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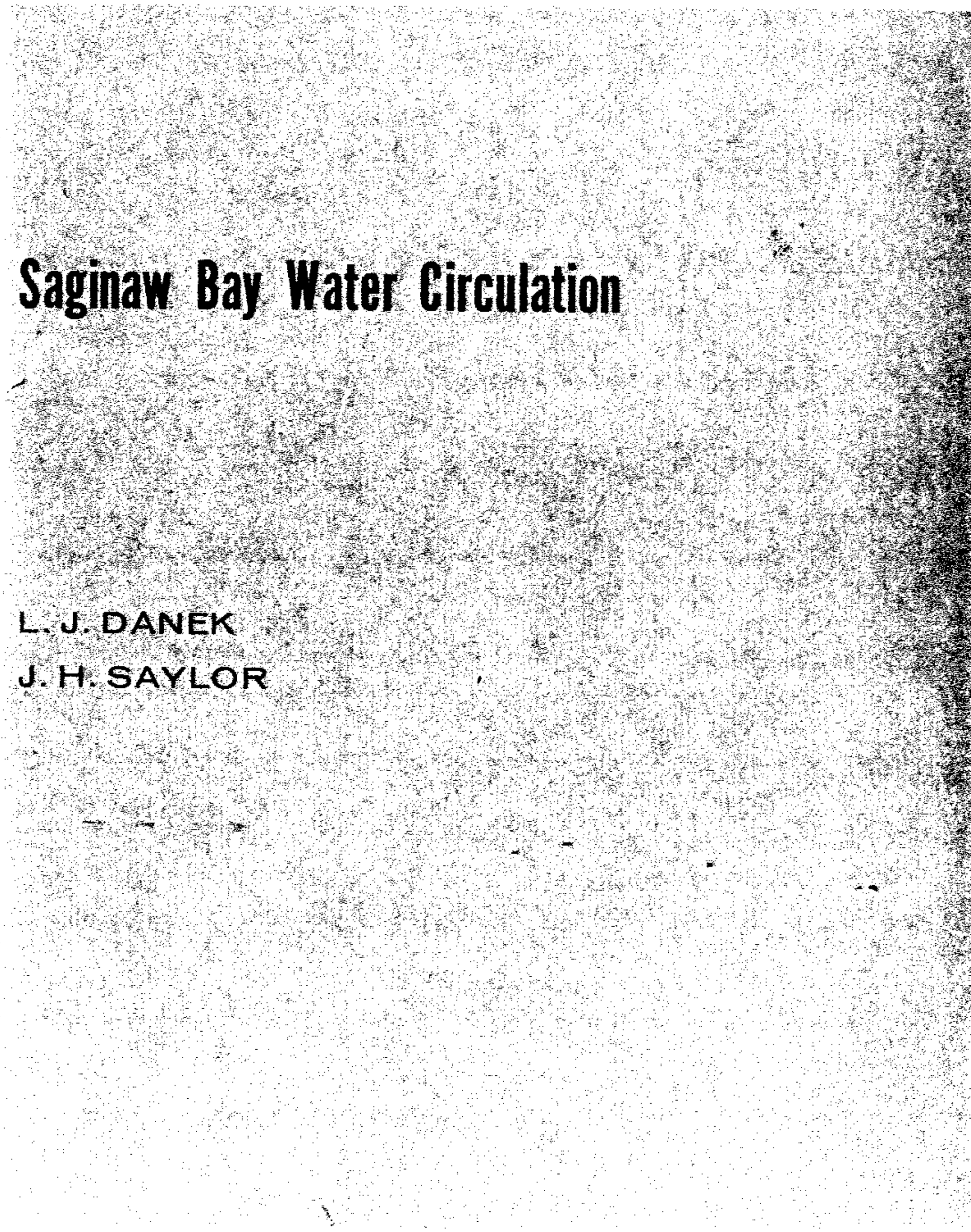

Saginaw Bay Water Circulation

L. J. DANEK
J. H. SAYLOR

BOULDER, COLO.
DECEMBER 1975

U.S. DEPARTMENT OF COMMERCE
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NOAA TECHNICAL REPORT ERL 359-GLERL 6

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FOREWORD

This report presents the results of a field study conducted during the summer of 1974 on Saginaw Bay, Michigan. Both Lagrangian and Eulerian current measuring techniques were used to determine the characteristic water circulation patterns of the bay and to find representative current speeds and volume transports during the summer. This study was partially supported through an interagency agreement with the National Environmental Research Center, Office of Research and Development, Environmental Protection Agency, under contract EPA-IAG-D4-0502 and is a contribution to the International Joint Commission Upper Lakes Reference study.

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SAGINAW BAY WATER CIRCULATION

L. J. Danek and J. H. Saylor

A combination of Lagrangian measurements and fixed current meter moorings during the summer of 1974 were used to determine the circulation patterns of Saginaw Bay. Because the bay is shallow, the water responds rapidly to wind changes. Distinct circulation patterns were determined for a southwest wind and a northeast wind. Speeds measured in the inner bay are on the order of 7 cm s^{-1} whereas in the outer bay the speeds average closer to 11 cm s^{-1}. A typical exchange rate between the inner and outer bay is 3700 $m^3 s^{-1}$ for winds parallel to the axis of the bay, but winds perpendicular to the axis of the bay cause little water to be exchanged.

The driving forces that control the circulation patterns in the bay are also examined. The water motions in the inner bay are driven almost solely by wind stress whereas the outer bay is also influenced by the circulation of Lake Huron and by the geometry of the area. Inertial oscillations are the most dominant periodic component of the flow. Seiche motions of Lake Huron and the bay itself were detected, but they are of little importance in determining the gross circulation of the bay.

1. INTRODUCTION

This report presents results of a 1974 field investigation of Saginaw Bay water currents and circulation patterns. Saginaw Bay is located on the southwestern coast of Lake Huron, centered at nearly 44°00'N latitude and 83°20'W longitude, as shown in fig. 1. The investigative program included the deployment of nine current meter moorings in the bay (fig. 1) in May, 1974, the establishment of a wind recording station at the Gravelly Shoal Lighthouse, and Lagrangian current measurements by use of drogues during three 2 week-long intervals while the moored current meters were in place. The current meters were retrieved in October 1974, giving approximately 5 months of continuous current speed and direction recordings.

The mouth of Saginaw Bay (from Point Aux Barques to Au Sable Point) is 42 km wide and has an average depth of 27 m. The bay's narrowest constriction is between Sand Point and Point Lookout with a width of 20 km and a mean depth of only 4 m. A line between these two points forms an approximate boundary between the outer bay (mean depth 16 m) and the much shallower inner bay (mean depth 4.5 m). The bay is 83 km long with its major axis aligned 40° east of north. An important feature of the bay is the relatively deep channel that runs through the inner bay. It is aligned nearly parallel with the major axis of the bay and has a maximum depth of about 14 m. The Saginaw River, which enters the bay at the southwestern end, drains an area of over 16,000 km^2 and passes through Bay City just prior to entering the bay. The average discharge of the river is about 100 $m^3 s^{-1}$, though it can increase to well over 300 $m^3 s^{-1}$ during the spring months. There are several small rivers that also flow into the bay, but their combined discharge is small compared to that of the Saginaw River.

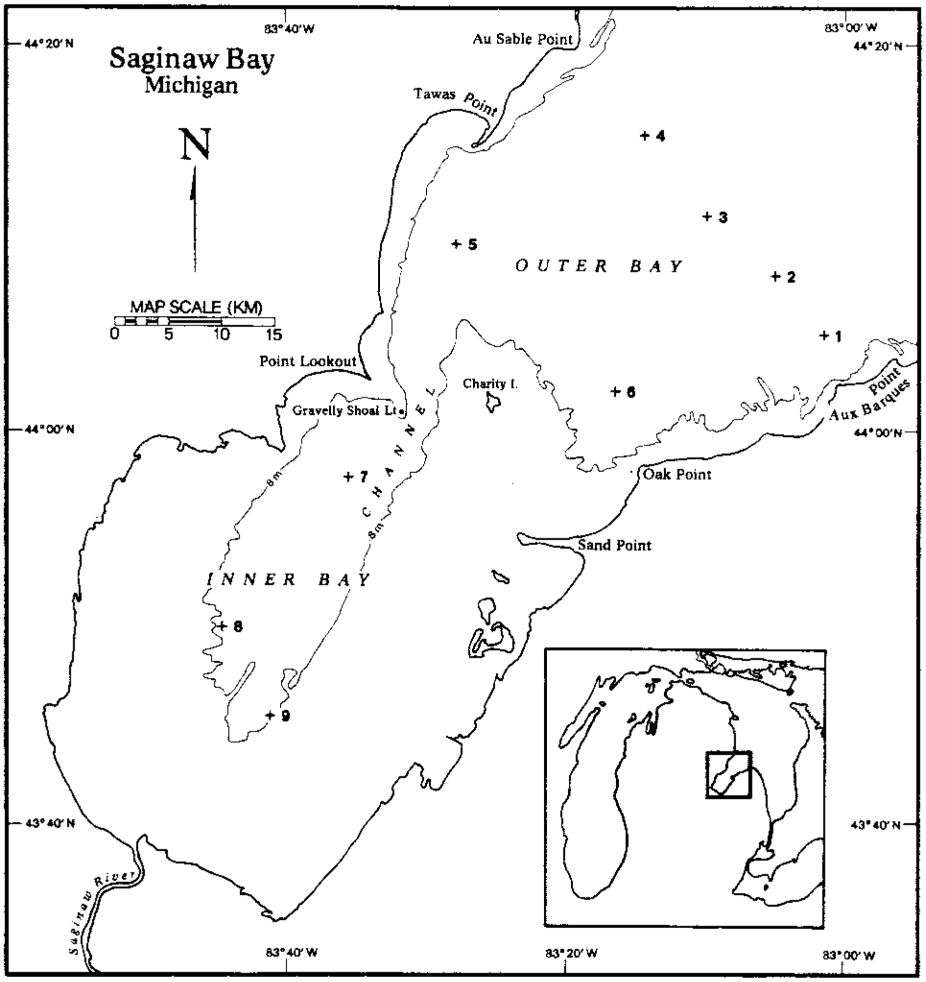

Figure 1. The study site showing the locations of the 9 current meter moorings and the wind station at Gravelly Shoal Lighthouse.

Because the water in the inner reaches of Saginaw Bay is shallow, currents in the inner bay are closely related to the wind; the measurements presented in this report establish the wind dependence. The outer bay interacts strongly with the larger scale circulation of Lake Huron. Saginaw Bay currents and the character of Saginaw Bay-Lake Huron interactions are important because of the heavy load of pollutants which enter Lake Huron through the bay. The Saginaw River discharges the wastes of the industrialized cities of Midland, Bay City, and Saginaw, Mich., and is the largest tributary source of undesirable materials discharged to Lake Huron. A long residence time and the pattern of water mass movement within Saginaw Bay have adversely impacted parts of the bay.

2. PREVIOUS STUDIES

Several qualitative studies have been done on the circulation of Lake Huron and Saginaw Bay. The first was by Harrington (1895), who conducted a drift bottle study on Lake Huron during 1892, 1893, and 1894. He concluded that the currents were quite variable, but that there was usually a strong southward current along the west shore of the lake. This current either passed by or flushed through the mouth of Saginaw Bay, in either case strongly influencing the circulation in the outer bay.

Ayers et al. (1956) used a dynamic height method for fresh water plus verification from a drift bottle study to determine the circulation of Lake Huron. It was concluded that the usual summertime circulation was counterclockwise with strong southward flow along the west shore of Lake Huron. Part of this southward flow entered the northern part of the mouth of Saginaw Bay, flushed through the outer bay, and flowed eastward to Lake Huron along the southern coast. The flow then continued southward along the west coast of Lake Huron. They also suggested that a similar counterclockwise loop existed in the inner bay, with water entering the bay along the west shore and flowing out along the east shore, and that at times a slowly rotating eddy occurred near the mouth of the outer bay.

Johnson (1958) performed extensive drift bottle studies in Saginaw Bay and Lake Huron. His findings confirmed the earlier observations of a strong southerly current along the western shore of Lake Huron, and he made special note of the prominence of this current in the southern part of Lake Huron below the mouth of Saginaw Bay. In the bay itself, he concluded that normally a counterclockwise gyre exists, with water entering the bay along the west shore and leaving along the east shore in a fashion similar to that suggested by Ayers et al. He states, however, that it is difficult to generalize about the circulation of the bay because it is so highly dependent on local winds, adding that ".... it seems possible that a surface current might change in response to a rapidly changed strong wind in a matter of hours," (Johnson, 1958, p. 16).

Beeton et al. (1967) used chemical distributions, mainly Cl^- and Na^+, to trace the water movements in the bay. They determined that winds from the northeast, east, and southeast produce a clockwise circulation in Saginaw Bay and west and southwest winds drive a counterclockwise circulation. They state that the circulation can shift from clockwise to counterclockwise in a matter of 4 days or less, a conclusion also suggested by data from the Michigan Stream Control Commission (1937). Beeton et al. also stated that the flow of Saginaw River water was out of the bay along the eastern shore and that this deflection to the right may be influenced by the Coriolis force. Rogers et al. (1975) used remote sensing to detect water masses in Saginaw Bay. They used Earth Resources Technology Sattelite (ERTS) imagery plus ground truth data collected by the Environmental Protection Agency (EPA) to map areas of constant turbidity. Their work showed that during the 1 day of investigation, more turbid water was found along the eastern shore. This again suggested that clearer Lake Huron water entered Saginaw Bay along the west shore, mixed with more turbid Saginaw River water, and exited along the eastern shore of the bay.

Allender (1975) developed a numerical model to simulate the circulation of Saginaw Bay. The development of such a model requires the specification of boundary conditions at the mouth of Saginaw Bay with Lake Huron. By examining water level records from within Saginaw Bay and from Lake Huron near the bay mouth, Allender concluded that prominent bay modes of 3.3 hr and 1.8 hr were driven by forcing waves with these periods in Lake Huron; shorter period waves were felt to be strongly damped in the bay. Therefore, periodic functions of the velocity field were specified as boundary conditions at the bay mouth, adjusted in intensity to yield Saginaw Bay water surface oscillations near the observed amplitudes. He stated that the circulation pattern of the bay can change completely in 8 hr or less, fully responding to a newly-imposed wind stress and reaching a new equilibrium state. The general pattern derived in the inner bay was current flow in the same direction as the wind in shoal areas with return flow in the deeper channel near the center of the bay. Since the prevailing wind is from the southwest, the usual circulation was characterized by water from the outer bay entering through the deep channel and leaving along the eastern coast.

A recent study of Lake Huron currents by Sloss and Saylor (1975) examined current meter records from Lake Huron and the mouth of Saginaw Bay. They noted the strong southward current along the west shore of Lake Huron north of Saginaw Bay, but did not speculate on circulation patterns in the bay itself. A detailed review of chemical, biological, and physical studies of Saginaw Bay and a discussion of the hydrology of the area is presented in Freedman (1974).

3. METHODS OF DATA COLLECTION

3.1 Current Meters

Eighteen Geodyne model A-100 film recording current meters were installed in Saginaw Bay during May, 1974, and were operational through October, 1974. A maximum of three current meters were attached to an anchored line and suspended in the water column by a subsurface float. A small surface float attached to the end of a ground line 30 to 40 m in length was used to mark the location of the moorings and to aid in the recovery of the meters. Because of mechanical and electrical problems, several of the meters failed; this left some holes in our proposed sampling grid. Locations and depths of the meters are given in fig. 1 and table 1.

Table 1. Current Meter Locations and Dates of Operation.

Meter No.	Site No.	Lat. (N)	Long. (W)	Depth (m)	Duration
2A	2	44°5.2'	83°2.4'	10	17 May-15 Oct.
2B	2	44°5.2'	83°2.4'	20	28 May-15 Oct.
2C	2	44°5.2'	83°2.4'	30	17 May-15 Oct.
3B	3	44°11.5'	83°10.9'	20	18 May-15 Oct.
3C	3	44°11.5'	83"10.9'	30	18 May-15 Oct.
4A	4	44°15.3'	83°15.0'	10	18 May-15 Oct.
4B	4	44°15.3'	83°15.0'	20	18 May-15 Oct.
5A	5	44°10.1'	83°28.9'	7	18 May-16 Aug.
5B	5	44°10.1'	83°28.9'	15	18 May-3 Oct.
6A	6	44°2.3'	83°17.3'	7	17 May-8 June
6B	6	44°2.3'	83°17.3'	10	17 May-16 Oct.
9A	9	43°45.6'	83°41.4'	7	20 May-18 Oct.

Each current meter sampled the velocity for a 50-s interval every 30 min and accumulated over 7200 data points for the duration of the study. The Savonius rotors on the meters have a threshold speed of 2.5 cm s^{-1} and an accuracy of 2.5 cm s^{-1} for speeds less than 50 cm s^{-1}. The sensitivity of the direction vane is alignment within 10° of the current direction at a current speed of 2.5 cm s^{-1}, and within 2° at 10 cm s^{-1}, with a resolution of 2.8°. The meters recorded the velocity in binary code on standard 16-mm photographic film. Eight of the films were sent to Geodyne for automated processing and the decoded raw data was stored on magnetic tape. The rest of the films were read and decoded manually.

3.2 Drogues

Drogues were tracked for three 2-week sessions from abroad the *R/V Shenehon*, one session each in June, August, and October of 1974. The results are shown in Appendix A. The drogues consisted of a surface buoy plus a subsurface panel. The buoy was made from a pneumatic float and a radar reflector that extended 1.5 m above the water surface. The panel was a current cross made of sheet metal that could be set to any desired depth in the water column. During this study the panels were set only at depths of 2 m or 5 m. The cross-sectional area of the panel was 1.86 m^2. One drogue and one anchored radar reflector were deployed at each launch site, and the drogues were tracked by radar using the anchored buoy as a reference point. Typically five drogues were launched along each transect with a 2.5-km spacing between drogues.

3.3 Wind

A wind station was installed at the Gravelly Shoal Lighthouse near Point Lookout. Both wind speed and direction were measured by a Bendix wind recording system. The data was continuously recorded on a strip chart and later digitized into hourly averages. The sensor location was approximately 23 m above the water surface. The distance to the nearest point of land was 4.5 km, so that local interferences were minimal. Due to the isolated location of the station, constant servicing was not possible. Consequently a few relatively short gaps appeared in the data. The gaps included about 10 days of record during the 5-month study. For computation of monthly wind statistics, the gaps were filled with data obtained from Tri-City Airport (located 20 km WSW of Bay City) after wind speeds were adjusted to make them more consistent with the generally higher speeds measured at the lighthouse. The adjustment procedure followed was to average the speeds recorded for 1 week prior and 1 week after the gap in the record at both the lighthouse and the airport and adjust the airport speed during the record gap by the observed ratio of speed difference.

4. RESULTS

4.1 Drogues

Since most of the inner bay was too shallow for current meter moorings, the drogue studies were concentrated in this area. The results are plotted on figs. A. 1 through A. 13. During 25 days on the bay, 117 drogues were tracked for an average of 5 hr each. The average speed for the drogues was 6.7 cm s^{-1}. The speeds in several areas of the bay varied considerably from this average. Near Point Lookout, where the channel has its narrowest constriction, the average speed was 10 cm s^{-1}. The water entering or leaving the bay was apparently funneled through this constriction, causing the higher speeds. The water in the southeastern section of the bay was nearly stagnant, with average speeds less than 4 cm s^{-1}. This is the same area where the highest ion concentrations were reported by Beeton, et al. (1967). In the central part of the inner bay the speeds were typically slower in the channel (average speed 6.2 cm s^{-1}) than in the shallow water areas on either side (average speed 8.8 cm s^{-1}).

All of the drogue panels were set at a depth of either 2 m or 5 m. There was no appreciable difference between the average speeds measured at the two levels. One exception to this was on 6 June (fig. A. 1), when the speed measured at the 2-m level was more than twice the speed at the 5-m depth. There was also a difference in direction between the two levels of approximately 30°. The reason for the difference was bottom friction, as the water was only 7-m deep and the 5-m drogue was deep enough to be in the region where the bottom effects were important. Only on that day were drogue panels set that close to the bottom.

Since it was not possible to do a synoptic survey of the entire bay, the drogue data were compiled to present on one chart observations made during similar wind conditions in various parts of the bay. This provided a reasonably accurate picture of the circulation of the inner bay for two prevailing wind directions. The transects from 6 June, 8 June, 14 June, 21 August, and 22 August are plotted on fig. 2. The wind was out of the southwest during all of these days. The results show that the circulation

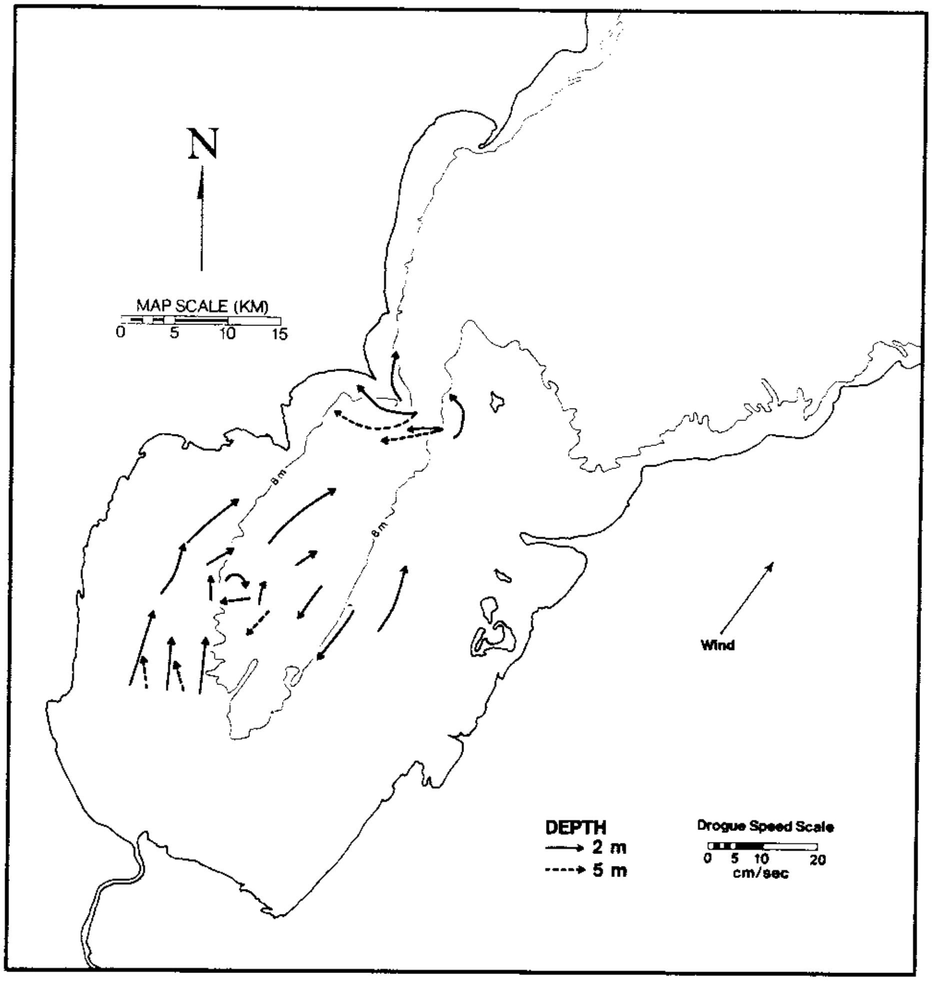

Figure 2. Compilation of drogue tracks for a southwest wind from 6 June, 8 June, 14 June, 21 August, and 22 August.

is characterized by a clockwise gyre in the western portion of the inner bay (fig. 3). The water in the shallow eastern area flows in the same direction as the wind and enters the outer bay between Charity Island and Oak Point. There is a well defined return flow in the channel past Point Lookout which fans out somewhat as it enters the inner bay. The Saginaw River water enters from the southwest and mixes with the bay water. Some of the river water then branches off into the western portion of the bay, but most of it flows into the shallow eastern area, causing the high ion concentrations reported by Beeton et. al. (1967).

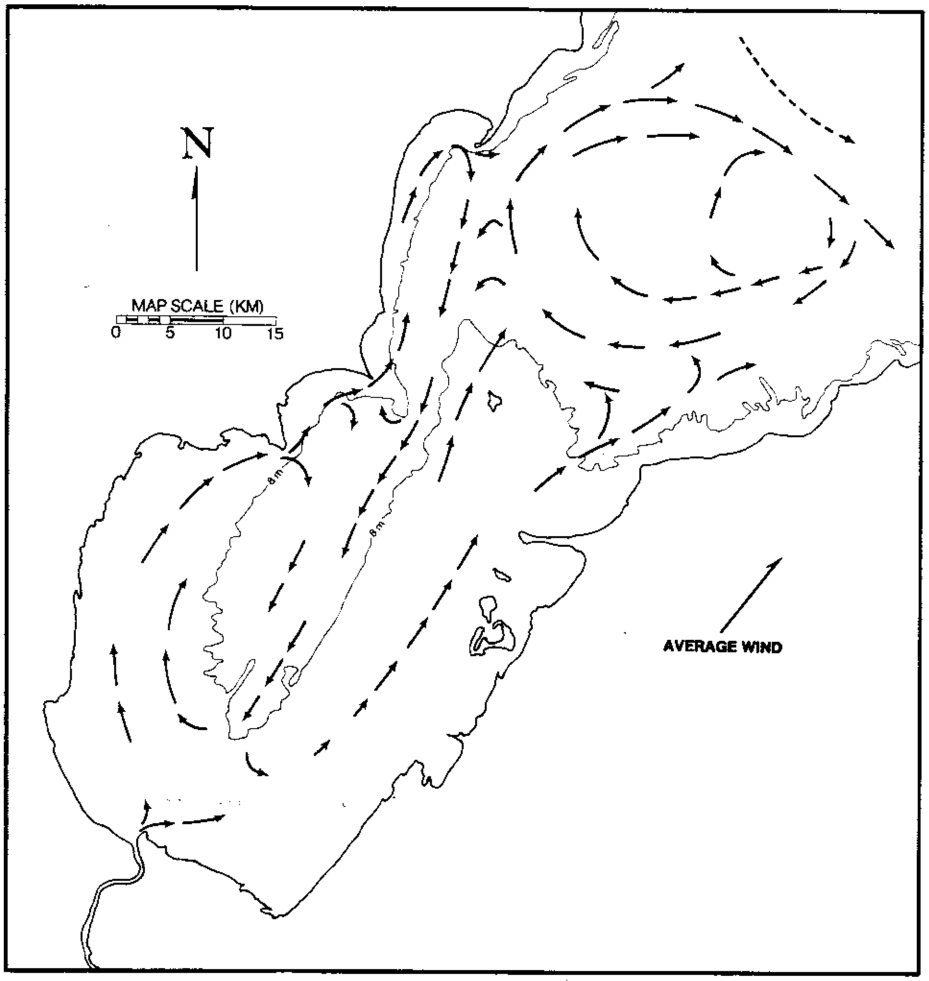

Figure 3. Circulation pattern for a southwest wind.

The wind was usually out of the southwest, but there were a few occasions of northeast winds during the Lagrangian current studies. The drogue tracks for these days, 23 August, 28 August, and 12 October, are plotted on fig. 4. An average velocity was also computed from meter 9A for these 3 days and the result plotted on the same figure. From this data

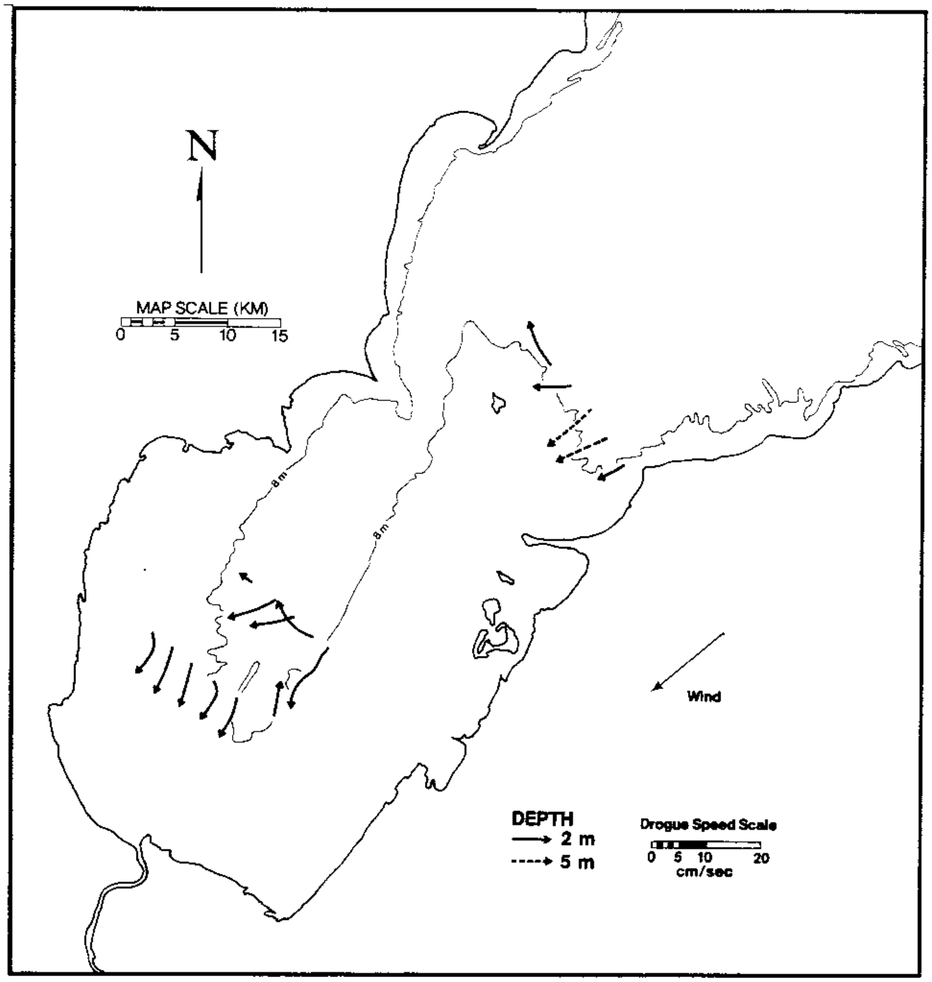

Figure 4. Compilation of drogue tracks for a northeast wind from 23 August, 28 August, and 12 October plus average velocity vector from meter 9A.

the circulation driven by a northeast wind was determined and plotted on fig. 5. The flow is characterized by a counterclockwise gyre in the western inner bay. The water enters along the eastern shore between Charity Island and Oak Point and flows out in the channel past Point Lookout. The circulation pattern is similar to that for a southwest wind except that the current directions are just reversed.

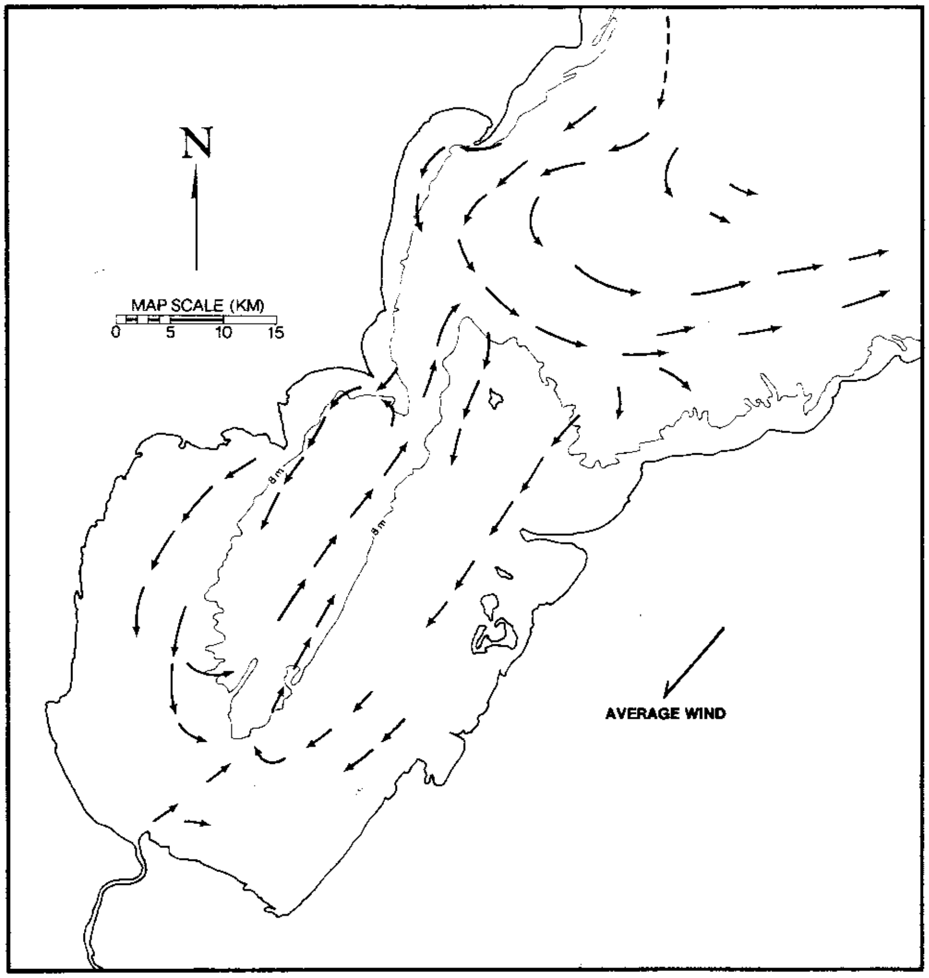

Figure 5. Circulation pattern for a northeast wind.

On 22 August (fig. A. 6) the drogues were deployed across the channel near Point Lookout. The wind was out of the southwest with an average speed of 5.8 m s^{-1}. Drogue panels were set at both 2 m and 5 m, making it possible to estimate the vertical profile of horizontal velocity and to compute the volume of water entering the inner bay. The estimated transport was 3700* m^3 s^{-1} or 37 times the average flow of the Saginaw River. Since the volume of the inner bay is about 8.5 x 10^9 m^3, it would take only 26 1/2 days for this flow to fill the inner bay.

It was also possible to estimate the volume of return flow in the channel from the drogue tracks of 14 June (fig. A. 4). The wind was again out of the southwest with an average speed of 5.0 m s^{-1}. The estimated return transport was 7100 m^3 s^{-1}. This is larger than the previous estimate, but this transect was further south and much of the transport was due to the recycling of water from the shallow western region as illustrated in fig. 3.

The highest speeds were recorded during a storm on 26 August (fig. A. 7), with wind again out of the southwest. The drogues were deployed in the channel and were in the region of the return flow, therefore moving into the wind. Speeds of over 30 cm s^{-1} were measured, which represents a return transport of 18,600 m^3 s^{-1} through this section of the channel. The speeds and transports measured may have been even higher because the drogue movements were no doubt somewhat impeded by the strong wind.

On several days the wind changed rather abruptly and became steady out of the southwest. This presented an opportunity to examine the response of the bay to sudden wind changes. The typical response is that in all areas of the inner bay the water initially moves with the wind. After approximately 8 hr a return flow developes in the central channel of the bay. Of course residual currents and the intensity of the wind affect the circulation and lag time before a return flow developes and a new equilibrium state is established, but the above results seem typical for a southwest wind. On 12 June (fig. A. 3) and 8 October (fig. A. 11) the water in the shallow western section of the inner bay reacted to the wind change by moving in the same direction as the wind. The easternmost drogue on 12 June, though, had a much smaller velocity than the others. It was launched in the channel and its progress was retarded by the development of the return flow. On 29 August (fig. A. 8) the magnitude of the wind was small, but the development of the return flow could be seen along the eastern edge of the channel. On 20 August (fig. A. 5) the flow could actually be seen reversing directions. The wind became southwesterly about 0200. The current initially followed the wind, but between 1000 and 1100 the flow reversed directions. Thus it took 8 to 9 hr for the return flow

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* Transports and volumes referred to in this section have been calculated using the 1-m stage existing during the period of investigation. Physical dimensions referred to in the introductory section were scaled from lake charts giving depths relative to the International Great Lakes Datum (1955).

to develop. The magnitude of the bay wind was rather weak, however, and a stronger wind would have caused the bay to fully respond more rapidly. Still this estimate agrees well with some of the previous work on the bay (Johnson, 1958; and Allender, 1975).

Conductivity and chloride were measured at 5-min intervals enroute to and from the drogue transects during most of the Lagrangian current studies. The data collected, however, were not sufficient to trace the water masses in the bay. Because of the rapidly changing circulation patterns in the bay, samples taken on one day could not be correlated with previous days' measurements. In order to determine flow patterns with chemical analyses, a survey of the entire bay must be completed in a single day unless the study can be conducted during a period of relatively constant wind. The data collected, however, show a sharp gradient with values highest near the Saginaw River. The conductivity is twice as high near the mouth of the river as the overall average of the bay. The values in specific areas of the bay varied considerably from day to day, but no general trends were apparent.

4.2 Current Meters

Since most of the inner bay was too shallow for current meter moorings, most of the meters were deployed in the outer bay (see fig. 1). Histograms of current direction are used to display the data. The histograms were constructed by sorting the current direction into 40° sectors. The percentage of data points falling into each sector was computed and the average speed for each sector was calculated. The average speeds were divided into three categories: low (<8 cm s^{-1}), medium (8 to 15 cm s^{-1}), and high (>15 cm s^{-1}), and the results are displayed on the histograms. Monthly histograms were computed for all of the meters and are shown in Appendix B. A similar summary of wind data for each month is given on the same figures. Histograms of current direction for the entire recording interval were also computed and are shown in fig. 6.

The average speed computed for all the current meter data was 10.6 cm s^{-1}. The highest averages were recorded by meter 6B (13.7 cm s^{-1}) and meter 5A (13.0 cm s^{-1}). These two meters were located near the division between the inner and outer bays. The only meter in the inner bay (meter 9A) recorded an average speed of 7.9 cm s^{-1}. The speed recorded at the 30-m level near the mouth of Saginaw Bay averaged only 7.7 cm s^{-1} (meters 2C and 3C). The direction measured at the 30-m level was much more stable than the direction recorded closer to the water surface. This indicates that the flow along the bottom near the mouth is rather slow and relatively free of turbulence. Meter 6B, on the other hand, is located in an area of high turbulence. Large fluctuations in direction and a high variance calculated for the velocity components plus large amounts of energy in the high frequency range of computed power spectra (discussed in the next section) indicate that this is an area of strong turbulence. This meter is located near the division of the inner and outer bay. Apparently the water from the inner region mixes with the water in the outer bay in this area and causes these highly variable currents.

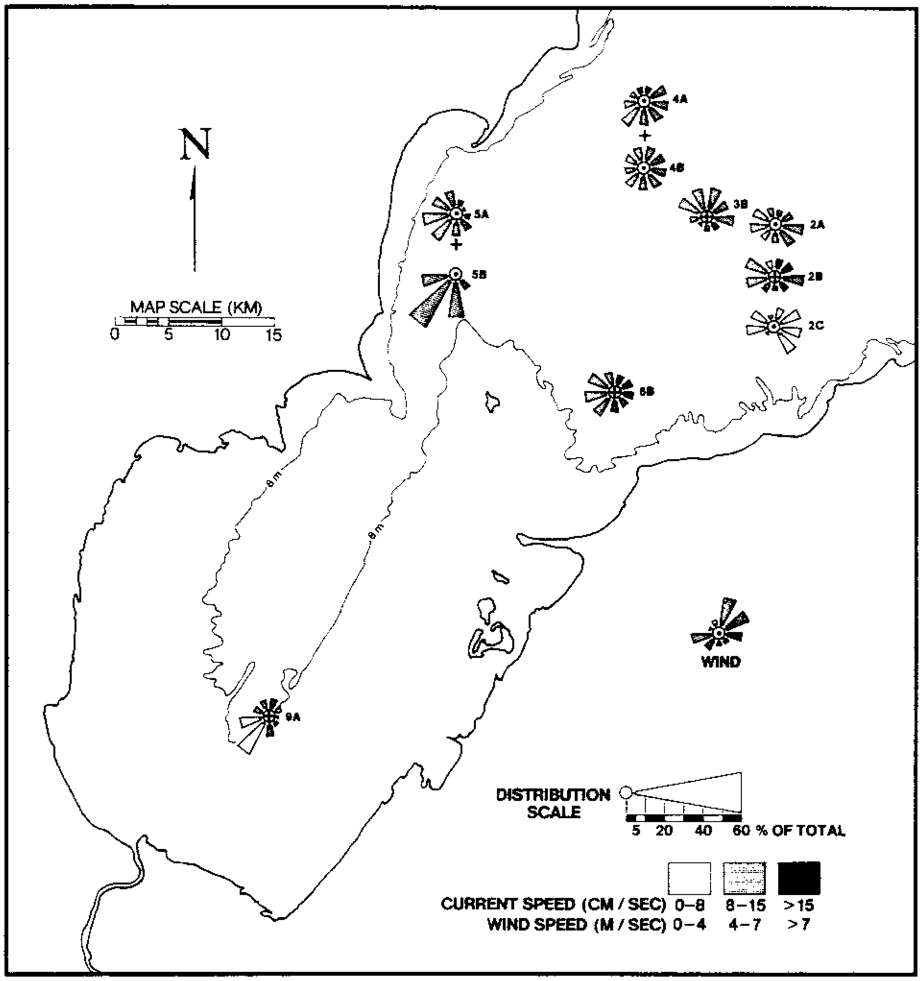

Figure 6. Histograms of current direction for the entire period of study.

Histograms computed for the entire length of the current meter records (fig. 6) show the high variability of the flow, with the current direction for some of the meters almost equally distributed around the compass. This is due not only to the variable winds, but also to the importance of inertial currents in certain parts of the bay. Meter 9A, though, shows a very consistent flow to the southwest. The prevailing wind is out of the southwest, causing a return flow to move down the channel past meter 9A and producing the prominent flow in this area. Meter 5B shows a strong southwest flow near the mouth of the channel because it is in the zone of return flow for southwest wind and in the inflow to Saginaw Bay from Lake Huron during northeast wind.

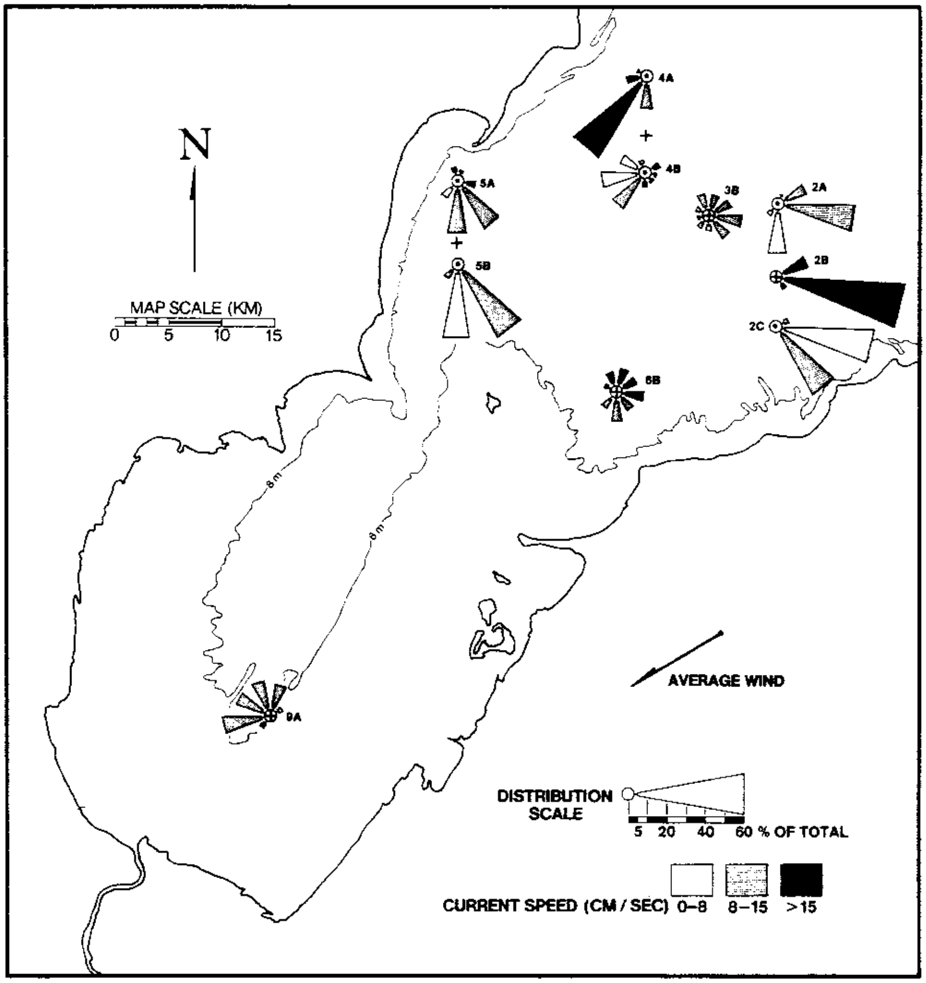

Figure 7. Histograms from 22-27 June -- northeast wind.

Since the currents are so highly dependent on the local winds, the character of the bay circulation during several meteorological events was examined. Histograms of current direction were computed for periods when the wind was relatively constant for at least 2 days. Since the two predominant wind directions during the summer of 1974 were out of the southwest and out of the northeast, the response of the bay to winds from these directions was analyzed. On 22-27 June and 20-22 July the wind was constant out of the northeast. The histograms for these periods were plotted on fig. 7 and 8, respectively.

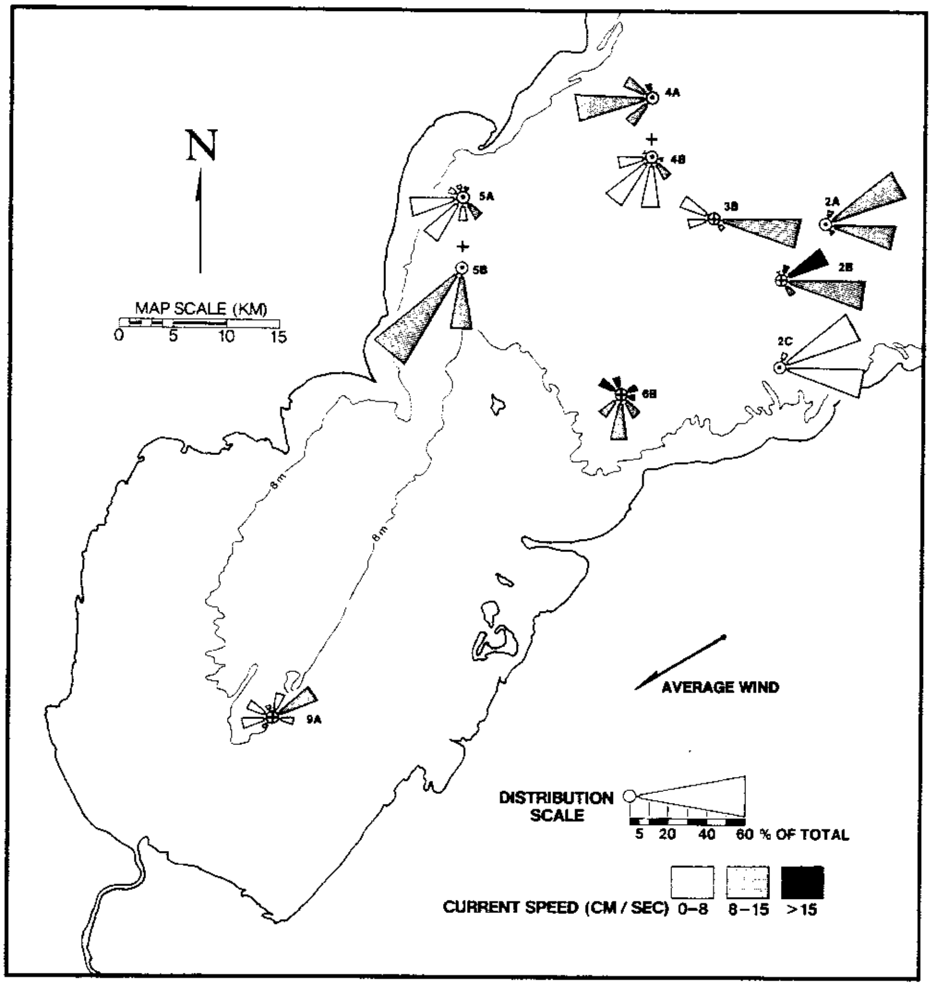

Figure 8. Histograms from 20-22 July -- northeast wind.

The results for the two episodes are quite similar. The flow in the outer bay is characterized by a counterclockwise gyre; water enters the bay at the northern edge of the mouth, flushes through the outer bay, and flows back into Lake Huron along the southern part of the bay mouth as indicated by the histograms at site 2. An illustration of this pattern, plus the circulation derived from the drogue results for a northeast wind in the inner bay, is shown in fig. 5. The vectors on this illustration represent a vertically averaged horizontal velocity.

On 20-22 August and 3-5 October the wind was constant out of the southwest. The histograms for these periods are plotted on fig. 9 and 10. The results from these episodes are markedly different from those computed for a northeast wind. The flow from Lake Huron enters the bay through the southern part of the mouth. The water flushes through the outer bay in a clockwise sense and flows out along the northern edge. This circulation pattern, plus the flow pattern determined from the drogue results for a southwest wind, is illustrated in fig. 3. As noted earlier, the flow past site 5 is usually to the southwest under both wind conditions, influenced more by the gross circulation and geometry of the bay than by the direct influence of the local winds.

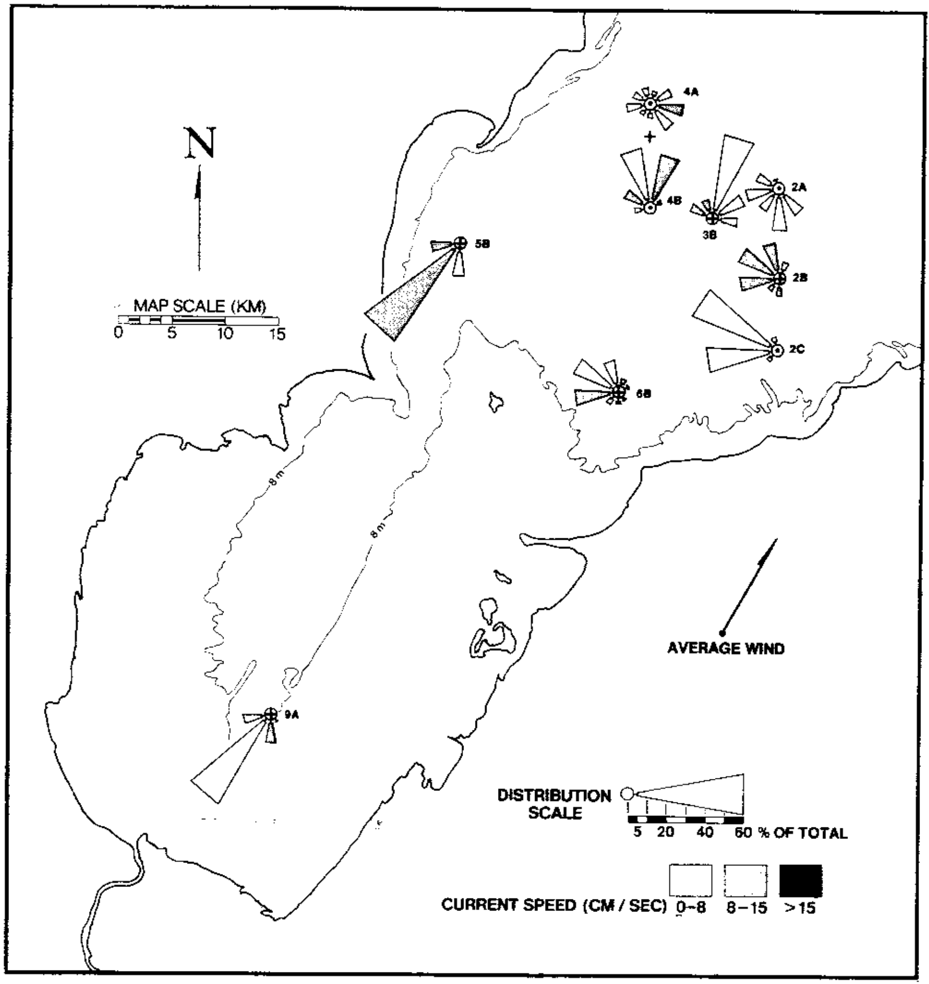

Figure 9. Histograms from 20-22 August -- southwest wind.

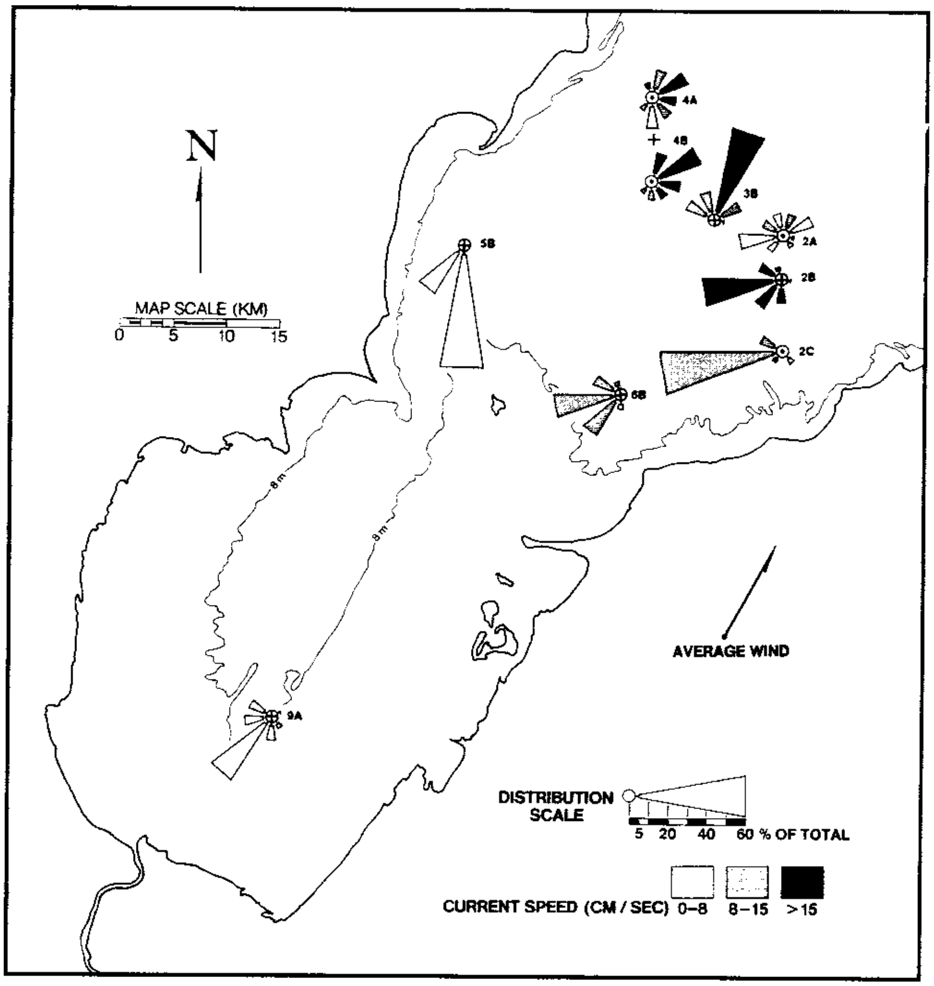

Figure 10. Histograms from 3-5 October -- southwest wind.

4.3 Power Spectra

Spectra were computed for both the east-west and north-south velocity components. The fast Fourier transform (FFT) method was used to obtain the spectral estimates. The u and v components of the velocity time series for each meter were divided into subsets of 256 data points in length. The subsets were linearly detrended and tapered at the ends. Overlapping data subsets for each meter were then transformed and the power spectra ensemble averaged. This result was smoothed by the Hanning method, and spectral estimates for the entire time series were obtained. Frequently several points were averaged together before transforming to give better resolution in the low frequency range. Several of the spectral estimates are shown in Appendix C.

The most prominent spike in the power spectra was found near the inertial frequency. The inertial period in Saginaw Bay varies from 17.33 hr in the southern part of the bay to 17.18 hr near the mouth of the bay. An energy density peak is centered at approximately 17.1 hr on the spectral estimates. The energy spikes are greatest for meters near the mouth of the bay where the water was just over 30-m deep. At times the flow is almost purely inertial as illustrated by the progressive vector plot from meter 2B shown in fig. 11. There are still significant amounts of energy near the inertial period at sites 5 and 6 even though the water is only 15-m deep. At site 9 the water depth is less than 8 m and the energy peak at the inertial frequency is very small though still noticeable.

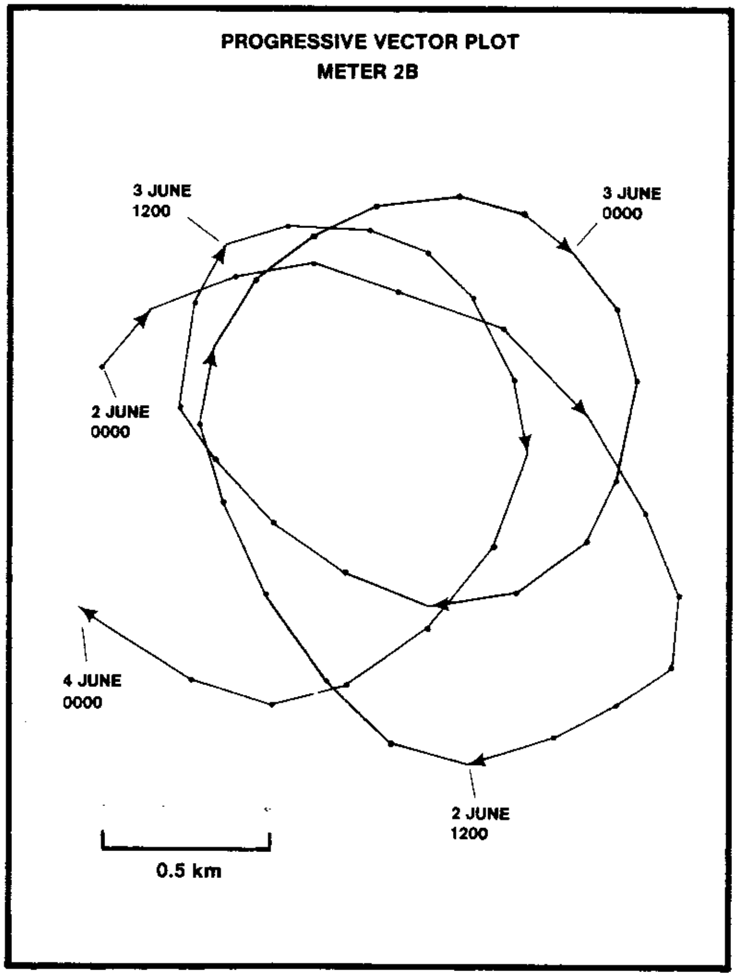

Figure 11. Progressive vector plot of data from current meter 2B showing 17.1-hr inertial period.

Several of the meters show energy concentrations at various other frequencies. There are energy peaks in the 13.5 to 14.0 hr range. These peaks are especially noticeable in the data from meters 4B, 5A, and 9A and are usually strongest in the east-west component. Allender (1975) also found an energy peak near the 14-hr period in spectra computed from water level records on the bay. As of now the cause of this energy concentration is unknown.

Several of the spectra show energy concentrations near 11.1 and 9.7 hr. The first mode of Saginaw Bay as calculated by Rockwell (1966) is 10.0 hr. His work did not include frictional effects, and the water level in the bay was significantly greater during this study than depths used by Rockwell from lake charts. Since deeper water would decrease the period of oscillation and the inclusion of frictional effects would tend to increase the estimated period, either of the above peaks may be due to the bay's first mode. It is difficult to determine which is the dominant correction without further numerical work. The primary longitudinal mode of Lake Huron is near 6.5 hr. Several of the spectra show energy near this period though not at significant levels. Other frequencies containing energy concentrations are the lunar semidiurnal tide near 12 hr and the diurnal wind response at 24 hr.

The higher frequency oscillations in the bay were also examined. Since the sampling interval was 30 min, the period corresponding to the Nyquist frequency was 1 hr, so periods shorter than this could not be examined. The results show that there is no significant energy concentration in the currents in any frequency band with a period below 5 hr (fig. C.6 and C.7). The spectrum from meter 6B does show several spikes; however, none of these appear on the spectra from the other meters.

5. CONCLUDING REMARKS

The currents in Saginaw Bay are quite variable and highly dependent on the local winds. The inner bay circulation is especially susceptible to wind changes. The circulation patterns in the inner bay, though, are predictable for winds out of the southwest or northeast, as a stable pattern develops in approximately 8 hr after a wind shift. The circulation pattern in Saginaw Bay driven by a southwest wind is shown in fig. 3, and the circulation pattern driven by a northeast wind is shown in fig. 5. Since wind from directions just slightly different than these will cause only small perturbations to the flow field, as revealed during several of the drogue tracking intervals, it is felt that the two circulation charts are essentially representative of wind from the southwest and northeast quadrants.

Winds blowing transverse to the longitudinal axis of the bay (i.e., from the northwest or southeast) also cause the circulation pattern to change quickly. The flow pattern seems more confused than when the wind is nearly parallel to the axis of the bay, but not enough data were collected under these wind conditions to determine a general circulation.

The outer bay responds less rapidly to wind changes and the circulation patterns are less predictable because the flow is strongly influenced by currents in Lake Huron. The predominant southerly current along the west shore of Lake Huron frequently flushes through the outer bay. A northeast wind causes this current to flow through the outer bay in a counterclockwise sense whereas the current flow past the mouth of the bay under a southwest wind and drives a large clockwise eddy in the bay. The existence of such an eddy was suggested by Ayers et al. (1956). The flow in the outer bay may be further complicated by temporal variations in the circulation pattern in Lake Huron.

The natural modes of lake surface oscillation for both Lake Huron and Saginaw Bay can be detected in the power spectra of the velocity components, but the energy near these frequencies is much smaller than that near the inertial frequency. The inertial flow is the most dominant periodic component of the circulation, especially in water over 20-m deep. At times the flow near the mouth of the bay is almost purely inertial. This demonstrates that care must be taken when doing Lagrangian measurements in water over 20-m deep. The study should last through at least one inertial period so that the effects of the inertial component can be filtered out. Energy density peaks also occur at the semi-diurnal tidal period, at the diurnal wind period, and at an unexplained period near 14 hr. There are no consistent peaks in the power spectra for periods shorter than 5 hr. Peaks in spectra from water level records were noted in previous work (Allender, 1975) for this high frequency range, but these water level fluctuations are not associated with periodic currents with enough magnitude to appear on the spectra computed from the velocity time series. Apparently these high frequency components are of small importance to the overall circulation in the bay.

6. REFERENCES

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7. APPENDIX A. DROGUE RESULTS

The average drogue speed is given by the straight line distance between the ends of the velocity vector. The shape of the vector is similar to the trajectory of the drogue though the actual distance the drogue traveled is much less than the illustrated vector. The solid line for the wind velocity gives the average wind during the study; the dashed sections give the average velocity for the two 6-hr periods prior to the study.

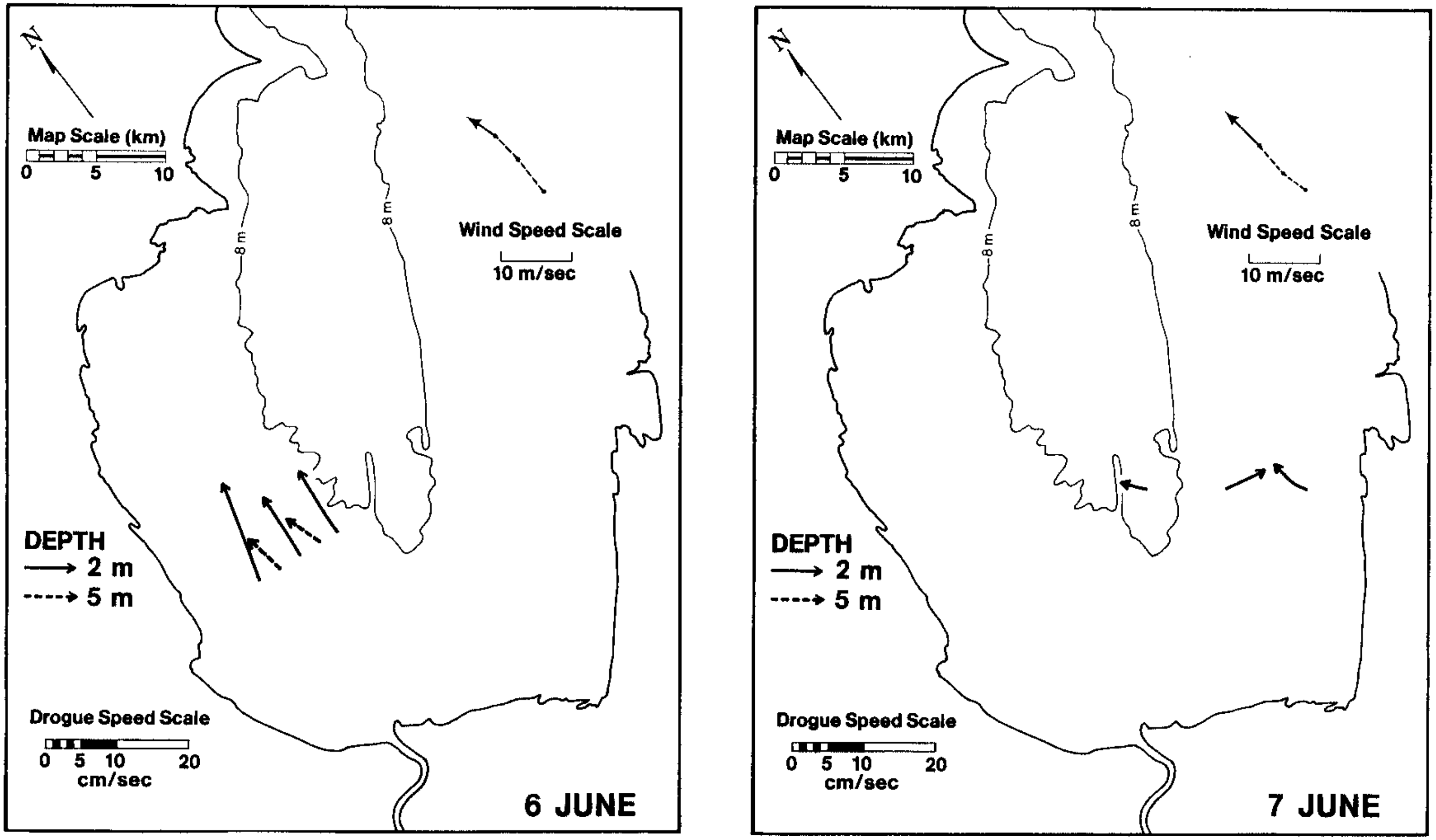


Figure A.1. Drogue results from 6 June and 7 June.

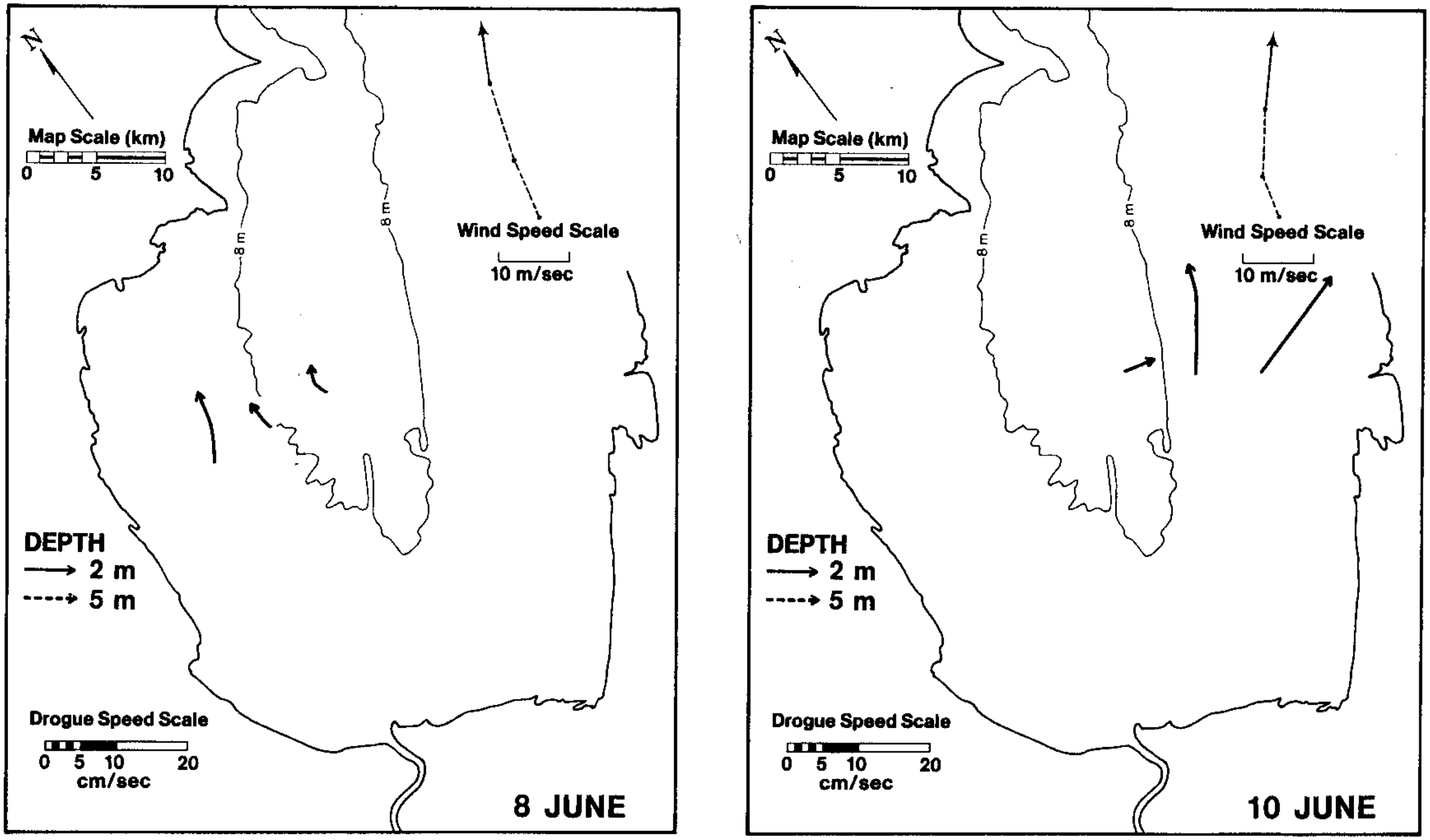


Figure A.2. Drogue results from 8 June and 10 June.

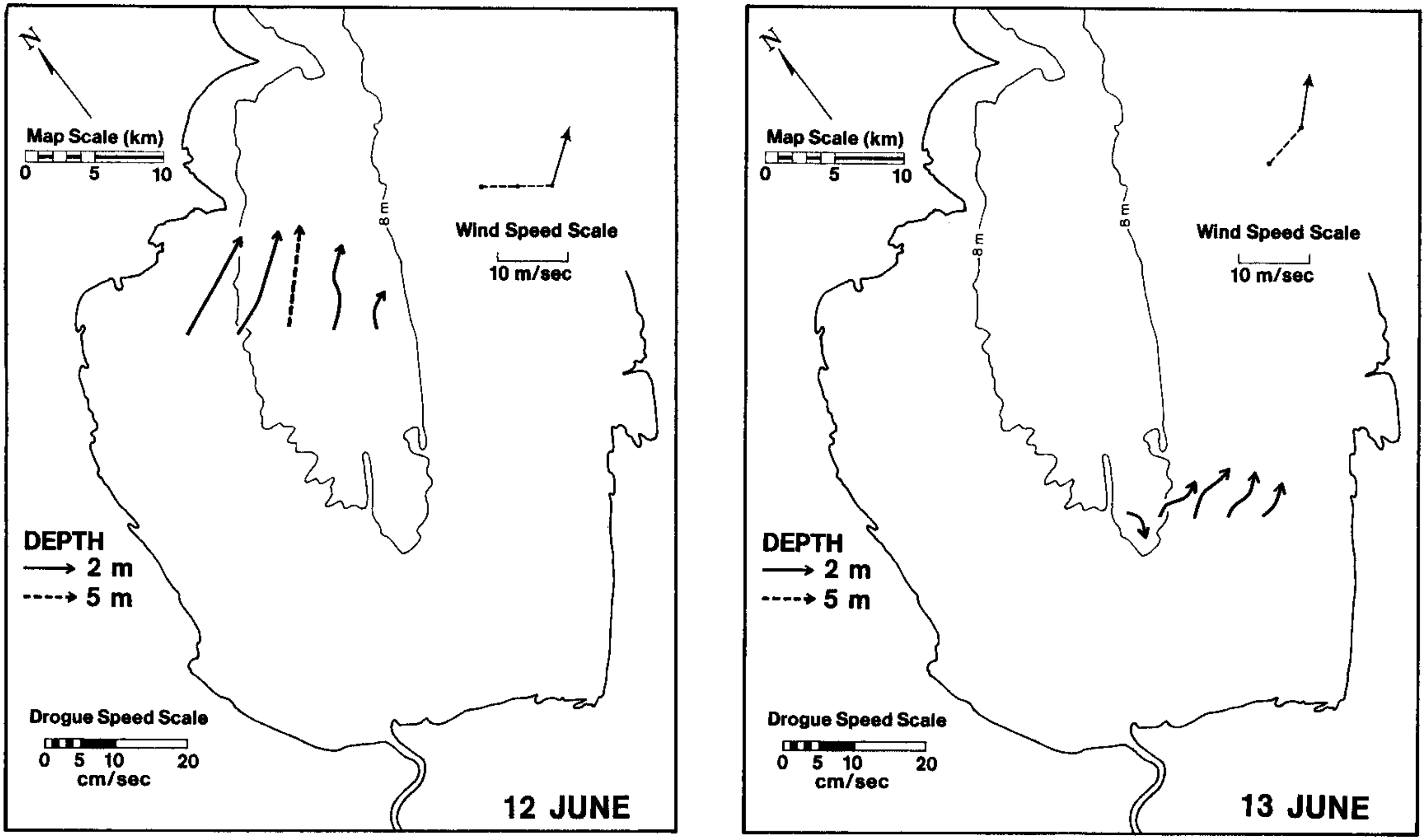


Figure A.3. Drogue results from 12 June and 13 June.

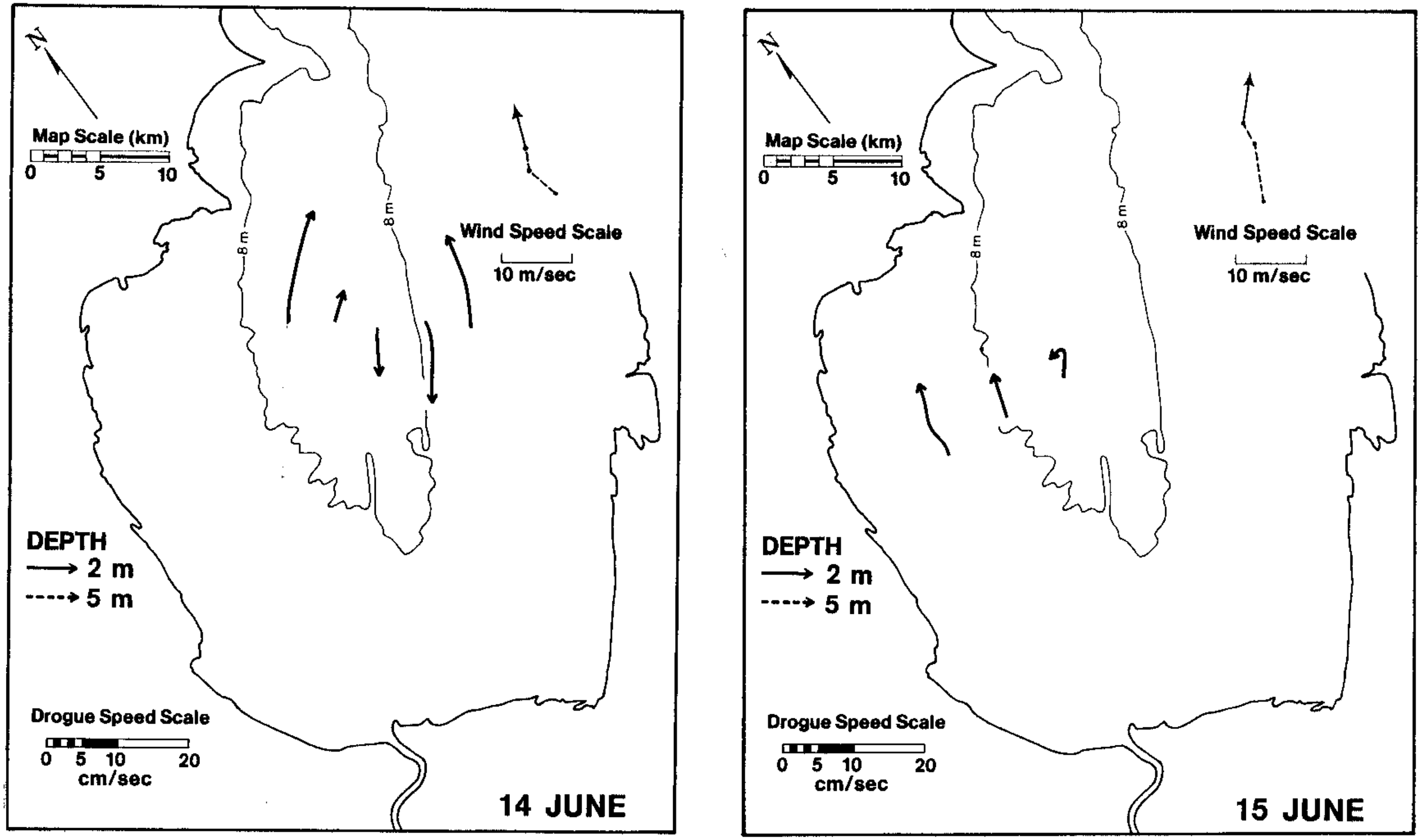


Figure A.4. Drogue results from 14 June and 15 June.

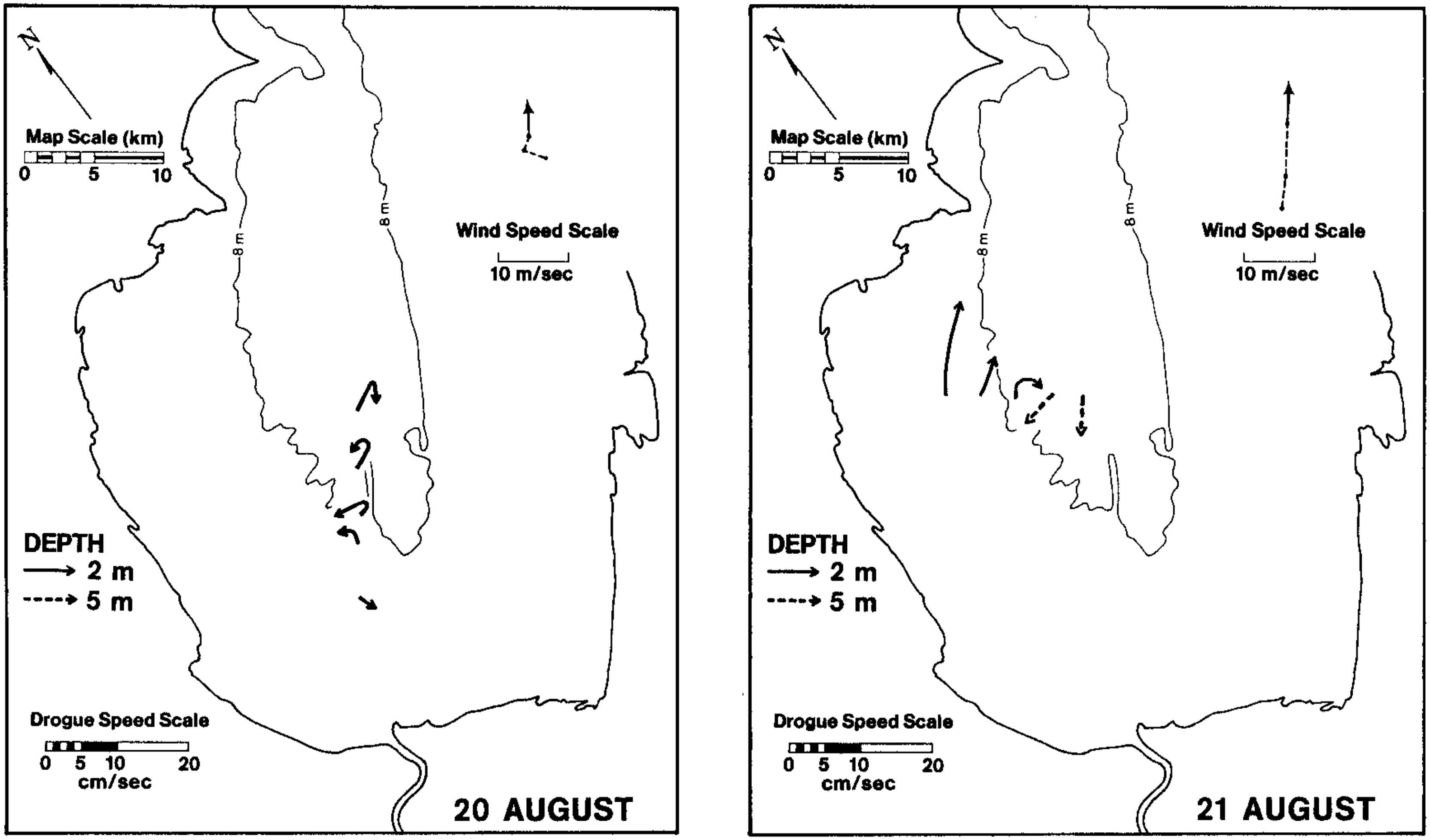


Figure A.5. Drogue results from 20 August and 21 August.

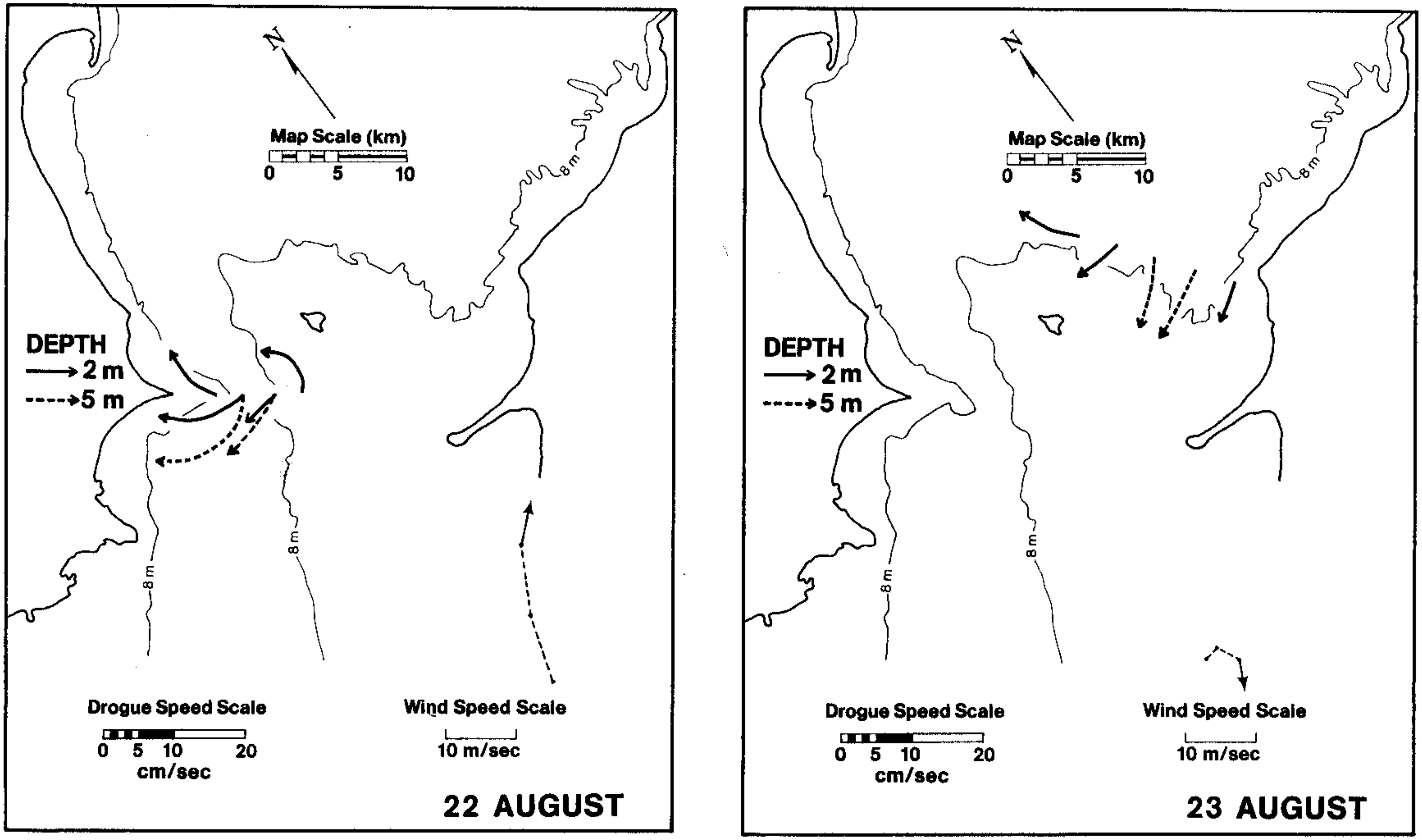


Figure A.6. Drogue results from 22 August and 23 August.

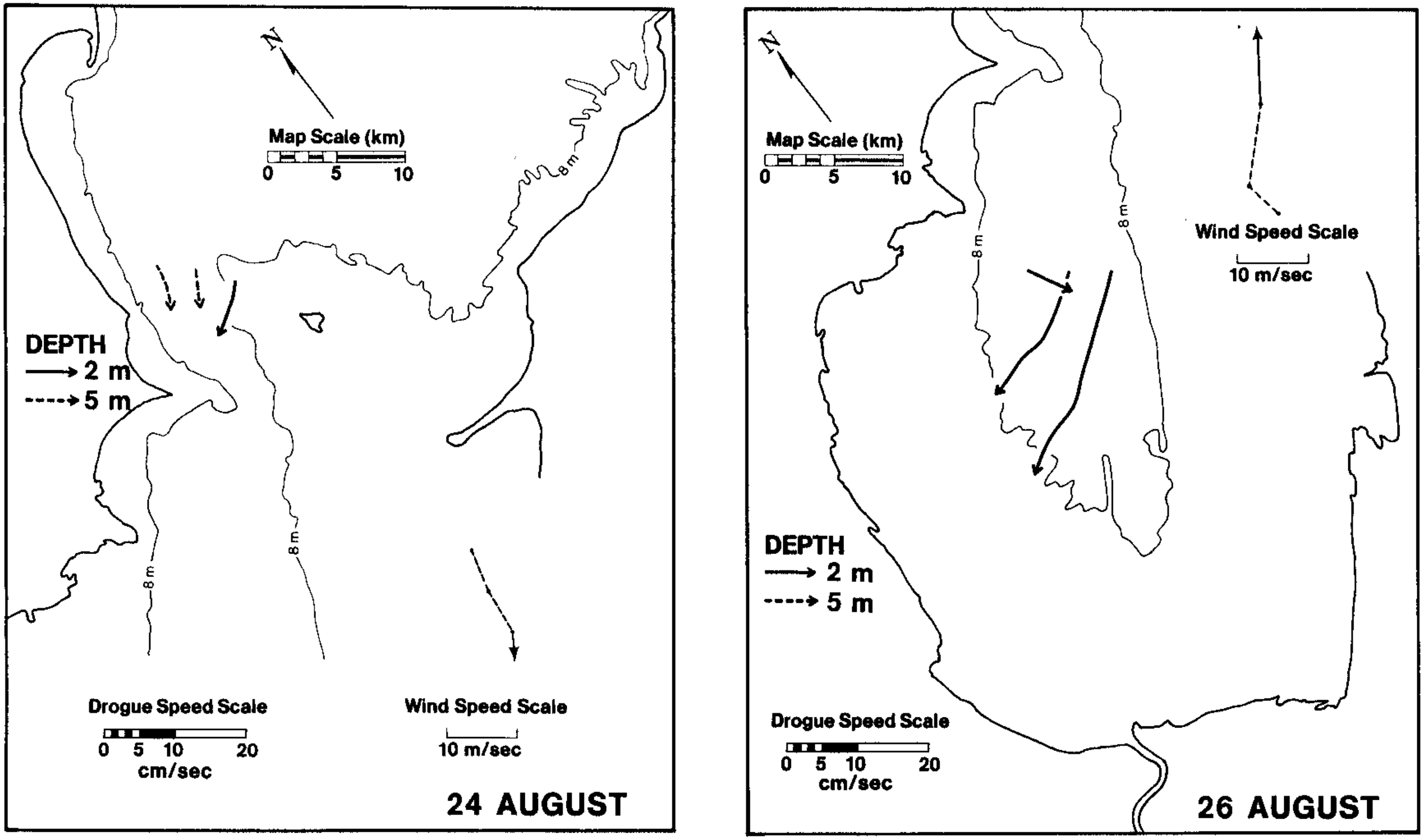


Figure A.7. Drogue results from 24 August and 26 August.

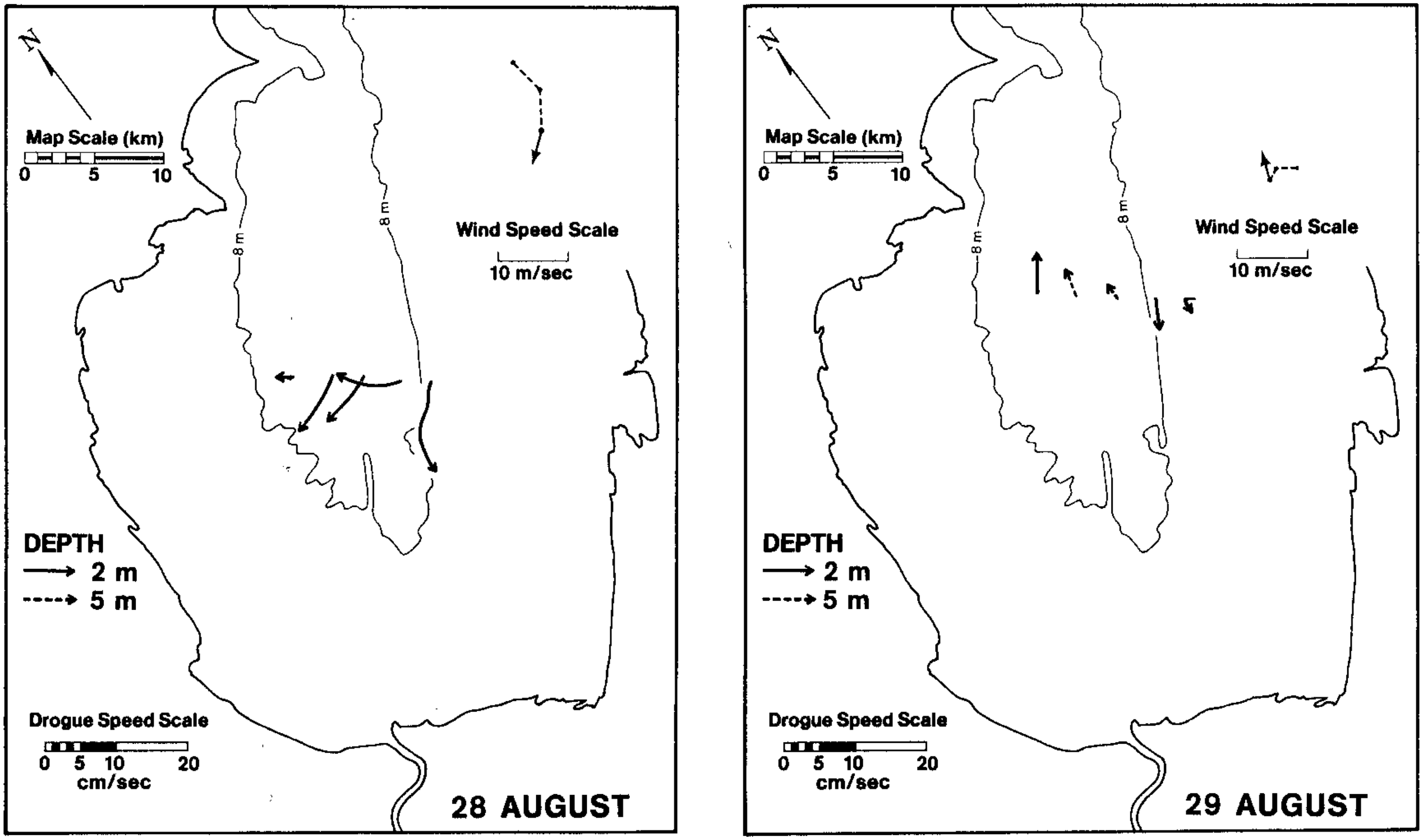


Figure A.8. Drogue results from 28 August and 29 August.

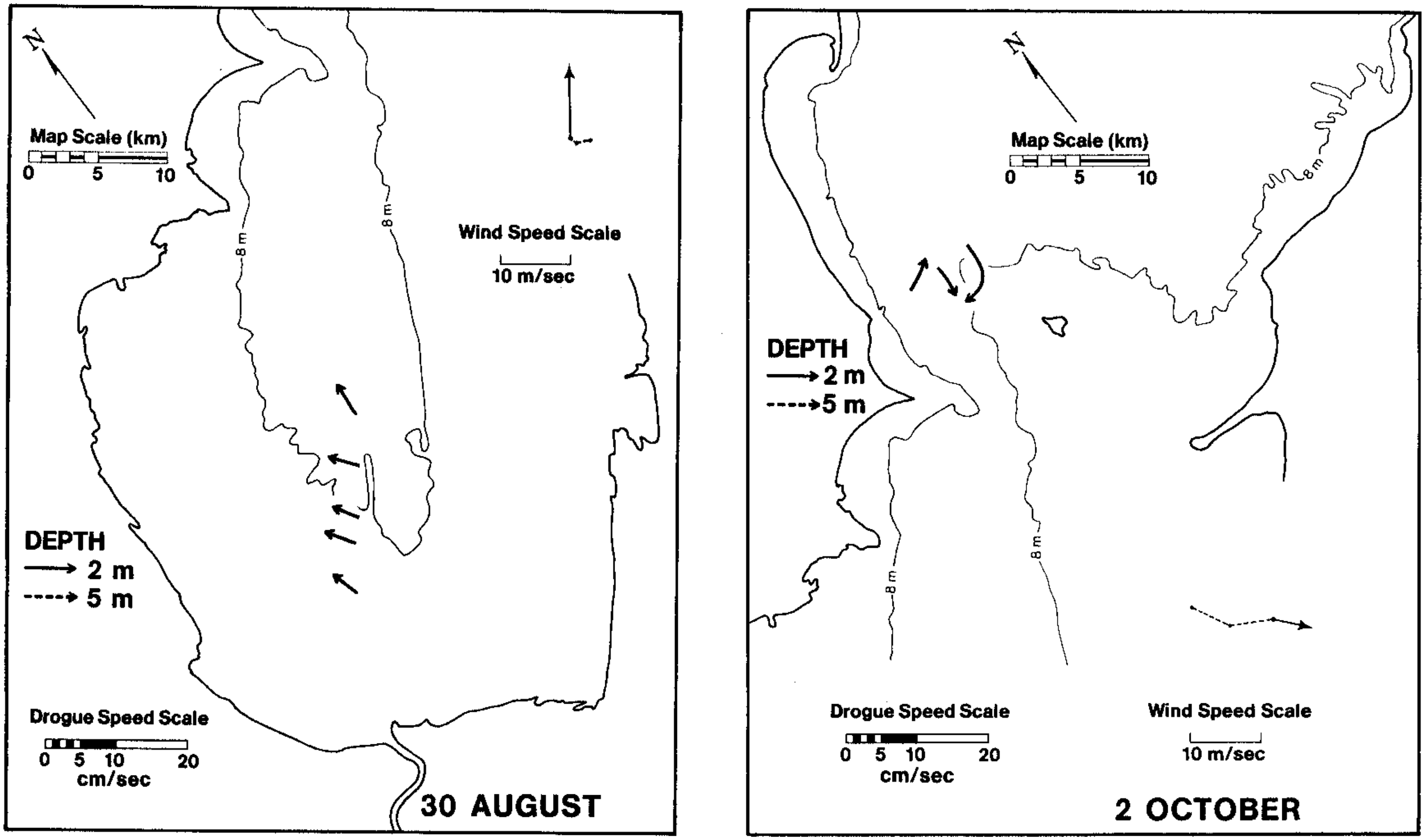


Figure A.9. Drogue results from 30 August and 2 October.

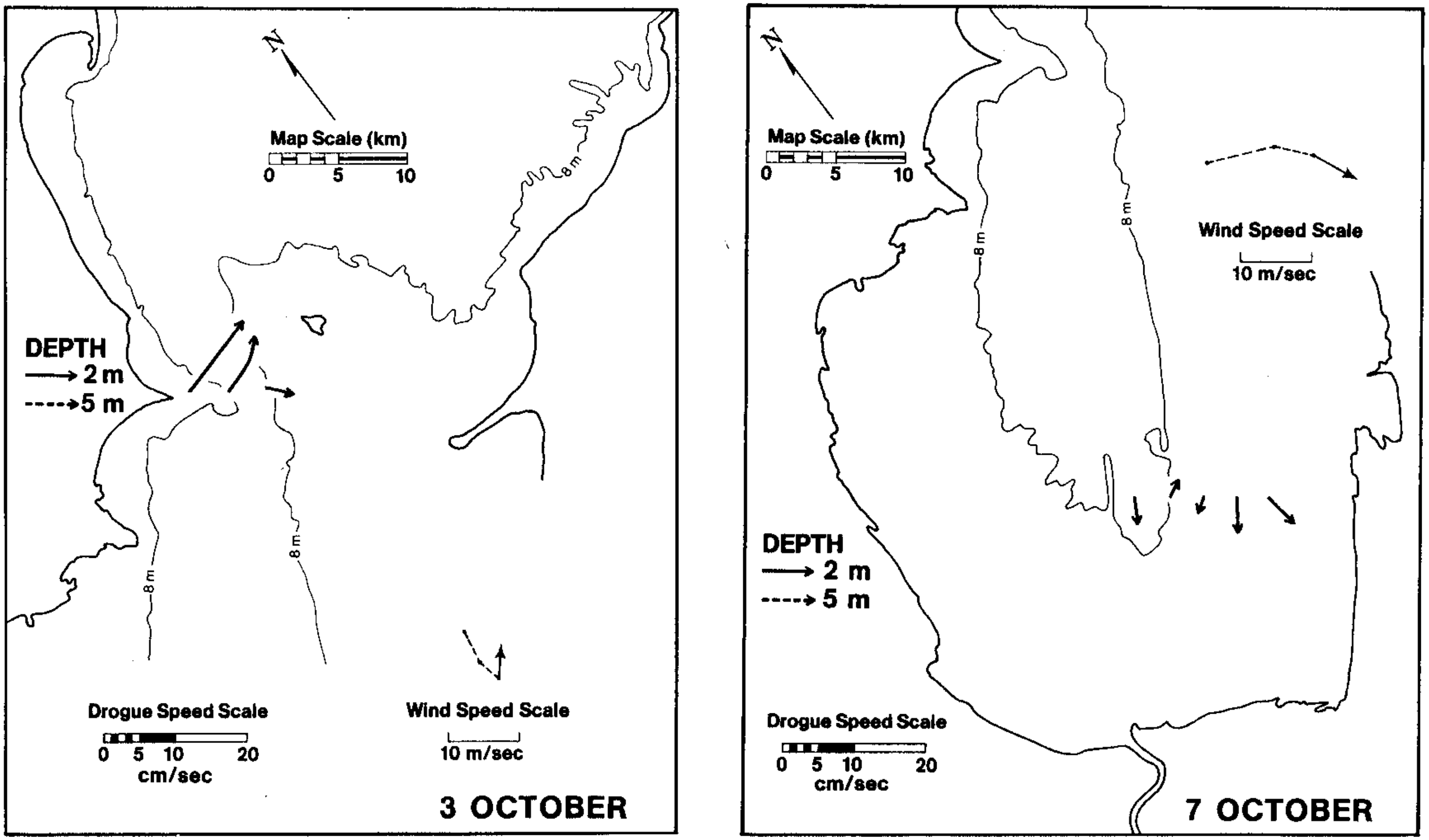


Figure A.10. Drogue results from 3 October and 7 October.

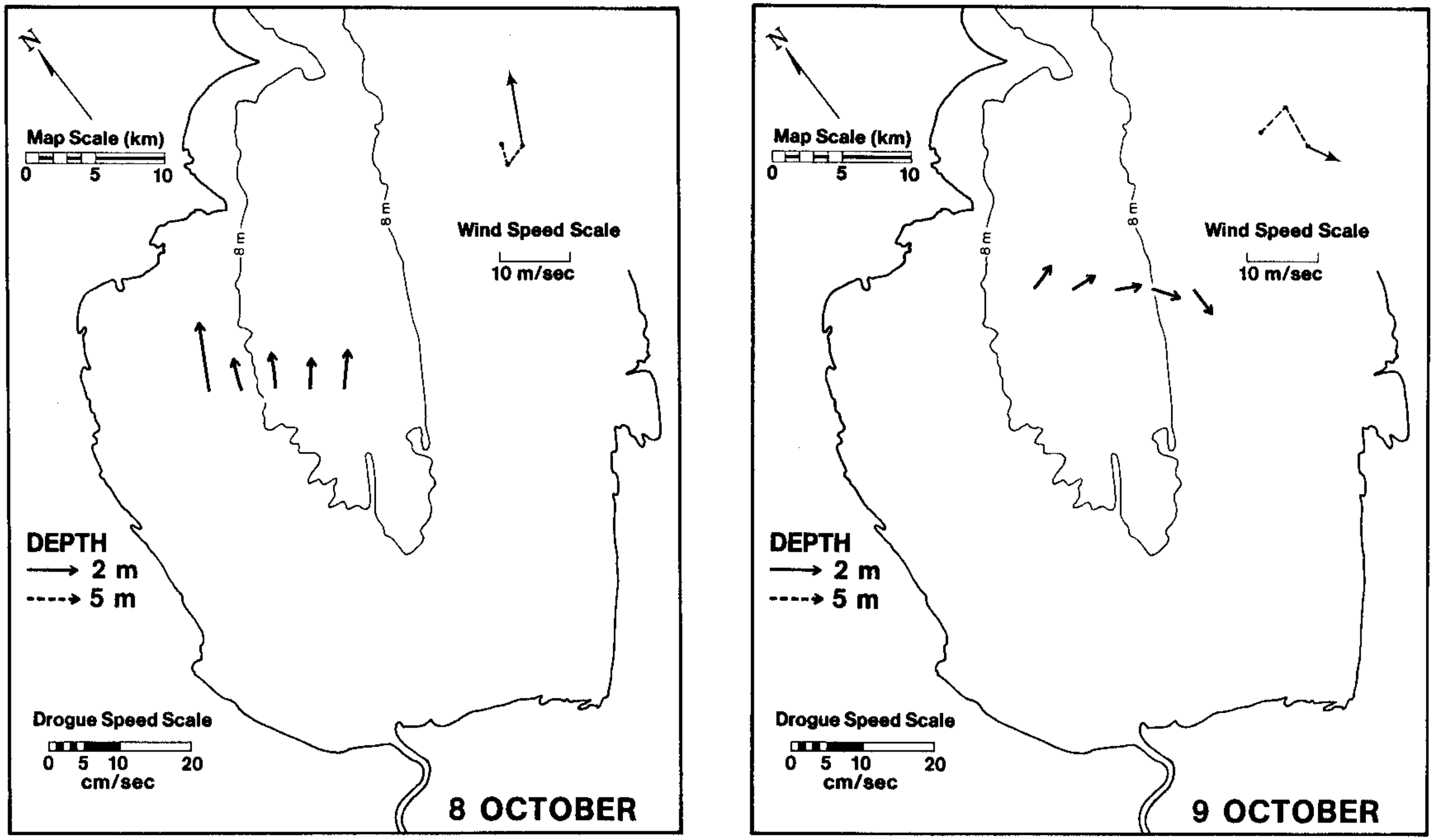


Figure A.11. Drogue results from 8 October and 9 October.

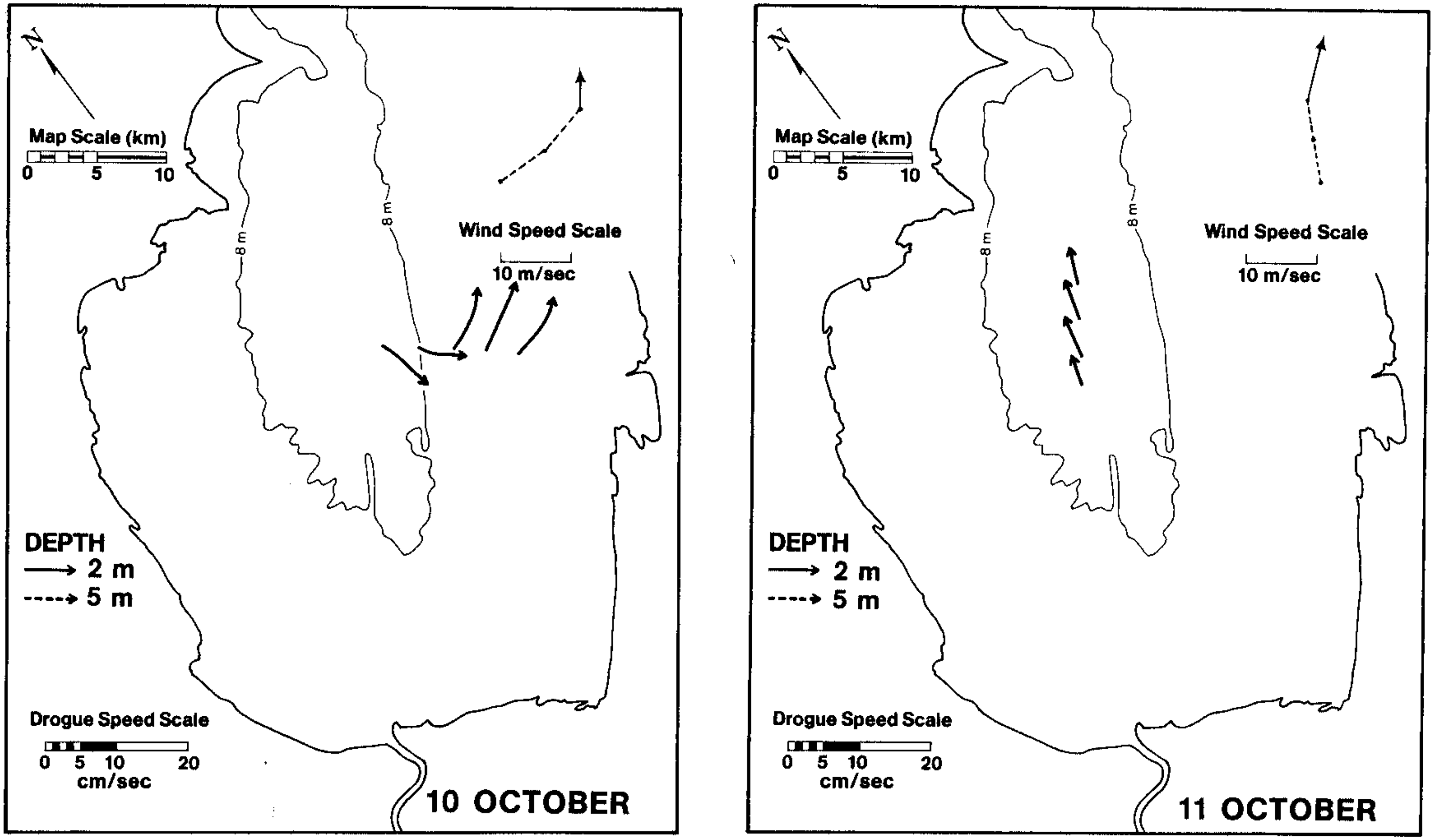


Figure A.12. Drogue results from 10 October and 11 October.

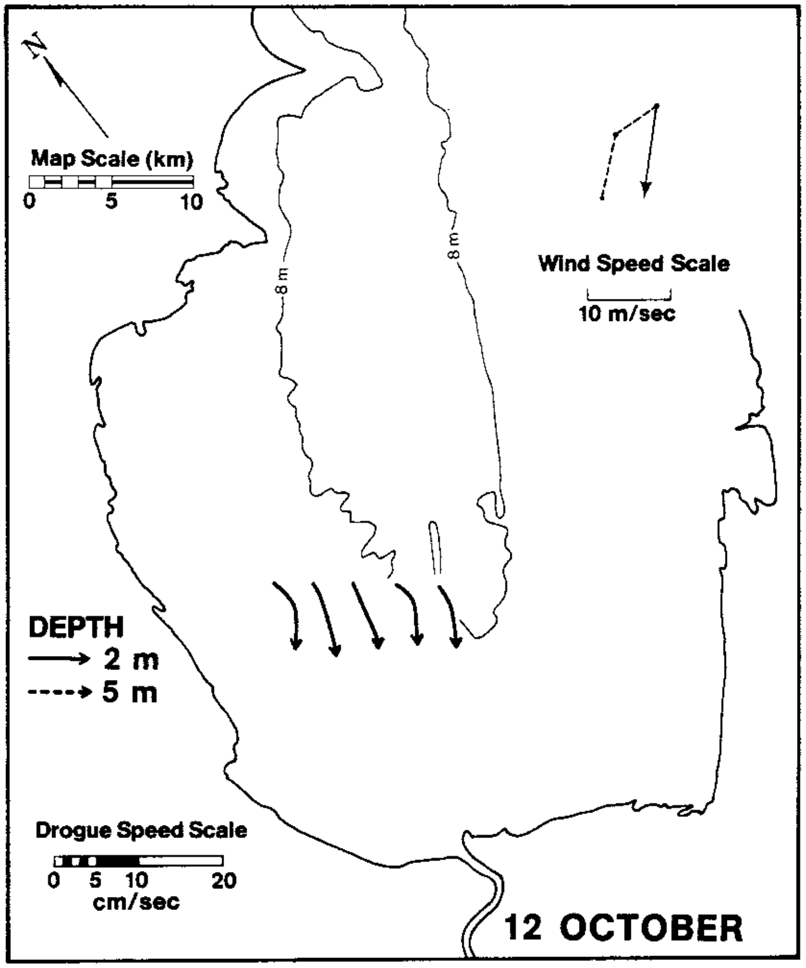


Figure A.13. Drogue results from 12 October.

8. APPENDIX B. MONTHLY CURRENT DIRECTION HISTOGRAMS

Histograms show the percentage of current meter data in each sector. Similarly, monthly wind roses are given showing the direction toward which the wind was blowing (i.e., to be consistent, the oceanographic convention was also used for the wind direction so that a wind out of the north was plotted in the south sector).

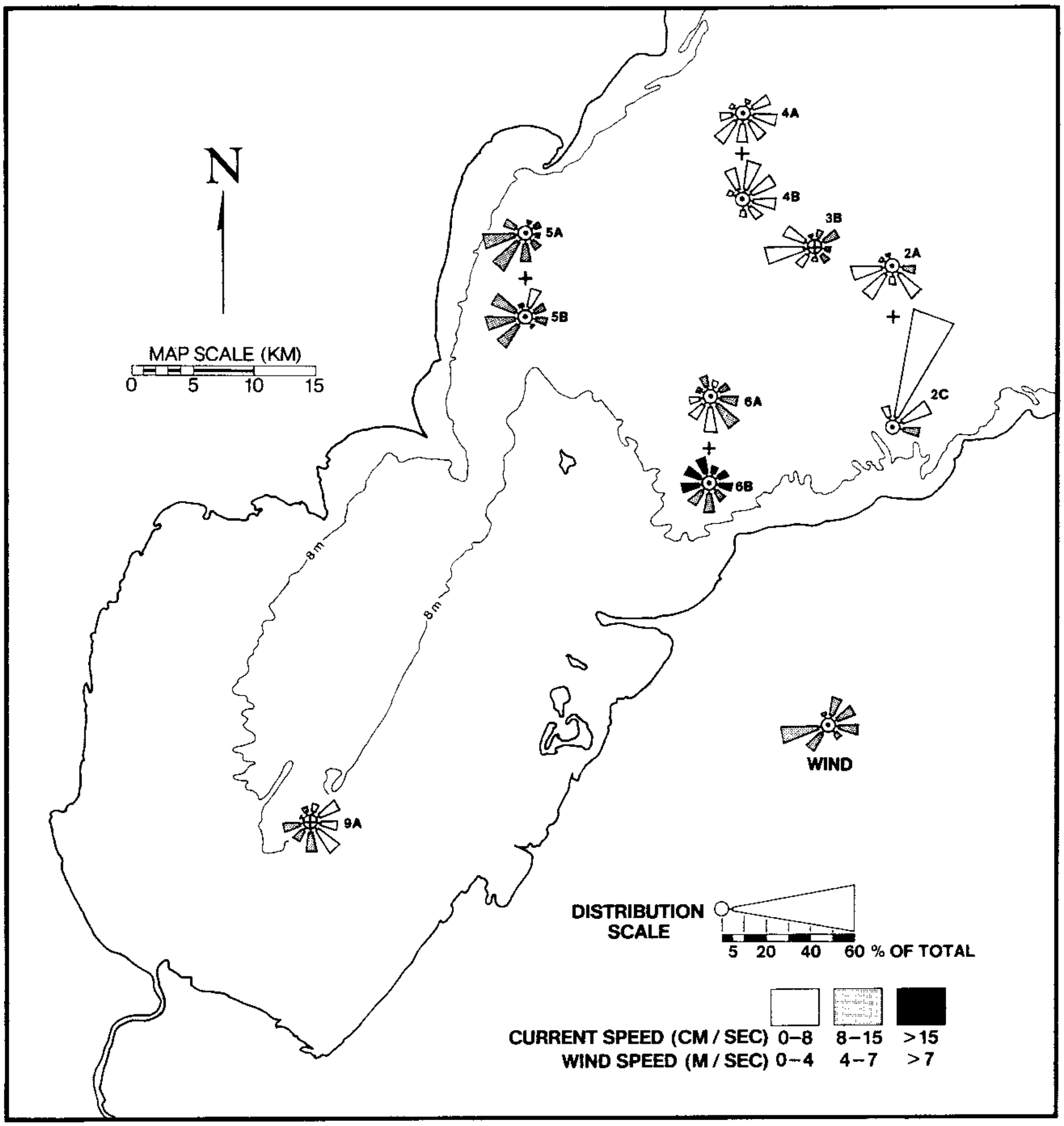


Figure B.1. Histograms of current direction for May.

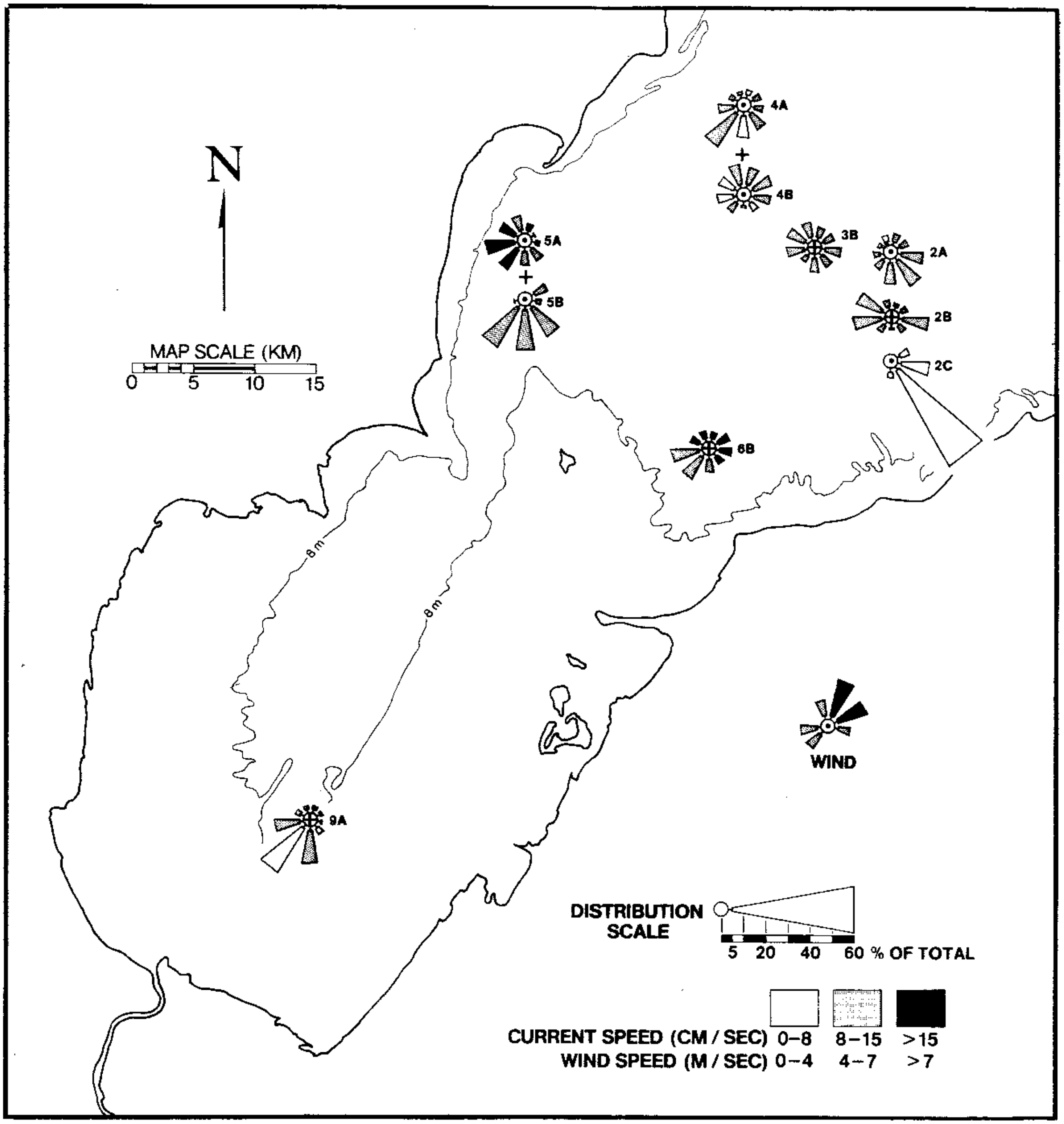


Figure B.2. Histograms of current direction for June.

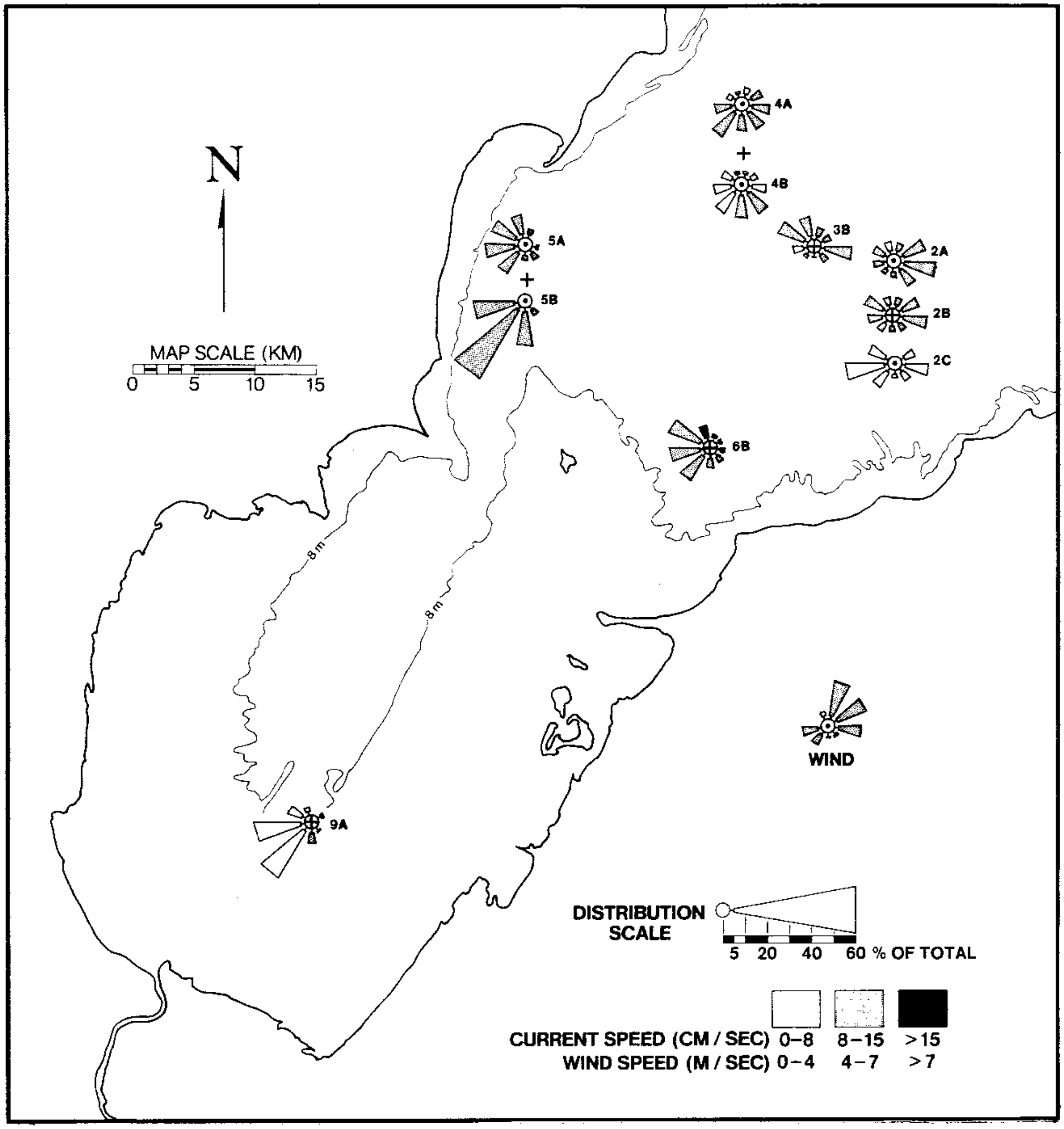


Figure B.3. Histograms of current direction for July.

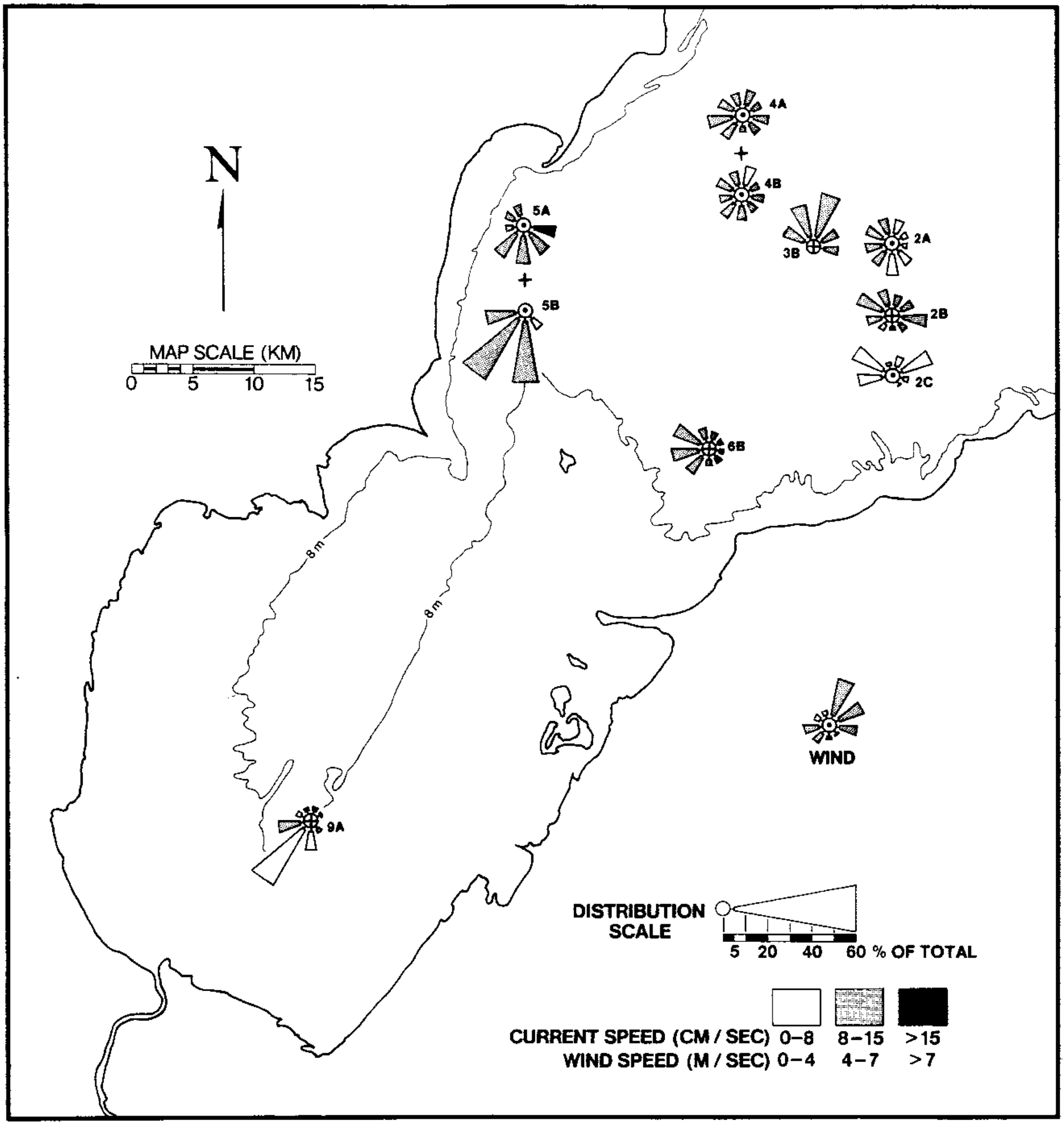


Figure B.4. Histograms of current direction for August.

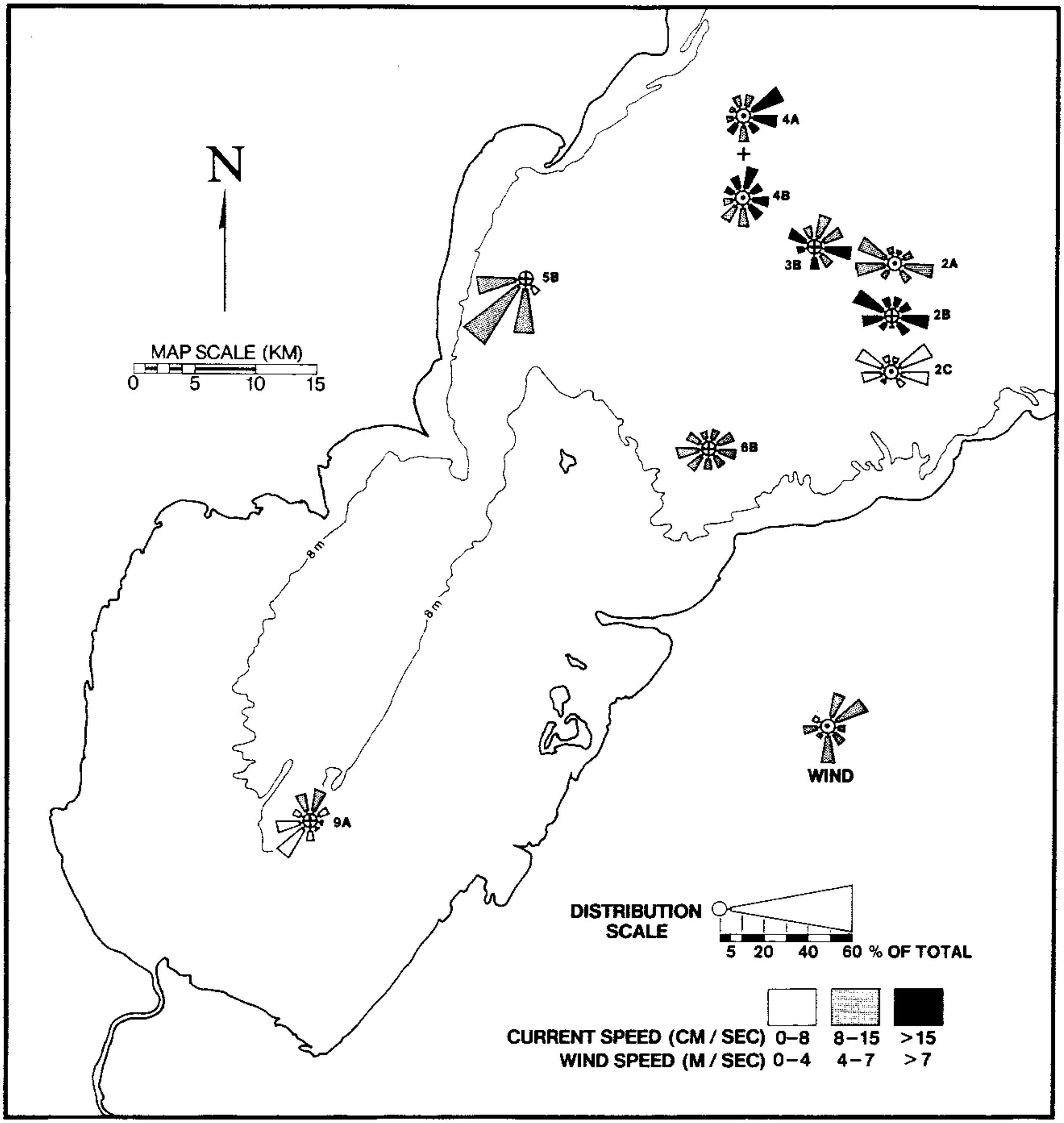


Figure B.5. Histograms of current direction for September.

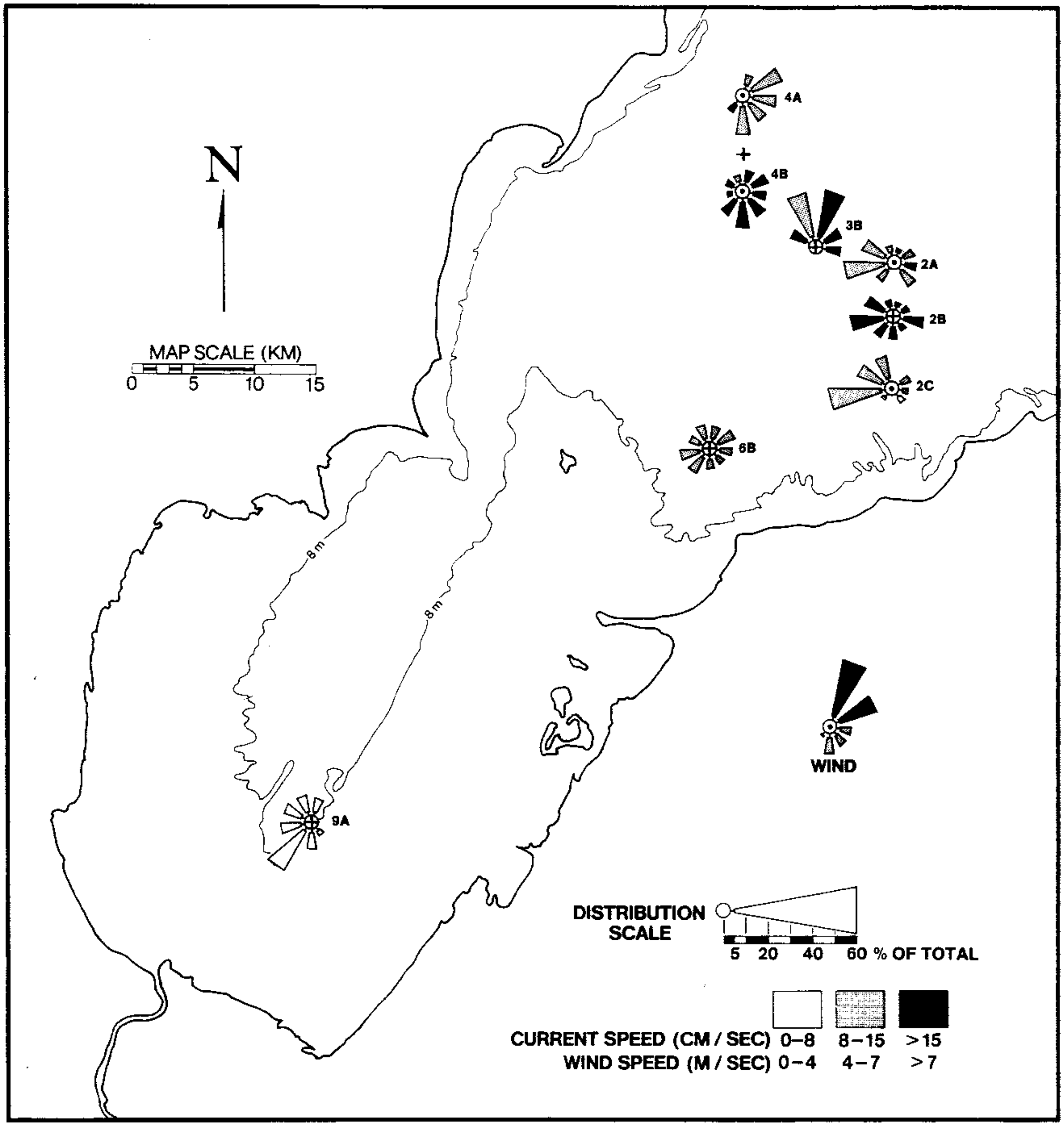
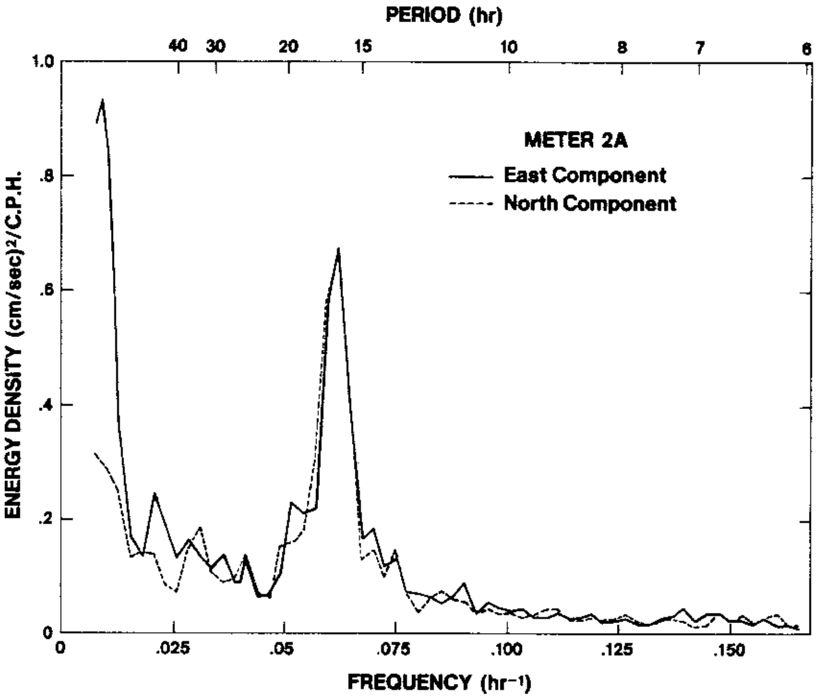


Figure B.6. Histograms of current direction for October.

9. APPENDIX C. POWER SPECTRA ESTIMATES



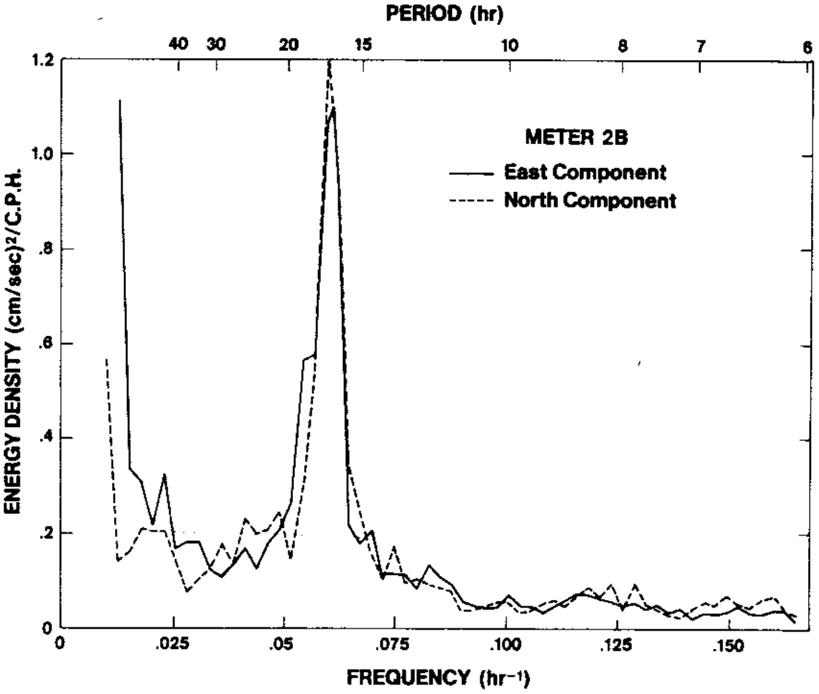
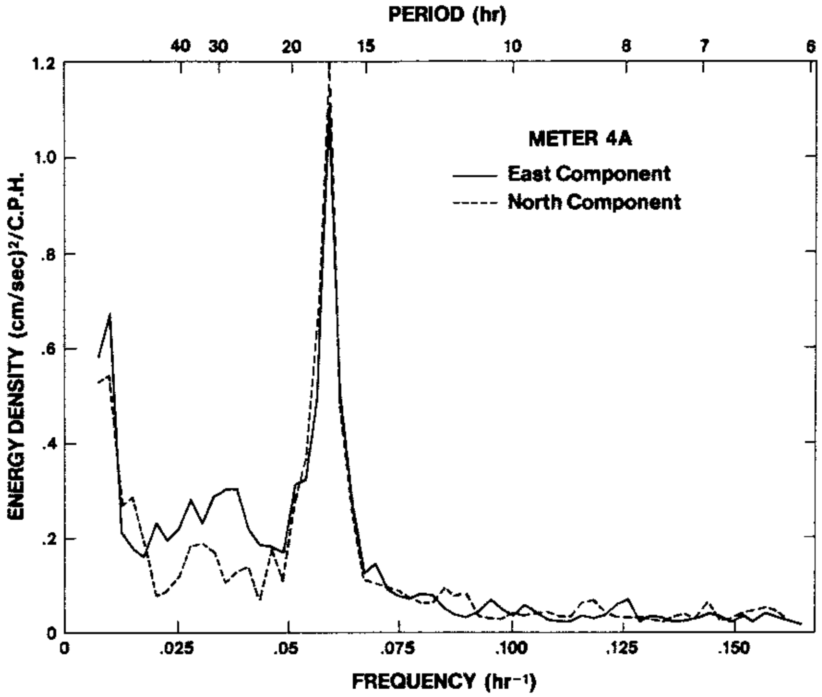


Figure C.1. Power spectra estimates for data from current meters 2A and 2B, duration - 3072 hr, degrees of freedom - 15.5.



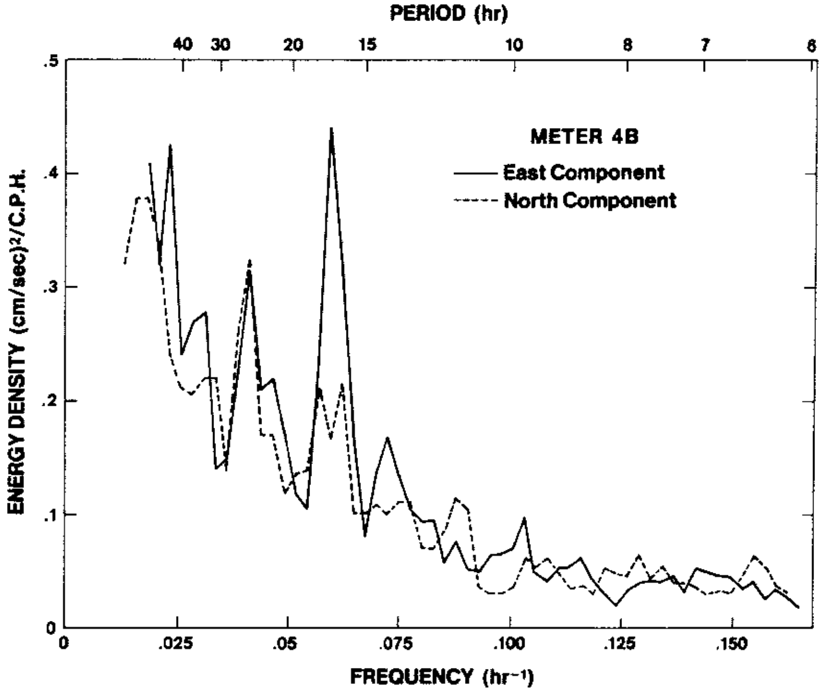


Figure C.2. Power spectra estimates for data from current meters 4A and 4B, duration - 3072 hr, degrees of freedom - 15.5.

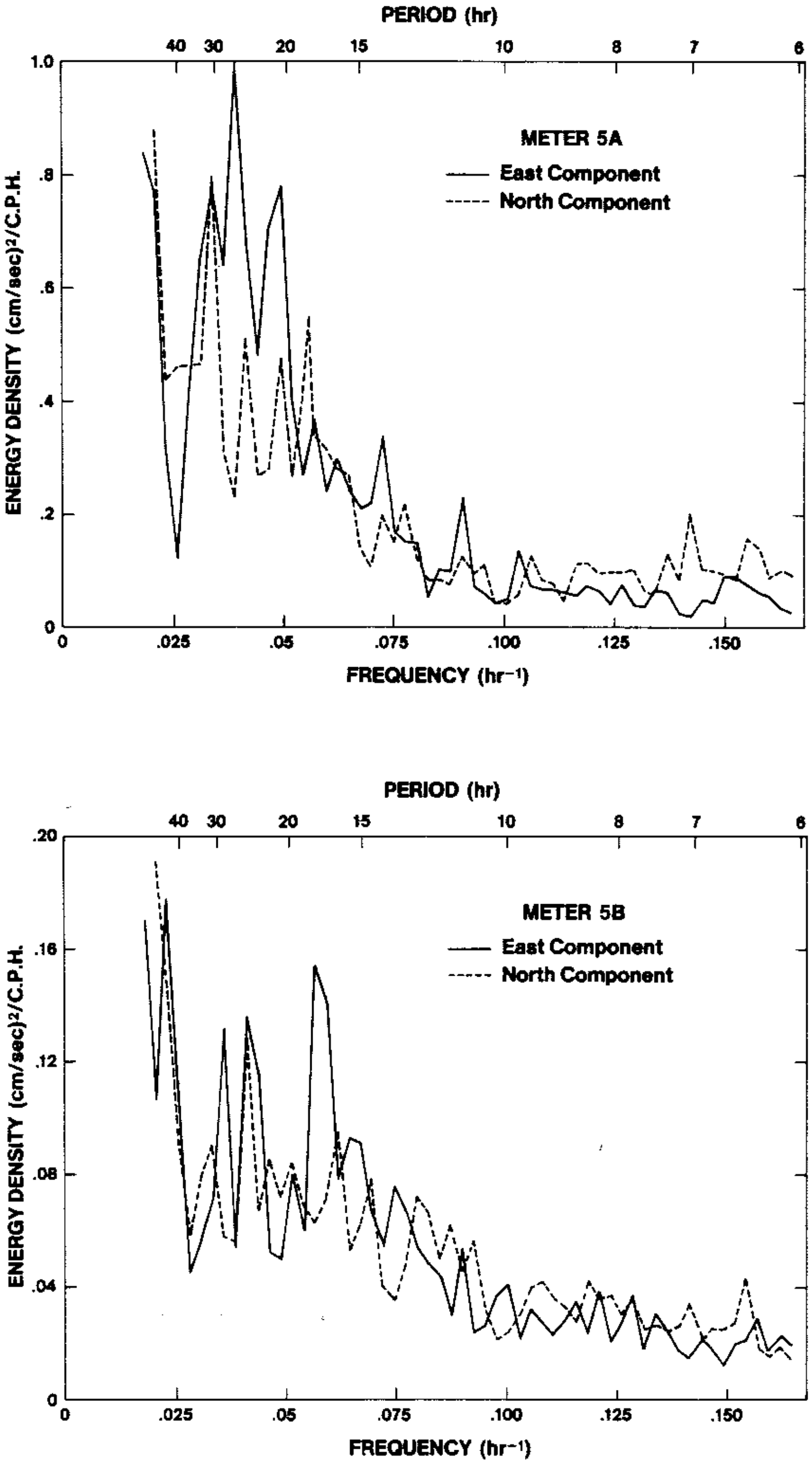


Figure C.3. Power spectra estimates for data from current meters 5A and 5B, duration - 3072 hr, degrees of freedom - 15.5.

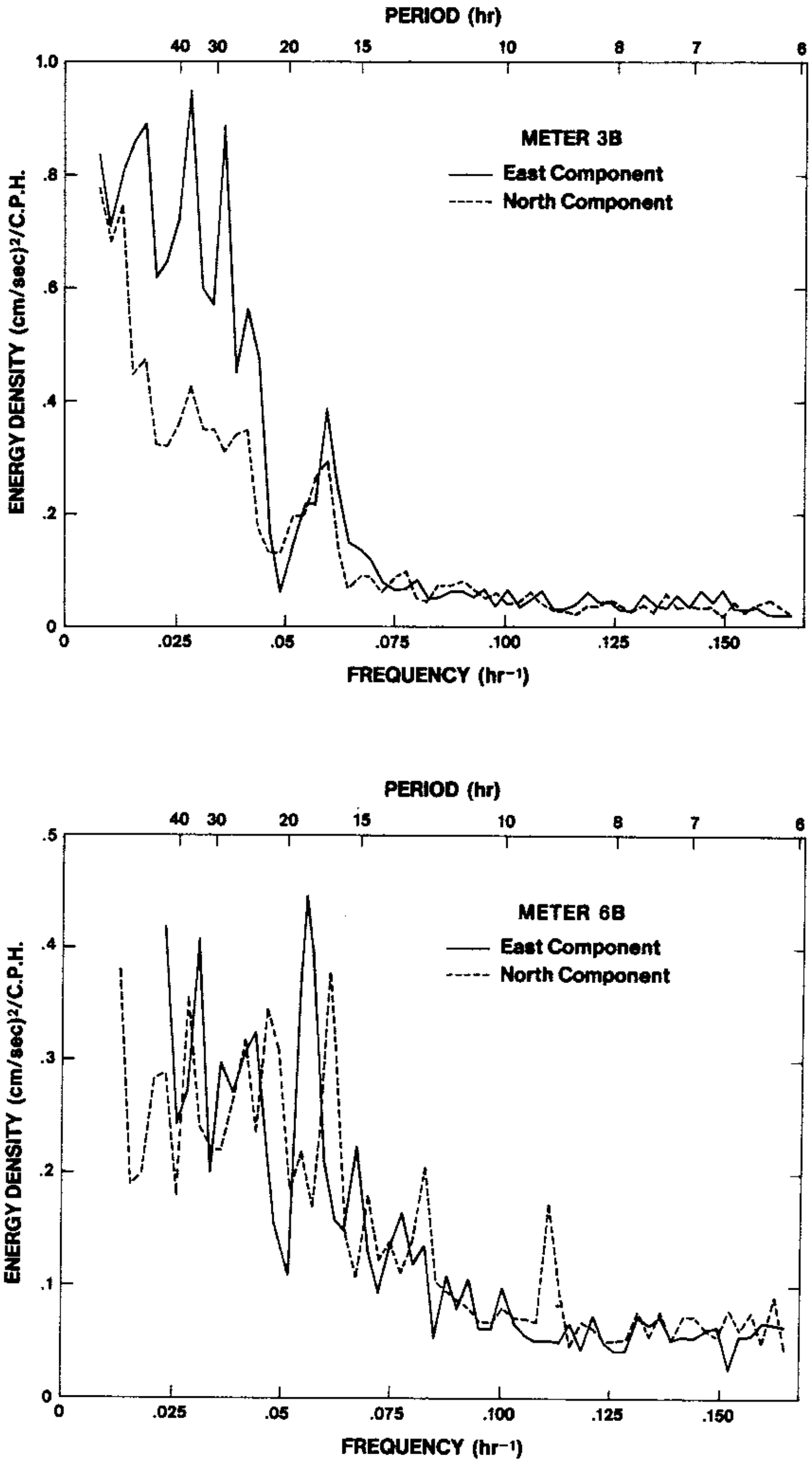


Figure C.4. Power spectra estimates for data from current meters 3B and 6B, duration - 3072 hr, degrees of freedom - 15.5.

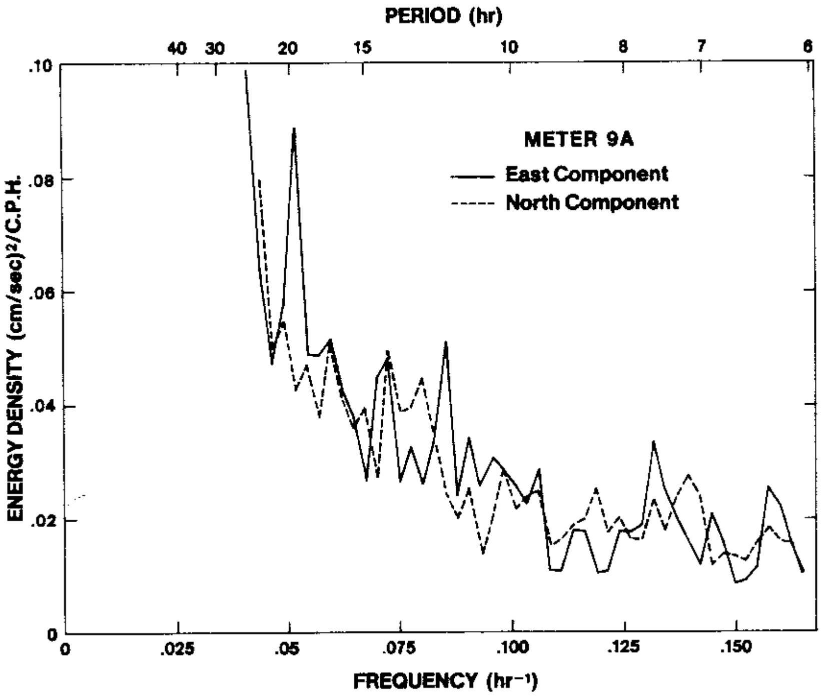


Figure C.5. Power spectra estimate for data from current meter 9A, duration - 3072 hr, degrees of freedom - 15.5.

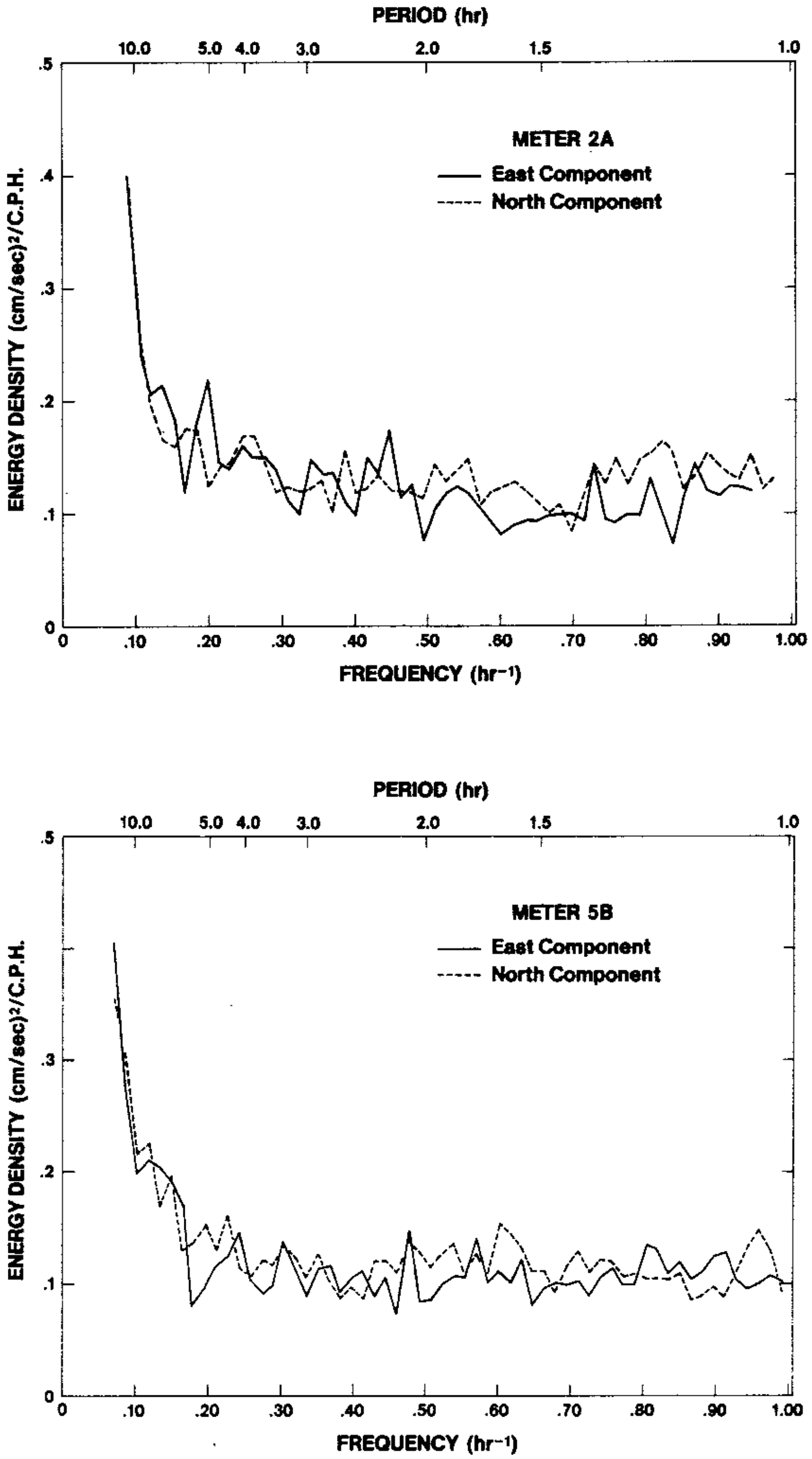
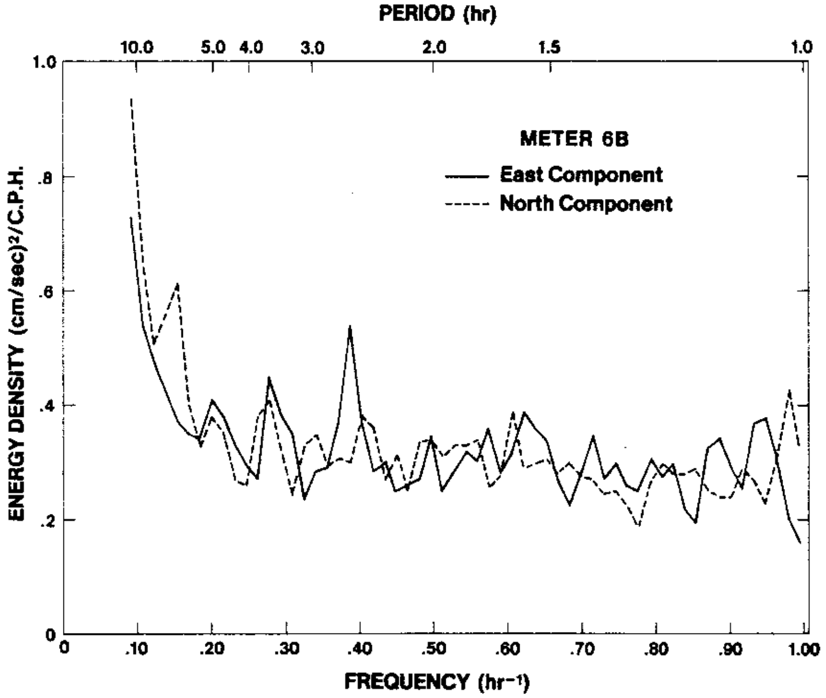


Figure C.6. Power spectra estimates for data from current meters 2A and 5B, duration - 2048 hr, degrees of freedom - 63.5.



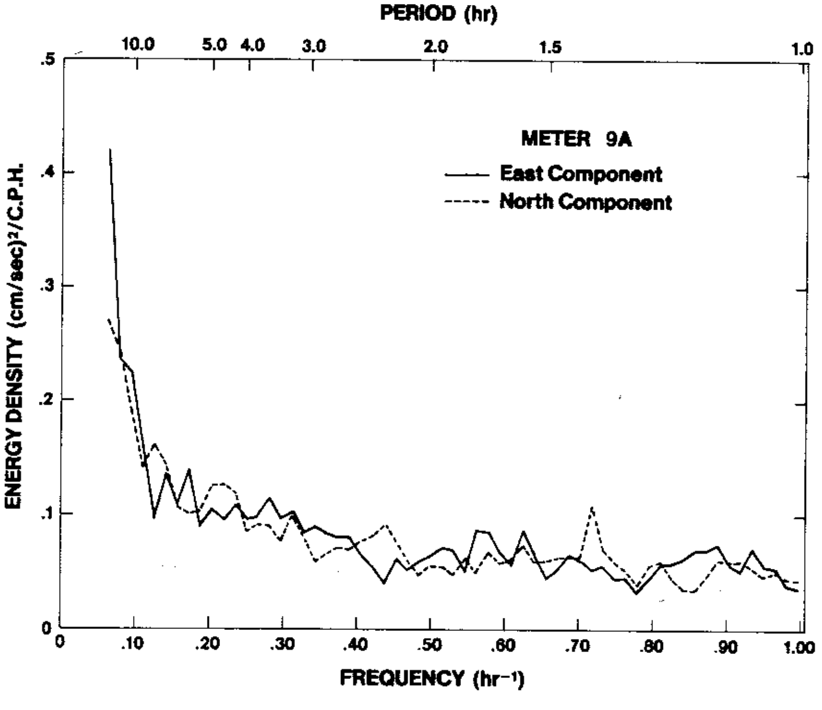


Figure C.7. Power spectra estimates for data from current meters 6B and 9A, duration - 2048 hr, degrees of freedom - 63.5.

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