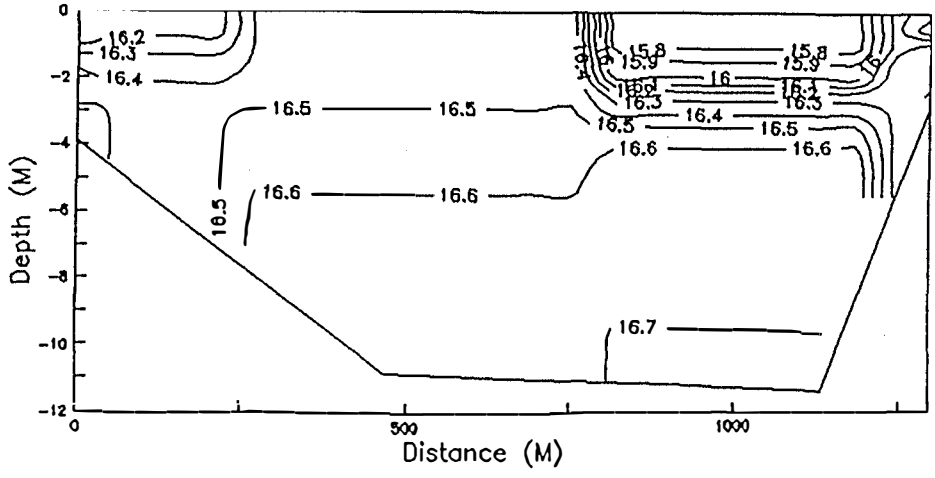




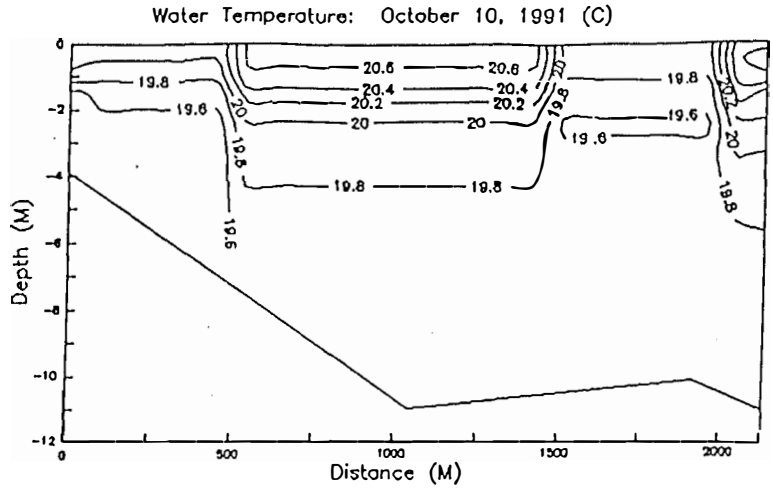
IV-5-3A Vertical structure of temperature, salinity, and density (top to bottom) along Langley transect A on 10 October 1991 (ref. IV-5-1). Viewer orientation is looking towards the Bay mouth (to the south-east).

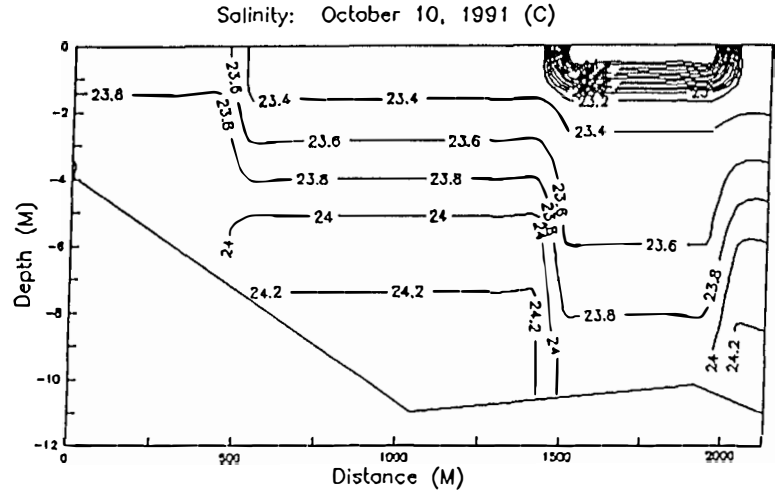


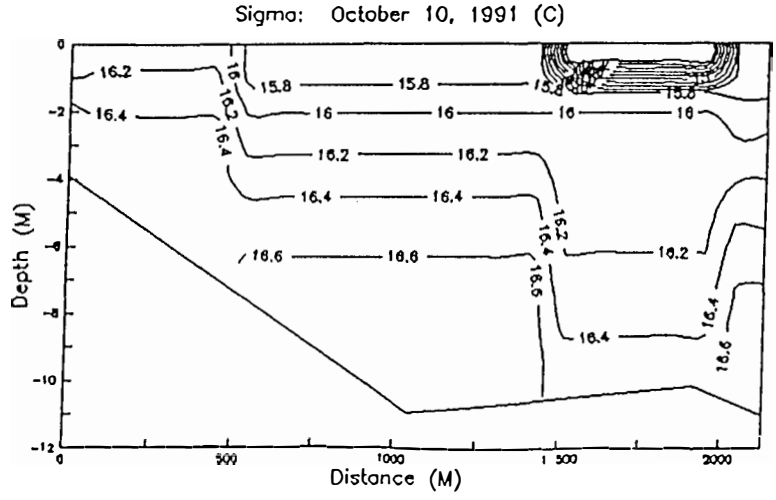




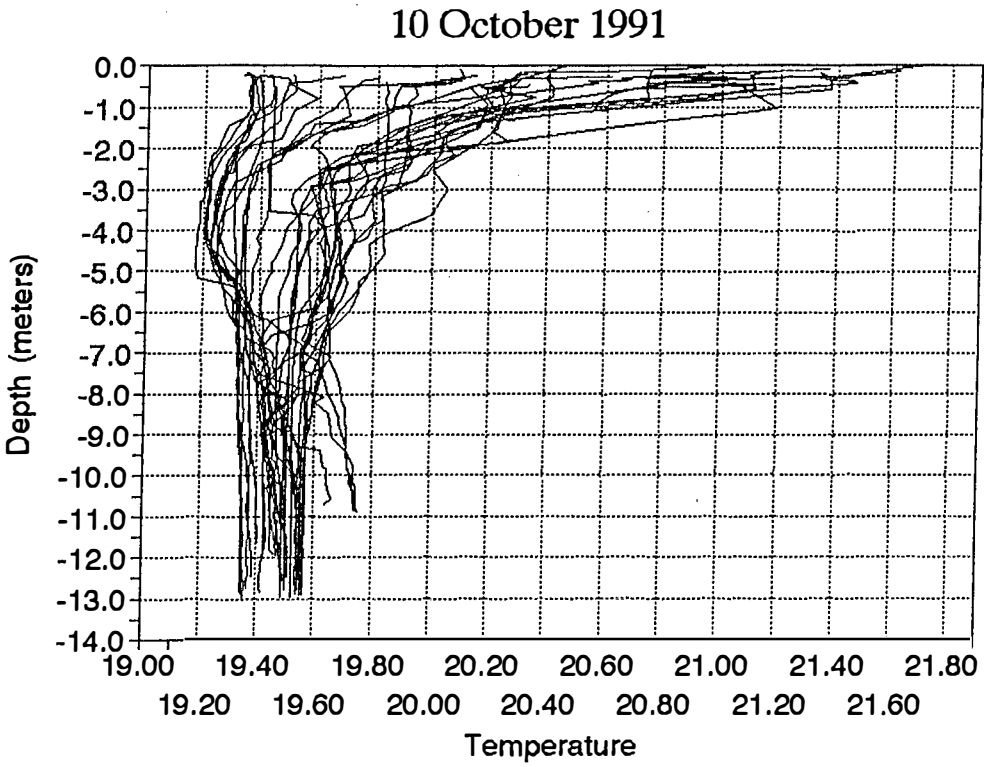
IV-5-3B Same as IV-5-3A except for transect B.



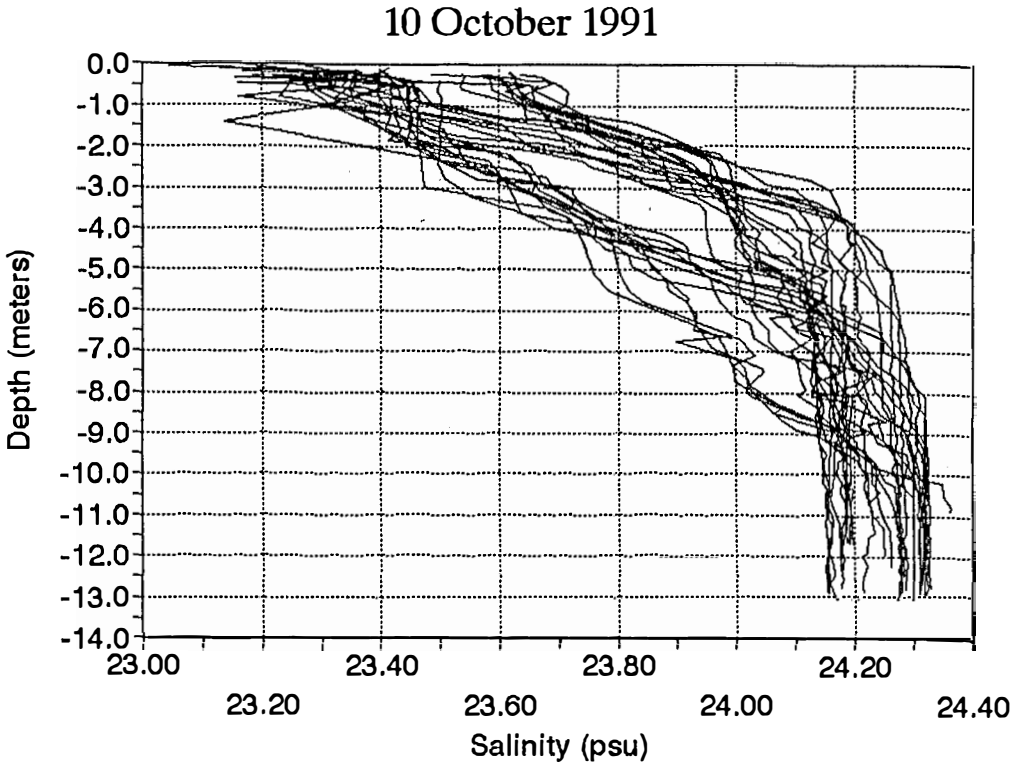




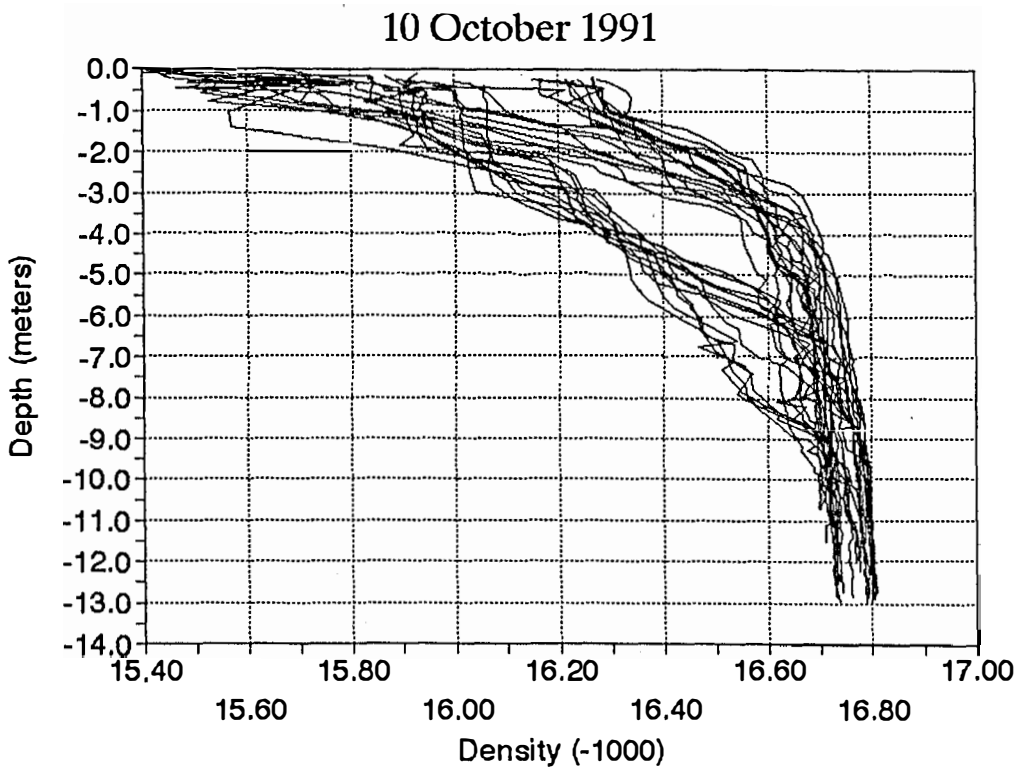
IV-5-3C Same as IV-5-3A except for transect C.



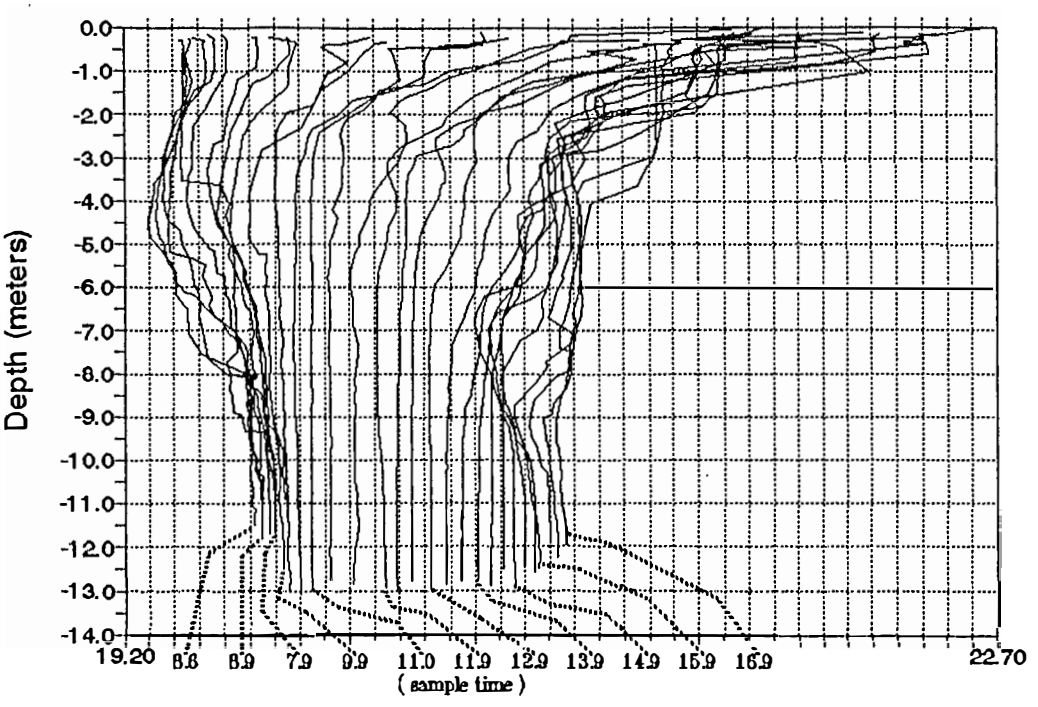
IV-5-4 Cluster plot of temperature with depth for stations sampled along drogue trajectory.



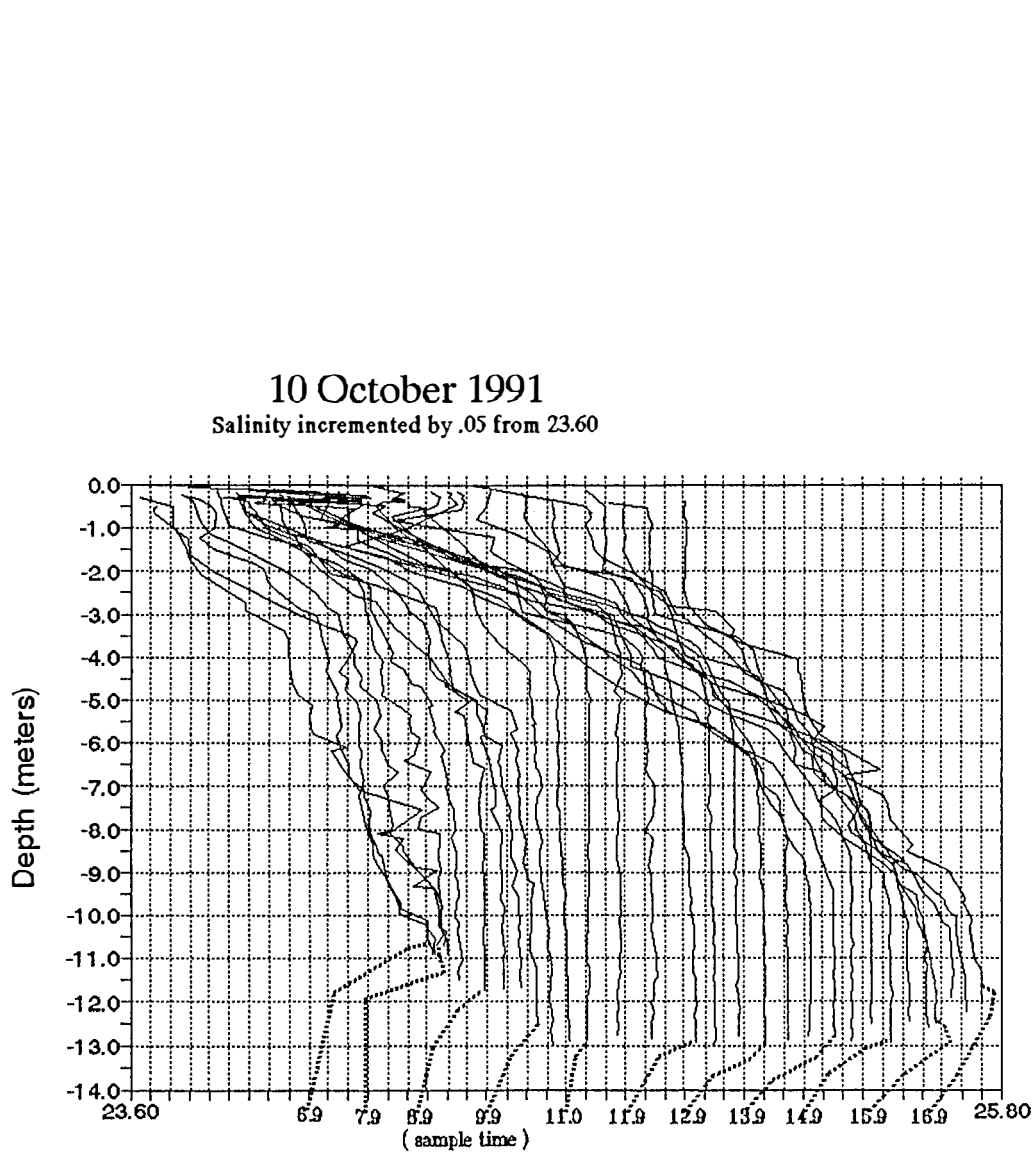
IV-5-5 Cluster plot of salinity with depth for stations sampled along drogue trajectory.



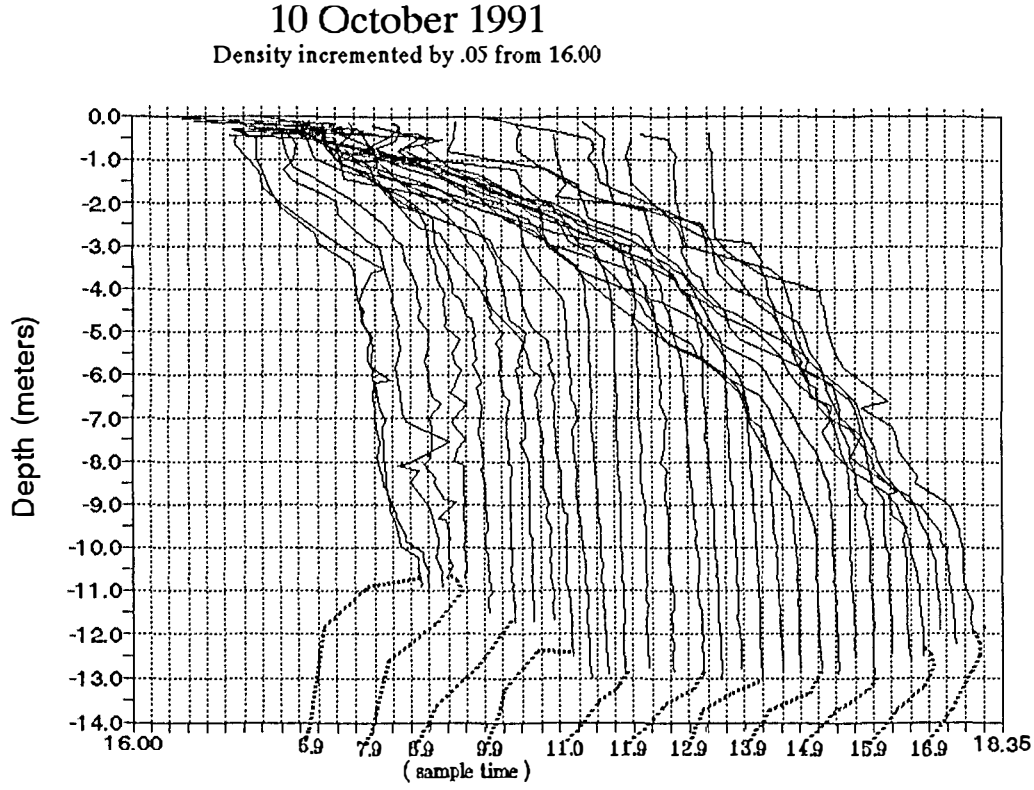
IV-5-6 Cluster plot of density with depth for stations sampled along drogue trajectory.



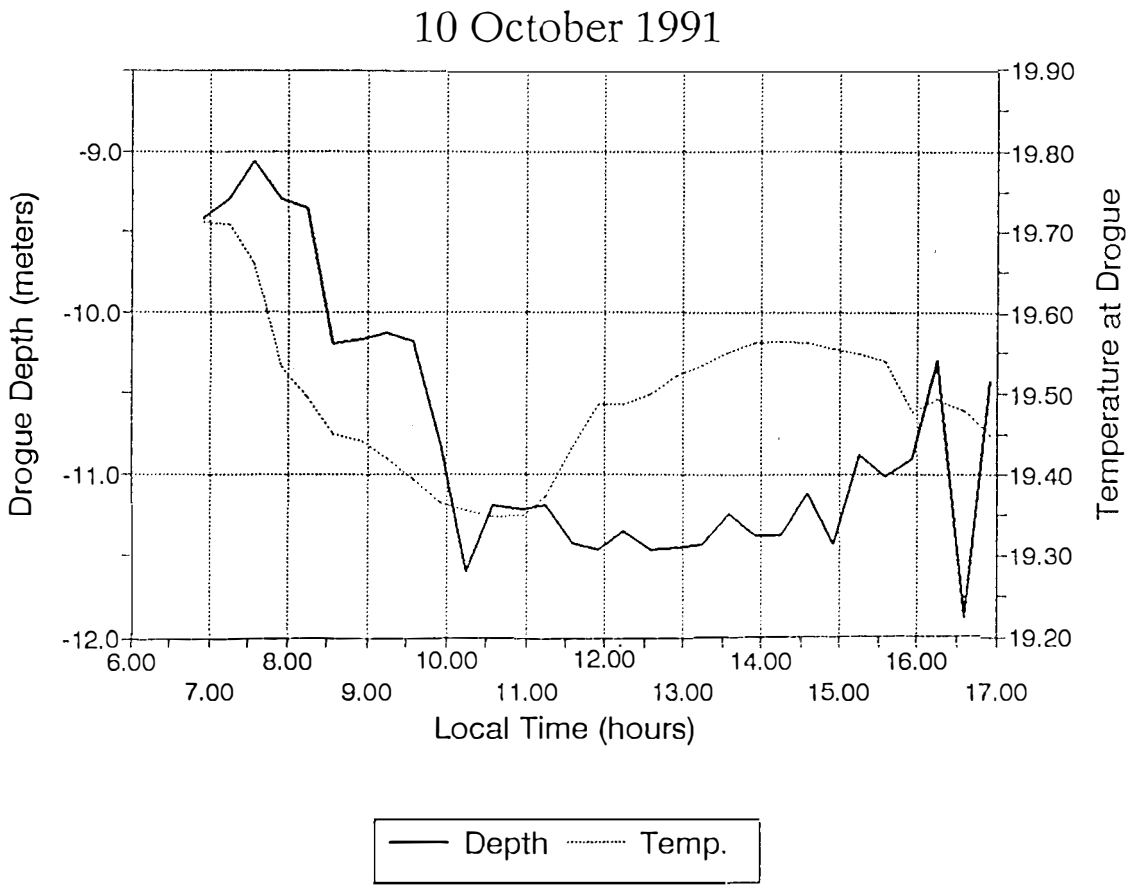
IV-5-7 Sequential plots of temperature with depth along drogue trajectory with offset of 0.1°C.



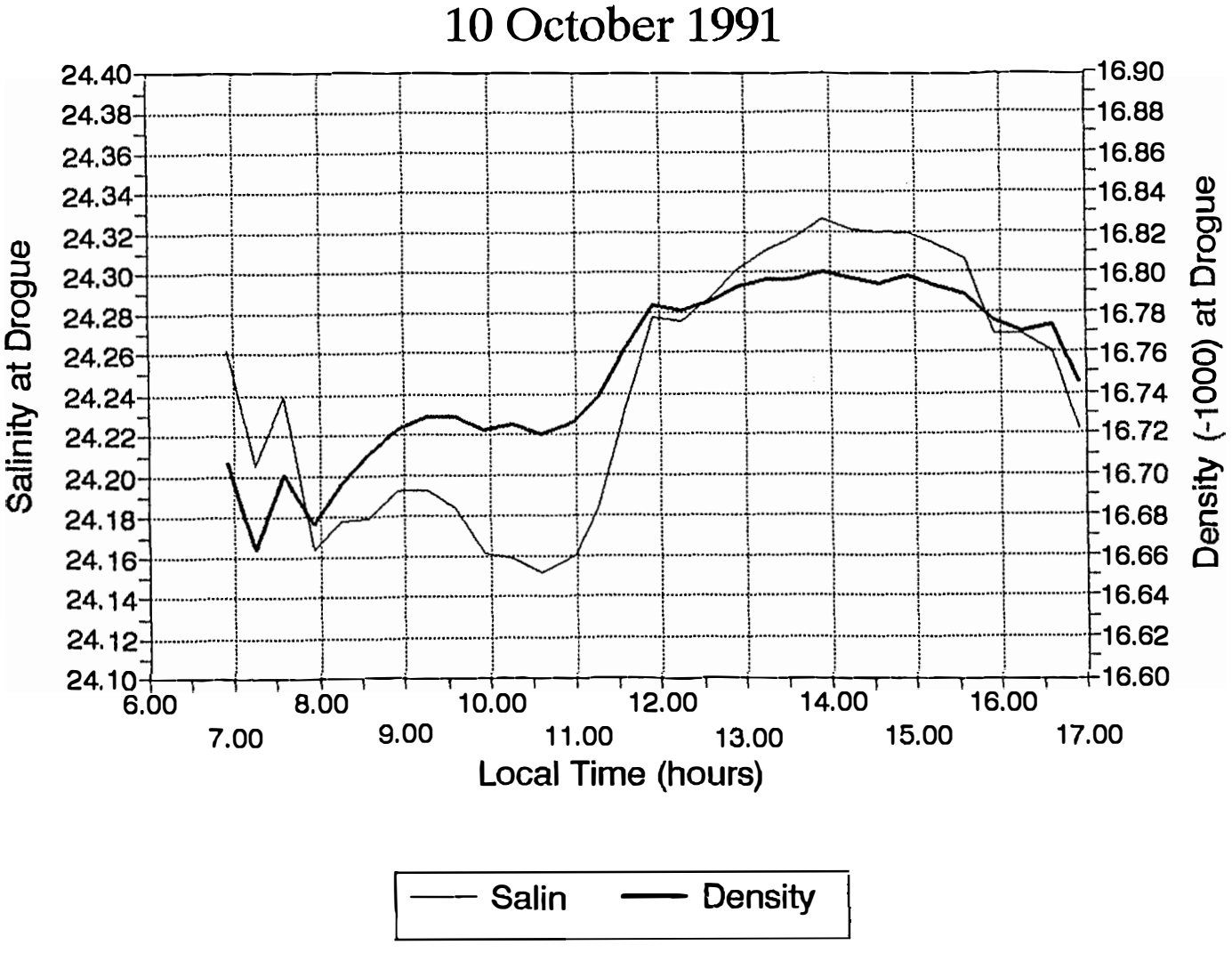
IV-5-8 Sequential plots of salinity with depth along drogue trajectory with offset of 0.05 psu. Note strengthening and depression of halocline with time.



IV-5-9 Sequential plots of density with depth along drogue trajectory with offset of 0.05 kg m^{-3}.



IV-5-10 Temporal variations of drogue depth and temperature at drogue along its trajectory.



IV-5-11 Temporal variations of salinity and density at drogue depth along its trajectory.