THE FORCED UPPER OCEAN DYNAMICS EXPERIMENT IN THE ARABIAN SEA: RESULTS FROM THE MULTI-VARIABLE MOORED SENSORS FROM DEPLOYMENT-1 OF THE WHOI MOORING

by C. Ho, C.S. Kinkade, C. Langdon, M. Maccio, J. Marra

LDEO TECHNICAL REPORT
LDEO-96-5

Department of the Navy
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Contract #
N-00014-94-1-0450

July 25 1996

Lamont-Doherty Earth Observatory
Columbia University

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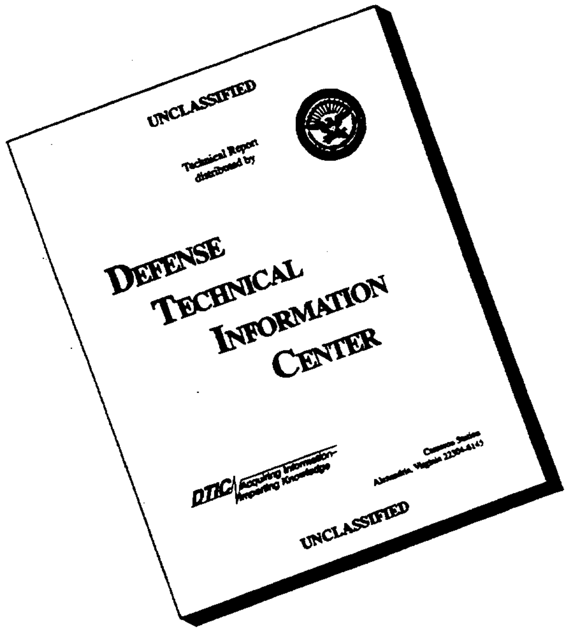

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THE FORCED UPPER OCEAN DYNAMICS EXPERIMENT

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1. GUIDE TO FIGURES WITH CAPTIONS

2. INTRODUCTION

Multi-variable moored systems (MVMS) (Dickey et al., 1991)were used to collect physical and bio-optical data over a 1-year period in the Arabian Sea as part of the ONR sponsored program. "Forced Upper Ocean Dynamics." The MVMS consists of a fluorometer. a thermistor, a conductivity sensor, a photosynthetic available radiation (PAR) sensor, a beam transmissometer. a 683nm upward vertical radiation sensor (Lu683), a dissolved oxygen sensor with a temperature sensor, and a vector measuring current meter (VMCM).

The mooring was deployed south off the Arabian Peninsula at 15° 30.04' N and 61°29.99' E, from October 14 (day 287), 1994 to April 17(day 107), 1995. The overall mooring is shown in Fig. 2. The subsurface moored array included four MVMS. This report discusses data collected by two MVMS (at 10 m and 65 m), Prepared by LDEO. Two others were deployed at 35 m and 80 m by the Ocean Physics Group at the University of Southern California. For data on the VMCM's temperature sensors, and data from the meteorological buoy at the surface, see Trask et al. (1995).

The mooring was centrally located among an array of four other subsurface moorings, two to the west deployed by Dan Rudnick and two to the east deployed by Charlie Eriksen. Thus the mooring site was an array of five moorings, centered in the one which held the MVMS'.

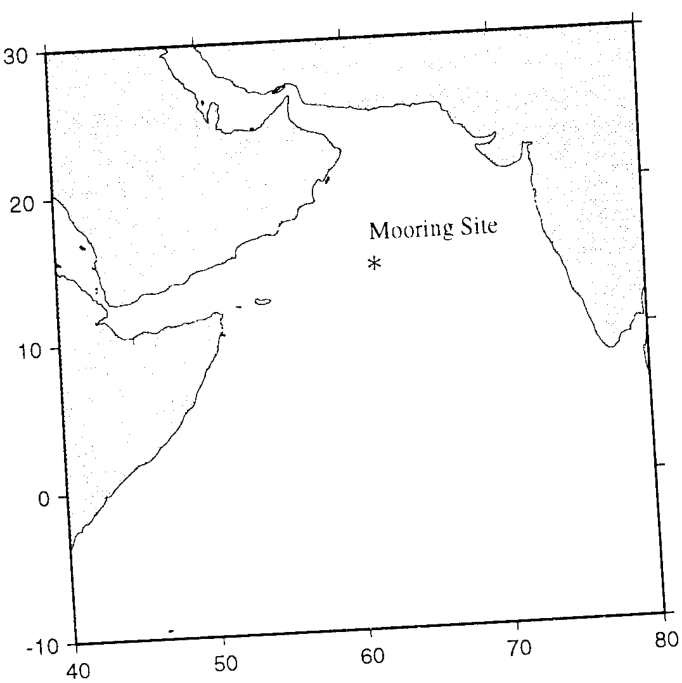

Fig. 1 The geographic location of the mooring

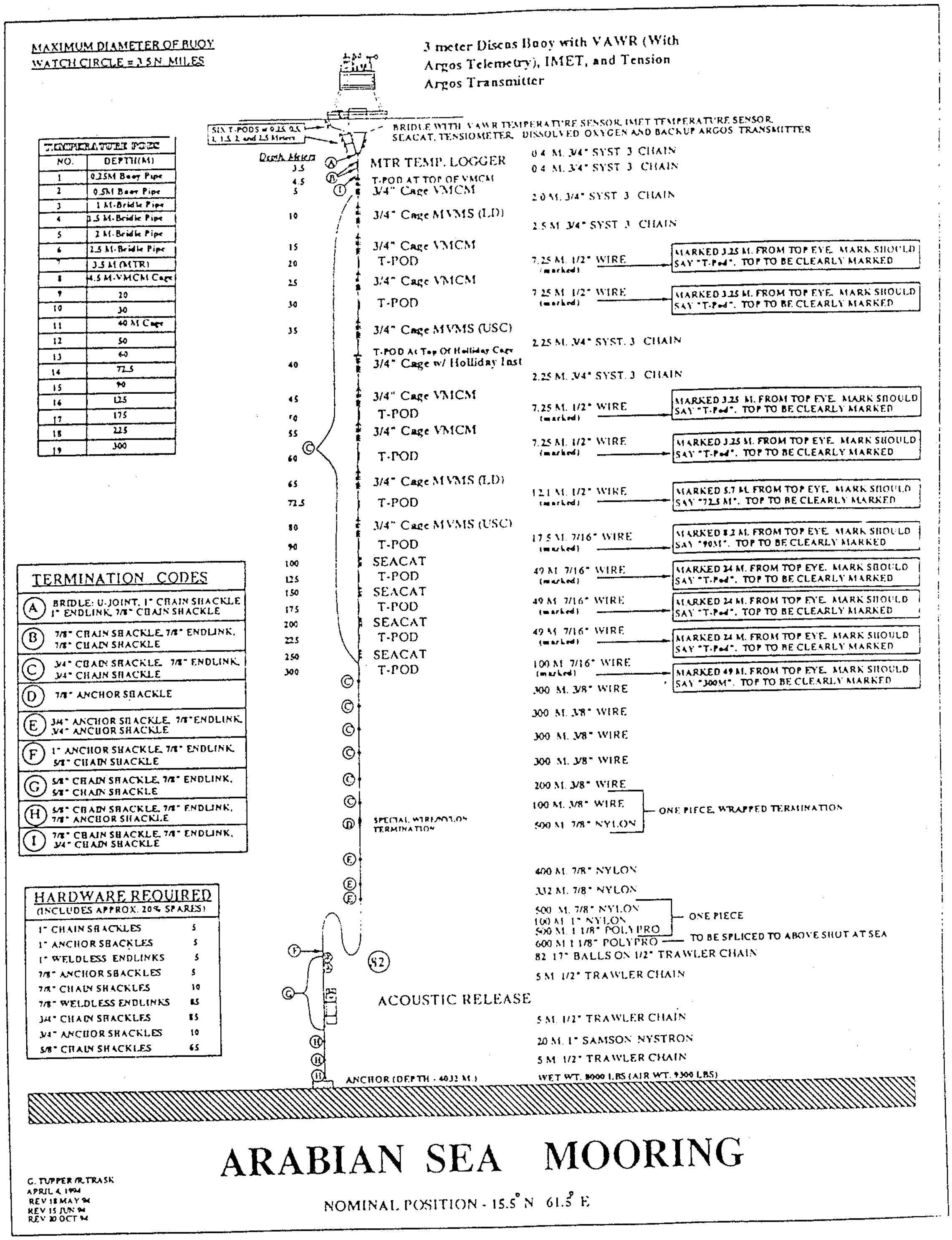

Fig.2 The mooring diagram

2.1 Record Format

All signals from sensors are processed by a Tattletale Model 6 computer and results were stored in a hard disk as ASCII files. Records are put into files every 256 second. Each record contains 15 fields: Sample number, Wake up signal, time, date, FLuorometer, TEmperature, COnductivity, PaR, TRansmissometer, Lu683, Voltage, electrical current(I), Dissolved Oxygen, dissolved oxygen temperature and VMCM readings. A typical record is shown below:

```
S 00023101 W 00085158 06:58:39 12/09/94
FL 0093 TE 35810 CO 10230 PR 0161 TR 4599 683 0000 V 1336 I 0340

DO 1851 08E7
VM
F02F53456FF9DF307FCF4F9888F505A3C005D8B3B27CE00D311F90000538181A0
934E0
```

Except for the date, time and VMCM readings, all numbers are in decimal format.

3. SENSOR CALIBRATION CONSTANTS

3.1 Stimulated Fluorescence

Voltage from the fluorometer (Sea Tech, Corvallis, OR) was recorded at the fifth field. Calibration of all the fluorometers was done according to Marra and Langdon (1993). The formula used was:

$$\text{Chlorophyll } (\mu g\ l^{-1}) = m_{chl} * FLU + b_{chl}$$

where FLU is the value in volts.

Table 1 shows the values of the constants in the equation.(See Appendix A for details.)

Table 1: Fluorometer Calibration Coefficients

depth	SN#	m_{chl}	b_{chl}
10	95	0.643	0.111
65	9	0.404	0.034

3.2 Temperature

There are three thermistors on each MVMS. The first one is part of the VMCM. It will be discussed in the section for VMCM data. The second sensor was a Sea-Bird thermistor (SBE-3). Data were recorded in the sixth field of each data record. This temperature was calculated using the formulas:

```
R = A0 /TEM

Temperature(˚C)= 1/(AT+BT*ln(R)+CT*(ln(R))2+DT*(ln(R))3)-273.15
```

Temperature calibration coefficients, from a calibration by SBE, are in Table 2.

The third thermistor was part of the Endeco (Marion, MA) oxygen sensor. The data were recorded as the second number after the symbol 'DO'.

The formula used for calibration were:

```
R = A0 + A1 * TEM

Temperature(˚C) = 1/(AT+BT*ln(R)+CT*(ln(R))3)-273.15
```

The calibration coefficients are listed in Table 3.

Table 2: SBE Thermistor Calibration Coefficients

depth	SN	A0	AT x 10^3	BT x 10^4	CT x 10^5	DT x 10^6
10m	1091	5525.35	3.68106	5.85532	1.48561	3.07341
65m	1090	5423.24	3.68106	5.85896	1.48414	2.94372

Table 3: Endeco Thermistor Calibration Coefficients

depth	SN #	A0	A1	ATx10^3	BTx10^4	CTx10^7
0m	60	0	1	5.40168	-2.8202	1.55822
10m	50	8176.5	-0.8185	1.59310	2.15120	2.17907
65m	49	8160.6	-0.8168	1.48894	2.27701	1.42889

3.3 Conductivity

The conductivity sensors were model SBE-4, and calibrated by SBE prior to deployment. Conductivity, the seventh field of the data record, was calculated using the Sea-Bird formula

$$\text{Conductivity(mmho/cm)} = a * CON^m + b * CON^2 + c + d * t$$

where b, c, d and m are calibration constants for each sensor, and t, temperature in ^{0}C.

Constants for conductivity calculation:

Table 4: Calibration Coefficients for SBE-4 Conductivity Sensors

depth	SN #	a x 10^7	b x 10	c	d x 10^5	m
10m	356	1.67716	4.07735	-4.06756	4.38986	5.7
65m	839	69.2477	5.23879	-4.06684	-15.8095	4.5

Conductivity was then converted to salinity by formulas from UNESCO/ICES/ SCOR/IAPSO (1981).

3.4 Photosynthetically Available Radiation (PAR) (Scalar Irradiance), and 683nm Upward Vertical Radiance (Lu683)

PAR sensors are QSP-200 from Biospherical Instruments (San Diego, CA). Vpar was recorded in decimal numbers, in the eighth field. The PAR in μE/m^2/s was calculated from:

$$PAR = C / B * (A + Vpar)$$

where C = calibration constant supplied by the manufacturer
B = gain from the signal processing board
A = offset from the signal processing board

Table 5: Calibration coefficients for QSL-200 PAR Sensors

depth	SN	A x 10^5	B	C
10m	4234	0.0	1	292.30
65m	4233	0.0	12.5	280.59

Lu683 sensors (model QMR-200) are also from Biospherical Instruments. V683 was recorded in decimal numbers, the tenth field. Lu683 in $\mu E/m^2/s/nm/str$ was calculated from:

```
Lu683 = C / B * (A + V683).
```

```
where C = calibration constant supplied by the manufacturer
      B = gain from the signal processing board
      A = offset from the signal processing board
```

Table 6: Calibration coefficients for QSL-200 Lu683 Sensors

depth	SN	A x 10^4	B	C
10m	7015	-2.0	50	1.3984
65m	7017	-5.4	350	1.992

3.5 Transmissometer

Sea Tech 25 cm pathlength transmissometers were used. The sensor output voltages, TRAN, were recorded in decimal numbers, in the ninth field. The conversion from voltage to %transmittance was:

```
X% = 20*((A / B) * (TRAN - Z)
```

```
where A = air calibration voltage supplied by the manufacturer
      B = present sir calibration voltage
```

The coefficients used were in table 7.

Beam attenuation coefficient was calculated by:

$$b.a.c. = - \ln(X\%/100) / 0.25 - (b.a.c)_{clear\ water}$$

where $(b.a.c.)_{clear\ water}$ = 0.2757, which was the average b.a.c. of deep water at the mooring site.

Table 7: Calibration Coefficients for Sea Tech Transmissometer

depth	SN#	A	B	Z
10m	46D	4.730	4.668	0.00
65m	223	4.660	4.604	0.00

3.6 Dissolved Oxygen

Type 1133 Dissolved Oxygen Sensor was supplied by Endeco (Marion, MA). Calibration was performed by C. Langdon. Sensor output voltage, V_{O2}, the twelfth number, was converted to physical units using following procedures. The first step was to convert voltage (V_{O2}) to current units:

$$DOX = CA+CB*V_{O2}$$

The DO concentration (O_2) in µmol/l was calculated as:

$$O_2 = Ss(T,S)*[(DOX/OA+OB*T)]$$

where Ss is the solubility coefficient with units µM/kPa, dependent on VMCM temperature (T, °C) and average salinity (S, in psu). Ss is given by equation:

$$Ss = Cstar/(0.20946*(101.325-pH_2O))$$

where

$$TK = T + 273.15$$
$$Cstar = exp(A1+A2/TK+A3/TK^2+A4/TK^3+A\%/TK^4+S[A6+A7/TK+A8/TK^2])$$

$$pH_2O = exp((-216961/TK-3840.7)/TK+16.4754$$

with
$$A1 = 1135.90205$$
$$A2 = 15750.1$$
$$A3 = -6.642308*10^7$$
$$A4 = 1.2438*10^{10}$$
$$A5 = -8.621949*10^{11}$$
$$A6 = 0.017674$$
$$A7 = -10.764$$
$$A8 = 2140.7$$

and the values of the CA, CB, OA, OB listed in Table 8. The TK and pH_2O equations come from Benson and Krause (1984) and Gnaiger and Forsther (1983).

Table 8: Dissolved Oxygen Calibration coefficients

depth	SN	CA	CB	OA	OB
0m	60	0.0	1	2.066	0.032
10m	50	0.0	0.01111	2.399	0.032
65m	49	0.0	0.01109	1.907	0.032

3.7 VMCM data

VMCM data are the last part of the record. It contains information on record count, north vector, east vector, rotor-2 counts, rotor-1 counts, compass value, and temperature. All data are recorded in hexadecimal. Each item is 4 characters long, except the compass value, which is 2 characters long.

3.7.1 Current Vectors

East and north current vector components, VE and VN, in engineering units (cm/s) were obtained from:

```
VE = K * VecE / t
VN = K * VecN / t
```

where K = 9.363 cm/count, VecE is the east vector count, VecN is the north vector count, and t is the averaging time interval in seconds. To account for magnetic declination, currents were rotated -19.5° (i.e. 19.5° west) using following formula:

```
new_VN = VN * cos(19.5) - VE * sin(19.5)
new_VE = VE * cos(19.5) + VN * sin(19.5)
```

3.7.2 VMCM temperature

The temperature sensor voltage was recorded in VMCM data as a hexadecimal number at character 23-26. The calibration formula were:

```
R = A0 * (A1 - TEM)/(A1 + TEM)
Temperature(˚C) = 1/(AT+BT*ln(R)+CT*(ln(R))3)-273.15
```

The calibration coefficients are in Table 9.

Table 9: VMCM Temperature calibration Coefficients

depth	SN	A0	A1	A Tx 10^3	B Tx 10^4	C Tx 10^7
10m	302703	54.422	9761.4	2.50051	2.45257	4.66091
65m	401405	54.417	10223.4	2.49041	2.50205	3.38378

4. REMARKS ON THE DATA

4.1 Data validation

Temperature, salinity, b,a.c. and chlorophyll data were checked against other independently collected data. During the time of October 1994 and April 1995, R/V T.G. Thompson passed by the mooring site several times and data were collected in the vicinity. Following is the list of these cruises and stations. HYD indicates that bottle samples were taken in addition to CTD data.

Cruises	sta	cast	latitude	longitude	date	time	type
TN040	02	01	15°30.36'N	61°29.56'E	Oct 15,'94	13:56	CTD
TN040	12	01	15°30,38'N	61°29.92'E	Oct.18,'94	21:26	CTD
TN040	16	01	15°29.98'N	61°44.08'E	Oct.19,'94	18:56	CTD
TN042	07		15°40.80'N	61°29.58'E	Dec.11,'94	10:59	HYD
TN042	07	03	15°40.80'N	61°29.58'E	Dec.11,'94	10:59	CTD
TN043	23		15°32.98'N	61°29.94'E	Jan 25,'95	17:40	HYD
TN044	03		15°30.96'N	61°30.30'E	Feb.14,'95	18:55	HYD
TN045	23		15°32.98'N	61°30.00'E	Apr.01,'95	09:59	HYD

If the data did not agree with these measurement, they were flagged with a number -9999.

4.2 Temperature

Six thermistors at both 10 m and 65 m functioned all the time with remarkable accuracy. Between the SeaBird thermistor and the VMCM thermistor, generally, the VMCM measured lower temperature by less than 0.02 °C. At times the SeaBird temperature was lower, but the difference never exceeded 0.01 °C. The difference might due to a differing response to temperature changes of two electronic circuits. The DOT measurements were about 0.05 °C less than both SeaBird and VMCM measurements.

4.3 Salinity

Conductivity sensor at 10 m, became unstable around Jan.16, 1995 (day 16) and the data drifted away from CTD measurement. Data after that day were considered unreliable and were flagged with -9999. The conductivity sensor at 65 m also suffered some unstable problems after February, 1995. The recorded signals were very noisy. The problem have been less serious than the 10 m sensor. Except for some spikes, the data agreed with CTD measurements. All spikes were removed and replaced by the previous good record by a computer program

4.4 PAR and Lu683

Both PAR sensors functioned well all the time. Both Lu683 sensors were also behaving well, but 10 m sensor had an amplifier gain problem. The signal was amplified too much causing an overflow. However, the overflow problem only happened near noon each day. All other data were properly recorded.

4.5 Beam attenuation coefficient

The glass windows of transmissometers at both 10 m and 65 m were found covered by gooseneck barnacles and filamentous algae at recovery. But the exact time the window started to show effects of fouling was not known. Details on the interpretation of transmissometer data can be found in Appendix A.

At 10 m, judging by the b.a.c. ~ chlorophyll relation, data after December 1, 1994 (day 335) (see Appendix A) were not reliable. These data were flagged -9999.

At 65 m, according to the b.a.c ~ chlorophyll relation, there was a period of 17 days (from October 30, 1994, day 303, to November 15, 1994, day 319) when data were not reliable. Our judgement is that the optical windows were temporarily fouled. These data were flagged -9999. Data after January 6, 1995 (day 371) were not reliable because of serious fouling and were all flagged -9999.

4.6 Chlorophyll

The fluorometer at 10 m had a serious fouling problem, while 65 m appeared problem free. But the pre-cruise calibration of both instruments were questionable. Appendix A discusses in detail how chlorophyll data were calibrated and verified. Basically, for 10 m, data after January 11, 1995 (day!1) were not reliable and flagged -9999 and for 65 m, all data were reliable.

4.7 Dissolved Oxygen

The 0 m sensor signal was very noisy between December 16, 1994 and February 4, 1995. Data during this period have been flagged -9999. After March 6, sensitivity fell off sharply because of to fouling and data have been flagged -9999. At 10 m sensitivity fell sharply after March 16. Data after this date have been flagged -9999. At 65 m the sensor failed because of membranae damage on Dec. 26, 1994. Data after this date have been flagged -9999.

The loss of sensitivity experienced by the oxygen sensors is thought to be from small holes in the membranae made by fish bite. At 65 m the membrane was gone when the sensor was recovered. On future moorings the oxygen sensors will be protected by a guard which will protect fish bite damage.

5. REFERENCES

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Benson,B. and D. Krause ,1984. The concentration and isotopic fractionationof oxygen dissolved in freshwater and seawater in equilibrium with the atmosphere. Limnol. Oceanogr. 29, 620-632

Gnaiger, E. and H. Forsther, (Eds.). 1983. Polarographic Oxygen Sensors. Springer-Verlag, New York, 370pp.

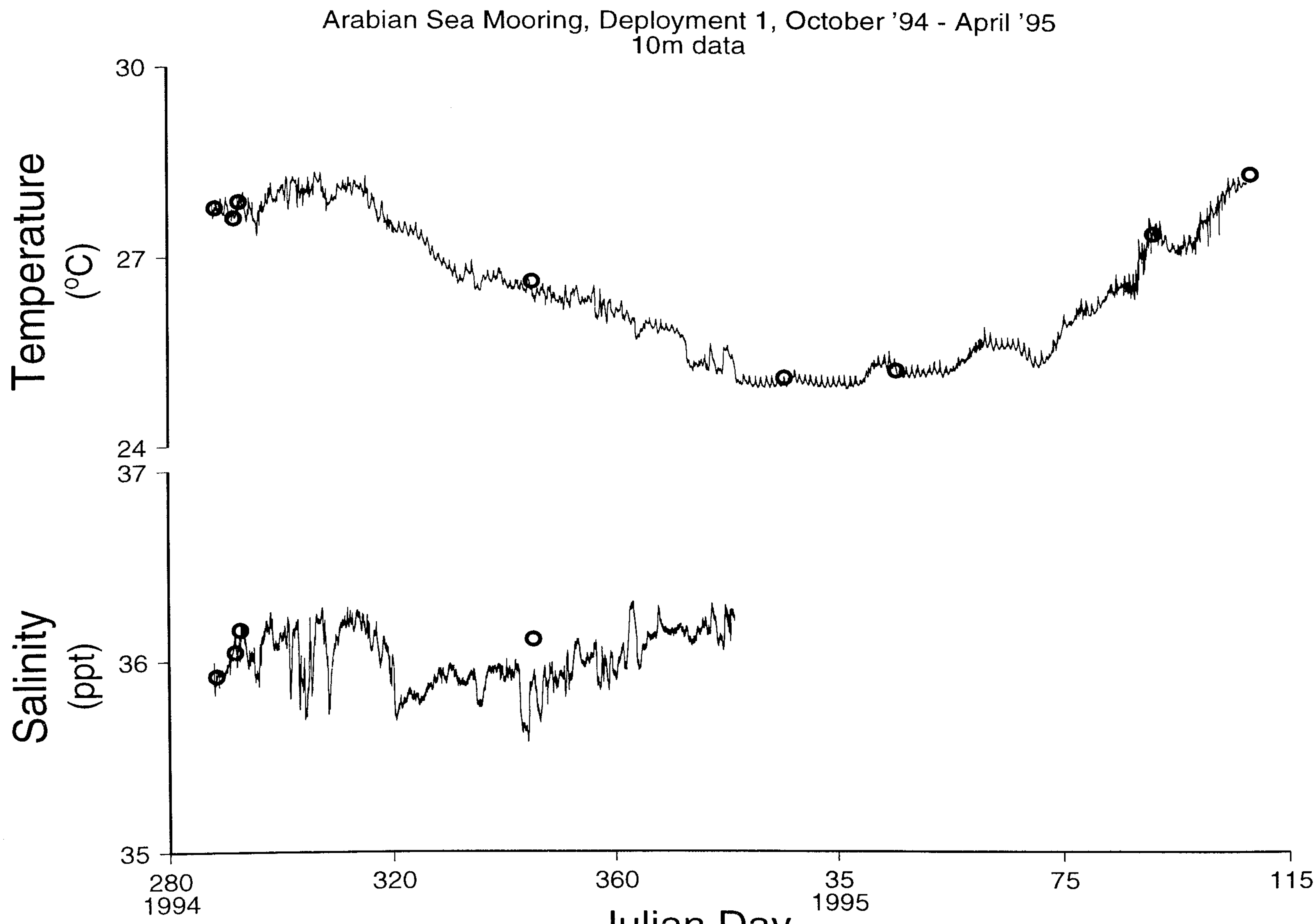
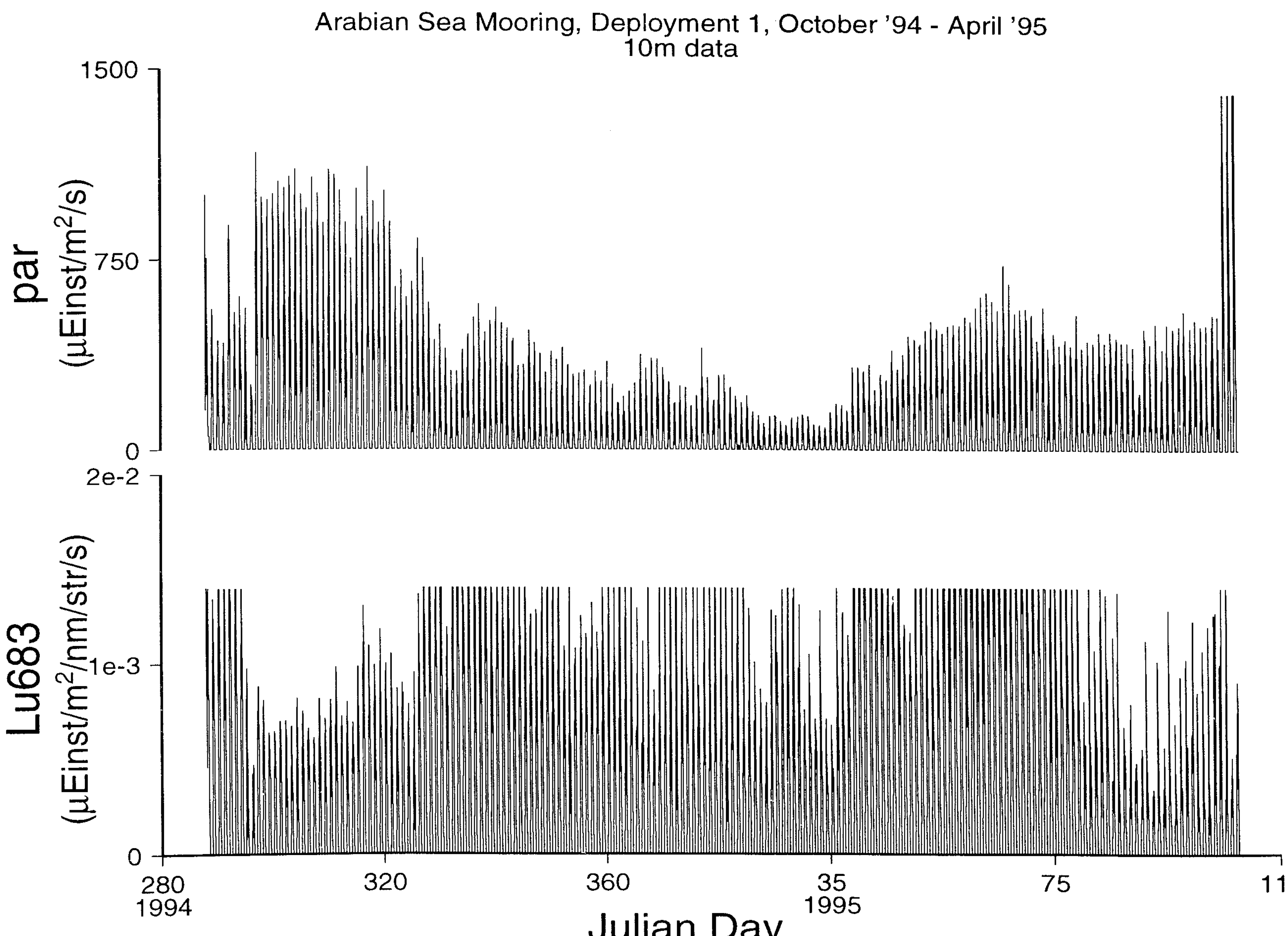
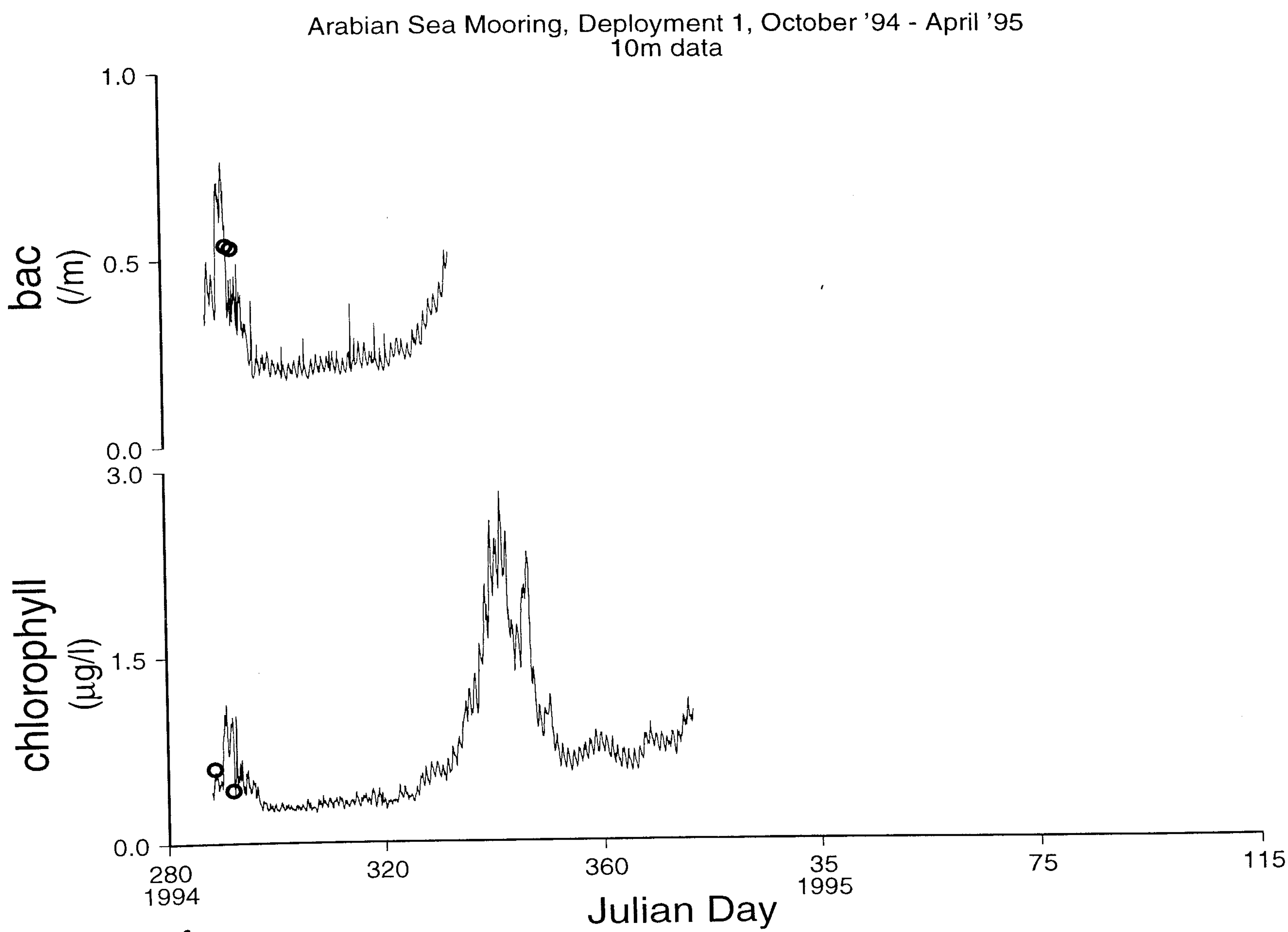

Arabian Sea Mooring, Deployment 1, October '94 - April '95
10m data
Temperature
(°C)
30
27
24
Salinity
(ppt)
37
36
35
280
1994
320
360
35
1995
75
115
Julian Day

Fig.3



Arabian Sea Mooring, Deployment 1, October '94 - April '95
10m data
par
(µEinst/m²/s)
1500
750
0
Lu683
(µEinst/m²/nm/str/s)
2e-2
1e-3
0
280
1994
320
360
35
1995
75
115
Julian Day

Fig.4


Arabian Sea Mooring, Deployment 1, October '94 - April '95
10m data
bac
(/m)
1.0
0.5
0.0
chlorophyll
(µg/l)
3.0
1.5
0.0
280
1994
320
360
35
1995
75
115
Julian Day
Fig.5

Arabian Sea Mooring, Deployment 1, October '94 - April '95
10m data

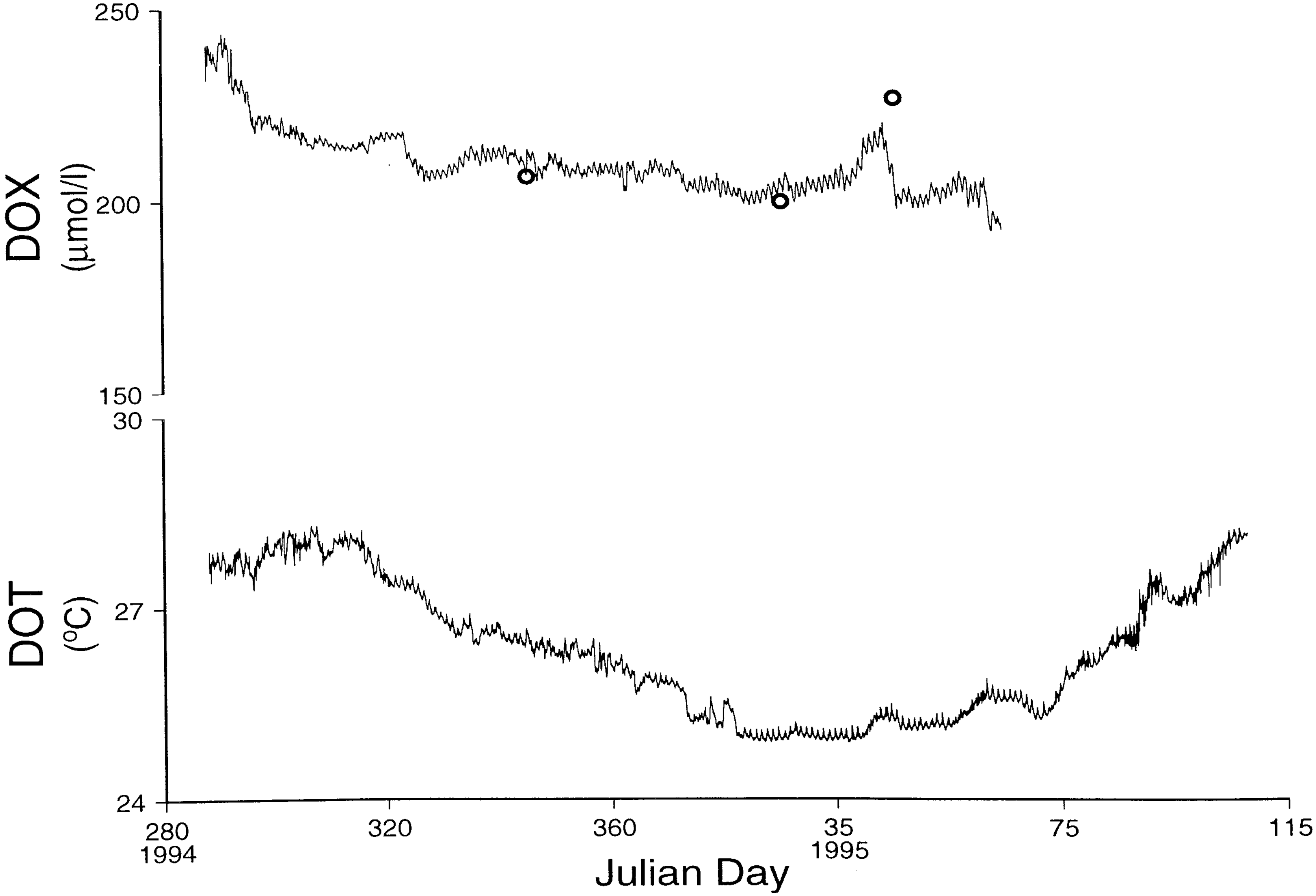
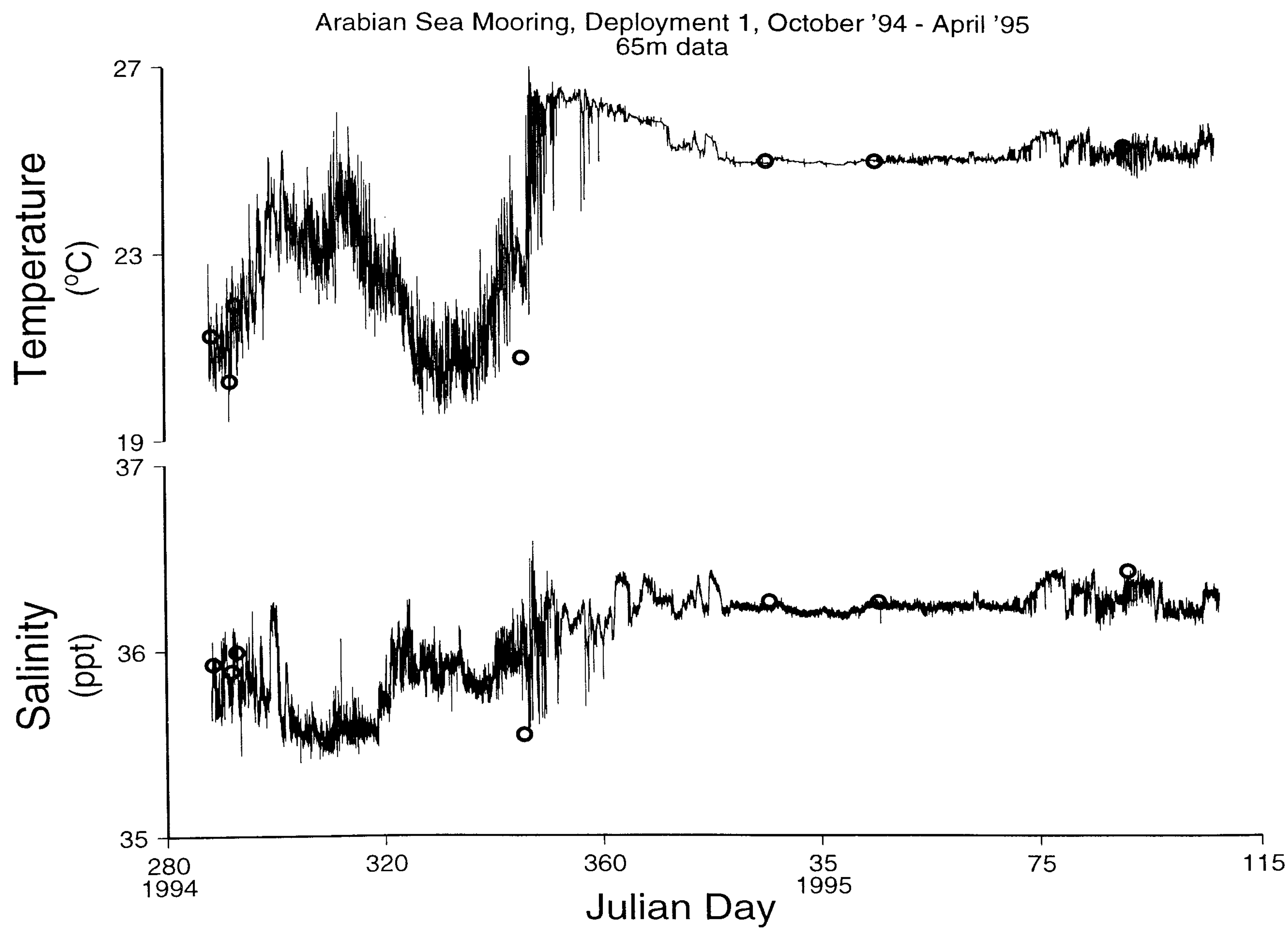
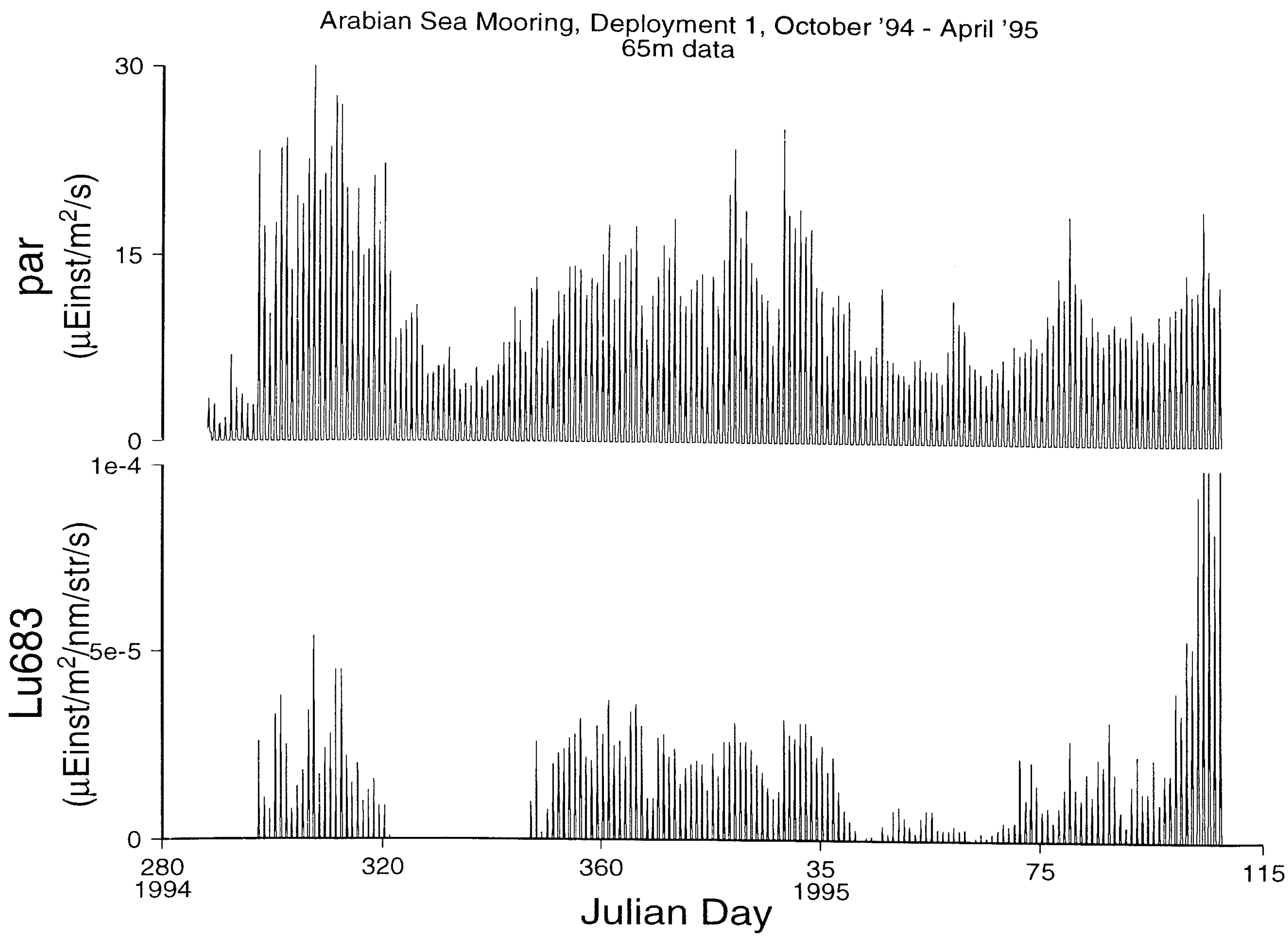


Fig.6


Arabian Sea Mooring, Deployment 1, October '94 - April '95
65m data
Temperature
(°C)
27
23
19
Salinity
(ppt)
37
36
35
280
1994
320
360
35
1995
75
115
Julian Day
Fig.7



Arabian Sea Mooring, Deployment 1, October '94 - April '95
65m data
par
(µEinst/m²/s)
30
15
0
Lu683
(µEinst/m²/nm/str/s)
1e-4
5e-5
0
280
1994
320
360
35
1995
75
115
Julian Day

Fig.8

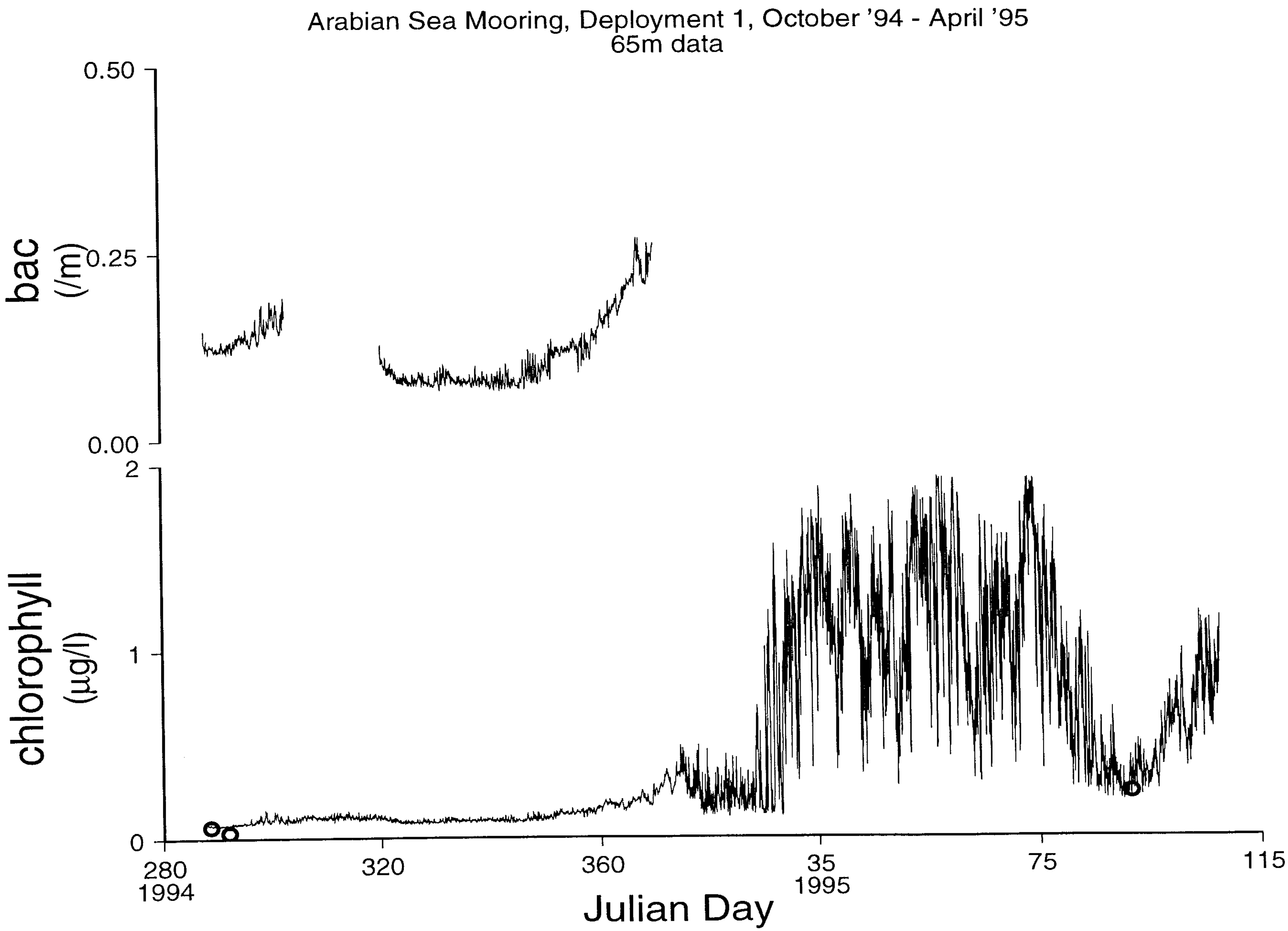

Arabian Sea Mooring, Deployment 1, October '94 - April '95
65m data
bac
(/m)
0.50
0.25
0.00
chlorophyll
(µg/l)
2
1
0
280
1994
320
360
35
1995
75
115
Julian Day

Fig.9

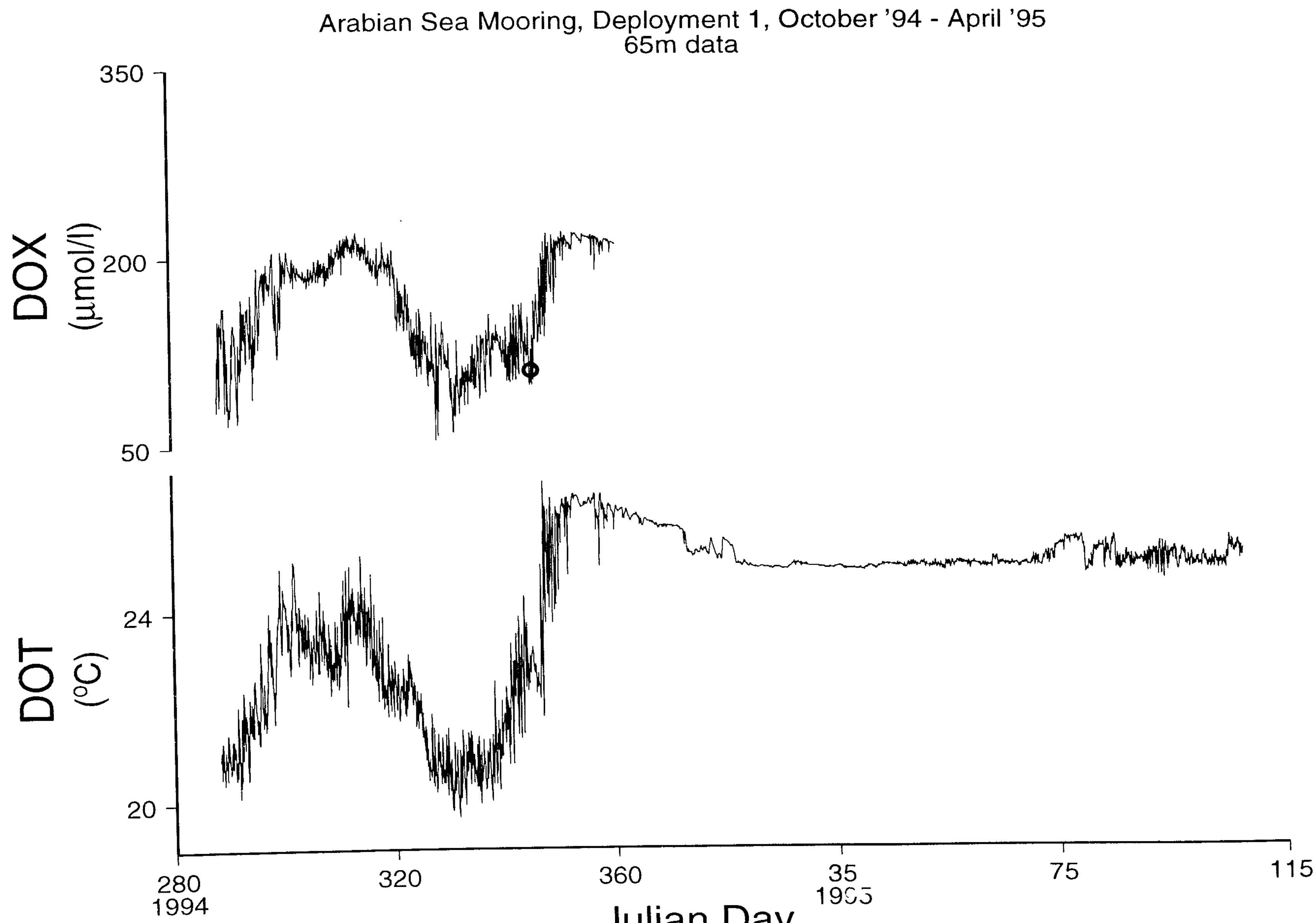
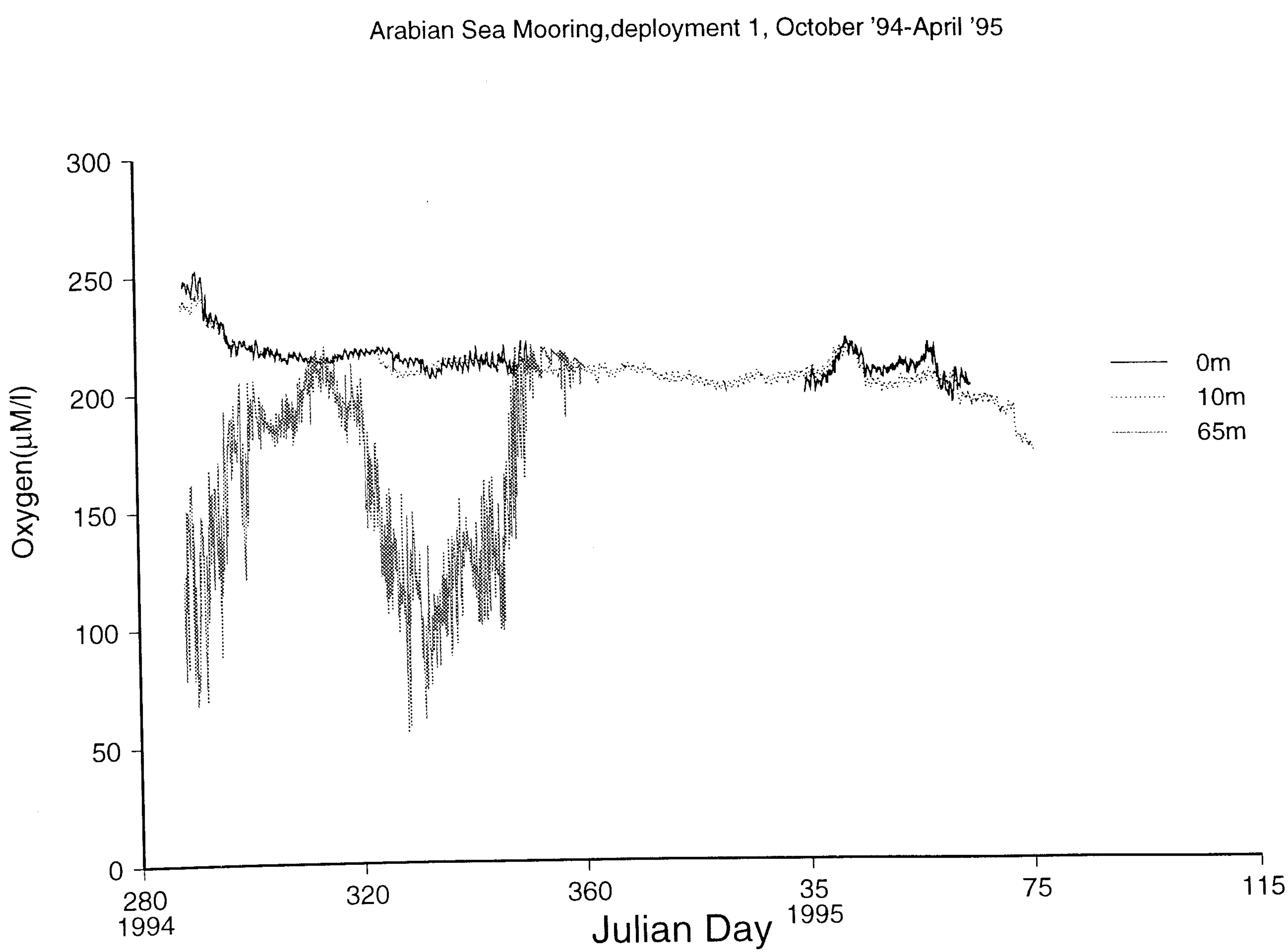

Arabian Sea Mooring, Deployment 1, October '94 - April '95
65m data
DOX
(µmol/l)
350
200
50
DOT
(°C)
24
20
280
1994
320
360
35
1995
75
115
Julian Day

Fig.10



Arabian Sea Mooring,deployment 1, October '94-April '95
Oxygen(μM/l)
300
250
200
150
100
50
0
280
1994
320
360
35
1995
75
115
Julian Day
0m
10m
65m

Fig. 11

Arabian Sea Mooring, Deployment 1, October, '94 - April, '95

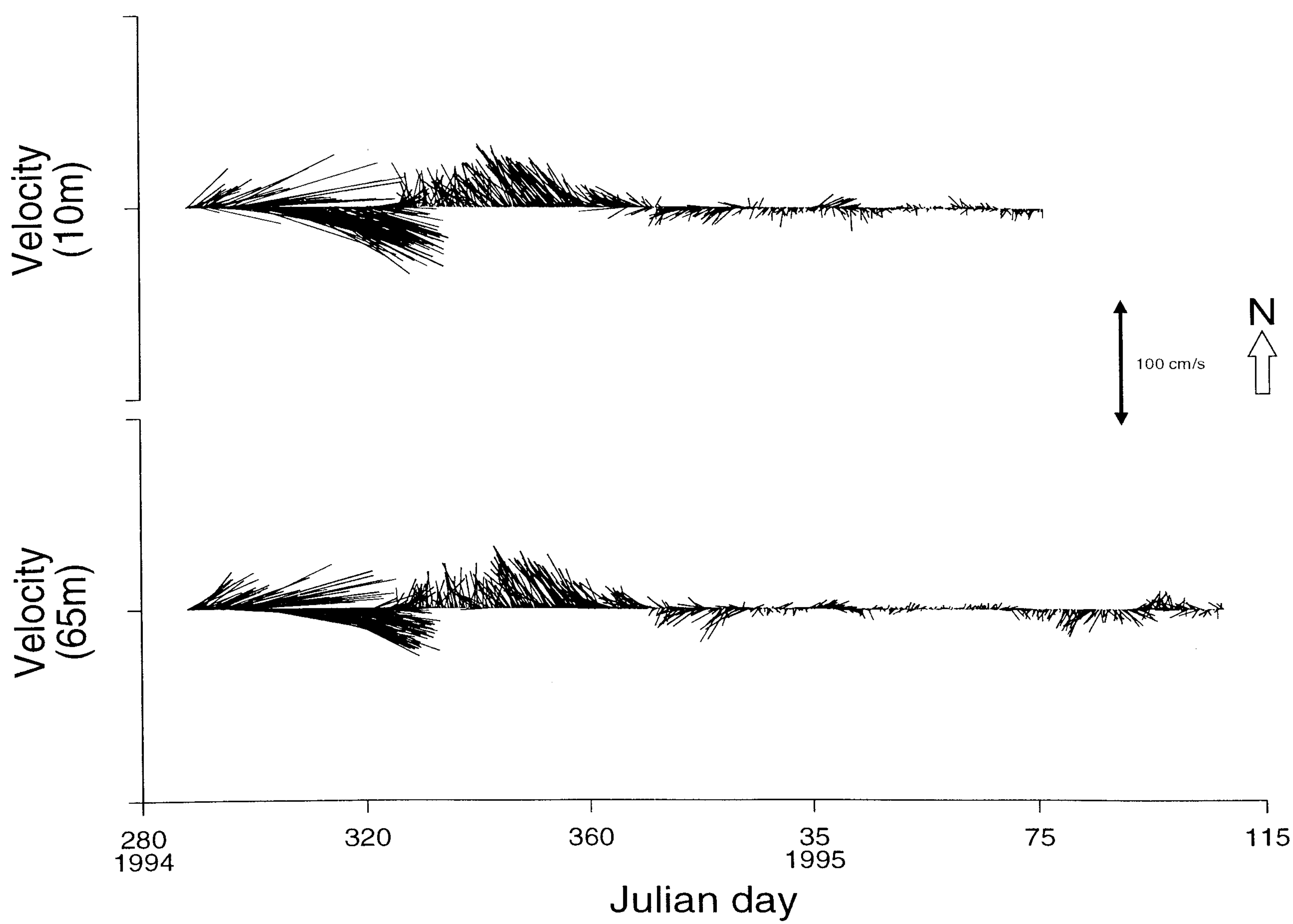


Fig.12

Appendix A: Calibration of the moored stimulated fluorescence data and evaluation of beam transmissometer data

A0: Introduction

Fouling was to be expected for the Arabian Sea mooring, and it occurred to a different degree depending on the sensor and its position (depth) on the mooring. Fluorometers and transmissometers were the most susceptible and the raw data had to be examined very carefully.

A1: Fluorometer Calibration Equations

On the cruise to deploy the mooring (TN040, October, 1994), we were able to collect a few chlorophyll samples to compare with the moored fluorometers. The chlorophyll analyses done on the cruise were a factor of 2-3 times lower than the laboratory calibration, completed a few months prior to the cruise. Since the lab calibration produced chlorophyll values much higher than the historical data from the Arabian Sea, we came to the conclusion that it was in error. Repeated checking of the laboratory calibration. however, failed to reveal the problem.

Since there were few calibration points for the fluorometer at the mooring site on subsequent cruises, and before it was suspected of being fouled, we settled on an alternative method. We calibrated the fluorometer used on the CTD in terms of chlorophyll a, and used this to compare with the moored fluorescence values. In this way, we were able to re-cast the moored fluorescence data in terms of chlorophyll a, and also determine where in the record the fluorometers became fouled.

During Cruise TN045 (Process cruise 2) extensive bottle samples were collected for chlorophyll analysis using Turner Designs fluorometer which had been calibrated with pure chlorophyll a (R.R. Bidigare, personal communication). Many of these samples were collected from CTD casts, which also used a fluorometer from SeaTech, and which was set at the same scale as the moored SeaTech fluorometer. Therefore chlorophyll values and the CTD fluorometer voltage readings supplied the best information to calibrate the moored fluorometers.

All chlorophyll data collected from CTD casts were identified, and the corresponding fluorometer reading from the same depth were extracted from the CTD files. The data separate into two groups: shallow water (< 30 m) and deep water (> 30 m) (Fig. A1). The variable fluorescence yield (fluorescence/chlorophyll) as a function of depth has been noted previously (e.g., Marra and Langdon, 1993). Since there were two depths where mooring data were collected, sets of chlorophyll and fluorescence data were selected for calibrating the two fluorometers: data at depths less than 30 m were used for 10 m moored fluorometer and data at depths between 60 m and 70 m were used for 65 m moored fluorometer.

Fig. A2 shows the two group of data points. Linear regression produced two calibration equations.

chl = 0.627 * Volt + 0.123 <30m

chl = 0.374 * Volt + 0.048 >60m and <70m

After the above equations were applied to fluorometer readings, chlorophyll values were calculated as shown on Fig. A7 and A8.

A 2: <u>CTD Fluorescence Data</u>

During all Processes and Seasoar cruises, CTD data were collected in different locations, some close to mooring site while others were some distance away. Since, in general, weather conditions and chemical properties were the same in the area of Arabian Sea, it is believed that these CTD fluorescence measurement could be very useful reference to determine whether mooring data were in a reasonable range. Those data were calibrated by the above equations and listed in Appendix B. Data points were marked on mooring plots to verify the correctness of mooring data (Figs. A7 and A8).

Data collected during mooring deployment cruise (TN040), mentioned in section A.1 were marked on Figs. A3 and A4. These data coincide with mooring data, as they should.

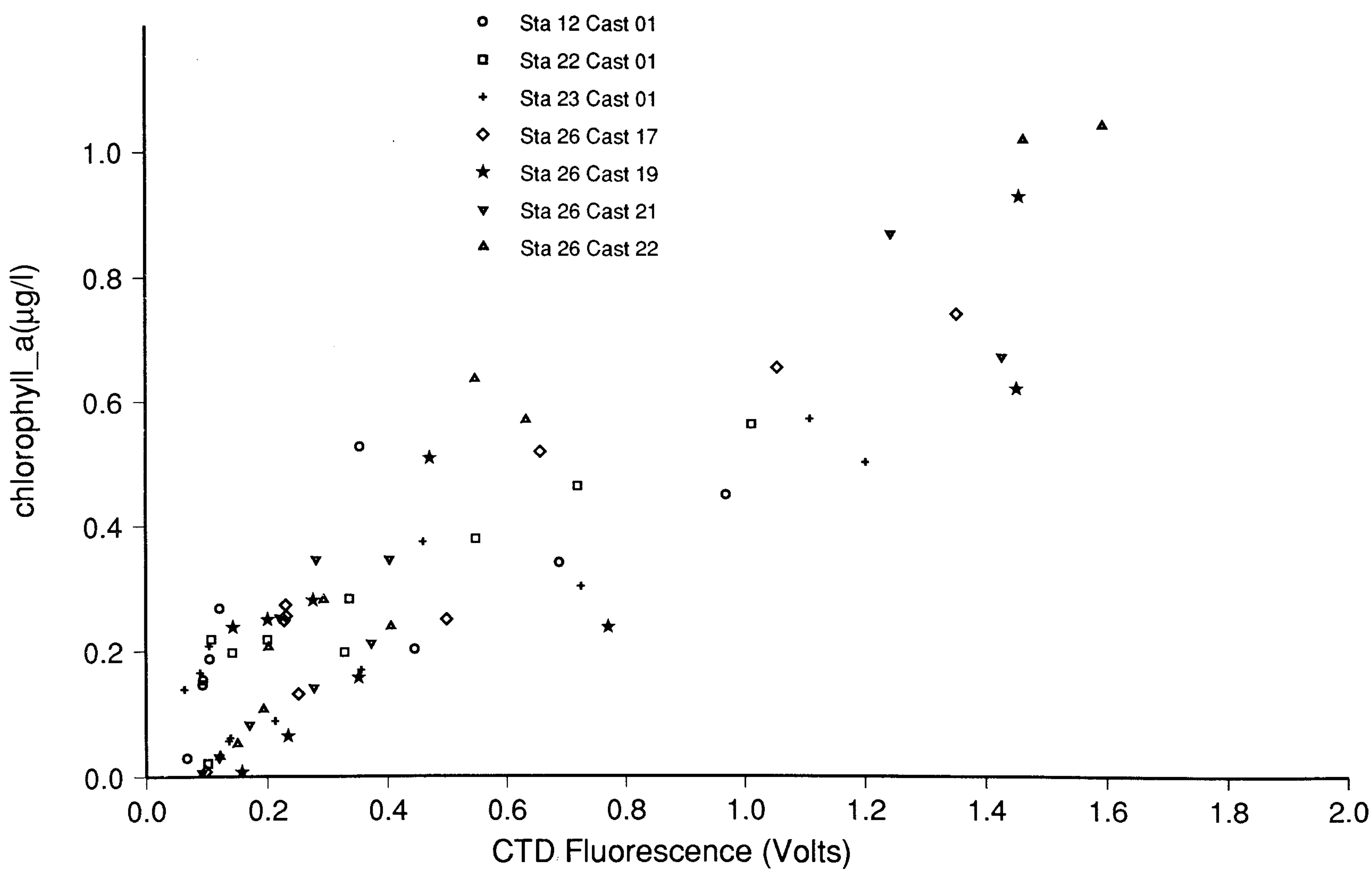
Early in the chlorophyll record, around Day 295, a CTD 'tow-yo' was done between the sites of Charlie Eriksen's Profiling Current Meter moorings. These were southeast and northeast of the central mooring. The tow-yo was Station 26 of TN040. It is tempting to conclude that the chlorophyll maxima observed on the tow-yo represent downstream advection of the peak in chlorophyll observed at the mooring on about Day 289. However, the chlorophyll maximum seen from the tow-yo is associated with a high salinity layer that is not seen at the mooring (C. Eriksen, personal communication). Thus, the two chlorophyll maxima result from small-scale variability in the chlorophyll. They are a contemporaneous rather than sequential phenomenon. The high salinity water was within 25 km of the mooring, but was never detected by the mooring sensors.

A3: <u>Transmissometer Data</u>

Transmissometers are more sensitive to fouling than fluorometers.The optical windows are larger, and are made of glass which is more easily fouled than one the plastic window of the fluorometer. Since the fluorometer readings were carefully calibrated and well-supported by CTD values, chlorophyll data were used to determine the reliability of the beam attenuation coefficient (bac). All recognizable bac signals before serious fouling were plotted in Figs.A3 and A4. Chlorophyll vs. bac were plotted in Figs A5 and A6.

For the 10 m instrument (Fig. A5), data before Day 334.85, show a reasonable linear relationship between chlorophyll and bac. This indicated that before Day 334.85, bac data were as reliable as chlorophyll data. After Day 334.85, the relation is untenable, then we determined that bac data after Day 334.85 to be discarded.

For the 65 m mistreatment (Fig.A6), several linear relations existed over different periods of time. We determined that data between Day 288 and Day 302.81, and data between 320.44 and Day 371.85 were reliable. Between Day 308.27 and Day 314.65, there was a linear relationship between chlorophyll and bac, but bac values themselves are elevated by previous unsatisfactory bac data. Thus, for this period, bac data will be discarded. All other data are also discarded.



Sta 12 Cast 01
Sta 22 Cast 01
Sta 23 Cast 01
Sta 26 Cast 17
Sta 26 Cast 19
Sta 26 Cast 21
Sta 26 Cast 22
chlorophyll_a(µg/l)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
CTD Fluorescence (Volts)

Fig. A1

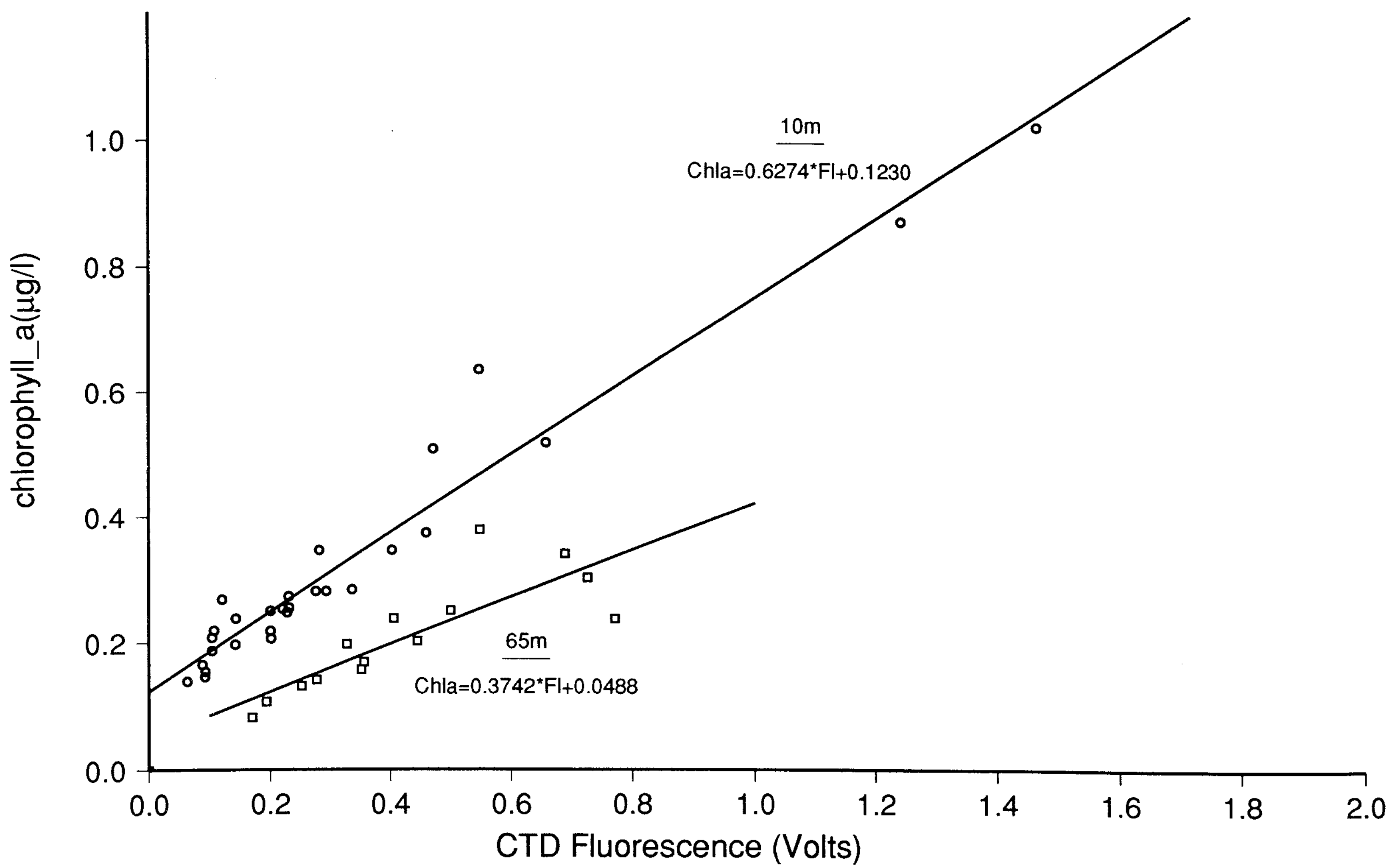

10m
Chla=0.6274*Fl+0.1230
65m
Chla=0.3742*Fl+0.0488
chlorophyll_a(µg/l)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
CTD Fluorescence (Volts)

Fig. A2

1994 mooring 10m

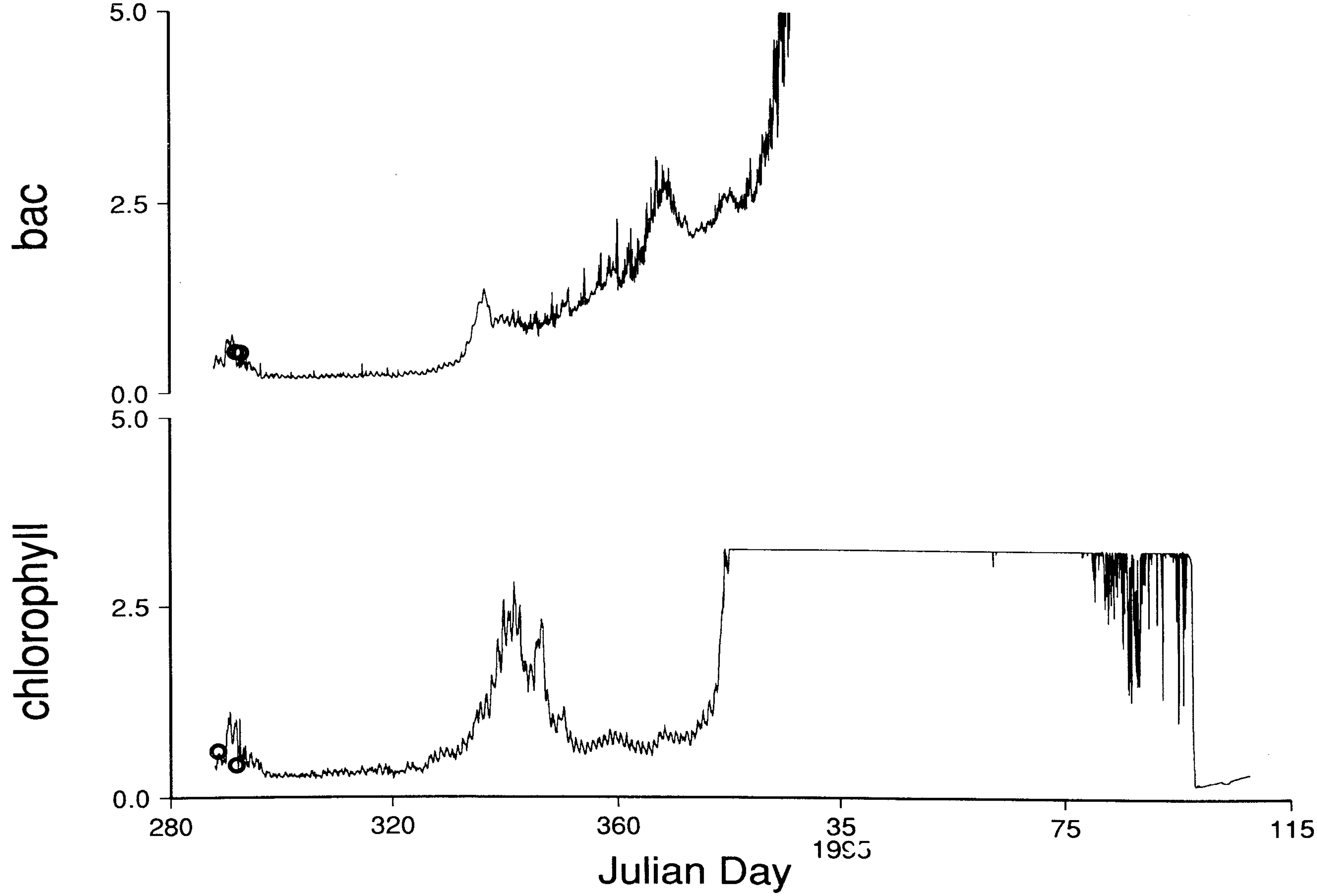


Fig.A3

1994 mooring 65m

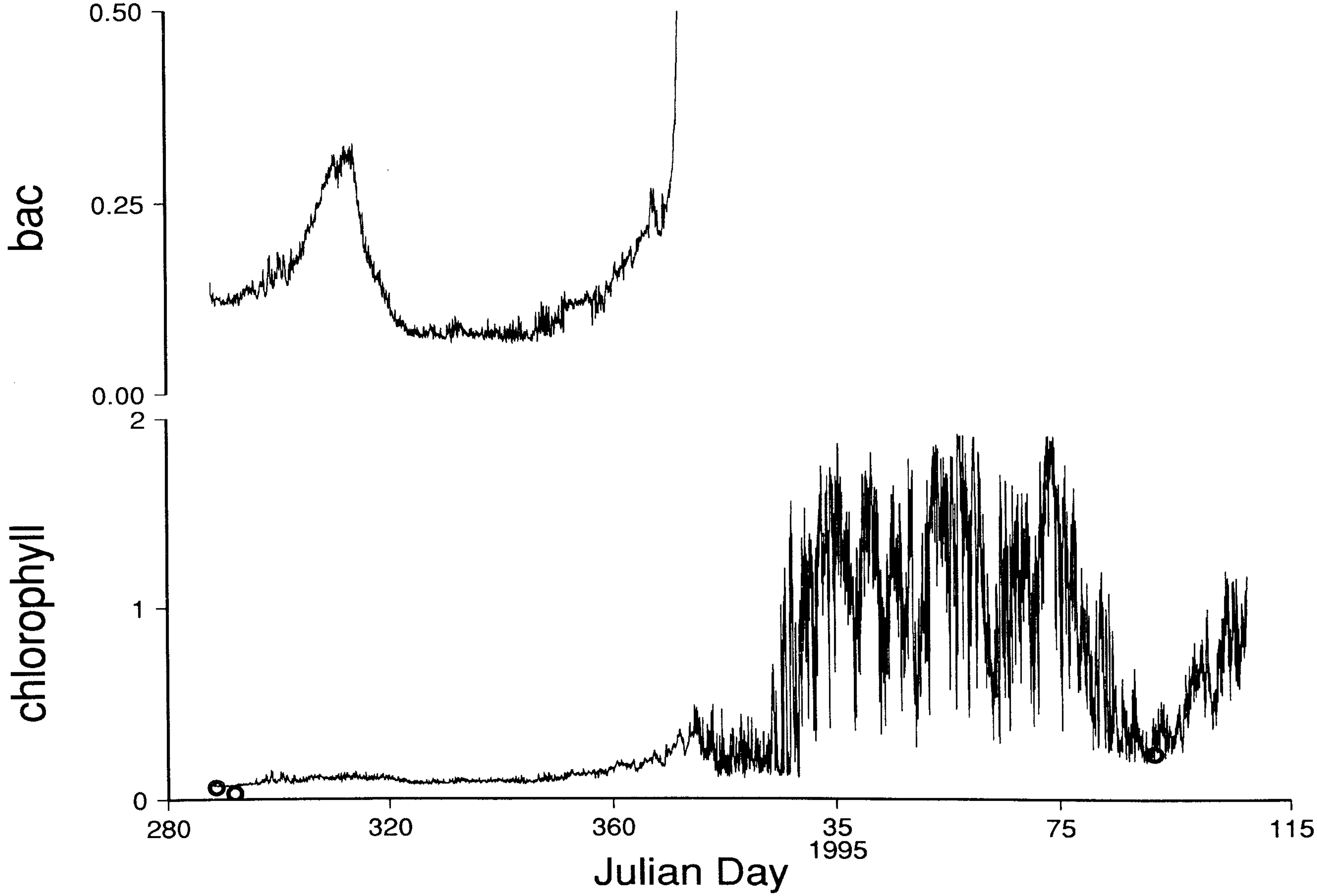


Fig.A4

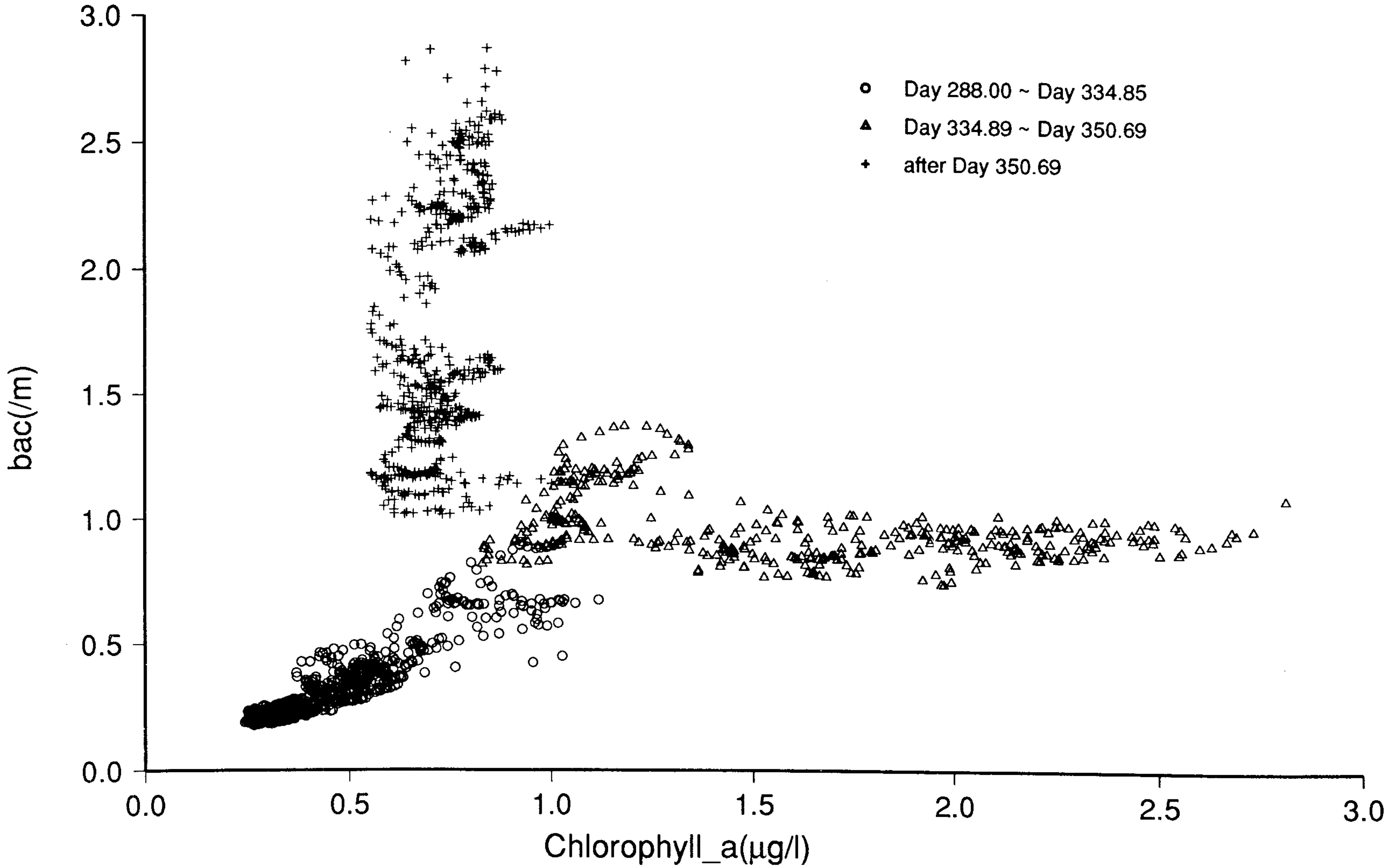

3.0
2.5
2.0
1.5
1.0
0.5
0.0
bac(/m)
Day 288.00 ~ Day 334.85
Day 334.89 ~ Day 350.69
after Day 350.69
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Chlorophyll_a(μg/l)

Fig. A5

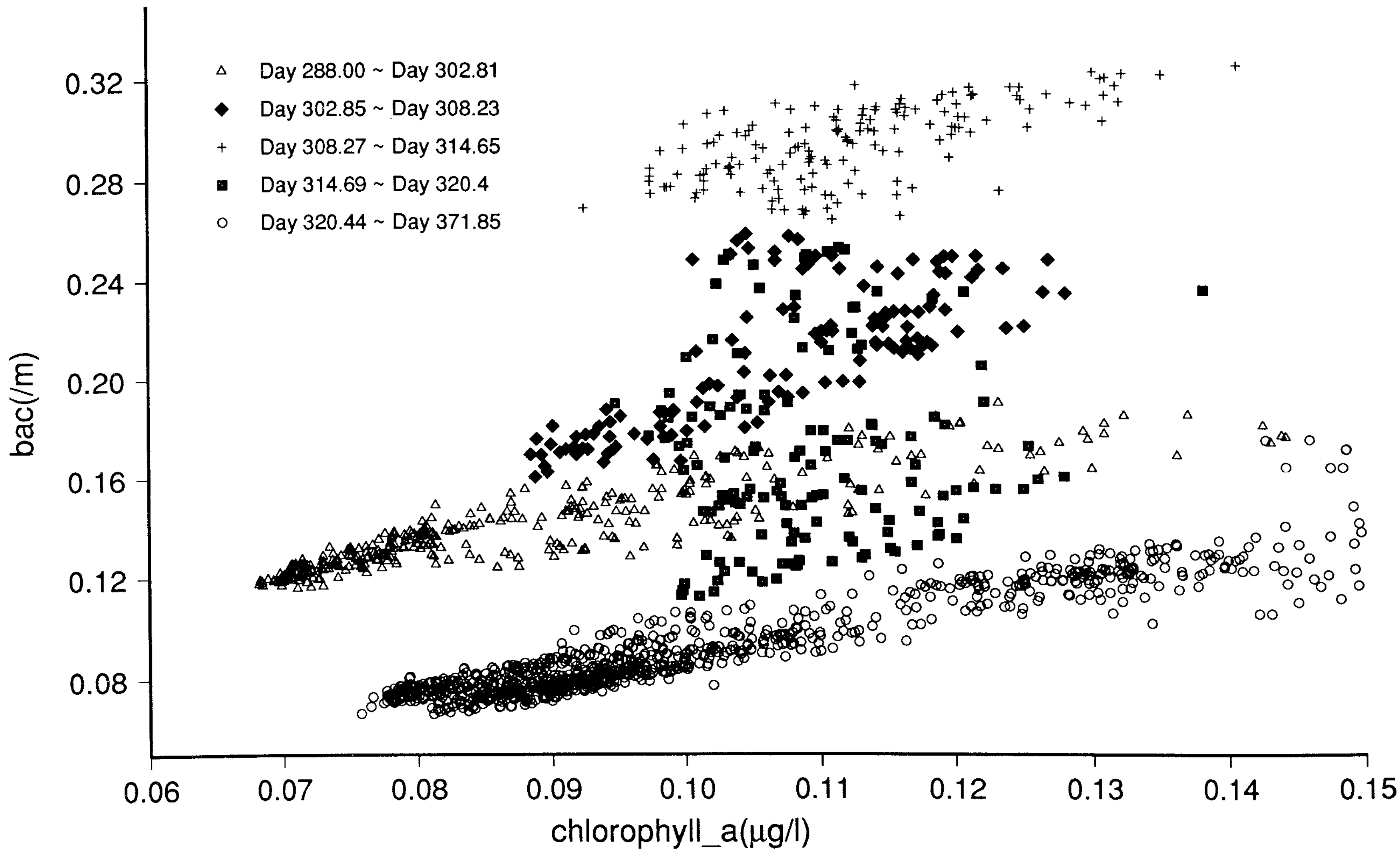

Day 288.00 ~ Day 302.81
Day 302.85 ~ Day 308.23
Day 308.27 ~ Day 314.65
Day 314.69 ~ Day 320.4
Day 320.44 ~ Day 371.85
bac(/m)
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
chlorophyll_a(μg/l)

Fig. A6

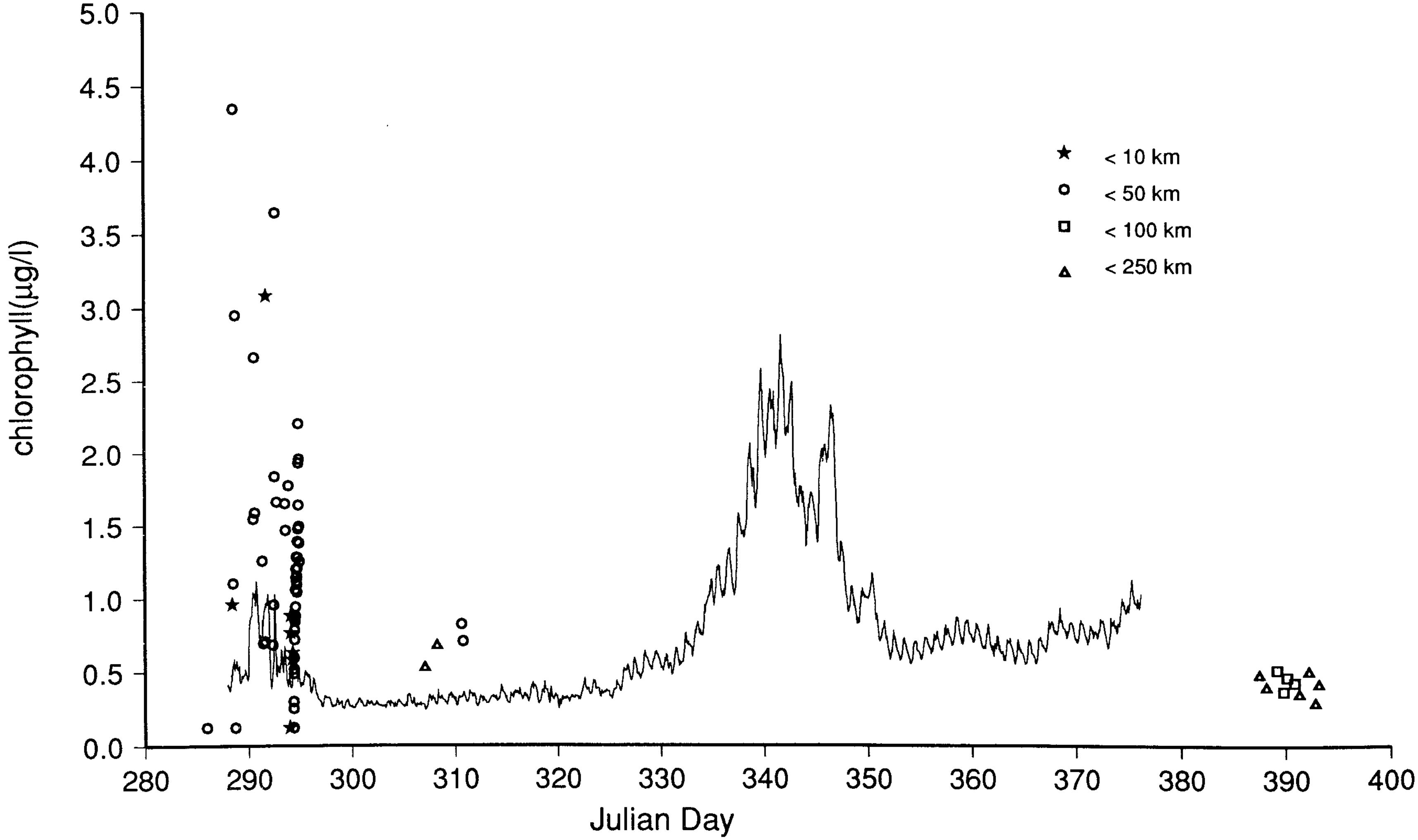
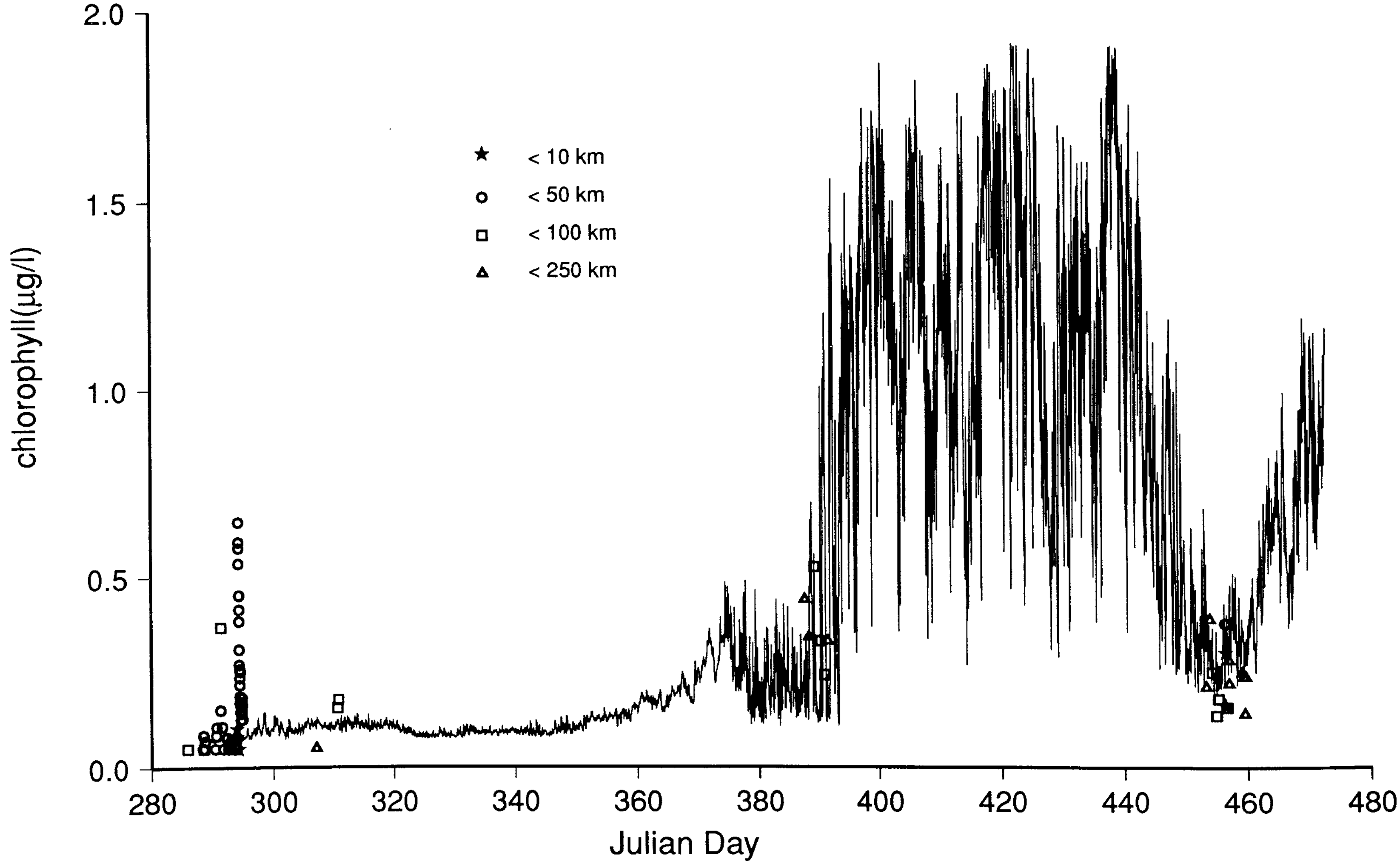

5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
chlorophyll(µg/l)
< 10 km
< 50 km
< 100 km
< 250 km
280
290
300
310
320
330
340
350
360
370
380
390
400
Julian Day

Fig. A7



chlorophyll(µg/l)
2.0
1.5
1.0
0.5
0.0
280
300
320
340
360
380
400
420
440
460
480
Julian Day
< 10 km
< 50 km
< 100 km
< 250 km

Fig. A8

Appendix B: Referenced CTD/Bottle data

Cruise/ station/ cast	time (day from 01/01/1994)	latitude	longitude	10m chlorophyll (μg/l)	60m chlorophyll (μg/l)	dist. from mooring (km)
TN04000101	285.953	16.0081	61.4929	0.123	0.049	51.924
TN04000201	288.414	15.5003	61.4922	0.961	0.049	10.775
TN04000301	288.501	15.6128	61.3858	1.102	0.084	24.214
TN04000401	288.619	15.8387	61.1504	4.343	0.049	56.293
TN04000501	288.705	15.7268	61.2707	0.123	0.049	39.982
TN04000502	288.760	15.7248	61.2668	2.945	0.069	40.199
TN04000601	290.456	15.7224	61.2651	1.543	0.049	40.201
TN04000701	290.559	15.4995	61.2682	2.656	0.084	33.183
TN04000801	290.638	15.3869	61.3845	1.585	0.105	24.338
TN04000901	291.318	15.2672	61.2868	1.256	0.151	39.025
TN04001001	291.409	15.1615	61.1531	0.693	0.368	56.065
TN04001101	291.615	15.2737	61.5008	0.705	0.106	24.709
TN04001201	291.727	15.5067	61.4988	3.081	0.049	10.145
TN04001301	292.333	15.2684	61.7401	0.683	0.076	27.064
TN04001401	292.425	15.1625	61.8515	0.957	0.079	42.088
TN04001501	292.547	15.3869	61.6178	1.837	0.049	11.450
TN04001601	292.622	15.5	61.7346	3.640	0.049	13.462
TN04001701	292.698	15.6119	61.6176	1.660	0.049	11.328
TN04001801	293.506	15.7209	61.731	1.651	0.049	25.681
TN04001901	293.580	15.8382	61.8505	1.468	0.049	42.086
TN04002001	293.674	16.0364	61.9988	1.076	0.049	66.839
TN04002101	293.857	15.7258	61.501	1.774	0.049	24.658
TN04002201	293.964	15.5145	61.5292	0.123	0.081	7.230
TN04002301	294.024	15.5179	61.5445	0.883	0.101	5.827
TN04002401	294.065	15.5221	61.562	0.765	0.071	4.395
TN04002501	294.212	15.4919	61.5347	0.588	0.049	6.582
TN04002502	294.217	15.4914	61.5358	0.632	0.049	6.482

Cruise/ station/ cast	time (day from 01/01/1994)	latitude	longitude	10m chlorophyll (μg/l)	60m chlorophyll (μg/ll)	dist. from mooring (km)
TN04002601	294.325	15.2671	61.745	0.123	0.646	27.438
TN04002602	294.341	15.2719	61.749	0.253	0.594	27.248
TN04002603	294.356	15.2774	61.7483	0.299	0.578	26.743
TN04002604	294.372	15.2872	61.748	0.520	0.536	25.918
TN04002605	294.387	15.2986	61.747	0.489	0.452	24.939
TN04002606	294.404	15.3105	61.7478	0.595	0.414	24.034
TN04002607	294.420	15.3103	61.7465	0.720	0.384	23.967
TN04002608	294.437	15.3341	61.7452	0.787	0.311	22.042
TN04002609	294.453	15.347	61.7453	0.871	0.271	21.100
TN04002610	294.470	15.3607	61.7462	0.843	0.236	20.195
TN04002611	294.486	15.3723	61.7465	0.846	0.170	19.439
TN04002612	294.501	15.3837	61.7465	0.879	0.187	18.700
TN04002613	294.517	15.3947	61.7459	0.944	0.217	17.993
TN04002614	294.533	15.4066	61.7452	1.060	0.259	17.265
TN04002615	294.548	15.4182	61.7433	1.055	0.252	16.497
TN04002616	294.563	15.428	61.7427	1.144	0.186	15.981
TN04002617	294.581	15.4429	61.7405	1.199	0.172	15.162
TN04002618	294.599	15.4583	61.7395	1.284	0.186	14.559
TN04002619	294.615	15.4694	61.739	1.117	0.172	14.238
TN04002620	294.632	15.4842	61.7371	1.199	0.142	13.804
TN04002621	294.651	15.5027	61.7356	1.042	0.160	13.564
TN04002622	294.667	15.5169	61.7348	1.097	0.124	13.587
TN04002623	294.685	15.5322	61.7332	1.149	0.145	13.705
TN04002624	294.701	15.5471	61.7325	1.210	0.149	14.063
TN04002625	294.719	15.5625	61.732	1.281	0.150	14.610
TN04002626	294.736	15.5778	61.731	1.390	0.143	15.237
TN04002627	294.754	15.595	61.7295	1.477	0.151	16.062
TN04002628	294.772	15.611	61.7282	1.478	0.141	16.958
TN04002629	294.789	15.6277	61.7278	1.641	0.142	18.063
TN04002630	294.806	15.6443	61.7279	1.929	0.163	19.287

Cruise/ station/ cast	time (day from 01/01/1994)	latitude	longitude	10m chlorophyll (µg/l)	60m chlorophyll (µg/l)	dist. from mooring (km)
TN04002631	294.823	15.6602	61.7303	2.199	0.168	20.649
TN04002632	294.839	15.6754	61.731	1.958	0.170	21.892
TN04002633	294.856	15.6906	61.7339	1.494	0.164	23.291
TN04002634	294.873	15.7063	61.7396	1.380	0.182	24.902
TN04002635	294.892	15.7251	61.7441	1.254	0.126	26.730
TN04100501	307.056	16.4049	60.2357	0.523	0.049	163.712
TN04100601	308.257	17.2187	59.6066	0.673	0.124	263.202
TN04100701	310.623	15.9994	61.519	0.823	0.156	50.590
TN04100702	310.751	16.0027	61.5243	0.706	0.178	50.834
TN04301802	387.139	14.8330	64.2499	0.479	0.413	273.256
TN04301901	387.470	15.2511	63.4981	0.478	0.440	191.435
TN04302003	388.127	15.6331	62.7662	0.393	0.342	117.377
TN04302102	389.792	16.0000	62.0008	0.369	0.332	64.081
TN04302107	389.181	16.0000	62.0025	0.516	0.526	64.188
TN04302111	390.134	16.0167	62.0102	0.466	0.330	65.973
TN04302402	390.837	16.4310	61.2454	0.431	0.243	99.624
TN04302502	391.296	16.8033	60.5040	0.347	0.331	170.288
TN04302602	392.791	17.2006	59.7657	0.286	0.226	250.134
TN04302607	392.168	17.2033	59.7697	0.499	0.295	250.025
TN04302611	393.125	17.1998	59.7662	0.415	0.261	250.043
TN04501802	452.083	14.8350	64.2447	*	0.286	282.411
TN04501901	453.042	15.2499	63.4998	*	0.326	201.537
TN04501904	453.292	15.2349	63.4973	*	0.212	201.481
TN04502104	453.917	15.6322	62.7639	*	0.389	127.079
TN04502104	454.333	16.0087	61.9648	*	0.250	68.906
TN04502108	455.000	15.9894	61.9846	*	0.137	68.873
TN04502111	455.292	15.9788	61.9078	*	0.181	62.892
TN04502201	456.292	15.7679	61.7189	*	0.379	34.595
TN04502301	456.458	15.5058	61.4953	*	0.303	0.746
TN04502301	456.458	15.5058	61.4953	*	0.162	0.746

Cruise/ station/ cast	time (day from 01/01/1994)	latitude	longitude	10m chlorophyll (µg/l)	60m chlorophyll (µg/l)	dist. from mooring (km)
TN04502402	456.667	16.4310	61.2454	*	0.159	96.518
TN04502502	457.000	16.8163	60.5028	*	0.220	165.137
TN04502607	457.000	17.2581	59.7549	*	0.281	247.715
TN04502617	459.083	17.1906	59.7700	*	0.250	241.888
TN04502619	459.375	17.1998	59.7647	*	0.238	242.911
TN04502621	459.500	17.2019	59.7752	*	0.141	242.309
TN04502622	459.625	17.1841	59.8022	*	0.238	239.138

Appendix C: Calibration of Oxygen Sensors

Oxygen sensors were calibrated in the laboratory prior to deployment. The oxygen sensors were put in flasks containing distilled water and placed in a constant temperature bath. Certified gas mixtures of oxygen and nitrogen were bubbled through the flask. A digital barometer recorded the barometric pressure. The oxygen concentration in the flask was computed from knowledge of the temperature, barometric pressure, volume fraction of oxygen in the dry gas and tabulated values of oxygen solubility in distilled water (Benson and Krause,1984). Data was collected for 2 to 3 gas mixtures and air at 3 temperatures bracketing the temperature range expected at the mooring. A nonlinear least squares regression program was used to fit the data to an equation of the form:

```
O2 = Ss(T,S)*DOX/(OA+OB*T)
```

where O2 is the oxygen concentration in micromoles per liter, Ss is the solubility in micromoles per kPa, DOX is the sensor current in μa, T is the temperature in °C, S is salinity, and OA and OB are fitted parameters describing the sensitivity of the sensor and its dependence on temperature.

When the oxygen sensor data was validated against hydrocast oxygen data for stations located near the mooring (Table C1) it was found that the sensor data consistently underestimated the station data by about 10%. The most likely explanation is that the antifoulant coating is causing some loss of sensitivity. The antifoulant coating is applied just before the sensors are deployed and after the laboratory calibration is performed. It would be desirable to calibrate the sensor after application of the antifoulant but this is not possible because the laboratory calibration must be performed before the sensors are shipped, 1 to 2 months prior to the deployment. If the antifoulant were applied at this time much of its potency might be lost before the sensors were even deployed. A sensor deployed on the Seasoar which did not have a coating of antifoulant exhibited excellent agreement between laboratory calibration and in situ validation points. To correct for the antifoulant effect the sensitivity of the sensor was adjusted by a constant factor to bring the sensor data into line with the hydrographic data. This was accomplished in an objective manner by fitting the station oxygen data shown below and the oxygen sensor current at the time of the station to the equation above using the nonlinear least squares regression program. OB was held constant at the pre-deployment value. The pre-deployment value of OA was used as an initial guess and the program was allowed to find the value of OA which minimized the sum of squares.

Table C1: Hydrographic data from JGOFS stations occupied near the mooring during the first deployment

Cruise	Station	Depth	T(°C)	S(psu)	O_2(μM)
TN042	7	4	26.6	36.11	205.4
		63	20.75	35.54	109.5
TN043	23	3	25.08	36.25	206.8
		14	25.08	36.25	205.4
		63	24.98	36.26	200.2
TN044	3	3	25.20	36.29	227.4
		63	25.03	36.26	210.2
TN045	23	2	27.56	36.38	209.1
		11	27.41	36.46	211.0
		61	25.42	36.43	196.1

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Moorings, Bio-Optical, Current Meters, Fluorometers, Transmissometers, Dissolved Oxygen, PAR, Temperature, Salinity

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Multi-variable moored systems were used to collect physical and bio-optical data over a six month period (first of two six-month periods) in the Arabian Sea (15°30'N/61°30'E) from 14 Oct.'94-17 Apr.95. We present data from MVMS' positioned at 10 and 65 m depth. Calibration and validation issues are considered in the presentation of data.