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Climatology of Coastal Currents and Temperatures in Western Lake Ontario 1982 - 1992

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Draft NWRI Report

Climatology of Coastal Currents and Temperatures in Western Lake Ontario: 1982-1992

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Management Perspective

Title: Climatology of Coastal Currents and Temperatures in Western Lake Ontario: 1982-1992

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Current Status: Halton Region at the west end of Lake Ontario has proposed that their STP outfall in Hamilton Harbour should be moved to nearby Lake Ontario. While this move would protect the Harbour from the effects of projected expansions to the STP, there are many concerns for the quality of local drinking water and beaches in Lake Ontario. NWRI's Lake Remediation Project has been working in a cost recovery partnership with consultants contracted to Halton in order to supply the data and analyses of lake currents needed to design and site the outfall. The economic impact of the decisions affected is $27M in Halton Region. This report covers data on hand up to 1992. The value-added analyses show that the proposed location for the outfall is in a relatively unfavourable area and this means extra care will be needed in designing the outfall

Next Steps: Data for 1996 and 1997 which were gathered specifically for this study are being analysed and will be transmitted to the contractors this fall. NWRI scientists are making their own assessment and will be asked to comment on the conclusions of the contractors.

1.0 Introduction:

Dozens of communities around Lake Ontario's shores have long relied on the lake as a potable water source and a recreational haven; all the while using it as a convenient disposal site for wastewater. Improvements in water purification, and wastewater treatment technology have, to some degree, offset the deleterious effects of increased development; however, current technologies are nearing their limit, and demands for clean water, and suitable waste disposal locations continue to rise at an ever increasing rate. The western Lake Ontario shore from Bowmanville to Niagara-on-the-Lake is rapidly becoming one continuous urban community, still drawing drinking water from, and discharging effluent from sewage treatment plants into, a narrow near-shore band of lake a couple of kilometres wide. In the past, because the volumes of waste effluent were low enough, and separation between waste outfalls and water intakes was sufficiently large, waste concentrations were diminished to acceptable levels through mixing before reaching any water intake. Also, natural purification processes, such as biological degradation of harmful components, adsorption and settling of persistent toxins into sediments, etc., could assimilate the volumes that were introduced. While some local degradation may have occurred, midlake water quality remained high, enabling nearshore-offshore exchange processes to restore nearshore water quality. Although substantial advances have been made in the regulation of outfall location, and permissible effluent quality, the ever increasing total volumes of wastewater, and decreasing separation between intakes and outfalls, heighten the need to understand coastal circulation, dispersion, and exchange processes in greater detail.

One factor that has helped to minimize the degradation of western Lake Ontario waters has been that the wastewater treatment plants of Burlington and Hamilton have been discharging into Hamilton Harbour. This, of course, has been greatly detrimental to water quality in the harbour. Through tremendous effort and expense, substantial progress has been made toward restoring the harbour environment, and any development which threatens to retard - or, worse yet, reverse - this positive trend would be strongly opposed, and rightly so.

Estimates indicate that development in the Region of Halton over the next several years will require an increase in the mean flow capacity at the Skyway Wastewater Treatment Plant (WWTP) from the present 93,000 m^3/day to 140,000 m^3/day. Based on currently available technology, there is serious concern that the increased output from even a well tuned facility of that capacity would significantly degrade water quality in Hamilton Harbour. Addition of tertiary treatment facilities would be a very costly option, and the improvement to effluent quality one could reasonably expect might still be insufficient to prevent a net increase in contaminant loading with the increase in volume. One of the proposals to resolve this dilemma would have the Skyway WWTP outfall relocated in Lake Ontario some distance (say 1 to 2 km) offshore, adjacent to the plant site. The rationale for such a move follows the intuitive notion that the comparatively huge volume of the lake and its higher energy dynamics will dissipate the effluent far more efficiently than the limited volume of the harbour. While there is no doubt that this is true on a basin-wide scale, the potential for undesirable local effects

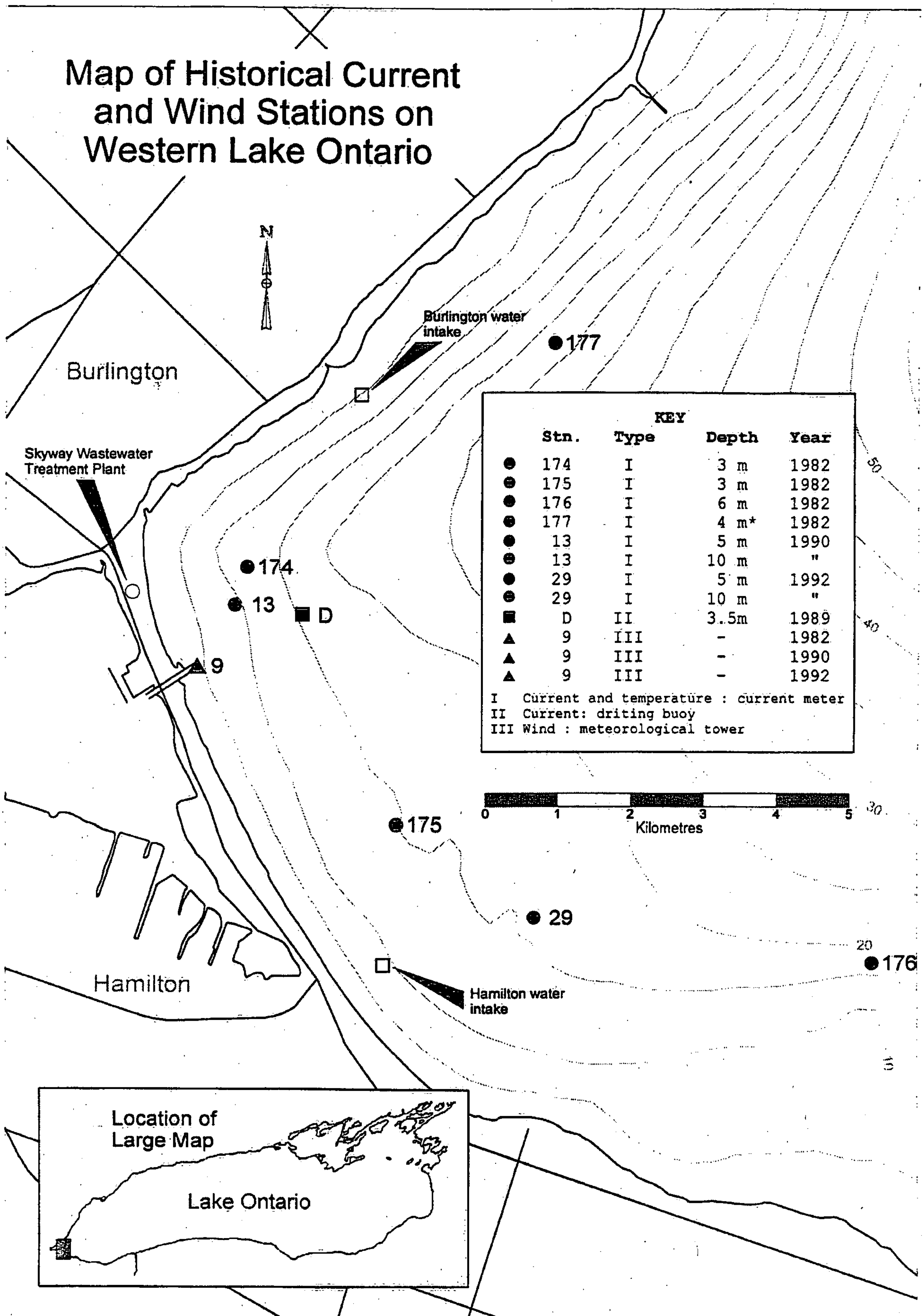

Figure 1.

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warrants cautious approach to this option. The region of Lake Ontario where the proposed outfall would be situated forms an open embayment, the shoreline of which is largely parkland with the only significant sandy beach on the western end of the lake: a beach already subject to frequent closures owing to high bacteria levels during hot summer weather. In addition, Burlington and Hamilton municipal water intakes both lie within a few kilometres of the site.

In order to evaluate the potential impact of the proposed outfall relocation we have turned to easily accessible historical data which might provide some understanding of the local coastal physical transport processes. All of the data archived in the main current meter data base at NWRI, from stations in the main body of Lake Ontario west of 79° 40' W longitude, were reviewed. Numerous satellite-tracked drifting buoy trajectories resulting from deployments near the proposed outfall site were also considered. Details of the available data, and those files ultimately analyzed, are summarized in Table1, and discussed under Data Base below. Figure 1 is a map of the area showing key features including instrument locations, and the drifter deployment site.

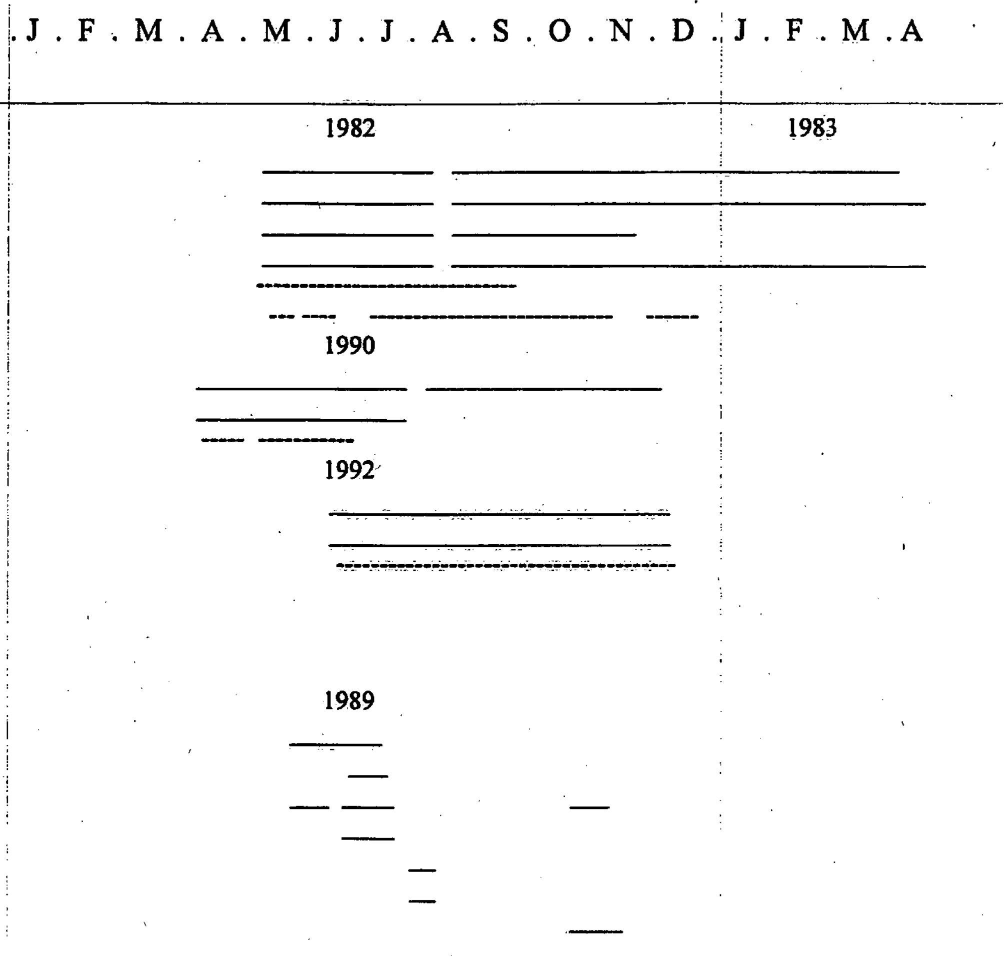
One of the best current data sets considered, in terms of spatial and temporal coverage, was collected at four sites by Ontario Ministry of Environment in 1982-83, and subsequently archived at CCIW. A comprehensive report, "Impact of Hamilton Harbour on Western Lake Ontario" (Poulton et al, 1986), includes results from the analysis of data from these four current meter stations. Readers are strongly encouraged to consult that report for a detailed analysis of a broad spectrum of physical, biological, and chemical parameters. Some of the statistics and methods of presenting them (e.g. wind and current rose-plots) presented here are similar or identical to those in the MOE report. They are products of our own statistical analysis and have been included for ease of comparison across the larger data base we are dealing with. We have included additional calculations such as persistence factor which was included in the MOE report for 1982-83 data and was considered to be a potentially useful parameter for the other data as well. Those comparing 1982-83 results in the two reports are cautioned to carefully observe value ranges and data periods when dealing with what may otherwise appear to be identical presentations.

As mentioned earlier, the coastal physical processes in the vicinity of the proposed Skyway WWTP outfall is the main interest of this report. A secondary interest, and one which will be increasingly important in the future, is the water movements of the entire western ten or so kilometres of the lake, where the restricting topography of the tip of the lake basin and its orientation to lee of the prevailing wind may create less favourable transport and dispersion conditions than those in the rest of the near-shore zone of the lake. The diagrams and discussion presented here attempt to illustrate, clearly and simply, the main current characteristics which ultimately determine the transport and diffusion of contaminants; and temperature characteristics which, as in the case of well developed thermal stratification, profoundly affect the circulation regime itself. Where possible, local wind data are presented along with current and temperature data to provide an estimate of the wind's influence on specific dynamic events in the lake.

Table 1. Summary of Current and Wind Data for Western Lake Ontario

___ Current meter/drifter data ---- Wind data

Station Number	Sensor Depth (m)	Water Depth (m)
174	03	12.2
175	03	12.2
176	06	18.3
177	04*	14.6
01	---	-----
09	---	-----
013	05	12.1
013	10	12.1
09	---	-----
029	05	25.5
029	10	25.5
09	---	-----
Drifter Number		
5380	3.5	
5381	3.5	
5385	3.5	
5387	3.5	
5388	3.5	
5389	3.5	
5396	3.5	
5397	3.5	



Note:

Station 177, 4 m depth.

The water depth at 1982 station 177 (MOE location code 1122) is recorded in NWRI references and Table 2.1, p2-11 of "Impact of Hamilton Harbour on Lake Ontario" (Poulton et.al.) to be 14.6 m, some 10 m less than chart depth (Canadian Hydrographic Service chart L/C2077) at that location. The possibility exists that the recorded depth is correct, and there was an error in recording the location: however, there is an anomaly in the temperature at that site indicating consistently colder temperatures than at station 176 which was supposedly 2 m deeper than station 177 (Figure 6), and much colder than stations 174, and 175 which were supposedly mounted only 1 m shallower than station 177. While such temperature anomalies do occur for periods lasting up to a few days during upwelling/downwelling events, consistent discrepancies of this duration are highly suspicious. If we assume that the location given for station 177 is correct, and consider that perhaps the tens digit of the station depth was recorded (or later interpreted) as a 'one' instead of a 'two', then the instrument depth - which was reportedly determined from a measurement from the bottom - would be about 14 m instead *of 4 m and the temperature record would become credible. Since we have no way to verify this theory after such a long time, we have left all depth references for station 177 unchanged, but have flagged them with an asterisk (*) to caution the reader of the possible error.*

2.0 Data Base:

All time-series current data from NWRI archives for Lake Ontario stations west of 79° 40' W longitude were reviewed. The qualifying data included files collected from 1969 to 1992, and are summarized in Table 1. Data collected prior to 1982 were not analyzed because of short duration and/or suspicious quality. After careful screening, the MOE data from 1982-83, and NWRI data from 2 depths at a single location from each of 1990 and 1992 were chosen for detailed analysis.

The four 1982-83 moorings provide quite good horizontal resolution of the western tip of the lake, but the single instrument at each site provides no direct insight into vertical structure. Also, the instrument depths varied, with two instruments at 3 m, and one at each of 4 m* and 6 m (see Note above). This could make spatial comparison of data difficult; however, some differences that we show among the stations would likely be enhanced if all were at the same depth. The records span almost a full year from May 10, 1982 until mid to late April 1983, except for station 176. The single moorings in each of 1990 and 1992 both had instruments at 5 m and 10 m depth, providing some information about the vertical current and temperature structure. These locations correspond reasonably well with 1982 moorings; so, while we cannot draw specific comparisons between measurements widely separated in time, we feel that these data show a number of additional features sufficiently well to warrant their inclusion in this analysis. The proximity of stations 174 and13 to the proposed Skyway outfall site makes further analysis of these past data records quite relevant.

Current meter data include time-series current speed and direction data plus water temperature at instrument depth. Where possible, nearby concurrent meteorological data are also included in the analysis. Time-series meteorological records include wind speed and direction, air temperature, surface water temperature, and relative humidity. For this analysis, only wind stress computed from wind velocity data is presented.

A variety of sample periods typically ranging from ten minutes to an hour are represented in NWRI archived current and meteorological data. The analyses presented here were done on hourly time series with samples centred on the hour, as generated from original data.

In addition to data from moored current meters and meteorological stations, results of the analysis of trajectories of satellite-tracked drifting buoy released about a kilometre east of the proposed outfall site in 1989 are also included in this discussion. The drifting buoys were equipped with 'roller-blind' type drogues suspended at about 3.5 m depth. Twelve releases from May to October 1989 were analyzed. They are summarized in Table 1. Unfortunately, none of these experiments included concurrent deployments of both current meters and drifting buoys. Drifting buoy data consisted of asynchronous series of time and position with sample intervals ranging from a few minutes to several hours. A computer program employing a polynomial function which preserves original values (Akima, 1972) was used to generate the hourly time-series which formed the basis for further analysis.

3.0 Analysis

Rose histograms, vector 'stick-plots', temperature plots, some progressive vector diagrams, and the calculations associated with these and some of the statistical summaries were produced by custom Unix-based programs. Maps, speed and stagnation period histograms, some progressive vector diagrams, and variance ellipse diagrams, along with many of the related calculations, were generated by a variety of PC graphic and spreadsheet software.

Where time-series output, illustrations, and values are based on other than hourly samples, it is so stated. In some cases the data have been averaged to a longer sample period; in others, only values at some fixed interval are displayed to improve clarity. Both wind and current vectors are always shown as direction to.

Three types of analysis are presented here: 1) graphic and statistical summaries, which cover whole record periods, and are presented in similar format for all data records used; and 2) specialized analysis directed toward a specific phenomenon or event, or employing specialized or enhanced techniques to achieve a specific result based on the time-series current and temperature data, and 3) specialized analysis of Lagrangian drifter data. In general, Tables 1 and 2, Figures 1 through 8, and related text fall into category 1). Figures 9 through 18 and their related text better fit category 2), and are the results of an effort to look at the data more intensely, from a new perspective, or at a different scale. Table 3 , Figures 19 through 21, and related text fall into category 3).

3.1 Descriptive summaries

Table 1 summarizes all of the data showing the station number used in this report (corresponds to NWRI mooring number), sensor depth, water depth, and a time bar indicating the period over which data was collected. Instrument stations, drifter release locations, and a few local features are shown on the map of the western end of Lake Ontario in Figure 1.

Some of the statistical methods we used to summarize the data are consistent with previous NWRI limnological summaries (Murthy and Dunbar, 1977; Jordan and Bull, 1977, etc.). While specific format and scale vary widely, rose plots, vector 'stick-plots', progressive vector diagrams, and time-series temperature plots like those presented here have become standard tools for looking at features of large time-series data records.

Table 2 summarizes several statistical parameters based on whole data records. Where gaps existed in the data, parameters have been determined only from values present, with no interpolation. Users are cautioned to verify that data records are from the same period and are of equal length, before making absolute comparisons in statistics. The persistence factor (resultant vector speed/mean scalar speed for same period) shown in Table 2 was given in the MOE report for 1982-83 data, and has been included here for all stations.

The rose histogram plots tabulate hourly wind and current data for 1982-83 (Figures 2), and for 1990 and 1992 (Figures 3), into speed and direction ranges. Vector directions are sorted into eight 45 degree sectors (directions are 'towards' for both wind and current in all types of vector plots). Speed ranges are defined as 0 to 3, 3 to 7, and greater than 7 cm/sec for current. For wind the numeric range limits are the same but units are m/sec. Different speed ranges are indicated in the drawings by the indicator's line width as shown in the key. The percentage of the total data record comprised of values of a given speed and direction is shown by the radial length of each segment of indicator line with respect to the radial percentage scale. The rose plots are drawn on a station map with shaded pointers showing the station represented.

Figures 4 and 5 show progressive vector diagrams for 1982-83, and for 1990 and 1992, respectively. These types of diagrams are created by drawing the hourly vectors with the start of each hour's vector joined to the end of the previous hour's vector. Vectors point in the correct direction and are scaled proportional to the displacement that would be achieved by maintaining the represented speed for an hour. The completed plot is a scaled representation of the actual displacement a free moving particle would undergo if subjected to the velocity regime defined by the current record. Each page shows an appropriate displacement scale and a key map indicating the stations represented. Naturally, such a representation created from a velocity record measured at a fixed point will bear little relation to actual displacements of particles subjected to the physical restraints and spatial variability of the real lake basin, but it does serve to illustrate characteristics of the velocity at the point of measurement, such as directional persistence, rotations, periodic meandering, etc. Note that locations of pvd segments on the page, including the relative location of subsequent segments of the same record after a gap in the data, are not to true scale.

Figures 6, 7, and 8 show time series wind stress (unfiltered), filtered current vector 'stick-plots', and temperature vs. time plots for entire data periods in 1982-83, 1990, and 1992, respectively. For current 'stick-plots' a low-pass digital filter with 18 - 24 hour cutoff was applied to the data to eliminate oscillatory motions at frequencies higher than the inertial frequency (about 17 hours for Lake Ontario). Elimination of the high frequency oscillations associated with turbulence, gives a clearer picture of longer period motions typically associated with larger scale forcing agents like basin-wide circulation phenomena, and significant meteorological events. The 'stick-plots' in these figures show every second hourly vector in each of the series to retain some semblance of graphic quality at the greatly compressed time scale used.

	1982					1990			1992		
	9	174(3m)	175(3m)	176(6m)	177(4m)*	9	13(5m)	13(10m)	9	29(5m)	29(10m)
Mean Vector Speed (a)	0.7	1.1	1.3	3.0	0.4	1.0	1.0	1.4	0.6	0.8	0.7
Resultant Direction (Degrees True)	126	210	141	106	237	88	265	226	141	250	229
Mean Temperature (Deg C)	12.1	6.3	6.6	11.1	4.3	13.5	10.2	7.1	13.9	12.5	10.9
Mean Scalar Speed (a)	3.4	3.5	5.0	8.1	4.8	3.5	3.1	3.1	3.6	3.2	3.6
Mean square Speed (a)	15.3	23.5	43.0	86.3	39.0	15.8	14.2	15.0	16.8	16.0	20.1
Mean Square U Speed (b)	8.0	5.0	17.2	63.0	16.0	7.9	3.8	6.7	10.3	9.0	13.2
Mean Square V Speed (b)	7.3	18.5	25.8	23.2	23.0	7.8	10.3	8.3	6.5	7.0	6.9
Variance (U,V) (b)	7.4	11.1	20.7	38.6	19.4	7.4	6.6	6.5	8.2	7.7	9.8
Persistence Factor	0.2	0.3	0.3	0.4	0.1	0.3	0.3	0.5	0.2	0.3	0.2
% Time in Stagnation (>= 12 hours)		77	58	16	56		38	38		41	34
% Speeds 0.0 - 3.0 (a)	47.6	64.3	39.8	12.3	40.8	47.4	58.9	60.3	45.1	57.0	50.9
% Speeds 3.0 - 7.0 (a)	47.3	24.2	39.8	32.8	38.9	46.3	35.8	33.1	48.8	35.1	37.1
% Speeds >= 7.0 (a)	5.1	11.5	20.3	54.9	20.3	6.3	5.3	6.6	6.1	7.9	12.0
Total Hours	4194	7867	8036	4647	8128	1908	5509	2687	4368	4368	4368

(a) cm/ sec for current; m/sec for wind
(b) (cm/ sec)^2 for current; (m/sec)^2 for wind

Table 2. Statistics from Time-series Current and Wind Data from Western Lake Ontario

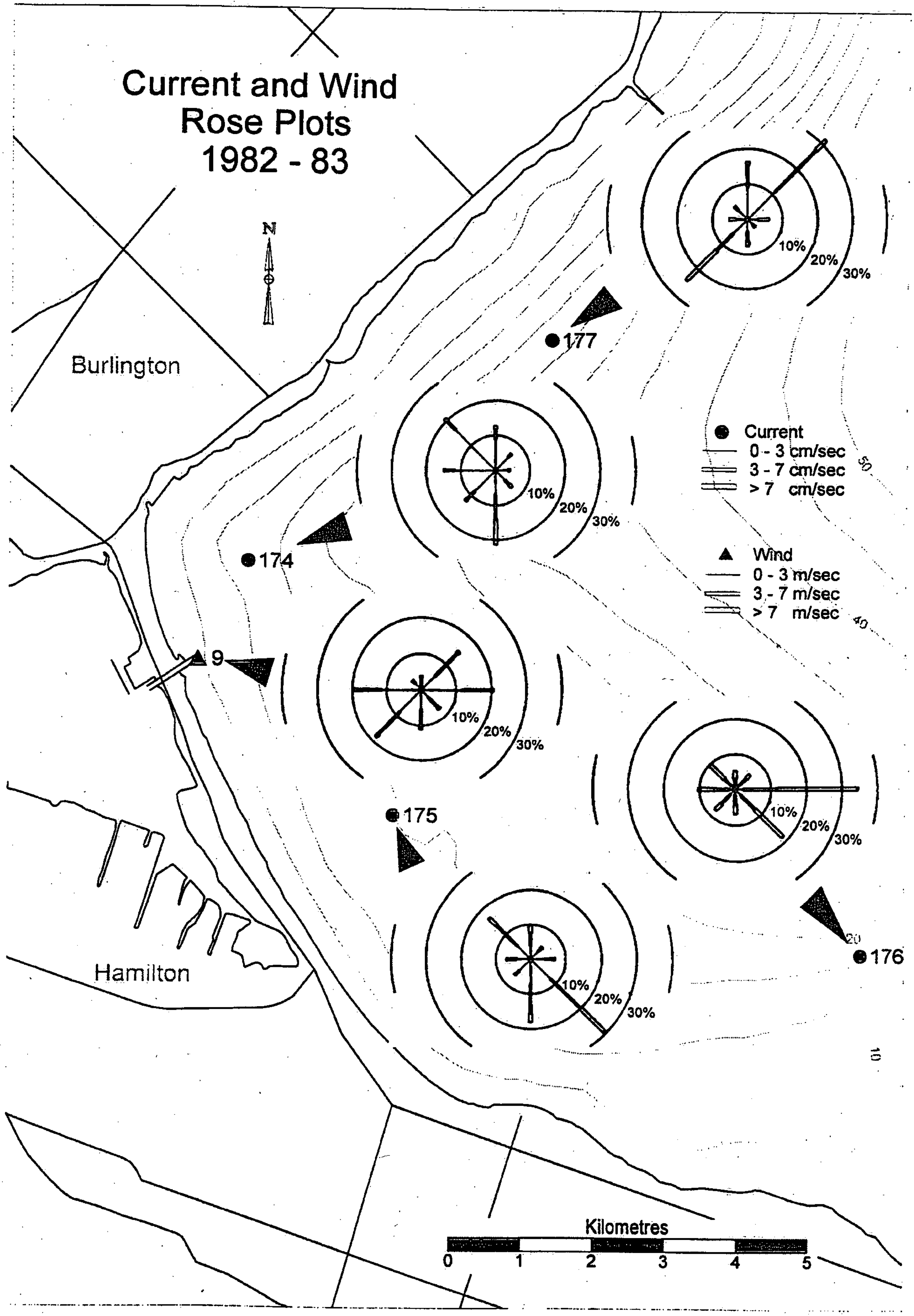


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Figure 2.

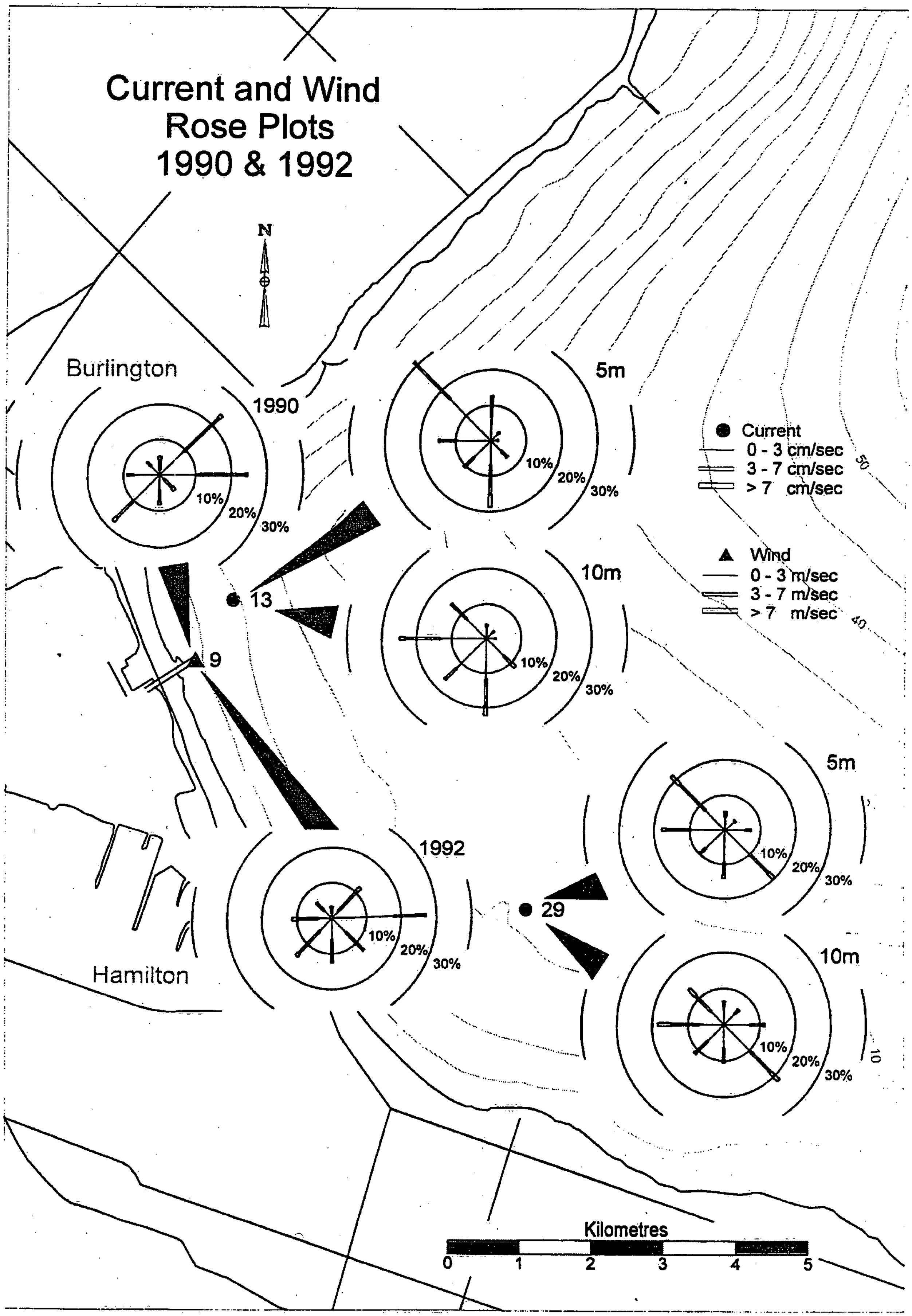

Figure 3.

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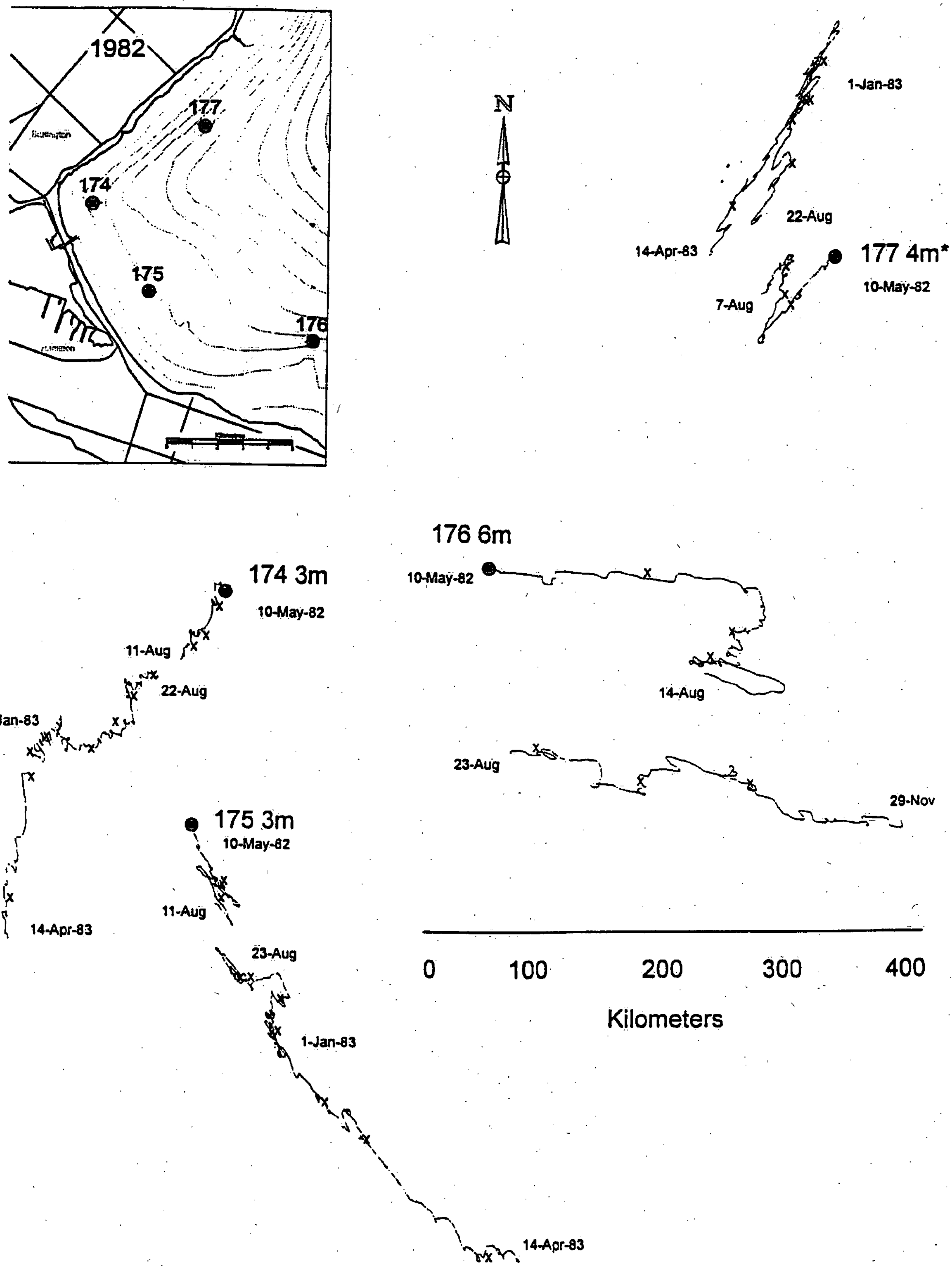


Figure 4. Current Progressive Vector Diagrams: 1982-83

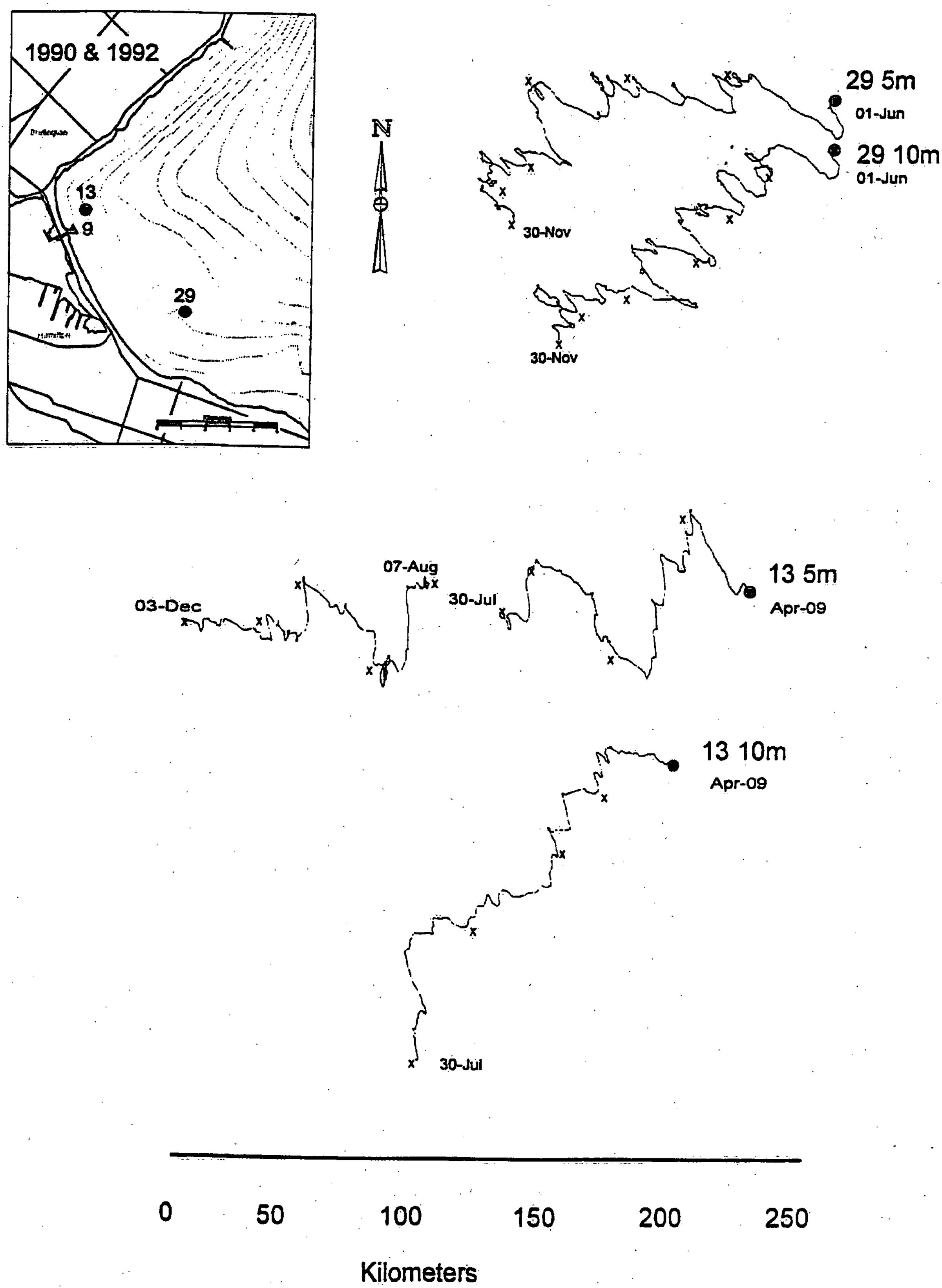


Figure 5. Current Progressive Vector Diagrams:1990 & 1992

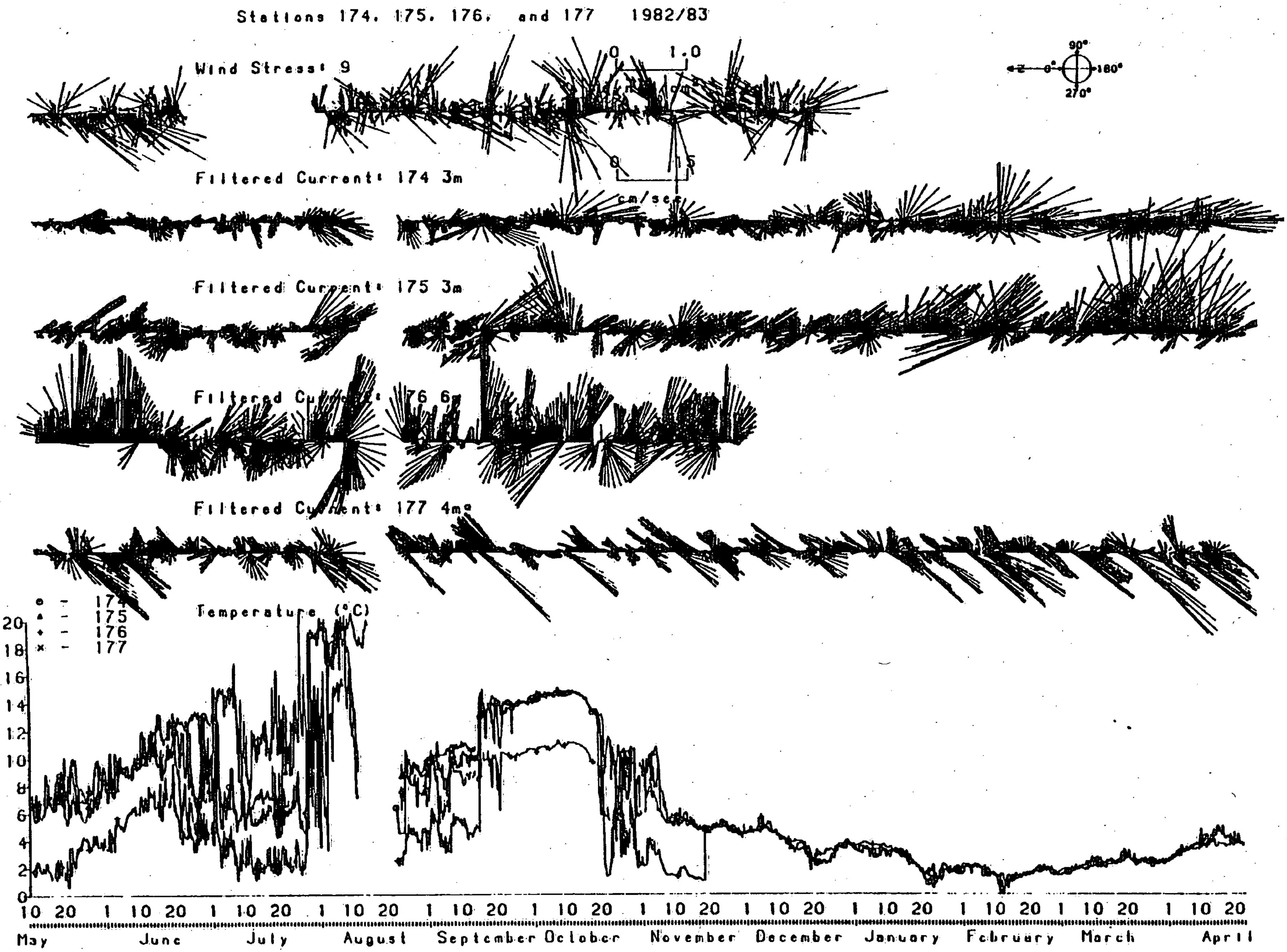


Figure 6. Vector 'Stick-plot' and Temperature Plot 1982-83

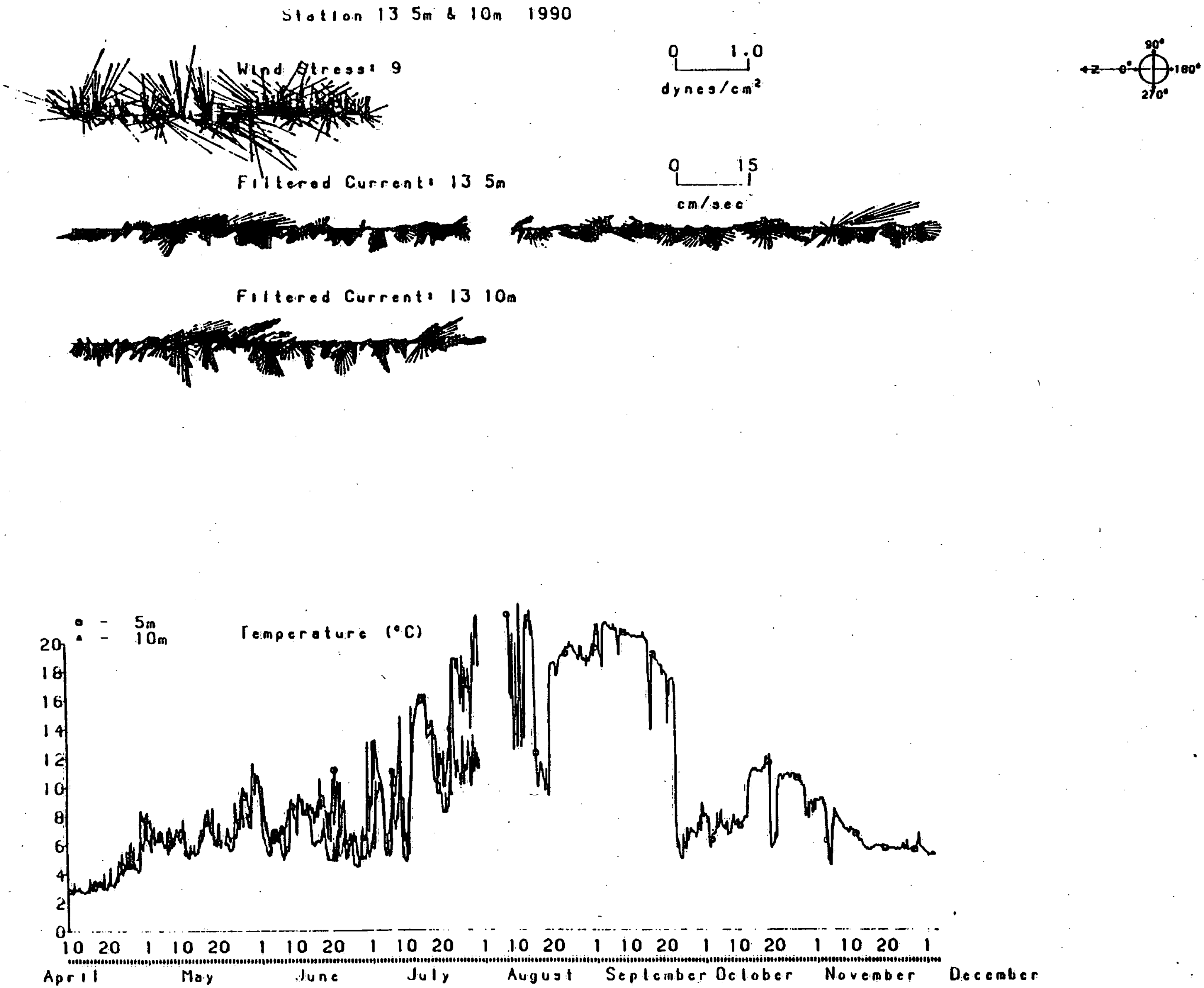


Figure 7. Vector 'Stick-plot' and Temperature Plot 1990

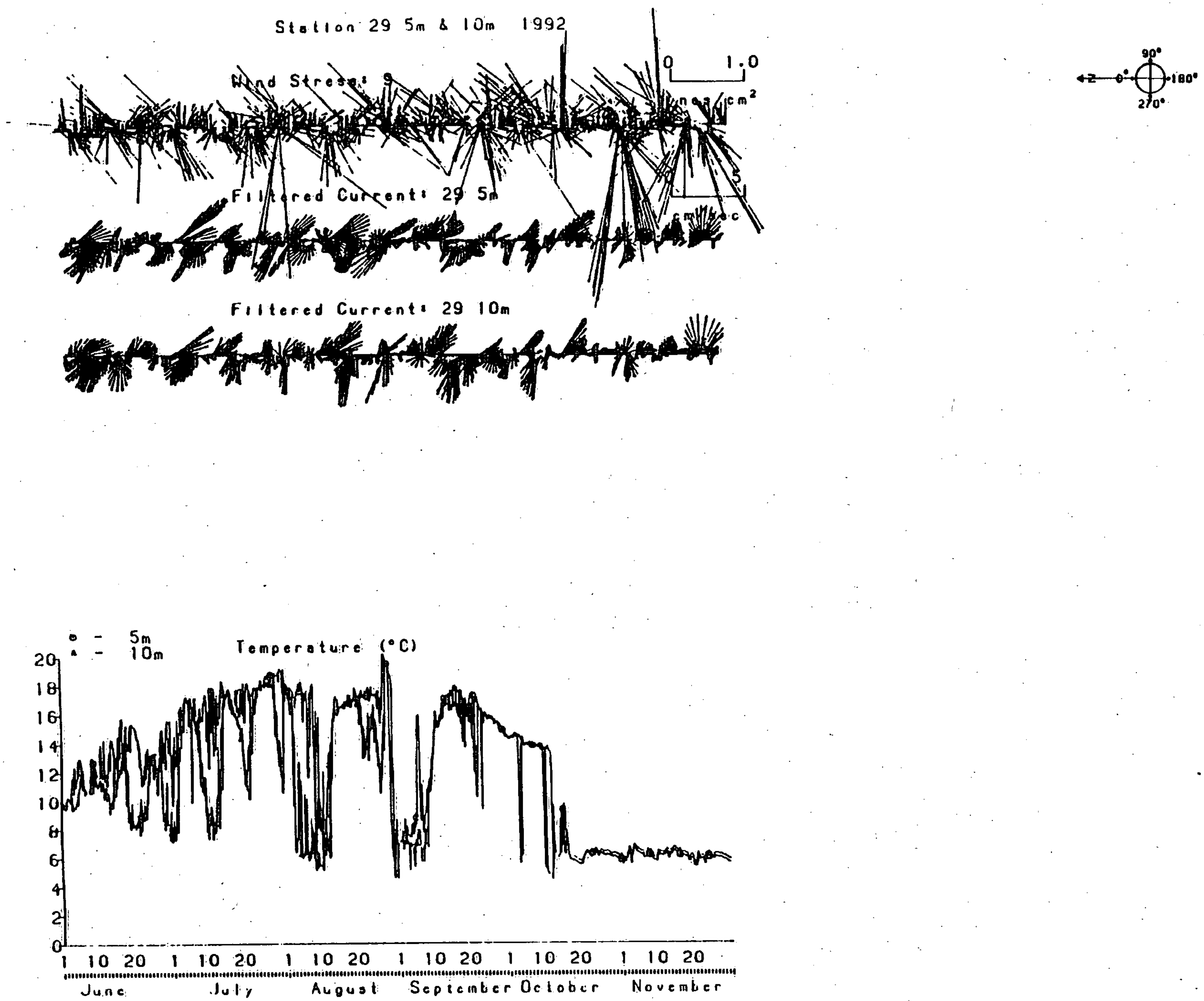


Figure 8. Vector 'Stick-plot' and Temperature Plot 1992

3.2 Specialized Analysis

Current speed distribution is plotted separately in Figures 9 and 10 for each sensor depth at each station. For long records covering a full range of seasonal and meteorological conditions, such plots provide a fair indication of the current speeds one might expect to find at a particular location, at least for comparable conditions. The number of instances of hourly current speeds in 1 cm/sec ranges from 0 to 20 cm/sec were plotted. Although lower speed values have been reported separately, readers are cautioned to avoid drawing any firm conclusions about the relative distribution of values which may fall below the sensing threshold of speed sensors used to collect the data. The threshold for 1982-83 data is likely about 5 cm/sec; and for 1990 and 1992 it would be down around 1 cm/sec. This topic is dealt with in more detail below, in the discussion on stagnation speeds. The cumulative percent of readings is included on each of the speed distribution plots. This curve provides another quick indicator of the relative importance of stronger currents at a site. As an example, if one compares the graphs for stations 174 and 176 in Figure 9, the velocity distributions show a very high instance very low current speeds at station 174, with very few instances of speeds above 10 cm/sec, while at station 176 the spike at low speeds is absent and an almost even distribution exists for speeds up to about 13 cm/sec. The percent cumulative occurrence curves for these two stations indicate that readings below about 6 cm/sec account for 95% of all values at station 174, while at station 176 speeds of 6 cm/sec and below account for less than 45% of all readings. Stations 175 and 177 produce profiles which show distributions somewhere between these two extreme examples. Similar profiles for 1990 and 1992 data indicate broad peaks at low values with relatively few higher speeds, probably owing to the fact that the records covered periods during which thermal stratification tended to isolate lower depths from the winds influence. Most of the late-fall, winter, spring isothermal period which is also a period of relatively strong wind events and better air-water energy coupling was missed in the 1990 and 1992 experiments. Somewhere in the hierarchy of factors influencing measurements taken in the different years, lies the effect of improved instrument sensitivity in the 1990 and 1992 records.

Extended periods of consistently low currents, referred to as stagnation currents, can lead to serious accumulation of contaminants around outfalls. When the volume of water passing the outlet drops, not only is simple dilution reduced, but vertical and lateral diffusion are greatly diminished. Thermal stratification may develop or intensify with reduced mixing; thereby, further inhibiting dispersion processes. The actual current speed and contaminant loading rate determine local concentrations, and the duration of the stagnation period determines the spatial extent of the contaminant 'patch'. The ultimate severity of the event obviously depends on these factors plus the proximity of the outfall to shore and sensitive water users (recreation areas, water intakes, wildlife etc.). We have attempted to arrive at some reasonable estimate of the frequency and duration of current stagnation in the western end of Lake Ontario from the current data analyzed. The results are shown in Figures 11 and 12. In order to quantify what might be considered stagnant currents we somewhat arbitrarily chose a duration of twelve hours or longer to be a significant period for currents to remain stagnant.

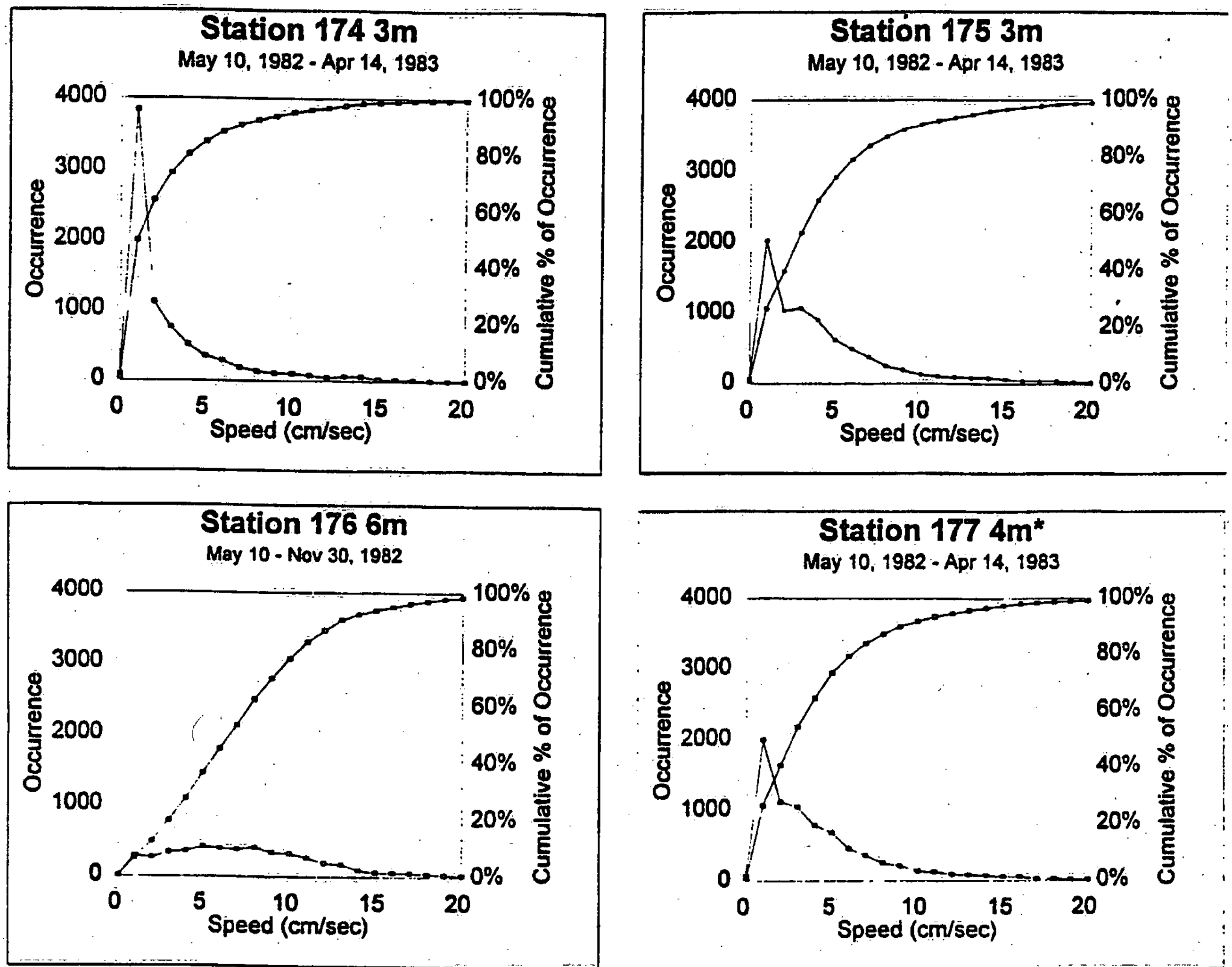


Figure 9. Frequency of Occurrence vs. Current Speed: 1982-83

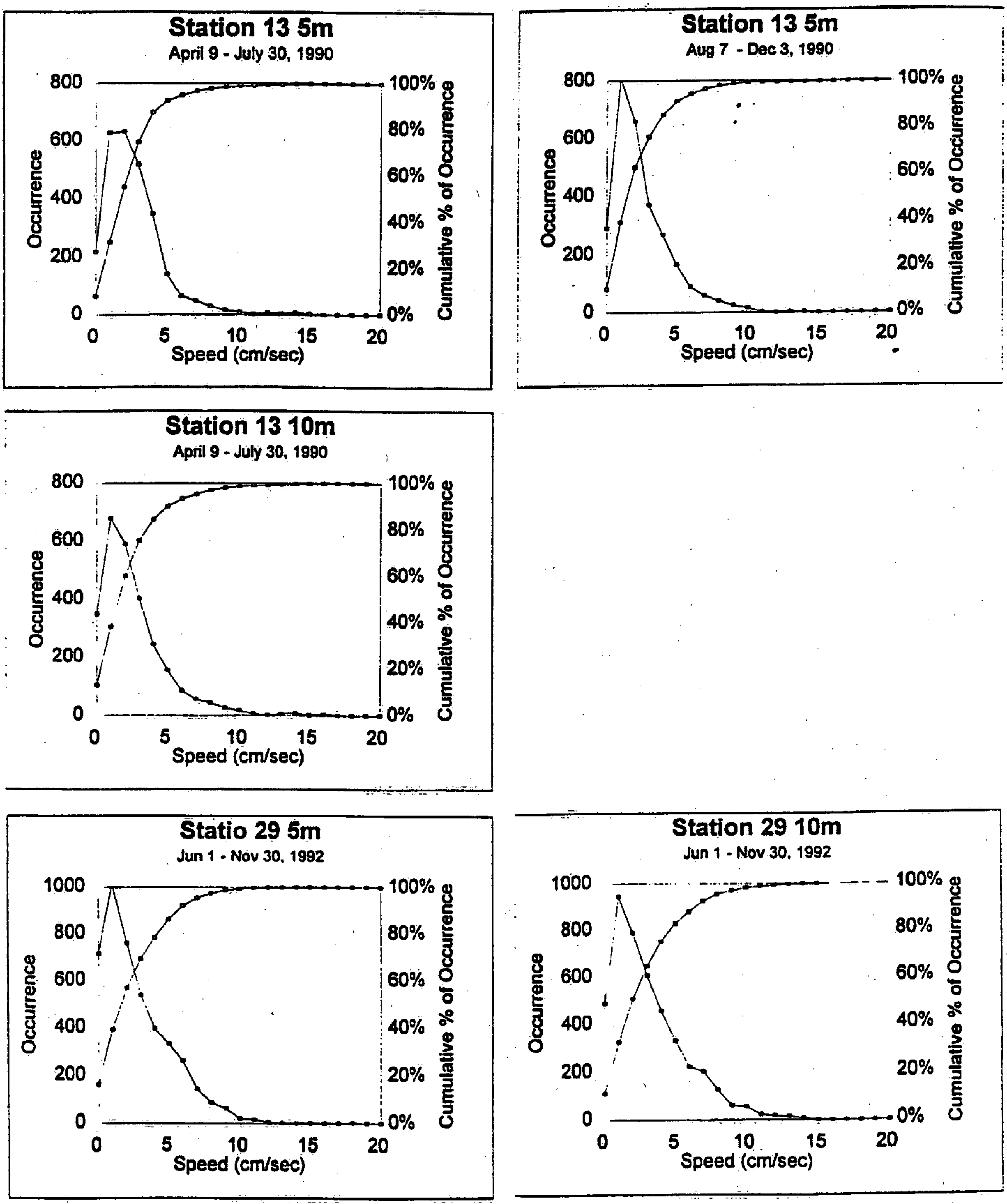
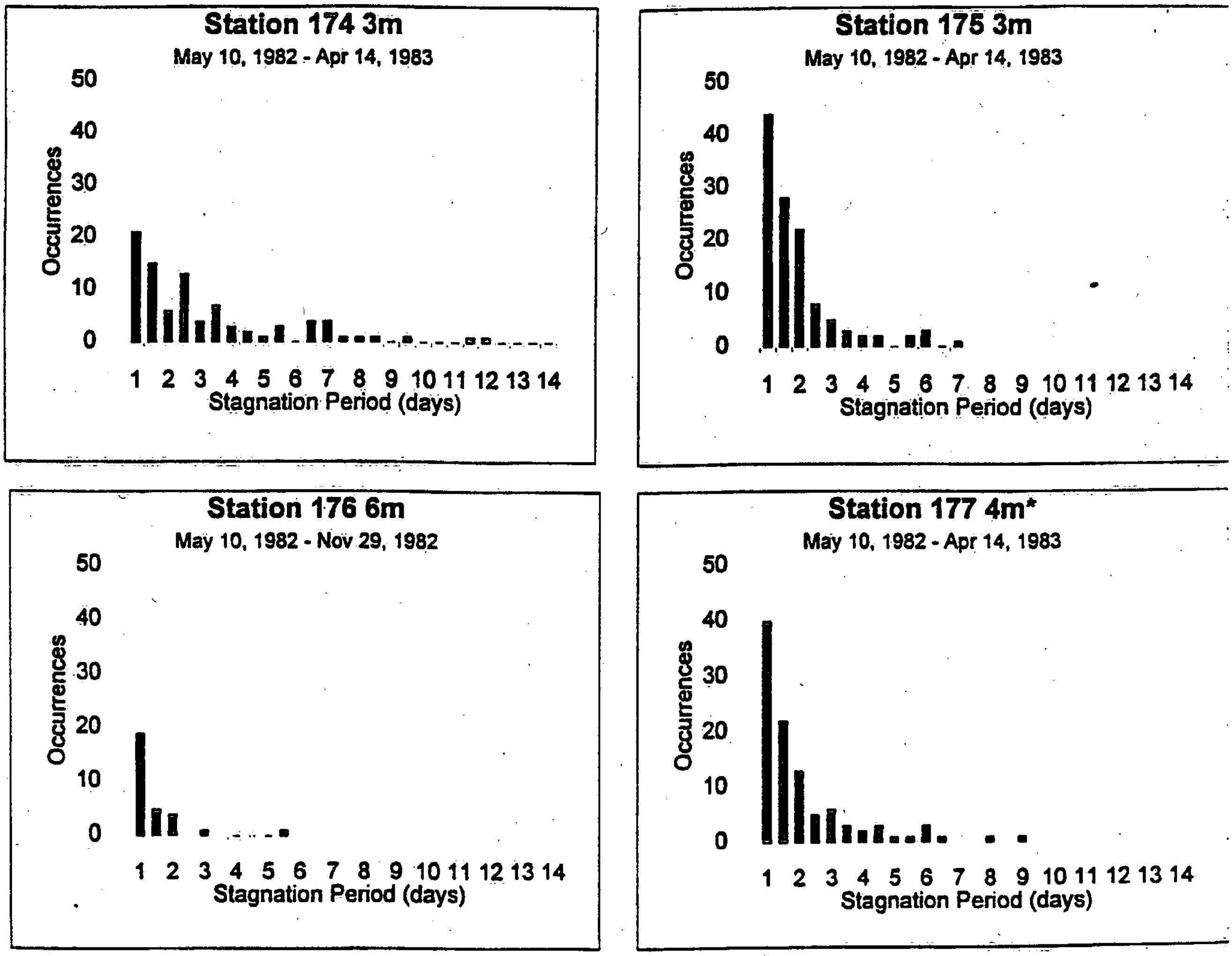


Figure 10. Frequency of Occurrence vs. Current Speed: 1990 & 1992

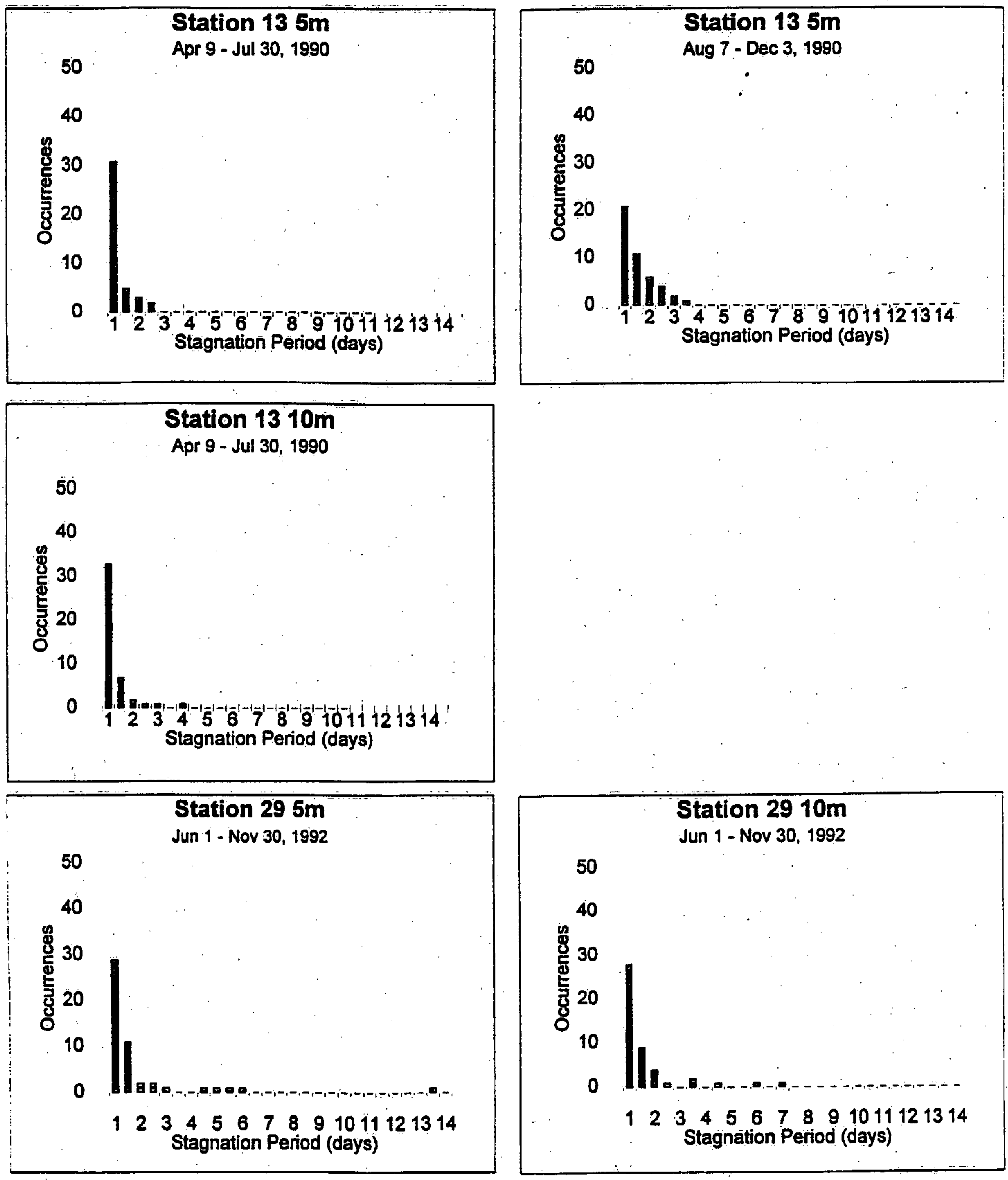
Poulton et al, in their report on 1982 Lake Ontario data, chose 5 cm/sec as the threshold speed below which currents were considered stagnant. The minimum detection threshold of the savonius rotor type current speed sensor on the AAnderaa current meters used to record these data, is also typically around 4 to 5 cm/sec. A further complicating factor enters into interpretation of data from instruments using this type of sensor. Since the savonius rotor is not sensitive to the direction of the flow, readings 15% to 25% above true speed may be obtained in instruments mounted close to the surface, due to the 'pumping' action of wave induced oscillatory motion. This speed enhancement effect is not likely to come into play at speeds down around instrument threshold, since winds strong enough to generate waves large enough to influence instruments several metres below the surface would, in all probability generate (non wave-related) currents well above threshold. Data for 1990 and 1992 were collected with Neil Brown current meters utilizing acoustic phase-shift sensors to determine current velocity. Since there are no moving parts, the lower speed measurement threshold is only about 1 cm/sec. The threshold of stagnation currents for these data was chosen to be 3 cm/sec, to be on the conservative side. Based on these selection criteria, the frequency of stagnation events was determined for increasing duration in twelve hour increments. The fraction of the total duration of the data record spent in stagnation, according to the above definitions, was also determined, and is presented for each station as a percentage on the line headed '% Time in Stagnation...' in Table 2. Station 174 has the highest occurrence of significant stagnation periods, at 77% of the time. It is also closest to the proposed Skyway WWTP outfall site. Station 13 (1990) was less than a kilometre from 174, but recorded significant stagnation periods only 38% of the total time. All else being equal one would expect the opposite difference, since station 174 was mounted closer to the surface than station 13, and was operated throughout the high energy winter period, where station 13 was not. Differences in instrument sensitivity, and the lower threshold used for station 13 calculations, may account for much of the discrepancy. It is also interesting that station 174 recorded incidents of stagnation lasting 14 days, while at the other three stations in the 1982-83 experiment, the longest stagnation period was 9 days (station 177).

While mean currents largely determine simple dilution rates and transport characteristics, variations in currents due to turbulence and other high frequency perturbations can be very important in dispersing contaminants through mixing and diffusion. The variance in a data record is a measure of these variations. Vector data can be manipulated to find a reference axis orientation such that the sum of the squares of x-components of vectors resolved to the new axes is a maximum (a minimum for corresponding y-component values). The x-axis of this configuration is sometimes called a 'principal axis'. Ellipses with major and minor axes respectively proportional to variance of the flow along and perpendicular to a principal axis were drawn for all current stations to provide an estimate of dispersion at each site. These are shown in Figures 13 and 14 for 1982-83, and 1990 and 1992 data , respectively. Owing to the gaps in 1982-83 data, the segments were processed independently and the results superimposed. The mean vectors for each segment are also plotted at each station, and, while scales differ, are intended to illustrate that the variance is much greater than the mean current; and hence, is much more important in determining the dispersion.



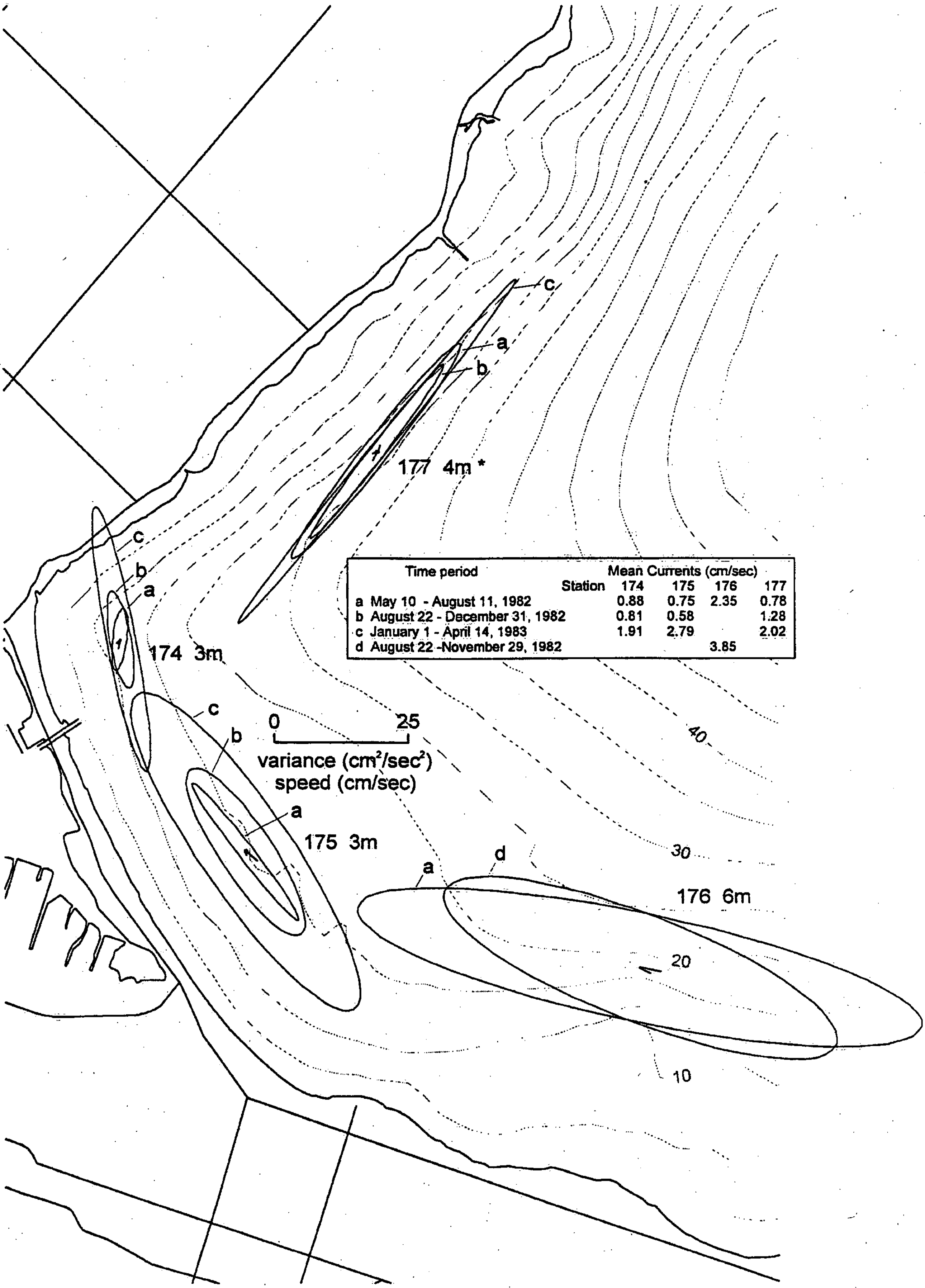
Stagnation threshold speed = 5 cm/sec

Figure 11. Frequency of Occurrence vs. Stagnation Period: 1982-83



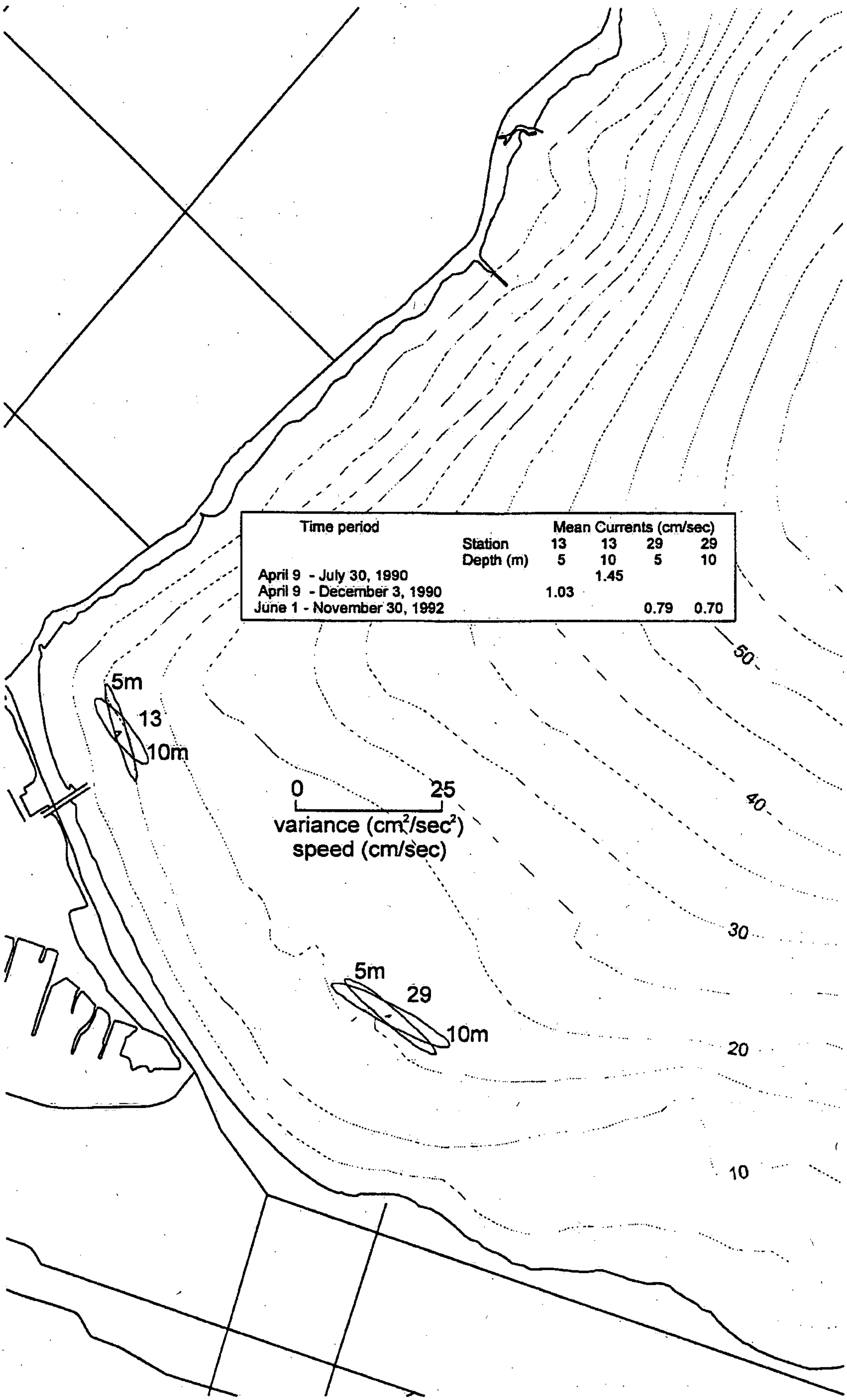
Stagnation threshold speed = 3 cm/sec

Figure 12. Frequency of Occurrence vs. Stagnation Period: 1990 & 1992



Time period	Mean Currents (cm/sec)			
Station	174	175	176	177
a May 10 - August 11, 1982	0.88	0.75	2.35	0.78
b August 22 - December 31, 1982	0.81	0.58		1.28
c January 1 - April 14, 1983	1.91	2.79		2.02
d August 22 -November 29, 1982			3.85	

Figure 13. Variance Ellipses and Mean Velocity Vectors: 1982-83



Time period	Mean Currents (cm/sec)			
Station	13	13	29	29
Depth (m)	5	10	5	10
April 9 - July 30, 1990		1.45		
April 9 - December 3, 1990	1.03			
June 1 - November 30, 1992			0.79	0.70

Figure 14. Variance Ellipses and Mean Velocity Vectors: 1990 & 1992

Figures 15, 16, and 17 are plots of current and temperature data for periods 4 to 9 days in length, and chosen to illustrate, in some detail, one or more features characteristic of thermally stratified conditions. Each consists of a progressive vector diagram of currents, vector 'stick-plots' of the same current data, and a corresponding plot of temperature vs. time for the same instruments. The episodes are all from 1990 and 1992 where stations had instruments at two depths, and contain examples of upwelling/downwelling, shear currents, and currents induced by internal waves. Each episode is described in some detail below. Although detailed local wind measurements were not available for the two periods in July 1990, daily velocity values from wind summaries for Toronto's Pearson Airport were used to approximate the wind field affecting the lake at that time. Comparisons with locally measured winds at times when they were available suggest that this was not an unreasonable approximation for our purposes here.

Upwelling and downwelling occur close to coastlines as part of a complex response to energy imparted to the water surface by wind drag, and are easiest to observe in temperature data, under thermally stratified conditions. This upward movement of cooler bottom water or downward flow of warmer surface water can be an important factor in the replenishment of near-shore waters, especially where contaminants are discharged below the thermocline where weak currents may fail to provide adequate dispersion in the receiving waters. Upwelling and downwelling events are more readily interpreted in data from stations with sensors at multiple depths.

Figure 15 illustrates conditions at station 13 over an 8 day period, July 7 to 14, 1990, which included an episode of upwelling followed by downwelling. Temperatures indicate stratified conditions, and a look back to Figure 7 which covers a much longer period, shows that this episode occurs on the underlying gradual summer warm-up cycle in the lake. On July 7 and 8, moderate winds with a significant component from the east appear to have forced warmer surface water into the western end of the lake, gradually elevating temperatures at both 5 m and 10 m depths by about 4° C. The progressive vector diagram in Figure 15 indicates currents at both levels at station 13 were light and toward the south. On July 9 somewhat stronger winds, predominantly from the west, swept surface waters eastward, drawing colder bottom water into the west end of the lake at lower levels, and upward in the water column near the western shore. Currents on July 9 were very light; toward the west at 5 m depth, and toward the west-south-west at 10 m. On July 10 moderate northerly winds produced little change in the thermal structure, and currents virtually died out. Beginning on July 11, light winds with a component from the east returned, southerly currents resumed, water temperatures rose about 10° C in a couple of days, and stratification between the two sensor levels vanished as downwelling intensified; and thus, thickened the warmer surface layer. Note that currents at the two levels differed little from each other throughout this period.

Figure 16 is a similar plot covering the eight day period July 22 to 28, 1990 at station 13, and illustrates some substantially different features from the earlier period. At the beginning of the period there was about a 3 to 4° C gradient between the 5 m and 10 m depths. Winds were light and blowing offshore. About mid-day

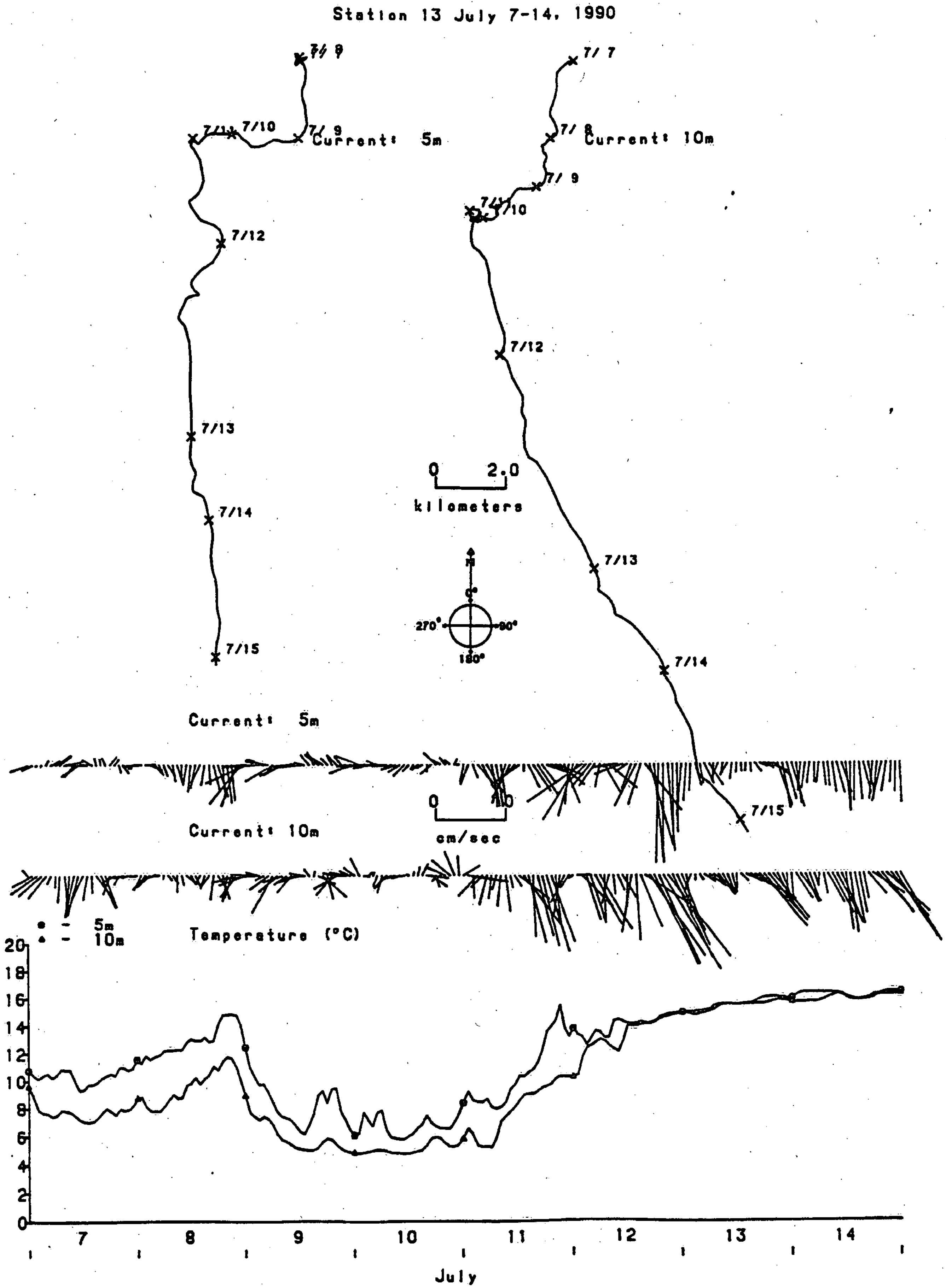


Figure 15. Progressive Vector Diagram, Vector 'Stick-plot', and Temperature Plot of Upwelling/downwelling Episode : July 7 - 14, 1990.

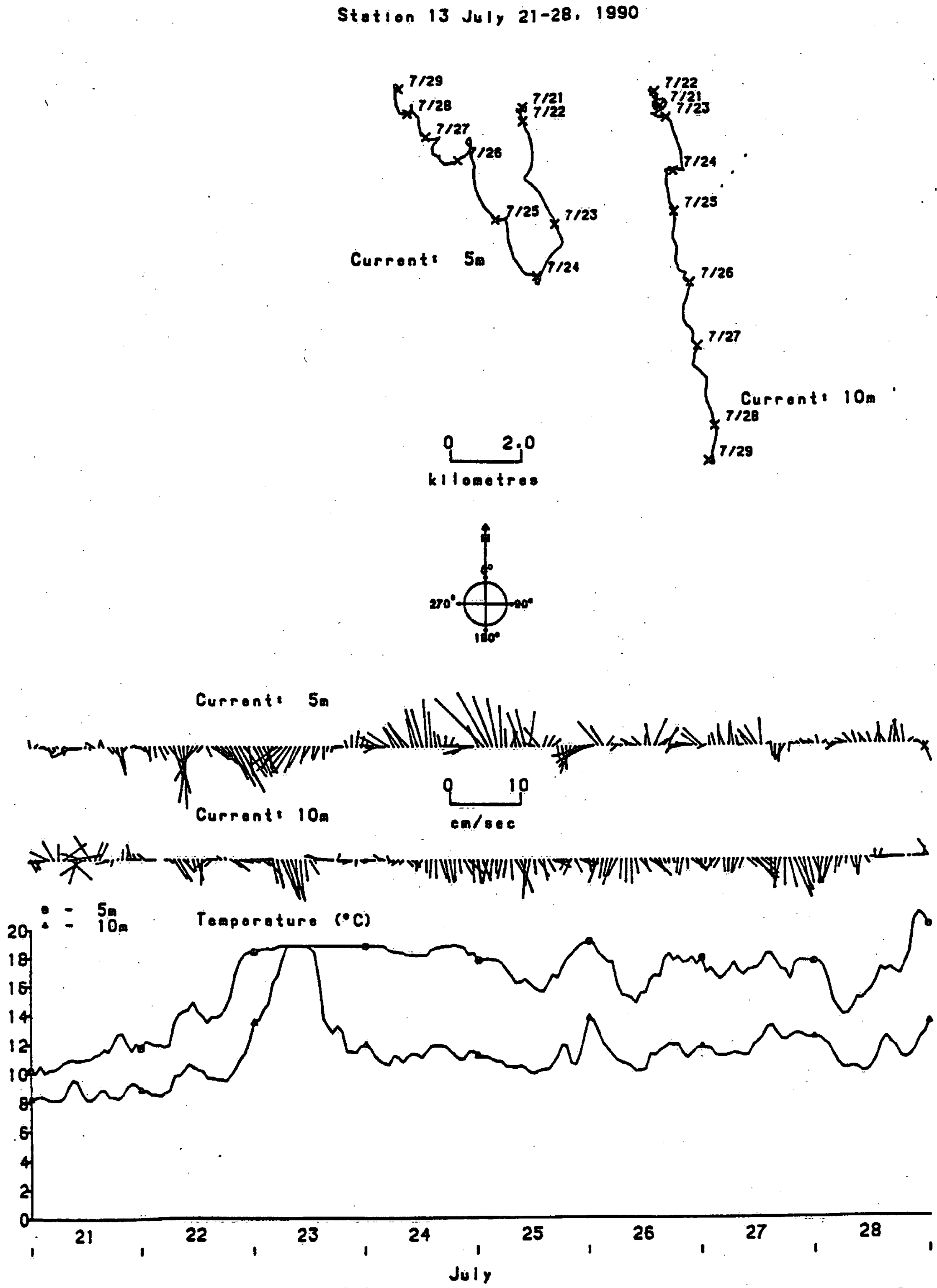


Figure 16. Progressive Vector Diagram, Vector 'Stick-plot', and Temperature Plot of Upwelling/downwelling and Current Shear Episode : July 21 - 28, 1990.

on July 22 temperatures at both depths began to rise quite rapidly until they reached about 19° C early on July 23. The surface temperature is unknown, but it seems reasonable to assume that it was not likely much higher than 19° C; therefore, we see what appears to be an episode of downwelling - an intrusion of surface water into lower depths -, but without any obvious forcing mechanism, such as wind, to overcome the relatively stable stratified conditions and enable the comparatively light surface waters to descend. Somewhat higher currents than would seem likely with the existing light offshore winds at the time, suggest that the warm water was swept into the area from further up the shore to the north-east, perhaps by forces generated by internal wave action. After a few hours the 10 m temperature fell off rapidly, while the 5 m temperature remained steady, resulting in an even stronger stratification than before the episode. This situation persisted throughout the rest of the period, with the occurrence of some cyclical temperature variations of 1° to 2° C which appear synchronized at both levels, lending more support to the presence of internal waves. The currents at both levels were well coupled prior to and during the downwelling event; however, as the progressive vector diagram clearly shows, there was a marked shear between currents at the two levels after the redevelopment of stratified conditions. Continuing light offshore winds resulted in weak erratic currents at 5 m with a mean component heading roughly north-west, almost into the wind. At 10 m they maintained their almost southerly flow throughout the period then weakened and turned westward, almost onshore, on July 28. This less than spectacular period serves well to illustrate how complex the water movements can be even under light, relatively steady forcing conditions. A downwelling event such as the one described provides a mechanism whereby effluent from a source at or near the bottom can mix vertically through the entire water column during a time when stratification might reasonably be expected to trap it below the thermocline.

A third episode illustrated in Figure 17 presents data from station 29 during the period August 4 to 7, 1992, and includes wind data from station 9 located on the east end of the pier along the Burlington Canal. This example demonstrates features similar to those in Figure 14 - light predominantly offshore winds , a thermally stratified water column, and strong current shear between the 5 m and 10 m levels. Station 29 was situated further offshore and in a much more exposed location than station 13 (see Figure 1); and therefore, may show some characteristics typical of the open lake. Inertial oscillations, with a period of about 17 hours at the latitude of Lake Ontario, develop where depth and distance from shore are sufficient to minimize frictional damping, in diminishing current fields after the driving force(s) - usually wind - relax. While some of the oscillations in this example have periods in the inertial range, they could also be a result of internal wave activity, generated by the response of a stratified water body to wind forcing. These wave-related current oscillations often exhibit periods close to the inertial period (Mortimer, 1975). The brief episode presented here distinctly shows oscillations in both the temperature and current records from the 10 m depth. At 5 m, similar oscillations are visible in the current data, but are not so obvious in the temperature record. The marked cycling of the temperature at 10 m may have been a result of vertical thermocline oscillations set up by the internal waves, causing the thermocline, with its sharp temperature gradient, to sweep up and down past the thermistor

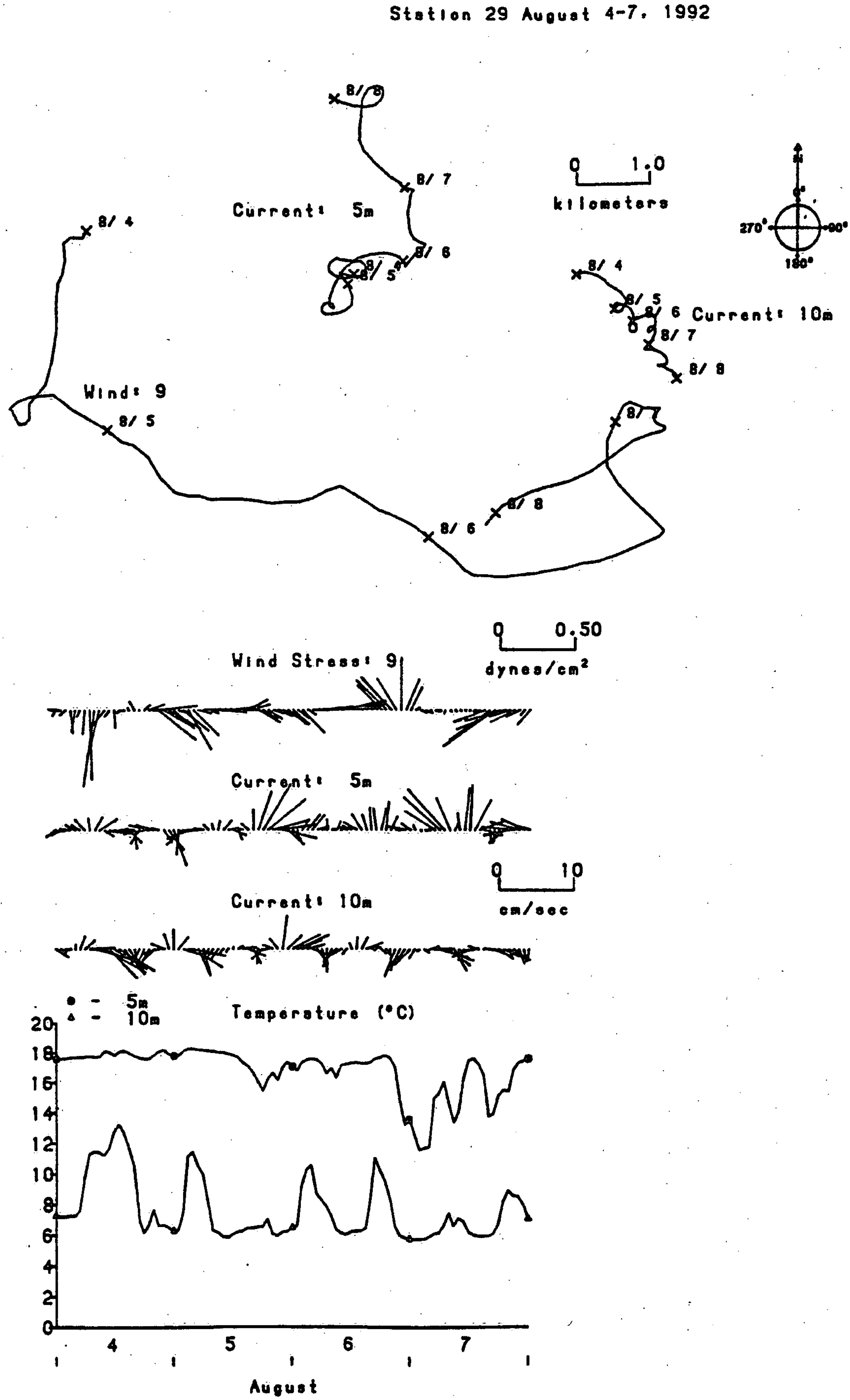


Figure 17. Progressive Vector Diagram, Vector 'Stick-plot', and Temperature Plot of Current Shear and Internal Wave Episode : August 4 - 7, 1992.

mounted on the moored current meter. Note the lack of coupling between the two current records - at times travelling in the same direction at other times in the complete opposite direction-, indicating ,as does the temperature record, that the water masses at the two depths were moving almost independently of one another. The progressive vector diagram shows that the mean flow over the period was indeed in opposite directions. Oscillatory motions and shear currents like those in this example, and turbulence associated with them, are very important factors in the dispersion of contaminants introduced into the nearshore zone, especially in the absence of a well defined shore-parallel current regime.

Currents along straight coastlines of large water bodies are predominantly shore-parallel, relatively strong, and typically persist for several days between direction reversals (Murthy, 1975). Naturally, with such well defined structure, the velocities are often similar at any given time at widely separated locations along the shore, and the similarities are readily visible in parallel time series vector 'stick-plots'. By contrast, similar plots of velocity vectors from stations along curved shorelines, such as the shore at the western end of Lake Ontario often appear erratic, even if there is a shore-parallel flow, simply because shore-parallel is a different directions at each location. Since large scale features such as shore-parallel currents are important in dissipating contaminants, it is advantageous to be able to recognize if and when they develop in an area. Also, if such gross features are more easily identifiable, other features may also become easier to recognize. Figure 18 is the result of an attempt to make shore-parallel currents more readily detectable in the records from 1982-83 stations 174, 175, 176 and 177. A large scale counter-clockwise rotation is known to develop on occasion (Murthy and Miners, 1989) in Lake Ontario west of the Niagara River. Such a large scale feature could have significant impact on the transport and dispersion of contaminants, and could be a significant part of the circulation climatology in an area. The four stations placed around the western shore in 1982-83 presented the opportunity to observe such shore-parallel flow if, indeed, it passes that close to the extreme western shore, and if it could be detected in the data. Normally, we plot east up the page when dealing with Lake Ontario to clearly illustrate the dominant east-west component which aligns with both the lake axis and the prevailing winds; however, in Figure 18, in order to better visualize the data in terms of shore-parallel and shore-perpendicular components, we essentially 'unfolded' the end of Lake Ontario by resolving each station's velocity components to new axes which align with the local shoreline instead of aligning with compass direction. Unlike the normal plot of this type where any direction on the plot is a constant geographic direction, the up-page direction here corresponds to shore-parallel currents to the right looking offshore; in other words, a counter-clockwise rotation around the west end of Lake Ontario. The plots are arranged down the page in the order in which one would encounter the current meter stations travelling in a counter-clockwise direction around the western shore. Vectors are daily averaged velocities. The compass diagram beside each set of vectors indicates the geographic orientation for that station's vectors. There are several significant features illustrated in this plot. As we might expect , the shore-parallel component dominates, especially in a strong current field, a fact dictated by topographic constraints. Also, stronger currents are generally associated with the counter-clockwise circulation due to factors related to prevailing winds and basin geometry. When we look

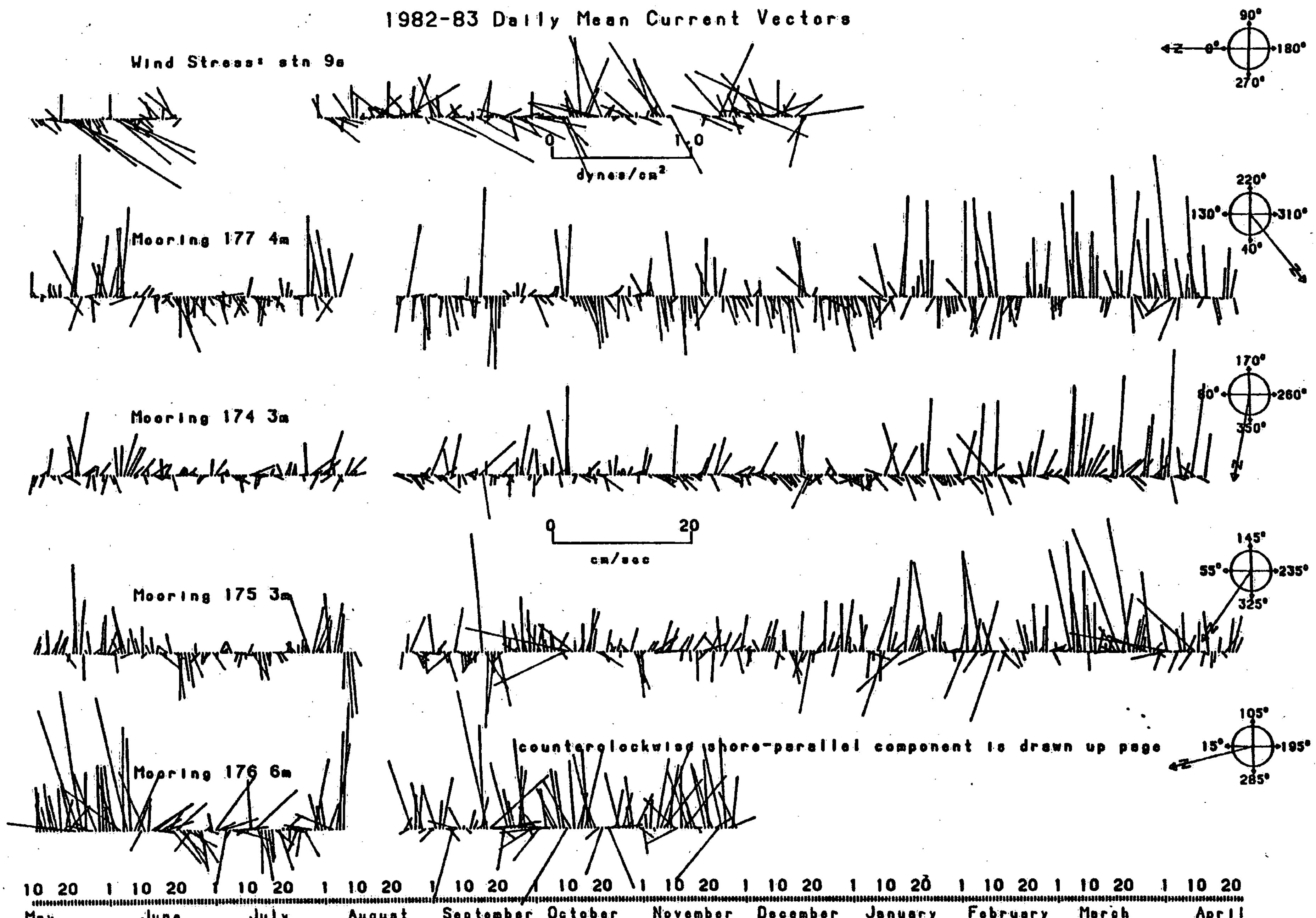


Figure18. Shore -parallel Enhanced Daily Mean Vector 'Stick-plot': 1982-83

at concurrent vectors at stations 177 and 176, the north-eastern and south-eastern extremes respectively, we find numerous instances of currents flowing, still shore -parallel, but away from the west end of the lake at both locations. This scenario prevails a good part of the time from September through November 1982. Obviously, water must come into the end of the lake to replenish this apparent outflow along both shores. Such a sustaining current is not evident in Figure 18, but if we look closely at data from stations 13 and 29, Figures 7 and 8, respectively, we find cases where currents at one or both depths travel at considerable angle to the shore, suggesting an inflow (in the scenario described here) or outflow at depth, which could very well be a balancing flow for nearby currents of an opposite sense. The other important feature of Figure 18 is the weak current regime at station 174, and its apparent lack of coupling with the other stations. As indicated above, even conditions of opposing flows at the other three stations can be reasonably explained as an area-wide phenomenon, but station 174, with notable exceptions during strong wind/current episodes, exhibits weak, erratic currents, suggesting that the area is generally outside of major circulation systems sweeping across the western end of the lake. This is in agreement with the stagnation calculations described earlier, and strengthens the importance of caution in the design and placement of outfalls in the area.

3.3 Dispersion Characteristics from Lagrangian Observations

Satellite-tracked drifting buoys were deployed in western Lake Ontario, in the vicinity of the Burlington Ship Canal, from May through October 1989. The duration of experiments ranged from 7 to 14 days. The drifter trajectories from all of the experiments are superimposed in Figure 19. The mean, and root-mean-square (rms) velocities of individual drifter trajectories, and the ensemble averaged zonal (east-west) and meridional (north-south) velocities for the combined data set were computed. Zonal and meridional mean velocities were 6.0 cm/sec and -0.4 cm/sec respectively. Corresponding rms velocities were 9.2 cm/sec and 7.0 cm/sec, indicative of large scale turbulent fluctuations; and therefore, enhanced mixing. Table 3 summarizes the mean and rms velocities for all experiments.

To quantify the dispersion characteristics, we have applied Taylor's theory of single-particle motion. The data base was enhanced by using a method first described by Colin de Verdier (1983). Assuming that drifter velocities become decorrelated within one integral time-scale, any two locations of the same drifter separated by more than one integral time-scale may be considered independent and restarted as a new track. For a decorrelation time-scale of 50 hours, which is roughly twice that of typical integral time-scale in the lake, the time series of hourly positions of the individual drifters were split up into a number of non-overlapping 50 hour time series. End segments shorter than 50 hours were not used. This yielded 57 pseudo drifter trajectories. The ensemble mean zonal and meridional velocities of the pseudo drifters are, 6.7 cm/sec, and 0.1 cm/sec respectively. Corresponding rms velocities are12.7 cm/sec, and 8.8 cm/sec. The apparent differences in the values for unmodified and modified series are due to loss of data in the end segments that were shorter than 50 hours long and were not used in the single-particle analysis.

Table 3. Statistics from Satellite-tracked Drifter Trajectories in Western Lake Ontario.

Time of Experiment	ID	Mean u (cm/s)	Mean V (cm/s)	rms u (cm/s)	rms v (cm/s)
May/Jun.	5380	2.89	-1.54	9.21	3.66
	5380	3.16	-0.75	6.60	4.98
	5381	8.21	0.71	8.31	6.32
	5385	3.00	-1.57	9.42	5.41
	5385	6.93	0.47	9.60	7.80
	5387	1.14	-1.11	7.00	5.33
July	5388	0.93	-0.57	4.35	3.65
	5389	1.02	-0.61	4.41	3.22
Sept./Oct.	5380	15.70	1.05	18.60	14.00
	5385	18.50	0.71	21.09	17.50
	5396	3.91	-0.04	6.73	6.19
	5397	6.98	-0.93	5.03	6.46

To derive the single-particle statistics, we first remove the background circulation. The dispersion is estimated from the cumulative effect of the motion due to turbulence. Figure 20 shows the 'smoke-stack' dispersion plot of the pseudo-drifters all emanating from the same location. Except for a few trajectories which show saturation effect just after deployment, the dispersion grows with time. The dispersion along the zonal direction is stronger than that along the meridional direction.

We also calculated auto-correlation functions from the pseudo-drifter trajectories. Both zonal and meridional auto-correlation functions fall off slowly with increasing time-lag (Figure 21). The zonal integral time-scale is 12.3 hours, which is about twice the size of the meridional integral time-scale of 6.7 hours. Corresponding zonal and meridional eddy diffusivities are 7.1×10^6 cm^2/s and 1.9×10^6 cm^2/s, respectively, and saturate after about twenty-five hours. These values are indicative of good mixing of water masses; however, it is important to note that these figures are based on drifter experiments lasting several days. This introduces a strong bias toward those periods when well established currents sweep through the area, which, as we have seen from current meter data are not necessarily typical of the area. Data from numerous drifter deployments were not considered because drifters were grounded after a few hours by weak onshore currents.

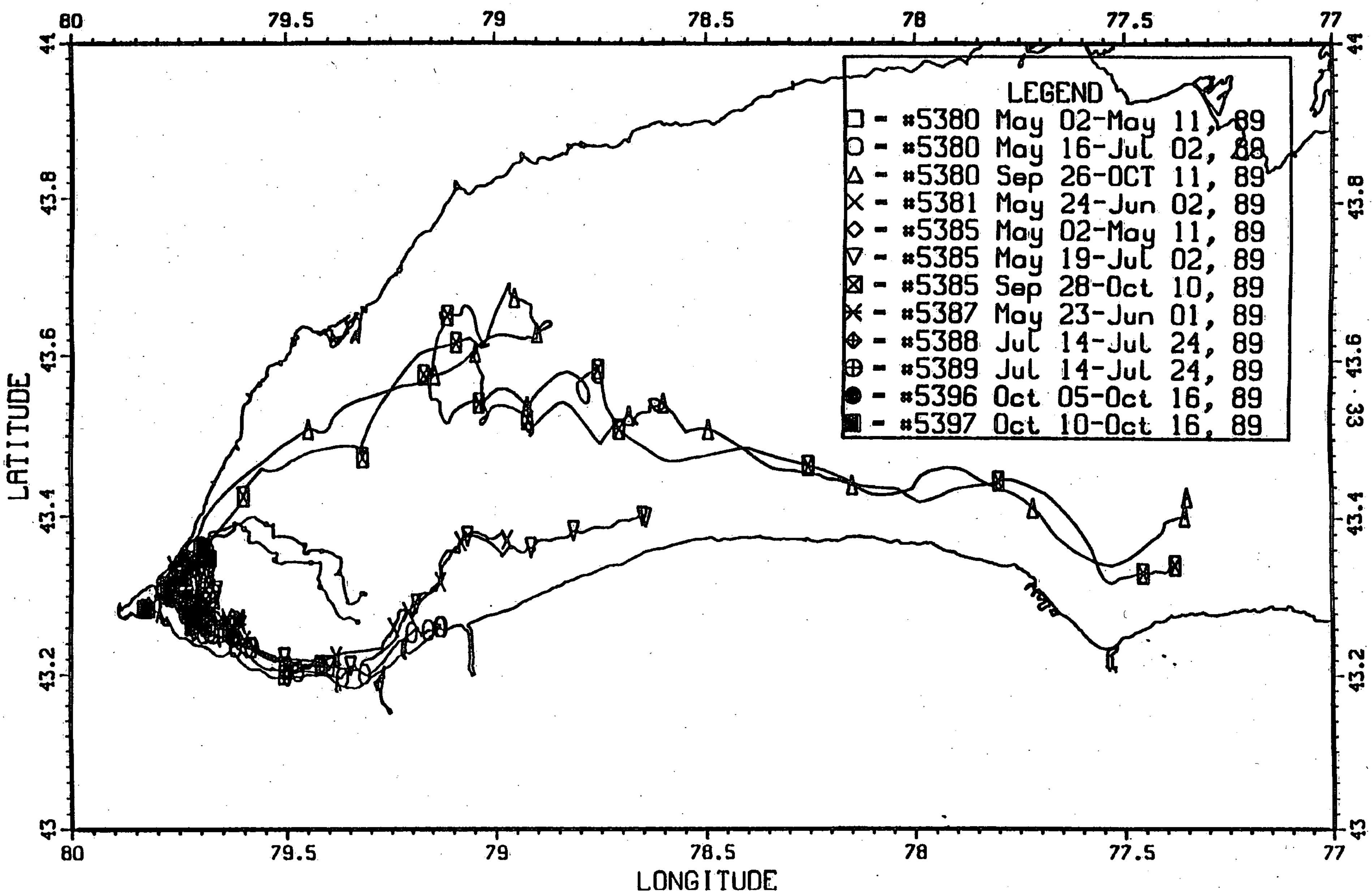


Figure19. Composite Drifter Trajectory Plot for Western Lake Ontario: 1989

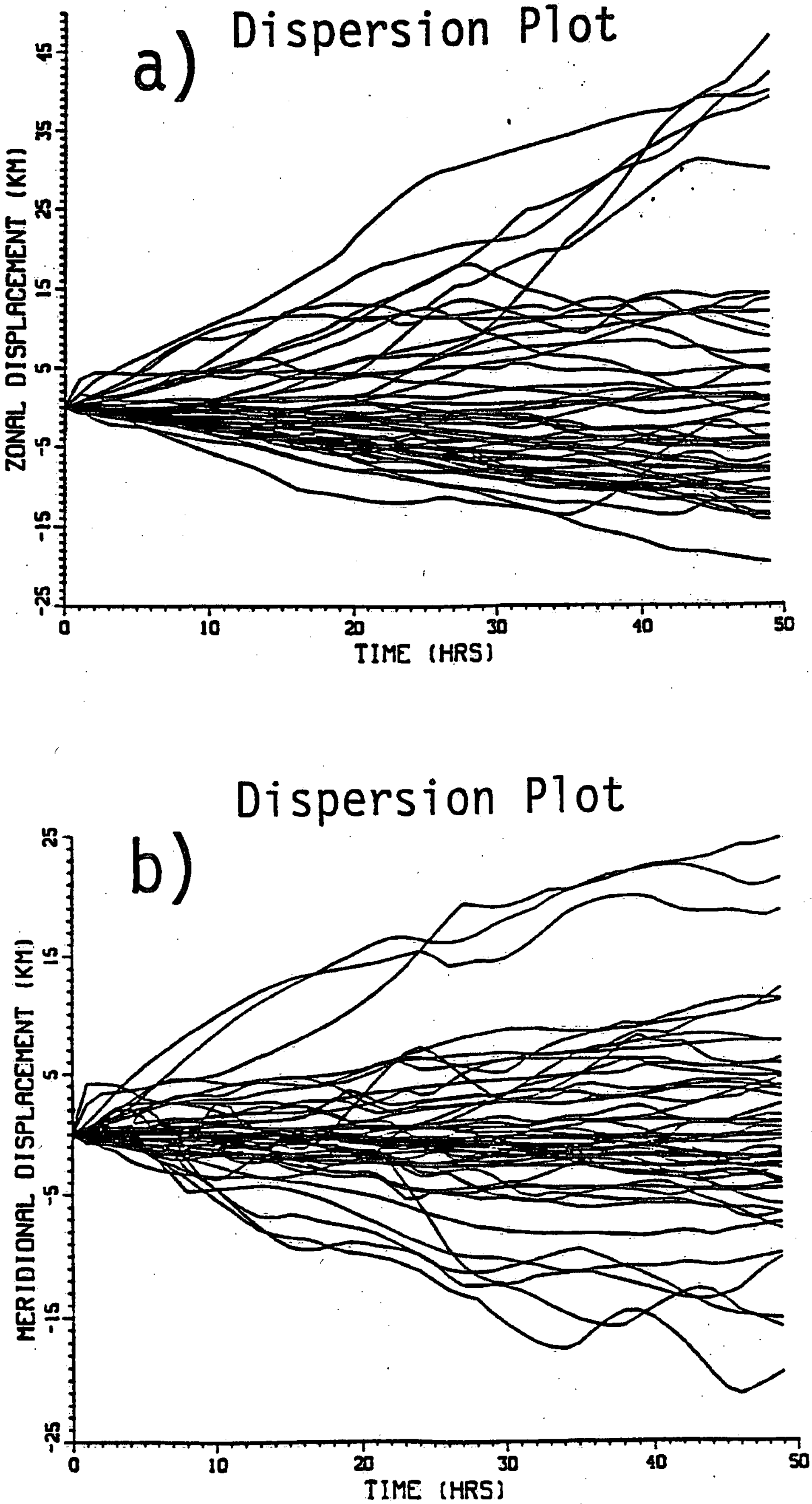


Figure 20. Dispersion Plots from Drifter Trajectories

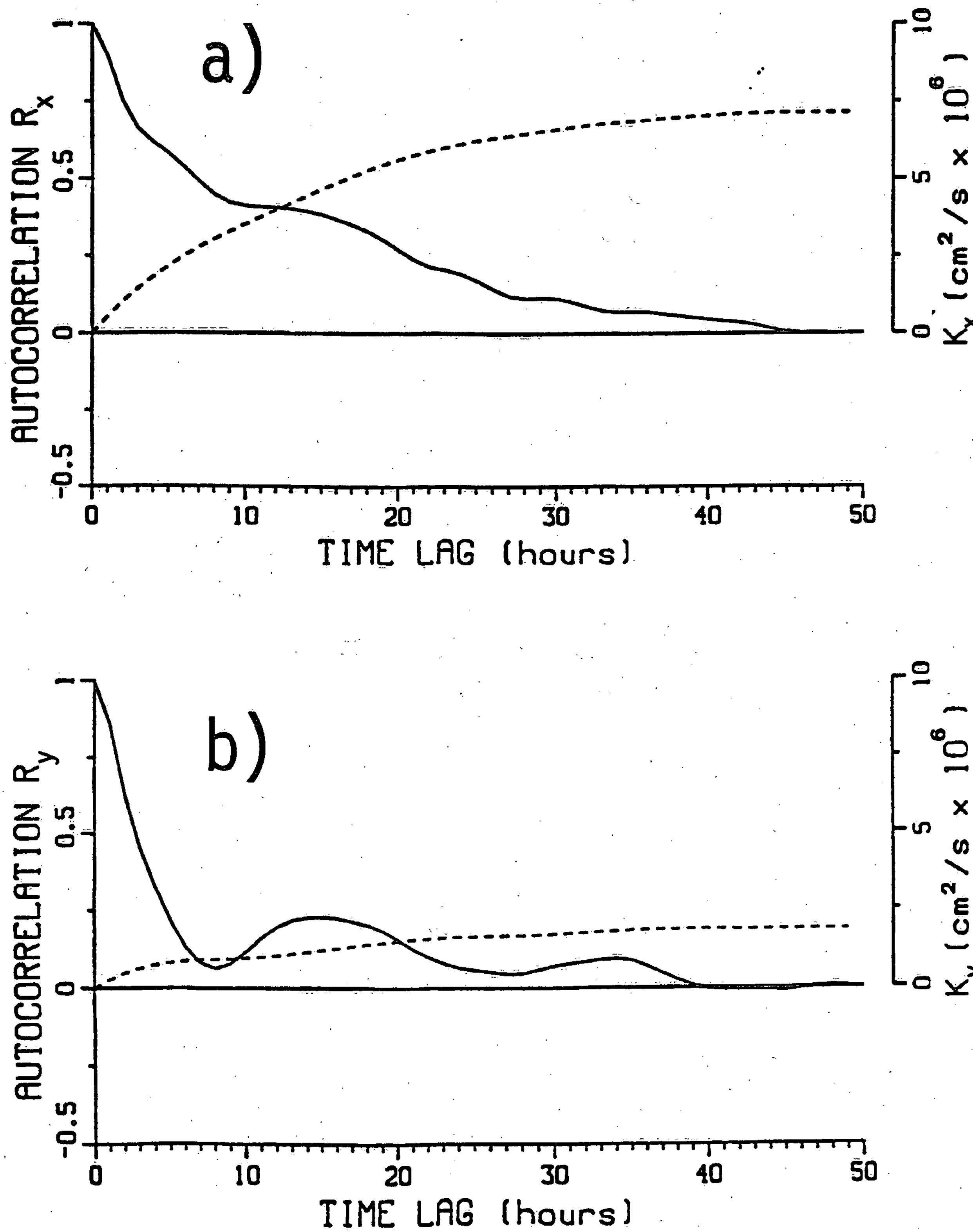


Figure 21. Autocorrelation and Dispersion Coefficient for Drifter Data: 1989

4.0 Conclusions:

A variety of statistical and graphic analysis techniques applied to historical data records taken in the western end of Lake Ontario have provided a fairly good picture of the physical limnological characteristics of the region. Without resorting to highly sophisticated analysis and modelling procedures it was confirmed that the area is not a particularly energetic part of the lake, as one would guess from basin topography and its relationship to prevailing local winds. Furthermore, the extreme north-west 'corner' of the area is substantially less energetic than the remaining part. That area, which encompasses the proposed Skyway WWTP outfall, based on minimum physical placement practices, appears to escape all but the most vigorous circulation 'systems' that develop in that region of the lake by virtue of its sheltered location.

Theoretical diffusivity estimates based on drifting buoy trajectories indicate adequate mixing, but are biased by the fact that calculations were, naturally, based on 'successful' missions, while many missions were excluded because weak local currents grounded drifters in shallow water after a few hours.

These findings indicate the need for cautious and thorough study before constructing any kind of outfall (or intake) in the extreme western end of the lake. Analysis of detailed data collected specifically for this project during 1996-97 will provide substantially further insight into the area.

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