Suspended sediment transport in the benthic nepheloid layer in southeastern Lake Michigan

Nathan Hawley

Great Lakes Environmental Research Laboratory

2205 Commonwealth Blvd.

Ann Arbor, MI 48105

Barry M. Lesht

Argonne National Laboratory

9700 S. Cass Ave.

Argonne, IL 60439

DISCLAIMER

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Abstract

Time series observations of water temperature, water transparency, and current velocity were made at four stations located on the lake slope of southeastern Lake Michigan. The observations show that during stratified conditions the benthic nepheloid layer is probably not maintained by the local resuspension of bottom sediment. A more likely source is sediment resuspended further inshore and then transported across the shelf and slope during downwelling events. Internal wave action may be an important source of energy for this transport. Although sediment trap studies suggest that resuspension does occur, it is more likely that the increased fluxes observed near the bottom are due to the vertical redistribution of material already in suspension. A benthic nepheloid layer also exists at times during the unstratified period, when occasionally enough energy reaches the bottom to directly resuspend bottom material at the sites.

Introduction

Although numerous studies have shown that the deep areas of Lake Michigan are depositional sites, little is known about the actual processes that move sediment from the shoreline to these areas (see review by Rea et al., 1981). Since most of the material deposited in the deeper areas is silt or clay-sized (Cahill, 1981), it is reasonable to suppose that the material is transported as suspended sediment, rather than as bedload. Haarsch and Rea (1982) estimated the mean residence time of suspended inorganic material in Lake Michigan to be 1.8 years - enough time for material to move from the shoreline to any site in the lake. They also found that during the stratified period (roughly June to October) suspended material was concentrated in two layers - one just below the thermocline and the other just above the bottom (the benthic nepheloid layer, or BNL). Benthic nepheloid layers have been found in all of the Great Lakes (Bell et al. 1980) and are also found in the world's oceans where they are generally believed to be due to local resuspension of fine-grained bottom material that is then transported along isopycnal surfaces (McCave, 1986).

Chambers and Eadie (1981) studied the BNL in southeastern Lake Michigan and found that although it persisted throughout the stratified period, its thickness varied between 5 and 25 m. They postulated that the layer was due to local resuspension augmented by material that was resuspended in the area where the thermocline intersects the bottom (approx. 10-40 m) and was then transported down the slope. Bell and Eadie (1983) made a series of water transparency profiles during and immediately after an autumn storm and found that upwelling generated by the storm reintroduced material from the BNL back into the epilimnion. In a sediment trap study, Eadie _et al_. (1984) concluded that resuspension of bottom sediment occurred in the profundal areas of the lake, a conclusion also reached by Robbins and Eadie (1991) based on the modeling of radionuclide concentrations in sediment trap samples. Studies of the BNL in Lake Ontario (Sandilands and Mudroch, 1983; and Rosa, 1985) and in Lake Superior (Baker and Eisenreich, 1989; and Halfman and Johnson, 1989) have also suggested that local resuspension is an important source of material for the BNL, but in none of these studies has resuspension actually been observed. Thus, although there is indirect evidence that material is transported into the profundal areas by a combination of resuspension and lateral movement in the BNL, there are no direct observations of these processes. Simultaneous measurements of both currents and suspended sediment load have been decribed at only two locations in the Great Lakes, both in southern Lake Michigan: Lesht and Hawley (1987) made measurements in 28 m of water, and Lesht (1989) made measurements in 10 m of water. Both of these studies were conducted at depths less than wave base, where wave action is the predominant cause of sediment movement (wave base in Lake Michigan is approximately 50 m, based on a maximum wave period of 8 s). This paper reports the first time series observations of temperature, current velocity, and suspended sediment concentration from the deeper areas of the lake. Our goal was to investigate the processes responsible for transporting sediment from the lake shelf to the depositional areas located in the deeper parts of the lake and to determine to what extent local resuspension supplied material to the BNL.

Lake Michigan

Boyce _et al_. (1989) describe the main features of thermal stratification and circulation in the Laurentian Great Lakes. Circulation in Lake Michigan is ultimately driven by the wind, but its large size (horizontal scales of hundreds of km and vertical scales of 100 m) makes rotational effects important. During the unstratified period (roughly November-May) the effects of the surface wind stress penetrate to the bottom in the shallower parts of the lake, so nearshore currents are in the direction of the wind with compensating return flow occurring in the center of the lake. When the wind ceases, vorticity waves are set up by the interaction of the current and the lake topography. In the southern basin of Lake Michigan vorticity waves have a period of about 4 days and rotate in a counter-clockwise direction (Saylor et al., 1980). These vorticity waves occur throughout the year and may be the cause of the long-term counter-clockwise circulation observed in the southern basin.

During the winter nearshore water temperatures drop below 3.85°C (the temperature at which fresh water reaches its maximum density) throughout the water column, so the water becomes unstable as it warms during the spring. This causes vertical convection and the formation of a thermal bar that moves outward from the shore toward the deeper parts of the lake. Once the thermocline is established (usually by early June) the effects of the surface wind stress can no longer penetrate to the bottom so vertical circulation is inhibited. A two-layer circulation is set up, with the upper water responding to the wind stress. This causes both seiche action and tilting of the thermocline. In Lake Michigan south winds cause the thermocline to tip downward along the eastern shore (causing downwelling of warm surface water), while north winds cause it to tip upward (causing upwelling of cold bottom water). In some cases changes in the thermocline depth may cause the speed of the hypolimnion currents to increase during downwelling episodes and to decrease during upwelling periods.

Pressure gradients caused by the seiche action also lead to the formation of internal waves along the thermocline. Mortimer (1980) showed that both standing Poincare waves (with a period of 17 h) and progressive inertial waves (with a period of 17.7 h) could exist in the southern basin of Lake Michigan, and that the presence of either one could explain the temperature and current velocity observations made there. Although standing Poincare waves fit Mortimer's data slightly better than do progressive inertial waves, Boyce and Chiocchio (1987) reported observations from Lake Erie that indicate the presence of progressive inertial waves. Both of these waves rotate in a clockwise direction - opposite to the counter-clockwise residual circulation. Our data sets are not long enough to allow us to distinguish between inertial and Poincare waves, so we have referred to these motions as being due to near-inertial oscillations.

Saylor and Miller (1988) documented the existence of Ekman layer flow in Lake Michigan during the stratified period. Because of the long-term counter-clockwise flow in the southern basin, flow in the Ekman layer should produce net downslope transport near the bottom. Bennett (1987) presented a simple model of Ekman flow in the southern basin of Lake Michigan and concluded that the flow could account for the deposition of material at intermediate depths. Bennett's results, however, are valid only for the basin as a whole. At any given location the local bathymmetry may result in a different transport pattern, so results from a single station cannot confirm or disprove the existence of mass transport in the Ekman layer. In any case, if downslope movement of material does occur, it is more likely to be episodic than continuous.

Methods

Time series measurements of current velocity, suspended sediment concentration, and water temperature were made in southeastern Lake Michigan during four deployments between 1984 and 1988. The first of these deployments was made west of South Haven, Michigan; the other three were made near Grand Haven, Michigan (Fig. 1a). Water depths varied between 65 and 100 m - all greater than wave base (approximately 50 m). Depth contours are relatively smooth and run approximately north-south at station 19 and north-northwest to south-southeast at the other stations. Transects of the bottom depth at the Grand Haven stations and at South Haven are shown in Fig. 1b. The transect offshore of Grand Haven can be divided into three segments: a fairly narrow area that extends to about 25 m depth (the lake shelf), a slope area in which the water depth increases rapidly to about 75 m, and the lake bottom. Stations 22 and 26 are on the lake slope, while station 21 is on the lake floor.

There is no well-defined slope at South Haven. Instead the depth increases fairly constantly to about 50 m, then increases at a slower rate until about 90 m. This flattening of the slope is probably due to the presence of a wedge of sediment that has been deposited in the area. The South Haven site is in a depositional area, while the stations near Grand Haven are in a transitional zone (Cahill, 1981). The presence of this sediment causes station 19 to be as far offshore as station 21, even though the water at station 21 is 25 m deeper.

The instruments were mounted on bottom-resting tripods with additional sensors mounted on the mooring wire in 1987 and 1988. Heights of the sensors are given in Table 1. Since the sampling schemes varied between deployments, they are given in the discussion of the individual stations. All water transparency measurements were made with 25 cm pathlength Sea Tech transmissometers. These readings were recorded to the nearest 0.001 volt over a nominal 5 volt scale. We used Hawley and Zyrem's (1990) equation for southern Lake Michigan to convert the measurements to the concentration of total suspended material (TSM). Hawley and Zyrem estimated the accuracy of their equation to be 0.3 mg l^{-1}. Temperature was measured with either an Analog Devices or a Yellow Springs thermistor; both these devices are accurate to 0.1°C. Current velocity was measured with a variety of electromagnetic current meters. During the first two deployments a Marsh McBirney 512 current meter with a separate directional sensor was used, Interocean S4 current meters were used during the third deployment, and a Marsh-McBirney 585 current meter was used in 1988. All of these meters were calibrated prior to deployment; both the precision and threshold for all three types is 0.5 cm s^{-1}.

Profiles of water temperature and light transmission were also made during the deployments. Generally, profiles were made at the beginning and at the end of each deployment and, in some cases, at other times as well. We determined from these measurements that significant fouling of the transmissometers occurred only during the deployment at station 26. This is discussed below. A set of cylindrical sediment traps (inner diameter = 10 cm, aspect ratio 5:1) was also deployed during each observation period (Table 2). Wind measurements were obtained from the NOMAD 7 weather buoy located in the center of the southern basin (Fig. 1).

Daily water intake temperatures during the deployments were obtained from the Muskegon and South Haven water utilities. Both intakes are located about 1.5 km offshore in 13 m of water. The South Haven measurements are made once a day, but the Muskegon data is the average computed from hourly measurements.

Sediment samples were obtained from all four stations with a Ponar sampler. The material from the top centimeter was wet sieved to separate the sand fraction prior to determining the sediment size distribution with a Spectrex model ILI-1000 laser particle counter. Results from these analyses are shown in Table 3. All of the sediments are predominantly medium and coarse silt with minor amounts of fine sand. No clay-sized material was found in any of the samples.

To remove short-period variations, all the time series data discussed below were passed through a 6-hour low pass filter. Hourly average values were computed prior to applying a fourth order Butterworth recursive filter. Spectral analyses of the data were done on the unfiltered observations. Because the data sets cover a limited amount of time, temporal resolution of the longer period energy peaks is fairly poor - at a period of 18 h the resolution is only about 2 hours.

Observations

Station 22

Continuous 15-minute averages of current velocity, water transparency, and water temperature were recorded at station 22. All sensors were sampled at 2 Hz. Vertical profiles were made at the station on 4, 12, 22, 23, and 25 October. These show that the water column was well-stratified throughout the deployment (Fig. 2), but that the depth of the thermocline varied by about 10 m. The profiles also show that the BNL varied in both intensity and thickness and that it sometimes included the entire hypolimnion. The sediment trap fluxes show both a large increase near the bottom and a distinct difference between the epilimnion measurements and those made in the hypolimnion.

TSM concentrations during the deployment (Fig. 3) varied over a fairly narrow range - between 2 and 4 mg l^{-1}. A noticeable periodicity is quite evident at the beginning of the deployment but is less evident after 9 October; spectral analysis of the TSM record for the entire deployment shows an energy peak at 26 h. The changes in TSM concentration prior to 9 October do not coincide with changes in the current velocity, so it is unlikely that they are due to local sediment resuspension. Although the current velocities are highest between 19 and 22 October, TSM concentrations increase only slightly during this period. The beginning of the increase coincides with the largest current velocities measured (approximately 18 cm s^{-1}), so this may be a resuspension event. The TSM increase seems to be cumulative, with three successive pulses of high current speeds increasing the TSM concentration. As the current begins to decrease on 20 October, the TSM concentration also decreases, but it then increases again, even though the current speed remains low. A detailed comparison of the current vectors and TSM concentrations shows that the current velocity was steadily southward between the time of the highest TSM concentration on 20 October and that on 21 October, so neither local resuspension nor lateral advection can be the cause of the 21 October TSM increase - unless there are lateral inhomogeneities in the TSM concentration.

The increased current velocities on 19-22 October are probably caused by the high winds on 18-19 October. Southerly winds on these days reached speeds up to 14 m s^{-1} with sustained speeds of over 10 m s^{-1}. These strong winds probably depressed the thermocline at the station site which caused the temperature to rise on 19-22 October. The smaller temperature variations during this interval may have been caused by additional movement of the thermocline due to near-inertial oscillations. Spectral analyses of the temperature and current records (at both depths) for the entire deployment period show that most of the energy in each record occurs at periods between 15 and 28 h with a peak at 18 h - close to the near-inertial period for the lake. This periodicity, and the rotary nature of the currents on 19-22 October, strongly suggest that internal waves were present during this time.

If the currents on 19-22 October were generated by near-inertial oscillations, then the increased current speed is consistent with the depression of the thermocline which reduces the cross-sectional area through which the waves travel. The change in wind direction on 20 October would dampen the near-inertial oscillations relatively quickly, but the thermocline depth should take longer to respond. This would explain why the current velocity decreased on 20-22 October even though the thermocline remained depressed. The temperature profiles shown in Fig. 2 show that the thermocline would have had to have been depressed about 25 m in order for a 0.5°C temperature change to occur. A depression of this magnitude is not unusual - a similar depression on the west shore of Lake Michigan was described by Mortimer (1971) as a "moderate downwelling.".

The highest TSM concentrations during the deployment occur between 10 and 15 October. This is also when the current speeds are lowest, so it seems unlikely that resuspension occurred. Until 11 October the currents are steadily southwest, so it may be that shelf water with higher TSM concentrations was transported downslope to the site. Between 11 and 15 October the currents form a single large loop, so the TSM peaks in this interval may be due to the lateral movement of an inhomogeneous water mass. The total displacement from 5 to 11 October is about 25 km, so nearshore material could have been transported to the site.

The poor correlation between the TSM and current velocity records makes it unlikely that local resuspension was an important process during the deployment, except possibly on 19-22 October. Advection of sediment from other locations may have occurred, but we have no way to estimate its extent. The changes in TSM could also reflect changes in the structure of the BNL. If an increase in current speed was not strong enough to erode additional sediment from the bottom, increased mixing might still increase the thickness of the BNL, thus requiring a dilution of the sediment concentration near the bottom. Fig. 2 shows that the configuration of the BNL varied substantially during the deployment - its thickness ranged from 18 to 30 m and the maximum TSM concentration varied from 4.5 to 2 mg/l. Exactly what causes these changes in the BNL is unknown, but they may occur as a response to some change in the flow field.

Station 21

Averages of 60 samples collected at 1 Hz were recorded every 15 m from all but one of the sensors during the entire deployment at station 21, but the temperature 0.9 meters above the bottom (mab) sensor did not work properly. Thus we have complete records of TSM at three depths (0.9, 16, and 26 mab), temperatures at 16 and 26 mab, and the current velocity measured 0.5 mab. Two vertical profiles were made during the deployment - one on the first day of the deployment and the other on 9 August, 4 days before the instruments were retrieved. These profiles (Fig. 4) show that the lake was well stratified during the entire deployment with a well-developed thermocline at 70-85 mab. Both profiles also show a BNL, but its thickness varied from 10 m on 18 July to over 30 m on 9 August. As at station 22, the sediment trap fluxes (Table 2) show a large increase near the bottom.

The data from this deployment is similar in many ways to that collected at station 22, but the additional TSM records higher in the water column allow us to better support our previous suggestion of vertical mixing in the BNL. All of the TSM records at this station (Fig. 5) show short-period fluctuations; spectral analyses of the records show that the largest energy peaks for the upper two levels occur at a period of 21.5 h, while the highest energy 1 mab occurs at 26 h. From 19 to 31 July the background TSM level 1 mab is quite high even though the current velocities are low, while later in the deployment the current velocities are high but the 1 mab TSM concentration is low. The

TSM records from 16 and 26 mab show the opposite pattern - they are low when the current velocity is low and higher when the current velocities increase (note that the increase begins on about 1 August 16 mab, but not until 5 August 26 mab). The peaks in the two upper TSM records show a high degree of correlation and resemble resuspension events (the increases in concentration nearer the bottom are larger than, and begin before, those further up in the water column) but they seem to correlate with decreased concentrations 1 mab. These changes in TSM concentration are consistent with mixing within, and thickening of, the BNL caused by the higher current speeds that occur beginning on about 1 August, but they are not consistent with the resuspension of bottom material.

Although wind speeds were much lower than during the deployment at station 22 - they seldom exceeded 8 m s^{-1} - they appear to have been strong enough to cause downwelling and to generate near-inertial internal waves. As at station 22, the increased current speeds are probably due to a combination of these processes. The rotary nature of the current velocities indicates the presence of near-inertial oscillations after 28 July. Prior to then, a progressive vector plot indicates that the current was predominantly downslope.

Water temperature measurements at the Muskegon water facility show that a downwelling event occurred just before the beginning of the deployment (on 13-16 July). This was followed by an upwelling that lasted from 19 to 27 July, and by a second downwelling episode that began on 28 July and lasted through the end of the deployment. The beginning of the second downwelling correlates quite well with the change in wind direction on 27 July. Due to the greater water depth at this station, the effects of upwelling and downwelling events do not show up in the temperature record since the top temperature sensor was at least 40 m below the thermocline. Although the maximum temperature change is only about 0.3°C, spectral analyses of both temperature records show a pronounced energy peak at a period of 18 h. This is consistent with the velocity power spectrum - which has a prominent peak at 18.5 h - and with the presence of near-inertial oscillations.

As at station 22, the high near-bottom TSM concentrations at the beginning of the record may be due to the advection downslope of a relatively thin layer of more turbid inshore water. This turbid water was then mixed into the water column by the higher current speeds caused by the downwelling event at the end of July. This change in the BNL is reflected in the profiles in Fig. 4. There is no evidence of local resuspension.

Station 19

The observations at station 19 were made entirely during the unstratified period. Continuous 15-minute averages of water transparency, water temperature, and current velocity were recorded. All sensors were sampled at 2 Hz. A vertical profile made on 15 May at a nearby station (3 km to the northeast) shows that the water was isothermal at 3.5°C, and that there was a weak BNL (the profiling unit did not work on 26 April). Several other profiles made during the last week of the deployment also show no thermal stratification and only a very thin BNL (Fig. 6). The fluxes determined from the sediment traps (Table 2) show only a small variation with depth; the flux 2 (mab), was only about 2 times that measured 25 mab and 4 times that at 50 mab.

TSM concentrations are low (Fig. 7) and vary over only a narrow range (1-2.5 mg/l). The record shows a more or less constant series of peaks lasting 1-2 days, separated by short intervals when the concentration is between 1 and 1.5 mg l^{-1}. Fluctuations in the BNL similar to those shown in Fig. 6 could easily account for the observed changes in TSM, but we do not know what caused these fluctuations. The maximum current speed occurred during the storm that began on 29 April. Although this storm is similar in intensity to the most severe storm at station 22, the maximum current speed is somewhat lower. Net water movement during the deployment was about 15 km to the southeast (upslope). As would be expected, there is no indication of near-inertial oscillations in the velocity or temperature records.

On 14 May, there were simultaneous increases in both current velocity and TSM concentration, so this may be a small resuspension event. Possible resuspension episodes also occur on 1-2, 4-6, and 8-9 May. Other TSM increases just as large, however, do not coincide with increased current velocities (on 29 April and 12 May, for example). The double peak in TSM on 4 and 6 May might be due to advection since the current direction changes from east to south. The low TSM concentration on 30 April-1 May - when the current speeds were the highest - could be due to mixing and dilution of the nepheloid layer. This would also explain the relatively uniform fluxes measured by the sediment traps.

The profiles in Fig. 6 indicate that suspended sediment is distributed almost uniformly throughout the water column, so the lack of variation in the TSM record is not too surprising. Although some minor resuspension events may have occurred, it appears that there is relatively little sediment available to erode. The current direction during the storm on 28 April- 1 May is opposite to the wind direction, so the station is located in the region of return flow, rather than where direct wind-generated currents reach the bottom. This may account for the relatively low current velocities observed during the deployment.

Station 26

The 50-day deployment at station 26 spanned the period when the thermocline was established. During this deployment we recorded one-minute averages of both temperature and current velocity at three depths, and of transparency at four depths. Velocity measurements were made at 2 Hz every 10 m, TSM measurements at 1 Hz every half hour, and temperature measurements at 1 Hz every hour. Unfortunately, several problems with the instruments degrade the quality of the data. The bottom-most current meter (at 1 mab) did not operate properly so we only have velocity measurements from 9 and 27 mab. The transmissometers at 2.5 and 10 mab were both mounted vertically, so material may have collected on the lenses. We believe that this did occur and is the reason for the poor agreement between the tripod TSM concentrations and those measured in a vertical profile made on 27 May. The profile measurements on this date were 6.68 and 0.51 mg/l at 2.5 and 10 mab; these are over 2 mg/l less than the corresponding tripod values of 8.96 and 2.92 mg/l. Although the tripod concentrations are higher than the profile values, we have not applied a correction to the tripod readings since we do not know when the fouling occurred. We do know that the tripod transmissometers were not fouled before 23 April, and we suspect that the fouling occurred sometime after 5 May. In addition, the transmissometer 1 mab fouled completely after 1 May, even though it was mounted horizontally. Finally, since the data tapes were filled on 5 June (12 days before the retrieval data), we do not have a vertical profile of temperature and transparency taken at the station at the end of the data records.

Vertical profiles taken at the station on 16 April, 23 April, 27 May, and 17 June (the retrieval date) show that the lake became stratified during the deployment (Fig. 8). The profile made on 23 April (not shown) shows that the lake was still isothermal, while the 27 May profile shows that stratification had begun by that time. Stratification was accompanied by the development of a BNL that at times was considerably more turbid than that observed at the other stations. The sediment trap fluxes (Table 2) show a large increase near the bottom - similar to that seen at stations 21 and 22.

Inspection of the current velocity data (Fig. 9 and Fig. 10) shows that the currents are persistently rotary after 12 May. Spectral analyses of both the current velocities and temperatures show an energy peak at 18 h in all of the records if the entire deployment period is analyzed, but show no peak if only the data prior to 12 May are included. Since an 18 h period is consistent with the presence of near-inertial oscillations, and since these oscillations do not occur if the water is unstratified, their persistent appearance after 12 May probably marks the onset of continuous stratification. Stratification may also have occurred on 3-5 May, but was not permanent.

During the unstratified period (through May 12, Fig. 9) there was one storm (on 21 April) with sustained wind speeds of more than 10 m s^{-1} and peak speeds of

14 m s^{-1}. This storm, however, did not produce the highest current speeds. Current direction at both depths was mainly northerly with the speeds at 9 mab slightly less than those at 27 mab. Temperatures at all three depths increased from below to slightly above the temperature of maximum water density (3.85°C) during this period; this accounts for the crossing of the temperature lines.

Although spectral analyses of the TSM records show no energy peaks during the unstratified period, several episodes of high TSM concentrations do occur. The 2.5 mab TSM record shows four such episodes. The first three of these events occur on 19-20 April, 21 April, and 24 April-1 May. Increased TSM concentrations during these events are also seen in the 1 and 10 mab records, and the third can be seen in the 25 mab record as well. In all of these episodes both the pattern of decreasing TSM as one moves away from the bottom and the time lag in the onset of the increases is consistent with local erosion of bottom sediment. Only during the second event, however, does the current record show the increase expected for local resuspension, even though the maximum speed is rather low (9 cm s^{-1}). Although the TSM records during the first event are very similar to those during the second episode, the event occurs when the velocity is at a minimum. The third episode is considerably different from the first two - rather than an abrupt increase and decrease in TSM concentration, there is a gradual increase for about 5 days followed by a decrease over the next 2 days. Maximum concentrations occur during a period when the velocity is higher than normal (27-29 April), but even higher velocities on 23-25 April produced only small increases in TSM. It is possible that the first and third episodes are due to lateral advection of material suspended elsewhere, but the pattern of the changes in the TSM records and the lack of a good source for the material (the flow is northerly, and essentially parallel to shore) argue against it.

After 30 April the transmissometer 1 mab saturated for the remainder of the deployment. We believe the apparent TSM peak recorded 10 mab on 2-4 May is also an instrument malfunction, since neither of the other TSM records show a similar increase. This peak may be due to the settling of material on the transmissometer lens and its subsequent removal. The higher concentrations recorded 2.5 and 10 mab during the rest of the deployment are also probably due, in part, to fouling of the sensors, but the profile on 27 May shows that at least part of the increase is real. The 25 mab TSM record shows a gradual decrease during the remainder of the deployment.

Conditions during the stratified period (Fig. 10) are characterized by the almost constant presence of near-inertial internal oscillations. Although these oscillations show up quite well in both the temperature and current velocity records, the current speeds are no greater than during the unstratified period. The variations are most pronounced in the temperature record 27 mab, particularly after 14 May. The vertical profile taken on 27 May shows that an oscillation of about 6 m would produce the changes in temperature seen on that date. Observations from a thermistor string reported by Gottlieb et al. (1989) also show oscillations of this magnitude in Lake Michigan. Although the temperature changes are smaller, the records at the other two depths show the same oscillatory activity.

There are also longer periods of increased temperatures. Between 30 May and 3 June the average temperature at all three elevations increased about 1°C before dropping quickly to its previous value. The temperature changes due to the near-inertial oscillations are superimposed on these changes - this is particularly evident at 27 mab. Water temperature readings from the Muskegon water intake facility show that a downwelling event began on 28 May and lasted until 3 June, so we believe that the temperature increase was associated with a depression of the thermocline until 3 June, and that the subsequent decrease was due to the elevation of the thermocline on 4 June. The elevated temperatures on 22-26 May may also be due to downwelling. In contrast to the results from stations 22 and 21, increased current speeds do not occur during these periods of elevated temperatures. It appears that either the density gradient at the thermocline was not great enough or that the thermocline depth was not sufficiently depressed to increase the speed of the currents generated by the internal waves.

Spectral analyses of the TSM data after 12 May show an energy peak at 25 mab, but none at either 2.5 or 10 mab. The 25 mab peak is at 18 h, so there may be a direct connection between the near-inertial oscillations and the TSM record at this depth. Although they show no short period fluctuations, the 2.5 and 10 mab TSM records both show increases during the periods when the water temperature is elevated (11-13 May, 22-26 May, and 30 May-4 June). Since the concentration increases at both depths, it is hard to explain the observations as being due to changes in the structure of the BNL, unless the BNL was very concentrated within the bottom 2.5 m. The increased TSM concentrations during the last two intervals are probably somehow associated with downwelling events (although the actual mechanism is unknown), while vertical mixing associated with the setup of the thermocline could explain the event on 11-13 May. Advection could also be responsible for the increased TSM concentrations (and for the event on 19-20 April as well), but the currents are essentially parallel to shore during all of these episodes, so downslope transport is unlikely. We have no good explanation for the large TSM increase in the 2.5 mab record on 7-10 May, or for the peak in the 10 mab record on 14 May, but they may be associated with the migration of the thermal bar and the onset of thermal stratification.

Only the TSM episode on 21 April shows the most classic feature of shear-induced local resuspension - an abrupt rise in TSM which occurs simultaneously with an increase in the current velocity followed by a gradual decrease in TSM after the velocity decreases. The TSM records during the episodes on 19-20 April and 24-30 April certainly look like resuspension events, but there is no obvious physical forcing for either. In addition to high TSM concentrations associated with low velocities, there are several instances of high velocities associated with low TSM concentrations. Although advection may possibly explain some of the high TSM episodes, the flow during this deployment is essentially either parallel to shore (through 12 May) or rotary, so cross-shelf transport is unlikely. Since the TSM episodes after 12 May correlate with the temperature variations, it appears that these are in some way caused by downwelling events.

Discussion

Although we had expected to find numerous instances of sediment resuspension in our data, there is only one unequivocal example. That occurs during the strongest wind event at station 26; winds of similar strength occurred during the deployments at stations 22 and 19 and may have caused resuspension, but we cannot be sure that they did. Current speeds during all of the deployments are generally low, so one reason for the lack of resuspension events could be that the wind stress during the deployments was inadequate to generate currents capable of suspending the sediment. There were no major storms during the deployment at station 21 - wind speeds seldom exceeded 8 m s^{-1} and none of these occurrences lasted more than a few hours - but during the storms in each of the other deployments wind speeds continuously exceeded 10 m s^{-1} for between 18 and 24 h, with maximum speeds of 14-16 m s^{-1}. A survey of the wind records over a 32-year period (Transport Canada, 1991) shows that storms of this size or larger constitute about 8% of the total wind record each year. If storms of the size reported here are not sufficient to induce resuspension, then - at least below wave base - either local resuspension must be caused by other mechanisms, or it does not occur very often. It is possible that higher wind stresses could induce currents strong enough to erode the bottom material, but we have no observations during any such events.

It is difficult to resolve our findings with the results of geochemical studies (Baker and Eisenreich, 1989; Robbins and Eadie, 1991) that strongly suggest that recycling of bottom material does occur. Part of the problem is semantic. If the term resuspension is taken to include the reworking of material near, but not actually on, the bottom, then the redistribution of material in the BNL observed by us could be termed resuspension. Robbins and Eadie (1991) do exactly this by defining a 'resuspendable pool' of material which includes material both on the bottom and within the bottom 20 m of the water column. If the material on the bottom and in the BNL is chemically identical, then the distinction between resuspension and redistribution may not be important. Both

Baker and Eisenreich (1989) and Olivarez et al. (1989) however, have shown that there are chemical differences between bottom material and material suspended in the BNL. For this reason, and because in sedimentological studies the term resuspension refers to bottom material, we prefer to use the term redistribution to emphasize that the material being recycled is already in suspension and is not a part of the lake bed.

Robbins and Eadie (1991) also found that the concentration of ^{137}Cs was almost constant throughout the water column during the unstratified period. Since ^{137}Cs is known to be associated with bottom material, this suggests that bottom material was continuously resuspended throughout the water column during the fall and winter. Their observations are similar to our sediment trap observations at station 19, when the fluxes were approximately equal throughout the water column. Apparently during the unstratified period enough energy must penetrate to the bottom to resuspend bottom material and mix it throughout the water column, as apparently occurred during the early part of the deployment at station 26.

During stratified conditions the periods of elevated TSM concentrations in the BNL seem to be associated with temperature increases caused by downwelling episodes. It may be - as Chambers and Eadie (1981) suggested - that movement of the thermocline in the region where it intersects the lake bottom resuspends bottom material, but all of our stations were in water deeper than that region (10-45 m depending upon the season). We have previously reported (Lesht and Hawley, 1987) observations made during October, 1981 at a site in 28 m of water just southwest of Grand Haven, MI. (station 81, Fig. 1a. The instrument configuration was identical to that used at station 19). In that investigation the thermocline moved past the station site four times. We found that increased TSM concentrations correlated with either surface wave activity, movement of the Grand River plume, or increased current speeds associated with upwelling events (this is different from what Chambers and Eadie proposed; they suggested that movement of the thermocline across the bottom caused sediment resuspension due to internal waves). Although it is not noted in our paper, the data (Fig. 11) also show that high TSM concentrations were associated with downwelling events. During the deployments reported here it seems likely that material was resuspended further inshore by the same wind events that caused the downwellings, and that this material was then transported across the shelf and down the slope by the downwelling water.

Neither the amount of material in the BNL, nor its thickness remains constant; integration of the TSM profiles at station 22 (Fig. 2) shows that for a 1 cm^2 cross-sectional area the total TSM in the BNL was 77 mg on 4 October (when the BNL was 30 m thick), 23 mg on 12 October (when the BNL was 18 m thick), and 35 mg (when the BNL was 30 m thick). Similar variations in total TSM are seen at both stations 21 and 26 but not at station 19 (but note that the profiles were made on consecutive days). Since local resuspension is not supplying the additional material, the source must be material advected from elsewhere.

During the stratified period the hydrographic conditions on the outer shelf and slope of Lake Michigan are similar in several respects to those found during the winter near the edge of the North Atlantic continental shelf. The depths are great enough to preclude frequent instances of wave-induced resuspension, and there is a sharp density front (Houghton et al. 1988) separating the shelf and slope water (analogous to the thermocline in Lake Michigan). During the winter the salinity and temperature gradients on the continental shelf are parallel, so the front intersects the bottom, just as the thermocline in Lake Michigan does. The position of this front moves across the continental shelf in response to the winds, similar to the movement of the lake thermocline during upwelling and downwelling events. Finally, the water further inshore on the continental shelf is well-mixed, as is the surface mixed layer above the thermocline.

Although the analogy is not perfect, it does allow us to compare our results to those obtained on the Atlantic continental shelf. Palanques and Biscaye (1992) found that during the winter high beam attenuation coefficients (directly related to TSM) were found in three areas: throughout the water column in nearshore waters, in a BNL where the base of the density front intersected the bottom, and in a second BNL near the shelf-slope break. Although we have no analog to the nepheloid layer at the shelf-slope break, our observations are similar to those reported by Churchill and Biscaye (1988) from a station located in 125 m of water. Churchill and Biscaye found that the density front described by Houghton et al. (1988) moved back and forth across the shelf past this station, and that highly turbid water was associated with this movement. The movement of this front can be compared to the upwelling and downwelling events in Lake Michigan. Churchill and Biscaye also found that turbid water existed on both sides of the front, similar to our 1981 observations that show highly turbid water on both sides of the thermocline. The water depth at Churchill and Biscaye's station was also great enough to preclude frequent instances of wave-induced resuspension, as is true of the data reported here (but not during the 1981 deployment). Our observations during downwelling events are similar to the periods during which the density front was at Churchill and Biscaye's site, while the rest of our observations at stations 21, 22, and 26 can be compared to their data when the front was further inshore. During these latter periods the data reported by Churchill and Biscaye are similar to ours - velocity and attenuation values are low and vary over a rather narrow range with little or no correlation between the two.

The TSM record from station 81 (Fig. 11) is somewhat different from the other Lake Michigan records; there are several distinct episodes of high concentrations separated by periods of lower, "background" levels. In this respect the record resembles that reported by both Churchill and Biscaye, and data reported by Lyne et al. (1990a) from several stations in waters 60-80 m deep located on the western Atlantic continental shelf. Lyne et als. stations were all in 60-80 m of water and were occupied during the winter months (December-May) when the water was well-mixed, but they show the same pattern of distinct events separated by periods of low, almost constant attenuation. Lyne et al. ascribe most of their events to resuspension caused by a combination of wave and current action. Although the water depths at Lyne et als. stations are considerably greater than 28 m, the long wave periods during the deployments (up to 14 s, Lyne et al. 1990b) allowed direct wave effects to penetrate to the bottom - as was true on several occasions at station 81. Thus, the station 81 TSM record shows both wave-induced resuspension events - similar to the observations of Lyne et al. - and other resuspension events similar to those observed by Churchill et al. when the front passed their station.

Flagg (1988) found that internal waves could reflect up onto the continental shelf, and that they supplied much of the energy in the frontal zone.

Palanques and Biscaye (1992) suggest that the energy from these internal waves is a primary cause of the highly turbid water associated with the movement of the front. If their suggestion is correct, then a similar process may occur in Lake Michigan if the internal waves are not standing Poincare waves. Calculations show that progressive internal waves with periods of 17.7 h will be reflected up the slope. However, although there are several instances where downslope transport may have occurred, there is no persistent downslope current present during any of our deployments.

Both station 19 and station 26 were located in waters too deep for direct wave action to reach the bottom, so the observations made at these stations are not analogous to those made by Lyne et al. Nor are the observations analogous to Churchill et als. data, since there was no thermocline (during the unstratified period only at station 26). The combination of a well-mixed water column and a depth greater than wave base seems to be unique to the Great Lakes. Although the depths were too great for direct wave action to reach the bottom, wind-generated currents were apparently sufficient to resuspend sediment during the deployment at station 26, even though the current speed was only 0.09 m s^{-1}. The higher velocities observed at station 19 may also have produced resuspension, but we cannot be certain. If our observations at these stations are typical of the conditions during the unstratified period, then there appears to be only a very limited amount of resuspension at these depths, even though the data of Robbins and Eadie (1991) strongly suggest that resuspension does occur during unstratified conditions. Progressive vector diagrams show no evidence of any downslope transport at either station, so even if material was resuspended further inshore, it would not be transported across the shelf. Near-bottom currents were also measured at station 21 during the winter of

1992-1993. That data shows steady transport to the northeast (upslope). Thus, there is little direct evidence of either resuspension or downslope transport during the unstratified period. Rea et al. (1981) suggested that downslope transport occurred during storms after the fall overturn, but we have no data to either support or refute this speculation.

There are several instances in our data in which relatively high velocities do not produce sediment resuspension. Similar occurrences have been reported from both the continental shelf (Churchill and Biscaye, 1988) and from the deep sea (Gross and Williams, 1990). Gross and Williams (1990) speculate that these "flow events" occur because - due to the difference in effective bottom roughness presented to currents from different directions - the bottom material is more susceptible to resuspension when the flow is in certain directions. Although there is no direct proof of this hypothesis, to date there is no better explanation for these events.

Also unexplained are the short-term variations (about a day long) in TSM concentration. Data from the 1987 and 1988 deployments suggest that these variations are due to changes in the vertical structure of the BNL, but what causes these changes is not clear. The changes may be due to the presence of internal waves, but except at station 26, spectral analysis of the TSM concentrations shows either no energy peak, or a peak period greater than 18 h.

Conclusions

Our data show that during stratified conditions very few episodes of sediment resuspension occur at depths greater than wave base in southern Lake Michigan. Current velocities are usually low, and are not strong enough to resuspend bottom material, but they do appear to be strong enough to redistribute material already in suspension in the BNL. Although resuspension may occur when the winds are stronger than those we observed, such episodes occur only rarely. During unstratified conditions enough energy occasionally reaches the bottom to resuspend bottom sediment throughout the water column.

Given that resuspension events occur infrequently - at least during stratified conditions - it is unlikely that the BNL is maintained by local resuspension, as suggested by Chambers and Eadie (1981), nor is it likely that the increased sediment fluxes near the bottom are due to bottom resuspension, as stated by Eadie et al. (1984). It is more likely that these enhanced flux rates are due to changes in the structure of the BNL in response to downwelling events, internal waves, and other unknown physical forcings, which redistribute material already in suspension - as suggested by Robbins and Eadie (1991). Although this may appear to be a trivial distinction, it may be important if the chemistry of the material in the BNL is different from that of the material found on the lake floor.

The BNL appears to be maintained by the episodic downslope transport of material from further inshore during downwelling events. Although Ekman layer flow may aid in this downslope transport, it does not appear to be a continuous process. During stratified conditions, the net transport was offshore during all of our deployments, but there were intervals during each in which the transport was toward shore. Our observations during the unstratified period both show net inshore transport. Internal waves are common during the stratified period and may supply the energy necessary for maintenance of the BNL.

Many of the features in our observations cannot be explained. We do not know why the same current speed sometimes resuspends sediment while at other times it does not. Nor do we know why there are short period changes in the structure of the nepheloid layer. The details of the mechanisms involved in the downslope transport during downwelling events also need to be examined more thoroughly, as does the relation of internal waves and the BNL. Clearly much remains to be done.

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Table 1 - Deployment data

Station #	19	22	26	21
Deployed	26 April, 1984	4 October, 1984	16 April, 1987	18 July, 1988
Retrieved	15 May, 1984	25 October, 1984	17 June, 1987	12 August, 1988
Latitude	42° 21.67' N	43° 0.95' N	43° 2.76' N	43° 0.72' N
Longitude	86° 40.56' W	86° 25.15' W	86° 22.68' W	86° 37.68' W
Depth (m)	70	75	65	96
Current hts (mab)	0.77	0.28,0.77	9,27	0.5
TSM hts (mab)	0.95	0.95	1.*,2.5,10,25	0.9,16,26
Temp. hts (mab)	1.1	1.1	1,9,27	16,26

mab= meters above bottom
* denotes partial record only

Table 2 - Vertical fluxes from sediment traps

Station	19	22	26	21
Deployed	23 April, 1984	4 October, 1984	16 April, 1987	13 July, 1988
Retrieved	16 May, 1984	25 October, 1984	17 June, 1987	9 August, 1988
Height (mab)		Flux in g m^{-2} d^{-1}		
1	13.60	26.65	25.09	-
2	11.70	-	-	-
3	-	-	14.98	-
5	11.01	11.76	-	10.48
10	9.04	11.00	7.05	3.24
25	6.34	4.20	4.57	1.24
40	-	-	3.71	-
50	2.94	0.53	-	0.80

Table 3 Grain size characteristics

Station	19	22	26	21
%Clay	0	0	0	0
% Silt				
4-16 μm	1	0	0	2
16-32 μm	55	11	43	19
32-64μm	31	74	36	74
% Sand	13	15	21	5

Figure captions:

1a. Locations of the moorings in southern Lake Michigan. The positions of the weather buoy (NOMAD 7) and the 1981 deployment (station 81) are also shown.

1b. Bathymetric profiles of the lake bottom near Grand Haven (solid line) and South Haven, MI. Positions of the moorings are also shown.

2. Profiles of TSM (heavy line) and temperature taken at station 22. Note that the depth of the thermocline varies by over 10 m and that the thickness of the benthic nepheloid layer (BNL) varies between 20 and 30 m.

2a. Profiles on 4 October 1984.

2b. Profiles on 12 October 1984.

2c. Profiles on 25 October 1984.

3. Time series data from station 22.

a. Stickplot of the winds measured at the NOMAD buoy.

b. Stickplot of the current velocity 0.77 mab.

c. Plots of temperature (dashed line), current speed (light continuous line) and TSM (heavy continuous line). TSM was measured 0.95 mab, temperature 1.1 mab, and speed 0.77 mab. Currents 0.28 mab (not shown) are similar to those 0.77 mab. Note that the maximum current speeds occur at the same time as increased temperatures, but that they are not associated with high TSM values.

4. Profiles of TSM (heavy line) and temperature taken at station 21. Note that the BNL increases in thickness from 10 to 30 m.

a. Profile on 18 July 1988.

b. Profile on 9 August 1988.

5. Time series data from station 21.

a. Stickplot of the winds measured at the NOMAD buoy.

b. Stickplot of the current velocity 0.5 mab.

c. Temperatures 16 mab(solid line) and 26 mab(dashed line), and the current speed (heavy solid line) 0.5 mab.

d. TSM concentrations 0.9 mab (heavy solid line), 16 mab(solid line), and 26 mab(dashed line). Note that the maximum currents speeds are not associated with high TSM values.

6. Profiles of TSM (heavy line) and temperature at station 19. Note that there is almost no BNL and that the temperature is isothermal.

a. Profile on 14 May 1984.

b. Profile on 15 May 1984.

7. Time series data from station 19.

a. Stickplot of winds measured at the NOMAD buoy.

b. Stickplot of the current velocity 0.77 mab.

c. Temperature 1.1 mab (dashed line), current speed (solid line) and TSM (heavy solid line). Note that the maximum speeds are not associated with high TSM values.

8. Profiles of TSM (heavy line) and temperature made at station 26. The water is isothermal at the beginning of the deployment but stratification has been

established by the end of May. Also note that even though the water is well-mixed in April, a BNL is evident.

a. Profile on 16 April 1987.

b. Profile on 27 May 1987.

c. Profile on 17 June 1987.

9. Time series data through 12 May at station 26.

a. Stickplot of winds at the NOMAD buoy.

b. Stickplot of current velocity measured 9 mab. The currents 27 mab are similar.

c. Temperatures at 1 mab (dotted line), 9 mab (dashed line) and 27 mab (solid line), and the current speed 9 mab (heavy solid line).

d. TSM concentrations 1 mab(dotted line), 2.5 mab (heavy solid line), 10 mab(solid line), and 25 mab(dashed line). The sensor 1 mab failed on 1 May. The peak at 10 mab on 1-4 May is probably due to instrument fouling. The increase in TSM values on 21 April are probably due to sediment resuspension.

10. Time series data from 10 May through 5 June at station 26. Note that there is a 2-day overlap with the data in Fig. 9.

a. Stickplot of winds at the NOMAD buoy.

b. Stickplot of current velocity measured 9 mab.

c. Temperatures at 1 mab(dotted line), 9 mab (dashed line), and 27 mab (solid line), and the current speed measured 9 mab (heavy solid line).

d. TSM concentrations 2.5 mab (heavy solid line), 10 mab (solid line) and 25 mab(dashed line).

11. Time series data from the 1981 deployment.

a. Temperature at 1.1 mab.

b. Current speed at 0.77 mab.

c. TSM concentration at 0.95 mab.

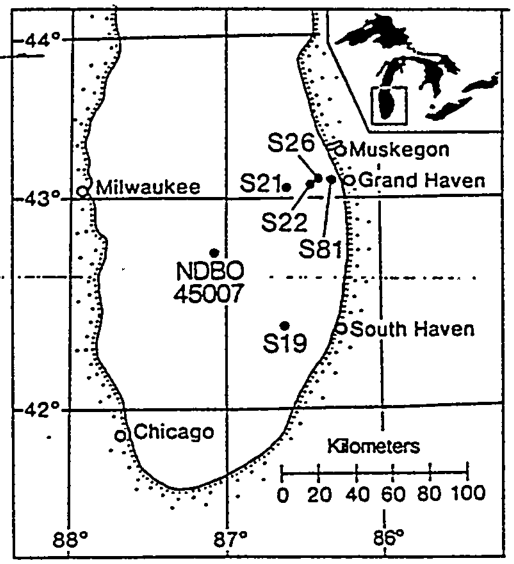


Fig 1a

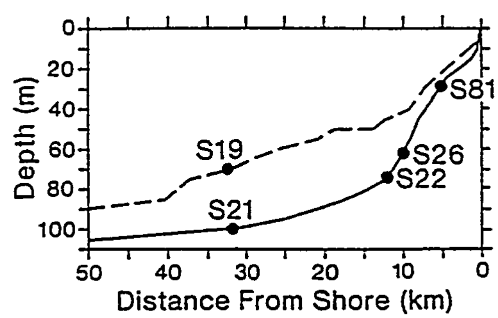


Fig 1b

Hawley + Lesht

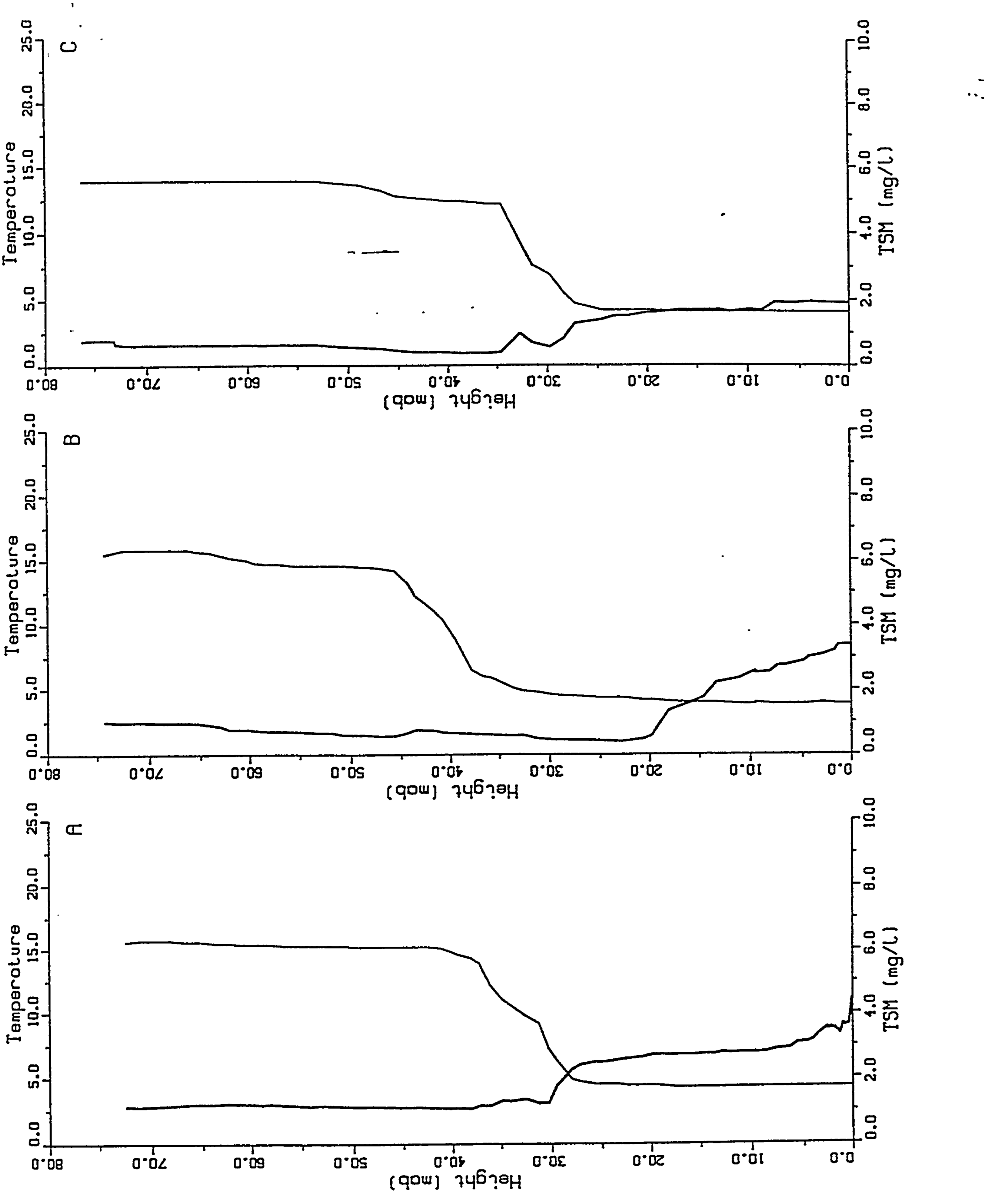


Fig 2
Hawley & Lesht

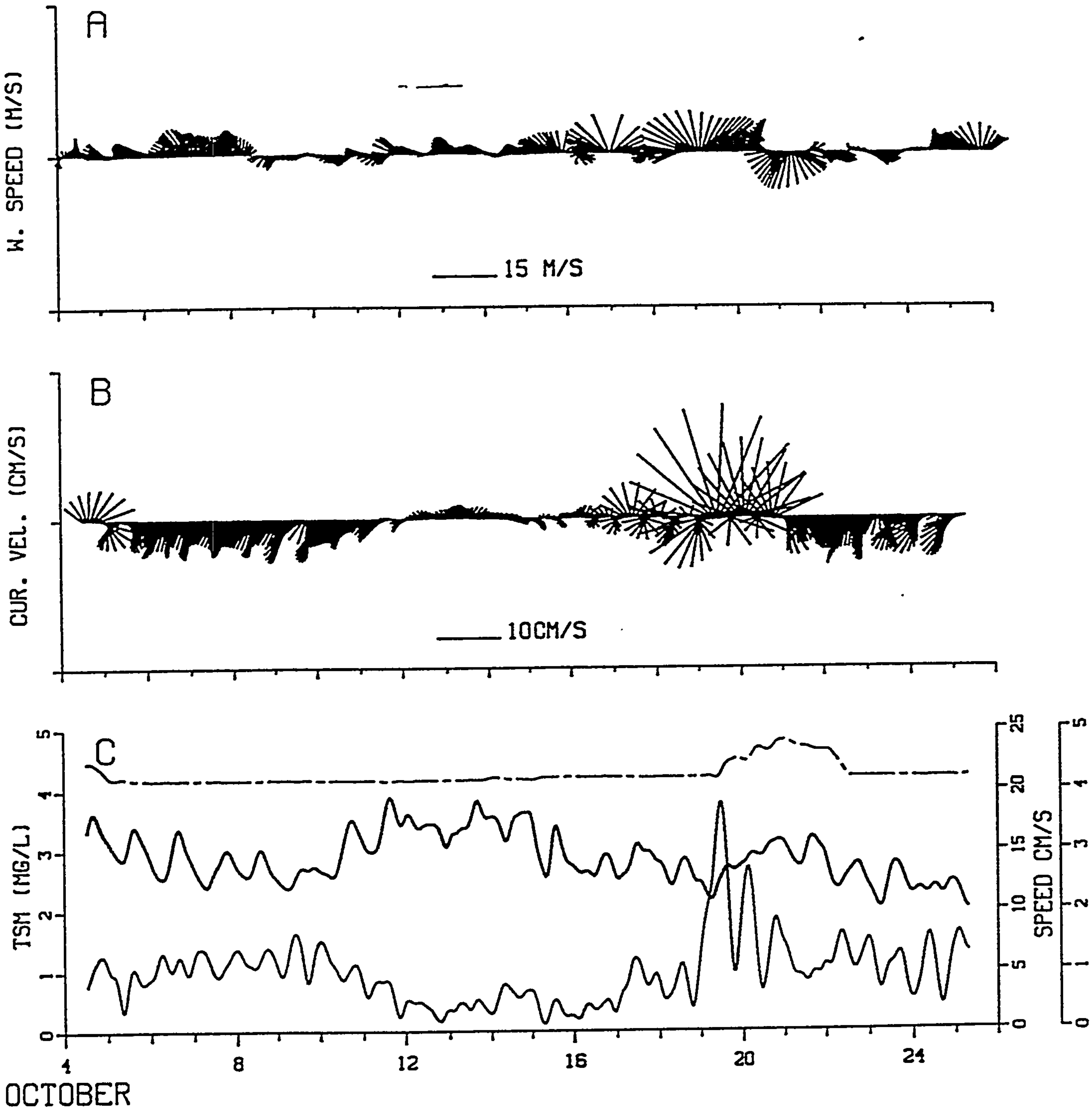


Fig 3
Hawley & Lesht

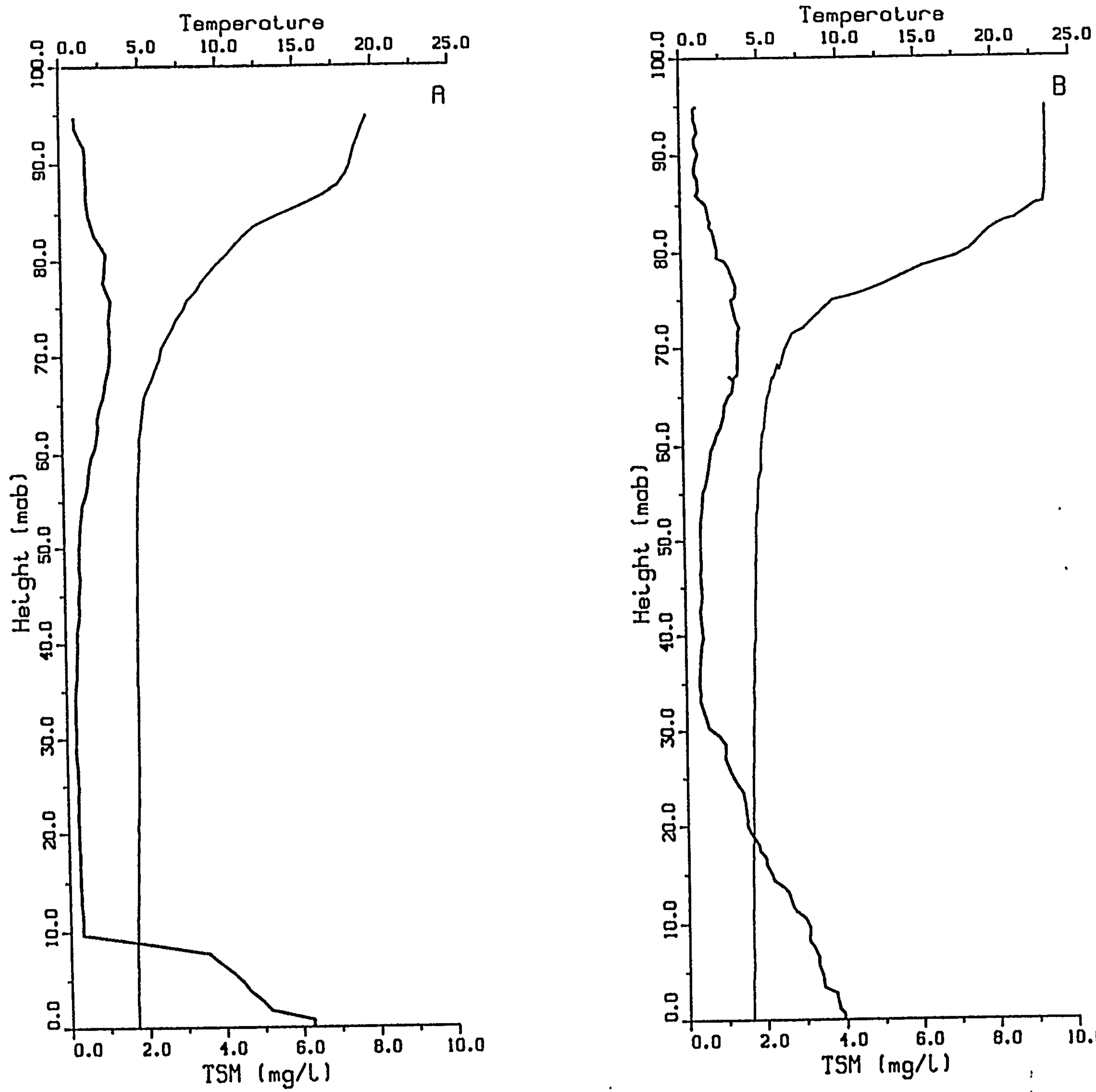


Fig 4
Hawley & Lesht

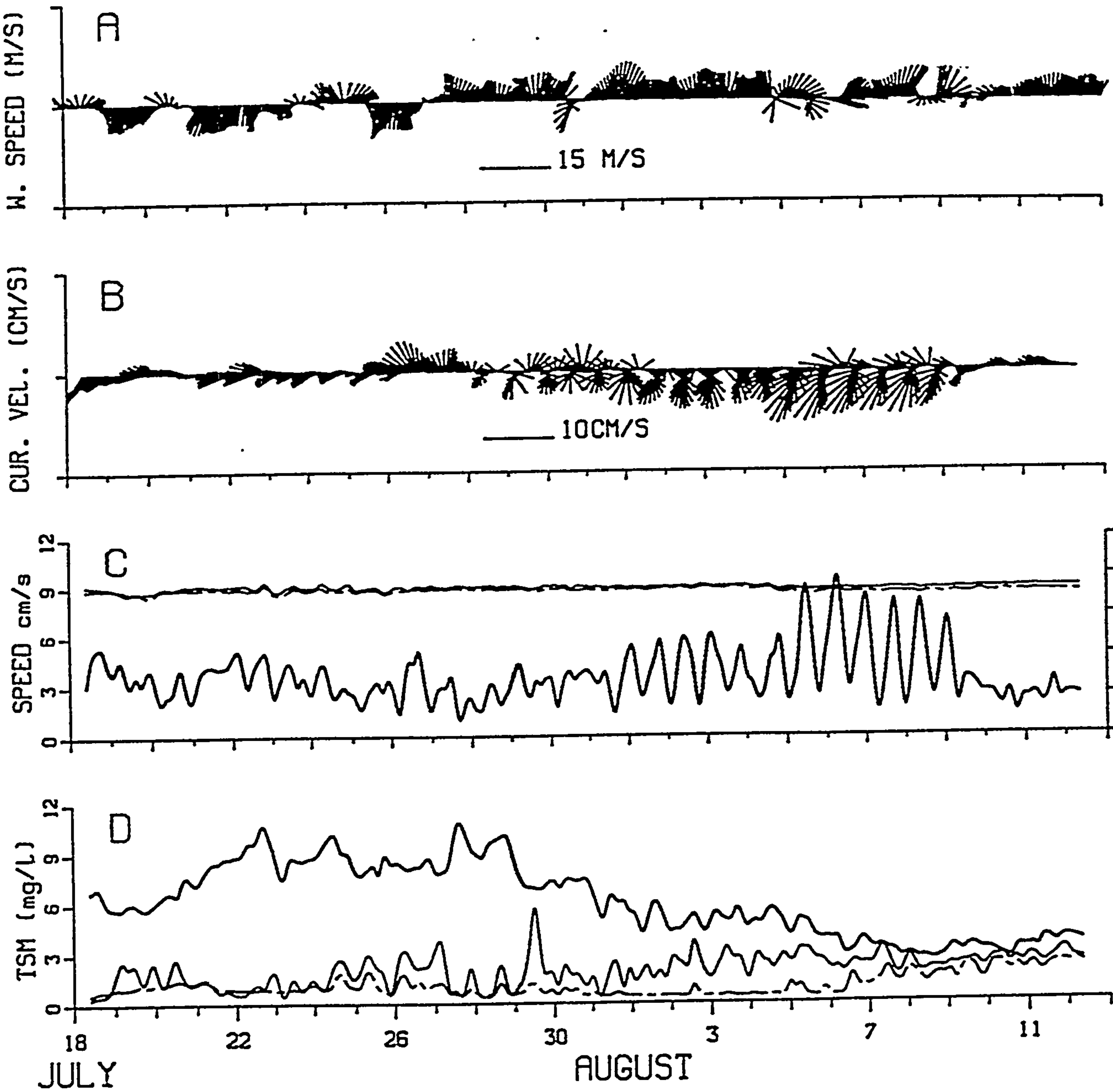
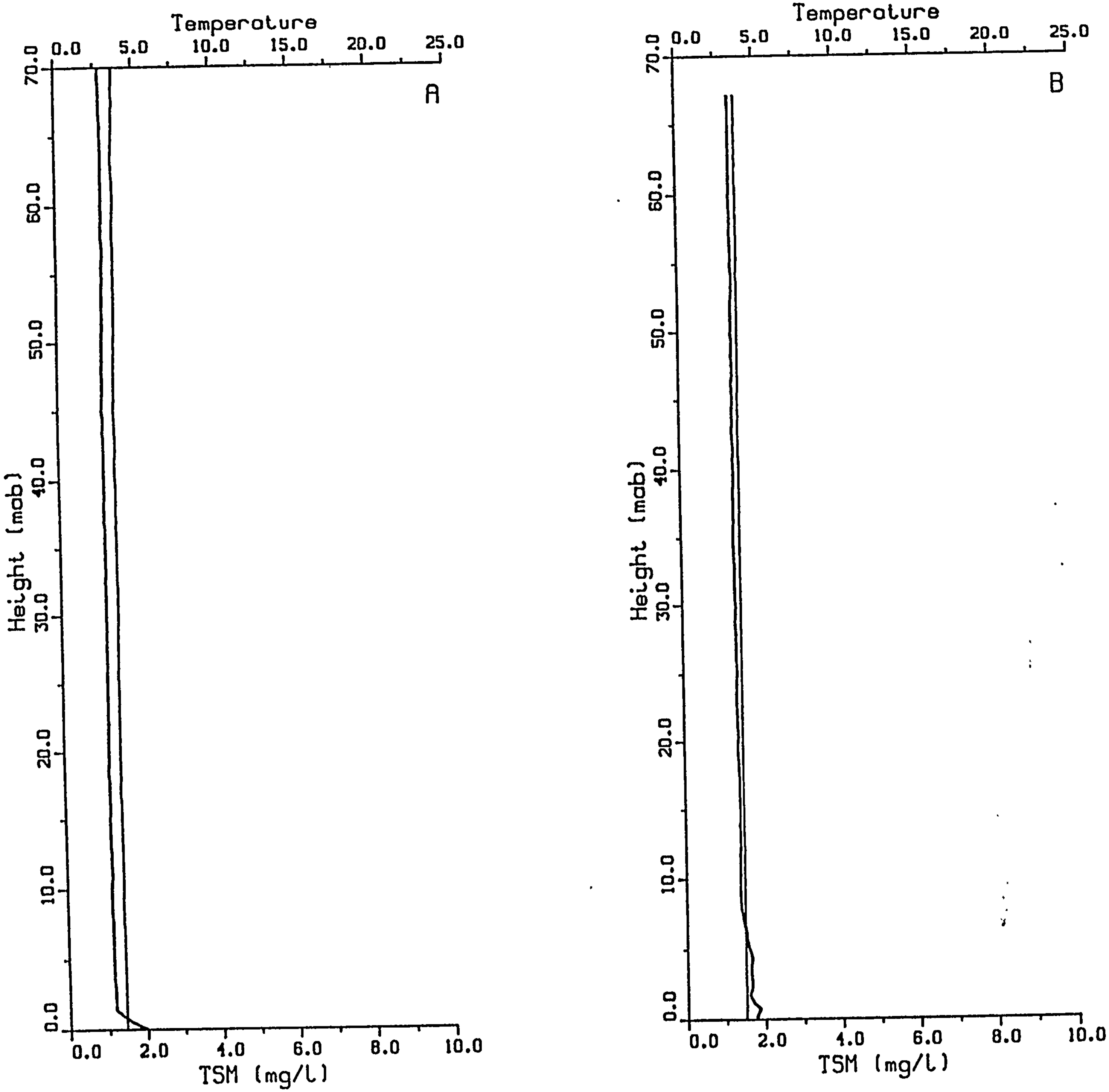


Fig 5
Hawley et al.


Temperature
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5.0
10.0
15.0
20.0
25.0
A
Height (mab)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
TSM (mg/L)
0.0
2.0
4.0
6.0
8.0
10.0
Temperature
B
Height (mab)
TSM (mg/L)

Fig 6

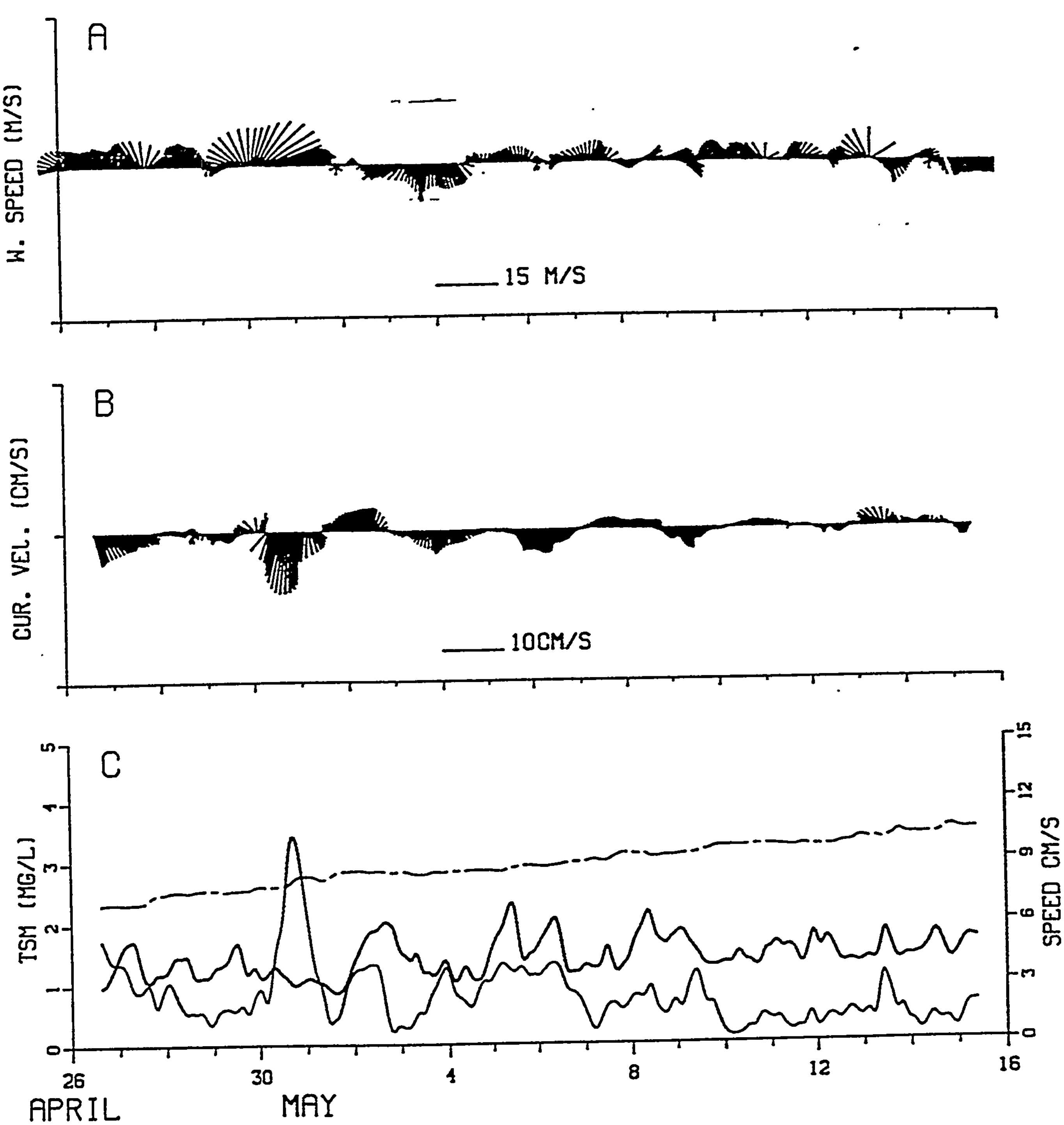

Fig 7
Hawley + Lesht

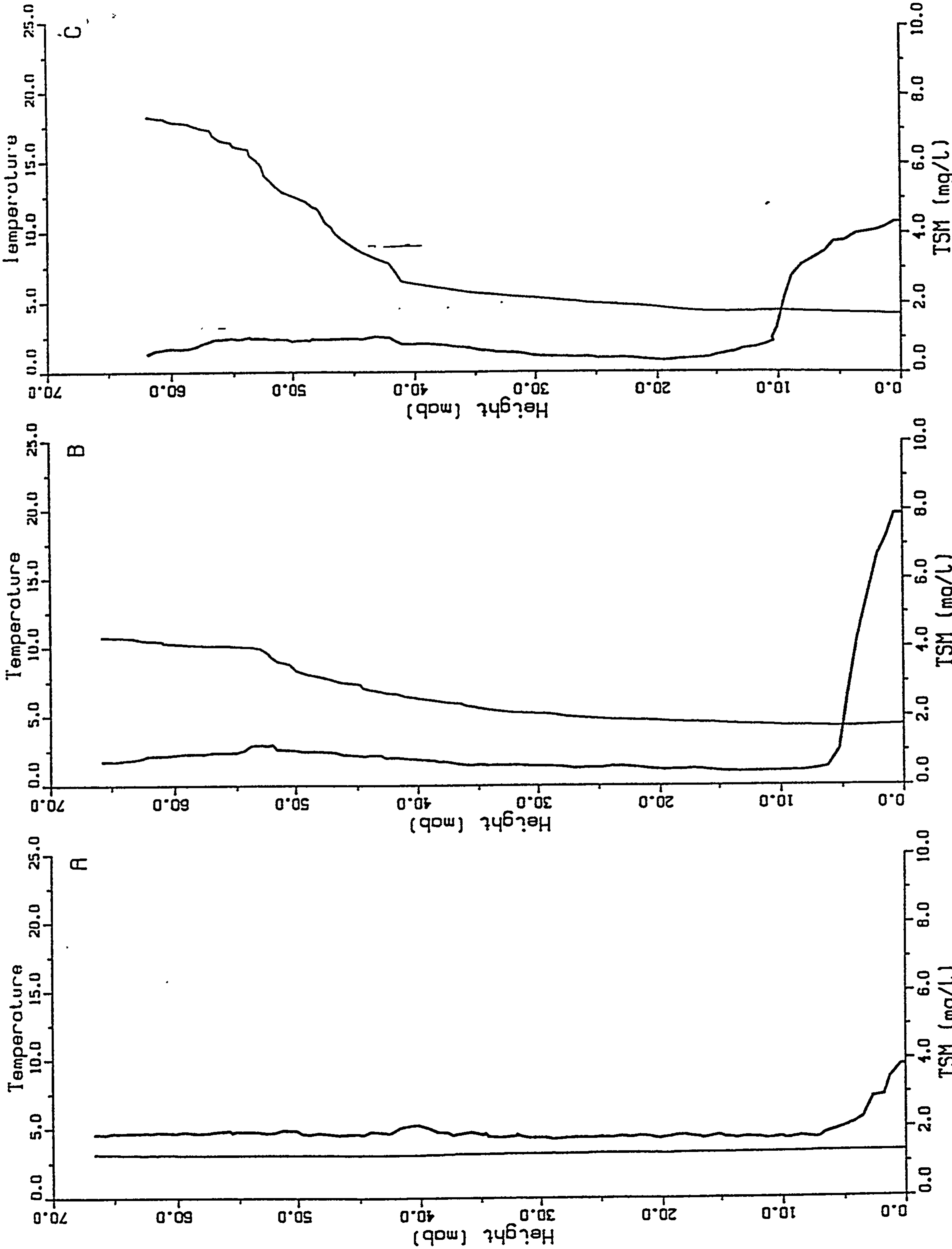

Fig 8
Hanley Lesht

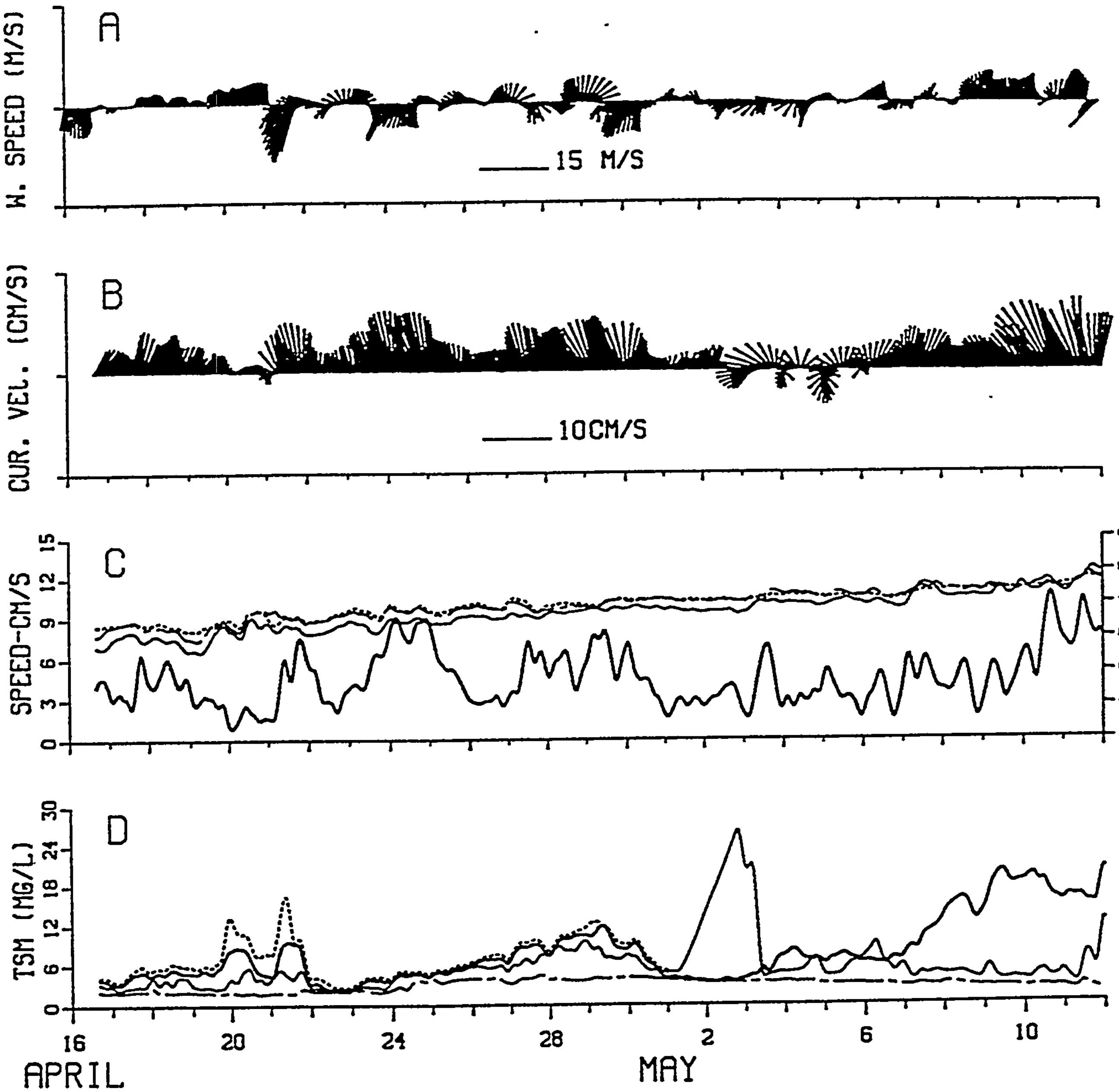

Fig. 9
Hawley + Lesht

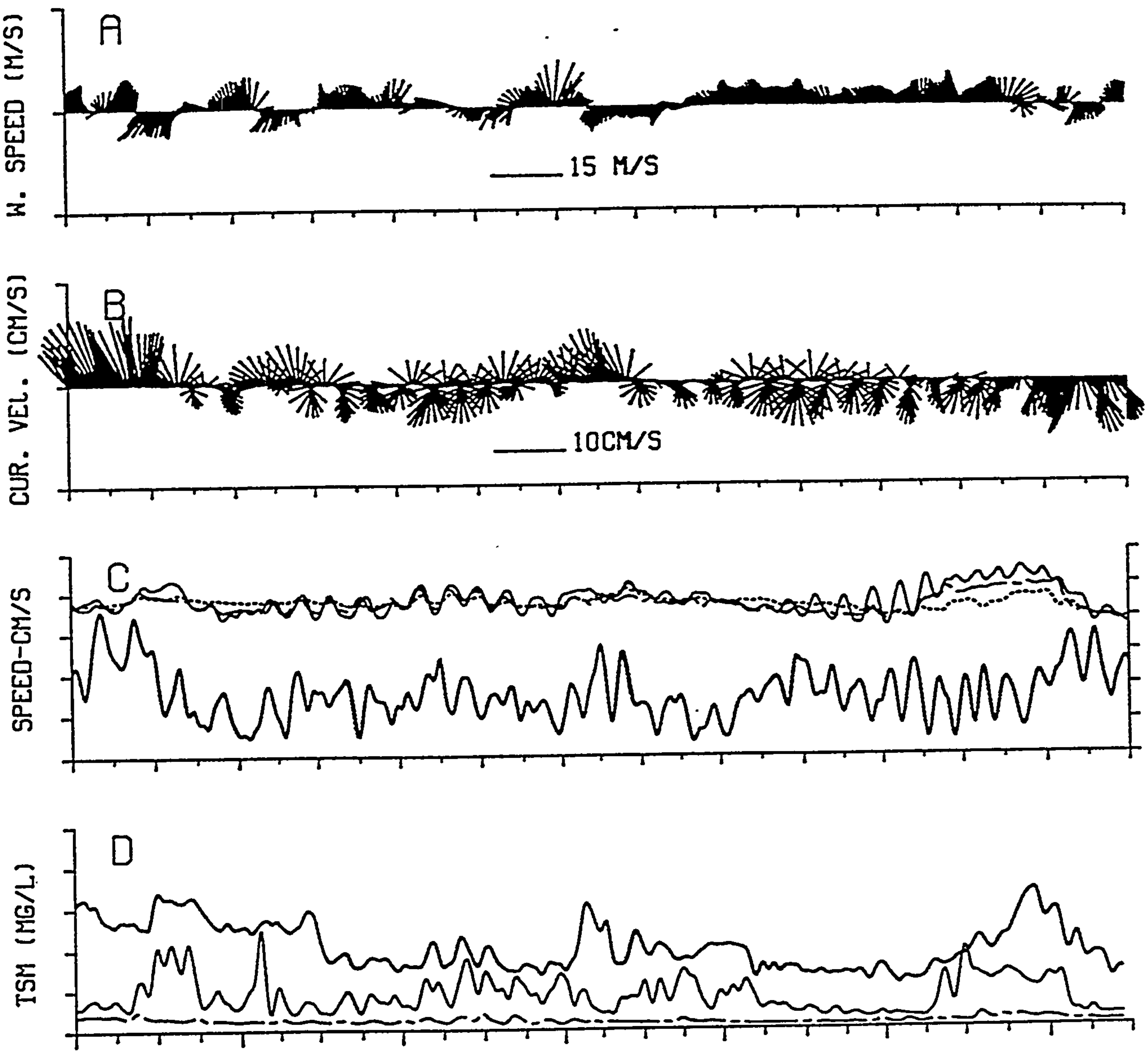

Fig. 10
Hadley + L

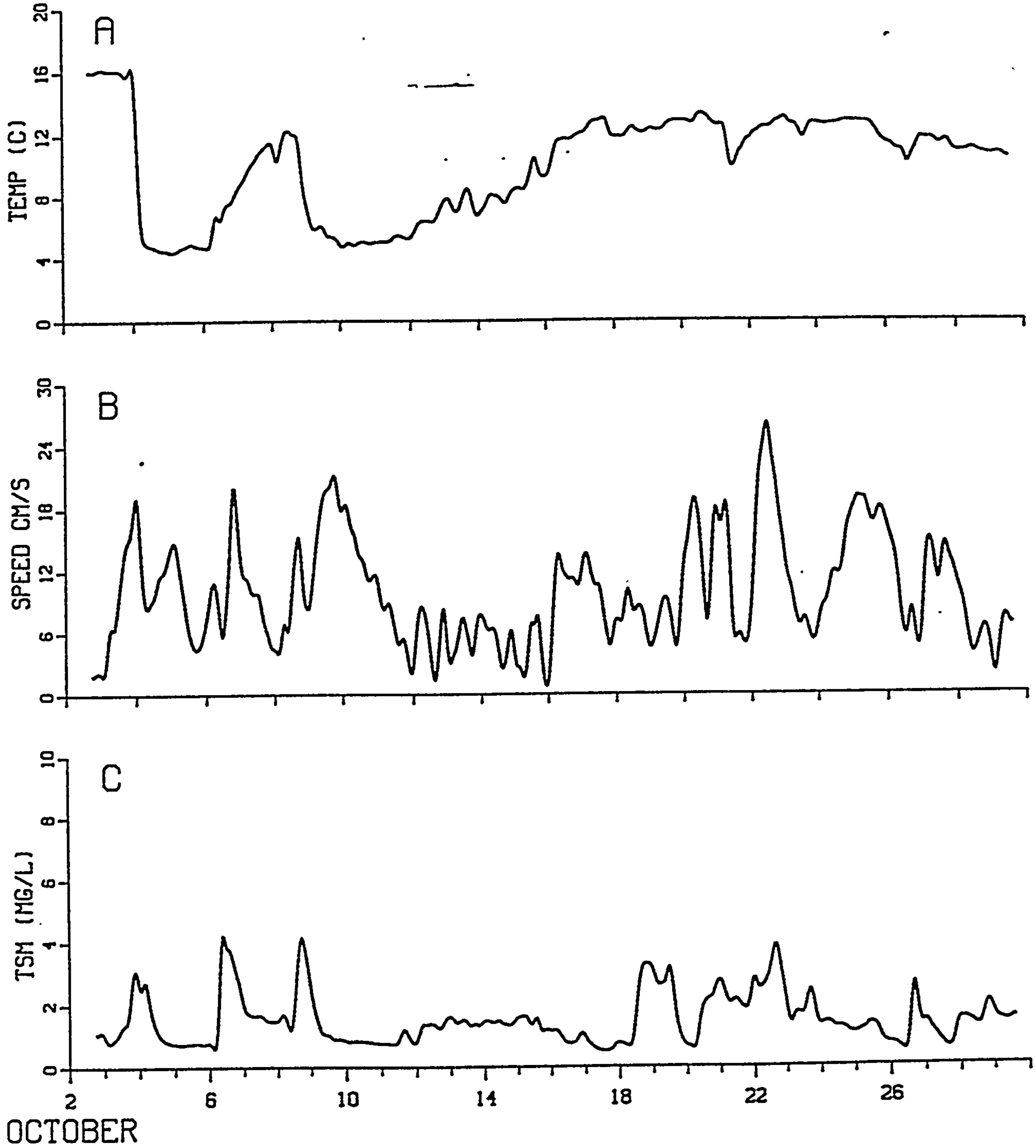

Fig 11
Hawley & Lee