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CURRENTS AND TEMPERATURES OBSERVED IN LAKE MICHIGAN FROM JUNE 1982 TO JULY 1983

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CURRENTS AND TEMPERATURES OBSERVED IN LAKE MICHIGAN
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Abstract. An array of 15 moorings, supporting current meters at 15 and 50 m depth, was in place in Lake Michigan from June 1982 to July 1983. Six moorings surrounded the southern basin on about the 75 m isobath, six closely spaced moorings transected the mid-lake ridge and adjacent valley, and three moorings occupied the centers of the southern and northern basins. In the southern basin, monthly-averaged currents are weakly anticyclonic during June and July, cyclonic during the rest of the year, and most intense during March. Temperatures and bidaily-averaged currents both show the effects of the gravest (4-day period) vortex-mode oscillation. Also, it is shown that the seasonal thermocline became well established much earlier in 1983 (early June) than in 1982 (middle August).

1. INTRODUCTION

From June 1982 to July 1983 an array of 15 current meter moorings recorded velocity and temperature data in Lake Michigan (Tables 1 and 2 and Figures la and lb). The position, water depth, and deployment and recovery times for each mooring are listed in Table 1. All moorings supported EG&G brand vector-averaging current meters (VACMs) at 15 and 50 m depth; moorings 13, 23, and 33 supported additional VACMs at 75 m depth and moorings 23 and 33 at 4 m above the bottom. This report contains plots of current velocities (Figures 2a and 2b and Appendix A), water temperatures (Appendices B and C), and meteorological data (Appendix D) from the National Data Buoy Center (NDBC) buoys 45007 and 45002, which are located near moorings 23 and 33, respectively. Also included are particulate mass flux data (Table 3) from 23 sediment traps located on 11 of the moorings. These data show the annual variability of the circulation and thermocline depth, and demonstrate the effects of wind-forced motions and oscillations (highly variable, 2- to 7day periods), the gravest vortex-mode oscillation (4-day period), and other phenomena on the currents and temperatures in Lake Michigan.

Table I.-Location, water depth, and deployment and recovery times for each mooring

Mooring	Latitude (degrees)	Longitude (degrees)	Water Depth (m)	Deployment Date (1962)	Deployment Time (EST)	Recovery Date (1963)	Recovery Time (EST)
1	42.69	66.42	75	June 7	1019	June 25	0931
2	42.05	67.04	75	June 6	0915	June 23	1507
3	42.69	67.52	75	June9	1000	June 23	1020
4	43.32	07.77	75	June9	1416	Aug. 16	1100
5	43.69	67.41	75	July13	1212	July 19	0855
6	43.75	67.35	100	July 13	1100	July 19	1006
7	43.61	07.29	126	July 13	0950	July 19	1120
6	43.49	97.21	102	July 12	1330	July 19	1220
9	43.37	87.17	50	June 10	1024	July 20	0957
10	43.33	67.14	50	June 10	1135	July 20	1029
11	43.46	66.73	126	July 12	1050	July 16	1036
12	43.66	66.66	172	July 14	1051	July 16	1436
13	44.51	66.63	247	July 14	1536	June 20	1636
23	42.71	67.06	153	June6	1410	July 21	1113
33	45.30	66.30	156	July 15	1126	June 21	1126

[1]GLERL Contribution No. 681

Table Z.-Instrument depth, and starting and stopping times of usable data for each current meter

Instrument Number	Moor-ing	Reference/ Actual Depth (m)	Start Point Date (1962)	Start Point Time (EST)	Stop Point Date (1963)	Stop Point Time (EST)
353	1	15 / —	June7	1100	June 24	1000
347	1	50 / —	June 7	1100	June24	0900
574	2	15 / —	June 8	1000	Jan.26	1200
555	2	50 / —	June 6	1000	June 23	1500
577	3	15 / —	June 9	1100	June 23	1000
576	3	50 / —	June 9	1100	June 23	,000
571	4	15 / —	June 9	1500	Aug. 16	1100
576	4	50 / —	June9	1500	Aug. 16	1100
570	5	15 / —	July 13	1300	Dec. 21'	0000
552	6	60 / —	July 13	1300	July 19	0900
275	6	15 / —	July 13	1200	July 19	1000
349	6	50 / —	July 13	1200	July 19	1000
352	7	15 / —	July 13	1000	March 28	1600
261	7	50 / —	July 13	1000	July 19	1100
318	6	15 / —	—	—	—	—
279	6	50 / —	July 12	1500	July 19	1100
311	9	15 / —	June 10	1100	July 20	1000
315	9	50 / 47	June 10	1100	July 20	1000
556	10	15 I —	June 10	1300	Jan.7	1100
553	IO	50 / 47	June 10	1200	July 20	1100
319	11	15 / —	July 12	1100	July 16	1000
260	11	50 / —	July12	1100	July 16	1000
277	12	15 / —	—	—	—	—
316	12	50 / —	July 14	1100	June4	1000
554	13	15 I —	—	—	—	—
573	13	50 / —	Aug. 21	1700	June 20	1600
274	13	75 / —	July 14	1600	June 20	1600
572	23	15 / —	June a	1500	July 21	1100
584	23	50 / —	June0	1500	July 21	1100
566	23	75 / —	June6	1500	July 21	1100
550	23	150 / 146	June6	1500	May 3	1100
575	33	15 / —	July 15	1200	June 21	1100
569	33	50 / —	July 15	1200	June 21	1100
583	33	75 / —	July 15	1200	June 21	1100
551	33	150 / 154	July 15	1200	June 21	1100

*This date occurred in 1962

2. DATA DESCRIPTION AND COMPUTATIONS

The depth and data period for each VACM are listed in Table 2. All VACMs yielded full data returns except those at 15 m on moorings 2, 5, 7, and 10, which yielded partial returns, and on moorings 8, 12, and 13, which yielded no returns. The velocity and temperature data were recorded by the VACMs at 15-minute intervals, and later averaged at hourly intervals. The meteorological data (air temperature, barometric pressure, and wind stress computed from velocity at 5 m above the lake surface) were measured from the NDBC buoys at hourly intervals. All aforementioned hourly data are herein referred to as the raw data. A Cosine-Lanczos filter with a 60-point taper (40-hour half-power point), described by Mooers and Smith (1968), was applied to all raw data to remove the dominant signal (i.e., the 14- to 17.5-hour inertial and/or basin-length internal wave oscillations; see Mortimer, 1971, for a description and Gottlieb et al., 1989, for examples). Unless otherwise noted, all computations and data presentations described here use the filtered data

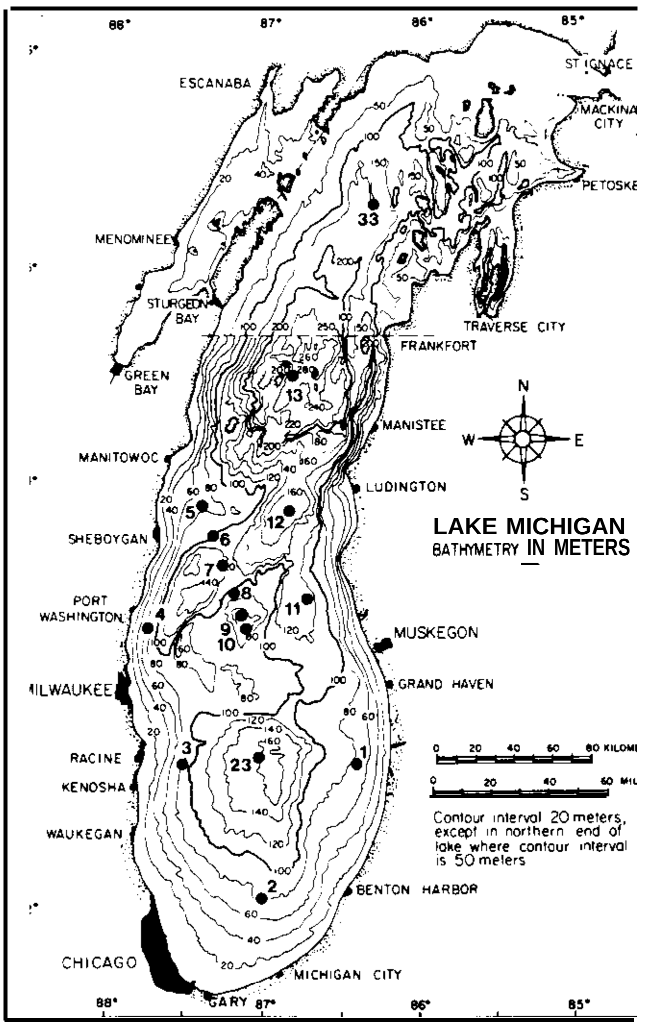

Figure la. Bathymetry and locations of the 15 moorings constituting the array in Lake Michigan. Moorings 23 and 33 were located close to National Data Buoy Center buoys 45007 and 45002, respectively. The exact locations, water depths, deployment and recovery times, and starting and stopping times of usable data are listed in Tables 1 and 2. (From Mortimer, 1971.)

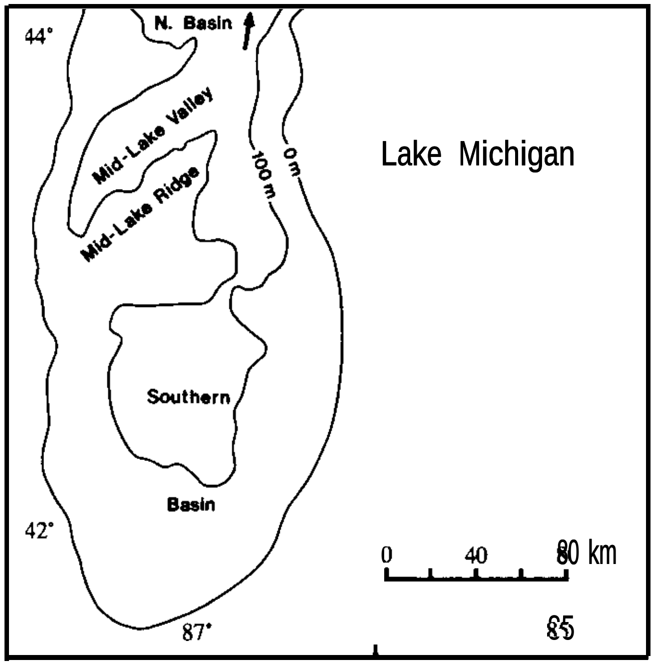

Figure lb. Major bathymetric features of southern Lake Michigan

The wind stress (Appendix D) was computed using $\tau = C_d W^2$, where W is the measured wind speed and $C_d(W)$ is the drag coefficient computed using the method of Liu and Schwab (1987). Under the assumption of no air-sea temperature difference (i.e., neutral stability), Cd becomes an almost linear function of W. Representative values for the minimum, maximum, mean, and standard deviation of Cd are 0.00012, 0.00215, 0.00102, and 0.00026.

3. DATA PRESENTATIONS

Examination of the monthly-averaged currents (Figures 2a and 2b) show that, for the features shown in Figure lb, the general circulation pattern is cyclonic around the northern and southern basins, cyclonic around the mid-lake valley, and anticyclonic around the mid-lake ridge. The monthly-averaged currents are strongest (up to 13 cm/s) and most organized during March, and are very weak and slightly anticyclonic around the southern basin (i.e., opposing the general circulation pattern) during June and July of both years. The currents are almost always southeastward and northeastward at moorings 13 and 12 respectively, implying a permanent convergent flow somewhere offshore of Manistee (see Figure la).

Filtered, bidaily-averaged currents (Appendix A) may be divided into three categories: (1) Relatively strong and steady currents (e.g., mooring 4 during March, Figures A.1 and A.2) reflect the general, wind-driven circulation pattern. The steady currents are strongest during winter and over periods of relatively steady winds, and are very weak during summer. (2) Superimposed on the steady currents are variable currents (e.g., mooring 3, 15 m depth during November, Figure A.l) that reflect the lake's response to variability in the atmospheric forcing (which occurs over 2- to 7day periods, Appendix D). Most of the currents displayed in Appendix A contain both a steady and variable component, and in some cases the two are indistinguishable. (3) Propagation of the gravest vortex-mode

Figure 2a.--Monthly-averaged currents computed from the raw data at each depth level for each mooring from 1982. The sticks point toward the direction the current is heading (north is up). The placement of the individual diagrams schematically represents the placement of the moorings in the array.

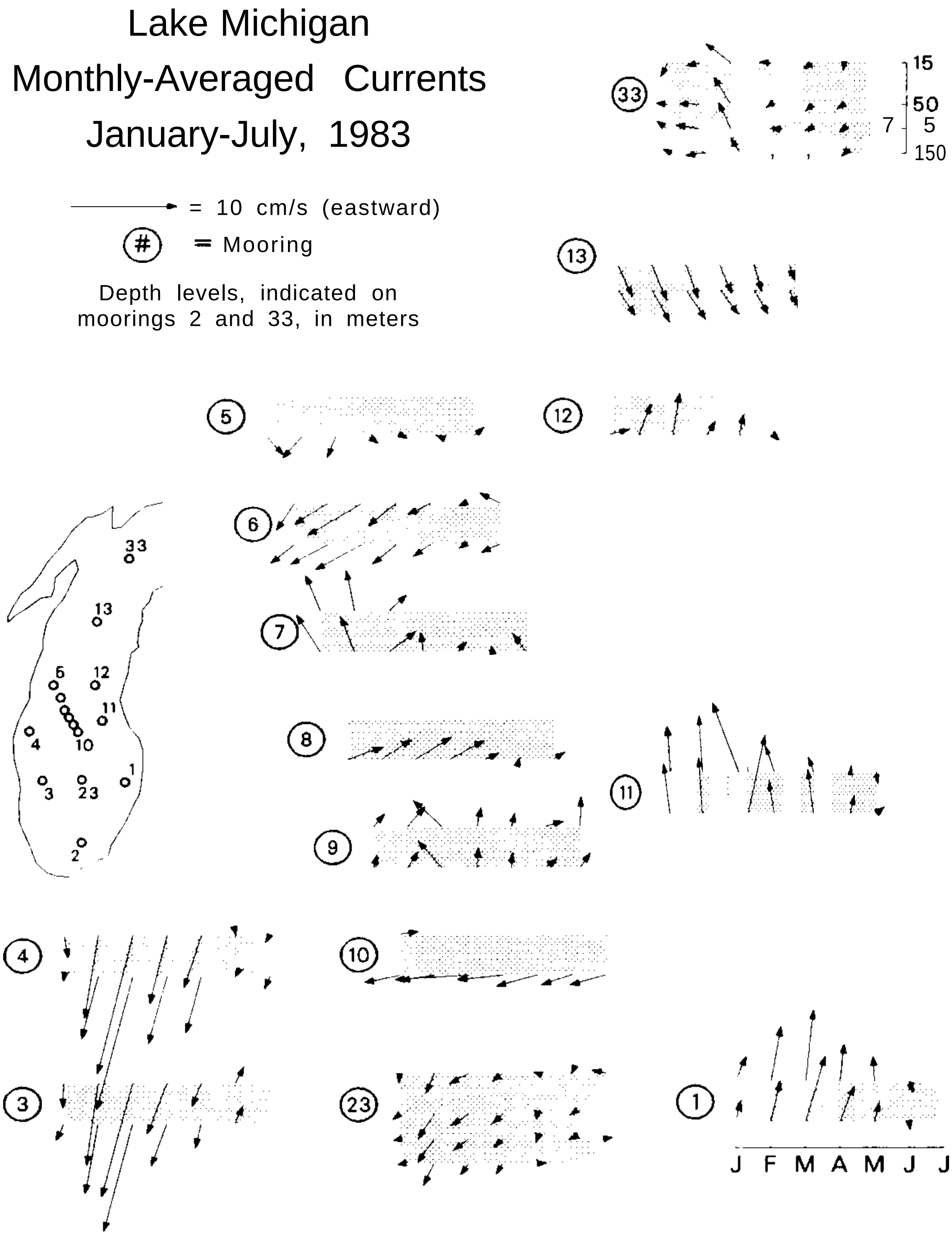

Figure **2b.--Monthly-averaged currents,** as in Figure **2a** but from 1983.

Table 3.--Mass fluxes computed from the sediment trap samples

Mooring	Trap Depth (m)	Period (days)	Mass (g)	Flux (g/m²/day)
1	20	380	11.092	3.840
2	20	350	7.549	2.483
3	20	379	5.741	1.058
4	19	433	7.704	2.217
5	20	371	3.509	1.225
7	20	371	4.141	1.377
11	20	371	5.795	1.927
12	20	359	4.547	1.520
12	72	359	1.717	0.574
12	147	359	12.722	4.077
12	167	359	26.250	8.755
13	19	341	1.150	0.415
13	145	341	1.207	0.435
13	221	341	3.529	1.313
13	241	341	10.754	3.893
14	21	341	1.770	0.543
14	58	341	3.050	1.107
14	133	341	7.395	2.575
14	153	341	12.722	4.502
23	24	405	4.947	1.495
23	55	408	4.872	1.473
23	131	405	2.481	0.750
23	151	405	13.030	3.939

oscillation (4-day period) in the southern basin produces currents (schematically diagrammed in Figure 3) that typically are rotary (e.g., mooring 9, early December, Figures A.3 and A.4). Vortex mode oscillations, described in detail by Saylor et al. (1980), are the lake's barotropic, long-period, topographically confined response to suddenly imposed wind stresses, and are similar in nature to continental shelf waves. Although weaker than the other two currents, rotary currents are observable during periods of weak, steady currents and/or at certain locations (i.e., moorings 9, 10 and 23). However, variability occurring over a 4day period in the currents (Appendix A) and temperatures (Appendix B) at other moorings is partially attributable to the vortex-mode oscillation.

Appendix B shows that the annual temperature cycle has a maximum around early September at 15 m depth, and early November at 50 m; minimums are found in late March at both depths. Very large (up to 13 °C) and abrupt (within a 6-hour period) temperature fluctuations concurrent with the annual cycle maximums at 15 and 50 m depth (Figures 8.1 and 8.2) are observed at moorings 1, 2, 3, and 4, indicating the response of the thermocline to wind and other disturbances. Large and abrupt fluctuations are also observed in early July 1983 at 15 m depth, at moorings 11 and 23 (Figure B.l) and at moorings 6 and 9 (Figure B.3), showing that in 1983 the thermocline penetrated through the 15 m depth level about 2 months earlier than in 1982.

Contour maps of weekly-averaged temperatures at 50 m depth (Appendix C) around the period of large temperature fluctuations (early November) are consistent with a cyclonic circulation of the waters above the thermocline. Very warm (7 to 8 °C) water formed in the shallow, southern end of the lake is drawn northward along the lake's eastern side, maintaining warmer temperatures as far north as mooring 12 (Figures C.3, C.4, and C.5). Cold (4.5 to 5.5 °C) water from the northern basin is carried southwestward through the mid-lake valley and then southward along the lake's western side.

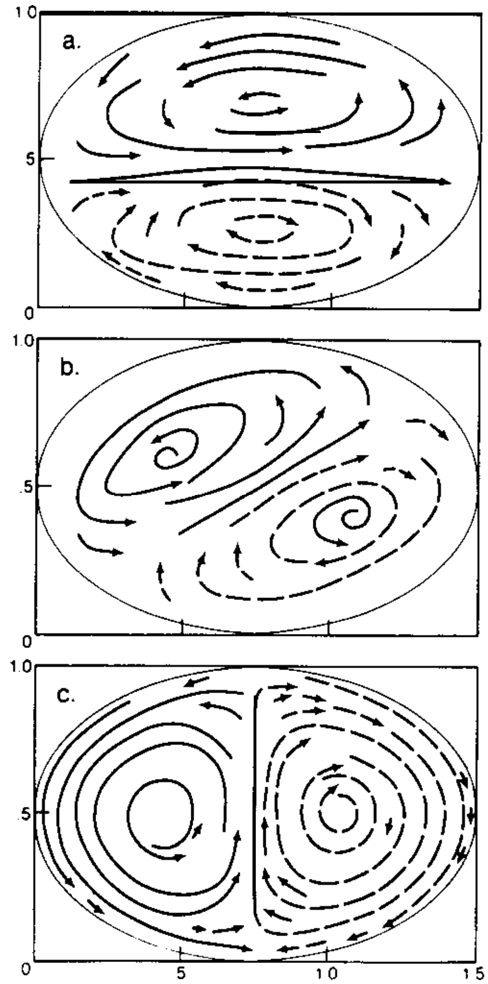

Figure 3.--The circulation pattern induced by me gravest vortex-mode oscillation in Lake Michigan's southern basin at times (a) t = 0, (b) t = 12 hours, and (c) t = 24 hours. (From Saylor et al., 1980.)

Especially prominent (Figures C.3 and C.4) are adjacent-lying tongues of warm and cool waters occupying the central (mooring 7) and southern (mooring 8) portions of the mid-lake valley, respectively. Consistent with a cyclonic circulation around the valley, the warm tongue appears to contain water entrained from the lake's warmer eastern side, while the cool tongue probably contains colder, upwelled water of northern basin origin.

4. REFERENCES

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LIU, P.C., and D.J. SCHWAB. A comparison of methods for estimating u_* from given u_z and air-sea temperature differences. Journal of Geophysical Research 92(C6):6488-6494 (1987).

Mooers, C.N.K., and R.L. Smith. Continental shelf waves off Oregon. Journal of Geophysical Research 73(2):549-557 (1968).

Mortimer, C.H. Large-Scale oscillatory motions and seasonal temperature changes in Lake Michigan and Lake Ontario. Special Report No. 12, Center for Great Lake Studies, University of Wisconsin, Milwaukee, 217 pp. (1971).

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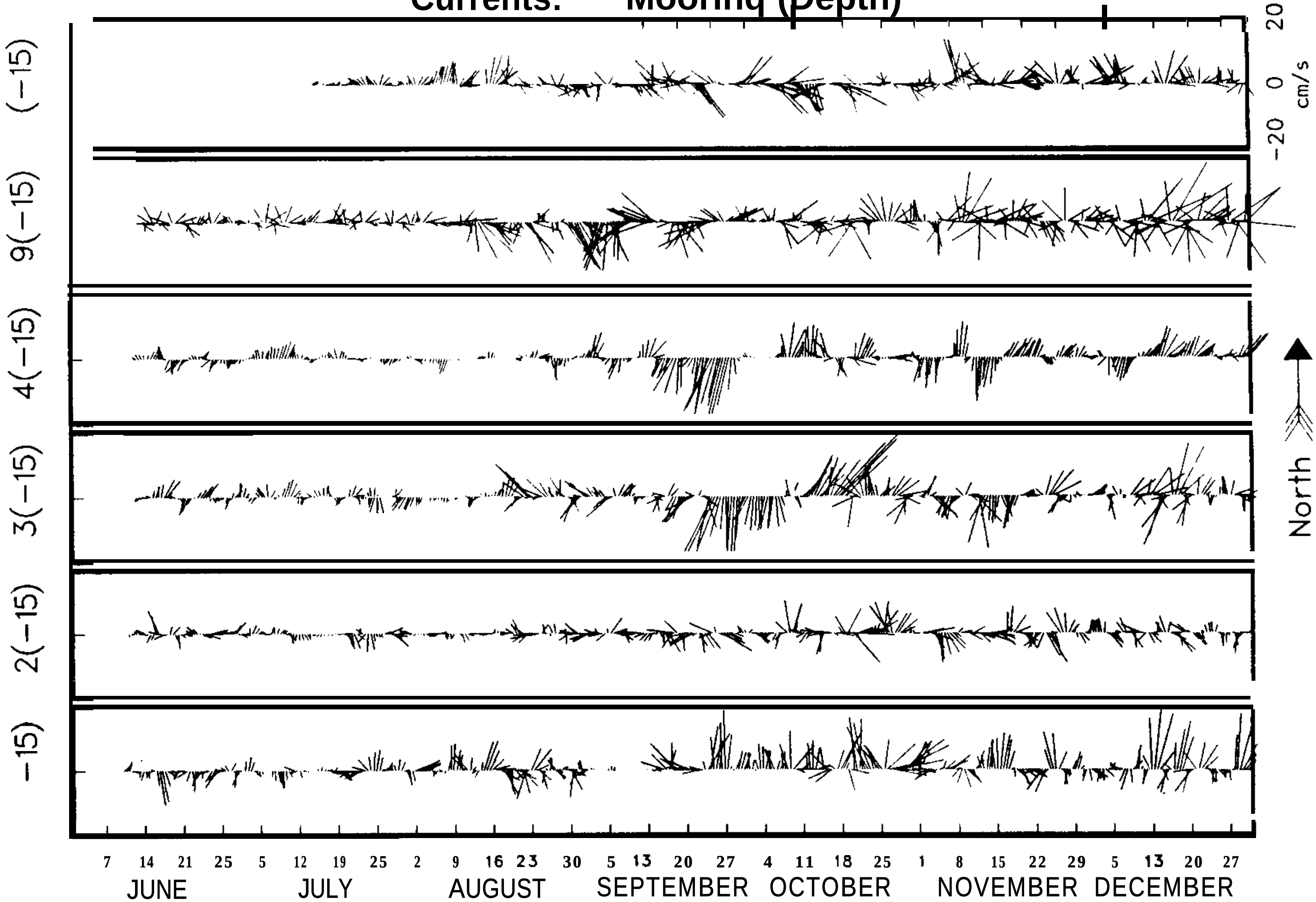
Appendix A: Bidaily-Averaged Currents

Stick diagrams of 40-hour low-pass-filtered, bidaily-averaged currents at the following moorings and depth levels:

Figure A.1--1, 2, 3, 4, 9, and 11 (15 m)
Figure A.2--1, 2, 3, 4, 9, and 11 (50 m)
Figure A.3--23, 10, 9, 7, 6, and 5 (15 m)
Figure A.4--10, 9, 8, 7, 6, and 5 (50 m)
Figure A.5--23, 11, 12, 13 (50 m), and 33 (50 and 15 m)
Figure A.6--23 (148 and 75 m), 12 (50 m), 13 (75 m), and
33 (154 and 75 m)

The sticks point toward the direction the current is heading (north is up).

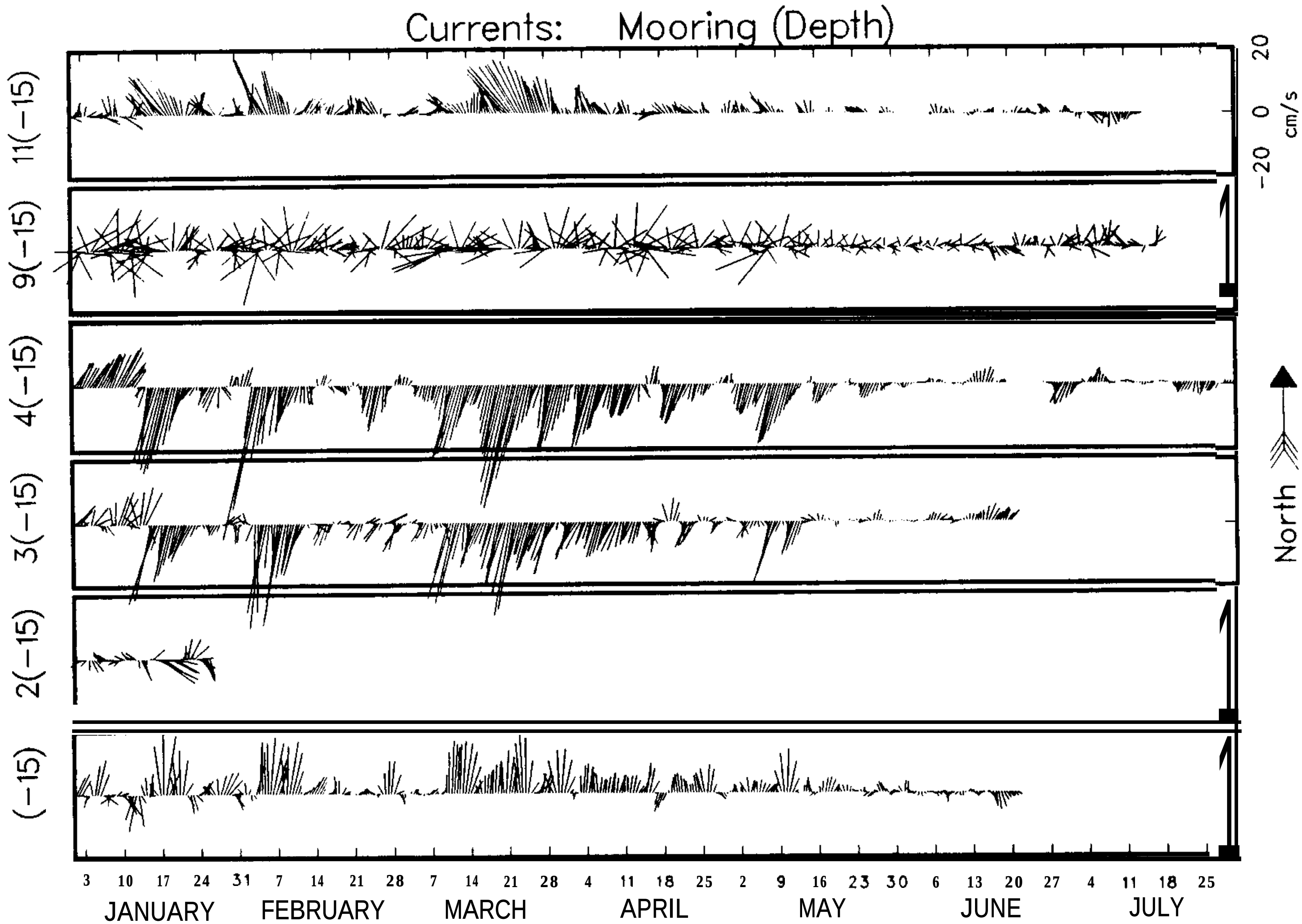
Currents: Mooring (Depth)



Lake Michigan 1982

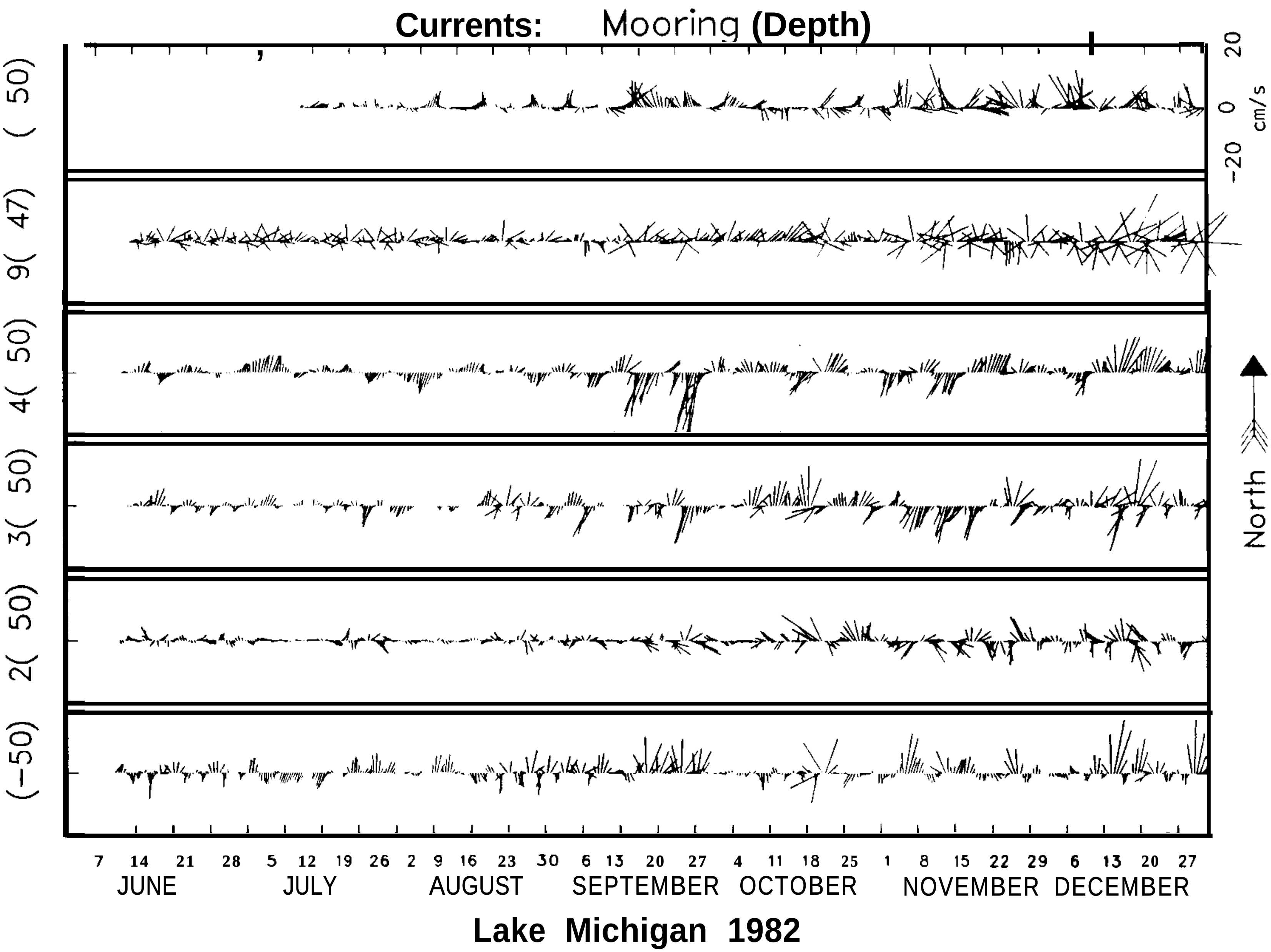
Figure A.1

2



Lake Michigan 1983

Figure A. 1 (continued).



Currents: Mooring (Depth)
(50)
9(47)
4(50)
3(50)
2(50)
(−50)
20
0
−20
cm/s
North
7 14 21 28 5 12 19 26 2 9 16 23 30 6 13 20 27 4 11 18 25 1 8 15 22 29 6 13 20 27
JUNE JULY AUGUST SEPTEMBER OCTOBER NOVEMBER DECEMBER
Lake Michigan 1982

Figure A.2

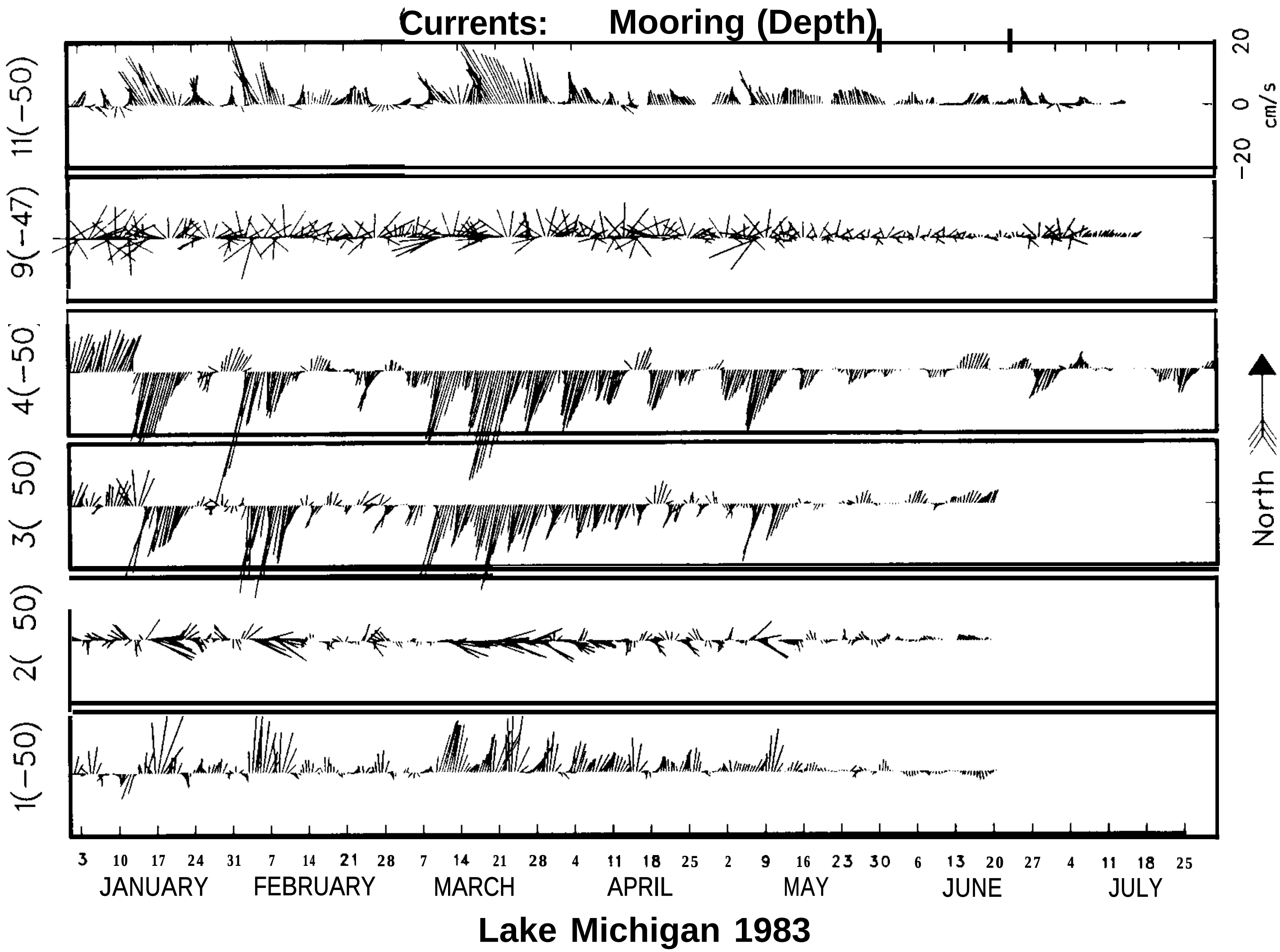
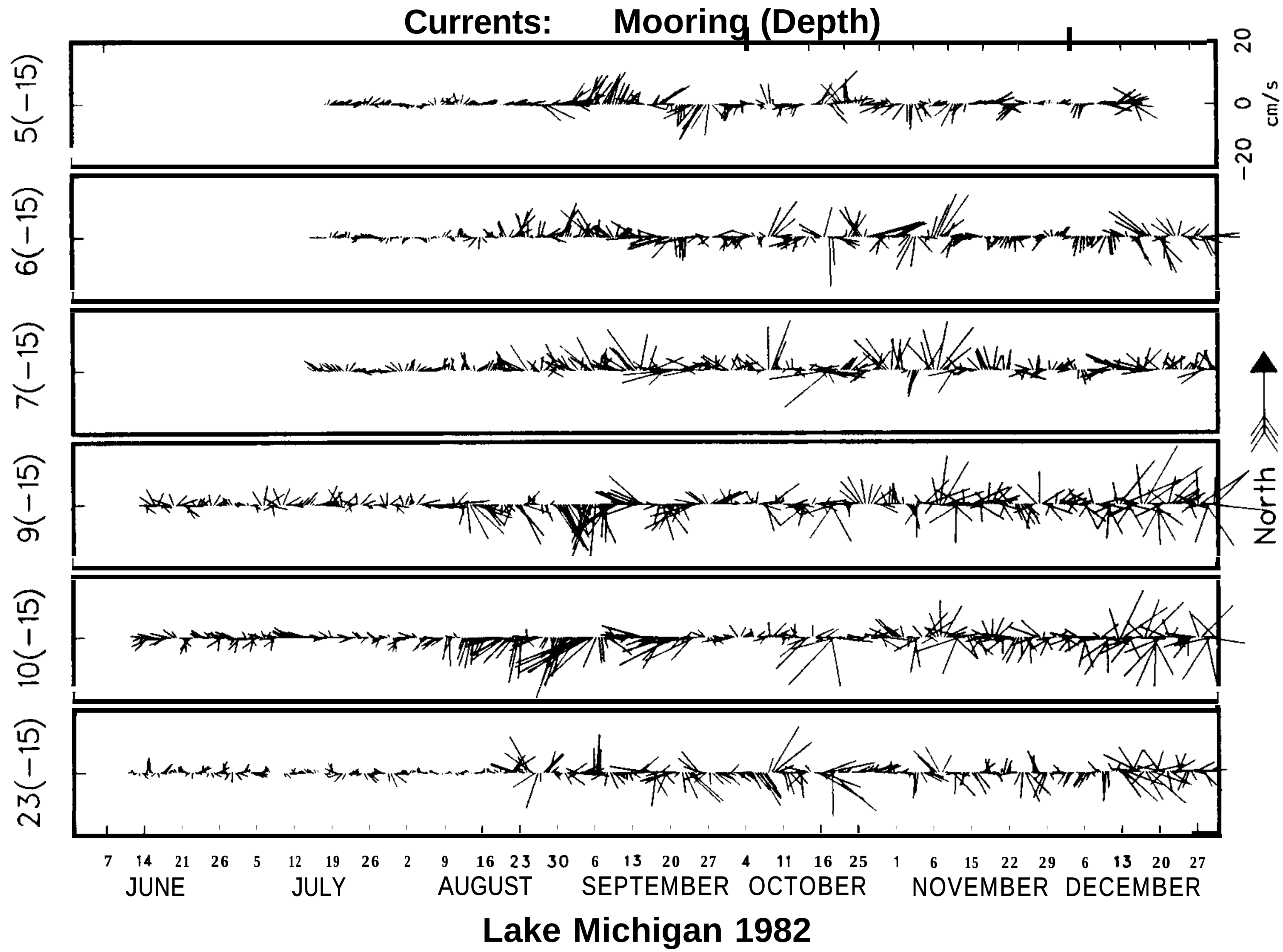


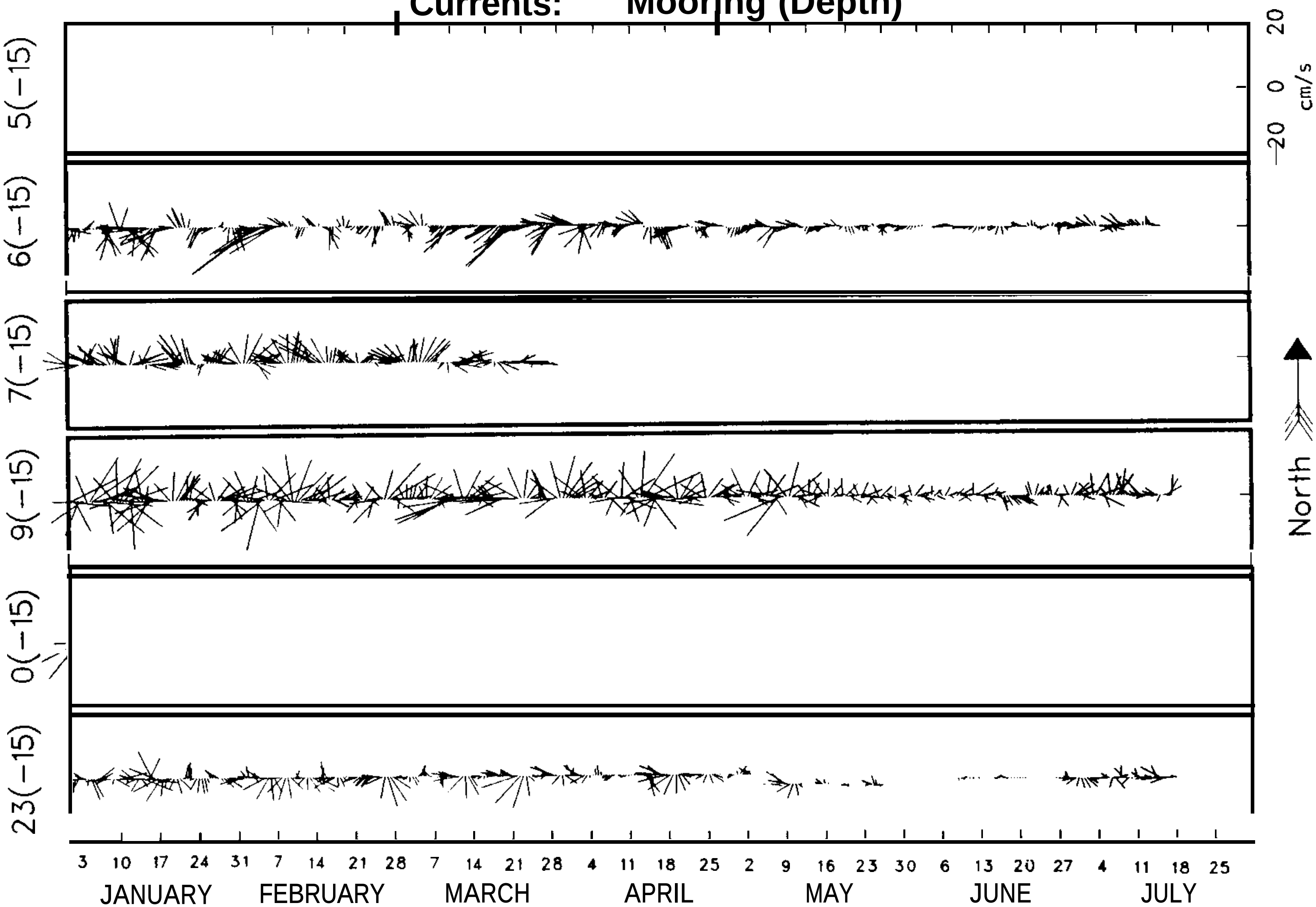
Figure A.2 (continued).



Currents: Mooring (Depth)
5(−15)
6(−15)
7(−15)
9(−15)
10(−15)
23(−15)
20
0
−20
cm/s
North
7 14 21 26 5 12 19 26 2 9 16 23 30 6 13 20 27 4 11 16 25 1 6 15 22 29 6 13 20 27
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
Lake Michigan 1982

Figure A.3

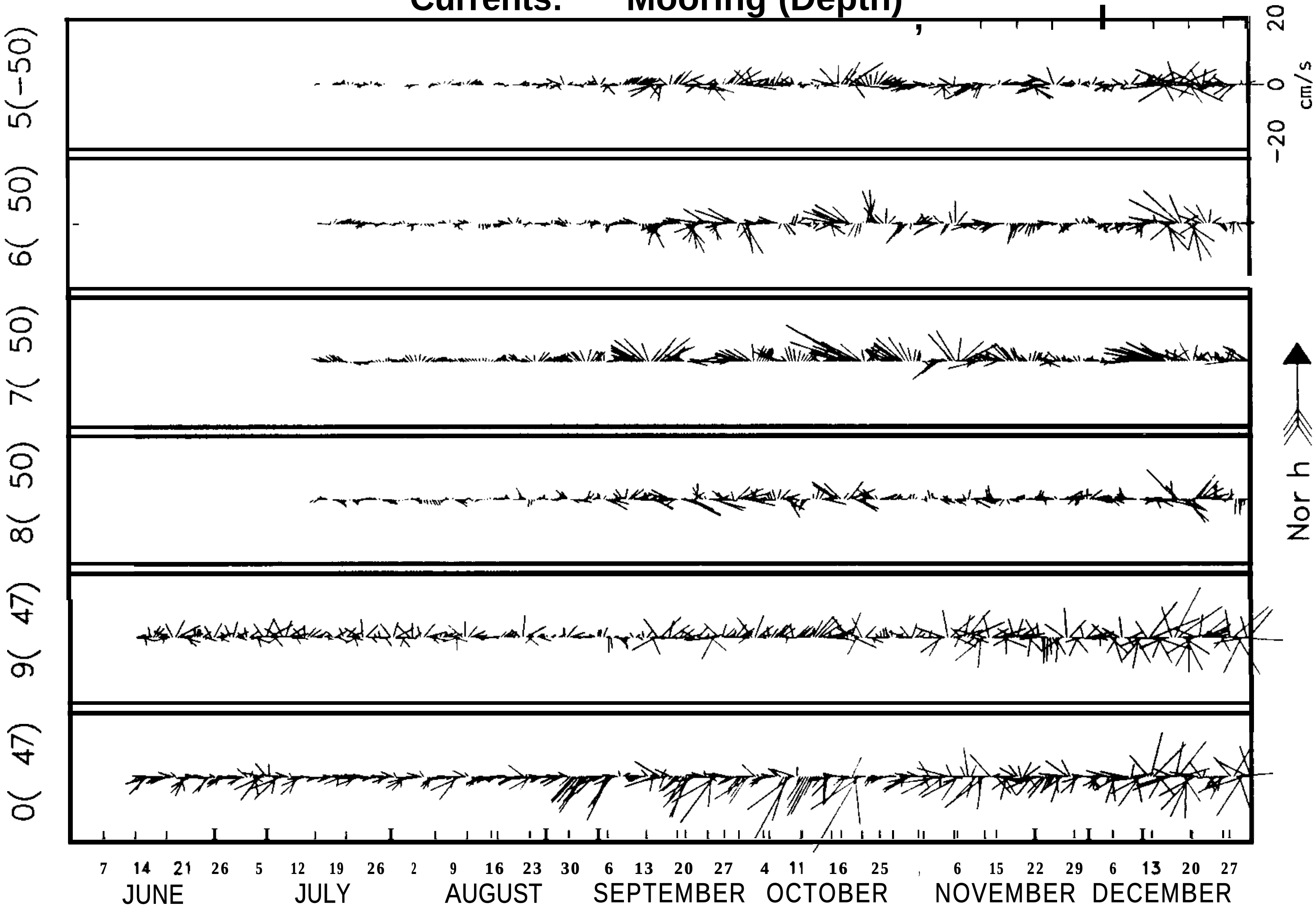
Currents: Mooring (Depth)



Lake Michigan 1983

Figure A.3 (continued).

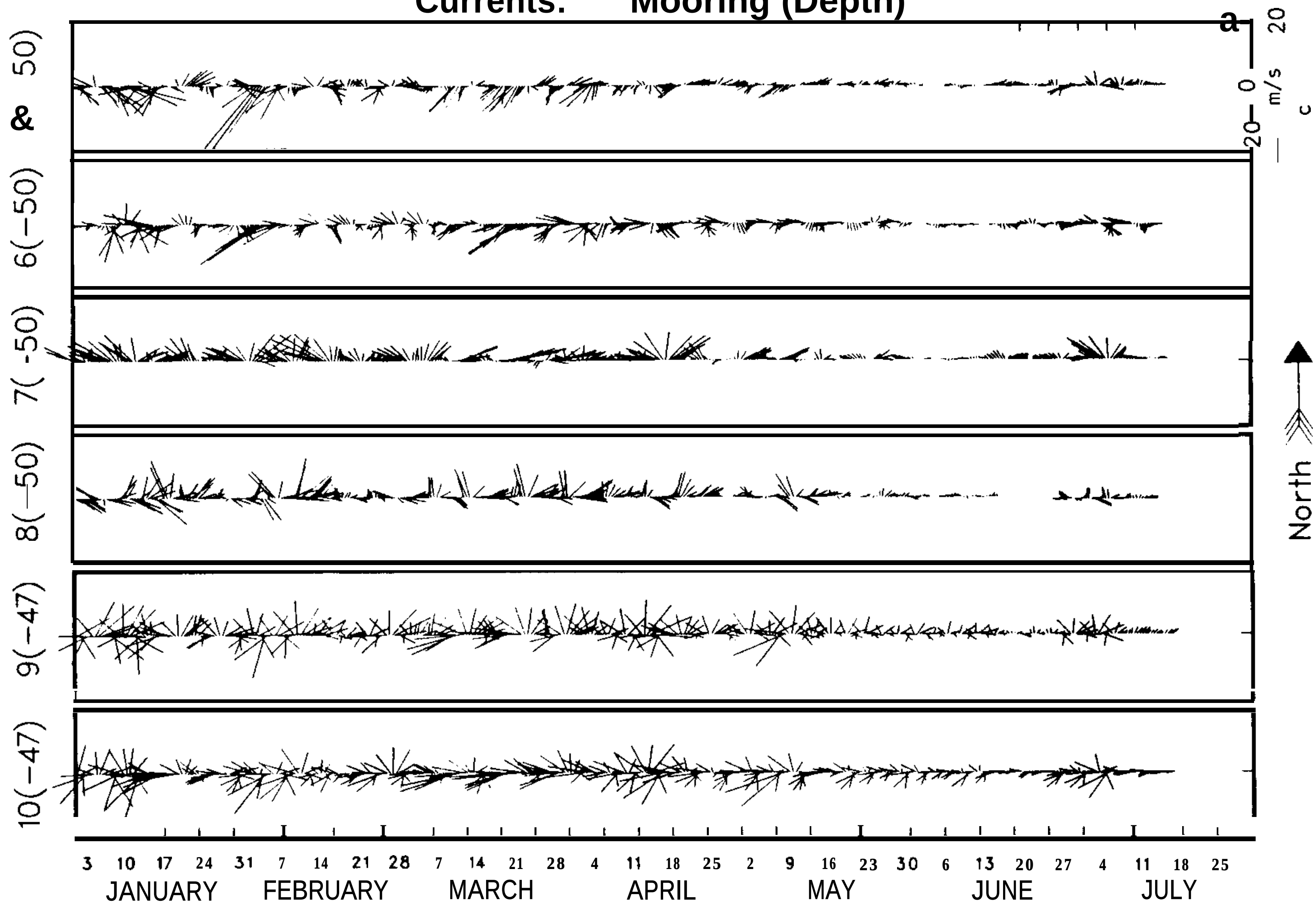
Currents: Mooring (Depth)



Lake Michigan 1982

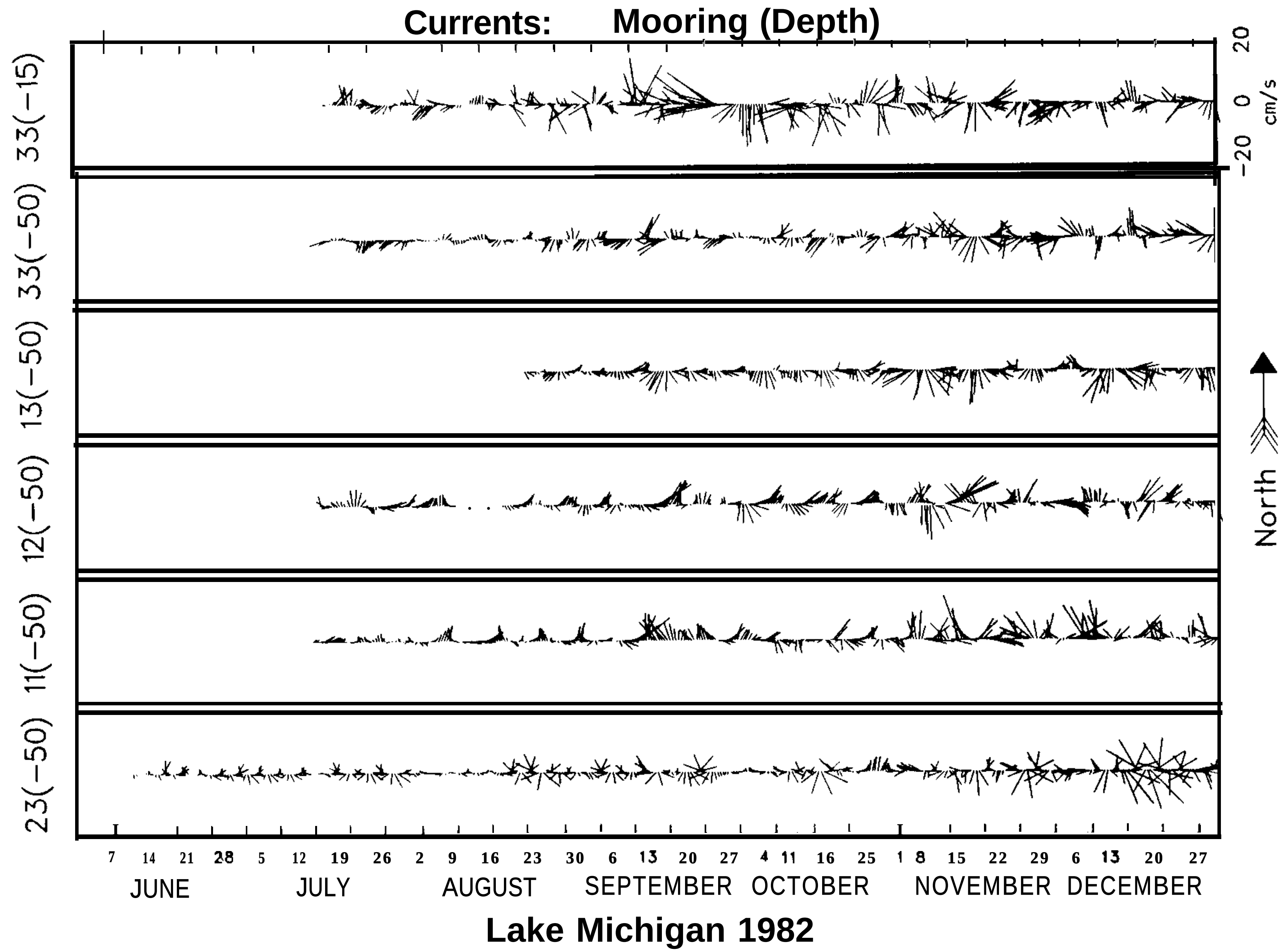
Figure A.4

Currents: Mooring (Depth)



Lake Michigan 1983

Figure A.4 (continued).



Currents: Mooring (Depth)
33(−15)
33(−50)
13(−50)
12(−50)
11(−50)
23(−50)
20
0
−20
cm/s
North
7 14 21 28 5 12 19 26 2 9 16 23 30 6 13 20 27 4 11 16 25 1 8 15 22 29 6 13 20 27
JUNE JULY AUGUST SEPTEMBER OCTOBER NOVEMBER DECEMBER
Lake Michigan 1982

Figure A.5

20

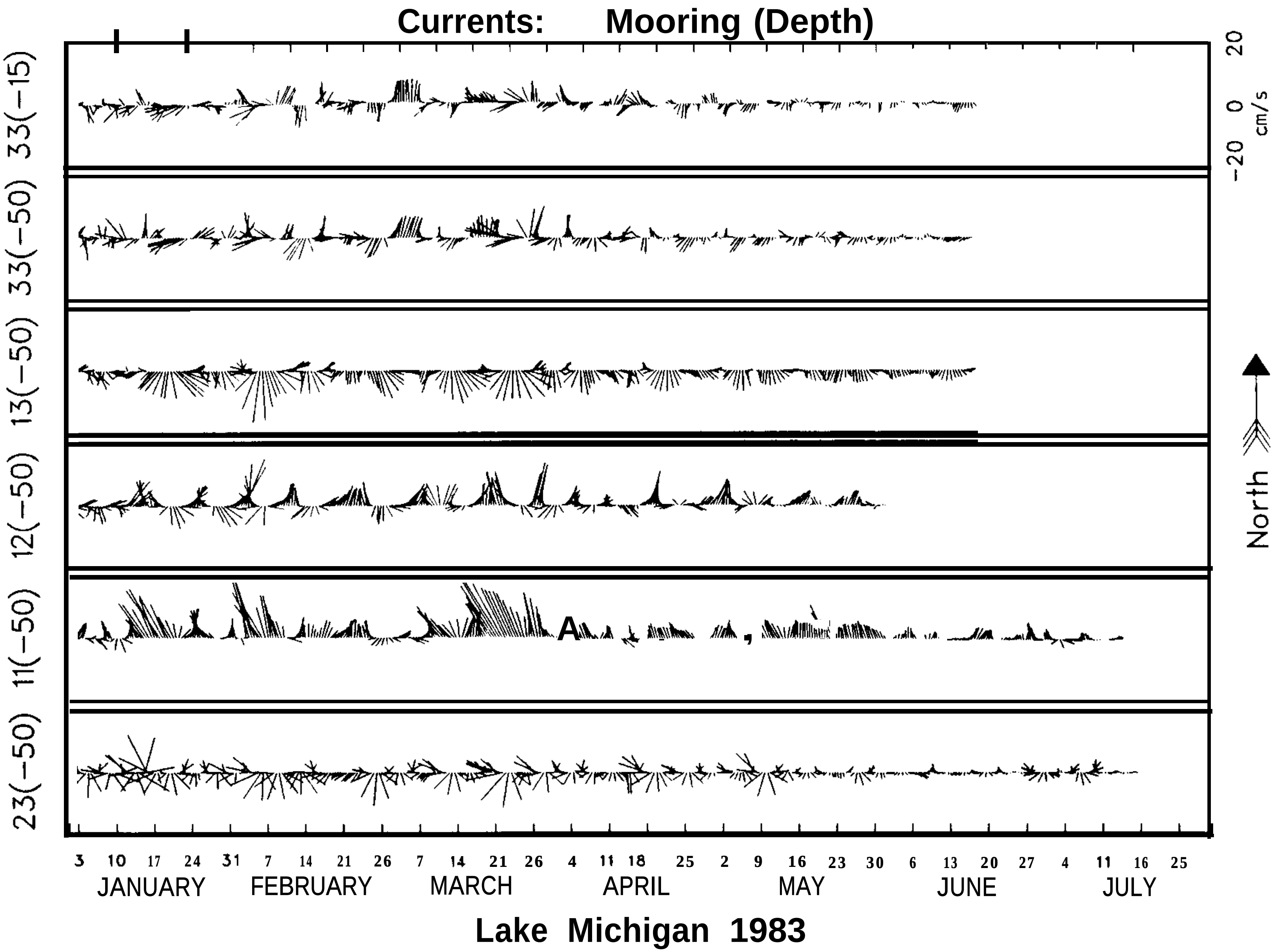


Figure A.5 (continued).

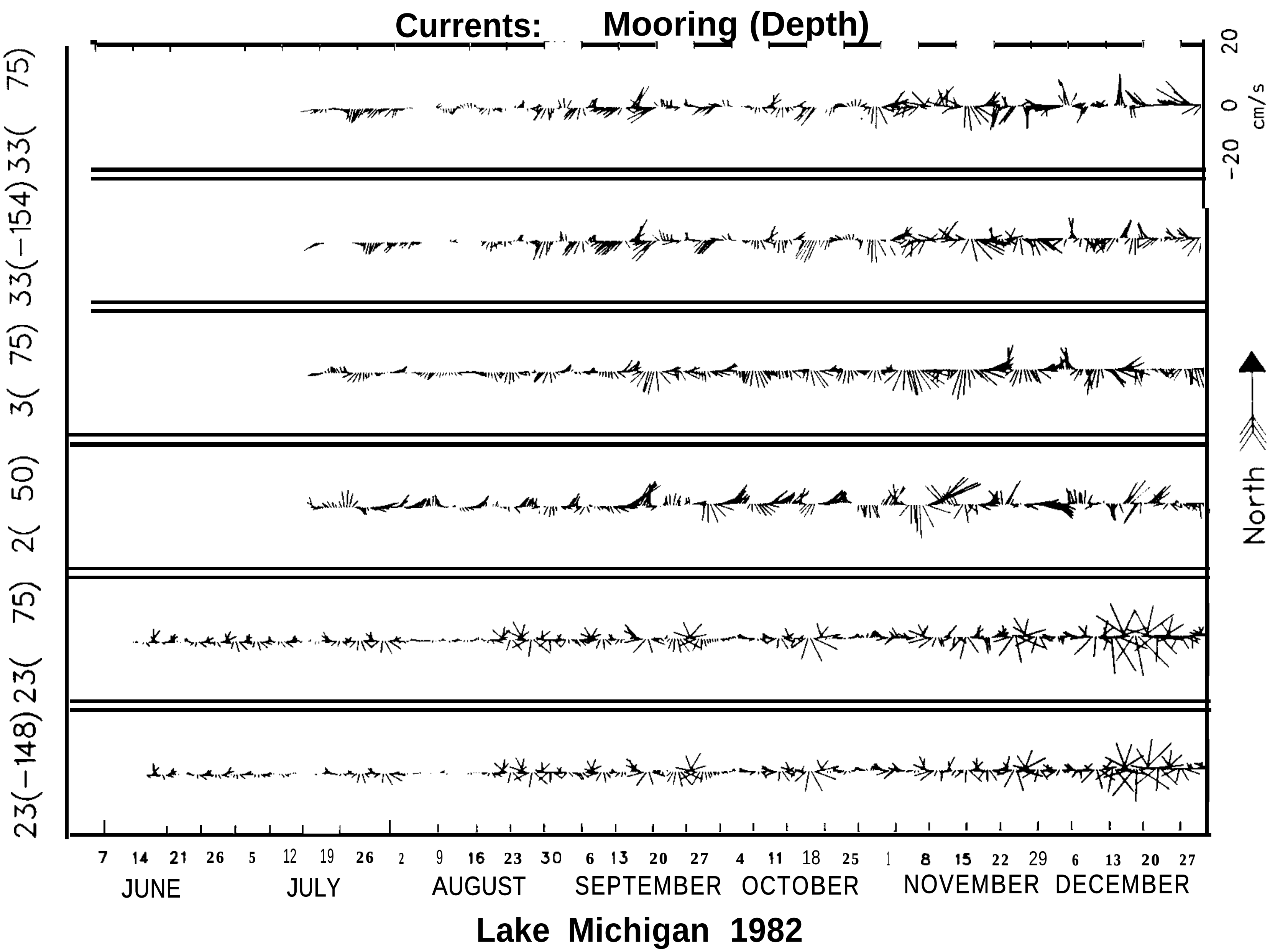
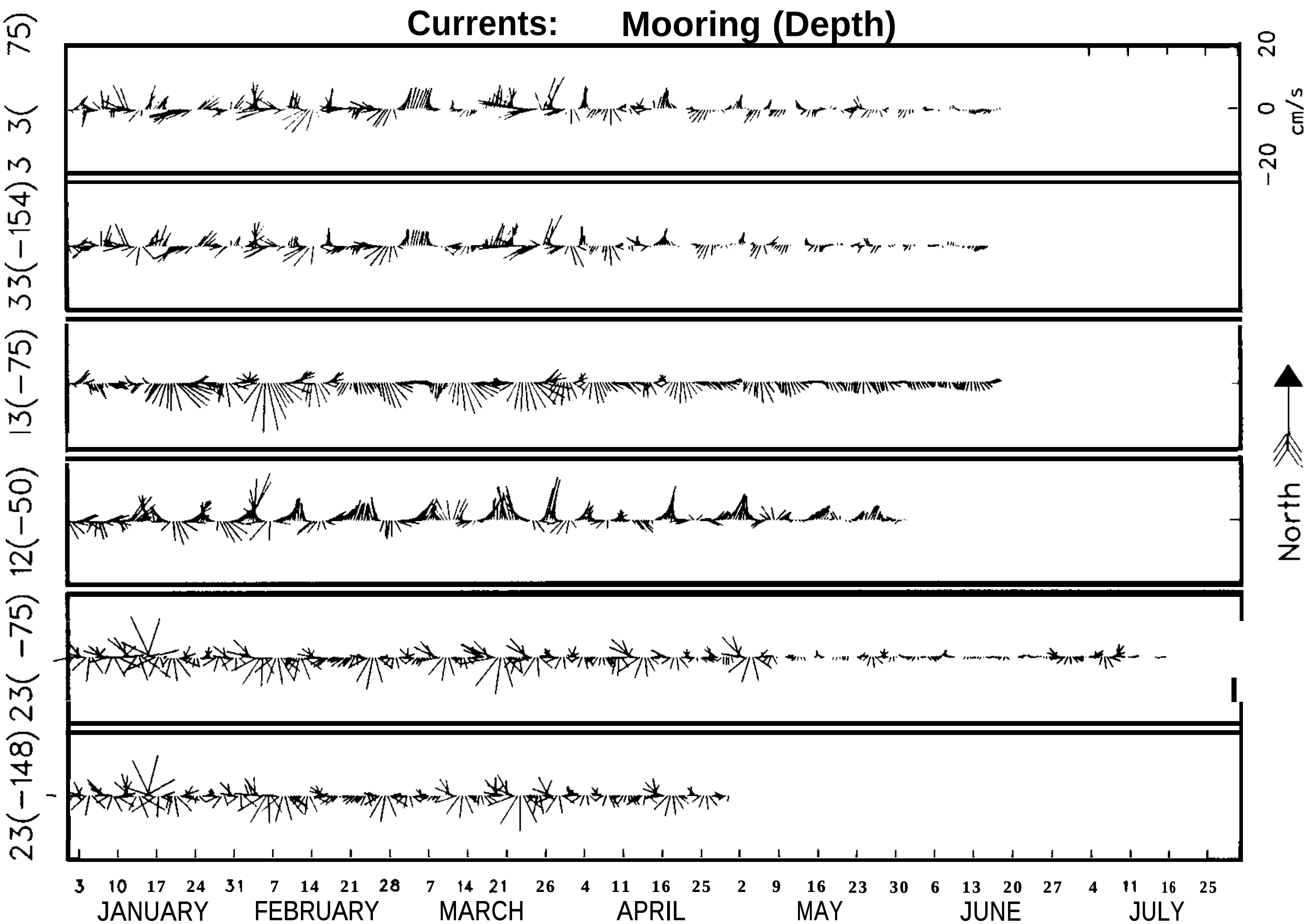

Currents: Mooring (Depth)
33(75)
33(−154)
3(75)
2(50)
23(75)
23(−148)
20
0
−20
cm/s
North
7 14 21 26 5 12 19 26 2 9 16 23 30 6 13 20 27 4 11 18 25 1 8 15 22 29 6 13 20 27
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
Lake Michigan 1982

Figure A.6



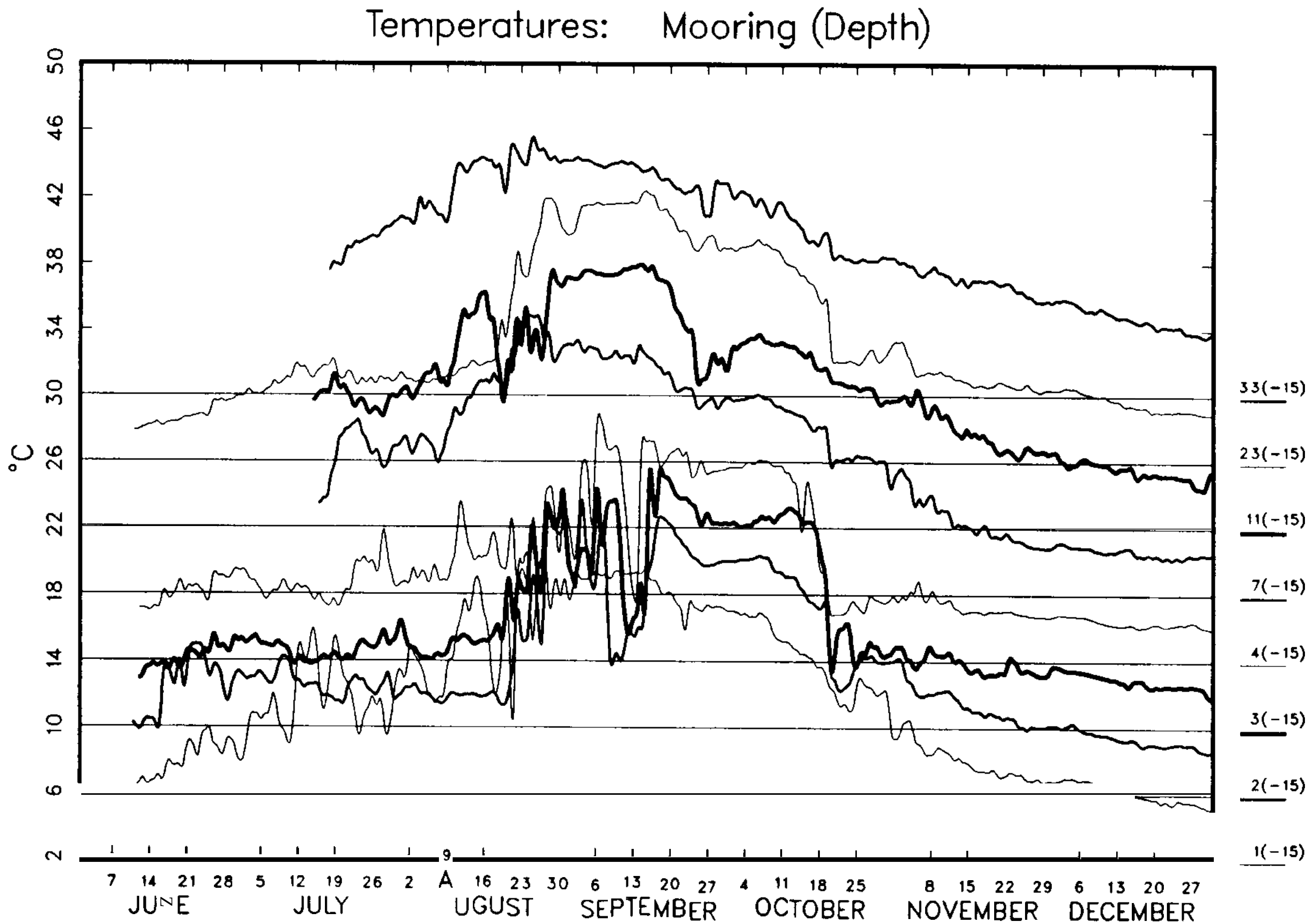
Lake Michigan 1983

Figure A.6 (continued).

Appendix B: Water Temperatures

Plots of 40-hour low-pastfiltered temperatures at the following moorings and depth levels:

Figure B.1--1, 2, 3, 4, 7, 11, 23, and 33 (15 m)
Figure B.2--1, 2, 3, 4, 7, 11, 23, and 33 (50 m)
Figure B.3--5, 6, 9, and 10 (15 and 50 m)
Figure B.4--8 (50 m), 12 (50 m), 13 (75 and 50 m),
23 (148 and 75 m), and 33 (154 and 75 m)



Lake Michigan 1982

Figure B.1

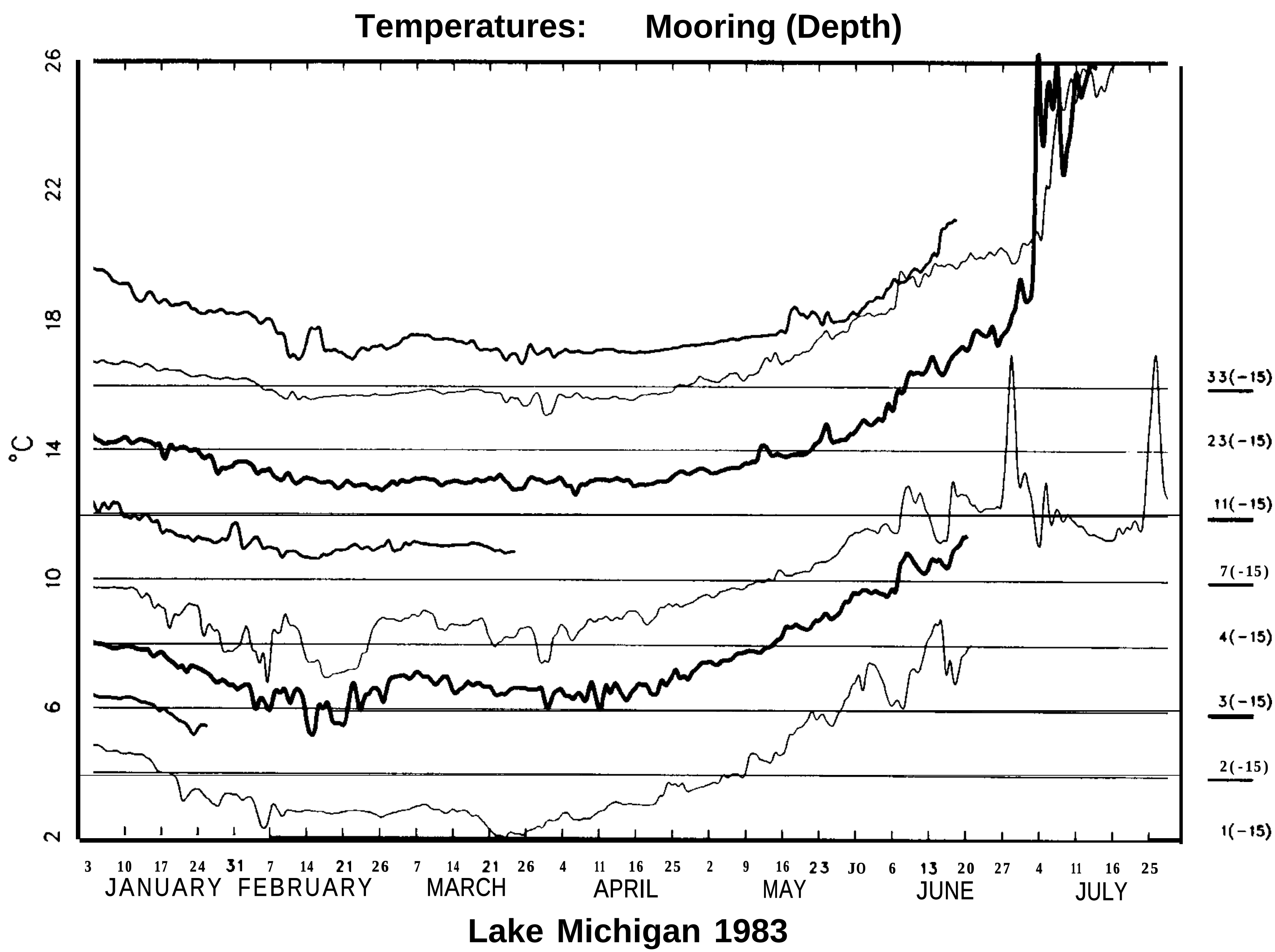
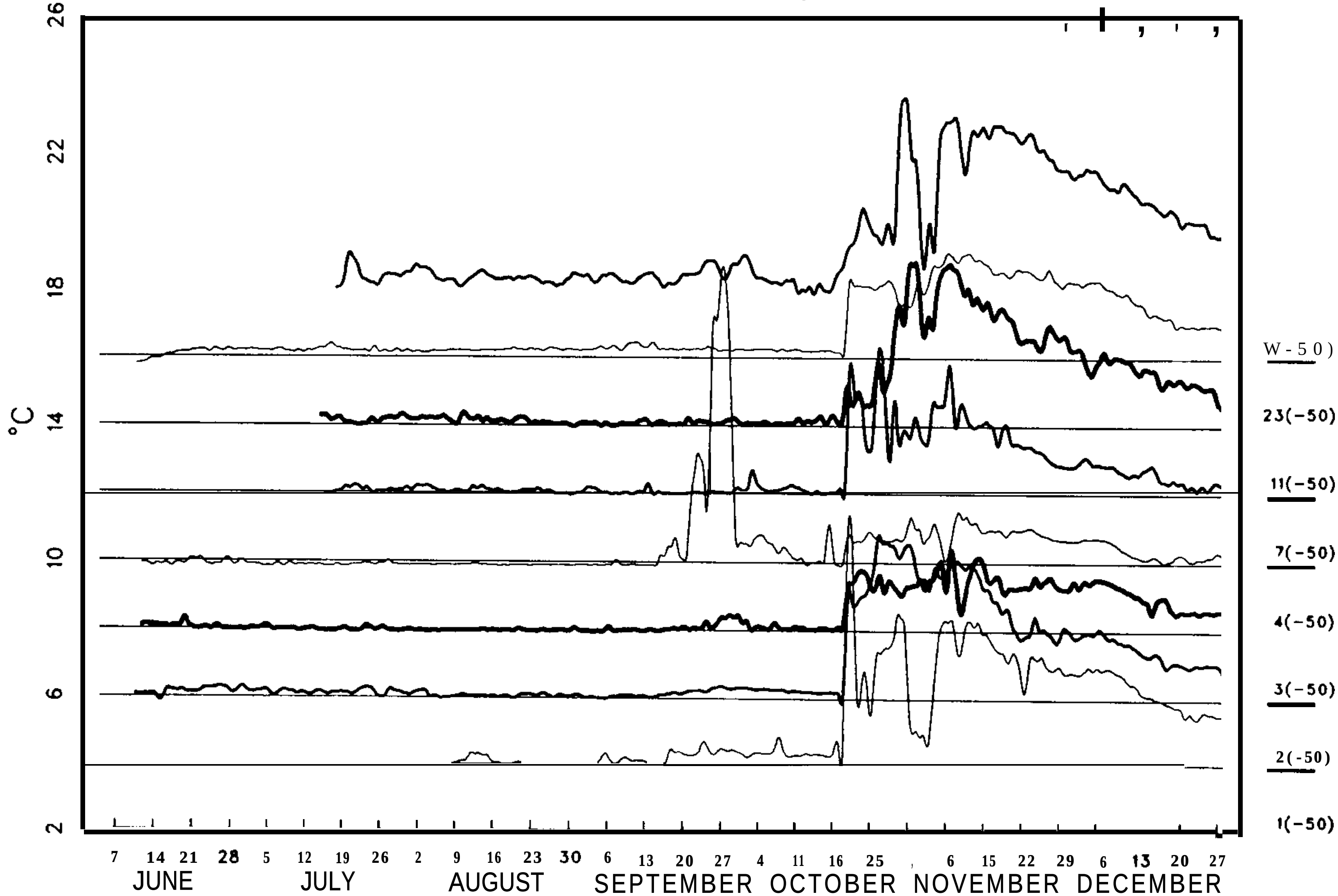


Figure B.1 (continued)

Temperatures: Mooring (Depth)



Lake Michigan 1982

Figure B.2

Temperatures: Mooring (Depth)

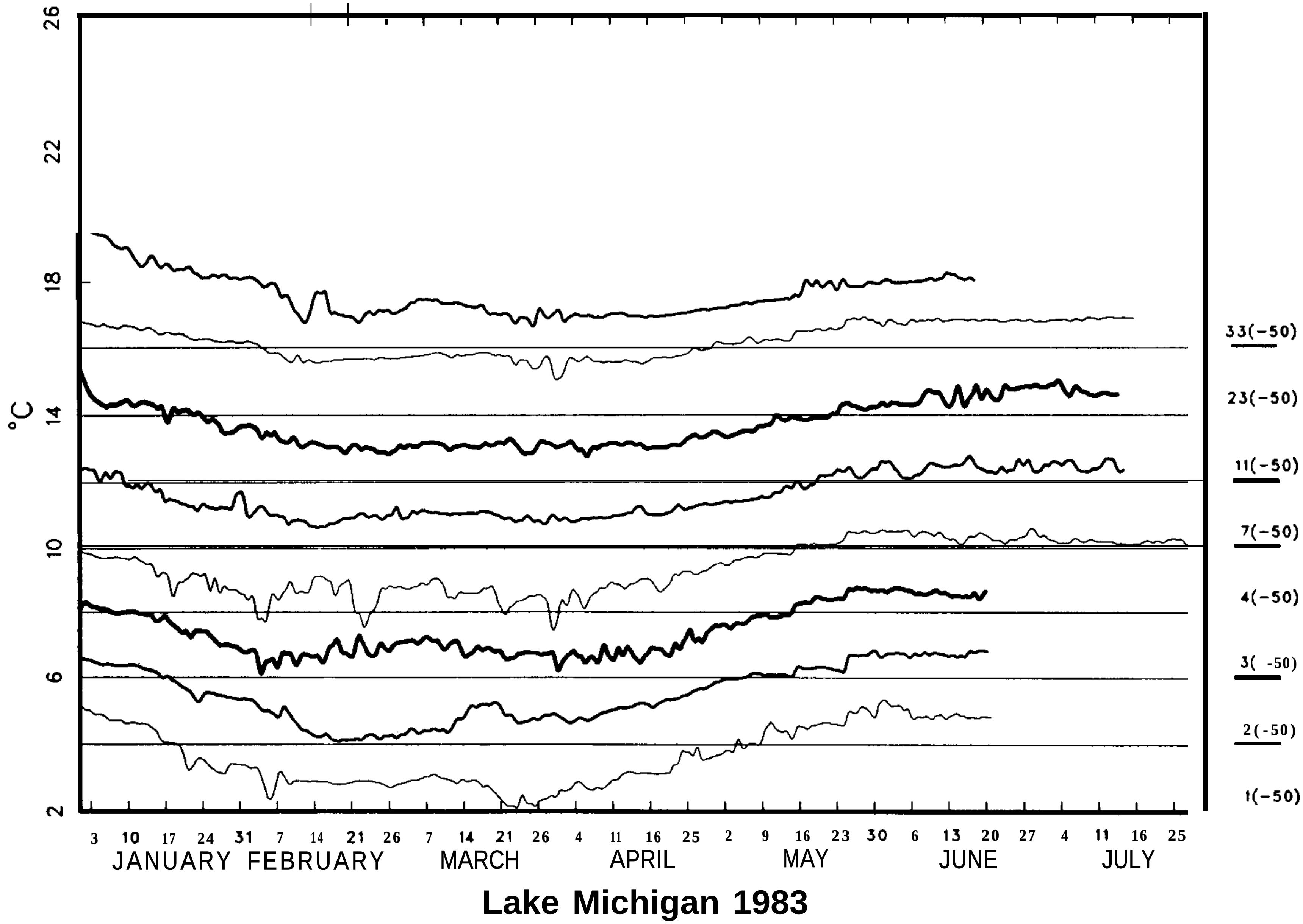
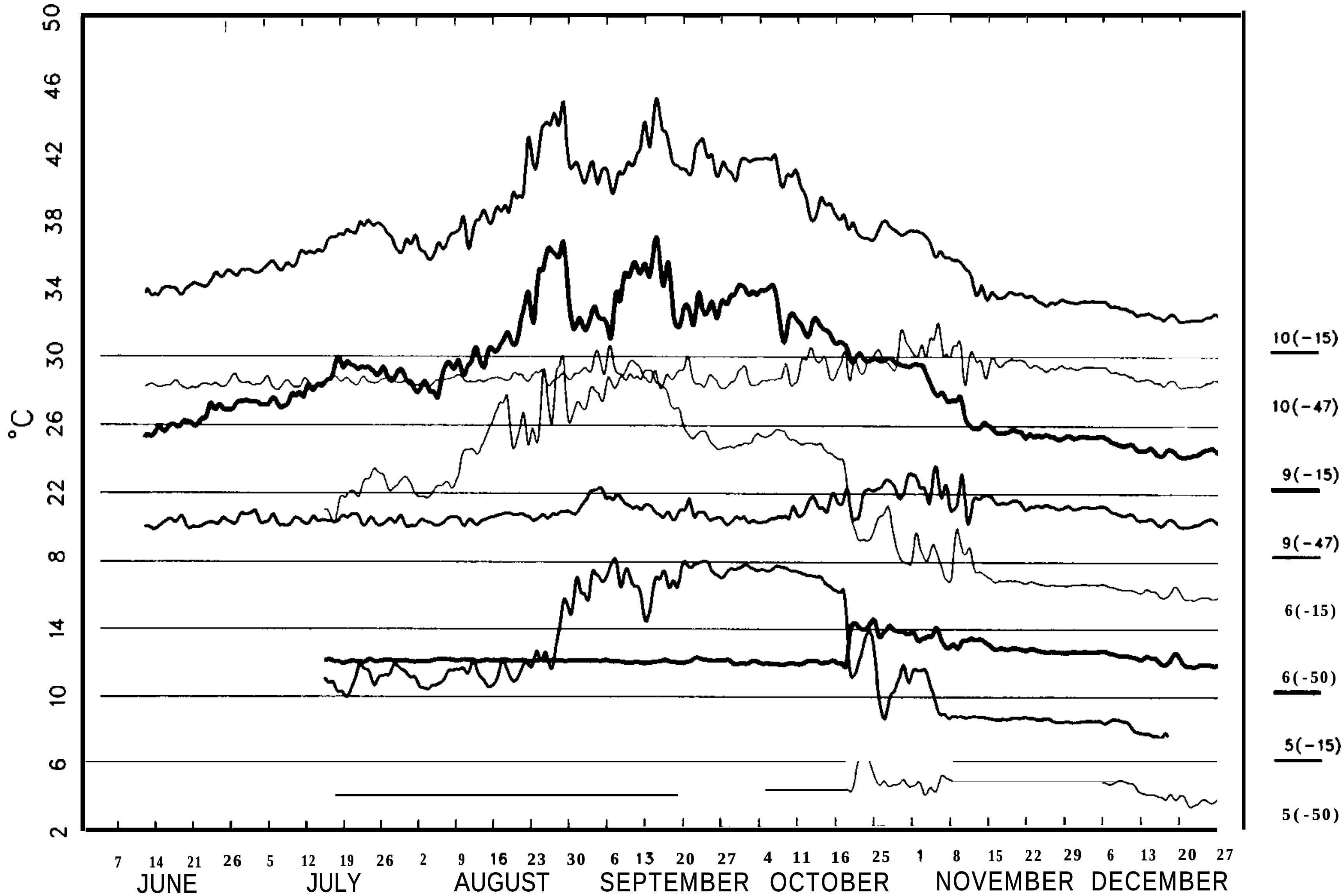


Figure 8.2 (continued).

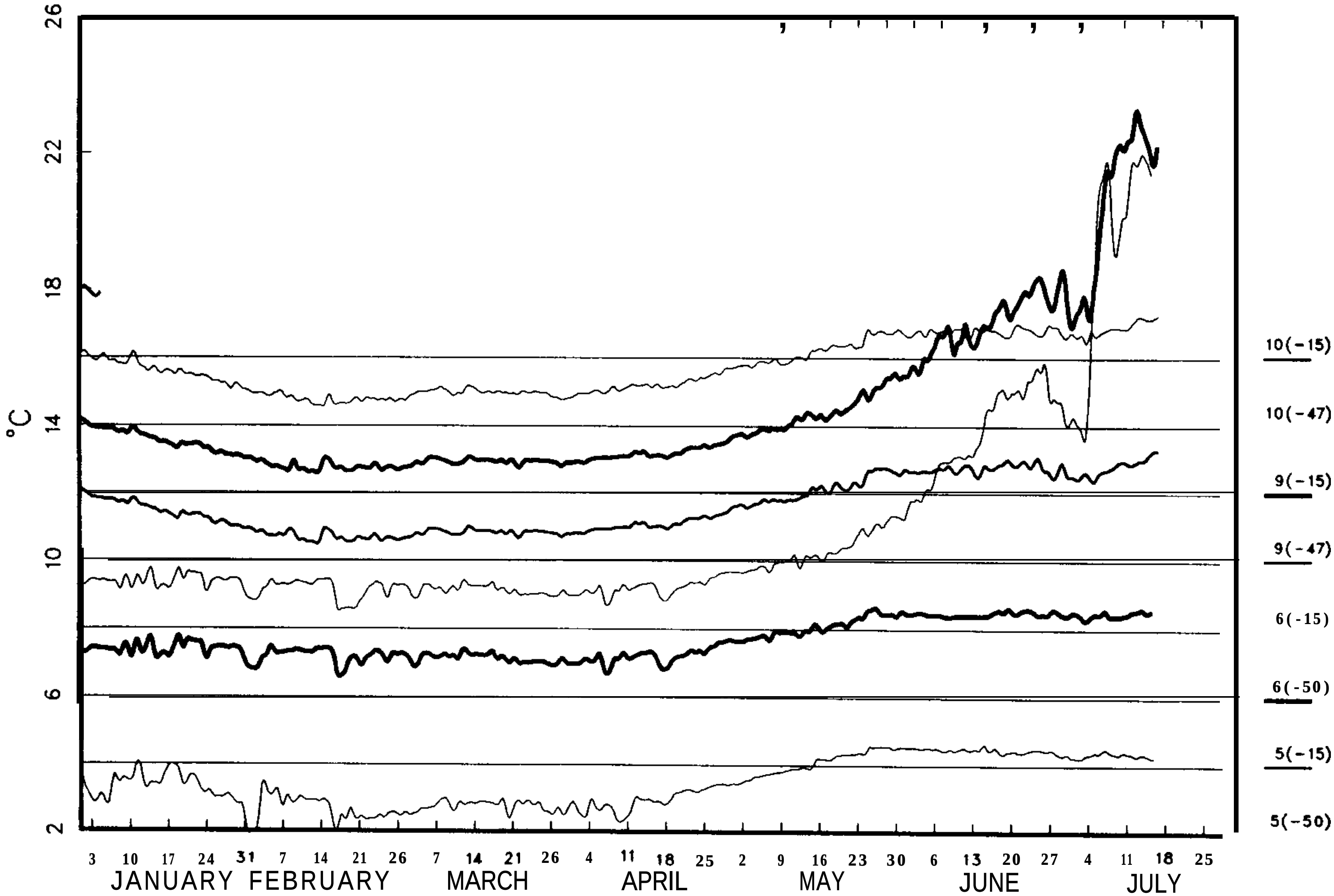
Temperatures: Mooring (Depth)



Lake Michigan 1982

Figure B.3

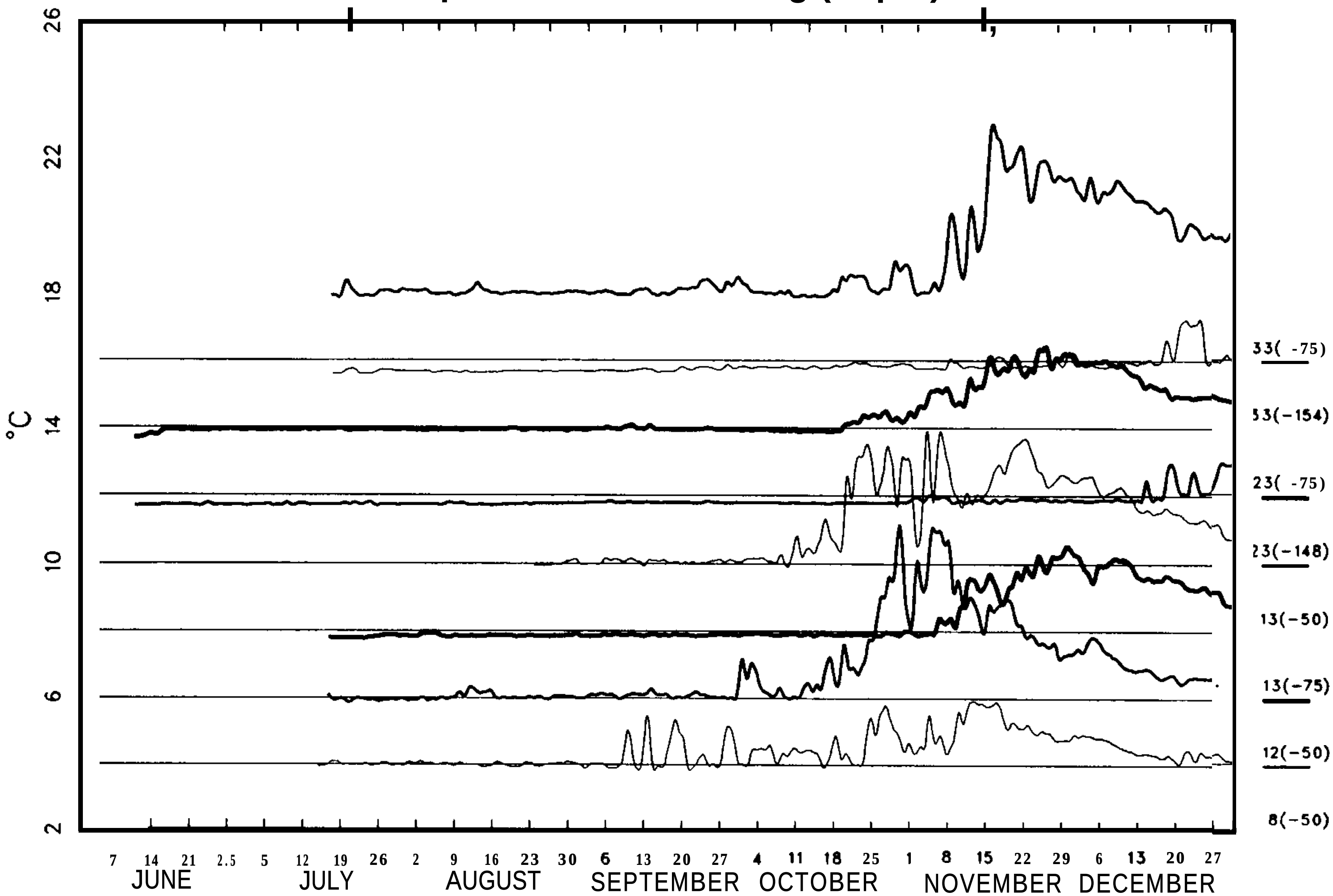
Temperatures: Mooring (Depth)



Lake Michigan 1983

Figure 8.3 (continued).

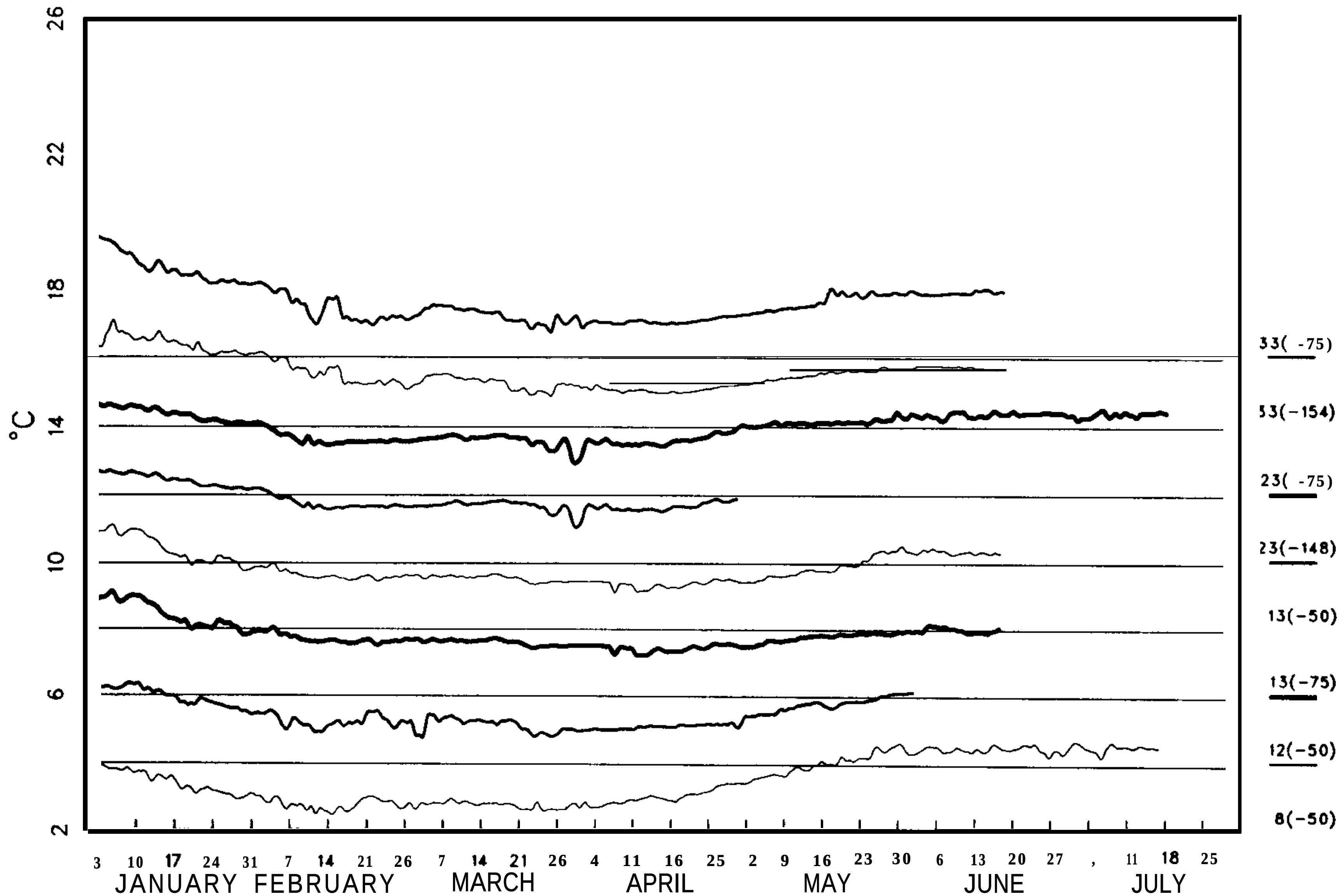
Temperatures: Mooring (Depth)



Lake Michigan 1982

Figure 0.4

Temperatures: Mooring (Depth)



Lake Michigan 1983

Figure B.4 (continued).

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Appendix C: Weekly-Averaged Water Temperatures

Contour plots of weekly-averaged temperatures at 50 m depth for the following weeks:

Figure C.1--October 15-22
Figure C.2--October 22-29
Figure C.3--October 29-November 5
Figure CA-November 5-12
Figure C.5--November 12-19
Figure C&November 19-26

The values of the temperatures for the above weeks at 50 and 15 m depth are listed in Table Cl.

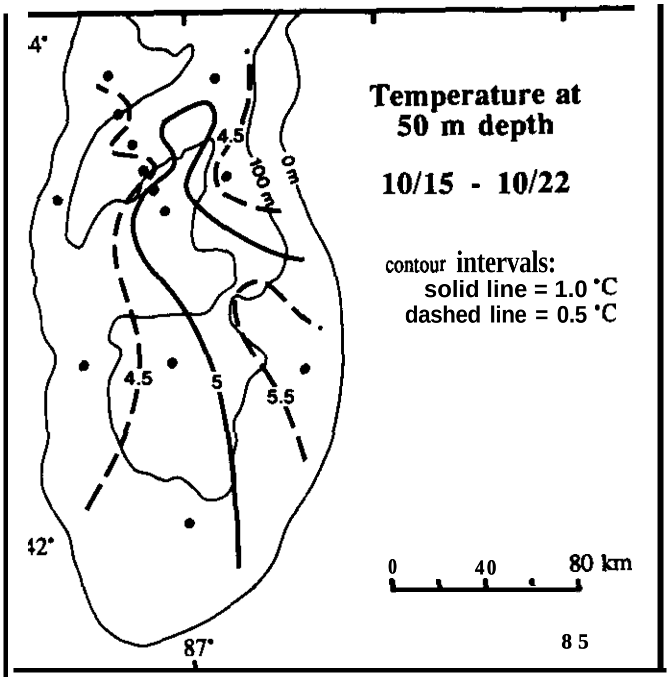

Figure C.1

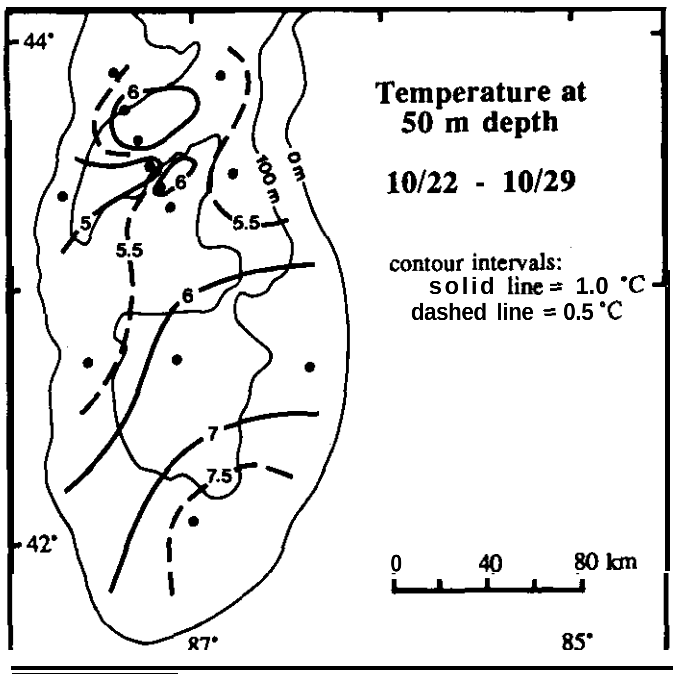

Figure C.2

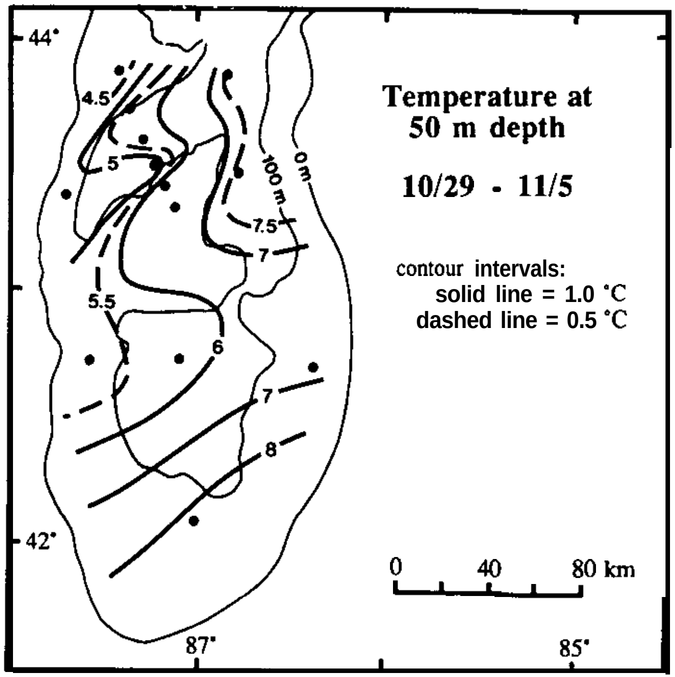

Figure C.3

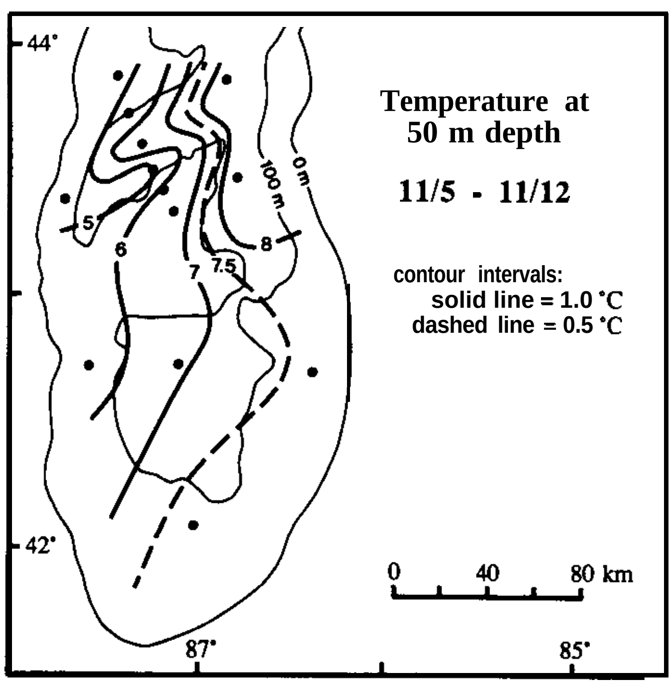

Figure C.4

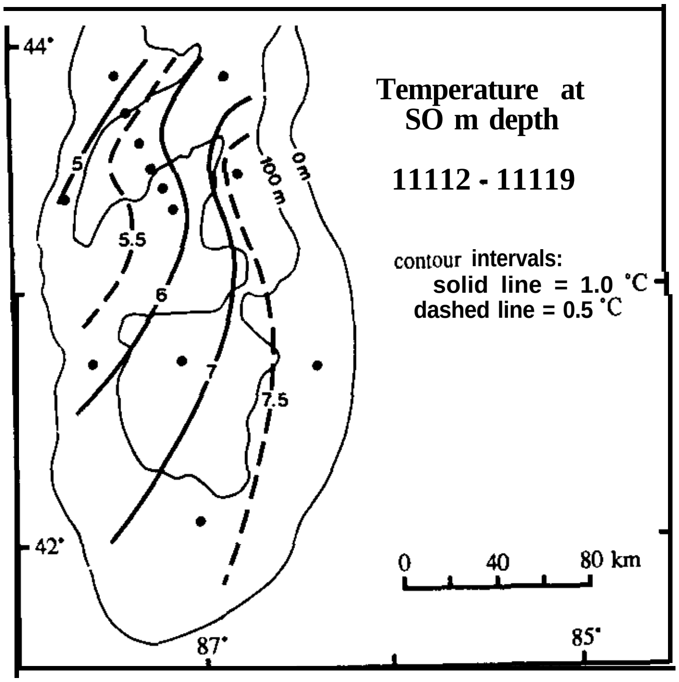

Figure C.5

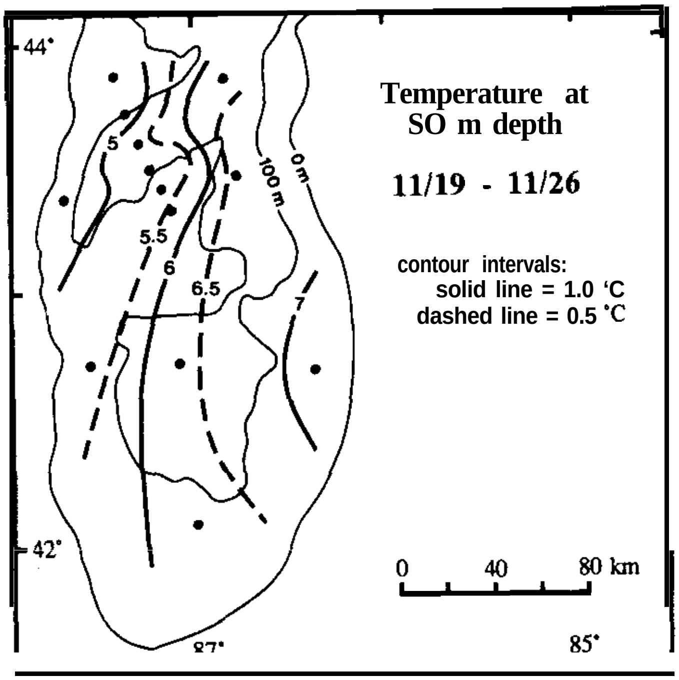

Figure C.6

Table C.1a--Temperature (°C) at 15 m depth

Dates	Mooring Number 1	2	3	4	5	6	7	a	9	10	11	12	13	23	33
10/01 10/08	16.87	16.11	14.26	13.61	13.64	13.32	13.66	—	13.66	13.71	13.09	—	—	15.06	3.93
10/08 10/15	15.49	15.41	14.60	13.44	13.41	13.15	13.34	—	11.65	11.90	13.12	—	—	14.45	3.91
10/15 10/22	13.58	12.65	11.66	6.63	11.36	11.53	11.76	—	10.96	10.56	11.64	—	—	11.66	3.94
10/22 10/29	11.97	9.39	7.06	5.62	7.41	6.07	10.24	—	9.66	9.43	10.56	—	—	6.23	4.31
10/29 11/05	10.65	9.64	6.57	5.74	7.29	6.54	9.45	—	9.41	9.33	9.77	—	—	a.75	4.37
11/05 - 11/12	8.84	6.13	6.27	5.96	5.02	6.35	7.51	—	7.48	7.60	9.32	—	—	7.43	4.95
11/12 - 11/19	7.88	7.36	5.77	5.11	4.76	5.25	6.14	—	5.64	5.62	7.61	—	—	6.69	5.46
11/19 - 11/26	7.27	6.62	5.54	4.99	4.76	4.62	5.54	—	5.53	5.59	6.74	—	—	6.66	5.63

Table C.1b--Temperature (°C) at 50 m depth

Dates	Mooring Number 1	2	3	4	5	6	7	8	9	10	11	12	13	23	33
10/01 - 10/08	4.37	4.29	4.14	4.59	4.31	3.99	4.21	4.31	4.46	4.67	4.07	4.55	4.11	4.27	3.70
10/08 - 10/15	4.38	4.22	4.07	4.16	4.25	4.01	4.13	4.35	5.05	5.36	4.11	4.16	4.29	4.25	3.76
10/15 - 10/22	5.80	4.73	4.35	4.34	4.55	4.43	4.66	4.31	5.41	5.41	4.36	4.76	4.96	4.62	3.76
10122 - 10/29	6.85	7.77	5.49	4.70	5.09	6.09	6.44	4.84	6.13	5.71	5.06	5.76	6.63	6.20	3.79
10/29 - 1 1/05	6.34	6.05	5.30	4.85	4.46	5.67	5.65	4.70	6.39	6.46	7.66	7.54	6.27	5.92	3.64
11/05 - 11/12	7.56	7.61	5.51	4.91	4.66	5.30	6.67	4.92	6.04	6.43	8.27	6.18	6.70	6.96	3.91
11/12 - 11/19	7.87	7.29	5.70	5.01	4.79	5.11	5.95	5.79	5.62	5.65	7.60	6.62	6.22	6.62	3.63
11/19 11/26	7.06	6.13	5.34	4.94	4.76	4.60	5.45	5.14	5.36	5.61	6.70	6.26	7.24	6.57	3.66

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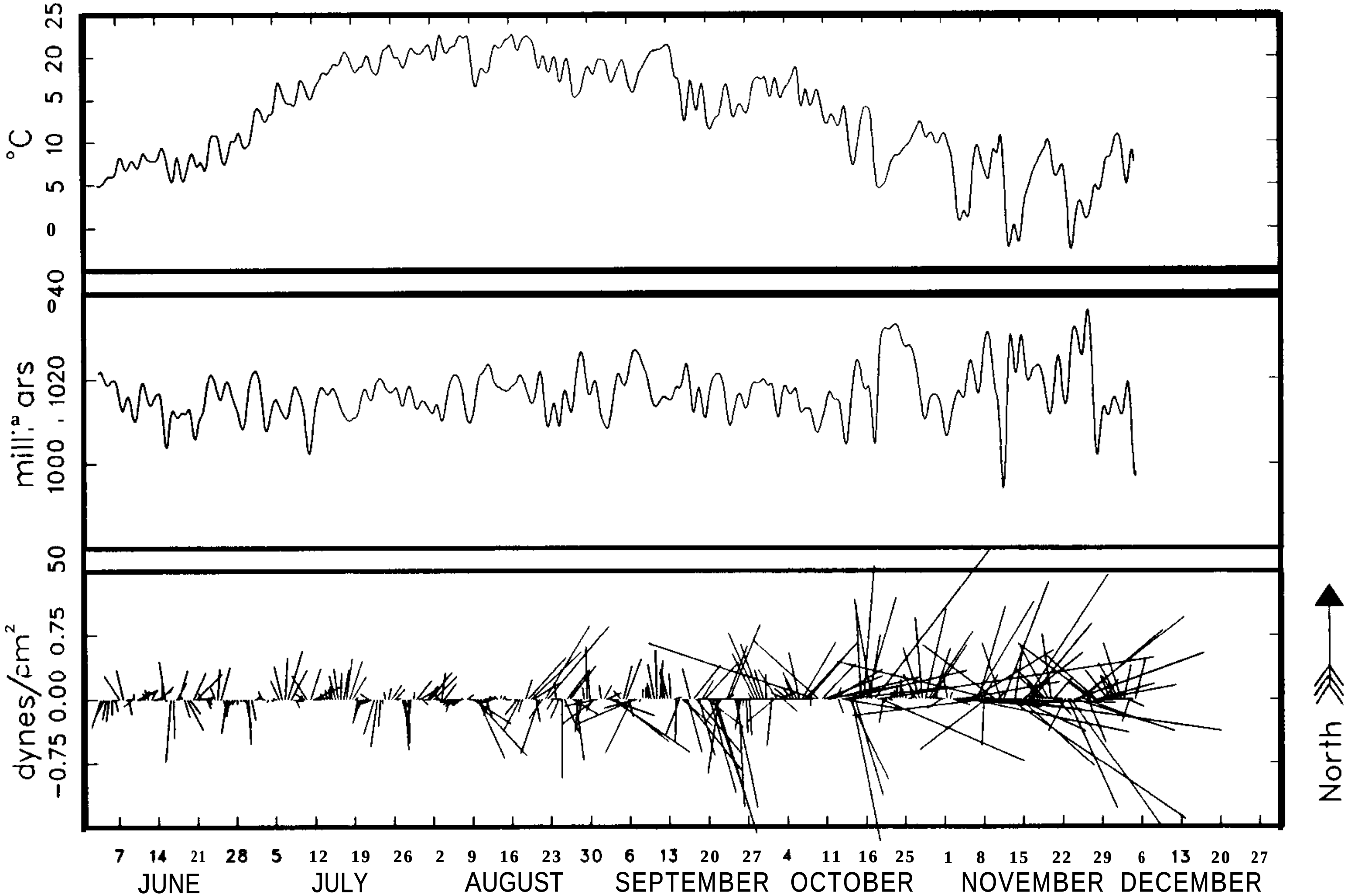
Appendix D: Meteorological Data

Stick diagrams of 40-hour low-pass filtered, bidaily-averaged wind stress (bottom panel; the sticks point toward the direction the wind is heading; north is up) and plots of barometric pressure (middle panel) and air temperature (top panel) at 5 m above the water surface from the following National Data Buoy Center buoys:

Figure D.1--Buoy 45007 (near mooring 23)
Figure D.2--Buoy 45002 (near mooring 33)

Wind Stress, Air Pressure and Air Temperature



Lake Michigan 1982 — NDBC Buoy #45007

Figure D.l

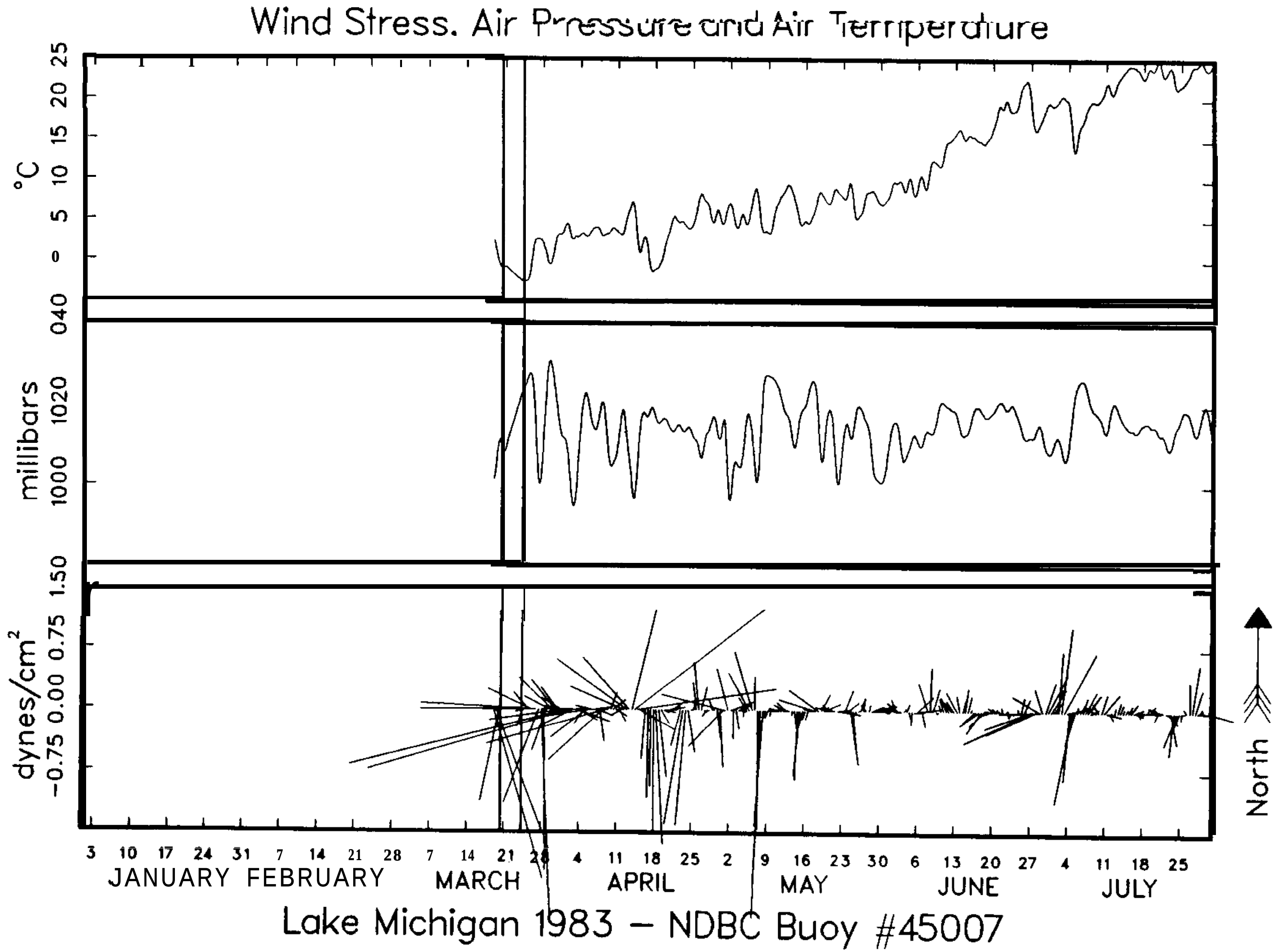
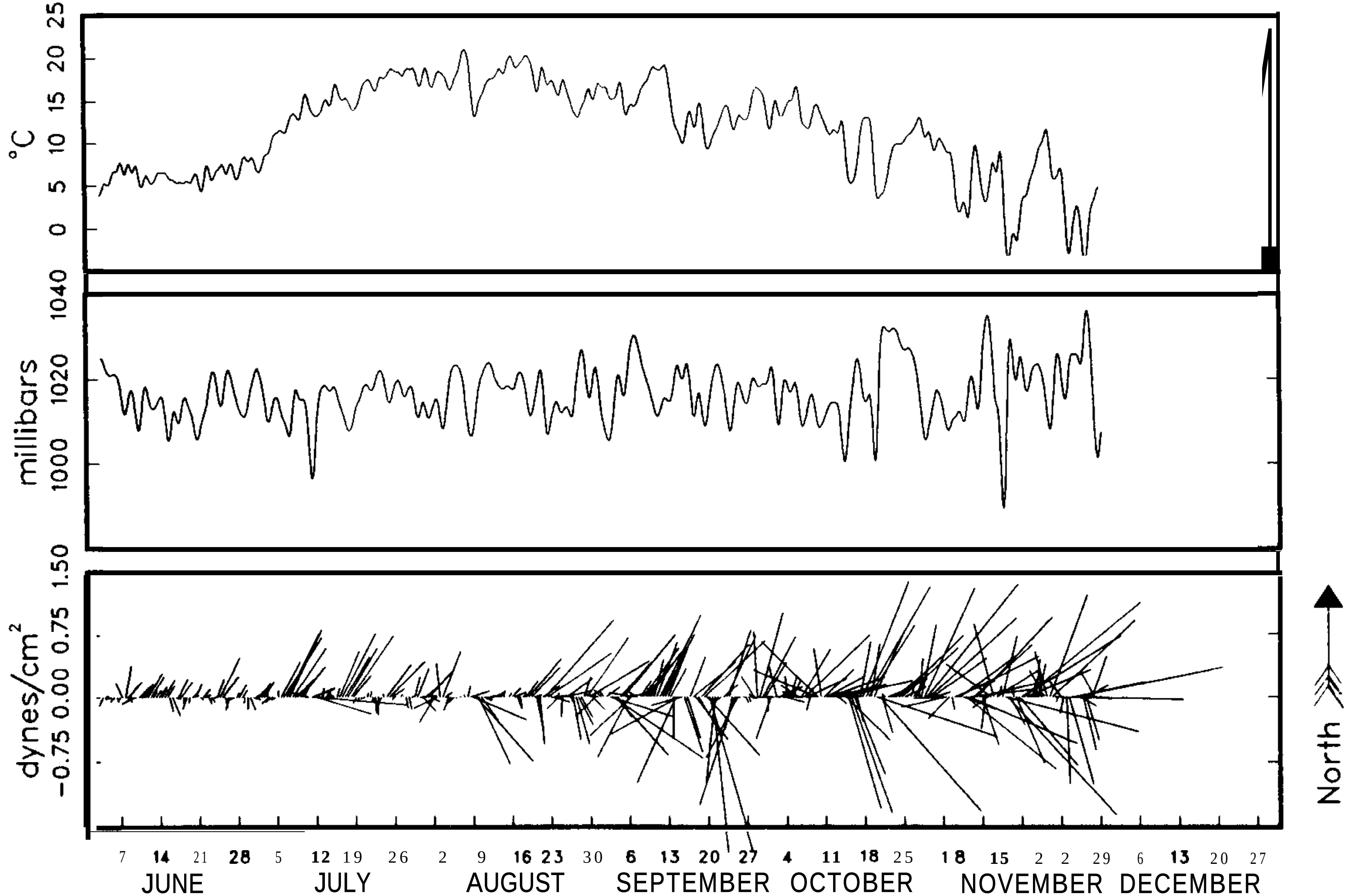


Figure D.1 (continued).

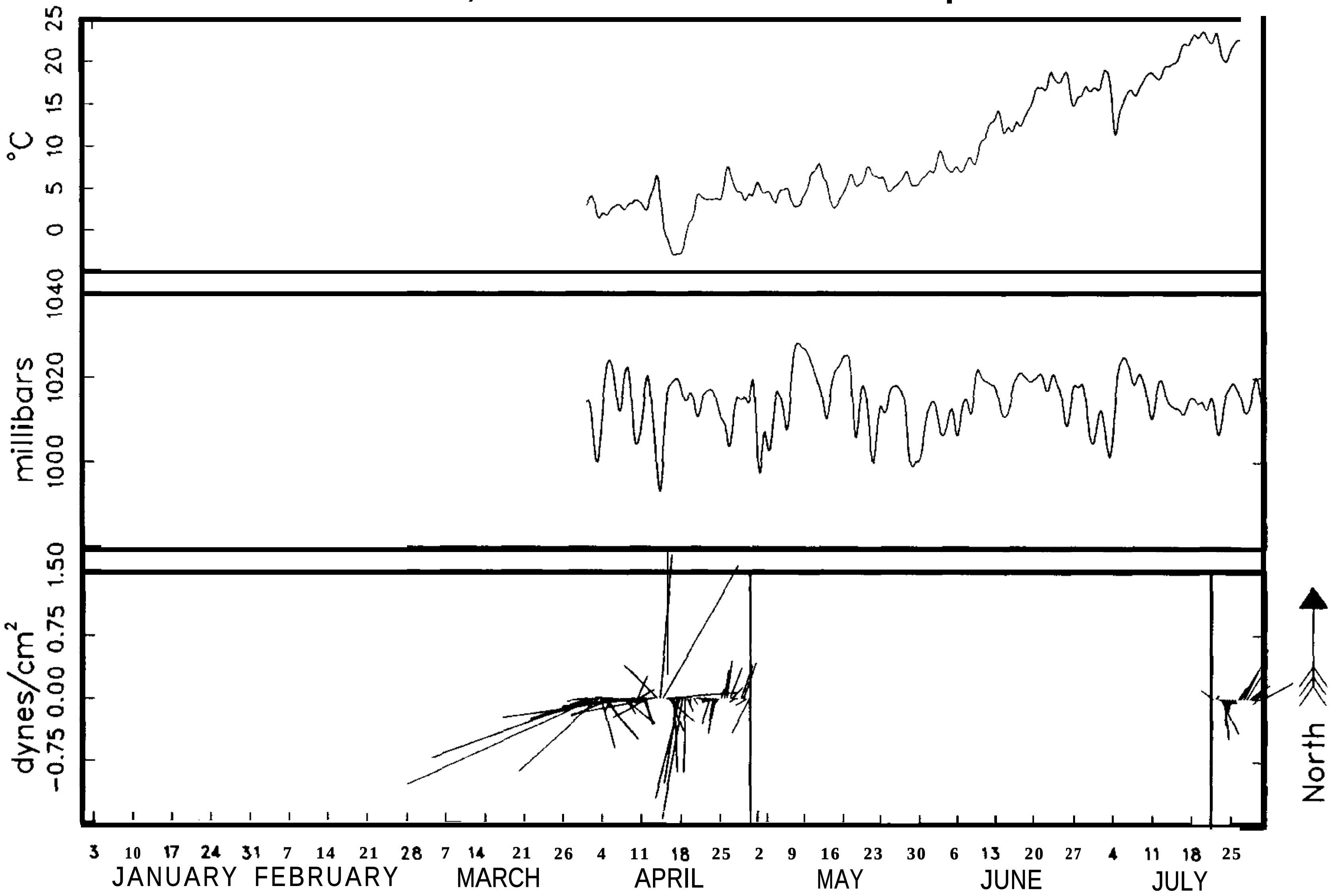
Wind Stress, Air Pressure and Air Temperature



Lake Michigan 1982 — NDBC Buoy #45002

Figure D.2

Wind Stress, Air Pressure and Air Temperature



Lake Michigan 1983 — NDBC Buoy #45002

Figure D.2 (continued).