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I.K. Tsanis, A. Masse, C.R. Murthy
and K.C. Miners

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Scientific Liaison Officer
C.R. Murthy
Physical Limnology Section
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario

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I.K. Tsanis,[1] A. Masse,[2] C.R. Murthy,[2] and K. Miners[2]

[1] Department of Civil Engineering
McMaster University
Hamilton, Ontario

[2] Lakes Research Branch
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario

MANAGEMENT PERSPECTIVE

The summer circulation characteristics of the Kingston Basin and the St. Lawrence River outflow area in Lake Ontario were examined from detailed time series current meter, meteorological buoys, and Lagrangian drifter data collected during two years in 1986 and 1987. The circulation in Kingston Basin is strongly influenced by the complex bottom topography, wind forcing and hydraulic effects. During the summer months the water column in the Kingston Basin is stratified resulting in a classical two-layer exchange flow at the open boundary between Lake Ontario and Kingston Basin. At the open boundary the currents in the epilimnion have a magnitude of 3.5-4.0 cm/sec and move towards the St. Lawrence River Channels while the currents in the hypolimnion have a magnitude of 2.0 cm/sec and move lakeward into the deeper part of Lake Ontario. These observed circulation features have potential application in planning long-term water quality monitoring in the Kingston Basin and St. Lawrence River outflow areas.

PERSPECTIVE-GESTION

Les caractéristiques de la circulation estivale du bassin de Kingston et de la zone de déversement du fleuve Saint-Laurent dans le lac Ontario ont été étudiées à partir de données chronologiques détaillées, recueillies en 1986 et 1987, par le courantomètre, les bouées météorologiques et le bateau dériveur. La circulation dans le bassin de Kingston est fortement influencée par la topographie complexe du fond, le forçage des vents et les effets hydrauliques. Pendant les mois d'hiver, la stratification de la colonne d'eau dans le bassin de Kingston produit un débit d'échange à deux couches à la zone limite ouverte entre le lac Ontario et le bassin de Kingston. À cet endroit, les courants dans l'épilimnion ont une vitesse de 3,5 à 4,0 cm/sec et sont orientés vers les chenaux du fleuve Saint-Laurent tandis que les courants dans l'hypolimnion ont une vitesse de 2,0 cm/sec et se dirigent vers la partie la plus profonde du lac Ontario. Ces éléments de circulation ont une application potentielle au niveau de la planification à long terme de la surveillance de la qualité de l'eau dans le bassin de Kingston et les zones de déversement du fleuve Saint-Laurent.

ABSTRACT

During the summers of 1986 and 1987 a network of current meter moorings, meteorological buoys and satellite drifters were deployed by National Water Research Institute (NWRI) to examine the circulation in the Kingston Basin and St. Lawrence outflow area. Power density spectra were computed along vector components and clockwise and anticlockwise components. Coherence and phase were computed between surface and bottom currents at the same mooring and between current and wind stress. The analysis reveals a varied response of currents to wind stress throughout the basin and also indicates the existence of complicated wind and hydraulic circulation patterns. The principal axes and mean direction of the measured currents show that the flow is strongly influenced by bottom topography. The numerous islands in the Kingston Basin affect the circulation. The mean barotropic flow along the north side of the Amherst Island is weak. However the currents exhibit high variability in response to barotropic pressure gradients induced by wind driven water level set-up with the flow around the Amherst Island being 180^{o} out of phase with the wind. During the summer months the flow in the Kingston Basin is stratified resulting in two layer flow at the boundary between the basin and Lake Ontario. The mean currents in the epilimnion move landward towards the St. Lawrence River mouth while the mean currents in the hypolimnion move lakeward towards Lake Ontario through three deep channels.

RÉSUMÉ

Au cours des étés de 1986 et 1987, un réseau de mouillages du courantomètre, de bouées météorologiques et de dériveurs satellitaires ont été déployés par l'Institut national de recherche sur les eaux (INRE) afin d'étudier la circulation dans le bassin de Kingston et la zone de déversement du fleuve Saint-Laurent. Des densités spectrales de puissance ont été calculées le long des composantes vectorielles et des composantes horaires et anti-horaires. La cohérence et la phase ont été calculées entre les courants de surface et les courants de fond au même mouillage, et entre le courant et la tension du vent. L'analyse montre des réactions variées des courants à la tension du vent dans tout le bassin ainsi que l'existence de régimes compliqués de circulation éolienne et hydraulique. D'après les principaux axes et la direction moyenne des courants mesurés, l'écoulement est fortement influencé par la topographie du fond. Les nombreuses îles dans le bassin de Kingston influent sur la circulation. L'écoulement barotrope moyen sur la rive nord de l'île Amherst est faible. Toutefois, les courants montrent de grandes variations parce qu'ils réagissent à des gradients de pression barotropes induits par la configuration du niveau de

l'eau causée par le vent quand l'écoulement autour de l'Île Amherst est en sens contraire du vent. Pendant la période estivale , l'écoulement dans le bassin de Kingston est stratifié et se présente sous forme d'écoulement à deux couches à la limite entre le bassin et le lac Ontario. Les courants moyens dans l'épilimnion sont orientés vers les terres, en direction de l'embouchure du fleuve Saint-Laurent tandis que les courants moyens dans l'hypolimnion se déplacent vers les lacs, en direction du lac Ontario en passant par trois chenaux profonds.

1. INTRODUCTION

Understanding the circulation at the entrance to the St. Lawrence River in Lake Ontario and the exchange flow between Kingston Basin and Lake Ontario is vital for assessing the loading, pathways and fate of contaminants in the St. Lawrence System. Little is known about the physical limnology of Kingston Basin. Freeman and Prinsenberg (1986) studied the exchange flows in the Adolphus Reach located at the outflow of the Bay of Quinte (Figure 1b). Considering the lack of knowledge of the physical processes in the Kingston Basin and its importance in the environment, the present study was initiated to give a general description of the basin's current structure.

Kingston Basin is a shallow semi-enclosed basin located at the eastern end of Lake Ontario (Figure 1a). At the northeast end of the Basin is the entrance to the St. Lawrence River. The river flows out of the basin at a rate of 7,500 m^3/s. The entrance of the St. Lawrence is divided into two channels running north and south of Wolfe Island. These channels cross Kingston Basin to connect the St. Lawrence River with the basin's border with Lake Ontario (Figure 1b). The water depth in Lake Ontario adjacent to the basin drops from an average depth of 20 m to 200 m in less than 40 km. Thus, deep lake currents which follow depth contours are isolated from the relatively shallow Kingston Basin. These deep lake currents form a large counterclockwise eddy adjacent to Kingston Basin such that most of the flow moving along the south shore of the Lake Ontario returns west along the north shore (Simons et al., 1985). The mean eastward transport in Lake Ontario is 70,000 m^3/s with a mean westerly transport in the order of 66,000 (Murthy et. al., 1987). This implies that only about 10 % of the eastward transport enters the Kingston Basin from Lake Ontario and leaves through the St. Lawrence River.

During the summers of 1986 and 1987, physical limnological experiments were conducted to determine the circulation within the Kingston Basin and the flow distribution in the main channels of the St. Lawrence River outflow. The experiments consisted of a network of moored, self recording current meters, meteorological buoys and satellite tracked surface drifters. The current moorings were deployed in Kingston Basin around Amherst Island near Stoney Point and along the main channels in the shallow regions to the east and west of the two main channels (Figure 1b). Clusters of drifters (up to 5) were deployed in the Kingston Basin between 25 August and September 15 (Figure 2). Spectral analysis of the current meter data and meteorological data was performed in order to determine the dominant and temporal scales of motion.

This paper attempts to delineate the main circulation characteristics within the Kingston Basin during the summer stratified period, as well as the interbasin exchange of water masses. It is divided into four sections. Following the introduction, the second section describes the physical experiments, the third section describes the means, principal axes and the spectral characteristics of the current and wind fields, and finally the conclusions of this study are presented in the fourth section.

2. PHYSICAL EXPERIMENTS

Description of Current Meter, Meteorological Buoy and Lagrangian Drogue Data

During the summer of 1986, five current meter moorings were deployed in the Kingston Basin/St. Lawrence River mouth area. These moorings are denoted by the letter 'A' following the mooring number. Each mooring had a surface and a bottom current meter. Surface current meters were positioned 12-m from the surface and bottom current meters were typically positioned 2-m from the bottom at locations shown in Figure 1b. Nine complete current meter records were obtained over the 140-day period from June 3 to October 16, 1986. During the summer of 1987, eleven current meter moorings were deployed in the same area (Figure 1b). These moorings are denoted by the letter 'B' following the mooring number. Similar to the 1986 experiment each mooring had a surface current meter 12 m from the surface and a bottom current meter 2 m from the bottom. Current data was retrieved from only 17 of the 20 current meters. The mooring number, meter depth and water depth can be found in Table 1. Wind data was obtained from a meteorological buoy located in the center of Kingston Basin (Figure 1b). The buoy recorded wind speed and direction and air temperature between June 2 to October 15, during 1986 and 1987.

The satellite tracked drifters consisted of a floating buoy tethered to a "roller blind" type drogue 3.5 m below the surface. This design has a drogue area to buoy area ratio of about 50:1 so that current drag is the dominant force on the drifter. Remote tracking of the drifter buoys is provided by the Argos satellite positioning system. The satellite system can provide about 8 to 12 positions per day at the latitude of Great Lakes with a position error less than 500 m (Pickett et al., 1983). The drifter positions were smoothed and sub-sampled at hourly intervals using an interpolation procedure that insures a smooth transition from one segment of the track to the next (Akima, 1970). Local velocities were computed from the differences in the hourly coordinate values.

In August a cluster of seven satellite-tracked drifters was deployed 17 km south of the north channel of the St. Lawrence River (Aug. 25 - Sept. 2, 1987). In September 1987 a cluster of four drifters was deployed 20 km south of the south channel of the St. Lawrence River. The September deployment consisted of a cluster of four drifters south of the south channel of the St. Lawrence River (Sept. 9 - 15, 1987). It is evident from the drifter tracks that the hydraulic effect is dominant close to the north and south channels of St. Lawrence River while away from the channels the variability is greater and is most likely due to wind forcing (Figure 2).

3. FLOW CHARACTERISTICS OF THE BASIN

3a Mean Wind and Current Field

Current and wind records were low-pass filtered using a Lanczos filter with a cutoff period of 12 hours to remove high frequency energy from the record. Vector means were then computed for the wind speed and the current records. The resulting vectors are plotted in Figure 3 and listed in Table 1. The mean wind speeds for the summers of 1986 and 1987 are similar in both speed and direction. Winds were from the southwest at close to 2 m/s as shown in the upper left corner of Figure 3.

In general, the mean current vectors do not follow the direction of the mean wind speed, with the exception of the surface currents at moorings 1B, 2B, 3A, 9B, 13B, and 14B. Moorings 1B and 2B are in the entrance channels of the St. Lawrence River, while the others in the list are located along the two deep channels that connect the main lake with the St. Lawrence River. The mean surface flows measured at these mooring are most likely due to a combination of the mean wind stress and the hydraulic circulation of the river.

In many cases the variability of the currents were much greater than the magnitude of the mean flow, thus the computed means may be unreliable. Circular statistics (Mardia, 1972) were used to estimate the directional mean, calculated from the frequency of occurrence of direction unweighted by the magnitude of the vector, and the 95% confidence intervals about the mean. These statistics are based on the Von Mises probability density function (see Appendix 2, Mardia, 1972). Confidence intervals were estimated for those mean directions that were significant at the 95% confidence level (Table 1).

The strongest mean currents were measured at the entrance to the St. Lawrence River at moorings 1B and 2B (Figure 3). Surface currents and the near bottom current at 2B (12 m and 20 m depth) were directed riverward with the strongest mean velocities (11-14 cm/s) at the surface meters. Each of these means were highly significant with the 95% confidence intervals about the directional means around 5 degrees. Such narrow confidence intervals are expected for hydraulically driven flow in a river. In Figure 2, the satellite tracked drifters showed a strong mean flow of surface water (3.5 m depth) into the entrance of the St. Lawrence River. These drifters had velocities of 20 cm/s as they passed by the current meter moorings 1B and 2B. Using the combined current meter data and satellite drifter data they show that 45% of the flow entering the St. Lawrence River travels through the north around Wolfe Island, while the remaining 55% of the flow travels through the south around Wolfe Island. Thus the total volume through the north channel is 3,700 m^3/s and the total volume through the south channel is 4,500 m^3/s.

Mooring 3A was located just outside of the entrance to the south channel, about 5 km upstream of mooring 2B. The mean surface current is directed towards the mouth but is only 25% of the magnitude of the surface flow at 2B. The mean is significant and the 15^o - 95% confidence interval indicates there is little variation in the direction of the current. In contrast, moorings 4A and 5B, located approximately 10 km from the entrance to the north channel of the St. Lawrence were not directed towards the river entrance. Freeman and Prinsenberg suggest the currents in this area are affected by Amherst Island. The mean currents at 4A, are small, significant and directed onshore. The surface mean current has a component toward the river entrance, while the bottom current has a small component toward the main lake. This together with the drifter tracks in Figure 2 indicate that mooring 4A may be located in an area of eddy motions.

The mean surface current at 5B is not significant and the near bottom current is barely significant with a confidence interval of 45 degrees. Freeman and Prinsenberg (1986) found that this is an area of strong oscillatory flow driven by wind driven water level set-up in Kingston Basin. Mooring 6B located in the Upper Gap to the west of Amherst Island is also in an area of strong oscillatory flow, however, here mean flow is significant and close to 2 cm/s directed towards the center of Kingston Basin. The flow around Amherst Island will be covered in more detail in the section on spectral characteristics.

In the center of the basin are two deep channels which connect the St. Lawrence River with the main lake area of Lake Ontario. Moorings 9B, 13B and 14B were located in these channels. Surface currents measured at these moorings were 3-4 cm/s and directed along channel towards the river entrance. At 9B the near bottom mean current was weak and the direction was not significant. This is probably due the meter being so close to the bottom, in a depression in the local bathymetry. The near bottom current at 14B is 1.8 cm/s and directed towards the main lake although its direction is influenced by the bottom topography. Similarly, the near bottom at 12B is significant and directed towards the main lake at 1.8 cm/s. The near bottom current at 12B and 14B and the surface currents at 13B and 14B suggest a two layer exchange between Kingston Basin and the main lake, in which surface waters move riverward and the bottom waters move lakeward. This can be thought of as a reverse estuary; however, there was not enough temperature/density data to support whether this was a density driven circulation.

Away from the main channels are moorings 8A and 7B on the west side of the basin and moorings 10A and 11B on the east side of the basin. The surface currents at 7B and 8A are 2-3 cm/s with significant directions. The mean surface currents at 7B, 8A, 9B and 14B suggest the presence of a large anti-clockwise semipermanent eddy in the western portion of Kingston Basin. The mean near bottom current at 7B is weak and the direction is not significant. Similar to 9B this meter was located in a depression in the local bathymetry. At

8A the near bottom current is directed along local isobaths with a lakeward component. This supports the two-layer exchange hypothesis.

In the eastern basin the near bottom mean currents are aligned along local bathymetry. The mean current at 10A is 1.8 cm/s and directed offshore, away from the river entrance. Contrary to most of the other near bottom currents, the near bottom mean at 11B was weak (0.8 cm/s) and directed towards the river entrance. The surface currents are stronger than the near bottom currents with speeds of 1.2-1.8 cm/s but more variable direction as indicated by the large (> 50 deg.) confidence intervals.

3b Principal Axes

The principal axes computed from the low-passed current meter records are plotted in Figure 4. The major principal axis is aligned along the angle of maximum variance for the current vector and the minor principal axis is orthogonal to the major axis. The lengths of the principal axes are analogous to the standard deviation of the current record along the major principal axis, and have units of cm/s.

Moorings 5B and 6B are located in narrow channels around Amherst Island, thus the currents are strongly polarized along-channel. The strength of polarization is measured by the major to minor axis ratio, also known as the ellipticity. For 5B and 6B the ellipticities of their principal axes are 50 and 30, respectively. The near bottom currents at the 5B and 6B have the longest major axes, with lengths of 9.2 and 7.6 cm/s, respectively. Flow is also strongly polarized along the channel at the entrance to the St. Lawrence (moorings 1B, 2B and 3A). The lengths of the major principal axes (4-5 cm/s) are smaller than those measured at 5B and 6B. At 1B and 2B the mean flow is larger than the variability estimated by the principal axes because the steady hydraulic flow of the river dominates the overall flow at this location.

The flow is strongly polarized along the channel near Stoney Point (12B). The major principal axis is 6.4 cm/s comparable in magnitude to the magnitude of the major principal axes measured at 5B and 6B. The strong oscillatory flow suggests there is important exchange between the main lake and this part of Kingston Basin.

In the center of Kingston Basin the principal axes have ellipticities close to one, suggesting that the direction of the flow is isotropic. This is partly due to the complex bottom topography of Kingston Basin with its many depressions and ridges. It is also related to a combination of local and remote wind forcing over the shallow semi-enclosed basin. Local forcing consists of the action of wind stress on the water surface, while remote forcing stems from barotropic pressure gradients generated by wind set up of water in the main lake. The latter always is a barotropic response while the former can be both barotropic and baroclinic depending on the water depth and stratification.

3c Spectral Characteristics

The current meter and the meteorological buoy data were analyzed using the rotary component method for spectral analysis of vector time series (Mooers, 1973 and Calman, 1978). Rotary spectrum analysis of the velocity signals was performed (Penicka, 1978). This analysis provided information on x, y, clockwise and anticlockwise spectra, and the vector components, coherence, and phase.

Figure 5 shows the clockwise and anticlockwise spectra of the wind stress for the summers 1986 and 1987. In both years the spectral characteristics were similar and the energy peaked in the meteorological forcing band (60-200 hours).

The coordinate system for the currents measured at mooring 5A was defined as positive x along-channel towards 60^{o} true and positive y cross-channel - 30^{o} true. This resulted in the kinetic energy spectra along-channel being two decades higher than the y-component (Figure 6). Much of the energy is contained in the meteorological (60-200 hours) and very low frequency (500 hours) bands with the overall energy being higher in the upper layer than the bottom one. Coherence between the surface (12 m) and bottom (20 m) along-channel currents were significant at periods greater than 60 hours. Similarly the along channel wind stress and along channel surface current were coherent at periods greater than 60 hours. The currents at 12 m and 20 m were in phase, while current at 12 m was 180^{o} out of phase with wind. This finding suggests the existence of a mean barotropic type flow around Amherst Island driven by the wind set-up of the lake. Westerly winds set up Kingston Basin creating higher pressure at the northeast end of Amherst island and relative lower pressure at southwest end, causing a flow out of phase with the wind. Because the surface area of the channel is small direct wind forcing is small. Similar 180^{o} phase difference was observed at 6B.

Rotating the x-y coordinate system of current spectra to align with the north channel of the St. Lawrence River at Wolfe Island, reveals an along-channel kinetic energy density two decades higher than the cross-channel y component (Figure 7). There is a significant spectral peak at 24 hours due to daily flow regulation in St. Lawrence River.

The kinetic energy density spectra of the upper and lower of the north and east current components at mooring 10A located to the east of the main channels is shown in Figure 8 with the x component directed due east and the y-component directed positive true north. The spectral energy of the surface current (12 m) is an order of magnitude higher than the bottom current (20 m). The spectra reveal significant peaks in the meteorological band and significant coherence in this band and higher periods. Coherence between the surface current at 12 m and bottom current at 20 m was significant at periods of greater than 60 hours. Both currents at 12 m and 20 m are in phase indicating possible barotropic type of flow driven by the wind set-up of the lake.

In Figure 9, the x-y coordinate system was rotated along the principal axis (40^{o} for the surface current and 20^{o} for the bottom current) resulting in an x-component of the kinetic energy density two decades higher than the y-component only for the bottom current of mooring 9B. The spectra of the x and y current components located in the northern deep channel crossing Kingston Basin are of the same magnitude. Coherence between the surface (12 m) and bottom(20 m) along channel was significant at periods greater than 60 hours. Similarly the along channel wind stress and along channel surface current were coherent at periods greater than 60 hours. The wind stress with the current at 39 m are 180^{o} out of phase indicating the existence of exchange flow in the hypolimnion directed lakeward. The inertial peak is evident and significant in both currents at 12 m and 39 m and 180^{o} out of phase at the inertial period. This is frequently observed for inertial currents.

3d Partition of Spectral Energy Variance

Because of the large number of current records it would be cumbersome to present each individual spectra. Instead, the total variance is computed for each of the 25 raw and low-passed filtered current records. The total variances are shown in the bar chart in Figure 10. The variance of the raw record is represented by the total bar height, the variance of the low passed filtered record is represented by the dark shaded portion of the bar. Clearly the residual variance, the remaining light shaded portion represents high frequency motion (<12 hours) and contributes little to the total variance.

Near the entrance to the St. Lawrence River, 1B, 2B and 3A, have relatively low total variance at both the surface and the bottom meters. Again this is due to the dominance of the hydraulic circulation. The greatest total variance is at 5B, located in the channel behind Amherst Island. The variances at 4B and 6B, both near Amherst Island, are also relatively strong.

In the central area of Kingston Basin, the variance measured near the surface is generally higher than the variance measured near the bottom. This is expected since near the bottom frictional stresses reduce the flow velocity and thus the overall variance. The smallest variances were measured at 10A and 11B on the eastern side of the basin. Although the surface variances measured at the moorings are typical of the surface variances measured elsewhere in the central area of the basin, the bottom variances are noticeably reduced compared to the bottom variances throughout the basin. This suggests that there is limited exchange of deeper water into the eastern basin, east of Pt. Peninsula.

Near the boundary between the main lake and Kingston Basin the variance is moderately strong near the bottom at 12B and the surface at 13B and 14B, thus indicate possible vigorous exchange between the lake and Kingston Basin.

The variance analysis is taken one step further by partitioning the variance for each record into separate physically meaningful frequency bands. The following four bands were used: (1) the very low frequency band (>500 hours); (2) meteorological forcing band (60-200 hours); (3) the diurnal band (23-25 hours); and the (4) inertial band (16.23-18.23 hours). First, the kinetic energy density functions for the 25 records were integrated and normalized (see Figure 5, Weisberg, 1976). The normalized variance were divided into the four frequency bands and plotted in figure 11. Later the normalized variance of each band was multiplied by the total variance to give the total variance found in each of the four frequency bands (Figure 12-15).

In eight of the 25 records the total variance in the four bands accounted for less than 50% of the total variance. This may be due, in part, to the narrowness of the diurnal and the inertial frequency bands chosen. In many cases the energy at the inertial and diurnal bands is smeared in frequency. See, for example, Figure 9 where the inertial peak for the bottom current record is between 12-20 hours. Thus the estimates of variance in these bands will most likely be underestimates.

Around Amherst island, at moorings 4B, 5B and 6B, almost 60% of the variance is accounted for by the four bands. Particularly at 5B, not only did it have the largest total variance, but it also has the most variance explained by the low frequency and meteorological band. By comparison the diurnal and inertial effects are small. Inertial energy is expected to be small in channels and large where there is unrestricted flow such as the center of the basin (Boyce et al., 1989).

The very low frequency motion (>500 hours) is representative of seasonal cycles such as stratification and seasonal changes in the wind field. It constitutes a small percentage of the variance measured at the near bottom current meters in the central basin. Figure 12 shows there is very little energy in this band in the near bottom current records, while the surface measurements are much higher. The very low frequency variance is also high at 5B and 6B, located in the channels behind Amherst Island. The low frequency variance in the surface currents of the central basin and the currents about Amherst Island is most likely due to seasonal changes in the wind field. This is supported by the high coherences between wind at frequencies lower than 2×10^{-3} cph shown in Figures 7-10. In the channels around Amherst Island the currents respond to the wind induced lake set up while in the center of the basin the currents are more likely directly wind driven; therefore, the response of near bottom currents in the center of the basin to the wind is lower than the surface water response to the wind.

Figure 13 compares the total variance in the meteorological band (60-200 hours) for each current record. This is the frequency band over which wind forcing is particularly strong (Figure 6). Again, 5B and 6B have the greatest variance. In the central basin, moorings 7B, 8A, and 9B have slightly higher variance in this band than the surface variance, while at 10A and 11B the near bottom variance is much smaller. A partial explanation is that 7B, 8A and 9B are located in the open area of the basin; therefore, exposed to stronger winds. Thus we expect more vigorous wind mixing at these locations. The difference is hardly significant, however. The near bottom variance in the meteorological band at 12B is quite strong. It appears that the wind drives the strong oscillatory flow in this small channel. The local bathymetry of the area (Figure 1b) shows that a shallow bar (<10 m) separates this small embayment from the central Kingston Basin, thus flow between the channel near Stoney Point and the central basin is probably limited and the flow in this area is unlikely to be affected by the hydraulic flow of the St. Lawrence.

Although the tidal currents in Lake Ontario are in the order of mm/s (Hamblin, 1974), significant peaks are found around 24 hours in the kinetic energy density spectra. Figure 14 compares the variance measured over the diurnal band for this experiment. The variance measured in the St. Lawrence (1b and 2b) are about 1 $(cm/s)^2$ and account for only 2% of the total variance (Figure 12). They are typically larger than most of the diurnal variances measured in the central basin. yet the strongest signals were found at 6b and 12b. It was found that at these stations 11B, 2B, 6B and 12B 24 hour signal was coherent with the wind ($\gamma = 0.8$) and approximately 180^o out of phase. This implies that the currents could be influenced by sea-breeze effects. Another possible reason for the 24 hour signals at 1B and 2B peaks is the daily river flow regulation by the power dam at Cornwall 150 km downstream (Tsanis and Murthy, 1990).

As theory and previous observations predict (Boyce et al., 1989) the variance in the inertial band is strongest near the surface in the central basin. Inertial motions are reduced in restricted areas such as in the narrow channels around Amherst Island, in the entrance channels to the St. Lawrence, and channel near Stoney point (Figure 15). The inertial motions are also reduced where the flow is restricted in depressions in the local bathymetry, such as 7B and 9B.

4. CONCLUSIONS

The flow in the Kingston Basin is strongly influenced by bottom topography as indicated by the principal axes and mean direction of the currents. Complicated wind and hydraulic induced patterns in the basin are evident from the present analysis due to basin's varied response to the wind stress. The hydraulic effect is dominant close to north and south channels of St. Lawrence River entrance while away from the channels the variability is due most likely to wind forcing. The surface currents in the central basin are directed toward the river entrance over the 2 deep channels connecting the river entrance with main lake. Deep currents in these channels tend to move slowly toward the main lake. The water column in the Kingston Basin is stratified resulting in a two layer exchange flow at the open boundary between Lake Ontario and Kingston Basin. At the boundary the currents in the epilimnion have a magnitude 3.5-4.0 cm/s and move towards the St. Lawrence River channels while the currents in the hypolimnion have a magnitude of 1.8 cm/s and move lakeward into the deeper part of Lake Ontario through three deep channels. Current variability is increased in the narrow channels due to polarization while in the inner bay the variability is smaller and directional isotropic.

The presence of the Amherst Island in the northern part of the basin enhances, due to current polarization, the response in surrounding channels. The flow around the Amherst Island is barotropic with the motion driven by the wind set-up of the basin. Observed mean surface currents and satellite tracked drifter motions suggest a anticlockwise eddy in the central part of Kingston basin to the northwest of the north deep channel leading to the St. Lawrence River. Flow in surface of the central basin is highly variable in direction suggesting eddy like motions.

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List of Captions

TABLE 1
CURRENTS IN KINGSTON BASIN

1986 & 1987

Mooring No. + current meter depth	Water Depth	Speed (cm/s)	Mean Direction (o)True north	Directional Mean (o)True north	95% Confidence Intervals in degrees
1B-12	21.5	11.5	59.4	58.9	5
1B-20		3.4	62.8	65.8	13
2B-12	21.5	14.1	51.1	51.3	5
2B-20		11.3	40.1	41.4	5
3A-12	18.0	3.1	23.8	16.2	15
4A-12	22.0	1.5	337.4	333.9	26
4A-20		1.6	268.2	286.7	30
5B-12	21.8	0.7	10.6	316.2	NS
5B-20		1.8	48.7	40.5	45
6B-12					
6B-23	24.5	2.0	218.7	262.3	NS
7B-12	33.0	1.7	228.4	348.0	29
7B-31		0.7	263.2	243.2	NS
8A-12	31.0	2.8	303.4	302.4	20
8A-29		2.9	260.9	257.9	18
9B-12	40.8	3.0	349.0	337.1	32
9B-39		0.8	355.7	3.5	NS
10A-12	22.0	1.9	316.5	321.5	52
10A-20		1.8	267.3	265.2	22
11B-12	33.5	1.2	53.6	65.4	52
11B-32		0.8	353.2	345.2	27
12B-12					
12B-29	30.5	1.8	219.6	224.1	NS
13B-12	52.0	4.0	22.6	19.3	23
13B-50					
14B-12	37.5	3.5	61.9	62.4	24
14B-36		1.8	113.2	119.5	29
1986 WIND SPEED		(m/s) 1.6	49.8	37.1	
1987 WIND SPEED		(m/s) 1.9	45.6	45.5	

NS denotes the mean directions were not significant at the 95% confidence intervals.

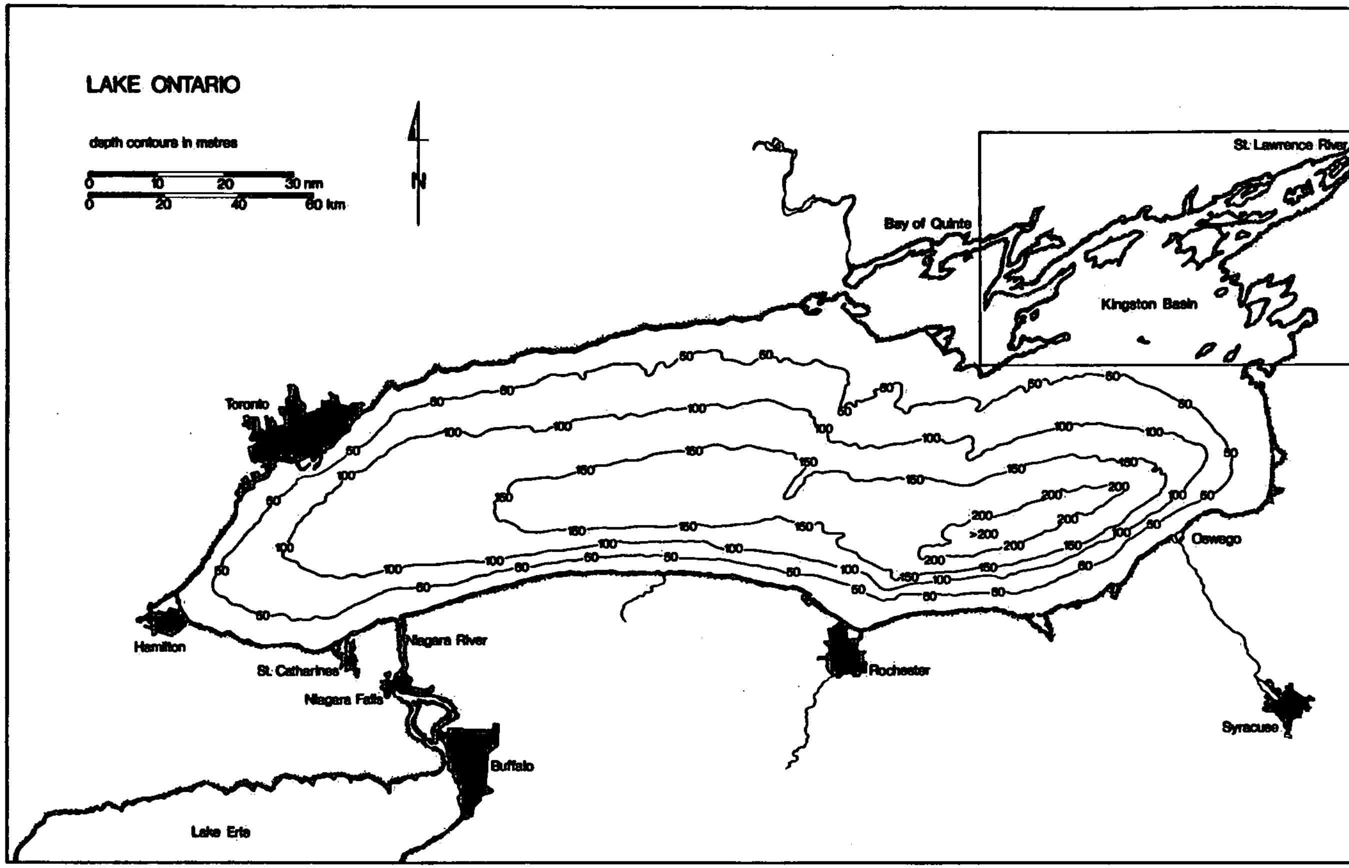

Fig. 1a Map of Lake Ontario including depth contours in meters

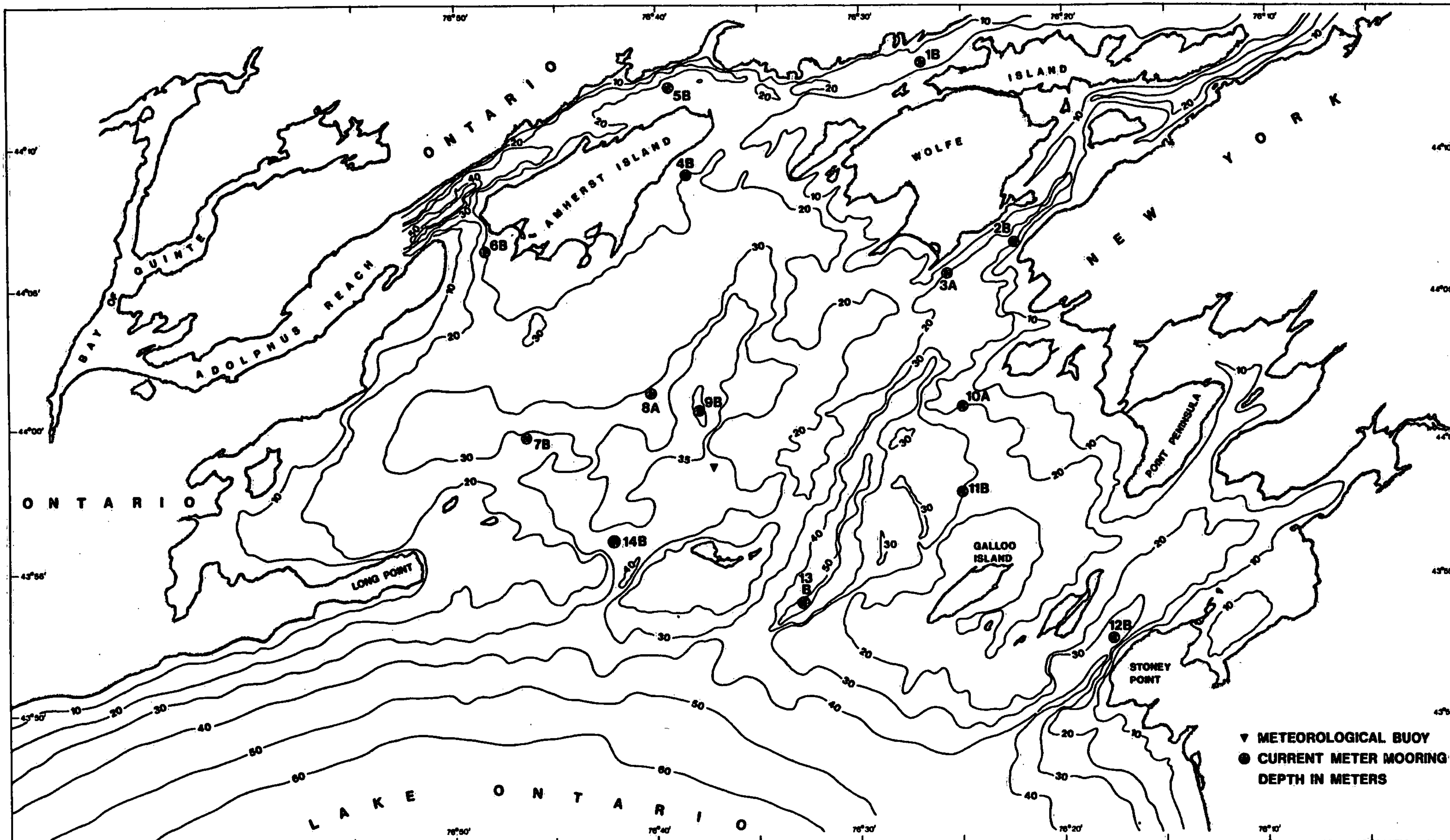

Fig. 1b Map of Kingston Basin indicating depth contours in meters and meteorological buoy and current meter locations

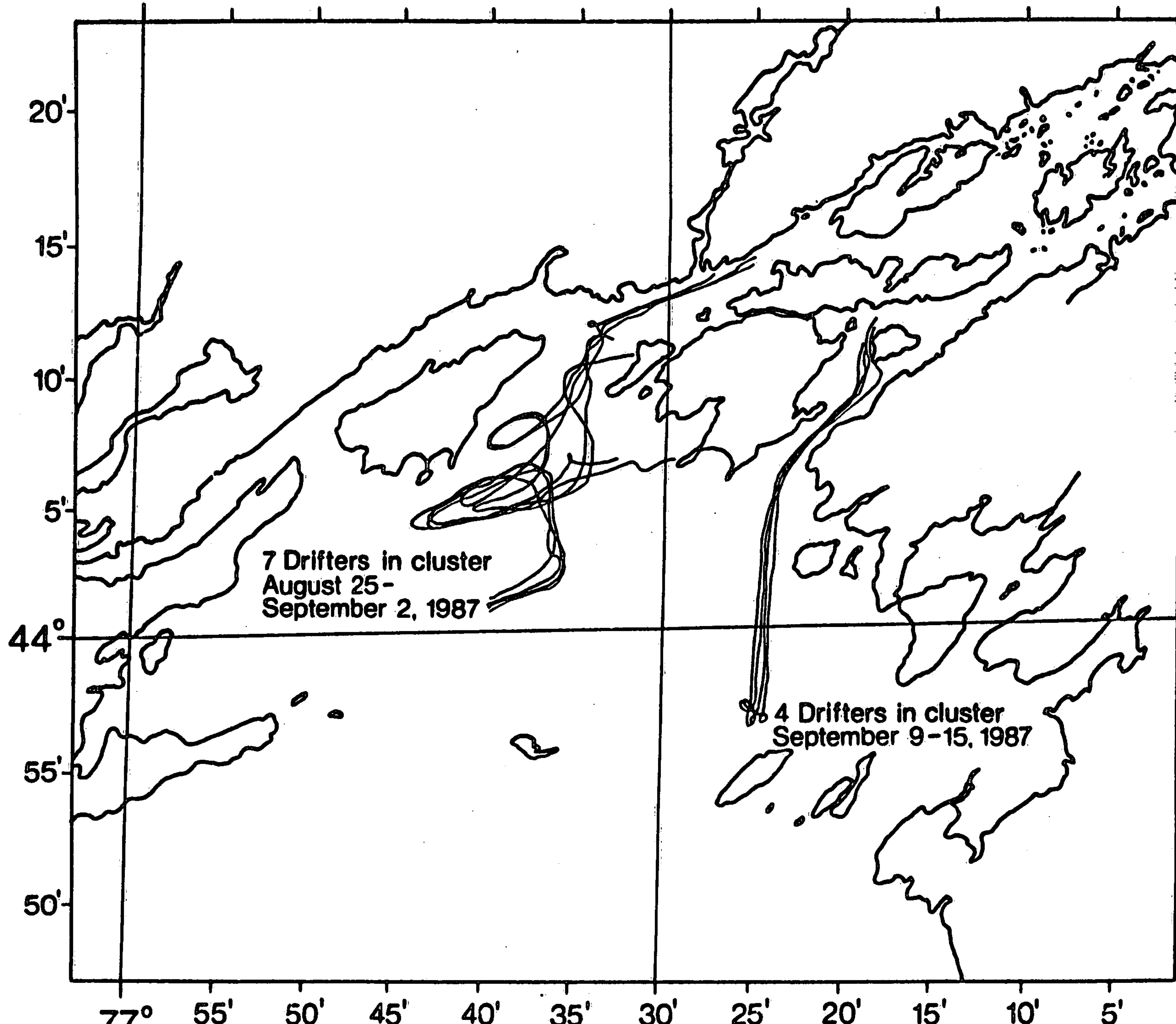

Fig. 2 Satellite-tracked drifter paths through the North and South Channels of Saint Lawrence River

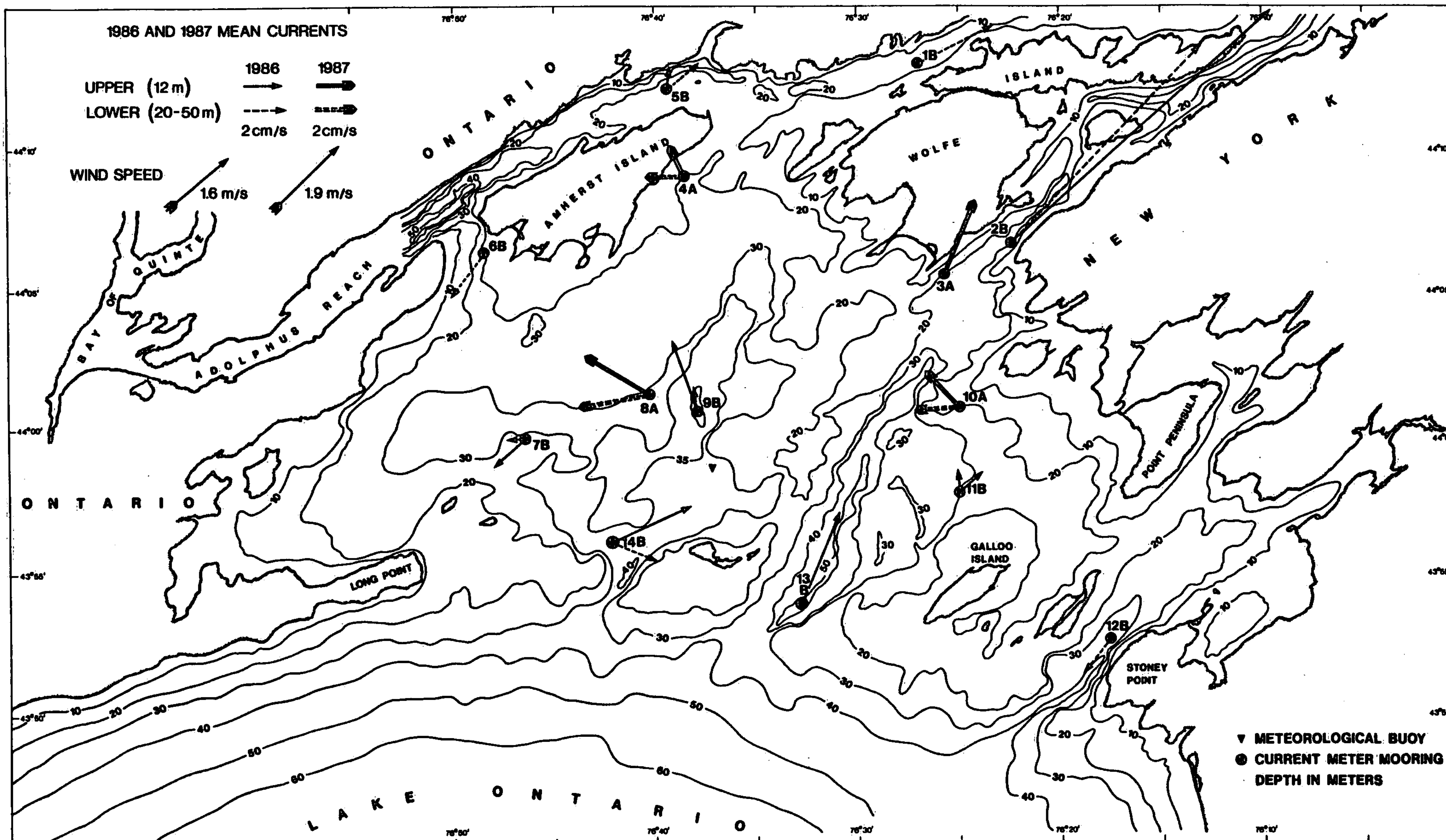

Fig. 3 Mean currents observed during the summer periods of 1986 and 1987 in Kingston Basin

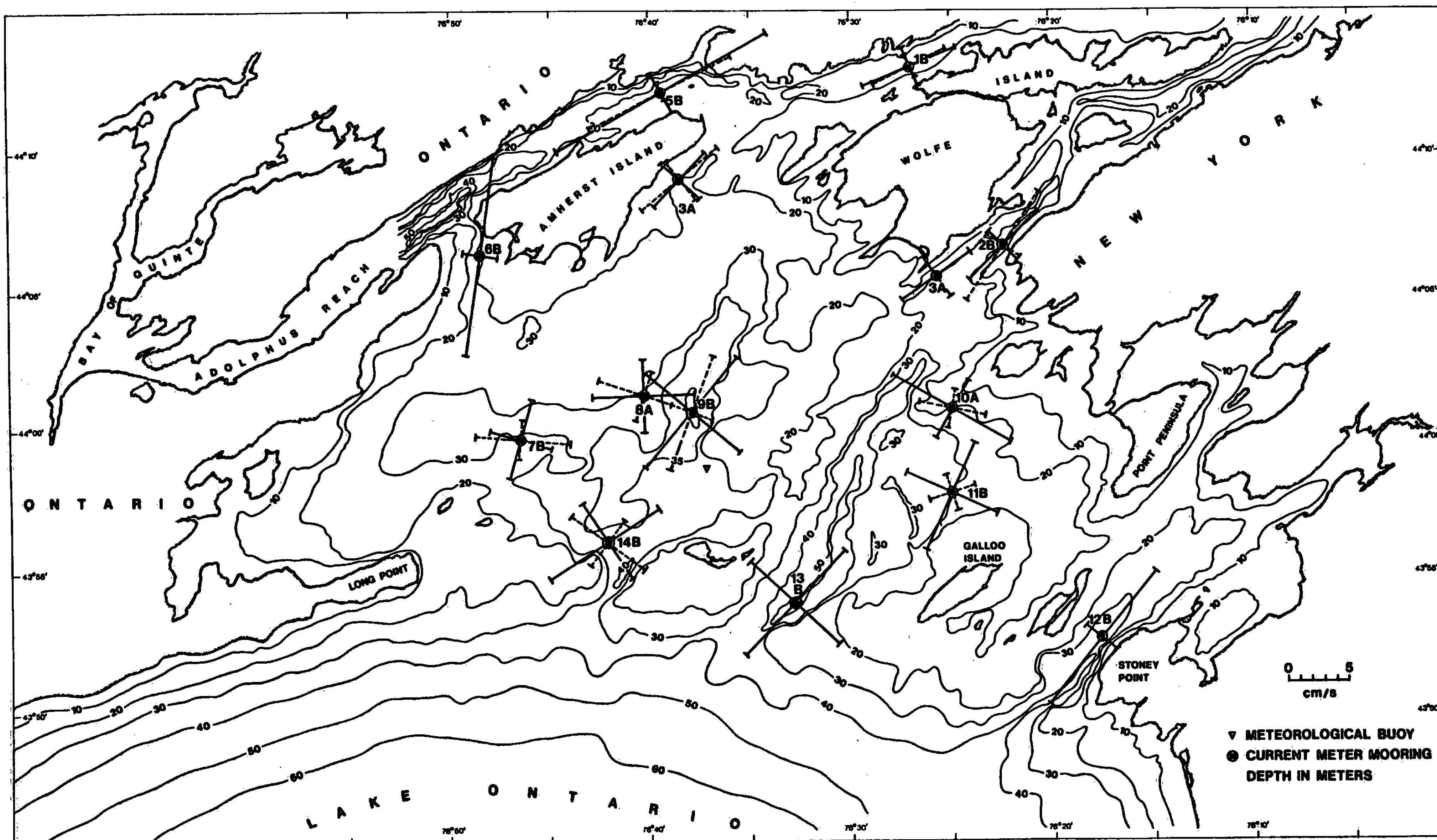

Fig. 4 Principal Axes of Currents observed during the summer periods of 1986 and 1987 in Kingston Basin

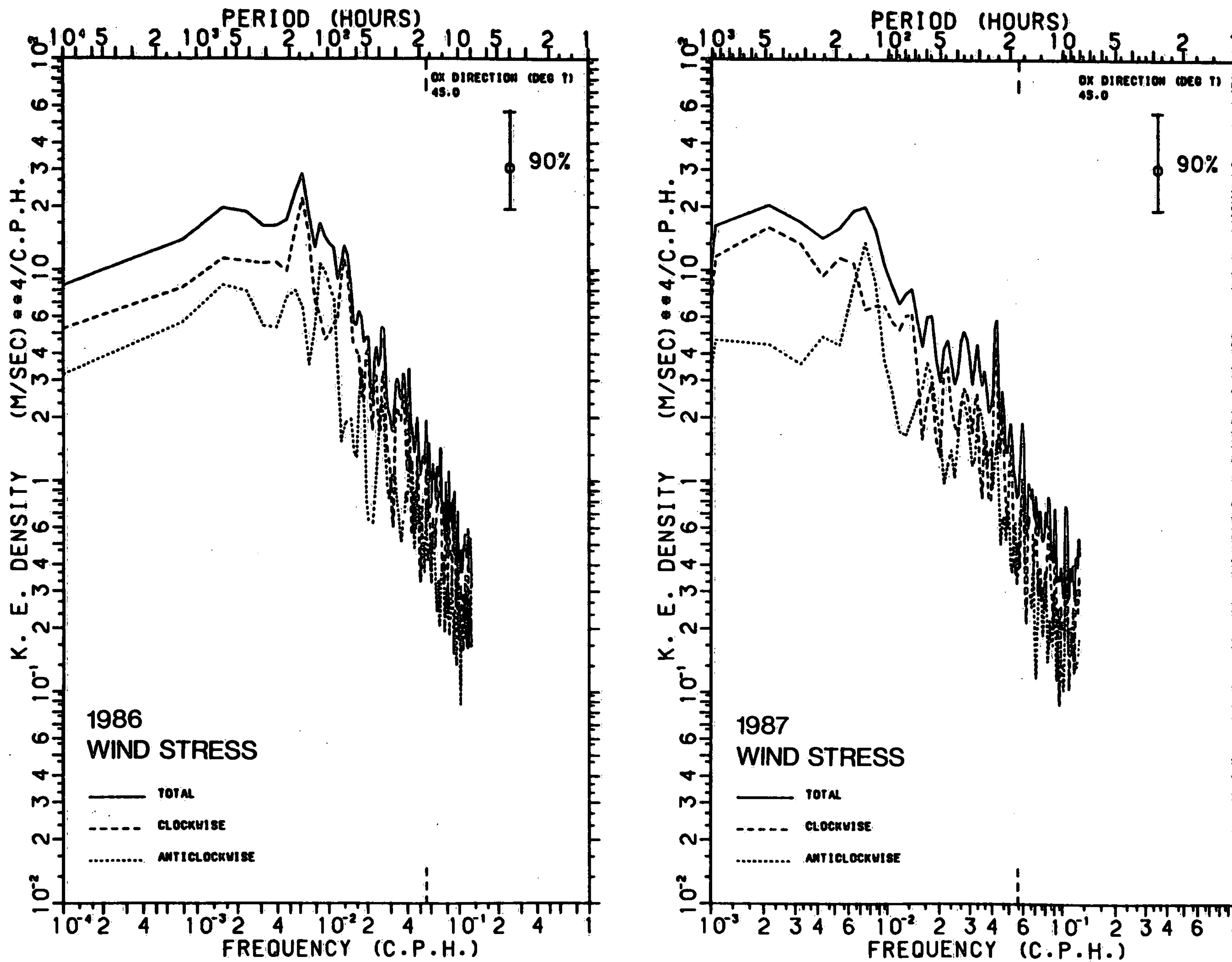

Fig. 5 Wind Stress Spectra for the summer periods of 1986 and 1987

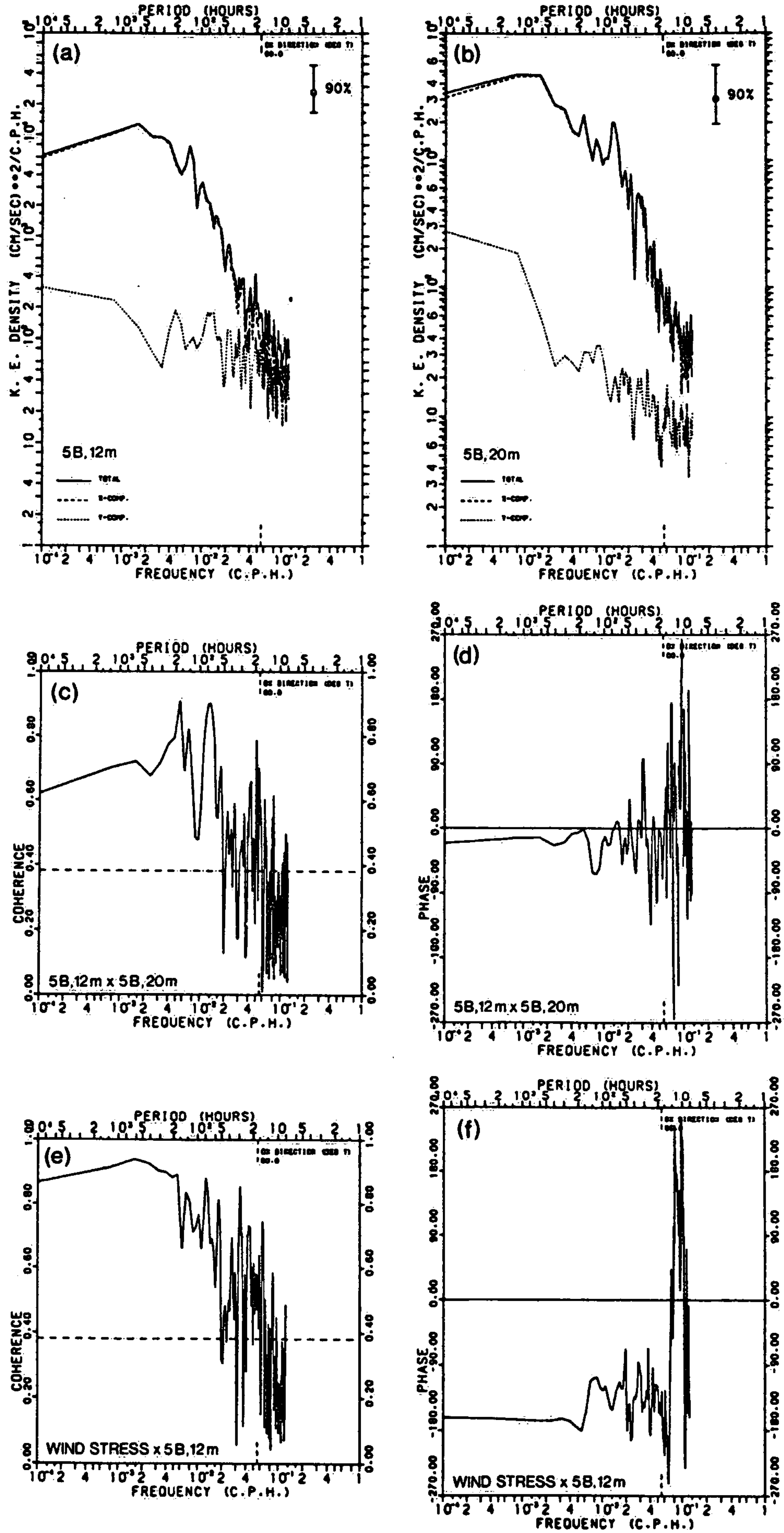

Fig. 6 Rotary x and y spectra, coherence and phase in Collins Bay Gap for the summer period of 1987

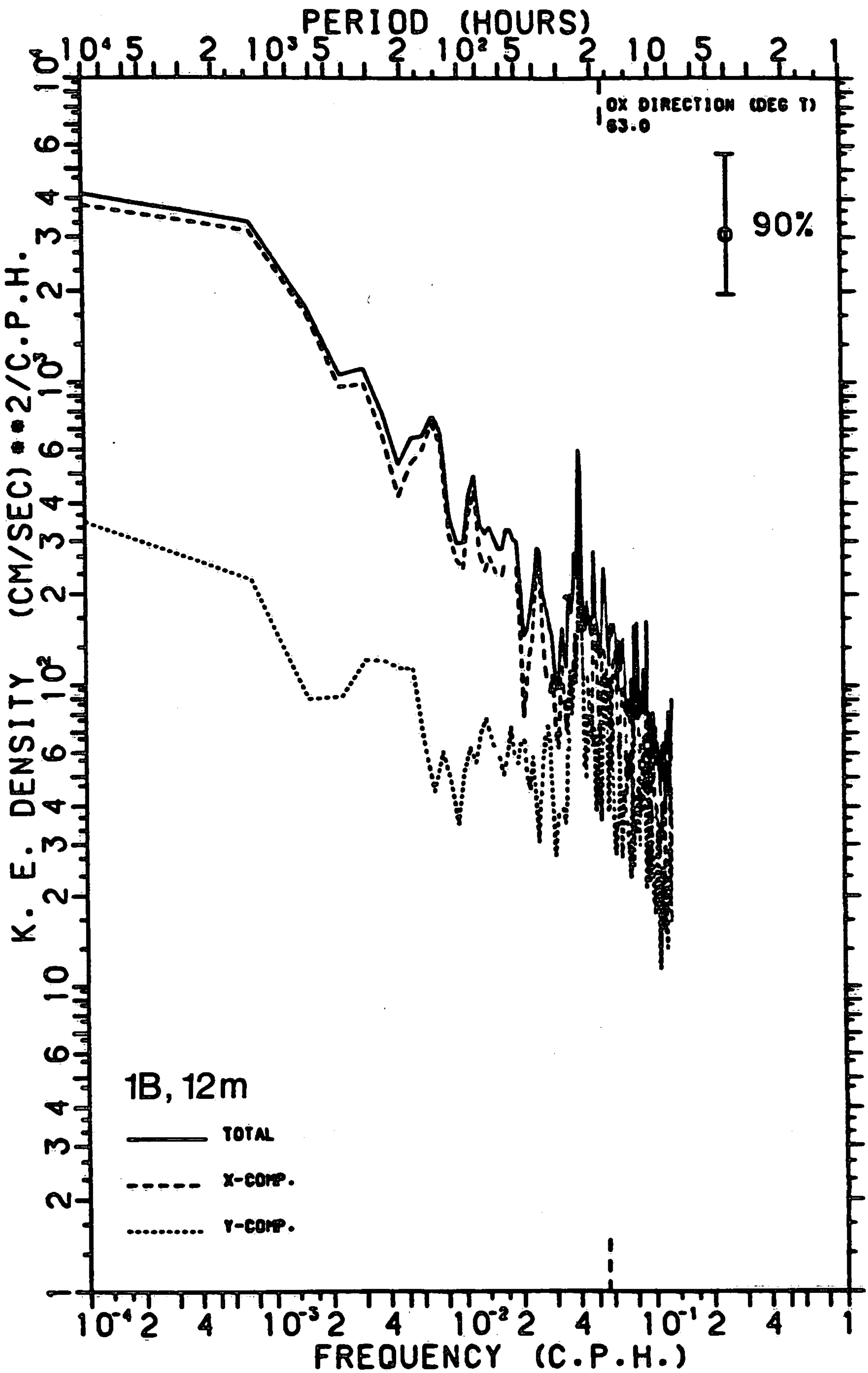

Fig. 7 Rotary x and y spectra in North Channel of Saint Lawrence River

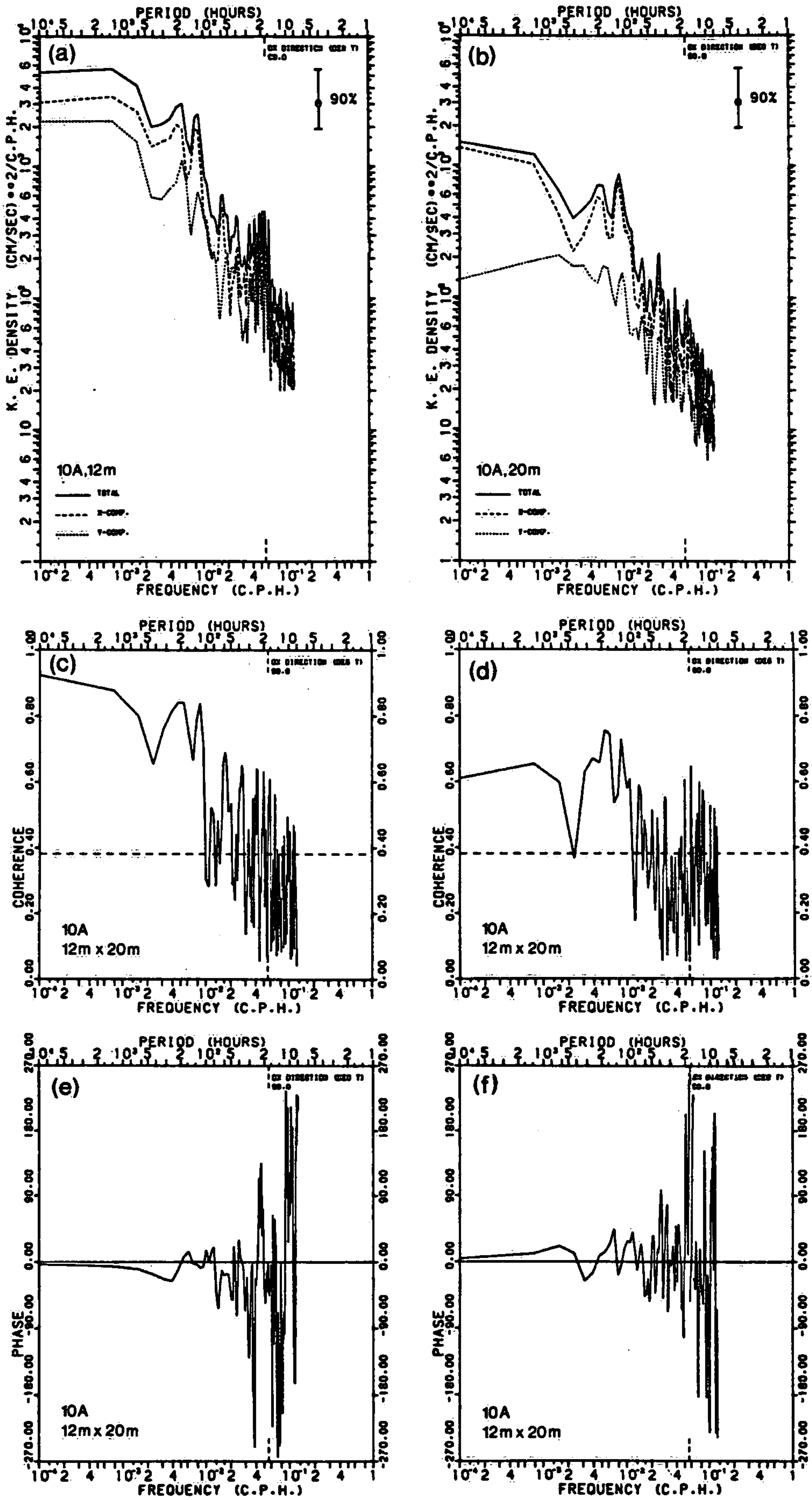

Fig. 8 Rotary x and y spectra, coherence and phase in Inner Bay for the summer period of 1987

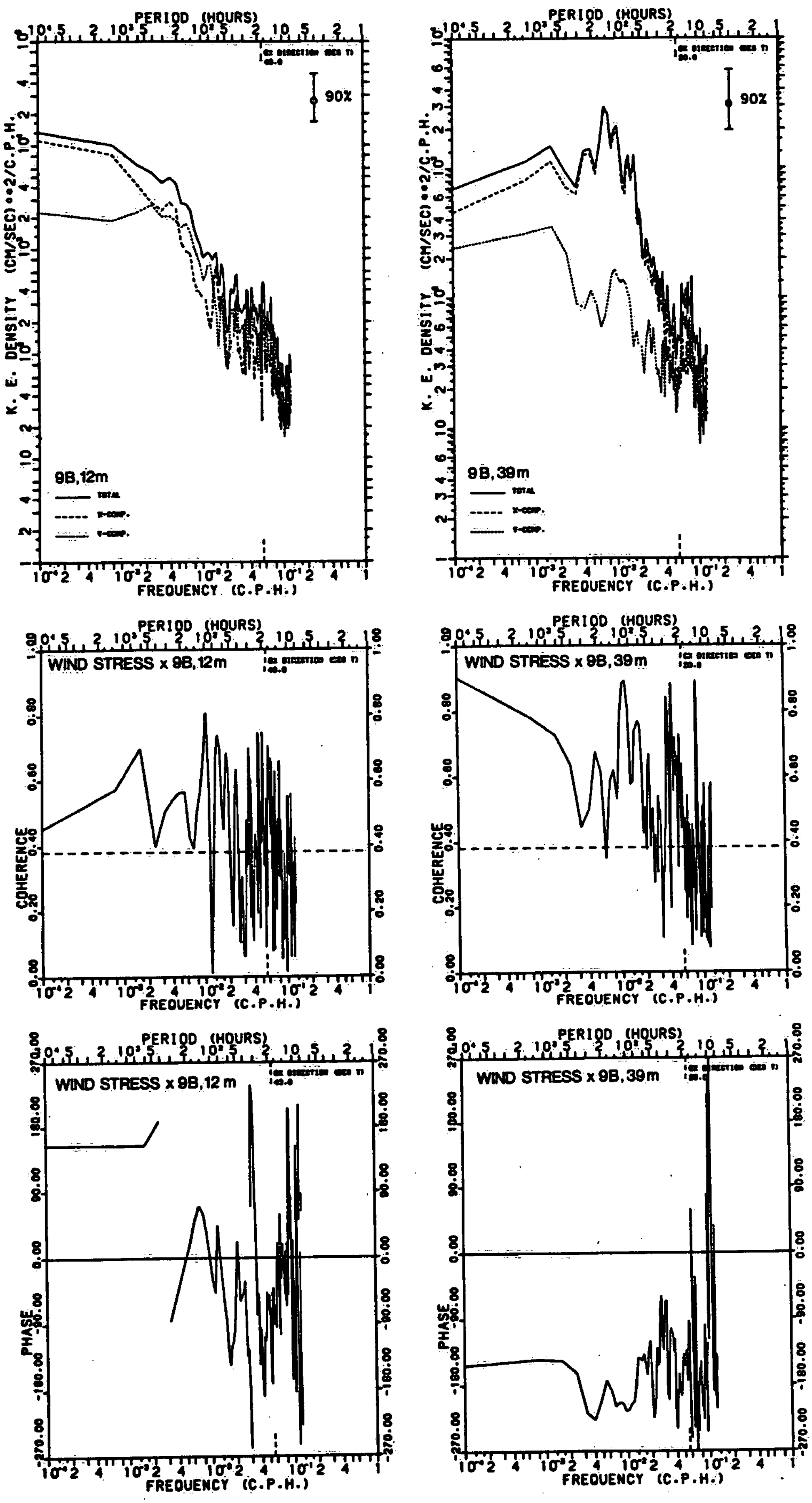

Fig. 9 Rotary x and y spectra, coherence and phase in the North channel of Inner Bay for the summer period of 1987

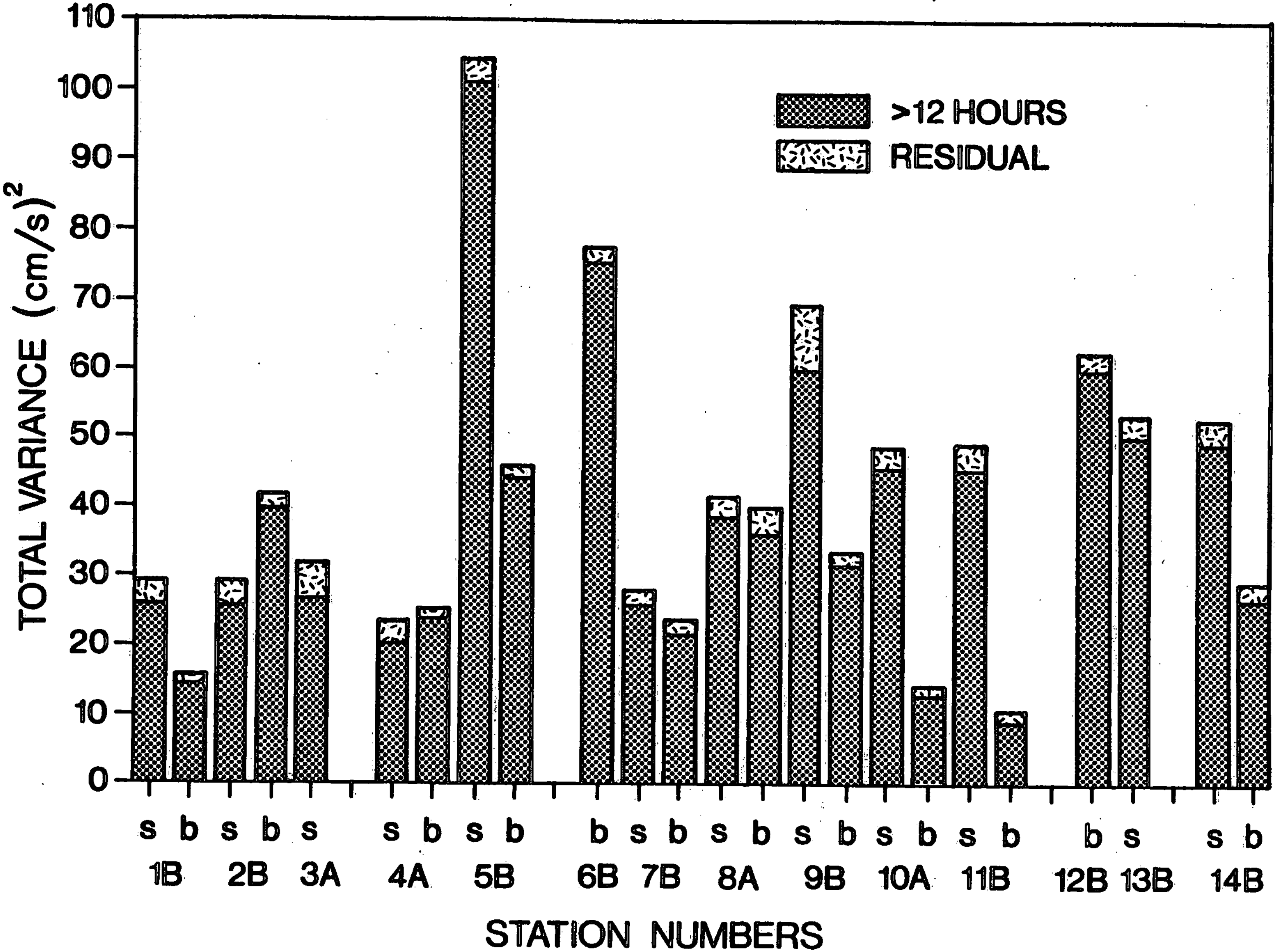

Fig. 10 Total Variance for all current meters in Kingston Basin

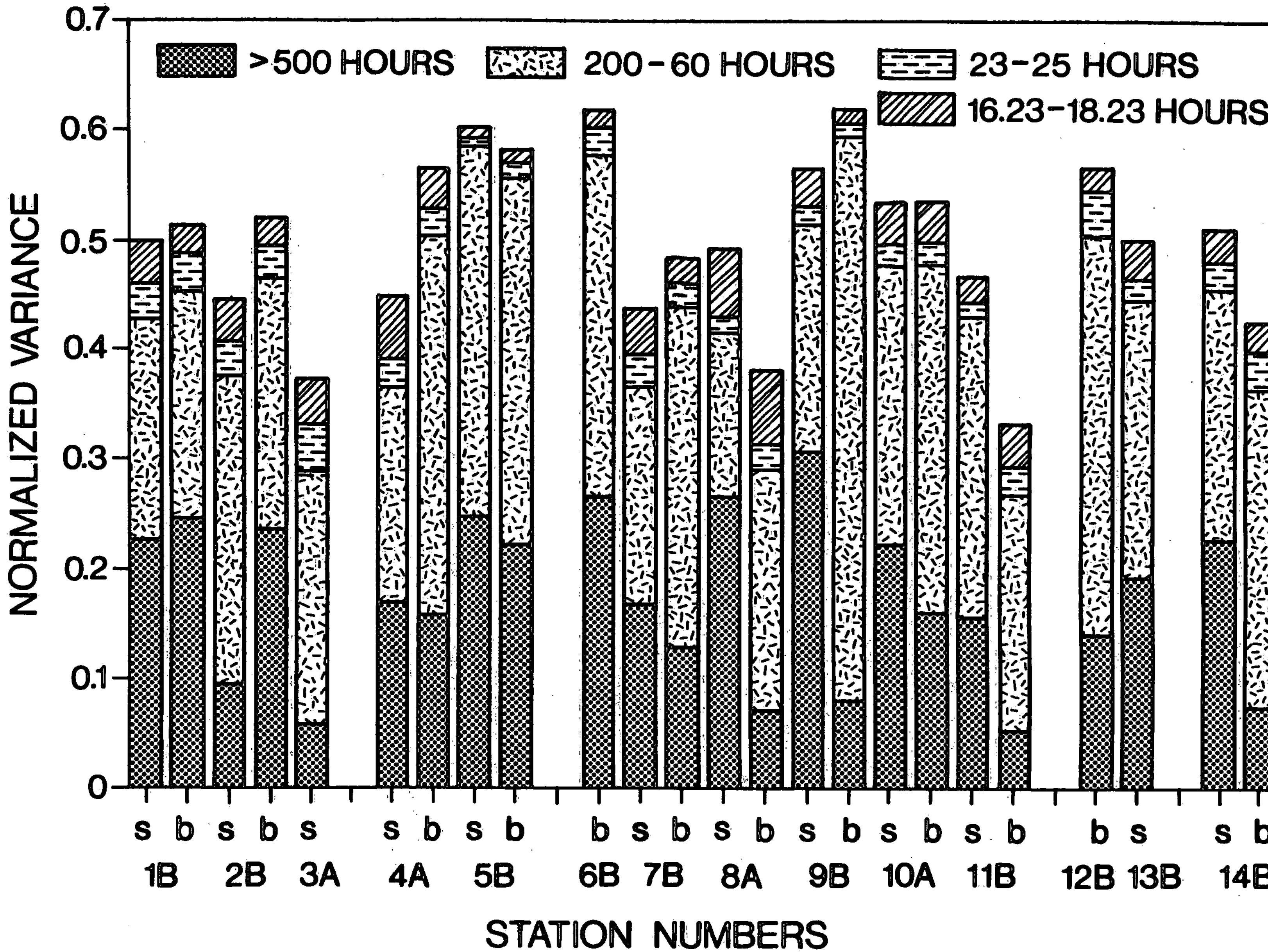

Fig. 11 Normalized Variance for all current meters in Kingston Basin

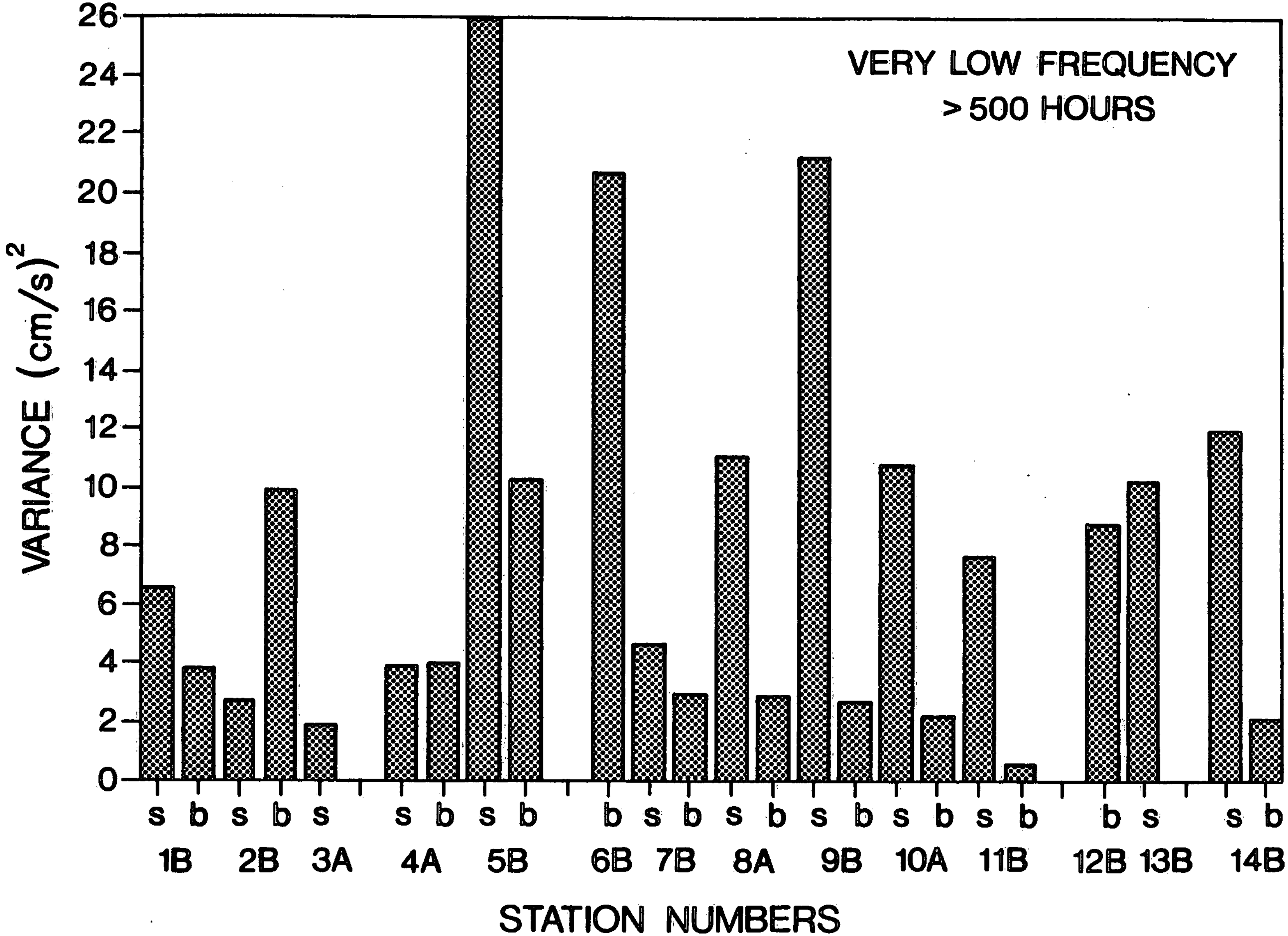

Fig. 12 Very Low Frequency Motion for all current meters in Kingston Basin

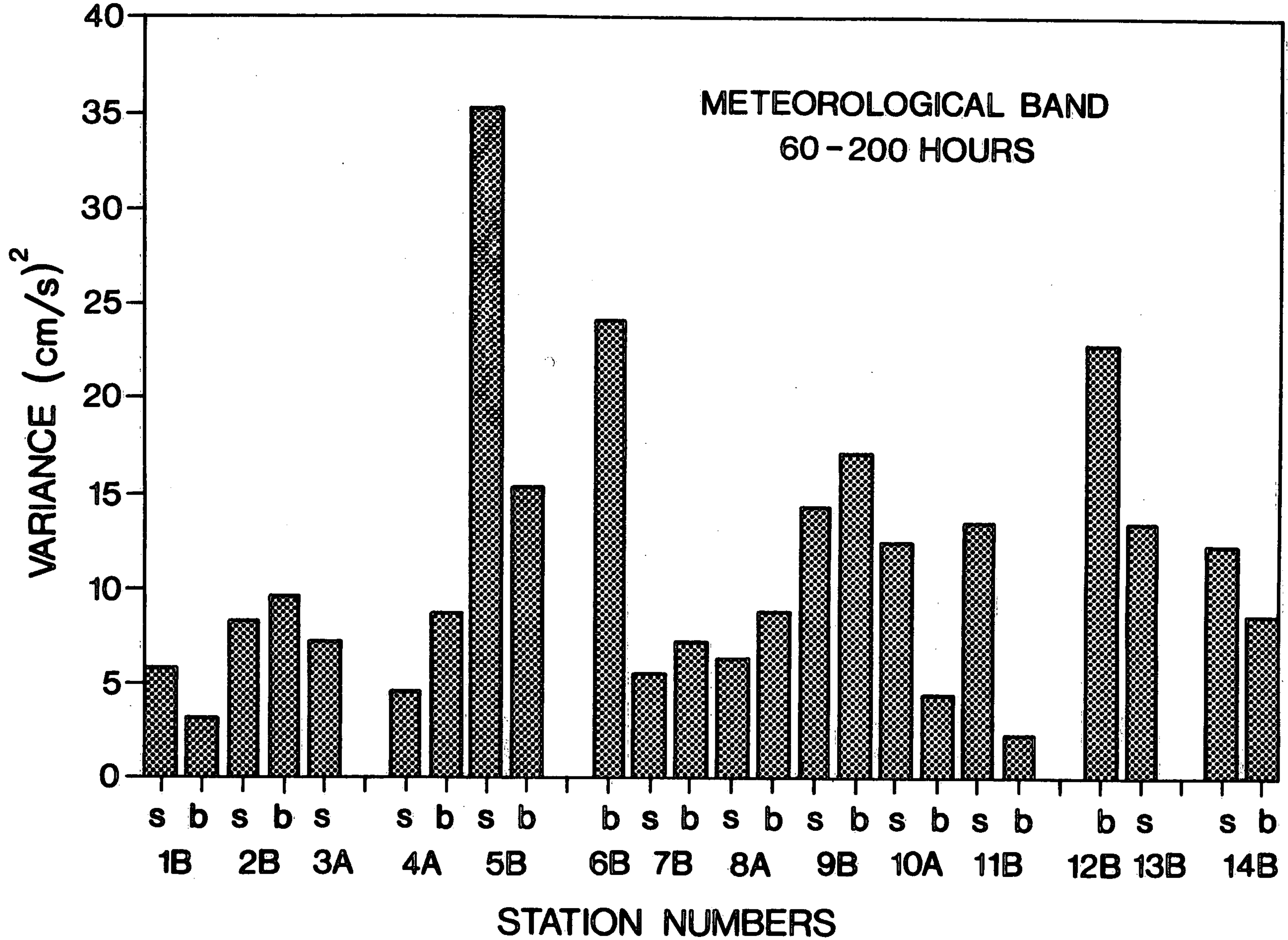

Fig. 13 Meteorological band for all current meters in Kingston Basin

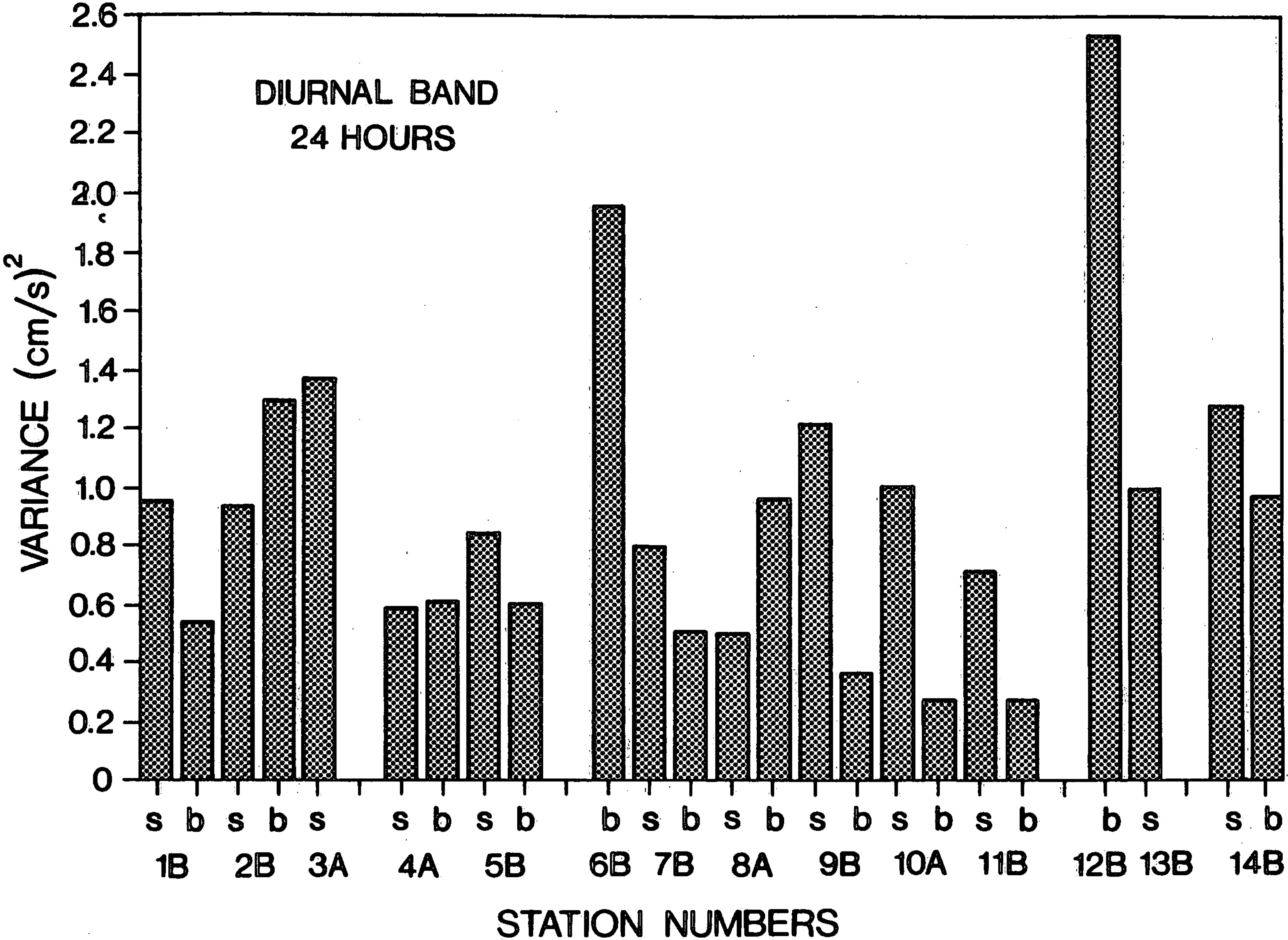

Fig. 14 Diurnal Band for all current meters in Kingston Basin

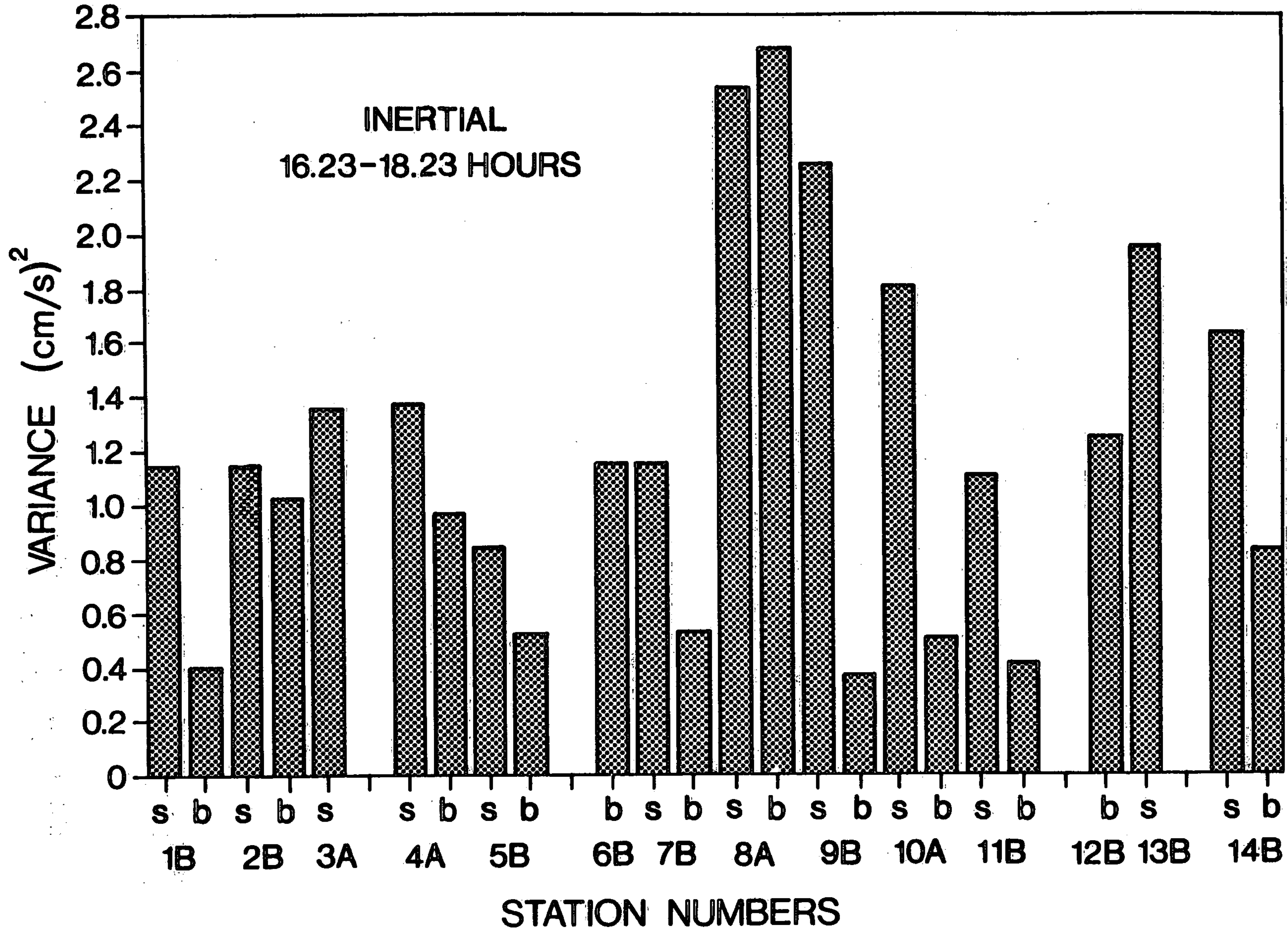

Fig. 15 Inertial Band for all current meters in Kingston Basin

NATIONAL WATER RESEARCH INSTITUTE
P.O. BOX 5050, BURLINGTON, ONTARIO L7R 4A6

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