SIMULATION OF POLLUTANT TRANSPORT ALONG THE NORTH SHORE OF LAKE ONTARIO

by

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ABSTRACT

Based on extensive current measurements in Lake Ontario near Pickering, empirical impulse response functions have been obtained which permit computation of coastal currents in this region from routine wind observations at Toronto Island Airport. The model may be expected to simulate about 75% of the variance of the actual currents in this region and to produce very reliable indications of alongshore current directions and reversals.

The empirical model for coastal currents has been combined with a stochastic disperson model using microcomputer technologies to predict the behaviour of contaminant spills in the nearshore zone of Lake Ontario. The model has been verified with the thermal effluent data collected near the Pickering Nuclear Power Generating Station.

RÉSUMÉ

En se fondant sur des mesures exhaustives des courants du lac Ontario enregistrées près de Pickering, on a obtenu des fonctions empiriques de réponse en impulsion qui permettent de calculer les courants côtiers de cette région à partir des observations courantes du vent effectuées à l'aéroport Toronto Island. On peut s'attendre que le modèle simule environ 75 p. 100 de la variance des courants réels de la région et indique de façon très fiable la direction et le renversement des courants côtiers.

Le modèle empirique des courants côtiers a été combiné à l'aide de micro-ordinateurs à un modèle stochastique de dispersion pour prévoir le comportement des contaminants déversés dans la zone littorale du lac Ontario. Le modèle a été vérifié à l'aide des données sur les effluents thermiques recueillies près de la centrale nucléaire de Pickering.

INTRODUCTION

From early December 1979 to the end of March 1980, the National Water Research Institute, the Ontario Ministry of the Environment and Ontario Hydro conducted a joint experimental program to study the behaviour of the thermal plume at the Pickering Generating Station on the north shore of Lake Ontario. In view of the impact of coastal currents on the transport and dispersion of waste heat and pollutants released in the nearshore zones of large lakes, the program included a detailed study of the climatology and structure of the current regime at this location. A complete summary of current meter observations, including energy spectra and frequency distributions of speed and direction, has been presented by Bull and Murthy (1980). The present study analyses the observations in terms of an empirical model which permits calculation of coastal currents on the basis of local wind history alone. The coastal current model is then used to predict the observed thermal plume.

There is considerable observational evidence that nearshore current fluctuations tend to be strongly correlated with alongshore wind variations. Especially very close to shore it is often possible to demonstrate that alongshore currents result from a simple balance between the counteracting forces of local wind and bottom friction

(Winant and Beardsley, 1979). However, theoretical studies as well as statistical analysis of current records indicate that current fluctuations in homogeneous coastal waters can also be related to topographic waves, generally referred to as shelf waves (see, Mysak 1980). Since such waves propagate in a counterclockwise direction around the perimeter of a basin in the northern hemisphere, observed current fluctuations at a given locality can, in principle, reflect wave generation by wind at some distant point. Consequently, a model of coastal currents at a single location requires a complete description of the wind field over the whole basin. Fortunately, however, the spatial scale of weather systems is typically much larger than a basin such as Lake Ontario and hence, in first approximation, the wind may be assumed to be uniform in space. This means that it is possible to establish deterministic relationships between local wind and current fluctuations which include not only the effects of local forcing by wind and bottom friction but also the influence of distant forcing through wave mechanisms (Simons, 1983). This is the physical basis for the present study.

OBSERVATIONS

The primary component of the current meter network during the 1979/80 Pickering experiment was a transect of self-recording

current meter moorings perpendicular to the local shoreline. The location of this transect is shown in the upper part of Figure 1. Current meters were placed at a depth of 12 m below the surface with a few additional meters near the bottom. The location of instruments with complete or nearly complete data records for the entire measurement period are shown in the lower part of Figure 1 and tabulated in Table 1. The latter also includes the dates of continuous operation of each current meter.

The time series data were resolved into alongshore and onshore components with the shoreline orientation taken to be 70° from north. Frequency distributions of current speed and direction presented by Bull and Murthy (1980) show that shore-parallel currents dominate throughout the entire period. For most stations, the alongshore component contributes more than 95% of the total current energy. The directions alternate between easterly and westerly with typical periods of five to ten days and with a slight bias towards the easterly direction. Figure 2 presents the mean value and standard deviation of the alongshore current component as a function of distance from the shore. The currents increase rapidly with offshore distance within the first few kilometers from the shore and then gradually decrease further offshore. It is apparent that a frictional boundary layer is established nearshore with bottom friction bringing the flow to a halt at the shoreline. In deeper water the current

direction will eventually reverse itself since the total transport through a cross section of the lake must vanish except for the relatively small hydraulic flow. For a discussion of the cross-sectional current distributions under conditions of wind forcing, reference may be made to Bennett (1974) while typical current patterns of topographic waves in Lake Ontario may be found in the paper by Rao and Schwab (1976).

Winds were measured at the Pickering site during the 1979/80 field program. For the present analysis, however, it is desirable to use wind observations which are representative of conditions over open water. Furthermore, for practical applications of the model, it is obviously necessary that winds are measured on a routine basis. The weather station at Toronto Island Airport maintained by the Atmospheric Environment Service satisfies these criteria. Observations at this site compare favourably with winds measured by meteorological buoys during another Lake Ontario field program in 1982. The wind-stress is computed from the conventional quadratic relationship between surface drag and wind speed. The drag coefficient was taken to be 1.2×10^{-3} for wind speeds less than 10 m/s with a linear increase to 2.4×10^{-3} for speeds of 20 m/s and equal to the latter value for greater speeds. These values were estimated from various hydrodynamic modelling studies of the Great Lakes (see e.g. Simons, 1976). It should be noted, however, that the overall value of the

drag coefficient does not affect the results of any future application of an empirical model as long as the same value is used all the time.

Since the present study is concerned with the above mentioned current fluctuations with characteristic time scales of a few days and longer, it is desirable to eliminate high frequency perturbations without affecting the frequencies of interest. This is accomplished by a digital low pass filter with frequency response equal to unity for periods longer than 24 hours and gradually decreasing to zero at 18 hours. This eliminates all effects of free surface seiches, tides and inertial motions in Lake Ontario, while retaining all fluctuations with periods longer than one day. Since the energy spectra of winter currents contain very little energy at periods shorter than one day, the total variance of the current records is only slightly reduced by this filter. Results for the alongshore current components are presented in Table 2. The same procedure applied to the wind stress has a somewhat greater effect and reduces its variance by about 20%. The filtered alongshore wind and current components for the entire period of measurement are displayed by solid curves in Figure 3. The dashed lines represent model solutions which will be discussed presently.

EMPIRICAL MODEL

Within the framework of linear dynamics, the response of a lake to a general wind distribution in time and space can be represented by the integrated effects of sequences of wind impulses applied to each point of the surface of the lake. This Green's function or impulse response method is familiar from the literature on storm surge prediction. The method becomes particularly simple if the wind field can be assumed to be uniform in space over the whole lake. In that case, the current, u, at a particular location can be written as the following convolution integral

$$u(t) = \int_{-\infty}^{t} R\,(t - t') \cdot \tau\,(t')\,dt' \qquad (1)$$

where τ is the wind stress history and R the impulse response function for the location of interest. Note that, although τ may be uniform in space, both u and R vary from point to point and hence the impulse response must be determined for each point of the lake. This can be done by using hydrodynamical models or, as done here, by comparing observed wind and current records. Similar computations for storm surges were made by Schwab (1979).

Due to friction, the lake has a finite memory and hence the integration has to cover only a limited time interval, T. Then, after a reversal of the direction of integration in time, (1) becomes

$$u(t) = \int_0^T \tau (t - t') \cdot R (t') \, dt' \qquad (2)$$

For practical applications, the integral is represented by finite differences with time interval Δt and memory $N = T/\Delta t$. Let the current be specified at integer multiples of Δt and let the wind stress be given as average values for each interval of Δt. Thus the winds and currents are staggered in time such that

$$u_i = u (i\Delta t) \qquad \tau_i = \tau \left[(i + \frac{1}{2}) \Delta t\right] \qquad i = 1,2,3 \ldots \qquad (3)$$

Then the integral (2) may be approximated by

$$u_i = \sum_{n=1}^{N} \tau_{i-n} \; R_n \qquad (4)$$

where $R_n = \Delta t \cdot R (n\Delta t)$. Given a series of wind observations and a current meter record, Equation (4) generates a system of equations which can be solved for the unknown impulse response. In order to

obtain reliable results, the length of the data series should be much longer than the length of the response function and the system must be solved by minimizing the squared differences between the lhs and rhs of (4). This is readily done by one of the least squares algorithms available in standard computer libraries.

After some experimentation a suitable time step for the present calculations was found to be 12 hours. The maximum length of the impulse response was taken to be 30 days, about one quarter of the total record length of 116 days. In order to utilize the complete current records, the wind record was extended backward in time by 30 days. In principle, both the current and the wind stress in Equation (4) are vector quantities and hence the response function consists of four independent time series. However, it was pointed out above that onshore current components in the study area are negligible compared to alongshore components. From theoretical studies and hydrodynamical model experiments (Gill and Schumann, 1974; Simons, 1983), it is known that such alongshore currents are primarily excited by alongshore wind components. Thus, in first instance, the least squares algorithm was applied to these components only. Convolution of the computed impulse response functions with the wind history results in the dashed curves of Figure 3. The agreement with observations is generally adequate, especially with regard to current direction and time of reversal.

The error patterns tend to be similar for all stations of Figure 3 which suggests erroneous estimates of wind stress, perhaps effects of non-uniform wind fields, or effects of onshore wind components. In order to investigate the latter, the least squares procedure was extended to include both wind components. Although this resulted in reduction of error variance, the response functions for the onshore wind component do not appear to converge for different truncation and hence the results are questionable.

The response functions for alongshore wind components show a rapid damping as a function of time and excellent convergence for different truncation. This indicates that the memory of the nearshore zone is much shorter than 30 days. The optimum length of the response functions may be determined from the behaviour of the error as a function of truncation. In order to compare different stations it is convenient to express the error in terms of observed currents. A suitable measure of the mean square error, which is minimized by the computer algorithm, is

$$\varepsilon \equiv \overline{(u_o - u_c)^2} \,/\, \overline{u_o^{\,2}} \qquad (5)$$

where the subscript o and c refer to observed and computed currents, respectively, and the bars refer to the whole period of observation. Also of interest is the mean error

$$\delta \equiv \overline{(u_o - u_c)} \,/\, \overline{u_o} \qquad (6)$$

Figure 4 shows the behaviour of these error indicators as a function of the length of the impulse response for each station. The curves of the mean square error exhibit a characteristic break point beyond which the error decreases very little with increasing memory. These points are indicated by black circles and will be taken to represent the optimum length of the response function. Table 3 presents the mean square error (5) for these truncated response functions as compared to the errors of the 30-day response functions. As seen from Figure 4, the mean error (6) also remains generally small if the response functions are truncated in this fashion.

As measured by the optimum length of the response functions, the memory of the lake increases with distance offshore from about five days at the shoreline to 15 days at the outer edge of the current meter array. This appears reasonable since effects of bottom friction may be expected to vary in proportion to the inverse of some power of the water depth.

For practical applications it is useful to interpolate the empirical response functions to regular increments of distance

offshore. The results are displayed in Figure 5 and tabulated in Table 5. In physical terms, the curves represent the local current response to a 12-hour wind impulse of 1 dyne/cm^2 = 0.1 N/m^2. The origin of the time axis is placed at the start of the wind impulse. Thus, during the first 12 hours, the currents increase more or less linearly with time. After the wind stops, nearshore currents are rapidly damped by friction, while offshore currents remain relatively constant for a few days. After about five days the current reverses itself due to topographic wave activity (Clarke, 1977; Marmorino, 1979; Simons, 1983). While the speed of the return current is relatively small, it should be noted that the effect of topograhic waves on the overall shape of the response functions is considerable.

POLLUTANT TRANSPORT MODEL FOR MICROCOMPUTERS

The empirical relationship (4) between the wind and the coastal current provides a description of nearshore circulation for use in pollutant transport models. Most conventional models are based on complex and time-consuming methods such as hydrodynamical modelling techniques (Simons, 1983) and objective analysis methods (Lam and Durham, 1984), which require the use of main frame computers. By contrast, the empirical relationship (4) can be implemented on a microcomputer. However, certain assumptions must be made if this relationship is used to model nearshore pollutant transport. In the

first place, equation (4) predicts only the alongshore component of the current at the transect line of current meters shown in Fig. 1 and hence a procedure is required to extend this computation to either side of this transect. Secondly, a description of the offshore current component and the turbulent water motions must be provided.

In order to extend the empirical relationship (4) to the east and west of the transect line, it is assumed that the radius of curvature of the shoreline and depth contours are much larger than the width of the coastal zone. In that case, it is known from observations that coastal currents tend to be aligned with local depth contours and, hence, each depth contour can be regarded as a streamline. Since the transport of water contained between any pair of streamlines must be conserved and since the depth remains constant along these streamlines, the current speed must increase (decrease) if the depth contours converge (diverge). Thus, given the alongshore currents at the transect line and given the depth contours in the coastal area of interest, the direction and the speed of the current are known everywhere. The computing procedure is as follows. First, selected depth contours are obtained from a bathymetric map. Next, the currents at the location of the transect line are computed from (4). Then, following each depth contour, the current direction is taken to be along the contour and the current speed changes in proportion to the inverse of the contour spacing. Finally, currents in any desired point are obtained by interpolation.

As pointed out earlier, the current component along depth contours carries more than 95% of the total current energy at most stations such that the component of the current across depth contours is usually small. For convenience, therefore, the latter can be regarded as part of the turbulence. That is, the water movements across depth contours can be regarded as random oscillations which will eventually cause the pollutants to be dispersed to the open lake. There are, of course, random current fluctuations along depth contours as well. A simple way to treat these turbulence effects is to assume equal randomness in all directions, i.e. a constant diffusion model (Lam and Durham, 1984). This alongshore flow - constant diffusion model can be implemented in a Lagrangian framework to avoid possible numerical dispersion (Lam and Durham, 1984).

Unlike the conventional Eulerian model in which the governing transport equation is based on a fixed coordinate system, the Lagrangian model is based on a moving frame which follows the parcel of water containing the tracer in question. In other words, the Lagrangian model framework moves in time and space according to some "averaged" current, e.g., the one defined by the movement of the centroid of a group of tracers. The fluctuations of the movement of each tracer with respect to this mean current provide a description of the randomness of the environmental turbulence as discussed earlier.

Given interpolated currents in all points of the area of interest at two times, t_n and $t_{n+1} = t_n + \Delta t$, the Lagrangian description of the pathway of a fluid particle from its original position x_n, y_n to its new position x_{n+1}, y_{n+1} is

$$x_{n+1} = x_n + \frac{\Delta t}{2} (u(x_{n+1}, y_{n+1}, t_{n+1}) + u(x_n, y_n, t_n)) \tag{7}$$

$$y_{n+1} = y_n + \frac{\Delta t}{2} (v(x_{n+1}, y_{n+1}, t_{n+1}) + v(x_n, y_n, t_n)) \tag{8}$$

Functional iteration is required because the unknowns x_{n+1}, y_{n+1} appear as arguments of the functions u and v on the right-hand side of the equations. A convenient initial guess is to put $x_{n+1} = x_n$ and $y_{n+1} = y_n$ on the right-hand side to start the iteration.

The present study uses the stochastic dispersion model of Simons et al. (1975). The pollutants are represented by an ensemble of particles and the model computes the displacements of the individual particles for a sequence of time steps of order one hour or less. At any time, each particle is displaced by the mean flow plus a random component simulating turbulent currents. The random effect results in different displacements of each particle and, since the mean flow changes in space and time, each particle will be subjected to different mean currents as the prediction progresses. The distribution of particles at any given time may be interpreted either

as the concentration distribution of the pollutant or as the probability of finding the pollutant in a given location.

The computation of the movement of individual particles proceeds as follows. Let x and y be rectangular coordinates with the x-axis along the mean orientation of the shoreline and the y-axis pointing toward the lake. Let U_j be the currents computed from the empirical equation at the location of the current meter transect such that j=0 represents the shore and j=1,2...10 are offshore points at 1 km intervals. Let $Y_j(x)$ be the y-coordinates of the shoreline (j=0) and the depth contours (j=1,2,...10) which cross the data transect at 1 km intervals. Finally, let Δu, Δv be the turbulent velocity components and x_0, y_0 the initial coordinates of the particle. The coordinates x_1, y_1 after time step Δt are then computed as follows.

First, the two depth contours adjacent to the initial point are found, say $Y_j\ (x_0)$ and $Y_{j+1}\ (x_0)$. Then the relative distance is defined as

$$r = [y_0 - Y_j\ (x_0)] \ / \ [Y_{j+1}\ (x_0) - Y_j\ (x_0)] \qquad (9)$$

Since the mean flow is assumed to follow depth contours, r remains constant along a streamline and the current speed changes in proportion to the inverse of the contour spacing. It follows that

$$u_0 = [U_j + r(U_{j+1} - U_j)] / [Y_{j+1}(x_0) - Y_j(x_0)] \qquad (10)$$

and hence the alongshore displacement is

$$x_1 = x_0 + (u_0 + \Delta u) \cdot \Delta t \qquad (11)$$

From the same assumption the offshore displacement is found to be

$$y_1 = Y_j(x_1) + r[Y_{j+1}(x_1) - Y_j(x_1)] + \Delta v . \Delta t \qquad (12)$$

More accurate results could be obtained by iteration such that the velocity would be determined by the new position as well as by the old one in accordance with (7) and (8), but this is not necessary for small time steps. Also, the above procedure should actually employ a system of curvilinear coordinates but this effect is small if the radius of curvature of the shoreline and depth contours are sufficiently large.

This model has been implemented on an IBM-PC micro-computer (Middleton and Swayne, 1985) and can be easily implemented on other similar computers. The program is stored on a diskette and is easy to operate. The input required is the wind record over several days and the output is the pollutant distribution represented by a group of prixels illuminated on the screen of the computer monitor. The density of prixels can be used to compute the probability distribution

or concentration of the pollutant. For example, Figure 6a shows the observed and computed results of the thermal plume at the Pickering Nuclear Power Generating Station on April 1, 1980. The model predicts reasonably well the plume movement from Pickering to Scarborough for a given easterly wind condition. Conversely, the model predicts accurately the plume movement from Pickering to Whitby for a westerly wind on March 4, 1980 (Fig. 6b)

SUMMARY AND CONCLUSIONS

Based on extensive current measurements in Lake Ontario near Pickering, empirical impulse response functions have been obtained which permit computation of coastal currents in this region from routine wind observations at Toronto Island Airport. The calculation is performed by convolution of the response functions of Figure 5 with the wind history in accordance with Equation (4). Note that, since the wind and currents as defined by Equation (3) are staggered in time, the current at a given instant is determined by a series of 12-hour mean winds preceding this current. Or, given a filtered wind record from which oscillations shorter than one day have been eliminated, the current at a particular time is obtained from wind stress values at the midpoints of a sequence of preceding time intervals of 12 hour duration. The most recent stress value is multiplied by R_1, the one before is multiplied by R_2 and so on, where R_n represents values of the local impulse response at multiples of

half a day. The model may be expected to simulate about 75% of the variance of the actual currents in this region and to produce very reliable indications of alongshore current directions and reversals.

Given the limitations of the water temperature as a tracer (Lam and Durham, 1984), the verification results of the pollutant transport model are encouraging. Indeed, because of the efficient algorithms adopted, the model execution is fast and the pixel movemnt movement on the microcomputer monitor is almost instantaneous for each entry of wind record. These simple but accurate computing technologies have now paved a new way for developing real-time, operational models for engineering applications such as crisis management of accidental spills of contaminants in the coastal zone.

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TABLE 1. CURRENT METER RECORDS USED IN PRESENT STUDY

Record	Offshore Distance (km)	Water Depth (m)	Instrument Depth (m)	Continuous Data Period Dates day/mo/year	Total Days
1	0.7	8.2	8	7/12/79-31/3/80	116
2	1.3	13.0	12	28/12/79-31/3/80	95
3	3.0	25.1	23	7/12/79-31/3/80	116
4	4.0	29.8	12	7/12/79-31/3/80	116
5	4.0	29.8	29	7/12/79-31/3/80	116
6	5.5	47.5	12	7/12/79-31/3/80	116
7	7.0	62.0	12	7/12/79- 4/3/80	89
8	9.0	72.0	12	7/12/79- 3/3/80	88
9	12.0	92.0	12	7/12/79-31/3/80	116

TABLE 2. VARIANCE OF ALONGSHORE CURRENTS BEFORE (a) AND AFTER (b) LOW-PASS FILTERING WITH CUT-OFF PERIOD OF 1 DAY

Offshore Distance		0.7	1.3	3.0	4.0	4.0	5.5	7.0	9.0	12.0
Instrument Depth		8	12	23	12	29	12	12	12	12
Variance	a	43	89	124	306	127	325	294	233	186
(cm^2/s^2)	b	36	86	121	304	125	323	292	232	183

TABLE 3. MEAN SQUARE ERROR AS DEFINED BY EQUATION (5) FOR (a) IMPULSE RESPONSES WITH UNIFORM LENGTH OF 30 DAYS AND (b) RESPONSE FUNCTIONS TRUNCATED AT BLACK CIRCLES OF FIGURE 4

Offshore Distance		0.7	1.3	3.0	4.0	4.0	5.5	7.0	9.0	12.0
Instrument Depth		8	12	23	12	29	12	12	12	12
Mean Square	a	.29	.28	.19	.20	.20	.23	.26	.27	.35
Error	b	.32	.30	.23	.22	.22	.24	.28	.29	.37

TABLE 4. EMPIRICAL CURRENT RESPONSE FUNCTIONS (cm/s) IN COASTAL ZONE OFF PICKERING FOR 12-HOUR WIND STRESS IMPULSE OF 1 dyne/cm^2 = 0.1 N/m^2

Days	Offshore Distance (km)										
	1	2	3	4	5	6	7	8	9	10	Rn
0.5	5.8	7.6	8.5	8.7	6.9	5.7	4.9	4.1	3.4	2.8	n=1
1.0	1.4	2.8	4.2	5.7	6.0	5.4	4.7	4.5	4.2	3.7	n=2
1.5	.5	1.6	2.9	3.6	4.3	4.6	4.4	4.2	3.9	3.6	.
2.0	.8	1.7	2.5	3.3	3.9	4.2	4.0	3.7	3.4	3.2	.
2.5	.6	1.3	2.0	2.7	3.3	3.6	3.4	3.1	2.9	2.8	.
3.0	.3	.8	1.5	1.9	2.7	3.0	2.9	2.7	2.6	2.6	
3.5	.2	.4	.7	1.0	1.7	2.2	2.3	2.3	2.4	2.4	
4.0	-.1	-.0	.1	.2	.7	1.1	1.4	1.7	1.8	2.0	
4.5	-.4	-.4	-.3	-.4	-.1	.1	.4	.6	.8	1.1	
5.0	-.5	-.7	-.9	-1.1	-.8	-.6	-.4	-.3	-.1	.1	
5.5	-.3	-.6	-.9	-1.1	-.9	-.7	-.4	-.4	-.4	-.2	
6.0	-.0	-.3	-.6	-.8	-.6	-.4	-.2	-.1	-.1	.0	
6.5		-.3	-.6	-.8	-.6	-.4	-.3	-.2	-.1	.0	
7.0		-.4	-.6	-.9	-.8	-.6	-.4	-.3	-.2	-.1	
7.5			-.5	-.7	-.7	-.6	-.6	-.5	-.4	-.3	
8.0			-.2	-.3	-.5	-.6	-.6	-.5	-.4	-.3	
8.5				-.2	-.6	-.7	-.6	-.5	-.4	-.3	
9.0				-.2	-.5	-.7	-.8	-.7	-.6	-.4	
9.5					-.1	-.3	-.6	-.7	-.7	-.6	
10.0					.0	-.2	-.5	-.5	-.6	-.6	
10.5						-.3	-.4	-.5	-.5	-.5	
11.0						-.2	-.4	-.5	-.6	-.5	
11.5							-.5	-.6	-.7	-.7	
12.0							-.6	-.7	-.8	-.8	
12.5								-.6	-.7	-.7	
13.0								-.4	-.5	-.5	
13.5									-.3	-.4	
14.0									-.2	-.3	
14.5										-.2	
15.0										-.1	n=30

FIGURE LEGENDS

Figure 1. Above: transect of self-recording current meter moorings in Lake Ontario near Pickering, 6 December 1979 - 1 April 1980, and routine wind station at Toronto Island Airport. Below: position of current meters in transect.

Figure 2. Means and standard deviations of alongshore currents in the coastal zone off Pickering, 7 December 1979 - 31 March 1980.

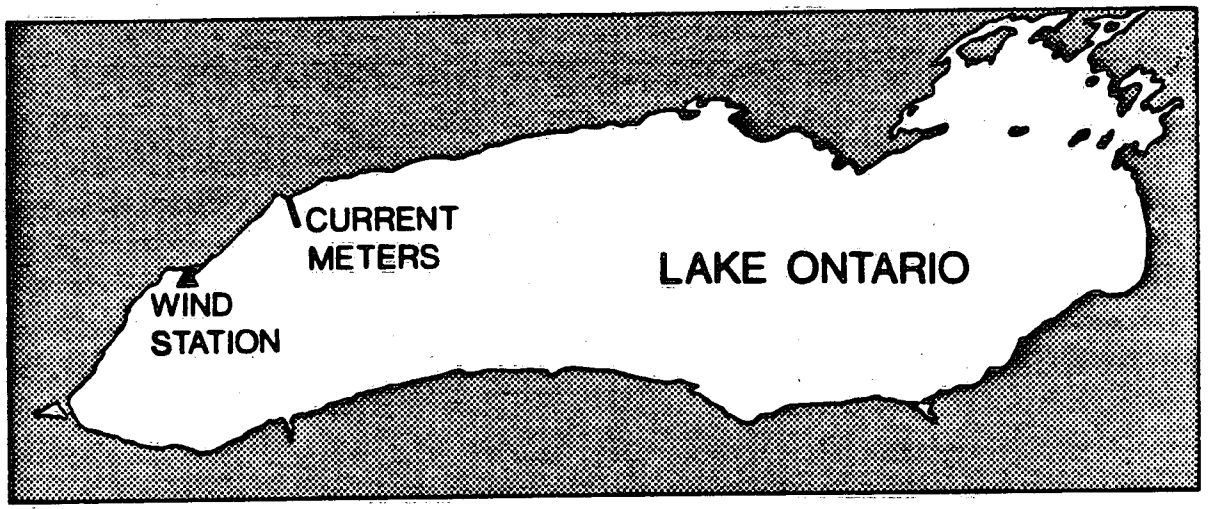
Figure 3. Mean square error (solid lines) and mean error (dashed) as defined by equations (5-6) for different truncations of empirical impulse response.

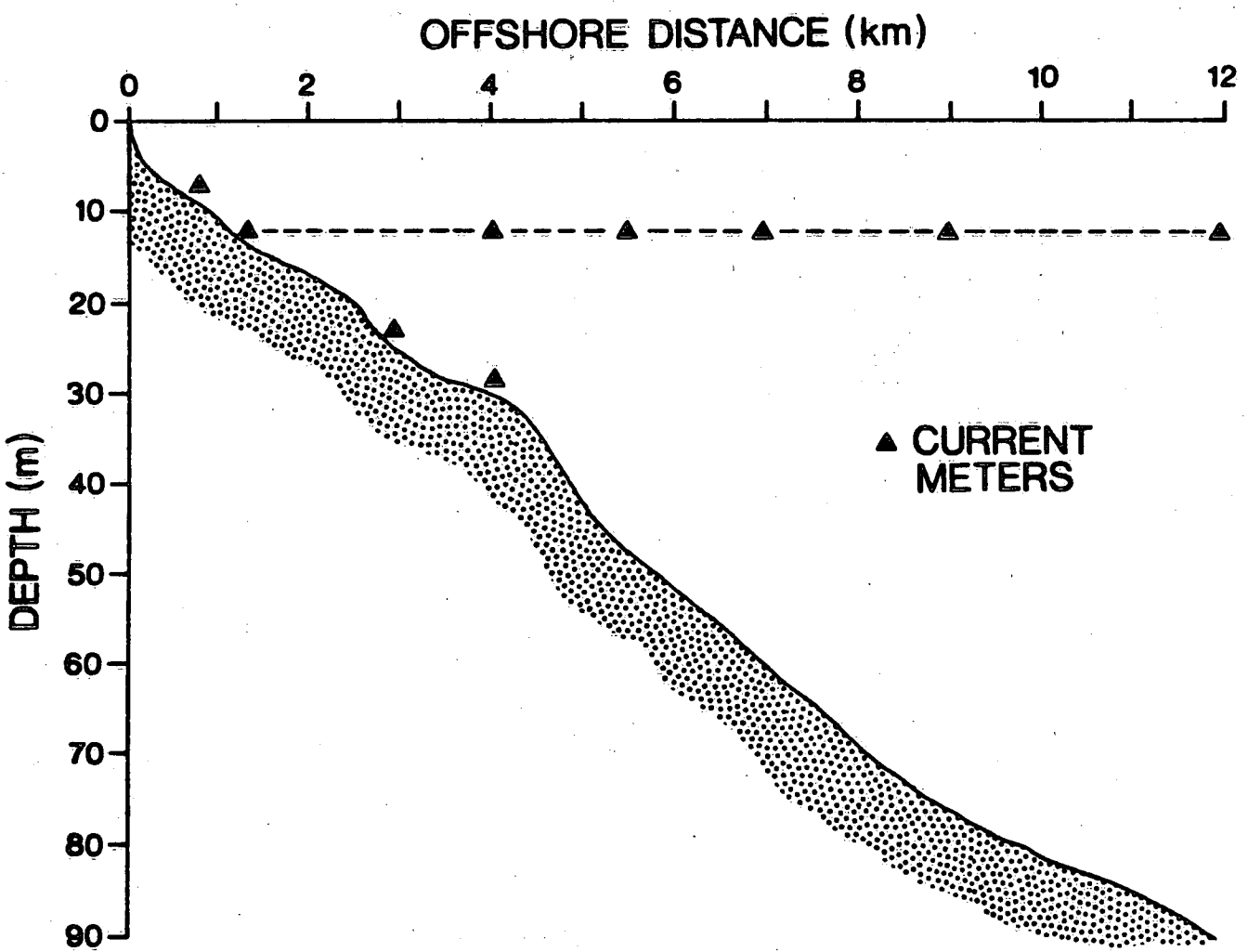
Figure 4a. Alongshore components of observed wind stress and currents (solid lines) and currents obtained from impulse response model (dashed).

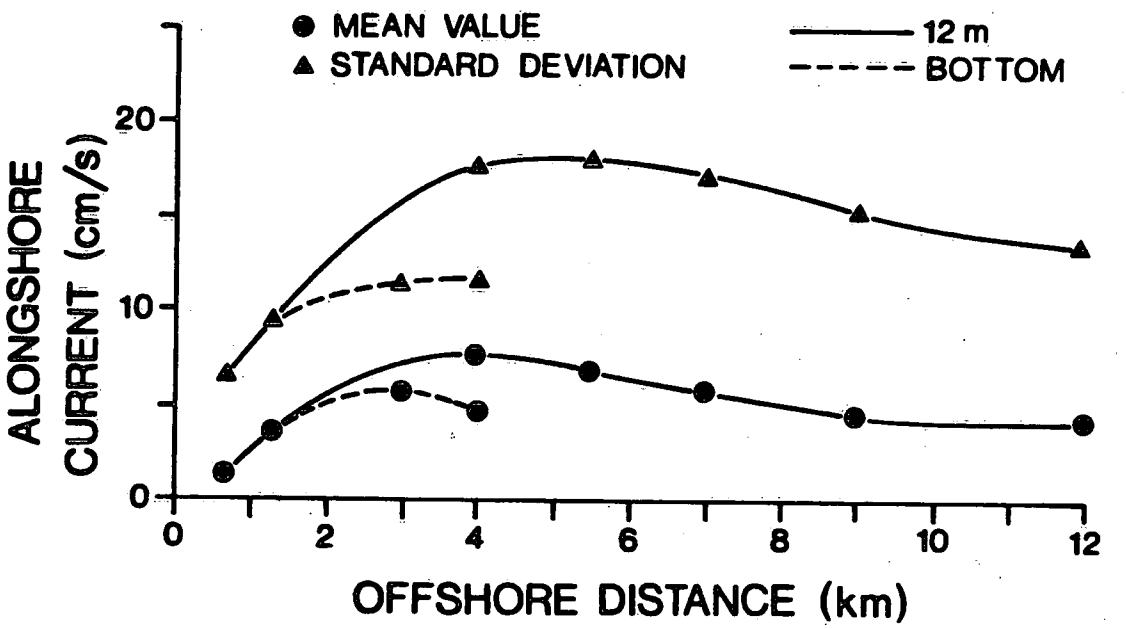
Figure 4b. Continuation of 4a.

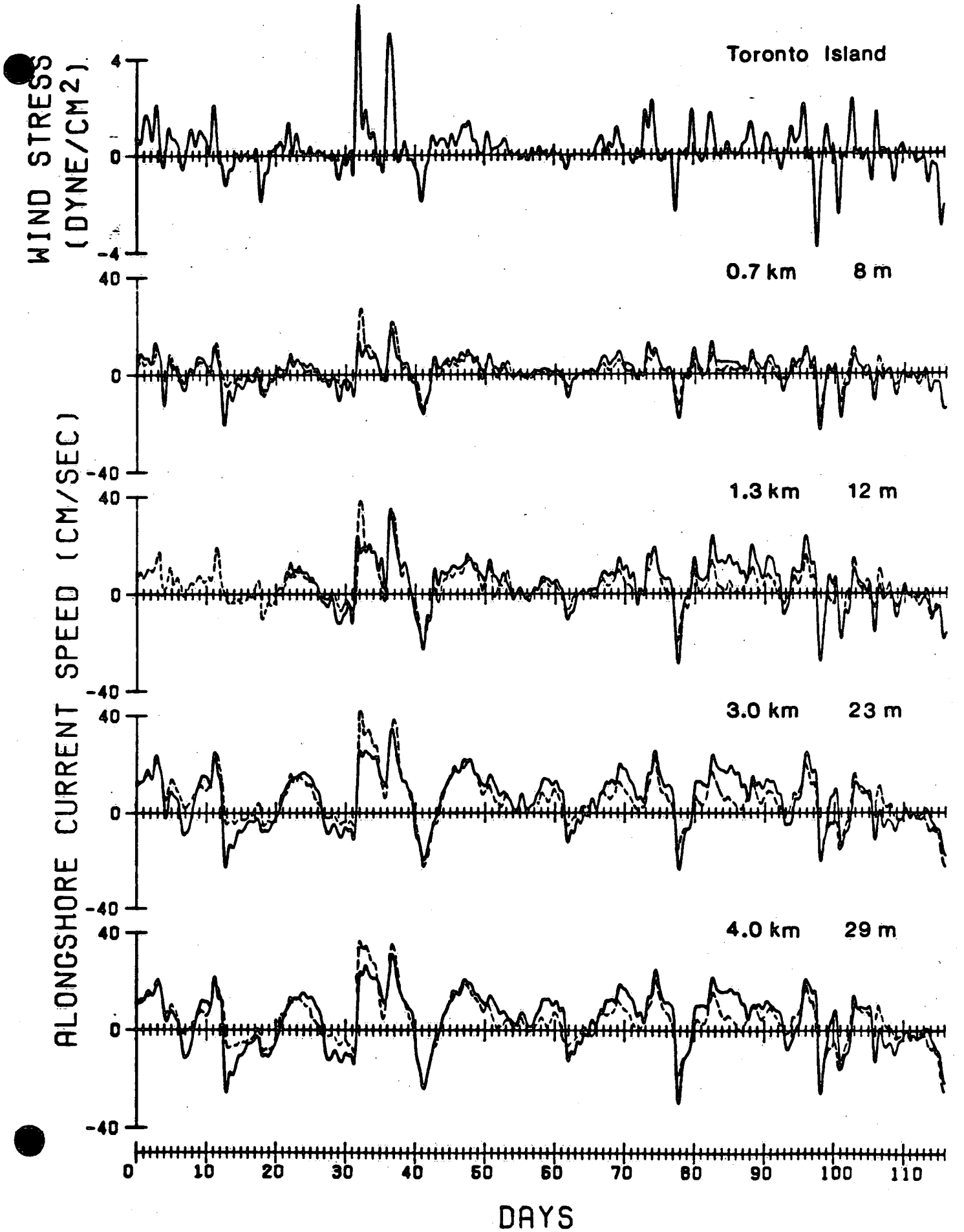
Figure 5. Empirical current response functions in coastal zone off Pickering for 12-hour wind stress impulse of 10^{-1} Nm^{-2}.

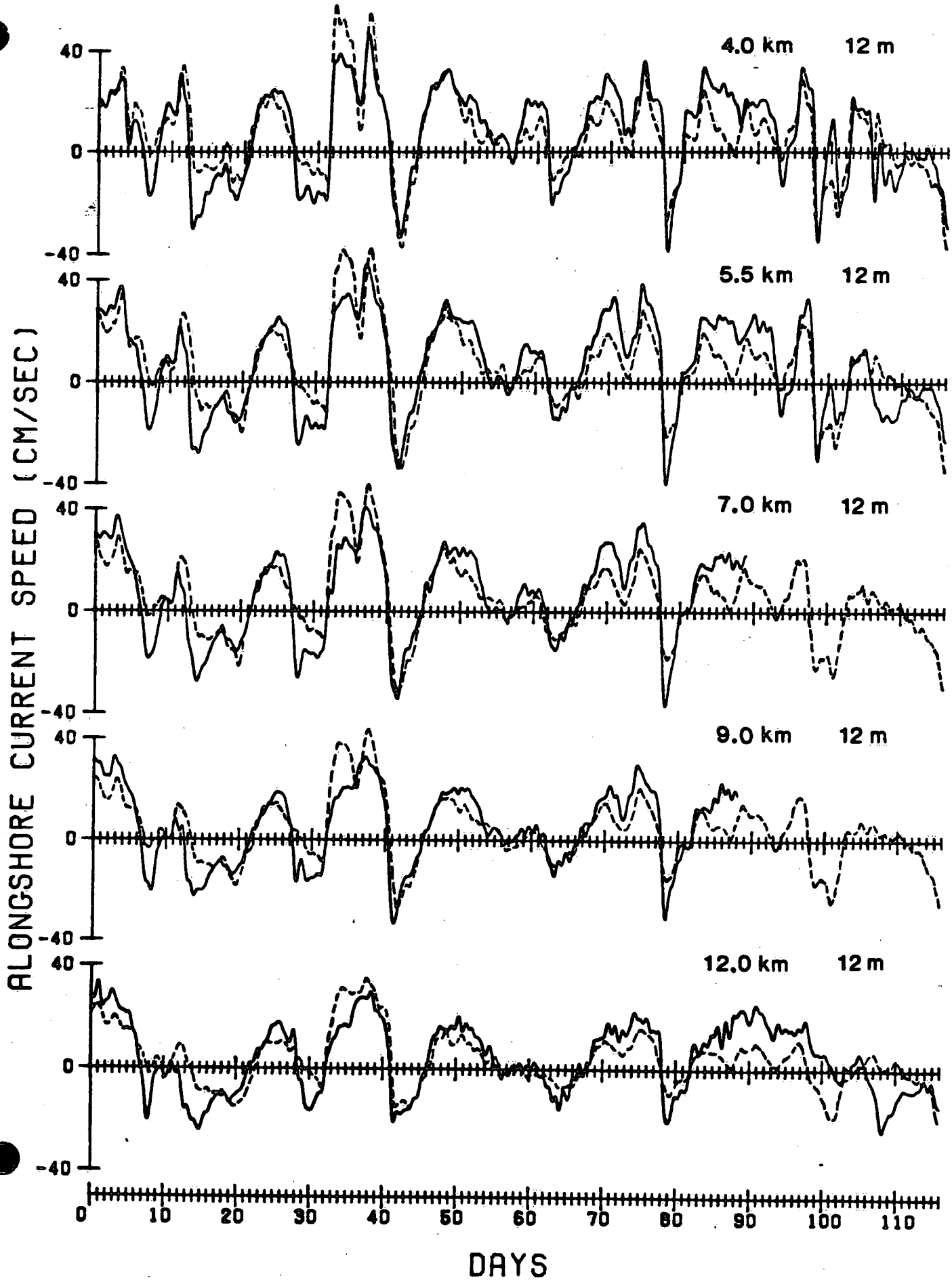
Figure 6. Observed (upper) and computed (lower) thermal plumes (°C) at the Pickering Nuclear Power Generating Station for (a) April 1, 1980 and (b) March 4, 1980. Each dot represents one (or more, if overlapped) prixel and the dashed contours are computed from the prixel density. The wind in km/h is indicated by the arrow.

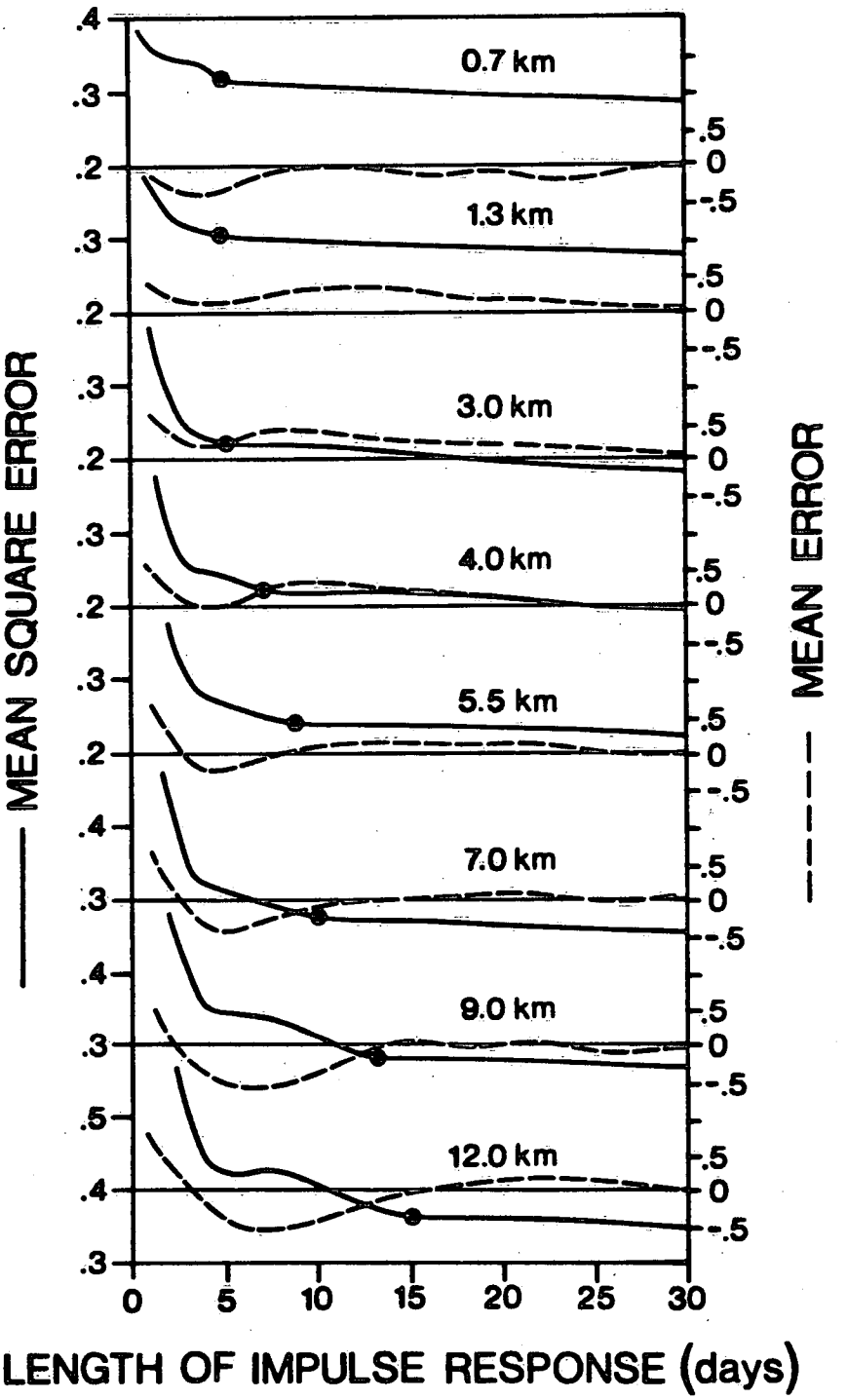

CURRENT
METERS
WIND
STATION
LAKE ONTARIO

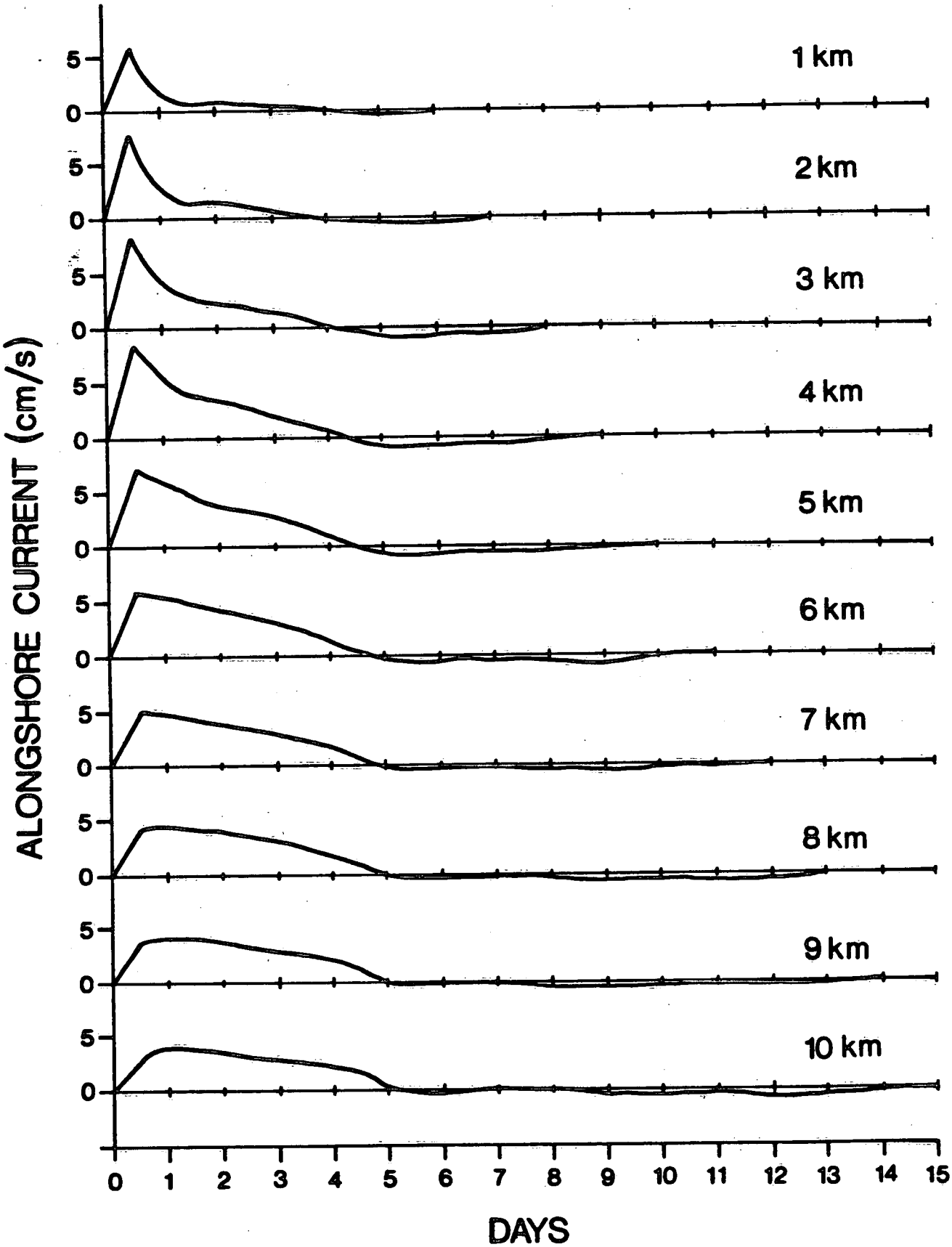

OFFSHORE DISTANCE (km)
0
2
4
6
8
10
12
DEPTH (m)
0
10
20
30
40
50
60
70
80
90
CURRENT
METERS


MEAN VALUE
STANDARD DEVIATION
12 m
BOTTOM
ALONGSHORE CURRENT (cm/s)
0
10
20
0
2
4
6
8
10
12
OFFSHORE DISTANCE (km)

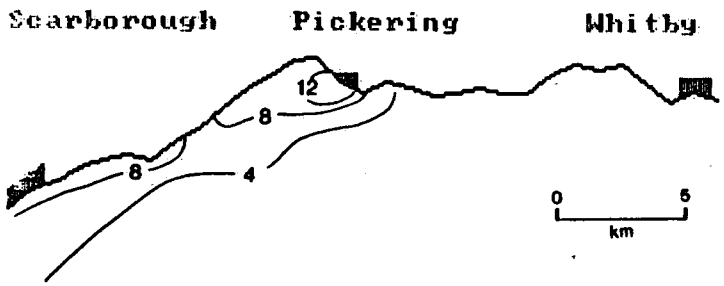

Toronto Island
WIND STRESS (DYNE/CM2)
4
0
-4
0.7 km 8 m
1.3 km 12 m
3.0 km 23 m
4.0 km 29 m
ALONGSHORE CURRENT SPEED (CM/SEC)
40
0
-40
0
10
20
30
40
50
60
70
80
90
100
110
DAYS

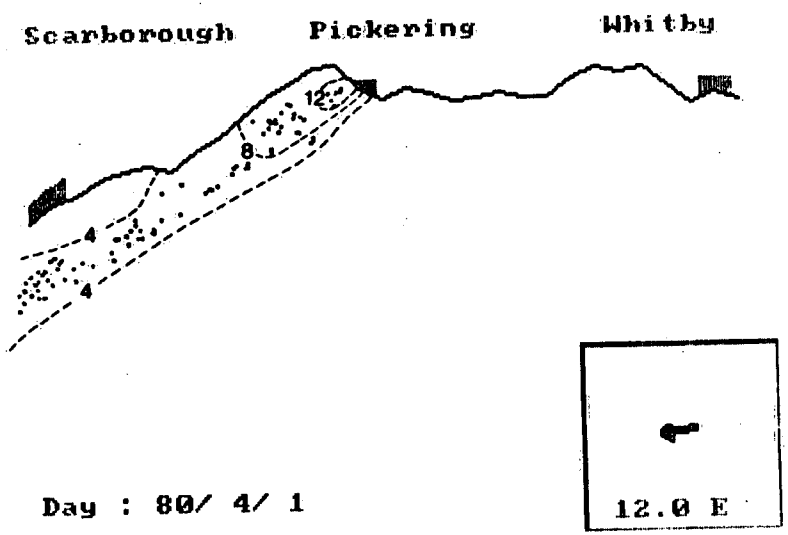

4.0 km 12 m
5.5 km 12 m
7.0 km 12 m
9.0 km 12 m
12.0 km 12 m
40
0
-40
ALONGSHORE CURRENT SPEED (CM/SEC)
0
10
20
30
40
50
60
70
80
90
100
110
DAYS


0.7 km
1.3 km
3.0 km
4.0 km
5.5 km
7.0 km
9.0 km
12.0 km
MEAN SQUARE ERROR
MEAN ERROR
LENGTH OF IMPULSE RESPONSE (days)
0
5
10
15
20
25
30
.4
.3
.2
.5
-.5


1 km
2 km
3 km
4 km
5 km
6 km
7 km
8 km
9 km
10 km
5
0
ALONGSHORE CURRENT (cm/s)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
DAYS

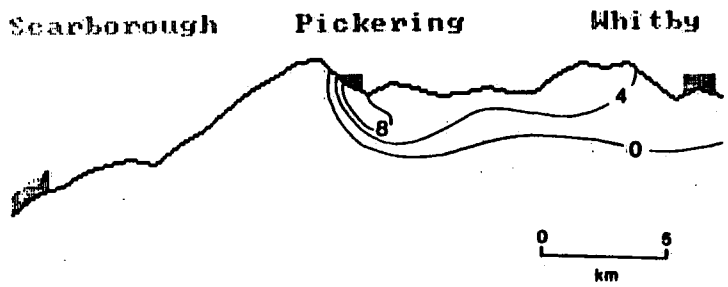
(a)

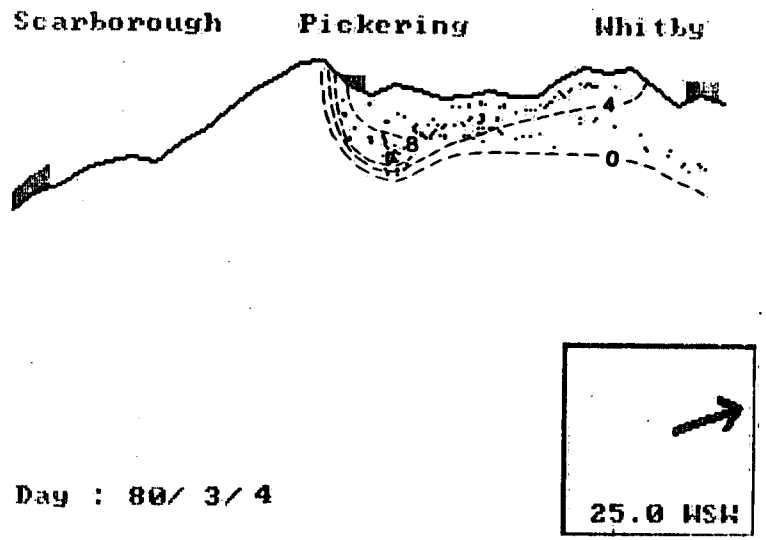




Day : 80/ 4/ 1

(b)





Day : 80/ 3/ 4