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NEARSHORE CURRENT AND TEMPERATURE MEASUREMENTS, WESTERN LAKE MICHIGAN

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ABSTRACT

Currents in the nearshore region of western Lake Michigan were characterized using measurements recorded at several mooring sites near Milwuakee Harbor, Lake Michigan during 1993-94. The observational array consisted of one mooring 7 km offshore in 23 m water that recorded current velocity and water temperature data for 450 consecutive days, two current meter moorings near the City of Milwaukee water intakes during summers in 1993 and 1994, and an additional mooring 10 km offshore during the 1994 summer. Meteorological and water temperature data were recorded on a National Data Buoy Center (NDBC) meteorological buoy moored 6 km offshore during the 1993 and 1994 open-water months.

Current patterns were strongly dependent on wind direction and speed during all seasons with the most effective winds corresponding to directions with the greatest fetch. Flow was generally constrained to shore-parallel directions interspersed by periods of very weak currents. Variability during summer stratification was generated by near-inertial baroclinic internal oscillations (Poincare'-type waves) superimposed on a quasi-steady barotropic current. Maximal current magnitudes were generally less than 30 cms^{-1}. Upwelling and downwelling events, a consequence of alongshore wind stress, were a regular feature, though the intensity was less than that generally observed on the eastern shore of Lake Michigan. Limited cross-shore transport was associated with the rotary, near-inertial, currents and the upwelling/downwelling activity during spring and summer when the lake was well stratified.

Water temperatures cooled to $4^{o}C$ by mid-December, decreased to near zero from mid-January to mid-March, and warmed to $4^{o}C$ by mid-April. Flow was southward during the isothermal months of December through June, with limited variability at subinertial (>2-day) time scales. Current magnitudes were markedly reduced when ice cover was present in the region. Cross-shore transport at the measurement sites off Milwaukee was minimal when the water mass was vertically homogenous as indicated by the lack of onshore-offshore flow. In winter, any cross-shore transport that occurred was primarily associated with flow over bathymetric features and the coastline geometry.

1.0 INTRODUCTION

The nearshore regions of the Great Lakes are heavily utilized for recreation, transportation, and commerce and provide habitat for wildlife and fisheries. Increasing environmental pressures and the resulting degradation of these nearshore areas are manifest by the fact that all Great Lakes Areas of Concern, as designated by the International Joint Commission, are in the nearshore zone. Effective management decisions are hampered by a lack of understanding of the physical dynamics, interactions with the biogeochemical processes, and nearshore-offshore coupling and exchange processes. In response to this need, NOAA initiated a Great Lakes Nearshore Hydrodynamics research program in 1993 in cooperation with the University of Wisconsin, the State of Wisconsin, and the U.S. Geological Survey, involving coastal physics, chemistry, and biology. The objective is to provide quantitative understanding of the transport, transformation, and fate of the contaminated materials and sediments as affected by hydrodynamic processes in the coastal region of the Great Lakes. Milwaukee Harbor and the adjacent nearshore region in western Lake Michigan were selected as the research site. This region is environmentally impacted by population pressures, point and nonpoint pollution sources, drinking water contamination, such as the 1992 Cryptosporidium crisis, and contaminant-laden sediments in the river/harbor complex. Project goals will be achieved through several project components such as measuring and modeling the biological activity/variability along thermal fronts and nearshore harbor regions, and increasing our understanding of the dynamics of nearshore fronts/plumes and the onshore/offshore transport. Results, techniques, and models developed in this study will be applicable to other coastal regions.

The 1993-1994 observational program measured biogeochemical and physical parameters, such as currents, winds, waves, and water temperatures in the nearshore region. This report presents the current, water temperature, and concurrent wind measurements collected during this 2-year study off Milwaukee Harbor.

2.0 MEASUREMENTS

Longterm current measurements have been made in Lake Michigan over the last several decades (Saylor et al., 1980; Gottlieb et al., 1989), however, the measurement sites were generally in water depths greater than 40 m. Nearshore current patterns in other lakes, e.g., Lake Huron (Csanady, 1967; 1970), Lake Superior (Ragotzkie, 1966), and Lake Ontario (Hamblin and Rodgers, 1967; Gunwaldsen et al., 1971), demonstrate that nearshore currents are complex and predominantly shore-parallel, with frequent direction reversals associated with varying wind stress. Numerous definitions of the ‘nearshore region’ can be found in the literature. One definition that is apropos for the Great Lakes was given by Sato and Mortimer (1975), “...the region in which unidirectional shore-parallel current patterns predominate and in which the rotary current components although detectable, do not assume major importance, as they do in offshore regions (and) ...is also the locale of upwelling and downwelling motions and the attendant geostrophic flows”. Their nearshore dynamics study in western Lake Michigan south of Milwaukee (Sato and Mortimer, 1975) suggested that the ‘nearshore region’ is greater than the 8-km width for Lake Ontario (Blanton, 1974) but less than 15 km.

To observe the currents over one annual cycle in the nearshore region of western Lake Michigan, one mooring, NS1, with two EG&G Vector Averaging Current Meters (VACM) was deployed 24 August 1993 at a depth of 23 m, 7 km east of the south entrance to Milwaukee Harbor (Figure 1). The meters were recovered on 16 November 1994. This tautline mooring consisted of a current meter at a depth of 11 m suspended immediately under a subsurface float, another VACM 5 m above the bottom, and an acoustic release attached to a 350-kg anchor. Surface wave effects are minimized with this mooring configuration, and the subsurface float was below the normal ice depth and ship draft. Vector averaged current components and water temperatures were recorded at 15-minute intervals. Both VACMs operated for the entire 450-day deployment.

During the fall of 1993 the late Dr. Alan Bratkovich (1951-1995) deployed two moorings, AB10 and AB30, each with one prototype electro-magnetic meter and one VACM near the city of Milwuakee water intakes (Figure 1). On these moorings the upper electro-magnetic current meter was suspended below a spherical surface buoy with additional flotation 1 m below the surface, and the VACM positioned several meters above the bottom. A 12-m length of anchor chain (120 kg) anchored the mooring and also maintained mooring tautness by allowing the upper section of chain to act as a damper by lifting/falling in response to surface wind waves and currents. The VACM data were recorded in the same manner as described above. In 1994 Dr. Bratkovich deployed two additional moorings, AB1 and AB3, each with two VACMs, near the same city water intake locations as in 1993, and mooring AB2, 10 km offshore in 34 m water (Figure 1). The same mooring technique was used with the upper VACM suspended at the 3-m depth below a spherical surface buoy and a second VACM nearer the bottom. Table 1 gives the mooring information and data availability from all moorings.

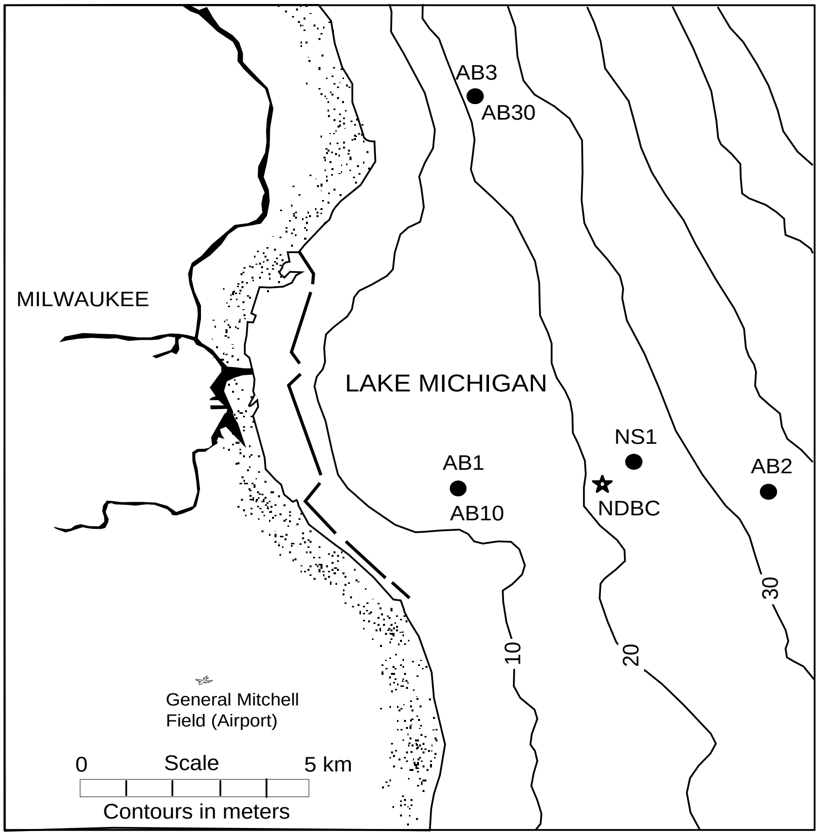


Figure 1.--Location map for the 1993-94 Milwaukee Nearshore Program and sites of the current meter moorings and NDBC 45010 buoy. The 1993 moorings AB10 and AB30 were in identical locations as the 1994 AB1 and AB3 moorings, respectively.

Currents in the Great Lakes, particularly in the nearshore region, are primarily wind-driven. The National Weather Service's meteorological station at General Mitchell Field (Milwaukee Airport) 5 km west of the Lake Michigan shore provided observations throughout the year. However, the differences between over-water and over-land winds caused by, for example, local air stability (differences between water and land temperatures) and surface boundary differences are well documented (Schwab and Morton, 1984). A National Data Buoy Center (NDBC) buoy, #45010, was moored in 20-m water 400 m southwest of the NS1 site during the 1993 and 1994 ice-free months to obtain the over-water meteorological conditions at the study site. In addition to measuring wind velocity 5 m above the water surface and other atmospheric parameters, water temperature 1 m below the surface and wave height, period, and direction were also recorded at hourly intervals.

3.0 DATA PRESENTATION

Hourly current velocities and water temperatures from the NS1 mooring for the 450-day collection period are presented in Appendix A. Velocity components (u,v) are positive in the offshore (x) direction and northward alongshore (y) direction, respectively. The currents were rotated to align with the local bathymetry as indicated, and the mean hourly velocities plotted in stick form. Wind velocities and near-surface water temperatures from NDBC 45010 are included when available. For periods when over-water winds were not measured, data from General Mitchell Field are shown. Throughout this report, wind directions have been converted to the oceanographic convention, i.e. wind direction toward, to facilitate wind and current comparisons. Current velocities and water temperatures from the five 1993 and 1994 Bratkovich moorings are also included in Appendix A when available. These current data were also rotated to align with the orientation of the local bathymetry except for data recorded at moorings AB10 and AB1. These moorings were located nearshore, north of a shallow cape protruding lakeward.

Table 1.--Mooring information and data availability parameters.

Mooring	Latitude	Longitude	Water Depth (m)	Deploy	Recover	Depth (m)/ Instrument	Data availability/ Parameters
AB10	43°00.29’	87°50.28’	17	08/24/93	10/14/93	-14 m	08/24/93-10/14/93 / uvt
AB30	43°05.04’	87°50.57’	22	08/24/93	10/14/93	-16 m	08/24/93-10/14/93 / uvt
NS1	43°00.38’	87°47.77’	23	08/24/93	11/16/94	-11 m	08/24/93-11/16/94 / uvt
						-18 m	08/24/93-11/16/94 / uvt
AB1	43°00.04’	87°50.05’	17	05/04/94	09/20/94	-3 m	05/04/94-09/20/94 / uvt
						-13 m	05/04/94-09/20/94 / uvt
AB2	43°00.04’	87°45.46’	34	05/04/94	09/20/94	-3 m	05/04/94-09/20/94 / t[a]
						-23 m	05/04/94-09/20/94 / uvt
AB3	43°04.99’	87°50.48’	22	05/04/94	09/20/94	-3 m	05/04/94-09/20/94 / t[a]
						-13 m	05/04/94-09/20/94 / uvt
NDBC	43°00.	87°48	20	06/26/93	11/10/93	+3m	06/26/93-11/10/93 /uv
(45010)				06/26/93	11/10/93	-1m	06/26/93-11/10/93 / t
				05/16/94	11/10/94	+3m	05/16/94-07/13/94 /uv
						+3m, -1m	05/16/94-11/11/94 /at,wt

[a] Rotor missing

4.0 RESULTS

4.1 Mean Currents and Temperatures

Monthly mean flow vectors from all operating current meters and from NDBC 45010 from August 1993 to November 1994 are shown in Figure 2. Monthly statistics for the current and wind components (u and v), water temperature, resultant velocity, and scalar speed are presented in Table 2. (Standard deviations are in parentheses.) The bimodal alongshore flow characteristics in the Great Lakes nearshore result in small resultant current velocity magnitudes when averaged over relatively long time periods; however, some consistent patterns can be implied from these monthly vector means. At NS1, directions were similar at both depths during the isothermal period of November through May, with slightly greater speeds at the upper level consistent with a wind-driven system. December through June mean current directions were toward the south, similar to directions observed at other measurement sites near the western shore (Gottlieb et al., 1989), and are consistent with the long-term mean counterclockwise circulation pattern in the southern Lake Michigan basin (Mortimer, 1988). The standard deviations of the alongshore current components were nearly equal for both depths with the minimum in spring and early summer. Monthly scalar current speeds were typically smaller in spring/summer and greater in fall. The ratio of the vector to scalar speed, a measure of the constancy or persistence of the current, was low for most months, which is characteristic of binodal currents. There was a slight increase in current velocities during the fall and winter months when currents responded barotopically to meteorological time scales, and velocities were weakest during stratification when near-inertial currents were a significant component in the flow.

Currents measured at the AB sites were not always consistent with observations at the NS1 site (Figure 2 and Table 2). For example, monthly mean scalar speeds recorded by the AB meters for the 50 days in 1993 were 10-25% greater than speeds at NS1. During the 1994 concurrent measurement period, the monthly mean speeds from AB2 at -23 m (34-m water depth) averaged about 80% higher than speeds from NS1 at -18 m. The currents are strongly coupled with the overwater wind stress, and considering that the deepest AB2 current meter was 5 m deeper and 3 km farther offshore, currents would normally be weaker. There was also an average 70% (150%) increase in the v(u)-component standard deviation. Similarly, at -13 m on AB3 (22-m water depth), speeds were about 80% larger than at -18 m on NS1.

Although the surface buoy taut line mooring design of the AB moorings permitted measurements nearer the surface (-3 m), the mooring is subject to significant vertical and horizontal motions. An indication of the intense stresses experienced by these moorings is the fact that the Savonious rotor on two of the VACMs at the 3-m depth were missing less than 9 days after deployment. It has been demonstrated that unsteady flow and mooring motions contribute to biases (primarily overspeeding) in VACM velocity measurements (Saunders, 1980; Beardsley, 1987; Halpern et al., 1981). A Savonious rotor overspeeds in unsteady flow because the rotor is an

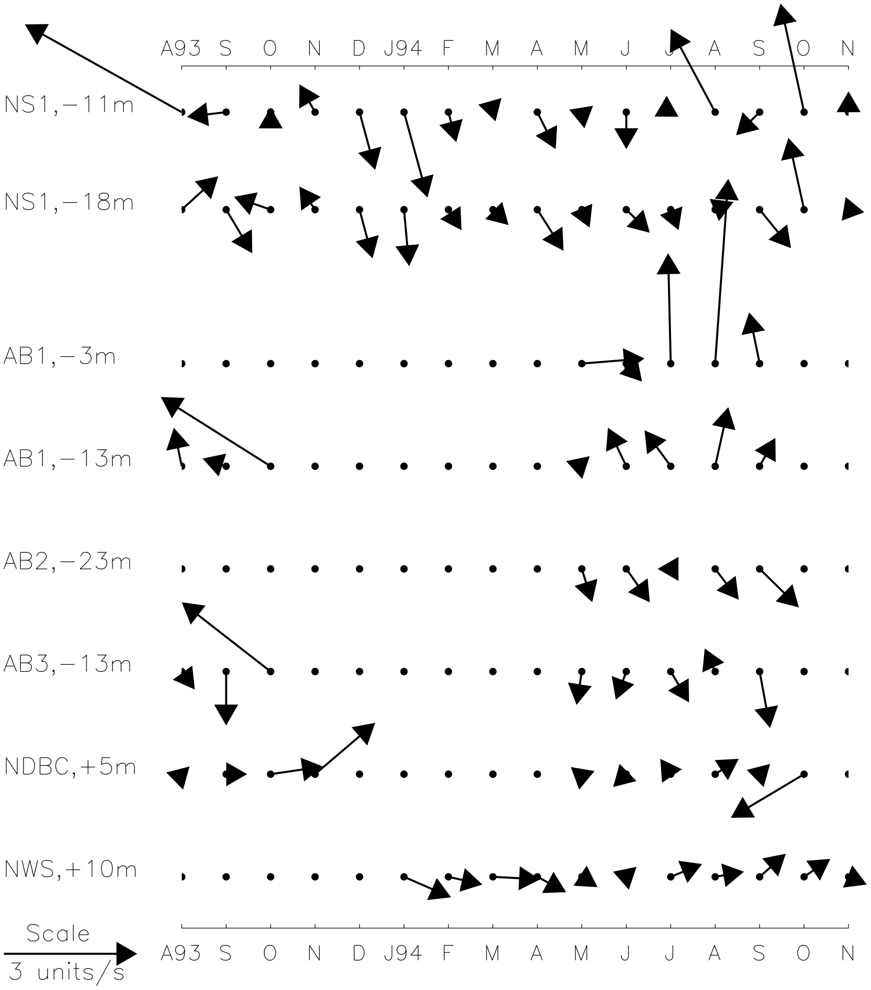


Figure 2.--Monthly vector mean currents (cms^{-1}) for the indicated moorings (see Table 2 for the specific dates). Arrows indicate the direction toward which the current is moving. Wind vectors from NDBC 45010 and Mitchell Field are in ms^{-1} and point toward the direction the wind is blowing. Wind vectors are computed only when concurrent current data are available.

omni-directional speed sensor that accelerates faster than it decelerates, the vane and vane follower have finite time lags in fluctuating flow, and vertical mooring accelerations cause rotor pumping. Mean scalar speeds at 4 m above bottom (-13 m) at AB1 exceeded the speed near the surface during four of the five months, suggesting that overspeeding is also pronounced at depth under a surface mooring. Comparisons of monthly speeds show that the differences between the deepest VACMs on AB2 and NS1 continued to increase up to the September retrieval time, which is consistent with the higher wind and wave conditions experienced as the season progressed. The current components were coherent in time, and near-inertial oscillations were generally in phase at all sites. It appears that, although the vector averaging capability of the current meters eliminates some of the windwave-induced biases (orbital velocities), vertical and horizontal mooring motions associated with a surface-type mooring technique have resulted in overspeeding. In another study, mean current speeds measured by VACMs on the subsurface float type of mooring and by an adjacent bottom mounted Acoustic Doppler Current Profiler (ADCP) compared to within 0.1 cms^{-1} and standard deviations to within 0.2 cms^{-1} at three depths for a 142-day summer period in Green Bay (Miller and Saylor, 1993).

Despite the overspeeding problems, data measured on AB moorings are qualitatively useful in describing general flow characteristics in this nearshore region and, therefore, are included in this report. The quality of the water temperature data measured by the VACMs was not affected because of slow thermistor response time. At the mooring AB10 and AB1, nearest the coast (3 km) and partially sheltered from the south by a 5-m-deep shoal area, the mean currents during summer were predominantly northward and, in general, nearly opposite the flows farther north at AB3 or offshore at NS1. It is assumed that flow at this location is subject to topographic steering from the shallow area to the south and circulation in the Milwaukee embayment.

Table 2.--Monthly statistics for current and wind components, water temperature, resultant velocity, and scalar speed.

NS1

Month	U (cms^{-1})		V (cms^{-1})		Rspd (cms^{-1})		Direction (°T)		Speed (cms^{-1})		Temp (°C)	
	-11 m	-18 m	-11 m	-18 m	-11m	-18m	-11 m	-18 m	-11m	-18m	-11 m	-18 m
Aug 93[a]	-6.0(5.8)	1.4(7.3)	3.8(8.2)	1.3(6.0)	7.1	1.9	302	047	10.7	8.9	13.4(3.2)	7.3(1.2)
Sep 93	-1.5(5.1)	1.0(6.4)	-0.2(7.9)	-1.7(5.5)	1.5	2.0	262	150	8.7	7.5	12.2(2.9)	8.1(2.6)
Oct 93	0.0(2.9)	-1.4(4.3)	0.2(7.5)	0.5(6.2)	0.2	1.5	000	290	7.0	6.6	9.6(0.9)	9.4(0.8)
Nov 93	-0.2(2.3)	-0.6(2.9)	1.2(6.8)	0.9(5.5)	1.2	1.1	350	326	6.4	5.3	6.3(0.7)	6.3(0.7)
Dec 93	0.6(2.2)	0.5(2.8)	-2.5(6.5)	-1.9(5.3)	2.5	1.9	167	165	6.2	5.2	4.1(0.9)	4.1(0.8)
Jan 94	0.9(3.0)	0.2(3.0)	-3.7(7.2)	-2.3(5.8)	3.8	2.2	166	175	7.1	5.5	0.6(0.7)	0.6(0.7)
Feb 94	0.3(1.9)	0.5(2.3)	-1.4(6.6)	-1.2(5.2)	1.3	1.0	168	146	5.2	3.4	0.1(0.1)	0.1(0.2)
Mar 94	0.1(1.7)	0.7(2.1)	-0.5(5.1)	-0.8(4.3)	0.4	0.9	169	140	4.2	3.7	0.8(0.4)	0.8(0.4)
Apr 94	0.7(2.4)	0.9(2.9)	-1.5(5.9)	-1.4(5.4)	1.8	1.9	155	147	5.3	5.1	2.9(0.9)	2.9(0.9)
May 94	0.2(1.7)	0.4(3.4)	-1.0(4.5)	-0.9(4.4)	0.7	0.7	169	156	4.4	4.7	6.7(1.6)	5.6(1.1)
Jun 94	0.0(2.8)	0.9(4.2)	-1.7(4.2)	-0.9(4.9)	1.6	1.2	180	135	4.5	5.3	10.9(2.1)	8.6(2.5)
Jul 94	-0.3(3.1)	0.3(3.9)	-0.2(3.9)	-0.8(3.9)	0.4	0.9	236	159	4.6	4.7	12.0(3.3)	6.6(1.4)
Aug 94	-1.7(2.9)	0.7(4.8)	3.6(5.0)	0.3(4.4)	4.0	0.8	335	067	6.2	5.6	14.8(3.9)	9.4(4.6)
Sep 94	-1.0(2.7)	1.3(4.2)	-1.0(5.7)	-1.5(5.2)	1.3	2.0	225	139	4.6	5.7	11.5(2.3)	8.9(2.6)
Oct 94	-0.9(2.2)	-0.7(5.2)	4.9(5.2)	2.8(5.7)	4.8	2.9	350	346	7.1	7.6	13.4(2.5)	10.4(4.5)
Nov 94[b]	0.0(2.5)	0.7(5.1)	1.0(6.0)	0.0(6.4)	0.9	0.6	000	090	6.1	7.8	8.4(0.7)	7.8(0.9)

[a] 25-31 Aug [b] 1-15 Nov

NDBC 45010 1993

Month	U (ms^{-1})	V (ms^{-1})	Rspd (ms^{-1})	Direction (°T)[c]	Speed (ms^{-1})	Temp (°C)
Jun 93[a]	1.7(3.6)	2.4(3.1)	2.9	216	5.2	14.5(0.7)
Jul 93	0.1(3.0)	-0.9(2.9)	0.9	351	3.9	16.7(2.0)
Aug 93	-0.3(2.6)	-0.3(2.9)	0.5	045	3.5	19.5(2.0)
Sep 93	-0.8(3.3)	0.0(4.0)	0.8	087	4.6	14.1(3.2)
Oct 93	-2.0(3.5)	-0.3(5.0)	2.0	082	5.7	9.6(0.9)
Nov 93[b]	-2.3(2.3)	-2.0(4.9)	3.1	049	3.8	6.9(0.4)

[a] 27-30 June [b] 1-9 November 1993 [c] Direction toward

AB10

Month	U (cms^{-1})	V (cms^{-1})	Rspd (cms^{-1})	Direction (°T)[c]	Speed (cms^{-1})	Temp (°C)
Aug 93[a]	-0.3(8.6)	1.5(7.5)	1.5	349	10.5	9.9(1.4)
Sep 93	-0.9(8.7)	0.3(6.8)	0.9	288	9.7	10.3(2.6)
Oct 93[b]	-4.2(6.4)	2.7(5.8)	5.0	303	8.9	10.3(0.5)

[a] 24-31 Aug 1993 [b] 1-14 Oct 1993 [c] Direction toward

AB30

Month	U (cms^{-1})	V (cms^{-1})	Rspd (cms^{-1})	Direction (°T)[c]	Speed (cms^{-1})	Temp (°C)
Aug 93[a]	0.5(8.3)	-0.7(5.9)	0.9	144	8.8	7.0(1.3)
Sep 93	0.0(8.3)	-2.1(6.2)	2.1	180	9.5	8.7(2.6)
Oct 93[b]	-3.4(8.6)	2.7(7.1)	4.3	308	11.1	9.4(0.6)

[a] 24-31 Aug 1993 [b] 1-14 Oct 1993 [c] Direction toward

Table 2 (cont.).--Monthly statistics for current and wind components, water temperature, resultant velocity, and scalar speed.

NDBC 45010 1994

Month	U (ms^{-1})	V (ms^{-1})	Rspd (ms^{-1})	Direction (°T)[f]	Speed (ms^{-1})	Temp (°C)
May 94	0.1(2.3)[a]	0.6(4.2)[a]	0.6[a]	194[a]	4.3[a]	9.5(1.5)
Jun 94	0.5(2.5)	0.5(4.0)	0.7	224	4.1	13.6(2.4)
Jul 94	0.4(3.0)[b]	-0.6(3.6)[b]	0.7[b]	330[b]	4.3[b]	17.5(1.4)
Aug 94	-0.9(2.4)[c]	-0.6(3.4)[c]	1.0[c]	056[c]	3.9[c]	17.7(1.5)
Sep 94	-0.4(2.8)	-0.4(2.8)	0.6	045	3.6	15.0(1.4)
Oct 94	2.8(3.2)[d]	1.7(4.5)[d]	3.3[d]	239[d]	6.8[d]	13.4(2.4)
Nov 94[e]						8.4(0.8)

[a] 17-31 May [b]1-12 July [c]12-31 August [d]1-6 October [e]1-9November 1994 [f]Direction toward

AB1

Month	U (cms^{-1})		V (cms^{-1})		Rspd (cms^{-1})		Direction (°T)		Speed (cms^{-1})		Temp (°C)	
	-3 m	-13 m	-3 m	-13 m	-3 m	-13 m	-3 m	-13 m	-3 m	-13 m	-3 m	-13 m
May 94[a]	2.4(3.9)	-0.6(8.6)	0.2(6.3)	0.2(5.7)	2.5	0.6	085	288	6.2	9.4	8.2(1.6)	6.9(1.0)
Jun 94	0.6(5.6)	-0.7(8.7)	1.2(7.0)	1.6(4.8)	0.9	1.7	026	336	7.5	8.9	13.0(2.6)	10.2(2.5)
Jul 94	-0.1(6.6)	-1.0(5.4)	4.2(8.2)	1.4(5.4)	4.3	1.7	359	326	9.5	9.9	16.1(1.7)	9.4(2.8)
Aug 94	0.5(6.5)	0.5(5.3)	7.2(10.0)	2.3(5.3)	7.2	2.4	004	012	11.7	9.5	16.8(1.9)	11.1(4.0)
Sep 94[b]	-0.4(4.5)	0.4(7.1)	1.9(5.2)	1.1(5.1)	1.9	1.2	348	020	5.7	7.7	13.6(1.4)	8.7(0.7)

[a] 5-31 May [b]1-20 Sep

AB2

Month	U (cms^{-1})		V (cms^{-1})		Rspd (cms^{-1})		Direction (°T)		Speed (cms^{-1})		Temp (°C)	
	-3 m	-23 m	-3 m	-23 m	-3 m	-23 m	-3 m	-23 m	-3 m	-23 m	-3 m	-23 m
May 94[a]	-	0.3(5.2)	-	1.3(6.9)	-	1.4	-	165	-	7.5	7.1(2.3)	4.9(0.8)
Jun 94	-	0.9(6.6)	-	1.3(7.8)	-	1.6	-	145	-	9.3	13.0(2.5)	6.4)1.1)
Jul 94	-	-0.5(6.1)	-	0.0(7.0)	-	0.5	-	271	-	8.6	17.8(1.4)	4.8(0.5)
Aug 94	-	0.9(7.9)	-	1.2(8.5)	-	1.5	-	142	-	10.4	18.2(1.4)	6.9(3.2)
Sep 94[b]	-	1.4(6.9)	-	1.6(8.0)	-	2.1	-	136	-	9.9	15.3(1.4)	6.2(1.2)

[a] 5-31 May [b]1-20 Sep

AB3

Month	U (cms^{-1})		V (cms^{-1})		Rspd (cms^{-1})		Direction (°T)		Speed (cms^{-1})		Temp (°C)	
	-3 m	-13 m	-3 m	-13 m	-3 m	-13 m	-3 m	-13 m	-3 m	-13 m	-3 m	-13 m
May 94[a]	-	-0.2(5.7)	-	1.3(9.6)	-	1.3	-	187	-	10.0	7.9(1.7)	6.4(1.0)
Jun 94	-	-0.4(6.2)	-	1.1(9.2)	-	1.1	-	199	-	9.9	12.8(2.3)	9.4(2.6)
Jul 94	-	0.7(6.6)	-	1.2(8.2)	-	0.7	-	149	-	9.3	15.2(2.2)	8.7(3.0)
Aug 94	-	-0.4(5.4)	-	0.9(7.5)	-	1.0	-	338	-	8.3	16.7(2.4)	10.6(4.7)
Sep 94[b]	-	0.4(5.6)	-	2.2(8.0)	-	2.3	-	170	-	9.2	12.9(1.7)	8.8(1.4)

[a] 5-31 May [b]1-20 Sep

Table 2 (cont.).--Monthly statistics for current and wind components, water temperature, resultant velocity, and scalar speed.

General Mitchell Field

Month	U (ms^{-1})[a]	V (ms^{-1})[a]	Rspd (ms^{-1})	Direction (°T)[a]	Speed (ms^{-1})
Jan 94	1.8(4.4)	-0.8(3.2)	1.9	115	5.4
Feb 94	1.3(3.9)	-0.3(3.9)	1.3	104	5.0
Mar 94	1.8(3.6)	-0.1(3.3)	1.8	093	4.5
Apr 94	1.1(4.7)	-0.6(5.0)	1.3	116	6.3
May 94	0.6(3.5)	-0.4(3.9)	0.7	126	4.8
Jun 94	0.1(3.2)	-0.5(4.1)	0.5	172	4.7
Jul 94	1.2(3.3)	0.5(3.4)	1.3	065	4.5
Aug 94	1.1(2.8)	0.2(3.5)	1.1	079	4.2
Sep 94	1.0(3.2)	0.9(2.6)	1.3	058	3.9
Oct 94	1.0(3.5)	0.7(3.6)	1.2	085	4.7
Nov 94[b]	0.7(2.7)	-0.3(4.3)	0.7	114	4.6

[a] Direction toward   [b] 1-15 November 1994

Monthly wind velocities from Milwaukee's Mitchell Field show little variability in speed (<2 ms^{-1}), with southeastward-directed winds in January 1994 backing to northeastward through the summer and fall months. Monthly mean winds from NDBC 45010 were weak, <1 ms^{-1}, except for the months with partial data (e.g., November 1993 and October 1994). A comparison of concurrent over-land and over-water wind measurements indicates that over-water winds were more clockwise by about 50° and were slightly weaker. Fall over-land/over-water wind directions were similar as the over-lake air became more unstable.

Scatter plots of NS1 hourly currents depict the seasonal characteristics (Figure 3). The transition from stratified to nonstratified conditions during the energetic fall period (September-October) evolves into vertically uniform currents aligned with the local bathymetry during the winter and spring months. Baroclinic currents, primarily near-inertial oscillations and weak onshore/offshore flow associated with upwelling/downwelling episodes, were superposed on the barotropic pattern as summer stratification again developed.

Progressive vector plots present an Eulerian time series in a Lagrangian format, recognizing that progressive vectors are representative of true current 'tracks' only when the flow is uniform over the region. NS1 current tracks for July 1994 are representative of typical summer flow patterns observed in the western Lake Michigan nearshore area (Figure 4). Southward flow, aligned closely with the local topography in response to several days of 5-8 ms^{-1} southwestward winds, was followed by slow, steady northward flow combined with a clockwise rotary component of near-inertial oscillations at NS1 (Figure 4d). The current tracks correspond to what Mortimer (1971) described as looping, cusping, and meandering patterns; the pattern depends on the ratio of the alongshore-to-rotary components. In contrast to the beginning of the month, after Day 200 the steady component disappeared, leaving only a weak rotary-type circulation. This has obvious implications on the dispersion and flushing of materials during these stagnant periods. Closer to shore near the southern Milwaukee water intake, near-surface currents from AB1 (Figure 4b) tracked northward interspersed by several days of near-zero flow for the month of July (mean velocity 4.3 cms^{-1}, 359°; scalar speed 9.5 cms^{-1}), while the near-bottom currents (Figure 4c) tracked northwestward (mean 1.4 cms^{-1}, 326°; 9.9 cms^{-1}) with greater east-west excursions. The near-bottom meter on AB3, near the northern water intake, recorded currents aligned with the topography and switched directions at 6-8 day intervals (mean 0.7 cms^{-1}, 149°; 9.3 cms^{-1}) (Figure 4a).

4.2 Wind Forcing

Sato and Mortimer (1975), from their analysis of 1973 wind and current observations in the nearshore region 20 km south of the 1993-94 Milwaukee, Wisconsin site, pointed out that winds blowing toward northeast through

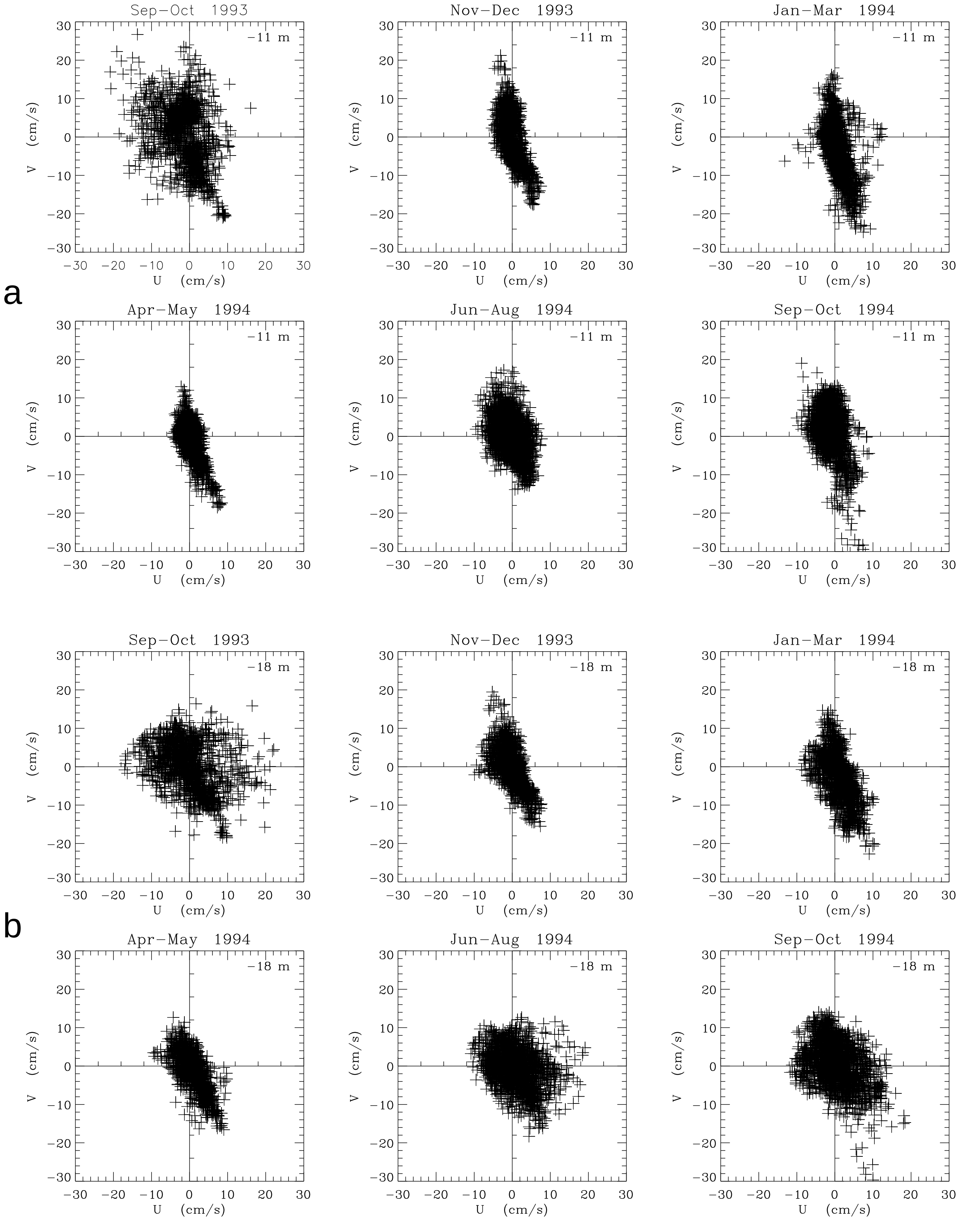


Figure 3.--U- and V-current component scatter plots for 2- and 3-month intervals for NS1 at -11m (a) and -18 m (b). Positive u is eastward; positive v is northward.

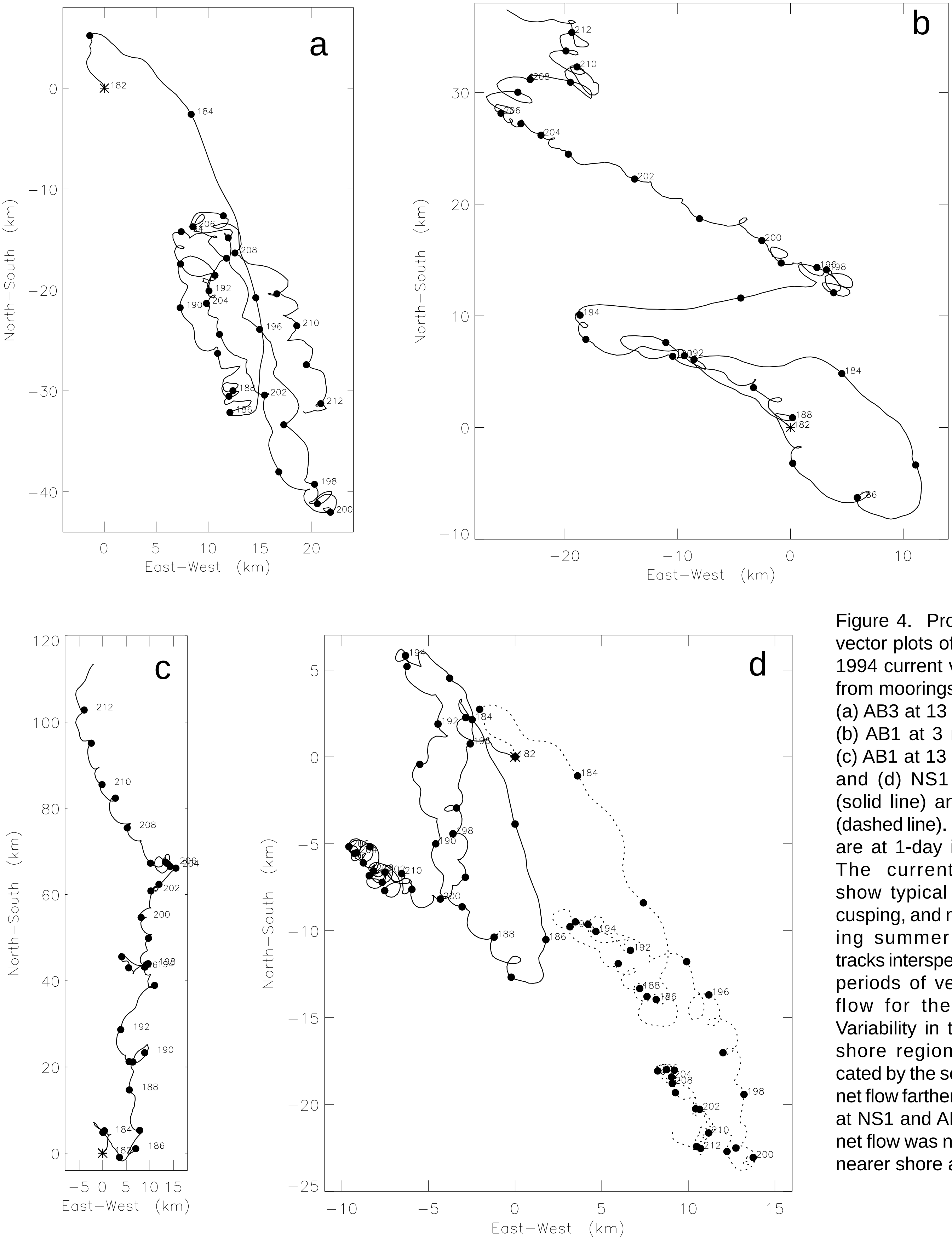


Figure 4. Progressive vector plots of the July 1994 current velocities from moorings (a) AB3 at 13 m depth, (b) AB1 at 3 m depth, (c) AB1 at 13 m depth, and (d) NS1 at -11m (solid line) and -18 m (dashed line). Symbols are at 1-day intervals. The current tracks show typical looping, cusping, and meandering summer current tracks interspersed with periods of very weak flow for the month. Variability in the nearshore region is indicated by the southward net flow farther offshore at NS1 and AB3, while net flow was northward nearer shore at AB1.

southwest provide limited fetch and exert minimal direct influence on nearshore currents. The maximal effect is derived from winds blowing along the axis of the lake. Hence, traditional statistical correlation and cross-spectral techniques generally indicate low correlation between winds and currents. Lag times between wind reversal and current response from their 1973 data varied widely and showed no systematic seasonal patterns, but did suggest shorter reversal times and greater frequency of reversals at locations nearer the shore. The 1993 and 1994 v-components of wind and current were subjected to a lagged correlation analysis that also produced mixed results. The 1994 data were separated into two segments because of a gap in the NDBC 45010 wind data; a 58-day interval from 17 May to 13 July, and a 57-day (39-day for AB moorings) interval from 20 August to 8 October (19 September). Similarly, data from 25 August to 13 October represent the 1993 measurements. The lagged correlation coefficient values for the alongshore (v) component were in the 0.5 to 0.7 range at lag times on the order of 6 to 10 hours (currents lag the wind) for the two measurement periods. Similar numbers were obtained by Sato and Mortimer (1975). While strong coupling of the current to the wind is evident from the time series plots (Appendix A), the response time of the current to changing wind stress is a function of wind direction, strength, previous flow conditions, and over-water stability. Small changes in coefficients between lag times suggest that the response times are highly variable. The u-component lagged wind and current correlation coefficient values were small.

Barplots of the frequency of occurrence of current velocity and water temperatures for a spring and a fall time period, when concurrent NDBC wind data were available, reflect that the maximal current response is dependent not only on the wind velocity, but also on the atmospheric stability. During 27 September-9 November 1993 (Figure 5) the water column was vertically isothermal, as shown by the identical temperature distributions at the three depths. Temperatures decreased from 10°C at the beginning of this fall segment to 6°C by mid-November. Wind directions were well distributed except for a scarcity of onshore-directed winds (<15%). Currents at NS1 were strongly bimodal and aligned with the local topography with relatively little vertical shear. Over-water wind

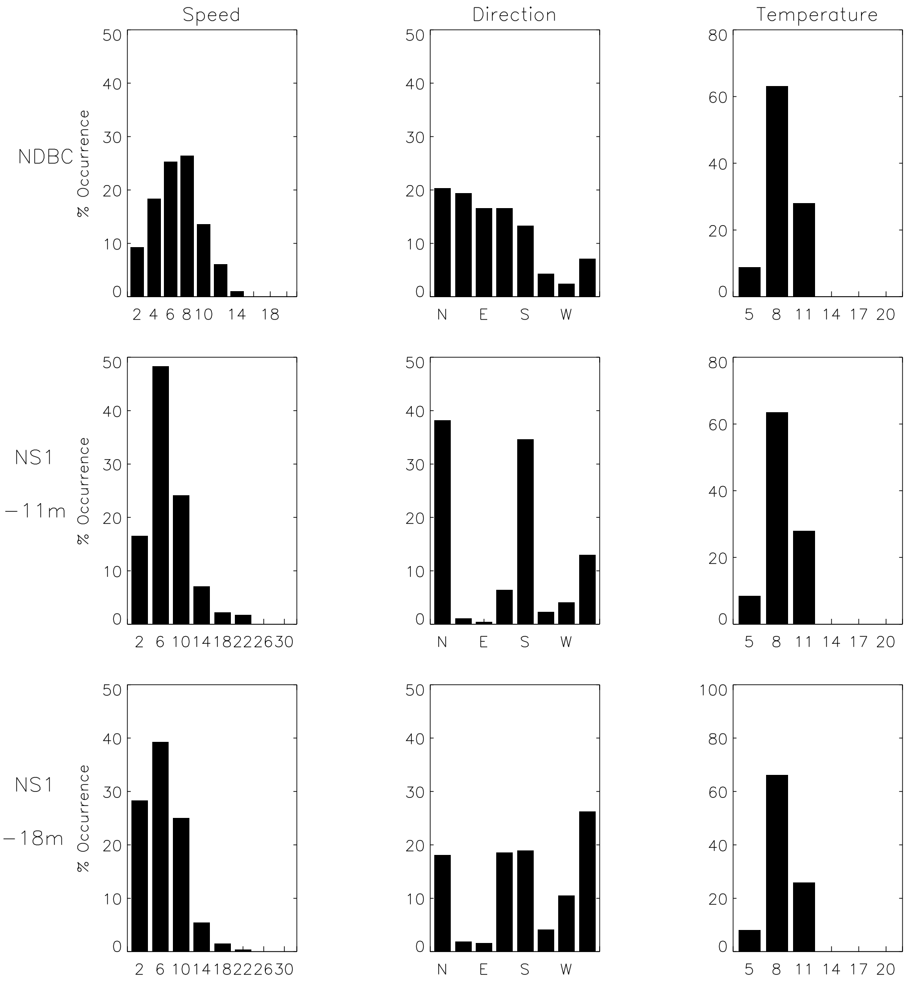


Figure 5.--Frequency of occurrence of wind speed and direction at 5 m above water and near-surface water temperature from NDBC 45010, and current speed, direction, and temperature from -11 m and -18 m from 27 September to 9 November 1993 (44 days). Wind direction is toward.

tracks for approximately the same time interval (Figure 6) show an alongshore component reversing every 3-6 days superposed on a general northeastward flow. Corresponding current tracks from NS1 (Figure 6) show rectilinear flow with direction reversals about every 5 days that lagged the wind by about one-half day. Note that cross-shore flow was minimal despite a significant eastward wind component during many of the days. In contrast, the 17 May-12 July, 1994 period (Figure 7) had a greater frequency of alongshore winds, but a decrease in the frequency of alongshore currents as well as smaller current magnitudes at NS1, because strong over-water stability insulated the lake from the wind stress. Note also that the current near the bottom at AB1 (14 m) has ESE-WNW components, similar to those seen in the July current tracks (Figure 4c). It is assumed that the flow is constrained topographically by the shoal to the south and, secondarily, by upwelling/downwelling circulation. This represents two mechanisms for cross-shore exchange in this nearshore area.

Figure 6.--Progressive vectors plots of the NDBC 45010 wind velocity (a), and NS1 current velocities (b) (11 m depth solid line, 18 m dashed) from 30 September to 18 November 1993, showing bimodal alongshore response of the currents to alongshore wind stress when the water is vertically homogeneous.

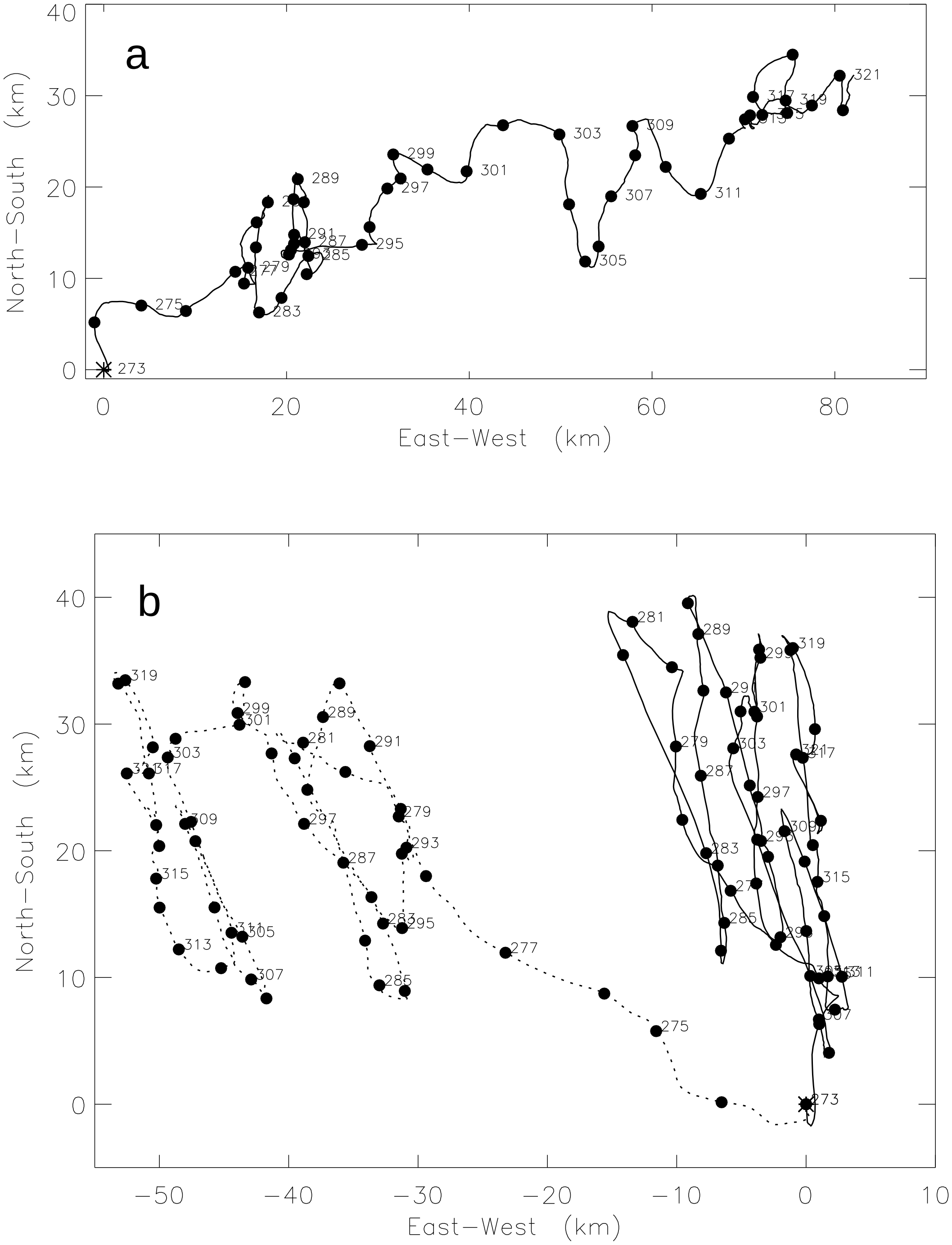
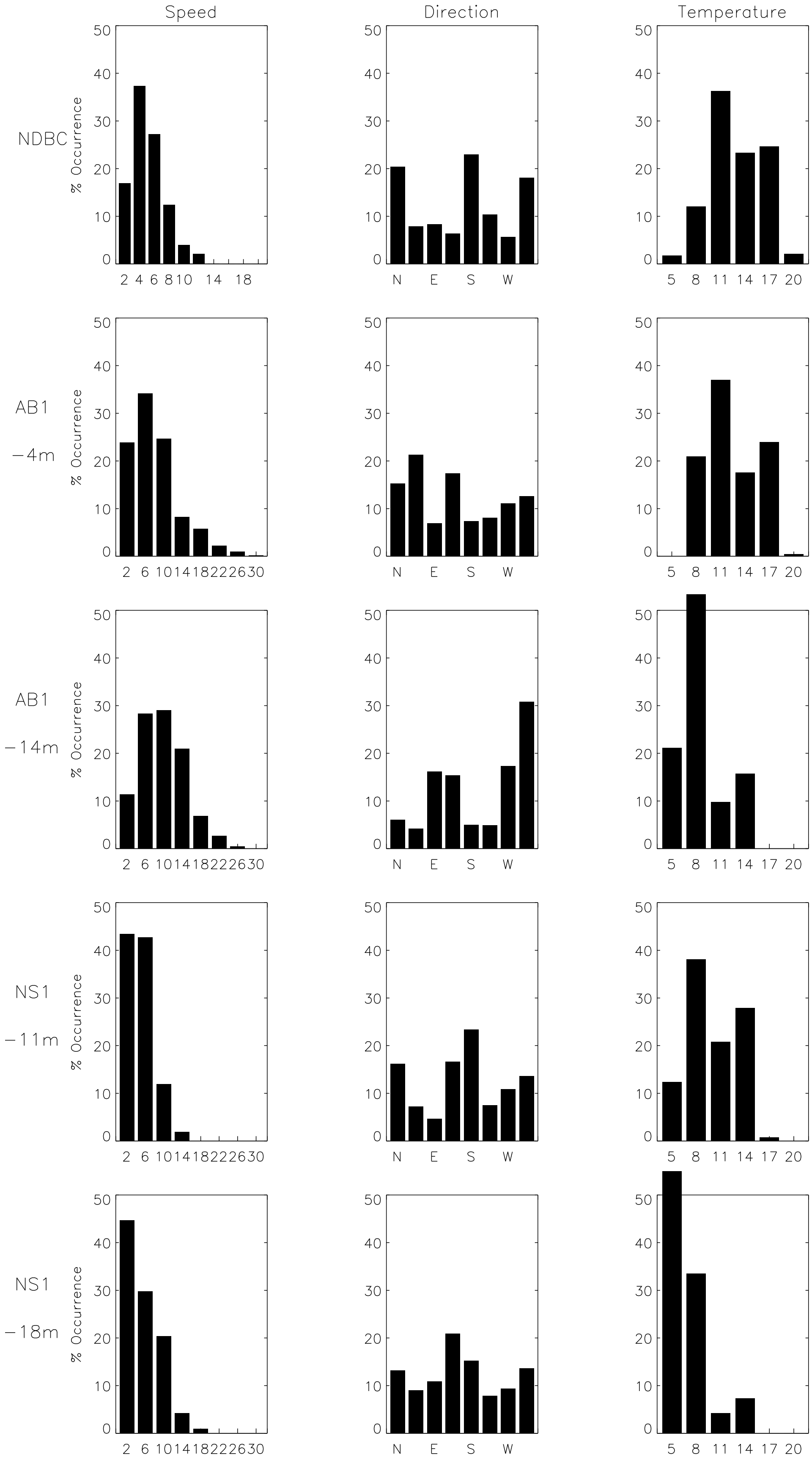


Figure 7. Frequency of occurrence of wind speed and direction at 5 m above water and near-surface water temperature from NDBC 45010, and current speed, direction, and temperature from all meaurement sites from 17 May to 12 July 1994.



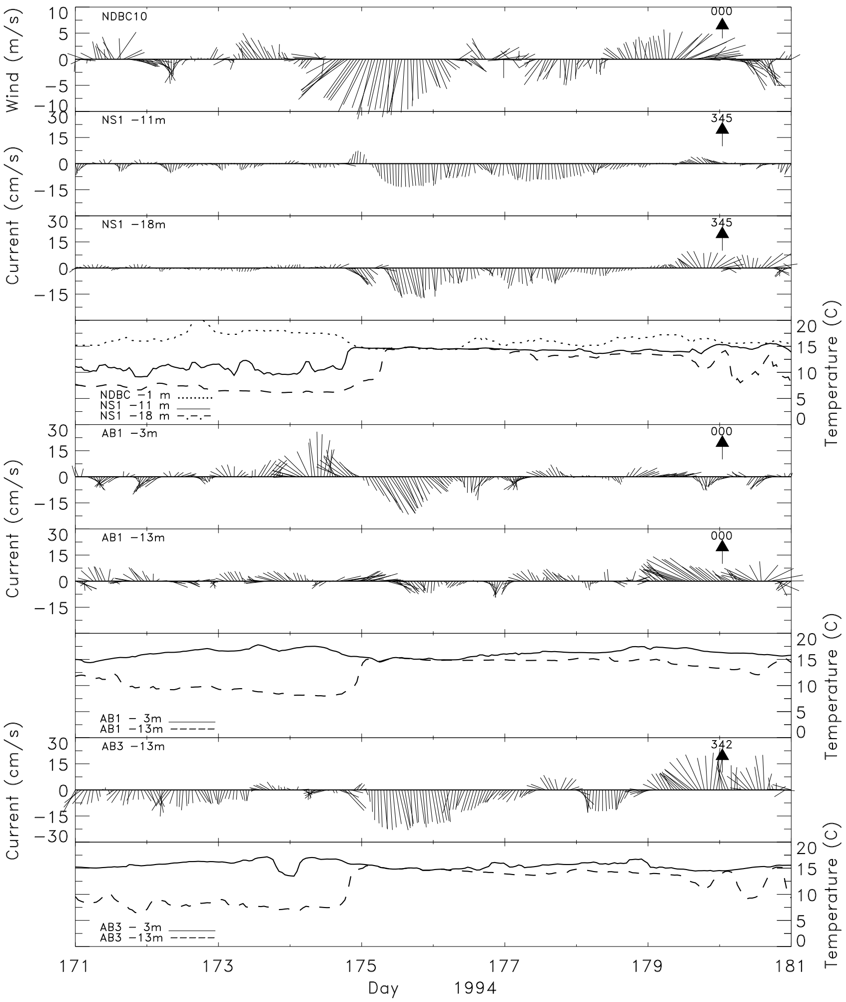
Lee (personal communication) developed a two-dimensional depth-averaged hydrodynamic model (Chen and Lee, 1991) and coupled it with a transport model (Lee and Chen, 1986; Cheong, 1988) modified for the Milwaukee Harbor and nearshore geometry. Initial visual comparisons of model results generated by a 36-hour 7.7 ms^{-1} north wind (southward directed) and measured currents at AB1, located within 400 m of the southern water intake (Texas Avenue Plant), compare well. NS1 mooring was just east of the modeled area, but the currents are directionally consistent with the model results. With a southeast wind, the lower portion of the water column generally flowed northwestward as predicted by the model. After initial adjustments the upper layer moved northeastward. However, because it is a depth-average model, the vertically averaged current would compare more favorably.

4.3 Upwelling/Downwelling

The longshore component of wind stress causes Ekman transport, confined to the upper layer, to flow toward or away from the coast depending on wind direction. When the transport is away from the coast, that is, when looking down-wind with the shore on the left, continuity requires that this offshore flow be compensated by an onshore adjustment current below the thermocline. This resulting adjustment causes an elevation of the thermocline depth (upwelling) in a band along the coast. A comparable depression of the thermocline (downwelling) occurs along the opposite shore. With sufficient wind stress, the thermocline intersects the surface in what Csanady (1977) termed ‘full’ upwelling. The upwelled thermocline front moves further offshore with continued or increased wind stress. The structure of the circulation with full upwelling is not fully understood. For example, it is not known whether the circulation is one cell (surface water moving offshore replaced by hypolimnetic water moving upslope) or two (convergence and downwelling at the front), or whether the process is reversible. Indications are that a one-cell pattern may occur during the formative phase and two-cell pattern during relaxation. Hamilton and Rattray (1978) have shown how a double-cell circulation can be set up, once the front is established. After the wind stress abates, geostrophic readjustment takes place, with part of the energy remaining nearshore as geostophic currents and shore-trapped Kelvin waves, and part radiating offshore as a dispersive ensemble of Poincare' waves covering a range of wavelengths and frequencies (Mortimer, 1993). Much of our knowledge on upwelling and downwelling in Lake Michigan and internal wave interactions in both the nearshore and offshore waters has been advanced by Mortimer (1963, 1971, 1980, 1988, 1993). The north-south orientation of Lake Michigan and the frequent northerly winds produce remarkable upwelling events along the eastern Lake Michigan shore. Southward of Big Sable and Little Sable Point, for example, are preferred upwelling locations due to bottom topography and coastal geometry. Upwelling along Lake Michigan’s western shore is not as intense, but upwelling is generally more persistent than on the eastern side because of the greater frequency of northeastward directed winds. When the thermocline does intersect the surface along the western Lake Michigan shore, the upwelled frontal boundary is generally more diffuse and convoluted with large eddies (Mortimer, 1988) and has been attributed to baroclinic instability (Rao and Doughty, 1981). With strong downwelling episodes, the leading waves form internal surge fronts (Simons, 1978; Mortimer, 1993), which may play a significant role in cross-shore transport. Therefore, an important consequence of upwelling/downwelling is the mass exchange between the nearshore and offshore waters with all its ecological impacts. These complex circulations, processes, and interactions associated with upwelling/downwelling are, as yet, not fully understood.

Data recorded in 1994 show several downwelling occurrences associated with southward currents as indicated by rapid temperature increases. Temperatures from NDBC, AB1, and AB3 indicate that five strong downwelling events occurred in 1994. Figure 8 illustrates a typical downwelling event. Light northward winds (2-5 ms^{-1}) during the last half of Day 173 generated northerly currents at AB1 and AB3, while further offshore at NS1, flow was very weak. Variable winds for the first 12 hours on Day 174 changed to southwestward at speeds to 10 ms$^{-1,}$ then backed to southward reaching 12 ms^{-1} through Day 175. Response flow at AB1 was northwesterly near-surface currents for about 6 hours, accompanied by a 3^{o}C drop in water temperature, while the near-bottom flow was directed offshore and temperature increased rapidly as the thermocline descended past the sensor. Currents and temperatures responded similarly north of Milwaukee Harbor at AB3. Farther offshore at NS1, the -11 m VACM recorded a sharp temperature increase, followed 12 hours later by a similar increase at -18 m. The depressed thermocline did not reach the 23-m depth 10 km offshore at AB2. The vertically isothermal nearshore

Figure 8. Typical downwelling episode generated by southward directed wind. The currents initially responded with onshore upper level and offshore lower level flow until vertical temperature uniformity is achieved, then followed by southward along-isobath flow. Water temperatures from -1 m at NDBC are included in Panel 4.



water mass then flowed southward for several days before a slackening of the wind and change in direction allowed the thermocline to relax.

No ‘full’ upwelling events were recorded during 1993-94. An episode during 27-28 August (Days 239-240) illustrates the typical upwelling response to northward wind forcing (Figure 9). For the preceding several days, currents at all moorings were ‘looping’ near-inertial currents, except nearsurface at AB1 where currents were consistently northward. As the wind veered from eastward to northward on the 27th (Day 239), currents turned more onshore near the bottom and offshore near the surface. The isotherms began to rise, as shown by the decrease in the upper level (-4 m) water temperatures from ~20^{o}C to 9.3^{o}C at AB1 and to 6.4^{o}C at AB3 at 0800 on the 28th (Day 240). At -11 m on NS1, the thermistor was recording the near-inertial, vertical oscillations of the thermocline, and any cross-shore flow associated with upwelling was masked by the rotational flow associated with the near inertial currents. The 1-m water temperature at the NDBC site decreased from near 20^{o}C to about 14^{o}C. No temperature changes that suggest upwelling were observed at AB2 10 km offshore in 34-m water. The cold epilimnion water may have intersected the surface nearer the shore in water depths <15 m.

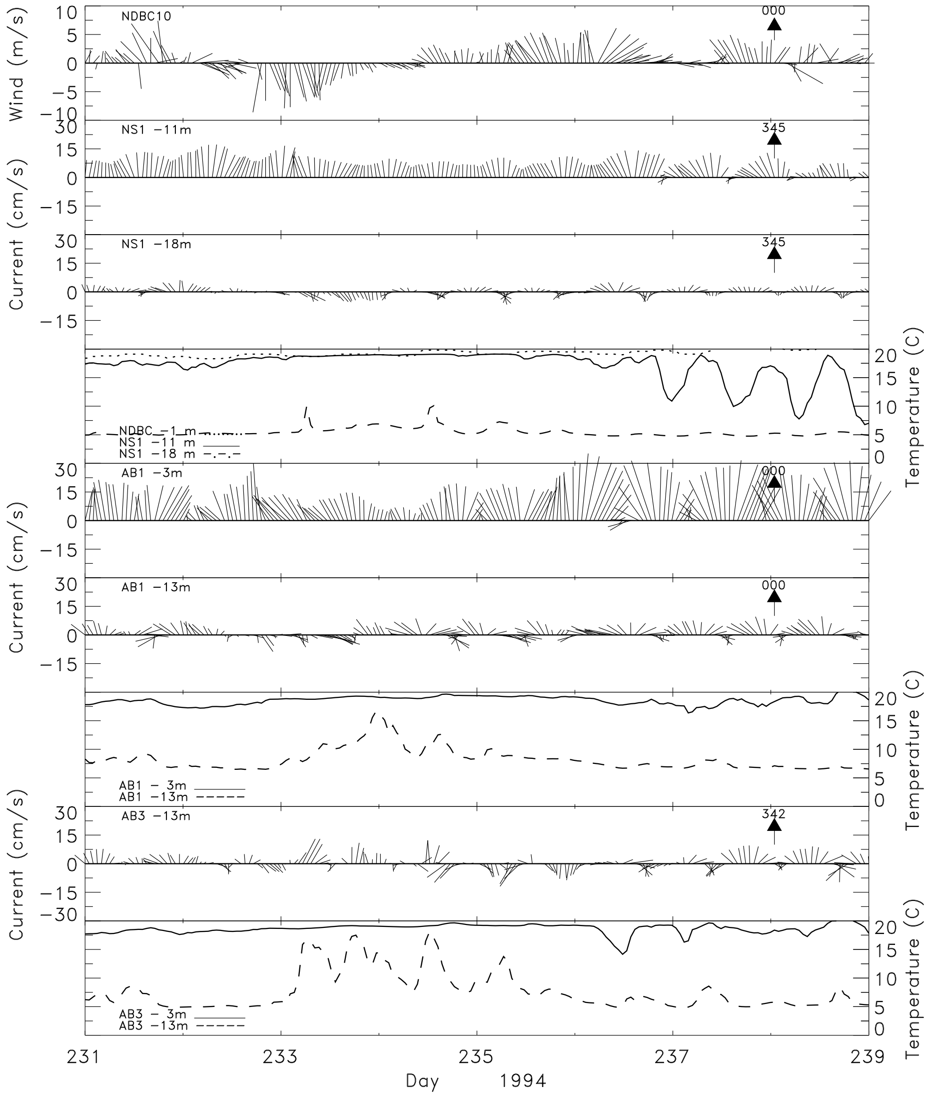


Figure 9. An example of an upwelling event in the nearshore region produced by a northward wind.

4.4 Winter Flow

Current and temperature measurements at NS1 provide an uninterrupted data set collected in water depths less than 25 m during winter in Lake Michigan. Water temperatures were vertically isothermal at 10^{o}C by the end of September, cooled to 4^{o}C by mid-December, decreased to near zero by 10 January, and warmed again to 4^{o}C by mid-April. A progressive vector plot of currents from 1 January through 30 April 1994 characterizes the winter flow (Figure 10). Episodes of moderate (20 cms^{-1}) southerly flow alternated with several days of very weak currents and direction reversals. Currents were vertically uniform and followed the isobaths with minimal cross-shore excursions.

Monthly current velocities were less than 2 cms^{-1} except for December and January when velocities approached 4 cms^{-1}. The scalar mean current speeds averaged less than 6 cms^{-1} with maximum speeds of about 30

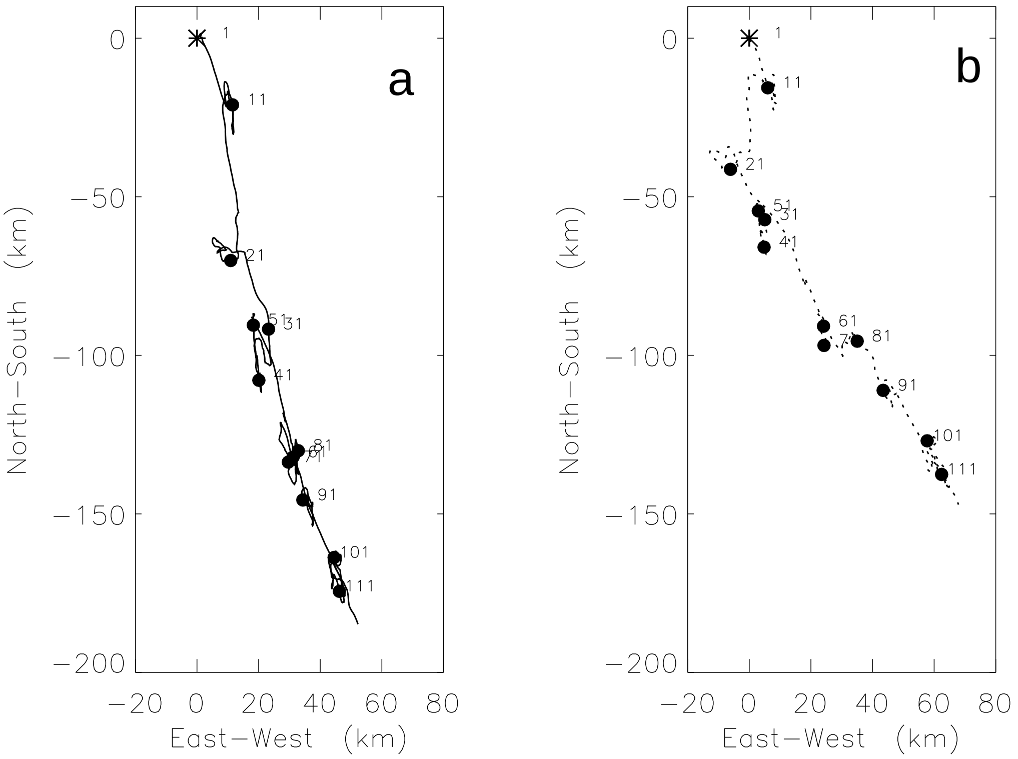


Figure 10. A 120-day progressive vector plot of currents at the 11-m and 18-m depths during the winter of 1994. Symbols are at 10-day intervals.

cms^{-1} in February and March. In contrast, 1983 winter current data from one mooring 40 km north of Milwaukee Harbor and another 40 km southeast of the harbor, both in 75 m water, recorded southerly flow for the first 5 months of 1983 with monthly mean vector velocities reaching 13 cms^{-1} for March (Gottlieb et al., 1989). Also, 1983 winter currents reached speeds of ~45 cms^{-1} and were persistently southward (northward currents occurred during only 7 days in March and April 1983). Ice cover is a significant factor in determining the strength and character of nearshore currents. Days with significant ice cover (70-100%) in the Milwaukee region, determined from the Great Lakes Ice Analysis charts, are indicated on the temperature panel in the timeseries plots in Appendix A. On Days 42-47 (11-16 February 1994) and 59-65 (28 February-6 March 1994), for example, ice covered much of Lake Michigan and current speeds were near-zero at NS1. During the 1994 winter an estimated 25 days with significant ice cover on western Lake Michigan and the Milwaukee region contributed to the low monthly current velocities during February and March. A narrow band of ice shoreward from NS1 persisted throughout much of the 1994 winter with no obvious impact on the measured currents. This shorebound band of ice may be a factor in the occurrence of the springtime plume observed in Lake Michigan (Eadie et al., 1996). The larger magnitude currents observed in 1983 were due, in large part, to the fact that "winter 1983 was one of the mildest winters in the past 200 years" and Lake Michigan's maximal ice cover was about one third of normal (Assel et al., 1984). Conversely, the winter of 1993-94 produced the most extensive ice cover in over a decade. Maximum ice coverages on Lake Michigan reached 78% compared to a 'normal' of 45% (Assel et al., 1996).

There are several potential impacts associated with the 1993-4 type of winter flow pattern. Effluents discharged into the nearshore region will not be effectively flushed out of the nearshore region and, with the weak bimodal flow episodes, could potentially impact both municipal water intakes to the north and south of the city. The dominant southward flow follows the isobaths with little cross-shore transport. The coastal geometry and bottom topography may be an effective forcing function for nearshore/offshore exchange, but little is known concerning the interaction of coastal geometry and alongshore currents. The presence of lake ice effectively cuts off the wind stress forcing, thereby reducing the nearshore energy and the mixing and dispersion of effluents.

5.0 CONCLUSIONS

Currents measured off Milwaukee Harbor reveal few new insights into the nearshore dynamics than have been reported in earlier nearshore investigations. Therefore, the conclusions drawn from the 1993-94 stratified season measurements taken in this study are analogous to those from Sato and Mortimer's (1975) nearshore program 20 km south of Milwaukee, Wisconsin, 20 years ago.

Nearshore currents in the Milwaukee Harbor area of Lake Michigan are characterized by low-frequency fluctuations, strongly polarized in the alongshore direction, with periods of several days that correlate with the local winds. The current lags the wind stress by 6-12 hours, with the more rapid response nearer the shore. The lag correlation coefficients magnitudes are only slightly different for lag times from 4 to 14 hours, suggesting that the lag is a function of the wind direction and magnitude as well as the previous current velocity. Wind-generated current reversals are characterized by a rapid acceleration followed by a slower deceleration after wind stress relaxation. With the onset of vertical stratification, large-amplitude internal waves at a wide range of time scales form on the thermocline. Cusp or looping-type currents, due to the near-inertial oscillations superimposed on a steady barotropic longshore flow, are present in the range of water depths, 15-35 m, where measurements were taken. Current magnitudes along the western shore off Milwaukee Harbor are moderate, seldom exceeding 30 cms^{-1}. Resultant current velocities are near-zero because of the bimodal character of the currents. Large interannual variability in currents and water temperatures is common and a function of the meteorological conditions and resulting upwelling and downwelling. No full upwelling episodes were observed at the measurement sites. However, less dramatic upwelling/downwelling events, observable by the migration of the thermocline past the fixed sensors, were a consequence of alongshore wind events. The onshore/offshore component of Ekman drift was short lived, lasting only 6-12 hours before the currents became vertically uniform in these water depths.

Currents are wind driven and vertically uniform when the water column is homogeneous from about the end of September through late April. The presence of ice cover has a major impact on current velocity in the nearshore and may be a determining factor in the generation of the spring plume event seen in the southern basin of Lake Michigan (Eadie et al., 1996). During winter, flow closely parallels the isobaths with minimal cross-shore transport. Effluents entering the nearshore region would tend to remain in the nearshore area. Bottom topography and shore geometry in the coastal region may be the primary parameters that control onshore/offshore interactions and the winter coastal circulation patterns.

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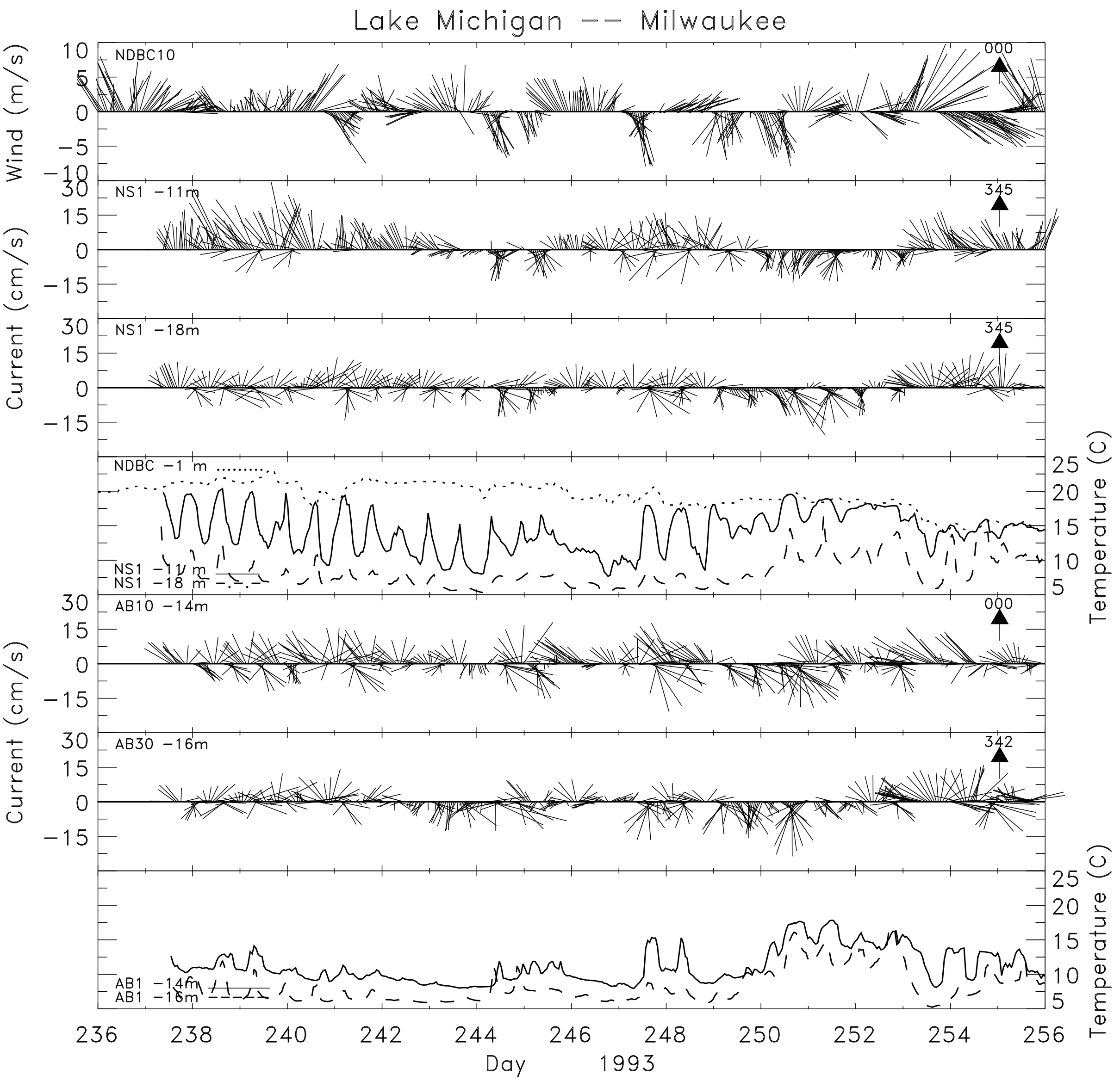
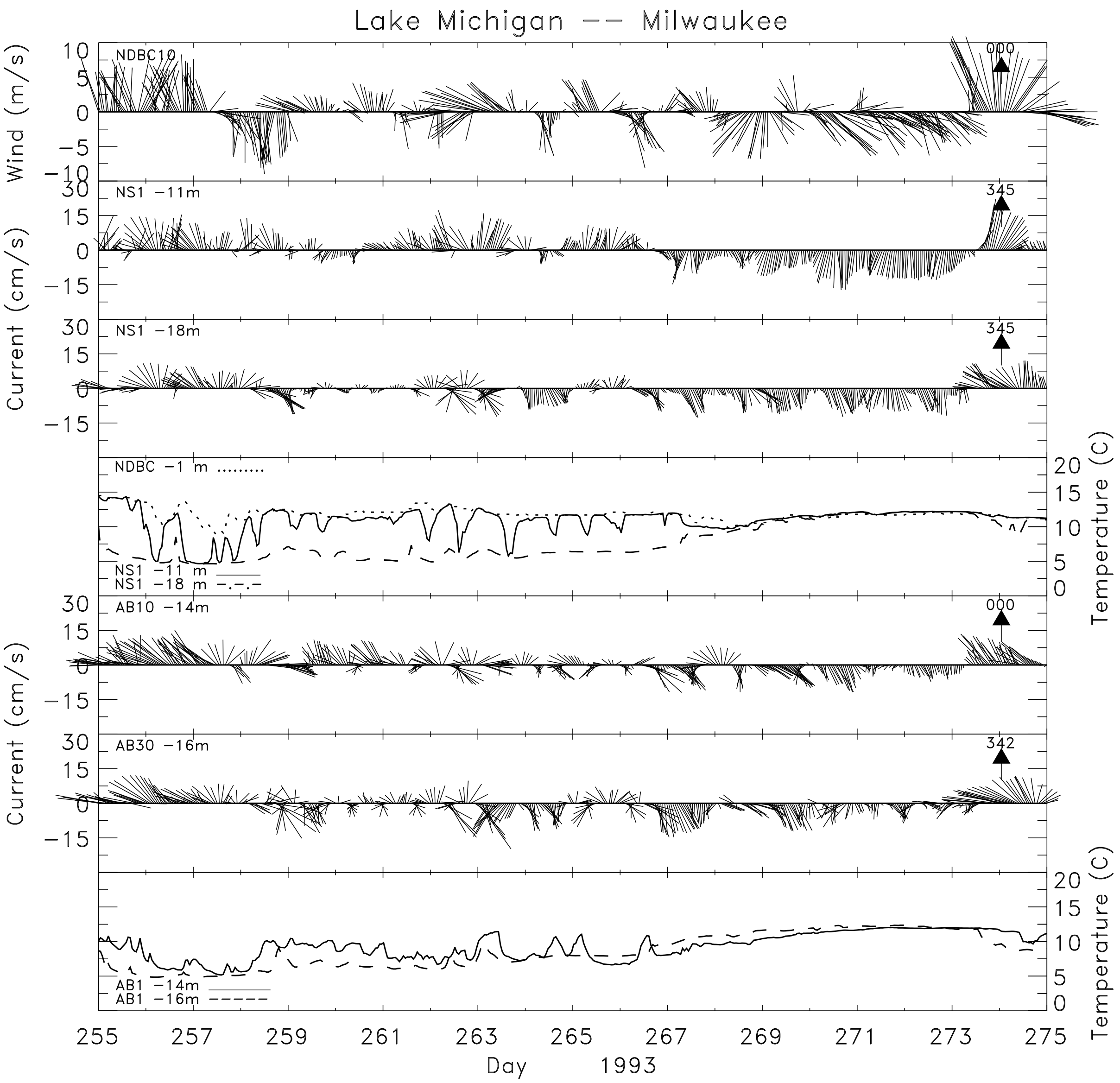
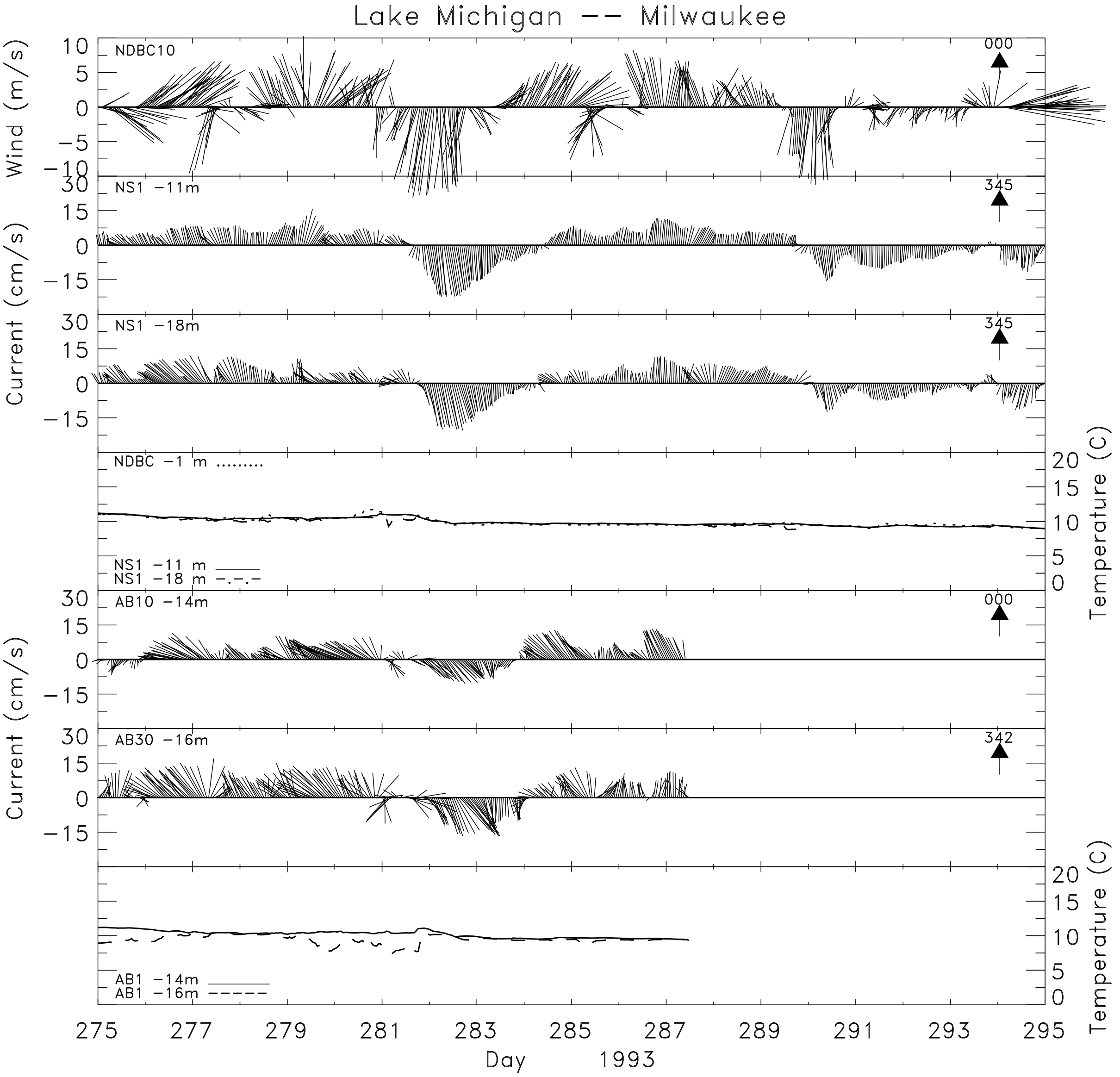
Appendix A:
Hourly Winds, Currents, and Water Temperatures

This section contains stick plots of the mean hourly winds and currents from the indicated moorings and depths. Currents from several moorings have been rotated to orient with the local bathymetry. Wind data are from either NDBC 45010 or the NOAA weather station at General Mitchell Field. Water temperatures were recorded at the current meter locations and at 1 m below the surface on NDBC 45010. Days on which there was significant ice cover are indicated by a hatched area in the water temperature panel.


Lake Michigan -- Milwaukee
NDBC10
000
Wind (m/s)
10
5
0
-5
-10
NS1 -11m
345
30
15
0
-15
Current (cm/s)
NS1 -18m
345
NDBC -1 m
NS1 -11 m
NS1 -18 m
Temperature (C)
25
20
15
10
5
AB10 -14m
000
Current (cm/s)
AB30 -16m
342
AB1 -14m
AB1 -16m
236
238
240
242
244
246
248
250
252
254
256
Day
1993


Lake Michigan -- Milwaukee
NDBC10
000
Wind (m/s)
10
5
0
-5
-10
NS1 -11m
345
30
15
0
-15
Current (cm/s)
NS1 -18m
345
30
15
0
-15
NDBC -1 m ....
NS1 -11 m ______
NS1 -18 m -.-.-
20
15
10
5
0
Temperature (C)
AB10 -14m
000
30
15
0
-15
Current (cm/s)
AB30 -16m
342
30
15
0
-15
Current (cm/s)
AB1 -14m ______
AB1 -16m ------
20
15
10
5
0
Temperature (C)
255
257
259
261
263
265
267
269
271
273
275
Day 1993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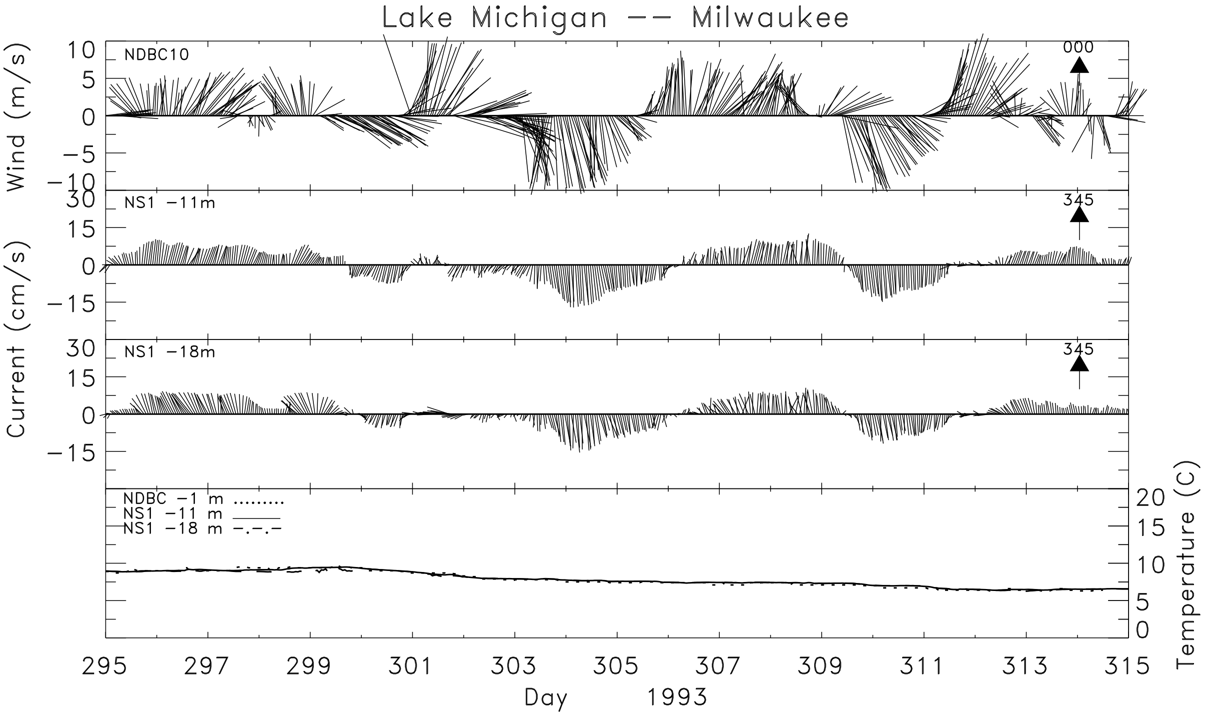
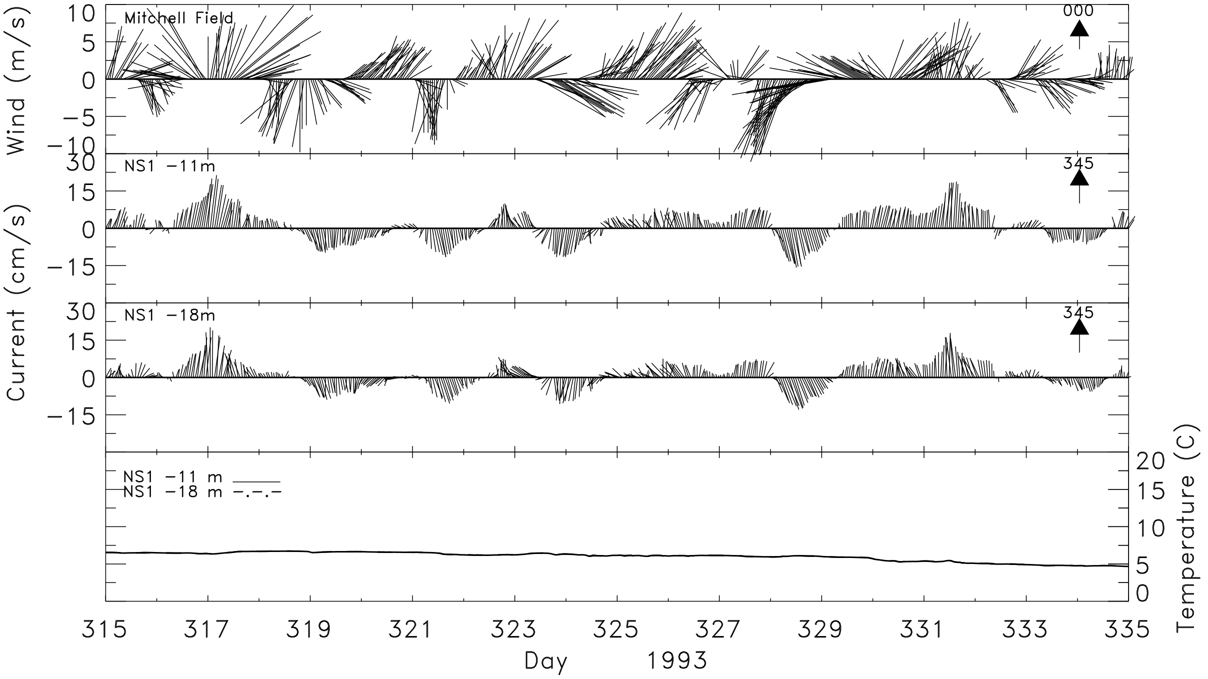
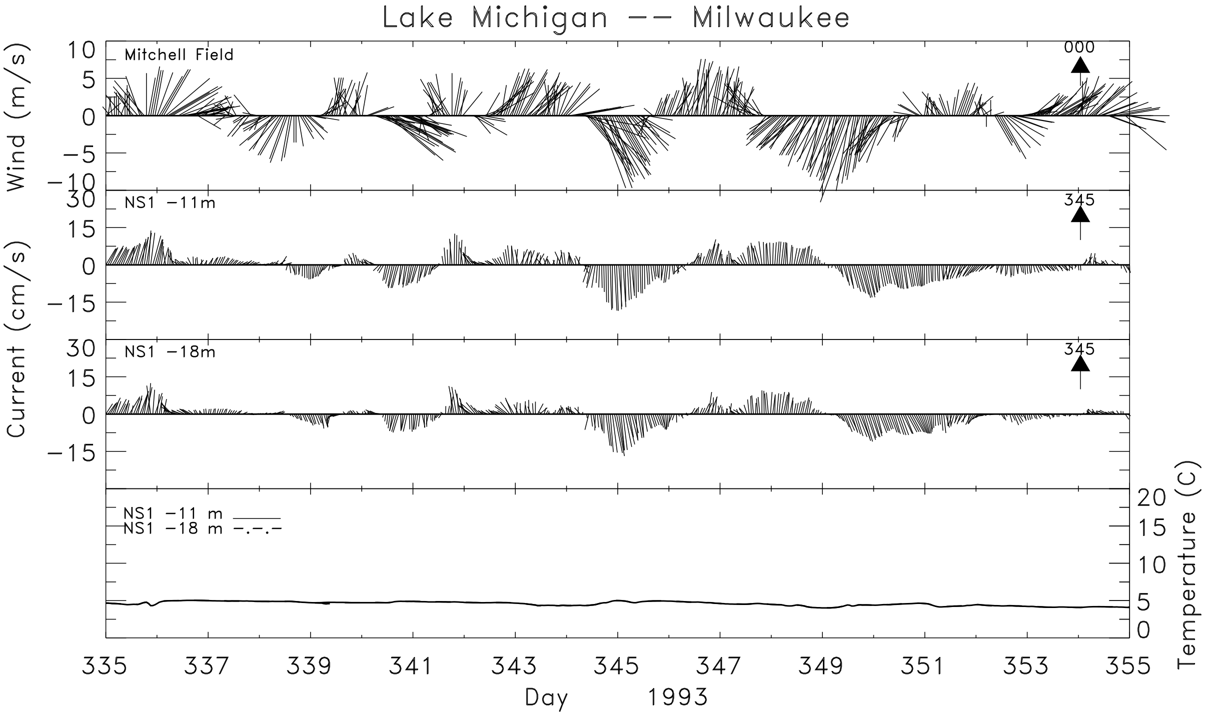
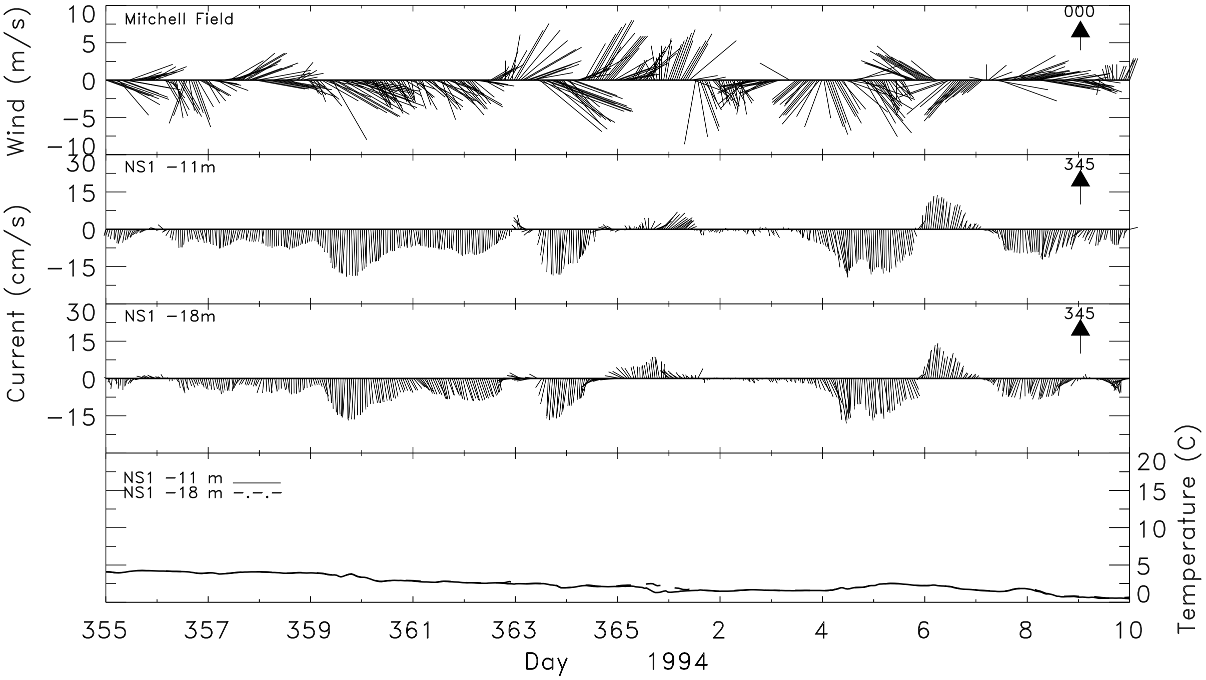
NDBC10
000
Wind (m/s)
10
5
0
−5
−10
NS1 −11m
345
30
15
0
−15
Current (cm/s)
NS1 −18m
345
NDBC −1 m ....
NS1 −11 m ______
NS1 −18 m −.−.−
Temperature (C)
20
15
10
5
0
AB10 −14m
000
AB30 −16m
342
AB1 −14m ______
AB1 −16m −−−−−
275
277
279
281
283
285
287
289
291
293
295
Day
1993


Lake Michigan -- Milwaukee
NDBC10
000
Wind (m/s)
10
5
0
−5
−10
NS1 −11m
345
30
15
0
−15
Current (cm/s)
NS1 −18m
345
NDBC −1 m ....
NS1 −11 m ______
NS1 −18 m −.−.−
20
15
10
5
0
Temperature (C)
295
297
299
301
303
305
307
309
311
313
315
Day 1993


Mitchell Field
000
Wind (m/s)
10
5
0
−5
−10
NS1 −11m
345
30
15
0
−15
Current (cm/s)
NS1 −18m
345
NS1 −11 m ______
NS1 −18 m −.−.−
20
15
10
5
0
Temperature (C)
315
317
319
321
323
325
327
329
331
333
335
Day 1993


Lake Michigan -- Milwaukee
Wind (m/s)
Mitchell Field
000
10
5
0
-5
-10
NS1 -11m
345
30
15
0
-15
Current (cm/s)
NS1 -18m
345
30
15
0
-15
NS1 -11 m
NS1 -18 m -.-.-
20
15
10
5
0
Temperature (C)
335
337
339
341
343
345
347
349
351
353
355
Day 1993


Wind (m/s)
Mitchell Field
000
10
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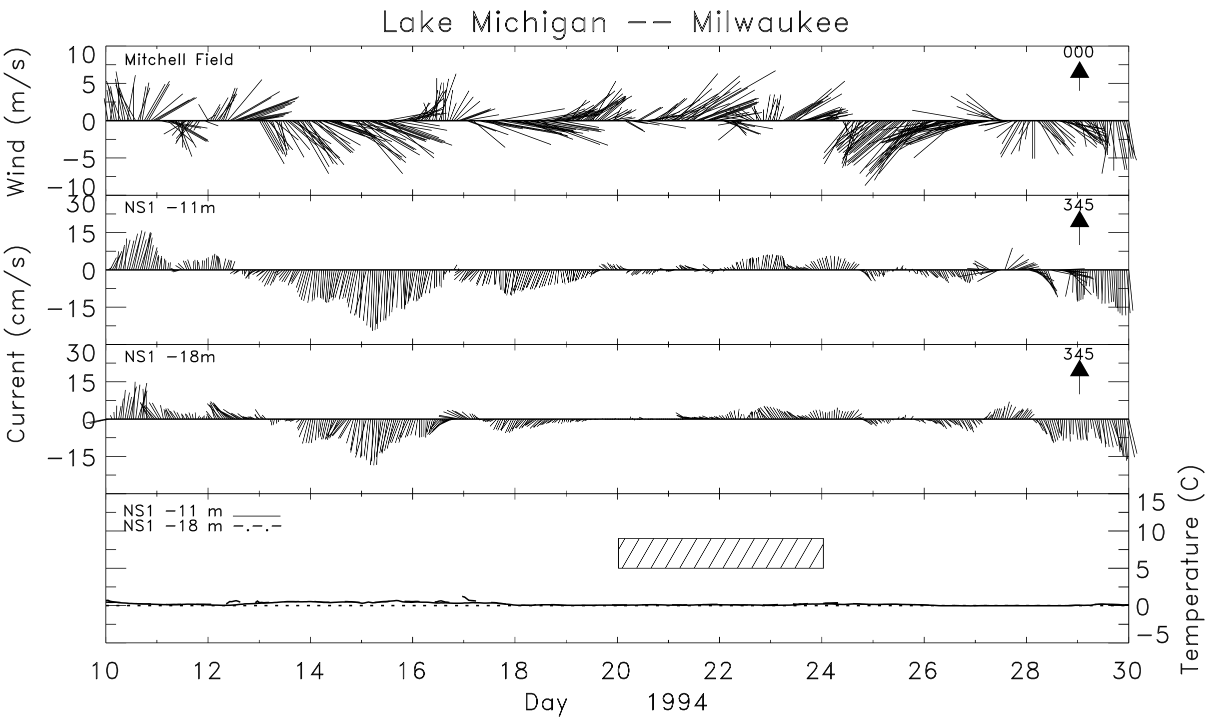
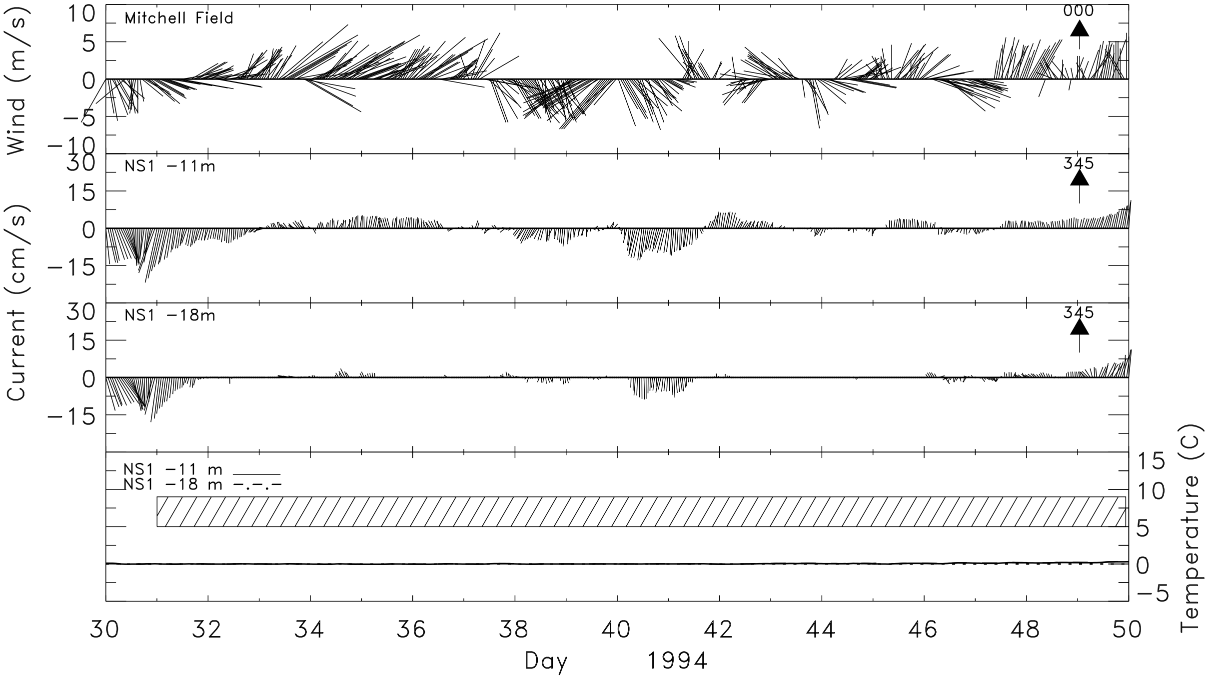
0
-5
-10
NS1 -11m
345
30
15
0
-15
Current (cm/s)
NS1 -18m
345
30
15
0
-15
NS1 -11 m
NS1 -18 m -.-.-
20
15
10
5
0
Temperature (C)
355
357
359
361
363
365
2
4
6
8
10
Day 1994


Lake Michigan -- Milwaukee
Mitchell Field
000
Wind (m/s)
10
5
0
-5
-10
NS1 -11m
345
30
15
0
-15
Current (cm/s)
NS1 -18m
345
30
15
0
-15
NS1 -11 m
NS1 -18 m -.-.-
15
10
5
0
-5
Temperature (C)
10
12
14
16
18
20
22
24
26
28
30
Day 1994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Wind (m/s)
10
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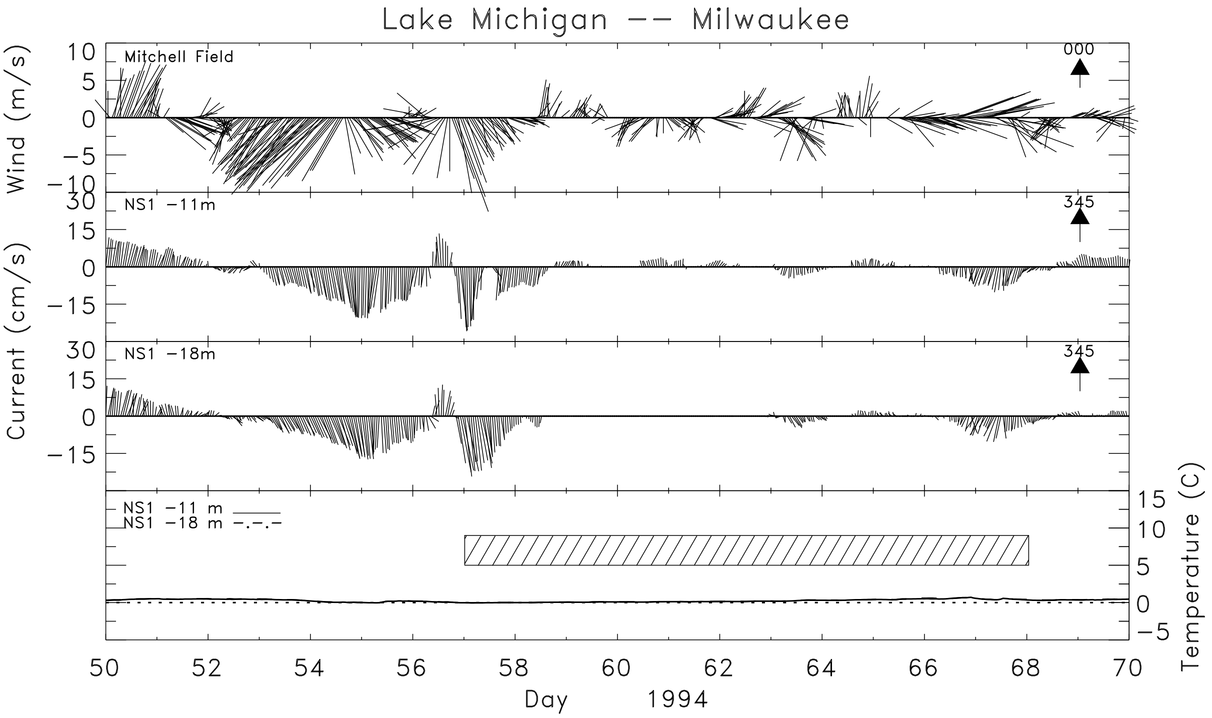
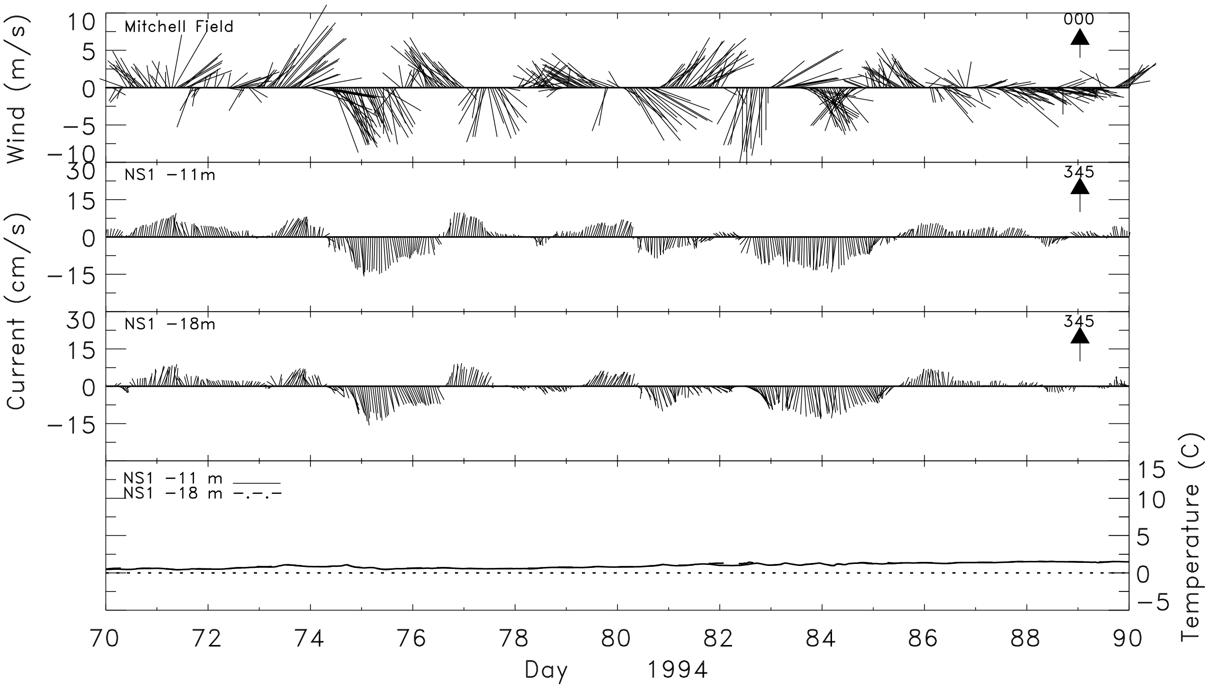
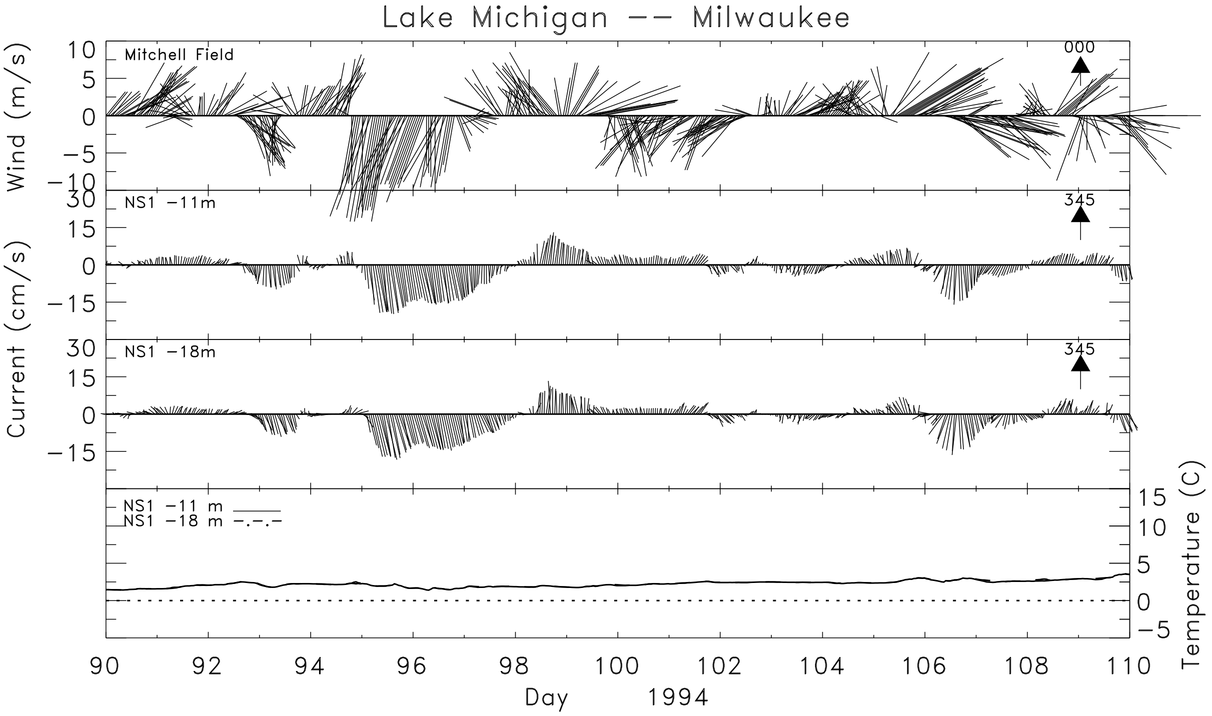
0
-5
-10
NS1 -11m
345
30
15
0
-15
Current (cm/s)
NS1 -18m
345
30
15
0
-15
NS1 -11 m
NS1 -18 m -.-.-
15
10
5
0
-5
Temperature (C)
30
32
34
36
38
40
42
44
46
48
50
Day 1994

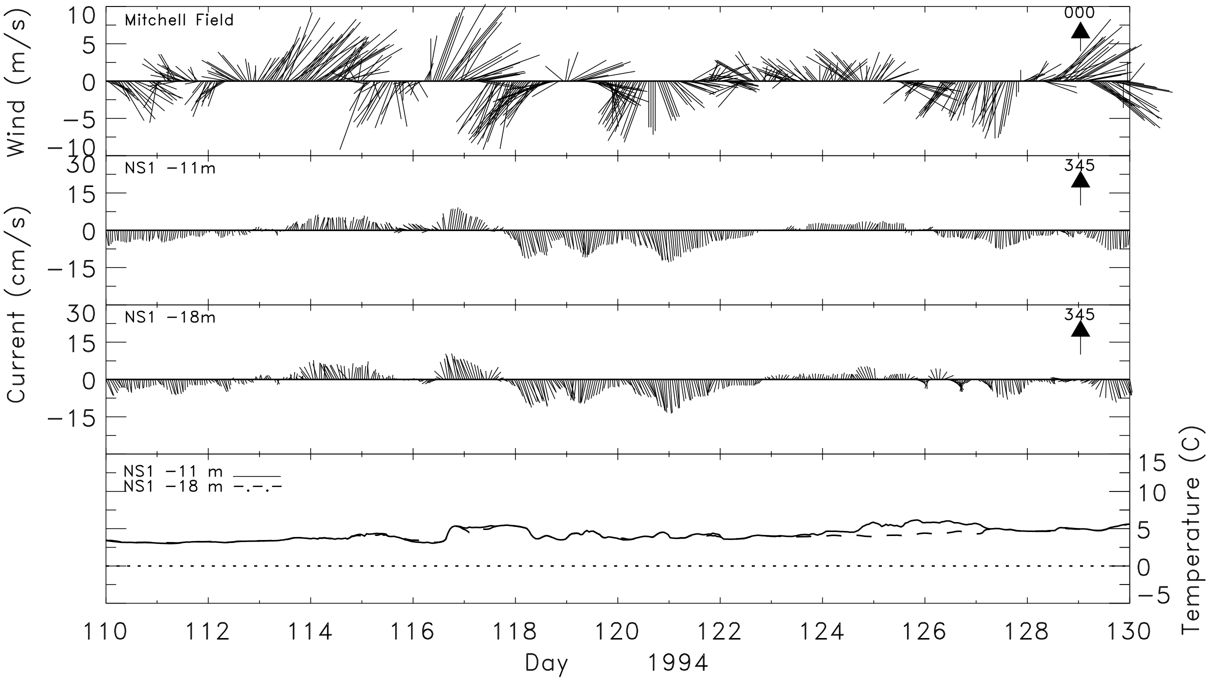


Lake Michigan -- Milwaukee
Wind (m/s)
10
5
0
-5
-10
Mitchell Field
000
Current (cm/s)
30
15
0
-15
NS1 -11m
345
NS1 -18m
345
NS1 -11 m
NS1 -18 m
Temperature (C)
15
10
5
0
-5
50
52
54
56
58
60
62
64
66
68
70
Day
1994



Wind (m/s)
10
5
0
-5
-10
Mitchell Field
000
Current (cm/s)
30
15
0
-15
NS1 -11m
345
NS1 -18m
345
NS1 -11 m
NS1 -18 m
Temperature (C)
15
10
5
0
-5
70
72
74
76
78
80
82
84
86
88
90
Day
1994


Lake Michigan -- Milwaukee
Wind (m/s)
Mitchell Field
000
Current (cm/s)
NS1 -11m
345
NS1 -18m
345
NS1 -11 m
NS1 -18 m -.-.-
Temperature (C)
Day 1994
90
92
94
96
98
100
102
104
106
108
110


Wind (m/s)
Mitchell Field
000
Current (cm/s)
NS1 -11m
345
NS1 -18m
345
NS1 -11 m
NS1 -18 m -.-.-
Temperature (C)
Day 1994
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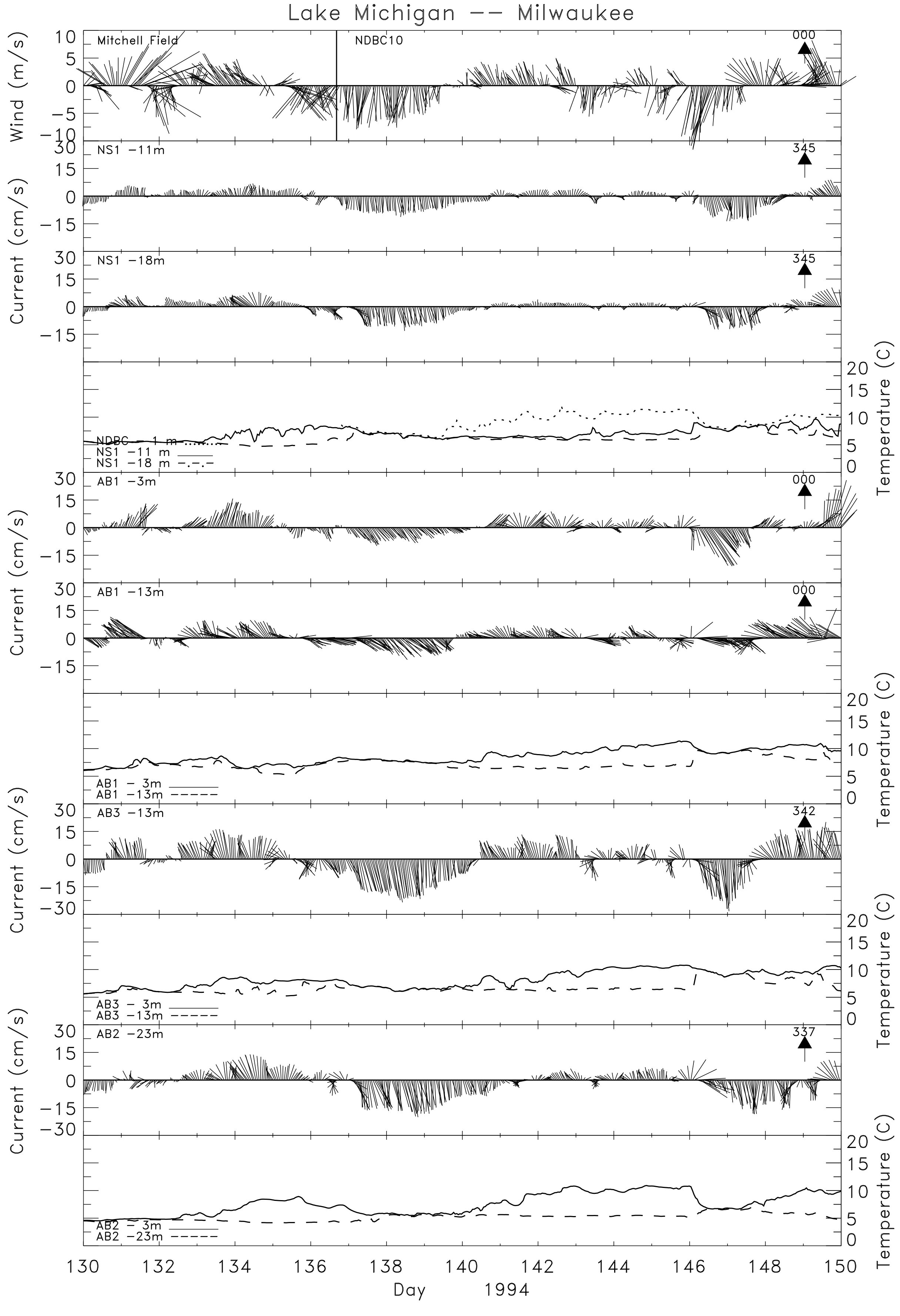
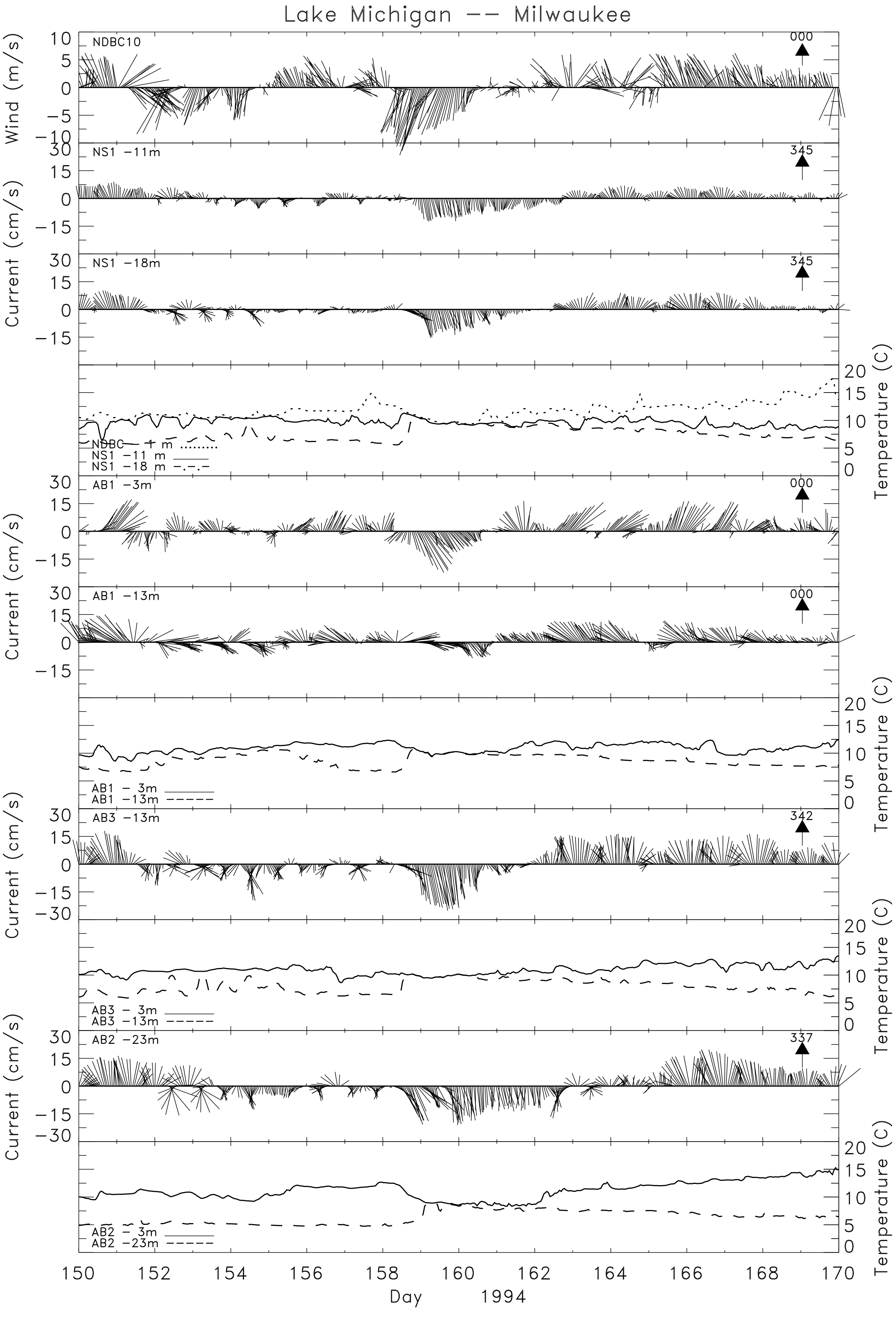
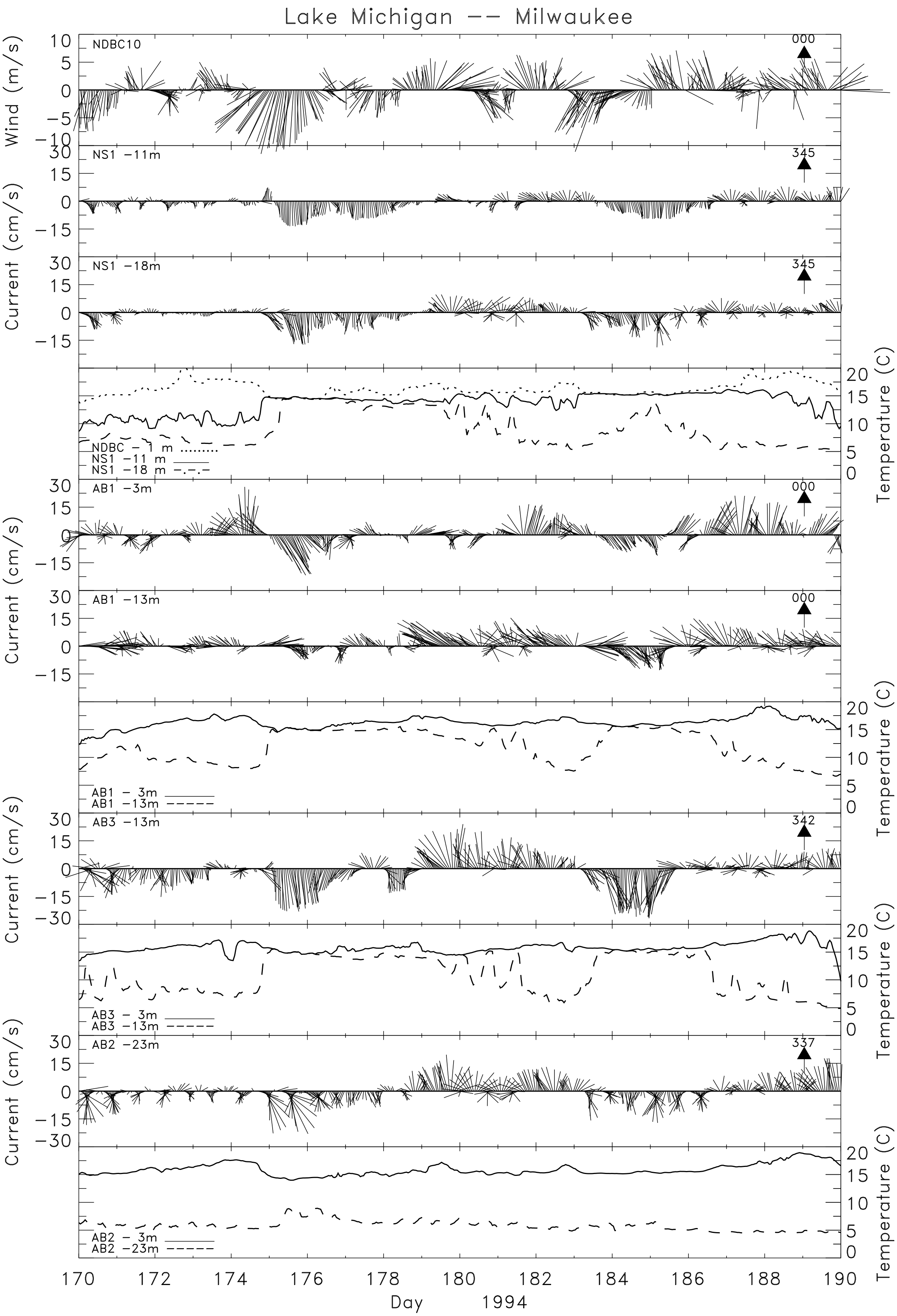
112
114
116
118
120
122
124
126
128
130

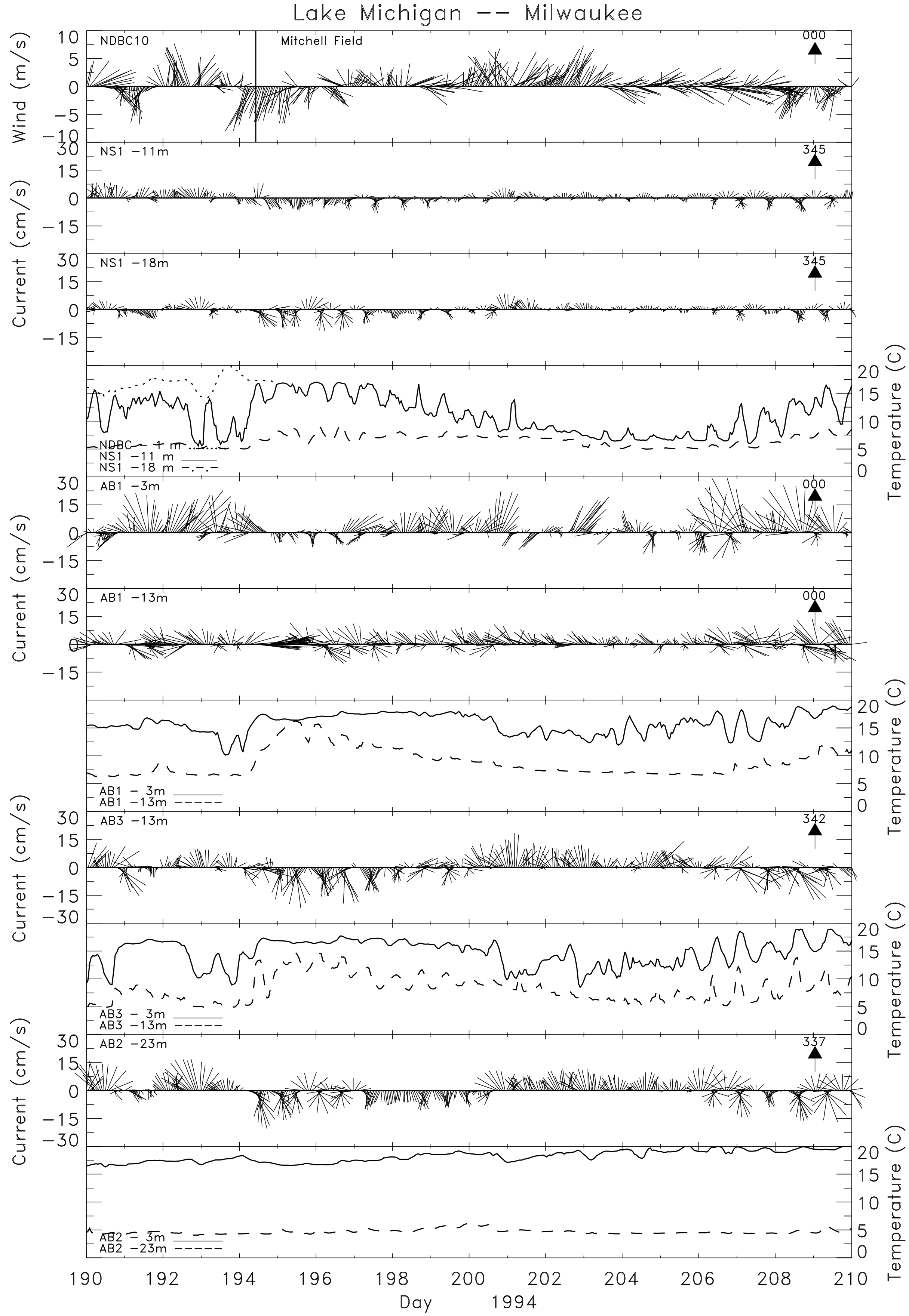

Lake Michigan -- Milwaukee
Wind (m/s)
10
5
0
-5
-10
Mitchell Field
NDBC10
000
NS1 -11m
345
Current (cm/s)
30
15
0
-15
NS1 -18m
345
Current
NDBC - 1 m
NS1 -11 m
NS1 -18 m
Temperature (C)
20
15
10
5
0
AB1 -3m
000
Current (cm/s)
AB1 -13m
000
Current
AB1 - 3m
AB1 -13m
Temperature (C)
AB3 -13m
342
Current (cm/s)
-30
AB3 - 3m
AB3 -13m
Temperature (C)
AB2 -23m
337
Current (cm/s)
AB2 - 3m
AB2 -23m
Temperature (C)
130
132
134
136
138
140
142
144
146
148
150
Day 1994


Lake Michigan -- Milwaukee
Wind (m/s)
NDBC10
000
NS1 -11m
345
NS1 -18m
345
Current (cm/s)
Current (cm/s)
Temperature (C)
NDBC -1 m ....
NS1 -11 m ______
NS1 -18 m -.-.-
AB1 -3m
000
AB1 -13m
000
AB1 - 3m ______
AB1 -13m -----
AB3 -13m
342
AB3 - 3m ______
AB3 -13m -----
AB2 -23m
337
AB2 - 3m ______
AB2 -23m -----
150 152 154 156 158 160 162 164 166 168 170
Day 1994

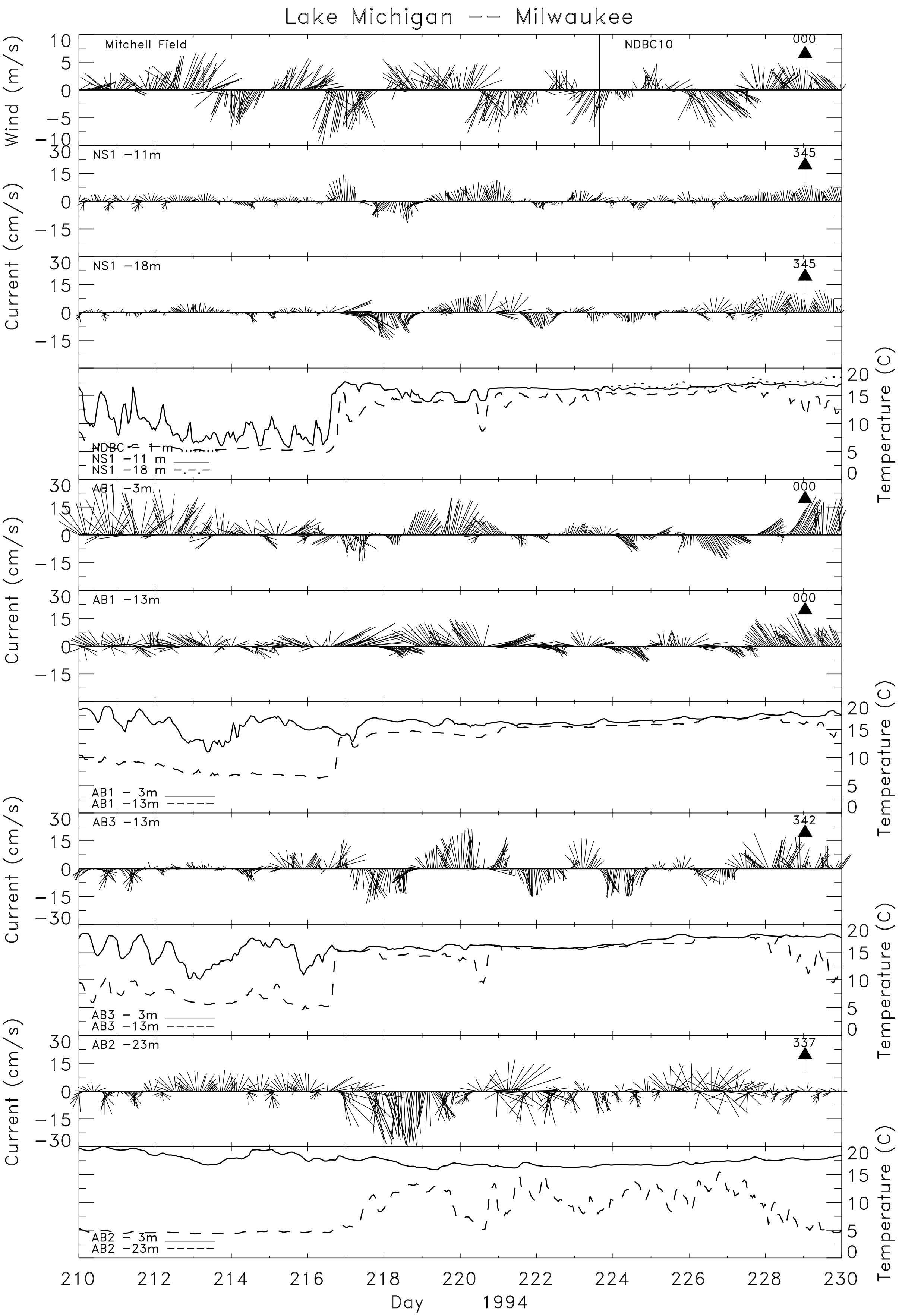
9a


Lake Michigan -- Milwaukee
NDBC10
000
Wind (m/s)
10
5
0
-5
-10
NS1 -11m
345
NS1 -18m
345
Current (cm/s)
30
15
0
-15
Temperature (C)
20
15
10
5
0
NDBC - 1 m ....
NS1 -11 m ______
NS1 -18 m -.-.-
AB1 -3m
000
AB1 -13m
000
AB1 - 3m ______
AB1 -13m ------
AB3 -13m
342
-30
AB3 - 3m ______
AB3 -13m ------
AB2 -23m
337
AB2 - 3m ______
AB2 -23m ------
170
172
174
176
178
180
182
184
186
188
190
Day 1994

9b


Lake Michigan -- Milwaukee
Wind (m/s)
10
5
0
-5
-10
NDBC10
Mitchell Field
000
NS1 -11m
345
30
15
0
-15
Current (cm/s)
NS1 -18m
345
20
15
10
5
0
Temperature (C)
NDBC -1 m
NS1 -11 m
NS1 -18 m
AB1 -3m
000
AB1 -13m
000
AB1 - 3m
AB1 -13m
AB3 -13m
342
-30
AB3 - 3m
AB3 -13m
AB2 -23m
337
AB2 - 3m
AB2 -23m
190
192
194
196
198
200
202
204
206
208
210
Day 1994

9c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NDBC10
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NS1 -11m
345
NS1 -18m
345
Current (cm/s)
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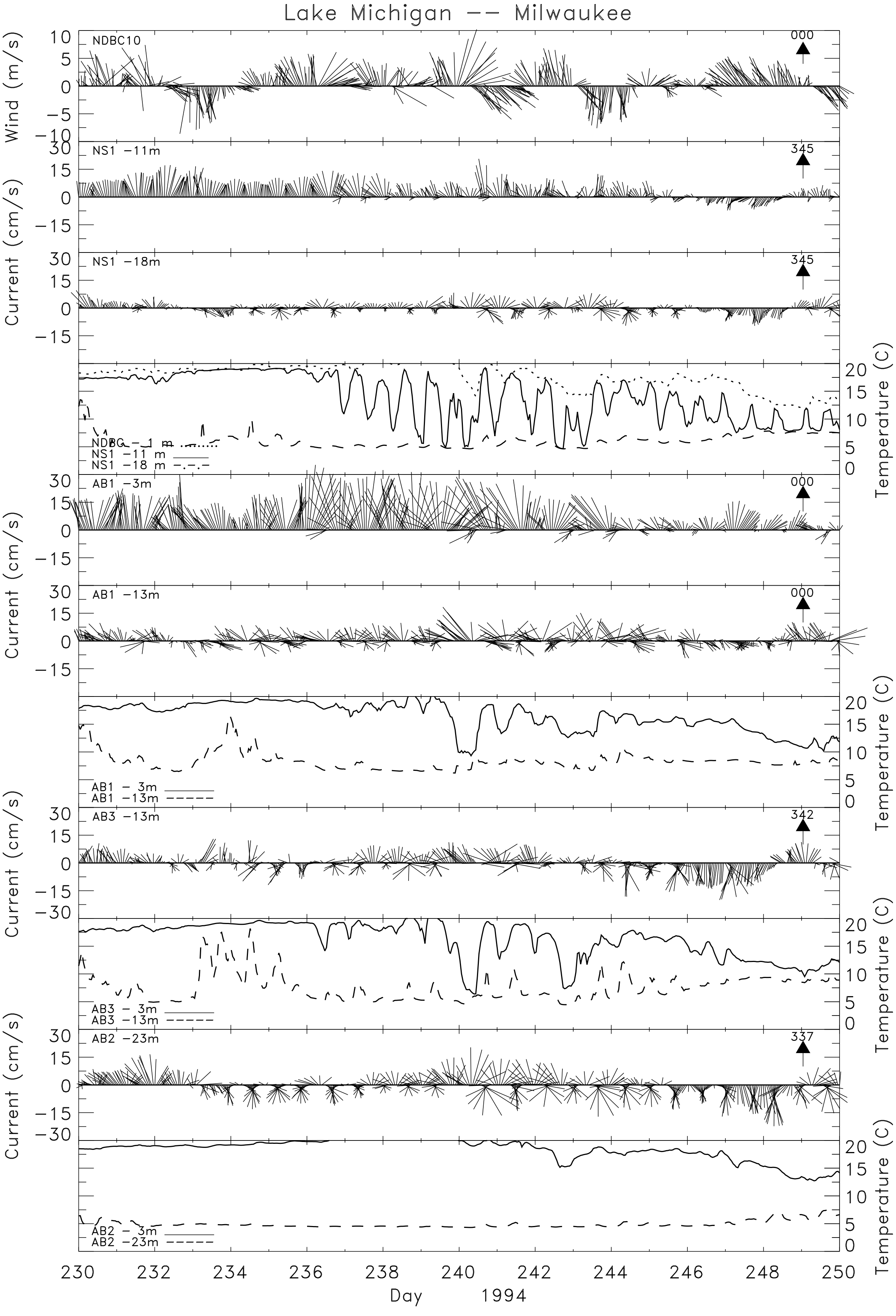
NS1 -11 m
NS1 -18 m
Temperature (C)
AB1 -3m
000
AB1 -13m
000
AB1 - 3m
AB1 -13m
AB3 -13m
342
AB3 - 3m
AB3 -13m
AB2 -23m
337
AB2 - 3m
AB2 -23m
210
212
214
216
218
220
222
224
226
228
230
Day 1994

9d



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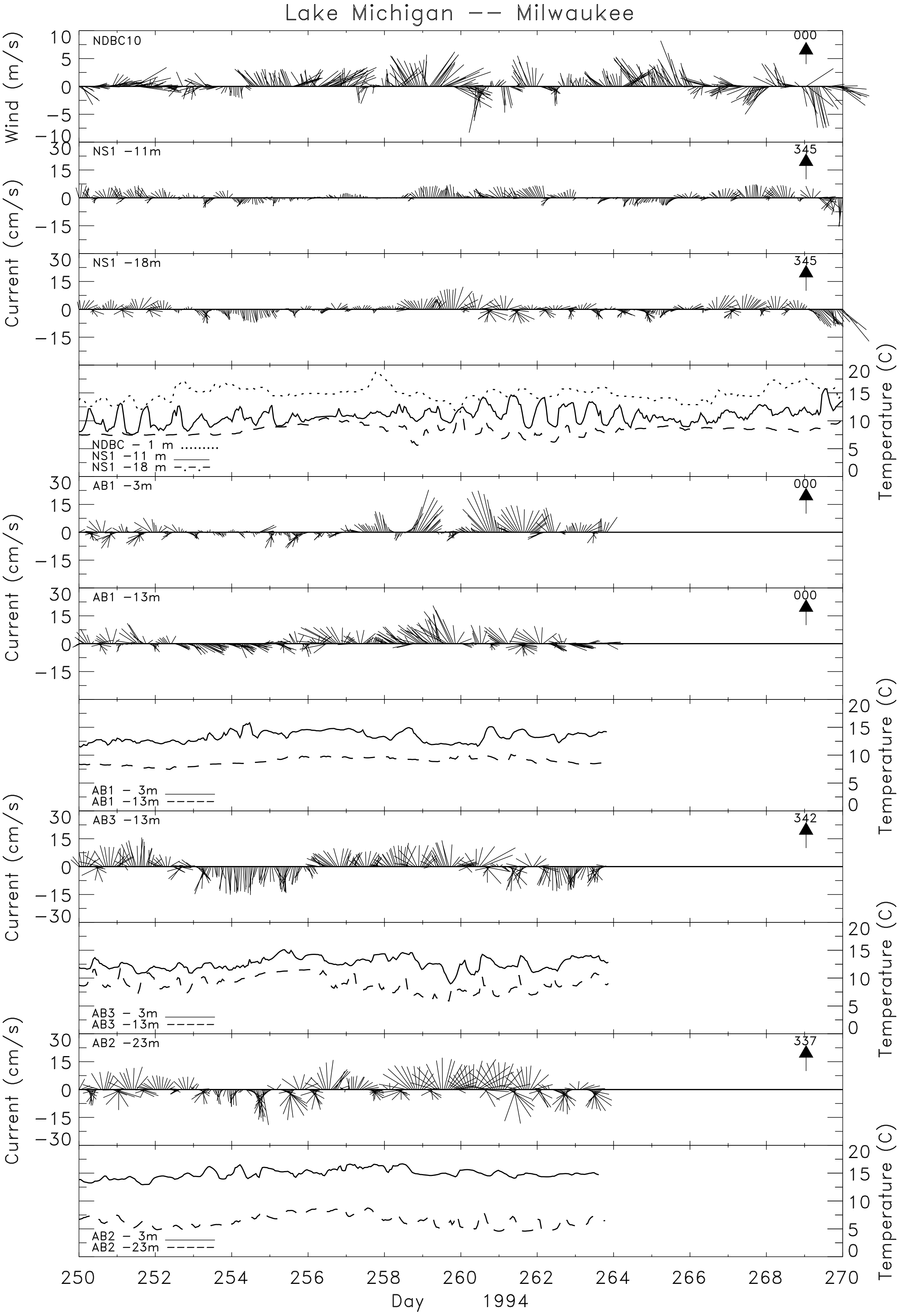
NDBC10
000
Wind (m/s)
10
5
0
-5
-10
NS1 -11m
345
NS1 -18m
345
Current (cm/s)
30
15
0
-15
NDBC -1 m ....
NS1 -11 m ______
NS1 -18 m -.-.-
Temperature (C)
20
15
10
5
0
AB1 -3m
000
AB1 -13m
000
Current (cm/s)
AB1 - 3m ______
AB1 -13m ------
AB3 -13m
342
Current (cm/s)
-30
AB3 - 3m ______
AB3 -13m ------
AB2 -23m
337
Current (cm/s)
AB2 - 3m ______
AB2 -23m ------
230
232
234
236
238
240
242
244
246
248
250
Day
1994

9e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Wind (m/s)
NDBC10
000
NS1 -11m
345
NS1 -18m
345
Current (cm/s)
NDBC - 1 m ....
NS1 -11 m ______
NS1 -18 m -.-.-
Temperature (C)
AB1 -3m
000
AB1 -13m
000
Current (cm/s)
AB1 - 3m ______
AB1 -13m ------
Temperature (C)
AB3 -13m
342
Current (cm/s)
AB3 - 3m ______
AB3 -13m ------
Temperature (C)
AB2 -23m
337
Current (cm/s)
AB2 - 3m ______
AB2 -23m ------
Temperature (C)
10
5
0
-5
-10
30
15
0
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250
252
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256
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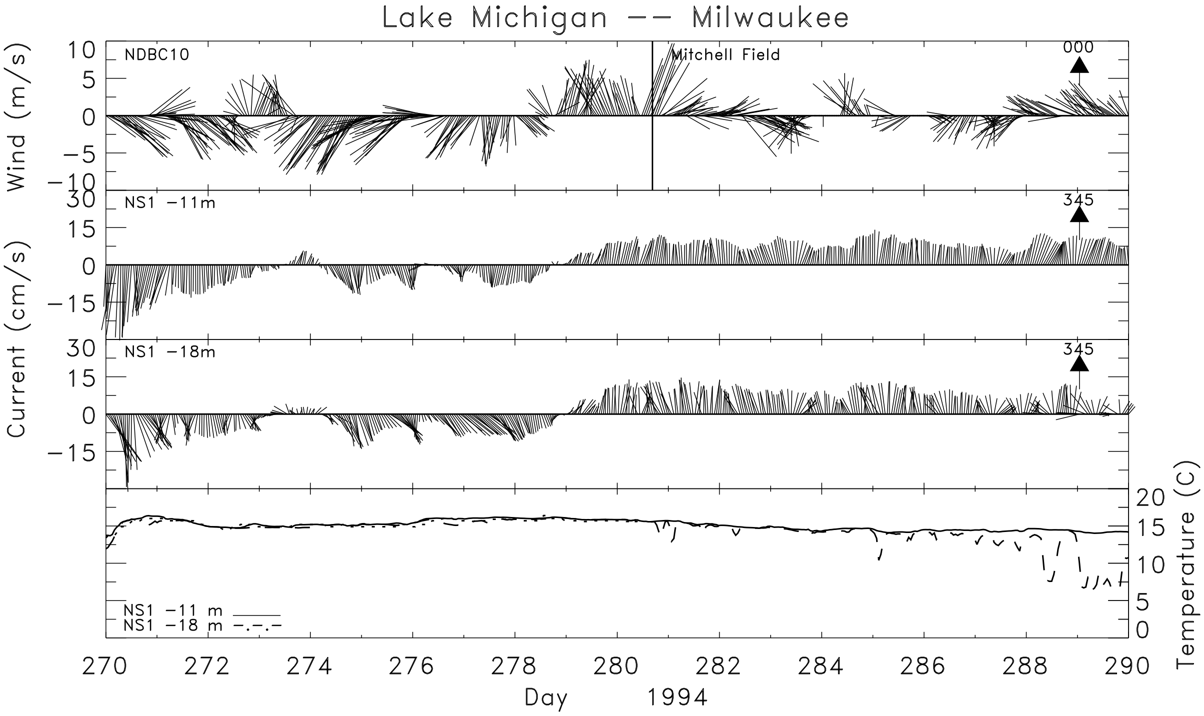
260
262
264
266
268
270
Day 1994

10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Mitchell Field
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Wind (m/s)
10
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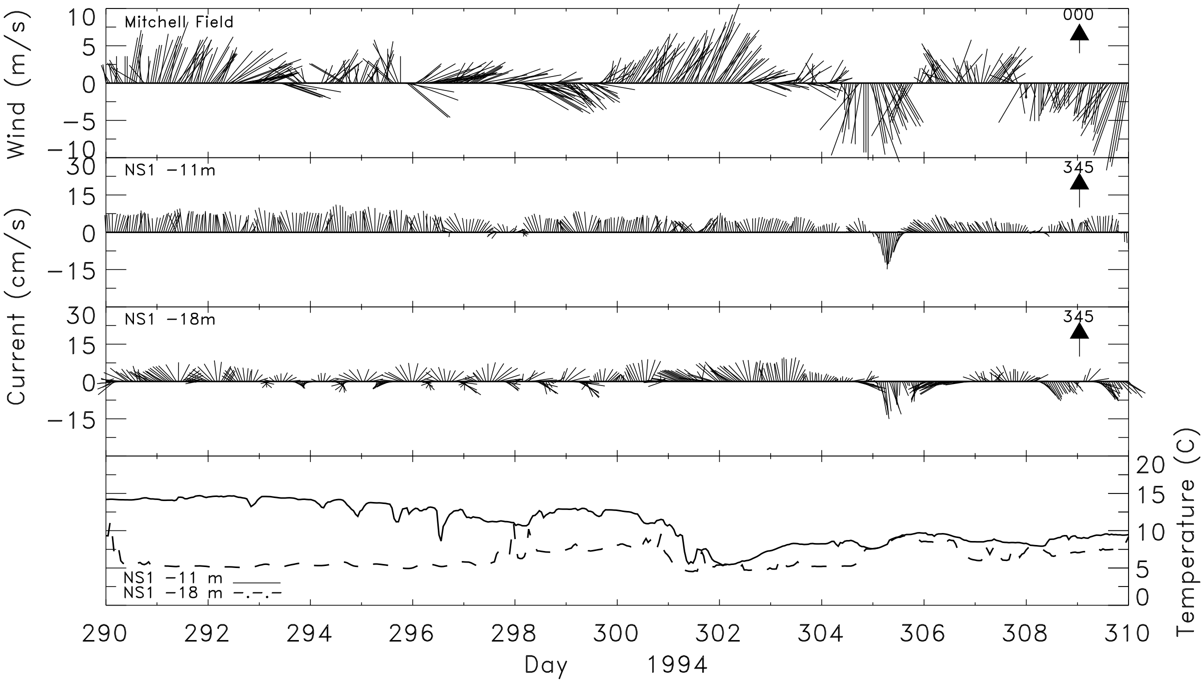
−5
−10
NS1 −11m
345
30
15
0
−15
Current (cm/s)
NS1 −18m
345
30
15
0
−15
20
15
10
5
0
Temperature (C)
NS1 −11 m ———
NS1 −18 m −.−.−
270
272
274
276
278
280
282
284
286
288
290
Day 1994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Wind (m/s)
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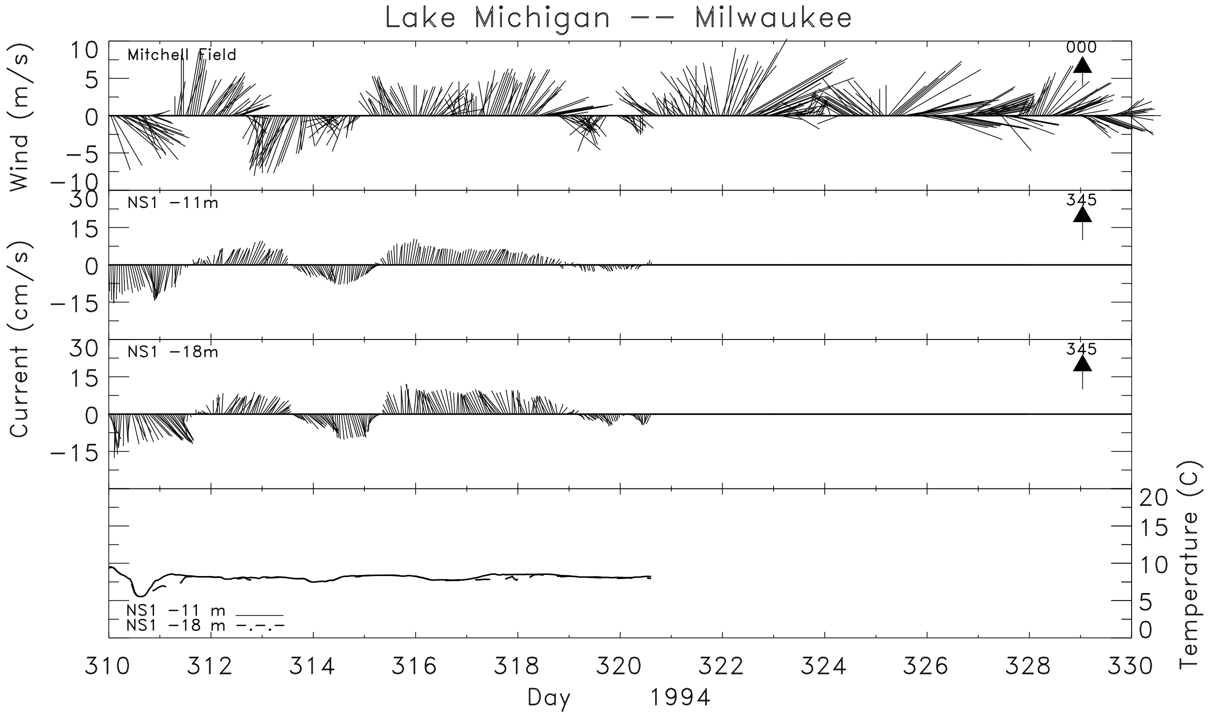
0
−5
−10
NS1 −11m
345
30
15
0
−15
Current (cm/s)
NS1 −18m
345
30
15
0
−15
20
15
10
5
0
Temperature (C)
NS1 −11 m ———
NS1 −18 m −.−.−
290
292
294
296
298
300
302
304
306
308
310
Day 1994

11


Lake Michigan -- Milwaukee
Mitchell Field
Wind (m/s)
10
5
0
−5
−10
000
NS1 −11m
30
15
0
−15
345
NS1 −18m
30
15
0
−15
345
Current (cm/s)
NS1 −11 m
NS1 −18 m −.−.−
20
15
10
5
0
Temperature (C)
310
312
314
316
318
320
322
324
326
328
330
Day
1994