TRACKING PHYSICAL & BIOLOGICAL CHANGE IN THE CENTRAL BASIN: CAN PHYSICISTS CLOSE THE DOOR

by

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EXECUTIVE SUMMARY

This paper dicusses one of the goals of the 1979/80 Lake Erie experiments, that of studying vertical fluxes of heat, momentum, dissolved and suspended materials in an open lake setting while accounting for the changes produced by horizontal transport processes. In order to minimize the effects of transport processes, the mid-basin experiment was located in a zone that is considered to be relatively homogeneous; horizontal gradients of temperature, dissolved oxygen, etc. are small. Time series measurements of physical and chemical parameters made at three-hourly intervals from an anchored ship during several week-long experiments showed small but significant changes over time intervals of less than a day. These changes appear to be due to the advection of parcels of water of slightly differing qualities. A study of current meter data from instruments separated by distances of the order of 10 km shows that horizontal mixing processes are sufficiently weak that horizontal variability or patchiness of water quality parameters can be advected by the mean flow through the control volume without being obliterated. A detailed heat budget of the mid-lake control volume confirms the presence of small-scale variability and demonstrates that the sampling in both the vertical and horizontal was inadequate to track it. Nevertheless, one-dimensional models that simulate the vertical fluxes of heat and momentum, as well as dissolved oxygen, are capable of accounting for changes at timescales of 48 hours and longer. The patchiness of the horizontal distributions, so detrimental to the directly measured budgets, appears as a random error in the simulations. Thus while pointing out the limitations of the direct-measurement of budget approach, the study confirms the value of simulation modelling as a means of hypothesis testing over periods of time long enough to average out the effects of "environmental noise". Although the Central Basin of Lake Erie is not typical of most of the Great Lakes, its particular geometry ensures that the mid-lake region is the least perturbed by the presence of the shoreline and is possibly the best site in the Great Lakes to study vertically-acting processes in the presence of stable stratification.

SOMMAIRE A L'INTENTION DE LA DIRECTION

Le présent article traite de l'un des buts des expériences réalisées en 1979-1980 dans le lac Erié, soit d'étudier les flux verticaux de chaleur, de quantité de mouvement et de matériaux dissous et en suspension dans un environnement de lac ouvert tout en tenant compte des modifications produites dans les processus de transport horizontal. Afin de minimiser les effets de ces processus de transport, l'expérience au centre du bassin a été réalisée dans une zone que l'on considère relativement homogène; les gradients horizontaux de température, d'oxygène dissous, etc. sont faibles. Des mesures chronologiques des paramètres physiques et chimiques réalisées à des intervalles de trois heures à partir d'un bateau ancré au cours d'expériences qui ont duré plusieurs semaines ont montré des modifications faibles mais significatives sur des périodes inférieures à un jour. Ces modifications seraient dues à l'advection de parcelles d'eau à caractéristiques légèrement différentes. Une étude des données courantométriques provenant d'instruments espacés d'environ 10 km a montré que les processus de mélange horizontal sont suffisamment faibles pour que la variabilité horizontale ou la distribution inégale des paramètres de qualité de l'eau soient modifiées par advection par l'écoulement moyen dans le volume

contrôle sans disparaître. Un bilan thermique détaillé du volume contrôle du centre du lac confirme la présence d'une variabilité à petite échelle et démontre que l'échantillonnage tant à la verticale qu'à l'horizontale ne permettrait pas de la déceler. Néanmoins, des modèles unidimentionnels qui simulent les flux verticaux de chaleur et de quantité de mouvement ainsi que l'oxygène dissous sont capables d'expliquer des modifications sur des périodes de 48 heures et plus. L'inégalité des distributions horizontales, si néfaste au bilan mesuré directement, apparaît sous forme d'erreur aléatoire dans les simulations. Tout en soulignant, par conséquent, les limites de l'approche de mesure directe du bilan, l'étude confirme la valeur de la modélisation comme moyen de vérifier des hypothèses pour des périodes de temps suffisamment longues de manière à annuler les effets du "bruit environnemental". Bien que le bassin central du lac Erié ne soit pas typique de la plupart des Grands lacs, sa géométrie particulière fait que la région du centre du lac est la moins perturbée par la présence du rivage et est peut-être le meilleur site dans tous les Grands lacs pour l'étude des processus à action verticale en présence d'une stratification stable.

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ABSTRACT

Among the goals of the 1979 and 1980 experiments were the documentation of physical processes thought to be important to chemical and biological processes, and the provision of data suitable for the development and improvement of lake models, particularly those involving vertical exchanges or interactions with the sediments. The area chosen for study is considered to have a relatively uniform horizontal distribution of properties so that vertically acting processes should be more easily observed. Nevertheless, a preliminary examination of the combined physical and biochemical data collected during the anchor station episodes of 1979 and 1980 shows evidence of changes produced by the advection of water of differing quality. In this study, measured currents at 10 m and 20 m depths are analysed to provide timescales for the flushing and mixing of a mid-basin control volume of 10 km diameter. Knowledge of these timescales is useful in the design of biochemical experiments. Data from current meters, thermistor arrays, and meteorological buoys are used to construct a heat daily budget of a control volume in mid-lake. This study confirms the presence of horizontal variability in the distribution of temperature and transport processes that produce significant changes at timescales of less than a day. We examine several one-dimensional (vertical) models by other authors that draw on the Lake Erie data set. The models are

succesful in tracking changes at seasonal timescales; deviations from observed daily averages at shorter timescales are attributed to a combination of transport processes and horizontal patchiness. The deviations do not appear to cause long term discrepancies between the observations and the models, indicating that the patchiness acts as a random "noise" in an essentially homogeneous environment. Finally, we discuss the limitations placed on "control volume" experiments by existing measurement techniques and by the transport processes and we make recommendations for improved experiments.

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RÉSUMÉ

Parmi les objectifs des expériences menées en 1979 et 1980 figuraient l'étude des processus physiques qui semblent liés particulièrement aux processus chimiques et biologiques et la cueillette de données adéquates pour permettre la mise au point et l'amélioration des modèles de lac, notamment ceux qui s'attardent aux échanges verticaux ou aux interactions avec les sédiments. La région que l'on a choisi d'étudier est considérée comme ayant une distribution horizontale relativement uniforme des propriétés; ainsi les processus à action verticale peuvent être plus facilement observés. Néanmoins, un examen préliminaire des données physiques et biochimiques combinées, prélevées depuis le navire ancré en 1979 et 1980, montre des indices de modifications dues à l'advection d'eau de qualité différente. Dans le cadre de la présente étude, les courants mesurés à 10 m et 20 m de profondeur sont analysés afin de déterminer les périodes nécessaires à la chasse et au mélange dans un volume contrôle du centre d'un bassin mesurant 10 km de diamètre. La connaissance de ces périodes sert à la conception d'expériences biochimiques. Des données provenant de courantomètres, de batteries de thermistors et de bouées météorologiques ont été

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utilisées pour construire un bilan thermique journalier d'un volume contrôle dans le centre du lac. Cette étude confirme l'existence d'une variabilité horizontale dans la distribution de la température et des processus de transport et qui produit des modifications significatives sur des périodes inférieures à un jour. Nous examinerons plusieurs modèles unidimentionnels (verticaux) mis au point par d'autres auteurs à partir de la série de données existant pour le lac Erié. Ces modèles permettent de suivre les modifications à l'échelle saisonnière; les déviations des moyennes journalières observées sur des périodes plus courtes sont attribuées à la fois aux processus de transport et à la distribution horizontale inégale.

Ces déviations ne semblent pas causer d'écarts de longue durée entre les observations et les modèles, ce qui semble indiquer que la distribution inégale agit comme "bruit" aléatoire dans un environnement essentiellement homogène. Finalement, nous traitons des limites imposées aux expériences sur un "volume contrôle" par les techniques de mesure et les processus de transport, et nous formulons des recommandations destinées à la conception d'expériences améliorées.

INTRODUCTION

One of the goals of the 1979 and 1980 experiments was to study some of the important physical and biochemical processes on site as opposed to inferring them after the fact from ship cruise data. Earlier work (for a recent assessment see El Shaarawi, 1984) had identified the offshore region of the Central Basin as one of horizontal homogeneity compared to the nearshore zones. The results of major processes affecting the dissolved oxygen regime, sediment oxygen demand, respiration, vertical mixing, photosynthesis, ought to be visible in a changing vertical profile and amenable to study via one-dimensional (vertical) models. A second goal of the experiments was to provide a set of data that would encourage the development and improvement of lake system models. These considerations prompted the co-collecting of physical and biochemical data (Robertson and Boyce, 1986). For both goals we are required to construct budgets of important physical and biochemical quantities across a mid-lake control volume. This paper describes our success with this approach, asseses some of the one-dimensional models applied to this data set, and makes recommendations for future experiments.

THE ANCHOR STATION EXPERIMENTS

Five times during the summer of 1979 and once during the summer of 1980 the C.S.S. LIMNOS occupied a station in the Central Basin of Lake Erie (41 50.7' N by 81 51.0' W). The site was located in the centre of an array of current meters, thermistor strings, and meteorological buoys , an array that defined in both years a mid-lake control volume enclosing a 8 km by 8 km (nominal) area of the basin. On each occasion, the station was occupied for several days and the LIMNOS served as a platform for around-the-clock observations and sampling. In 1980 the measurements at the central location were supplemented by spatial sampling over the the control volume from a second vessel. All of this data is summarized in both graphical and tabular form in the report by Robertson and Boyce, 1986. In this paper we select the August and September, 1979 anchor station periods as examples because the data is more detailed and because the periods are those of low hypolimnion oxygen and small hypolimnion volume.

Winds in excess of 20 knots occurred at the beginning of the August, 1979 experiment and the record from the thermistor arrays(Schertzer et al. 1986) shows that the temperature profile has evolved to a strongly two-layered structure with very intense gradients in the thermocline region. Bottom temperature increases from 10.1 C on August 13 to 12.0 C on August 18, but by 21 August it has decreased again to 10.5 C. The cooling phase must be the result of horizontal transport of water from elsewhere. During August 18, for example, bottom temperature increases from 11.2 C to 12.0°C while bottom dissolved oxygen concentrations decrease from 1.81 to 1.45 mg/l. Bottom currents are both strong and persistent, running approximately west for a total displacement of more than 10 km in a 24 hour period. The distribution of bottom temperatures observed at the current meter locations indicates transport of warmer water into the anchor station site and the combination of observed gradients and current run are sufficient to account for the warming. During the latter part of the day, the chlorophyll A concentration immediately below the thermocline increases considerably although the day is cloudy with very little incoming solar radiation. While significant changes in the biochemical parameters, dissolved oxygen and chlorophyll A take place in the hypolimnion during the day, the change in temperature seems to be the result of horizontal transport of bottom water. Are all of the observed changes in biochemical variables due to advection also?

By early September, 1979 the intense thermal gradients at the top of the themocline had weakened as a result of a period of calm weather. Strong winds on the evening of September 7 erased all transient thermal structure above the seasonal thermocline. At the same time the thickness of the hypolimnion increased and its temperature rose by 0.5°C. This is the signature of a downward entrainment event when thermocline water is entrained into a turbulent hypolimnion. At this time, the bottom current meters were now positioned in the thermocline because the hypolimnion thickness had decreased to 1 m; it is therefore impossible to estimate spatial gradients of hypolimnion temperature in the control volume and to determine whether such a change is due to bottom water transport. The warming of the hypolimnion, other things being equal, should have been accompanied by an increase in the concentration of dissolved oxygen. In fact the bottom values of dissolved oxygen concentration decreases more quickly than ever after this wind impulse, and the total phosphorus values increase. A possible, but unconfirmed interpretation of the September 7 - 8 changes is that the hypolimnion warmed and thickened due to the downward entrainment of thermocline water, but that the concomitant gains of dissolved oxygen were more than offset by a resuspension of oxygen-consuming material from the bottom. The other unconfirmed possibility is that of horizontal advection.

The anchor station records document many other events in which transport processes appear to have significant effects over and above the changes produced by locally acting processes. Despite the apparent homogeneity of the region in the large scale, there must exist a patchiness of the horizontal distributions with scales of several km that introduces "noise" of amplitude sufficient to often mask daily changes expected from local processes.

FLUSHING AND DIFFUSION TIMESCALES ESTIMATED FROM CURRENT METER

DATA

The horizontally averaged current over the 8 km by 8 km control volume is at each level and location an excellent approximation to the local current at frequencies less than 0.125 cph, a band that contains more than 80% of the total kinetic energy of horizontal motions. We may express the current at each point in the array as the sum of a spatially uniform average velocity and a local "fluctuation" velocity. We define a flushing time for the control volume as the time required for the entire volume to be flushed clear of the water it originally contained by the horizontally averaged current. This time can be roughly estimated as the horizontal diameter of the control volume divided a suitable average of the current. It will vary from depth to depth. A horizontally uniform motion contributes nothing to horizontal mixing because it contains no shears; the components of motion responsible for horizontal mixing must be represented in the "fluctuation velocity" series. These series should yield information on the horizontal mixing of fluid as it is carried along by the average flow. We define a mixing time as the time taken for a small blob of a dissolved tracer to mix to near uniformity across an area equivalent to that of the control volume.

Computation of Weekly Flushing and Mixing

At each of three levels, 10 m, 19 m and 21 m, three current time series yielding continuous records from June to October and separated in space by 8 to 10 km were selected. At each level the three records were vector-averaged to form an average current. All records were divided into week-long segments (168 hours). The mean current "run" for each 7-day segment was computed; this distance divided by 10 km gives the number of times a 10 km diameter control volume would be flushed by the mean current in a week. This ratio is of order 1.0 at all levels, but is largest at 10m.

Comparison of the "fluctuation" series (defined as the difference between local currents and the horizontally averaged current) spectra with the spectrum of the mean series shows that the energies in the fluctuation series are typically 25% of the energies in the mean series at the low frequency end of the spectrum (region of strong coherence among observed series) but that the spectral amplitudes of both series are similar at the higher, horizontally uncorrelated frequencies. The crossover between correlated and uncorrelated motion occurs at frequencies of the order of 0.125 cph where energies in the observed spectra are typically less than 25% of the low frequency peak. Moreover, comparison of the "fluctuation series" among themselves indicates a low frequency band of coherence with phase angles either 0 or 180 degrees. This indicates the presence of horizontal shears in the low frequency components of motion.

There are several approaches by which one may compute effective diffusion parameters from Eulerian current data. The method used here is based on a paper by Gezentzvei (1958) and has been adapted by Murthy and Dunbar (1981). The raw inputs to this computation are the fluctuation velocity series defined above. Means are removed. The Gezentsvei method segments the input velocity component records into episodes of positive and negative flow, each episode being characterized by a velocity scale and a length or time scale. Suitable averaging, using both components of velocity, leads to a horizontal diffusivity tensor which may then be rotated along principal axes. For our purposes, the figure of merit is a single horizontal diffusivity, KH, taken to be the geometric mean of the principal components of the diffusivity tensor. KH was calculated for each level, each 7-day episode, and each fluctuation series. The standard deviations of the individual KH's were typically 50% of the mean at the 19 m level and 25% of the mean at the 21 and 10 m levels

Kullenberg et al. (1973) propose an empirical formula relating horizontal eddy diffusivity to spatial scales of the diffusing patch for subsurface diffusion experiments:

KH = 1.1E-04*L**1.5 (L in cm, KH in cm**2/s)

This formula is based on the observed spreading of dye patches at depths between 15 and 50 m in Lake Ontario. Taking L = 1.0E+06 cm (10 km), the expected value of KH is 1.1E+05 cm**2/s. Murthy (1971) reports a diffusion experiment in the hypolimnion of Lake Erie's Central basin. A bag of dye was released in the hypolimnion to the north of the present mid-basin site. Over three days, the patch moved 3 km (mean current of the order 2 cm/s) and spread to a diameter of 1.4 km. An effective eddy diffusion parameter for this spreading is 1.0E+03 cm**2/s. Scaled to a patch size of 10 km by the Kullenberg formula, the diffusivity is 1.9E+04. From the Gezentsvei calculations we obtain an eddy diffusivity scale of 1.0 E+05 cm**2/s at the 10 m depth, and 1.0E+06 cm**2/s at 19 and 21 m. We conclude that the Gezentsvei diffusivities are large compared with the other measurements, possibly because they treat the large scale shears set up by inertial frequency and other low-frequency motions as random, uncorrelated motions. By filtering the fluctuation time series to remove the long-period, spatially coherent motions, the effective diffusivities are substantially but arbitrarily reduced. Given the approximate nature of all such estimates, the Gezentsvei diffusivities calculated from the unfiltered fluctuation series parameterize an upper bound of the mixing process.

A simple solution of the Fickian diffusion equation in cylindrical coordinates given by Carslaw and Jaeger (1959) leads to a definition of a mixing time for a control volume of radius R. An initial distribution of tracer material contained within the radius R and having a "radial wavelength" of order R is allowed to diffuse outward to a sink maintained at constant and zero concentration at the radius R. The time TD required for the initial concentration to be reduced to less than 0.1 its original value is approximately

TD = 0.4*R**2/KH

This time has been computed for each level from the average KH, segmented as described above.

In Figure 1 we assemble a sequence of 7-day averages of the flushing and the mixing timescales for 10, 19, and 21 m depths. We present this data as the number of times the water in the 10 km diameter control volume is replaced in the 7-day period by either process. At the 10 m depth, the control volume is flushed between 0.8 and 1.7 times in a seven-day period. The vigour of the flushing generally reflects the strength of the wind forcing. The number of effective water replacements due to mixing lie between 0 and 0.7. The corresponding average timescales for flushing and diffusion are 5.6 and 27 days. At the 19 m depth the volume is flushed between 0.3 and 1.25 times in seven days and the water is replaced by mixing between 0.16 and 1.1 times (flushing timescale = 9.1 days; mixing timescale = 11.1 days). At 21 m the volume is flushed between 0.32 and 1.14

times and the replacements due to mixing number between 0.1 and 0.3 in a seven-day period; the corresponding timescales are 9.6 and 34 days. The mixing timescales, almost certainly underestimated by this method, are in all cases much longer than a day, indicating that patchiness at the scale of the control volume is advected through the volume without being obliterated by the small-scale mixing.

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HEAT BALANCE AT A CENTRAL LOCATION IN LAKE ERIE

To test the completeness of our data set in order to distinguish between locally produced changes and those caused by transport of water, we examine the heat budget of the central basin control volume. The data from the thermistor arrays provide a good estimate of the heat stored within the water column. The surface heat flux may be estimated from meteorological variables. Heat flux to the sediments is small. Therefore, in the absence of horizontal advection, and within the limits of measurement error, the net daily surface heat flux ought to be mirrored exactly as a change in the heat stored within the water column. Should the differences between heat flux and heat content change be significant, we may then attempt to account for the difference by estimating horizontal heat flux from nearby current meter and temperature data. In this fashion we may hope to reveal the circumstances under which horizontal transport of heat becomes important, and also to establish the extent to which the combined temperature, meteorological, and flow data form a consistent ensemble, justifying a control-volume approach.

Data Base.

The availability of radiometer data determines the study period. In 1979 the interval is from June 17 to September 15. Two weeks of data from 1980 were examined, from July 28 to August 17 in support of the GVAPS experiment (Royer, Hamblin and Boyce, 1986). This paper deals mainly with the 1979 data.

Figure 2 shows the network of instruments employed in this study. It is centred on thermistor array station 45 and current meter station 27. This location is surrounded by four current meter moorings (Stations 29, 25, 31, and 33) that form an 8 km by 8 km square. Heat flux estimates will be referred to the control volume defined by this area and a water depth assumed to be a constant 24 m. As many as four current meters were deployed at each of these stations at depths of 10.0, 15.0, 19.5, and 21.2 m. A major shortcoming is the lack of current data above 10 m depth. Currents were sampled at intervals of 10 or 20 minutes and then averaged to hourly values. Only station 29 yielded a complete set of data throughout the period of interest. Data from the thermistor array stations 40,41, and 45 were averaged to hourly values at 20 different depths. These measurements were then interpolated vertically to a 1 m spacing starting 0.5 m below the water surface. The thermistor array and current meter stations are all contained in an area 13 km by 17 km. Four meteorological buoys were deployed in the immediate area. They measured wind speed and direction, air temperature, water temperature (surface), relative humidity, and one of them (Station 27) recorded solar radiation.

Net Daily Surface Fluxes of Heat and Changes of Stored Heat Content.

Daily estimates of surface heat flux and heat content changes were formed. The thermistor array data was simply averaged over 24 hours centred on noon (GMT) of each day. This procedure could alias inertial period fluctuations into the retained low frequencies. From the daily averaged temperature profiles, vertically averaged temperatures of the water column were calculated. We computed an average for the entire water column, an average for the top 10 m, and an average for the water column below 10 m, that portion of the water column effectively sampled by current meters.

A bulk-parameter heat exchange model was employed to estimate surface heat fluxes. This model is described by Schertzer and Lam (1982). An estimate of surface heat flux is formed every hour and these values are summed to yield net daily surface heat flux.

Current meter data was also smoothed preparatory to computing daily averages of horizontally advected heat. Because of the large inertial period fluctuations, a modified cosine tapered filter (Thompson, 1983) was applied to eliminate the possibility of aliasing this frequency into the daily averages. Cross-spectral analyses of currents in the mid-basin array (Boyce and Chiocchio, 1986a, this issue) show that the individual records at t common depth are very similar, and this has been confirmed through episode-by-episode analysis in the time-domain. This has prompted us to fill gaps in the current meter time series at stations 25, 31, and 33 with data from station 29 or station 27. Interpolated velocity profiles were constructed from 10 m to the bottom, with values reported at one metre increments of depth and assuming zero velocity at the bottom itself.

SIGNIFICANCE LEVELS FOR THE DIFFERENCE BETWEEN SURFACE HEAT FLUX AND HEAT CONTENT CHANGES IN THE WATER COLUMN.

Differences between the daily net surface heat flux and the corresponding daily change in stored heat of the water column will be due to either:

i) errors in the estimates of the surface heat flux and heat content change, or

2) advection of heat in or out of the control volume by horizontal currents.

Conduction of heat across the lake bottom is neglected. The significance of the advection term cannot be evaluated until an estimate of the errors is provided.

Let QMJ be the estimate of the surface heat flux (positive into the lake) per unit area over the Jth day (watts per m**2) and let HMJ be the estimate of the change in stored heat content over the Jth day per unit horizontal surface area of the water column (watts per m**2). Both QMJ and HMJ have been calculated as described earlier and are displayed in Figure 3. The calculations show an average heat gain of the water column due to "advection" amounting to 53 watts/m**2 while the fluctuations about this average are much larger, plus or minus 160 watts/m**2.

Two approaches are used to estimate the uncertainty of the residual VMJ = QMJ - HMJ. The first is a term-by term analysis of the surface heat flux model, while the second examines the energy budget of the whole lake calculated by Schertzer (1982) using ship cruise data, and estimates of surface heat flux from a combination of available land and lake data over the years 1969 through 1979. Typical absolute values of the heat flux terms plus estimates of the error (in brackets) for the month of July, 1979 are given below:

(a) net solar radiation 190 watts/m**2 (25)

(b) longwave radiation
from the atmosphere 365 watts/m**2 (5)

(c) longwave radiation
from the water surface 410 watts/m**2 (2)

(d) flux of latent heat
(evaporation) 100 watts/m**2 (50)

(e) flux of sensible heat 25 watts/m**2 (12)

The root sum of squares of the individual terms is 589 watts/m**2. The radiation terms are by far the most important. Assuming that these errors can be combined as a root sum of squares (not strictly true since the terms are not formally mutually independent), the combined error in the estimate of daily surface heat flux is +/- 55 watts/m**2.

The stored heat term is estimated from thermistor array data; the thermistors extend from the surface to the bottom with a nominal spacing of 1 m. The nominal accuracy of each temperature reading is +/- 0.1°C. A major source of uncertainty in the heat content estimate derives from the limited ability of the array to resolve the complex structure of the thermocline region. In late summer the transition from epilimnion to hypolimnion may be encompassed in as little as 3 m (2 or 3 thermistors). Internal waves cause the thermocline to move up and down a metre in a sinusoidal motion. The phase of these oscillations is random with respect to the sampling interval; the effect on the heat content measurements is that of a random noise. We compare net daily heat flux with differences of unweighted daily averages of heat content; allowing for the effects of differencing and averaging, the uncertainty in heat content change measured at a single thermistor array is +/- 50 watts/m**2, comparable to the uncertainty in the heat flux estimate.

From 1967 to the present, there have been ship cruises on Lake Erie that provided enough temperature data to form an estimate of the stored heat content of the entire lake. Schertzer and his colleagues (Lam and Schertzer, 1982) have estimated surface heat flux from historical meteorological data (daily net values). It is therefore possible to compare changes in heat storage between cruises with accumulated values of surface heat flux. This information can be used to deduce the uncertainty to be expected in the difference to be expected at a mid-lake control volume. We find by this method an uncertainty in the heat budget computations for the mid lake volume to be of the order +/- 200 watts/m**2 on a daily basis. This is almost four times the uncertainty of the heat flux measurements that has been estimatd term-by-term from the bulk parameter model. This is perhaps to be expected because the parameters entered in Schertzer's computations are frequently measured at nearby land stations and not directly over the lake.

There being no obvious objective fashion to refine these uncertainty estimates, we take +/- 100 watts/m**2 as - a rough measure of the uncertainty in our estimate of the daily heat flux due to transport processes. Reexamining Figure 3, it is evident that many of the observed "transport fluxes" are statistically significant and must be explained by water motions.

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HORIZONTAL TRANSPORT OF HEAT - INTERPRETATION AND ANALYSIS.

A comparison of the daily surface heat flux at stations 42 and 46 shows a root mean square error between them of +/- 36 watts/m**2, the smallness of the error being due perhaps to the use of the same values for incident solar radiation at both stations. In the final computations, an average of the heat flux computed at stations 42 and 46 will be used as an estimate for the entire control volume which should further reduce the uncertainty in the transport term.

On the other hand, comparison of the daily heat content change computed at the three different thermistor array sites did not reveal the same horizontal uniformity. The RMS error between stations is +/- 145 watts/m**2, substantially larger than any possible measurement error, and too large to be explained by local variations in surface heat flux. Water movements, inertial period internal waves, and a patchy horizontal distribution of temperature must be contributing to this variability. By averaging the three thermistor array stations and forming the difference with the daily surface heat flux, we are in effect applying a spatial smoothing so that the transport term that remains applies to transport processes acting at the scale of the control volume. This procedure should also eliminate much of the noise due to inertial period internal waves because the isotherm displacements at these frequencies are not coherent across the network of of thermistor arrays (Boyce and Chiocchio, 1986a). Referring to Figure 3, we draw the reader's attention to the large heat "losses" occurring between July 1 and July 4 and the strong fluctuations occurring from August 10 onwards culminating in a large apparent gain of heat of the water column starting August 29.

Over the July-August period of interest, the apparent transport term represents an average horizontal flow of heat into the control volume of 3.4 x 10**9 watts. This apparent heat flux is equivalent to a warming of the entire water column by 0.04°C per day. Its significance is marginal and indeed it might well be due to a systematic error in the calculation of the surface heat flux. Figure 3 shows the July 5 to August 5 interval to be a period of net heat gain by horizontal transfer. During this period the upper layer temperatures increase by about 6 C but the hypolimnion temperatures (Thermistor array at Station 45) do not show any trend over the entire period, although daily averaged hypolimnion temperatures may change by as much as 0.2°C from one day to the next. On the other hand, the month of August is more highly variable with strong episodes of both positive and negative heat changes by horizontal transport. Hypolimion temperatures increase by 0.05°C per day on the average, closely approximating a linear trend. This warming is clearly the result of vertical heat flux. The near constancy of the bottom temperatures in the month of July suggests that the long term horizontal transport, if any, takes place during that month above the seasonal thermocline. July has a more variable structure above the seasonal thermocline while the month of August more closely approximates an idealized two-layer system.

Before analysing the short term transport episodes, we wish to look more closely at how the surface heat flux affects the heat content of the water column. A depth of heat penetration can be defined as the distance from the surface within which the daily surface heat flux can be matched by the heat content change. This depth was calculated for each of the three thermistor arrays, giving three estimates of penetration depth per day for 91 days. 74% of these estimates gave penetration depths that were less than the total depth. The overall average of the penetration depth was 8.6 m. A typical value of the extinction coefficient for surface water is 1.0 m**-1 indicating that the heat is distributed downwards primarily by mechanical processes. The RMS difference between the surface heat flux and the heat content change in the top 10 m is +/- 90 watts/m**2, about half the RMS difference between surface heat flux and heat content change over the entire water column (Figure 4). Therefore a substantial portion of the heat content change due to horizontal transport must take place in the bottom 14 m.

The advective term may be expressed as the volume integral of the divergence of the heat flux vector:

$$Q_A = \int \rho C_p \nabla (T\vec{V})\, d\Omega$$

where ρ is the fluid density, C_p is the specific heat, ∇ is the divergence operator, T is temperature, $\vec{V}$ is the velocity vector, and $d\Omega$ is a volume element. We may consider the flow field, $\vec{V}$ to be comprised of a horizontally uniform part, $\vec{V_0}$, and a spatially variable part, $\vec{V_1}$. The spatially variable part of the field satisfies the relation

$$\frac{du_1}{dx} + \frac{dv_1}{dy} + \frac{dw_1}{dz} = 0$$

The expression for the divergence of the heat flux vector then becomes

$$U_0 \frac{\partial T}{\partial x} + V_0 \frac{\partial T}{\partial y} + u_1 \frac{\partial T}{\partial x} + v_1 \frac{\partial T}{\partial y} + w_1 \frac{\partial T}{\partial z}$$

We assume the spatially uniform flow to be represented by the current meters at any one of the locations, since the current meter records are strongly coherent.

From the isotherm depth plots (Schertzer et al. 1986), it can be determined that a vertical velocity scale for motion of the main thermocline is of the order of 1 m/day or 1.0E-05 m/s. From this figure and the vertical integral of the divergence of the velocity vector over the hypolimnion, we may estimate the magnitude of the local horizontal gradients of velocity. Taking 5m as the thickness of the hypolimnion, these gradients become of order 1.0E-06 s**-1. If these structures are coherent across the control volume they will produce velocity differences of order 1 cm/s.

The obvious first step is to calculate the heat advected to the control volume by the uniform (spatially averaged) current. Because there are no measurements of current above 10 m depth, we can only make this calculation for the interval from 10 m to the bottom. It was established earlier that the heat content changes in this lower region correlated poorly with the surface heat flux. Using temperature data from both the thermistor arrays and the current meters, the advected heat below 10 m was computed assuming that each of the current meter locations provided a reasonable estimate of the uniform flow. Differences among these estimates may be indicative of episodes where the spatially varying component of horizontal flow must be considered. Such episodes were found on July 1 to 6 and from August 26 onwards. The average of these computations, the heat flux due to the spatially averaged flow is shown in Figure 5 where it is compared with the heat content variations observed in the bottom layer. While the significant excursions of the computed advective heat flux from zero are of a magnitude comparable to those of the observed heat content change below 10 m depth, the two series show no resemblance overall.

Clearly the spatial variability of the flow across the dimensions of the control volume is important in resolving the heat budget and particularly the divergent component of flow that results in a vertical motion of the thermocline and a relative redistribution of the quantities of warm and cool water in the column. Recognizing that neither the quality nor the quantity of available data lend confidence to the approach, we nevertheless attempt an evaluation of the surface integral of heat flux on a control volume placed on the bottom of the lake in the form of an 8 km by 8 km horizontal square, 14 m high. The net horizontal flow into this volume is estimated from current meter data and this defines the average vertical velocity through the top of the volume. From the thermistor array data, estimates of the horizontal temperature distribution are made and these are used in conjunction with the current meter data to compute the horizontal heat flux into the control volume. The vertical heat flux is estimated from the temperature at 10 m depth and the inferred vertical velocity. Let us consider the balance in one horizontal dimension:

$$A_V (U_A T_A - U_B T_B) - A_H W T_{10} = \frac{\Delta Q}{\rho C_p}$$

$$W = (U_A - U_B) A_V / A_H$$

where A_V is the area of the vertical wall of the control volume, A_H is the area of the top (horizontal) of the control volume, U_A and T_A are the vertically averaged horizontal current and temperature respectively on one vertical wall, U_B and T_B correspond to the average velocity and temperature on the other wall. W is the resulting vertical velocity required to balance the mass flux. The signs of U_A, U_B, and W are chosen so that positive U_B and W indicate flow out of the control volume. ΔQ is the rate of change in heat storage within the control volume for which a significant scale is 1.0 x 10**10 watts for the 8 km by 8 km by 14 m control volume (see Figure 5). ~~and are the fluid density and specific heat~~. T_A and T_B differ only slightly between themselves but differ substantially (several degrees C) from the temperature at 10 m (T_{10}).

Despite these limitations, the net advected heat flux for the control volume was estimated from the available current meter and temperature data. Two estimates were made, one using data from station 29 to fill in the missing current meter data, and the other using data from station 27 for this purpose. Little difference was noted between the two estimates. The results are presented in Figure 6. The magnitude of the advected heat flux is correct, and there are enough correspondences between the observed heat content variation in the control volume and the computed advective flux to attempt some analysis on an event-by-event basis. The correlation between the two sequences over the entire record is not statistically significant, but if only the record from June 17 to August 26 is retained, the correlation becomes significant at the 1% level.

The heat loss and subsequent rebound in the first few days of July are matched by the estimated advection term. The signature of this event is clear in the detailed isotherm plots for the mid-lake thermistor array. Over that interval the hypolimnion thickens by 3 m and then subsides slightly. The positive peak near 15 July corresponds to the onset of brisk winds following an extended period of calm. Only at thermistor array 40, to the south does the main thermocline register any significant perturbation (transient 2 m thinning and rebound). The upper mixed layer, on the other hand, penetrates suddenly below the 10 m depth so that the assumption that the bottom 14 m of the water column are decoupled from surface events is violated. Around August 14 the thermocline is observed to drop suddenly by 2 m. This drop is mirrored by positive peaks in both the observed heat content change and the advected flux, indicating that this event is triggered by an egress of hypolimnon water from the control volume. From August 26 onwards, the correspondance is poor although Figure 3 indicates a very large heat gain of the water column in excess of the surface heat flux. In this time interval the thermocline again descends rapidly. Conditions at this time are not propitious for accurate estimates of the advection term since only 10 out of a possible 16 current meters were working.

An evaluation of the diffusive component of heat transport to the control volume as not attempted, first because the horizontal temperature gradients could not be accurately estimated, and second, because the preceeding analysis indicates that this component will be small.

We conclude that the failure to balance the subsurface heat budget of the control volume stems from an undersampling of both the temperature and velocity fields. The temperature field, in particular, is variable at scales smaller than the control volume.

onedim.mod 28/11/85

ONE DIMENSIONAL MODELS

While many of the daily differences between surface heat flux and changes in the stored heat content of the water column are too large to be attributed to measurement error and therefore must be the result of horizontal transport of heat into the control volume, we are able to confirm and interpret only a few such events in our direct computations of advective heat flux. These are mainly associated with episodes of internal mass distribution lasting several days. An example is the northward migration of the hypolimnion observed at the end of August, 1979. The weekly ship cruise data of 1970 (Blanton and Winklhofer, 1972) documents similar events. We conclude that many of the differences between daily estimates of surface heat flux and daily changes in stored heat in the water column can be attributed to variability in the velocity and temperature fields at scales smaller than the 8 km by 8 km control volume. Despite its ambitious scope, the sampling of temperature and velocity (in particular) is unable to resolve these variations adequately. On the other hand, the data have not indicated that the small long term trends of temperature are due only to advective processes. The non-zero mean of the apparent transport term could just as easily be attributed to a small systematic error in the surface heat flux estimate. It is true however that the distribution of the directions of the large scale motions responsible for flushing the control volume is biased at both the 10 m and 20 m depths, that the water flowing into the control volume tends to come from a preferred direction. Whichever way it comes, it will have spent many days in the offshore region of the central basin where it will be subject to broadly similar external forcing conditions. The existence of patchiness is evidence that all memory of past experience is not erased by horizontal diffusion, but we claim that its influence on longer term processes associated with the formation and decay of seasonal profiles is more that of a random noise than a systematic bias. A brief review of one-dimensional models of the Lake Erie water column supports this view.

Lam and Schertzer (1986) describe a thermocline model applicable to both the Central and the Eastern Basins of Lake Erie. The reader is referred to this paper for a detailed description. This model predicts the evolution of a temperature profile that is horizontally averaged across the entire basin. Inputs to the model are the horizontally averaged surface heat flux and wind stress. Vertical mixing is parameterized via an eddy diffusion coefficient that depends on surface buoyancy flux, wind stress, and density gradients. It should be emphasized that the particular form given to the parameterization is at the discretion of the modellers. There is an advantage to chosing a simple, mathematically robust form with a minimum of unspecified constants that conforms with intuition as to how a diffusion coefficient should depend on these features. The form chosen is consistent with the idea that vertical heat transfer is truly one-dimensional and does not depend on large scale circulation features such as upwelling or downwelling. The model is calibrated for Lake Erie (free parameters selected) by obtaining the best fit possible with observed sequences of wind stress, heat flux, and temperature distribution. The success of the model is then determined by how well it simulates the evolving temperature profile for independent input data. The model of Lam and Schertzer, by this criterion, is very successful. Horizontal averaging, of course, can mask the actions of processes such as upwelling and downwelling that transfer heat vertically but would certainly not be adequately simulated as a diffusion process. The greater depth of the Eastern Basin and the more diffuse thermocline lend themselves to upwelling and downwelling events more like Lake Ontario. The Lam and Schertzer model is less accurate in simulating the evolution of the thermal structure in the Eastern Basin, despite specific calibration for that basin, perhaps for the reason that significant portions of the vertical heat transfers do not occur via turbulent diffusion. By the same reasoning, the impressive success of the model in simulating the thermal structure in the Central Basin may be due to the dominace of vertical turbulent fluxes in that basin, that is to say the relative unimportance of edge effects.

One of the successes of the 1979 experiment was the clear documentation of an episode of entrainment of thermocline water downwards into the hypolimnion. This process had been invoked by Burns (1972) in order to explain simultaneous increases in hypolimnion thickness and temperature occurring between ship cruises in the 1970 Hypo experiments. The process is capable of supplying oxygen to the hypolimnion since the dissolved oxygen concentration in the thermocline waters is usually substantially higher than that of the hypolimnion water. Ivey and Boyce (1982) analysed the temperature, velocity, and meteorological records for the period July 28 to August 10, 1979 and demonstrate convincingly that the the warming and thickening of the hypolimnion occurring during that interval is due to the turbulent entrainment of overlying thermocline water into the hypolimnion. Moreover they concluded that the source of turbulent energy for this process was the friction of the mean flow over the bottom. Ivey and Patterson (1984) then adapted an existing thermocline model known as DYRESM (Imberger et al. 1981) that had been used with considerable success in lakes and reservoirs of small or medium size. Two crucial extensions were necessary, the first to incorporate the effects of the earth's rotation and the second, to include the mixing caused by turbulence in the hypolimnion.

In contrast to the Lam and Schertzer approach, the heart of the DYRESM model is a vertically integrated turbulent energy budget of the actively mixed layers (both top and bottom layers in the Central Basin case). The actively mixed layers entrain the quiescent fluid next to them at rates that depend on the supply of turbulent kinetic energy and the work that must be done to overcome the inertia of the quisecent fluid and to overcome the stability conferred by density stratification at the interface between the mixed layer and the quiescent fluid. An important source of turbulent energy is the velocity shear that develops across the entraining interface when the mixed layer is accelerated by a wind stress. This shear is computed from vertically integrated equations of motion. A rigorous treatment of the mean momentum transferred from wind to water would require a three-dimensional model that accounted for the boundaries of the lake. This is avoided by noting that the major component of mean velocity shear is periodic. In small lakes it is associated with the internal seiche, in large lakes, such as Lake Erie, with the rotating motions induced by Coriolis force (effects of the earth's rotation). Thus the maximum shear and its time of occurrence can be estimated from the wind stress, the mixed layer thickness, and the period of the oscillating motion. In Lake Erie, allowance must also be made for the fact that the wind vector associated with major episodes of forcing tends to rotate clockwise in the same direction as the surface mean water velocity, thus extending the interval of effective energy input to the mean motions. The energy budget of the bottom mixed layer is simplified following the conclusions of Ivey and Boyce (1982). The source of the turbulent energy is considered to be the stress exerted by the mean flow against the bottom (shear production of turbulence is neglected) and a portion of this energy entrains the stably stratified base of the thermocline into the turbulent hypolimnion. The mean flow in the bottom layer cannot be simply estimated without additional information as to how this flow is generated. Observed bottom flow is introduced to the model as an external forcing variable like the wind velocity. Although the model accounts for the periodicity of the wind-induced shear flow, there is also a complicating periodicity in the thermal structure - possibly induced through the mechanism of internal Poincare waves. Patterson and Ivey (1984) remove these motions by forming 48 - hour averages of the vertical distributions. Thus the model is adapted to the more slowly evolving mean temperature profile about which the short-term perturbations oscillate. Much of the turbulent energy is lost through dissipation; the model accounts for this through the specification of various mixing efficiencies so that the turbulent energy budget is actually concerned only with the fraction available to increase the potential energy of the water column or to agitate newly entrained fluid. The mixing efficiencies are determined from laboratory experiments or from other modelling studies. Experience indicates that these efficiencies are constant in the range of activity of interest. Heat transfer within the non-turbulent thermocline is modelled as a diffusion process; in this region the approach is similar to that of Lam and Schertzer. The model was run without "calibrating" it for the Lake Erie situation, an important contradistinction with the Lam and Schertzer model.

Simulations were performed for the month extending from mid-July to mid-August, 1979, a period that included the episode of downward entrainment studied by Ivey and Boyce and one that encompasses an evolution of the temperature profile from a situation where there is weak stratification above the seasonal thermocline to a sharply defined two layer structure. The simulation of the overall thermal structure is good; Figure 7 is reproduced from the Ivey and Patterson paper. The authors conclude that better simulation might have been achieved by particularizing the model to the Lake Erie case, but the main thrust of the study, to show that all the mixing processes included in the model, in particular those in the bottom mixed layer which had not been included in previous simulations, are necessary and important, seems to have been achieved. It was also demonstrated that some of the discrepancies between the simulations and the observations were due to advection but that these seem not to have led to accumulated error over the 30 day run.

Having established a successful one-dimensional mixing model for mid-basin Lake Erie and moreover one based explicitly on the phenomenon of turbulent entrainment of a stratified fluid, Patterson, Allanson, and Ivey (1985) then extend this work by developing a dissolved oxygen budget model of the Lake Erie water column, a model that uses the one-dimensional mixing model described above as the physical framework and also incorporates a dissolved oxygen model. The study uses data from both the experiments of 1979 and 1980, and as a further confirmation of the mixing model, the authors simulate the temperature profile at two locations separated by 15 km over 20 days in 1980. Meteorological inputs from the nearest buoy are applied to each run. At the end of each simulation, the model corresponds well with the observed structure, but at mooring 6, located on the western side of the array, the simulations and the observations diverge in the middle of the run. Heat budget calculations strongly suggest that the divergence of the calculations from the observations is the result of advection, apparent only at the western site. The oxygen model allows for surface flux of oxygen to and from the lake, photosynthetic production, respiration, and sediment uptake. It is beyond the scope of this paper to provide a critique of the Patterson et al. oxygen model; a somewhat similar model is descibed elsewhere in this volume (Lam et al. 1986). The goal of the study is to provide a model that incorporates the essential mechanisms, both physical and biochemical and thereby to gain some understanding of their relative importance. This goal seems to have been largely achieved. The authors conclude, for example, that the bottom mixed layer mechanism must be included in the model to achieve a good simulation of the temperature profile but that it contributes only marginally to the oxygen budget of the hypolimnion in comparison with the large sediment oxygen demand. The formulation of the bottom mixed layer entrainment model itself may no longer be appropriate when the thermocline region becomes very thin; when, in effect, both mixed layers seem to be in competition to entrain fluid from the same narrow stratified zone. A better understanding of this situation is of more than passing interest; it may be crucial in deciding the presence of seasonal stratification in lakes of the temperate zone (Gorham and Boyce, 1986). The DO model, like the mixing model it contains, demonstrates an ability to track the average distribution of dissolved oxygen over many days. There are several instances where the simulations deviate from observations in the short term, all of them seem to result from local inhomogeneities advected into the control volume. Persistent horizontal gradients of DO are not observed; it seems reasonable to conclude that long term changes are effected by vertically-acting processes. Thus it is essential that biochemical models be supported with adequate models of vertical mixing, a conclusion supported by Lam and Schertzer.

The success of the purely one-dimensional models in tracking both thermal structure and dissolved oxygen content over weekly and monthly time scales in mid-Central Basin confirms the essential horizontal homogeneity of the region. The analysis of the measurements of velocity and temperature show that this homogeneity is of a statistical nature, that the system contains variability at shorter time scales and at sub-basin space scales, variability that is effectively random.

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SUMMARY AND CONCLUSIONS.

The existence of horizontal variability coupled with transport processes introduces sufficient "noise" to the time series collected during the anchor station experiments to obscure many changes of local origin taking place at time scales equal to or shorter than a day. In order to resolve these changes into a locally acting and a transport-induced component, a local budget of the parameter under investigation in a mid-lake control volume is required. This entails a three-dimensional sampling of both the velocity and the parameter under study in the vicinity of the control volume. The 1979 and 1980 Lake Erie mid-basin experiments can be viewed as control volume or budget experiments for both heat and horizontal momentum. In this paper we have chosen to test the approach with a heat budget of the control volume.

Once the control volume is defined, it is possible to distinguish between horizontal flows with spatial scales of coherence larger than the control volume that act to move water horizontally through the control volume and thereby to flush it, and between smaller scale components that contribute to mixing across the control volume boundaries and thereby to a diffusive transport by turbulent "eddies". A simple control volume consisting of a vertical cylinder 10 km in diameter was chosen to represent the space scales of the mid-basin array. Flushing and mixing time scales were estimated at three levels, 10 m, 19m, and 21m below the surface. Horizontally averaged currents were used to define the flushing time scale while the local deviations from these averaged flows were used to compute effective diffusion coefficients, and in turn, mixing time scales for the control volume. The diffusion coefficients appear to be large when compared with results of dye diffusion experiments but by filtering out some of the large-scale shearing motions they could be made to approach accepted values. At all levels, persistent large scale currents replace the water in the control volume every few days. Although the directions of the net displacements vary, the distribution is biased to flows toward the west and southwest. Estimates of horizontal mixing timescales are long enough in all but a few isolated instances to ensure that small scale features are advected through the control volume without being obliterated. The relatively long mixing time scales may be the reason why a patchiness is maintained in the horizontal distributions although the origin of the patchiness, particularly in the hypolimnion, must be the result of large displacements of parcels of water.

Comparison of local estimates of daily surface heat flux with daily heat content change of the water column shows differences that are frequently much larger than those to be expected on the basis of error in either quantity. Such differences can only be produced by transport processes. The variability of local heat content changes computed at thermistor array lcations separated by 10 - 15 km is again much larger than that to be expected from measurement error; we take this to be the signature of horizontal variability or "patchiness". We determined that the daily heat content change of the upper 10 m of the water column tracked the surface heat flux more closely, indicating that much of the transport term was contributed by processes acting in the bottom 14 m of the water column. This is to be expected since the vigour of the exchanges between the near-surface water and the atmosphere should make this zone more nearly a reflection of the relatively homogeneous meteorological forcing. Attempts were then made to estimate the transport term in the bottom 14 m of the water column using a combination of current meter and thermistor array data. The velocity field was expressed as a spatially uniform component upon which was superimposed a spatially variable and possibly divergent flow. Diffusion processes were not considered; the neglect can be justified by the disparity of time scales noted above. The advective heat flux computed from the spatially averaged flow and the observed horizontal distribution of temperature was of the correct scale but otherwise totally uncorrelated with the transport term inferred from the heat budget. On the other hand, the advective flux estimated from the spatially variable flow (mean plus fluctuations) showed episodes that could be matched against similar events in the heat budget imbalance. These events seemed to involve internal redistributions of mass in the water column over periods of several days such as the thinning and northward movement of the hypolimnion occurring at the end of the measurement period. We were forced to conclude that our spatial sampling, in both the horizontal and the vertical was inadequate to resolve these differences, and indeed, the current meters themselves are inadequate to resolve the anticipated small but important differences.

Over the measurement period (mid-June to the end of September), the transport term inferred from the heat budget showed a positive mean, equivalent to a warming of the entire water column by 0.04°C per day. This is well within the error band of most of the components of the surface heat flux and could be explained as a systematic error in the heat flux model. If this is true, we are then justified in treating the heat budget of the Central Basin as a purely one-dimensional (vertical) problem. The success of Lam and Schertzer's (1988) basin-wide thermocline model is confirmation of this approach. The turbulent energy budget model applied at the mid-basin site by Ivey and Patterson (1984) supports this view even more firmly. Despite some obvious departures from the observed and calculated thermal structure that can be traced to transport events, the model tracks the evolving thermal structure over long periods (30 days or more) without showing accumulated divergence in either layer.

Thus the noise we observe in the heat transport term appears to be effectively random and without cumulative effect. Similar conclusions can be drawn from the dissolved oxygen model of Patterson et al. (1985).

While the study of the heat budget of a mid-basin control volume has yielded some useful insights, we have failed to close the gaps sufficiently to meet the goal of being able to differentiate reliably and at all times between locally produced changes such as the vertical redistribution of heat by entrainment and the transport of heat in and out of the control volume. Our inability to make long term measurements of velocity in the upper 10 m of the water column is a serious limitation. The GVAPS experiment described elsewhere in this volume (Royer, Hamblin, and Boyce, 1986) provides a technical solution. From the limited success with this profiling system obtained in 1980, we confirmed a conclusion drawn by Boyce and Chiocchio's (1986b) study of inertial period oscillations that seemingly minor details in the thermal structure support important features of the velocity profile and that strings of up to four self-recording current meters, the backbone of the present experiments, cannot alone resolve them. The horizontal variability of the temperature distribution recorded by the thermistor arrays and the large remaining errors even when these are averaged, indicates that we have undersampled horizontally within the control volume. This conclusion has also been drawn by

Boyce and Chiocchio (1986a) who attempted to compute internal pressure gradients by interpolating the density distribution through the control volume. They concluded that the 10 km (nominal) separation of the thermistor arrays was too large.

Would we have done better with a control volume of half the size, 5 km diamneter, say? The flushing timescale of this volume would have been of the order of two days, still adequate perhaps to resolve daily time scales. It is not possible to say whether averages of three or four thermistor arrays separated by a nominal 5 km, although improved, would be stable enough. While it is true that the energy in the fluctuating part of the velocity field would be substantially reduced, it is still probable that the spatially varying velocity field would have to be included in the computation of the transport term. With these separations we may be beyond the capabilities of the present current meters to discern small but important differences of order 0.5 cm/s in velocity. Reducing the horizontal scale does nothing to ameliorate the serious undersampling in the vertical. We conclude that a finer horizontal grid scale would improve the stability of the spatially averaged heat content and the estimate of the temperature field on the periphery of the control volume, but the gain would be partially offset by an increased relative uncertainty due to current meter error. A major conclusion of this study is that control volume or budget studies of parameters known to depend on stratification or to vary vertically because of biochemical activity, but that cannot be measured in a profile mode simultaneously in several places are likely to be less successful than the present heat budget study.

Thus the notion that we can determine locally acting processes by direct observation, after accounting for the transport term across the boundaries of a control volume, is impractical as a general, mechanically executed technique. Certain isolated events may lend themselves to this approach, but each event must be judged on its own merits. Interpretation of promising events is nevertheless valuable even if the interpretation remains at the descriptive level. The descriptive study of Ivey and Boyce, (1982), leading to the successful simulations of Ivey and Patterson (1984) supports this view. Here the model has been the integrating mechanism that confirms the subjective selection by Ivey and Boyce of a mechanism to explain an apparent incident of entrainment into a turbulent hypolimnion. That the models can be verified over periods of time long enough to average out the noise induced by the transport term is an extremely fortunate consequence of the statistically homogeneous conditions occurring in the offshore region of the Central Basin of Lake Erie. This site offers enormous potential as a natural limnological laboratory, albeit atypical of the Great Lakes. On the other hand, without the detailed data available from the spatial array of current meters and thermistor strings, we would not have been able to estimate the flushing and mixing timescales of the control volume defined by the array, nor would we have been able to assess the nature and the importance of the transport terms. For the same reasons that lake systems models require the armature of an adequate (physical) mixing model, so must process-oriented experiments be supported by adequate knowledge of the physically-induced variability. The answer to the question posed in the title, "Can physicists close the door?" is "No, not all the way yet, but the Central Basin of Lake Erie is one of the best place to learn how."

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FIGURE CAPTIONS

Figure 1. Time series of the number of water exchanges in the 10 km control volume effected in a 7-day period by flushing and mixing at both 10 m, 19 m, and 21 m levels.

Figure 2. Network of instruments in the mid-basin experiment area in 1979.

Figure 3. Time series plot of daily surface heat flux and daily heat content change of the water column for the mid-basin experiment area.

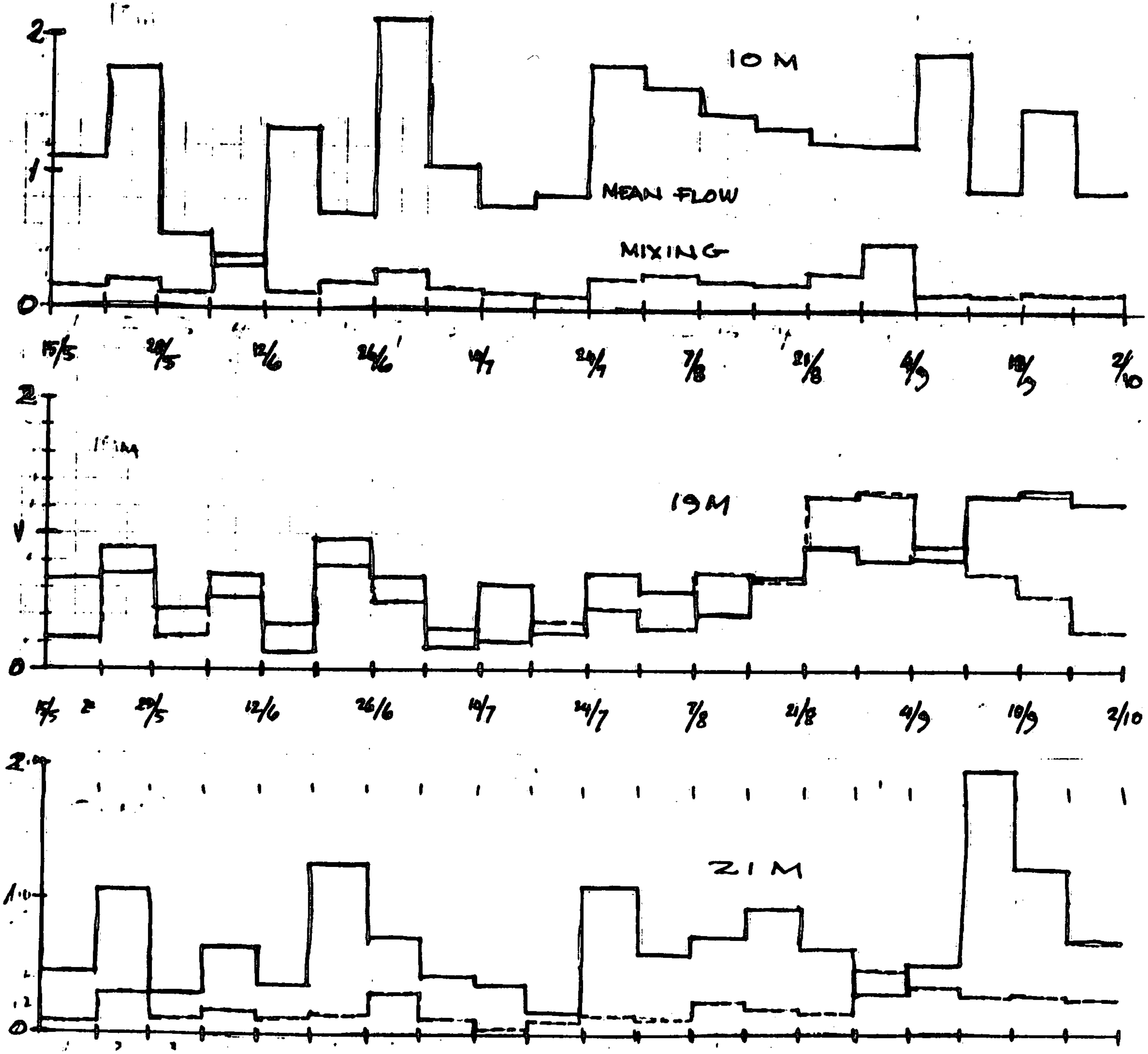
Figure 4. Time series plot of daily surface heat flux and daily heat content change in the upper 10 m of the water column for the mid-basin experiment area.

Figure 5. Time series plot of daily heat content change observed in the bottom 14 m of the water column and estimate of heat transported by the spatially averaged flow.

Figure 6. Time series plot of daily heat content change in the bottom 14 m of the water column and estimate of heat transported by the observed spatially variable flow.

Figure 7. Results of model simulations (solid lines) compared with field observations (dots) which are 48 - hour averages centred on 0000 hrs on dates shown. Figure reproduced from Ivey and Patterson (1984) [Fig. 4] with the authors' permission.

Figure 1


10 M
MEAN FLOW
MIXING
19M
21 M
2
1
0
1.0
15/5
29/5
12/6
26/6
10/7
24/7
7/8
21/8
4/9
18/9
2/10

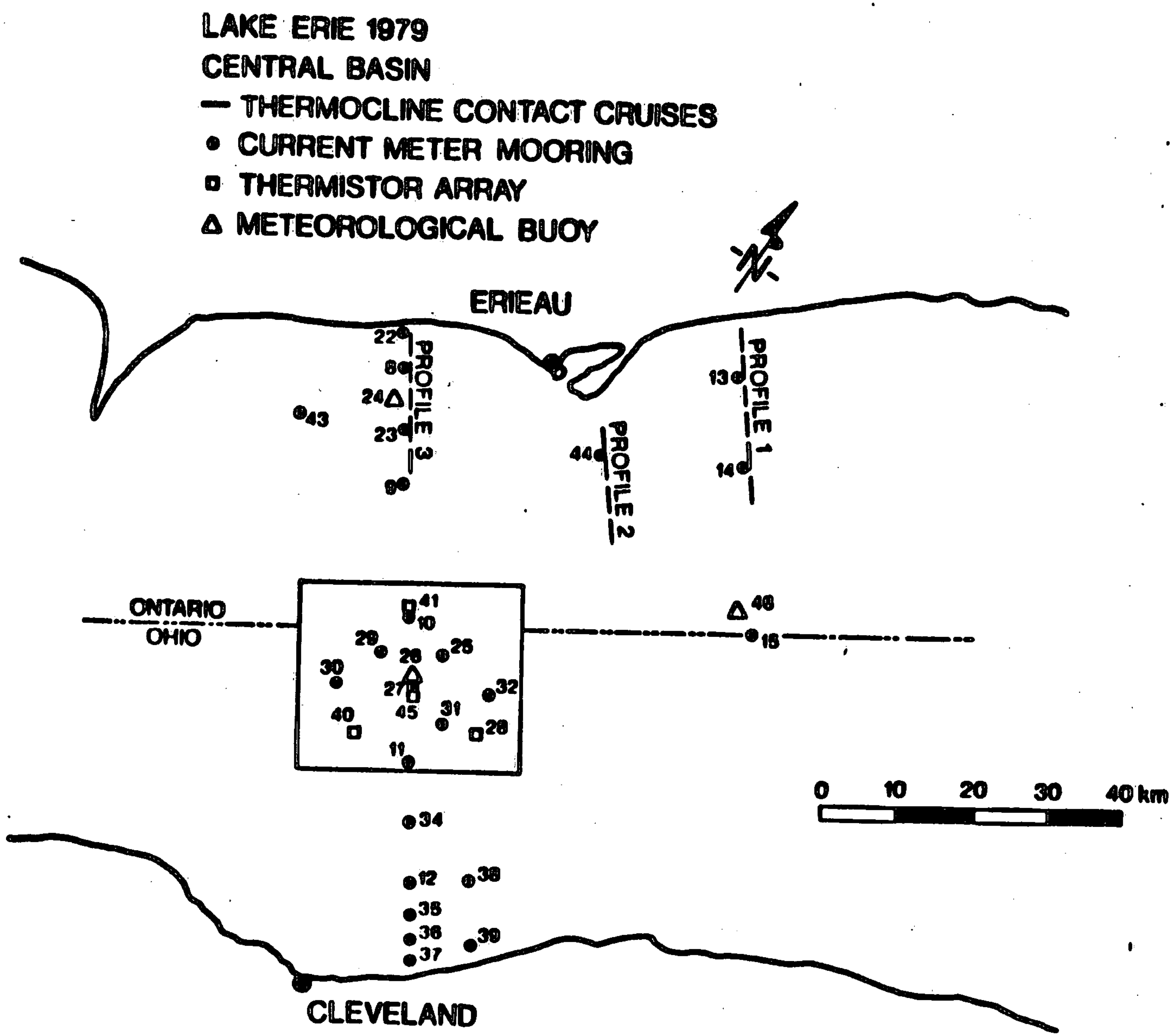
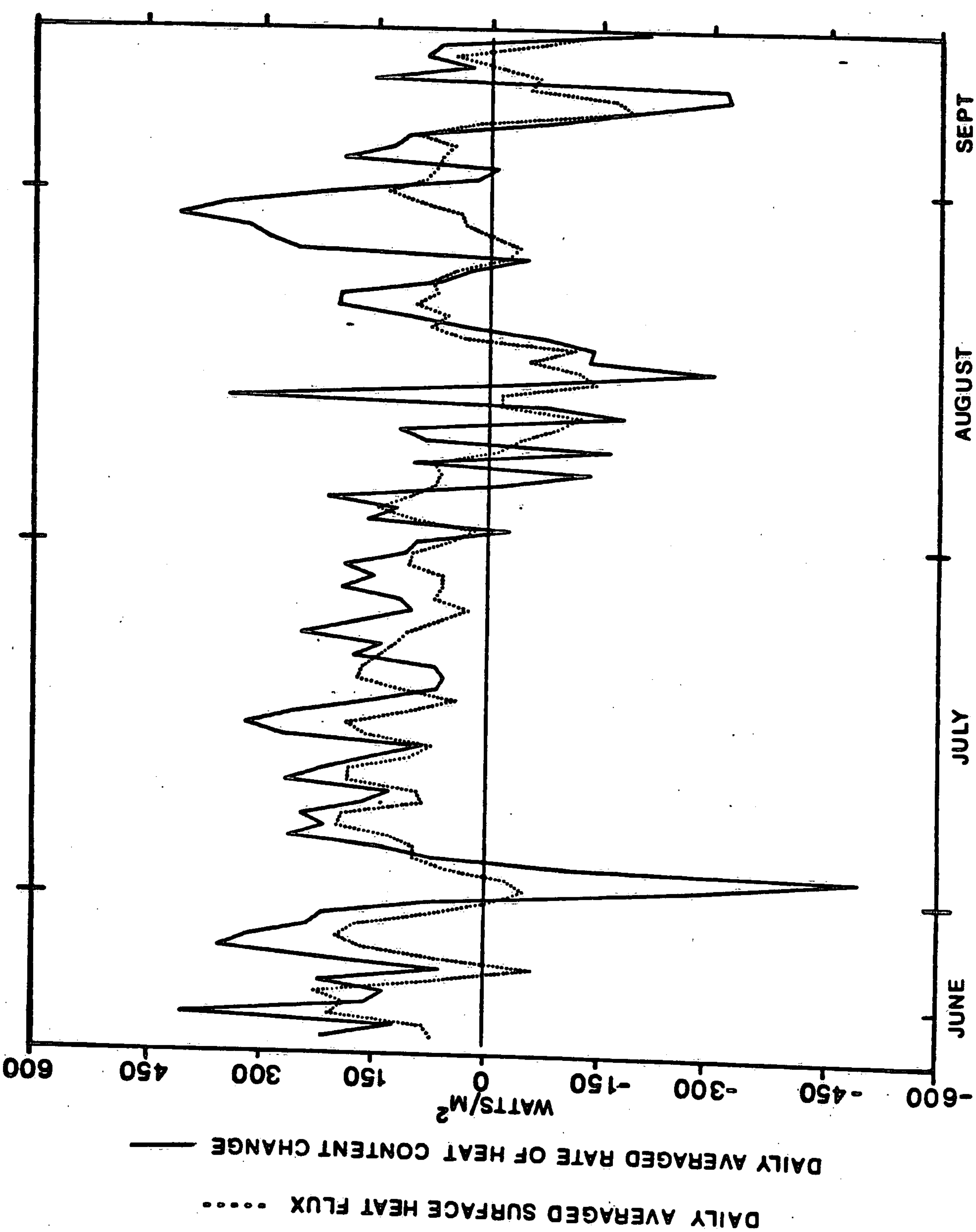

LAKE ERIE 1979
CENTRAL BASIN
— THERMOCLINE CONTACT CRUISES
● CURRENT METER MOORING
□ THERMISTOR ARRAY
Δ METEOROLOGICAL BUOY
ERIEAU
PROFILE 1
PROFILE 2
PROFILE 3
ONTARIO
OHIO
CLEVELAND
0 10 20 30 40 km
22
8
24
23
9
43
44
13
14
46
15
41
10
29
26
25
30
27
32
40
45
31
28
11
34
12
38
35
36
39
37

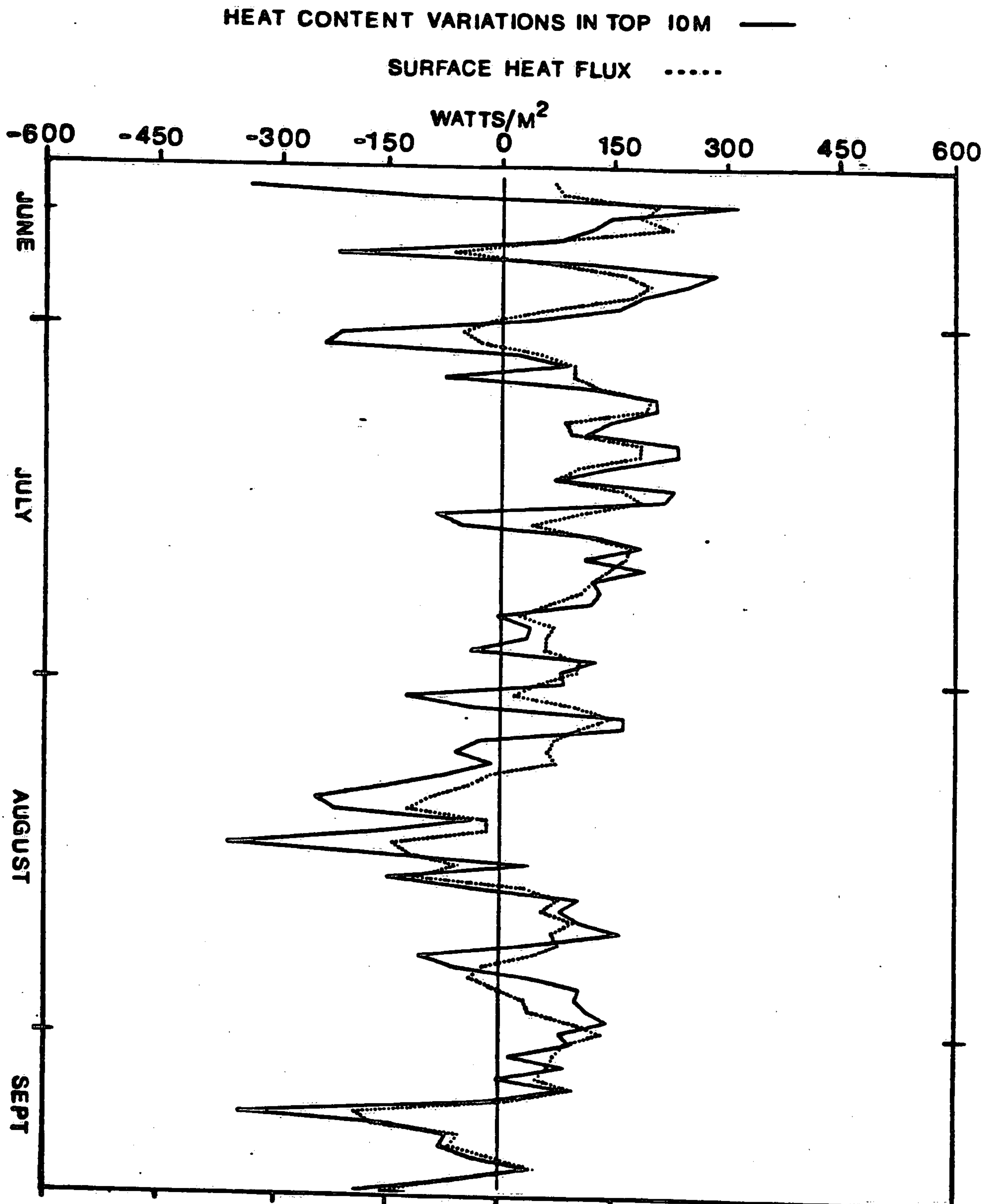
FIG 2

FIG 3



DAILY AVERAGED SURFACE HEAT FLUX
DAILY AVERAGED RATE OF HEAT CONTENT CHANGE
WATTS/M²
-600
-450
-300
-150
0
150
300
450
600
JUNE
JULY
AUGUST
SEPT

Fig 4


HEAT CONTENT VARIATIONS IN TOP 10M ——
SURFACE HEAT FLUX .....
WATTS/M²
-600
-450
-300
-150
0
150
300
450
600
JUNE
JULY
AUGUST
SEPT

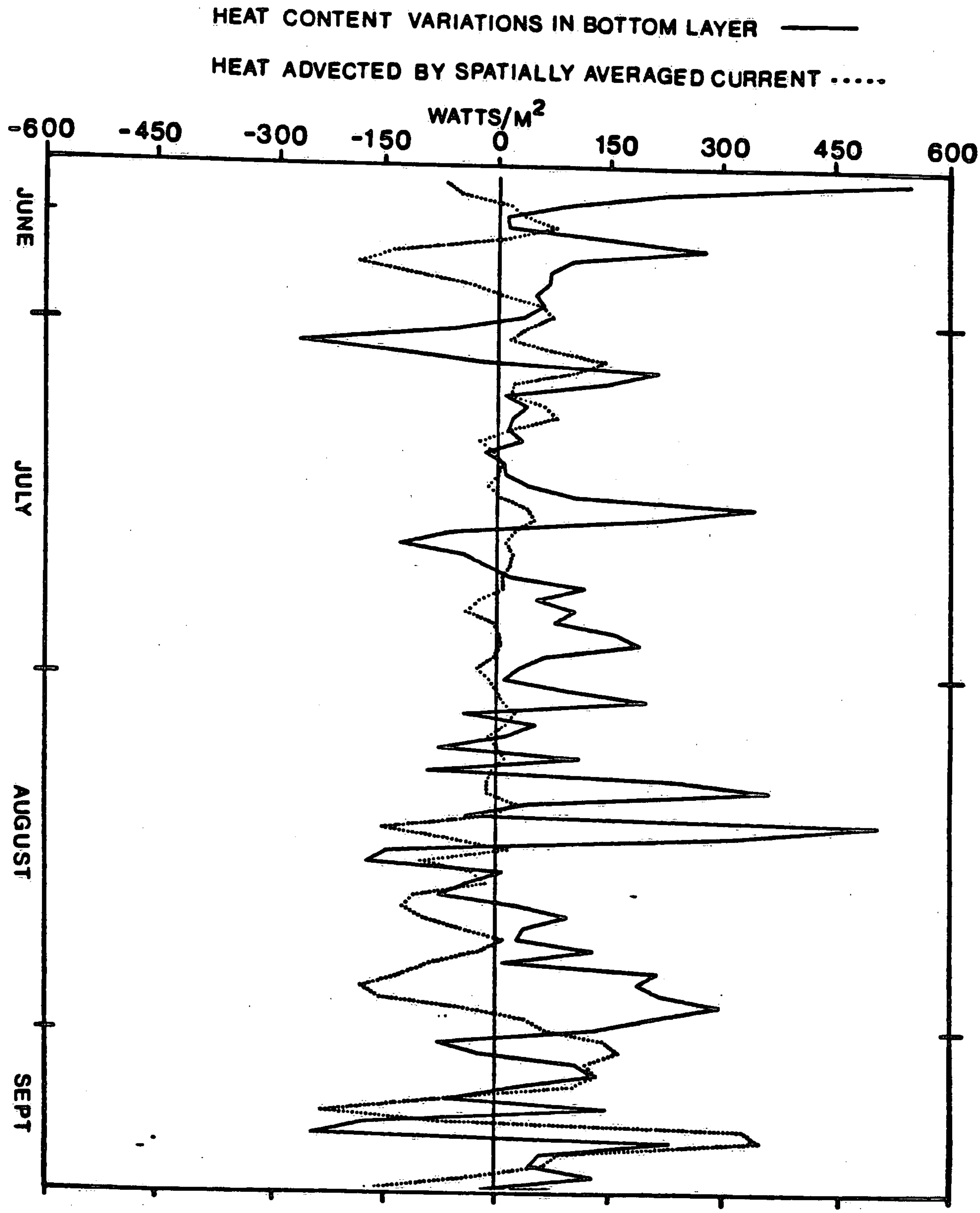

HEAT CONTENT VARIATIONS IN BOTTOM LAYER
HEAT ADVECTED BY SPATIALLY AVERAGED CURRENT
WATTS/M²
-600
-450
-300
-150
0
150
300
450
600
JUNE
JULY
AUGUST
SEPT

FIG 8

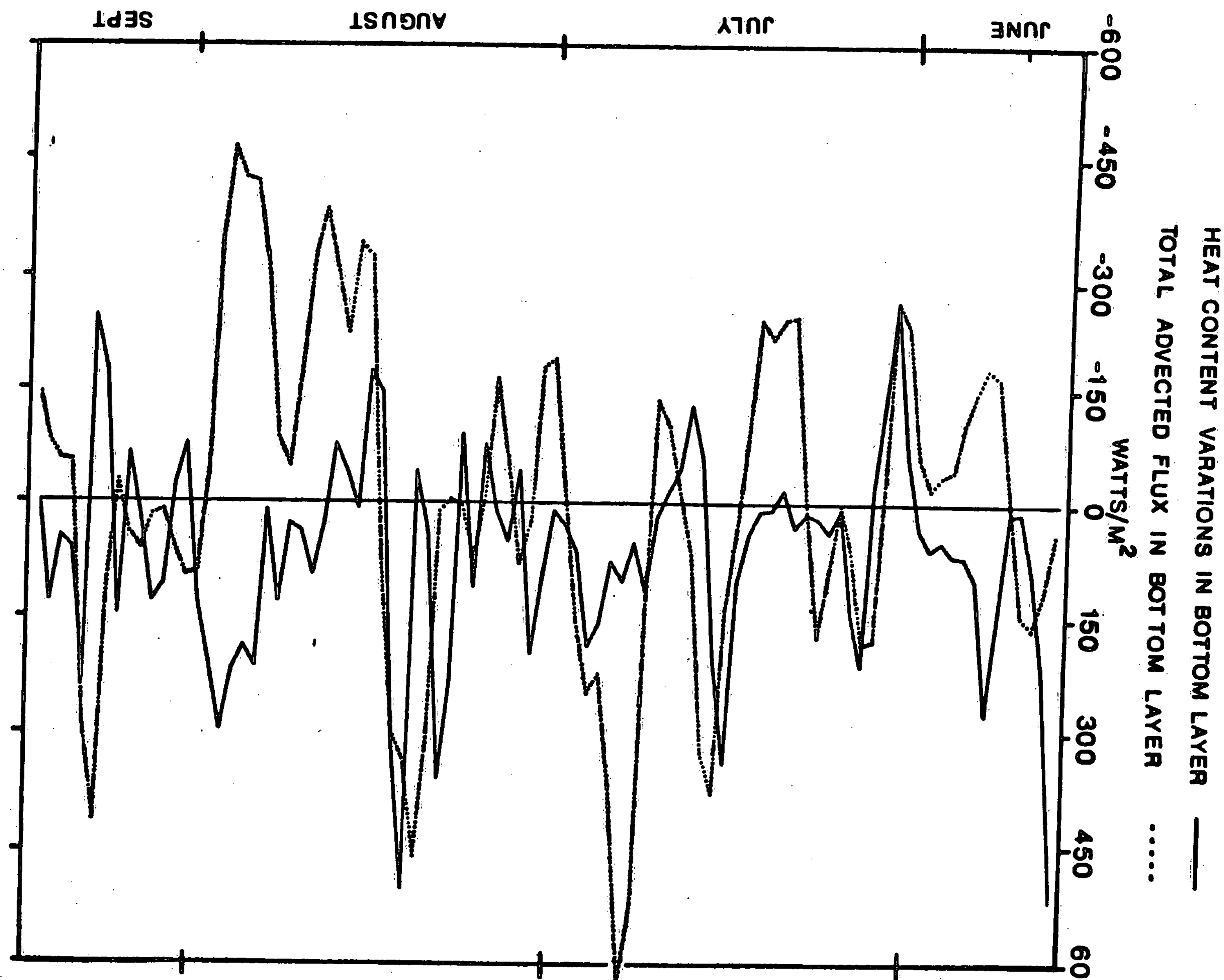
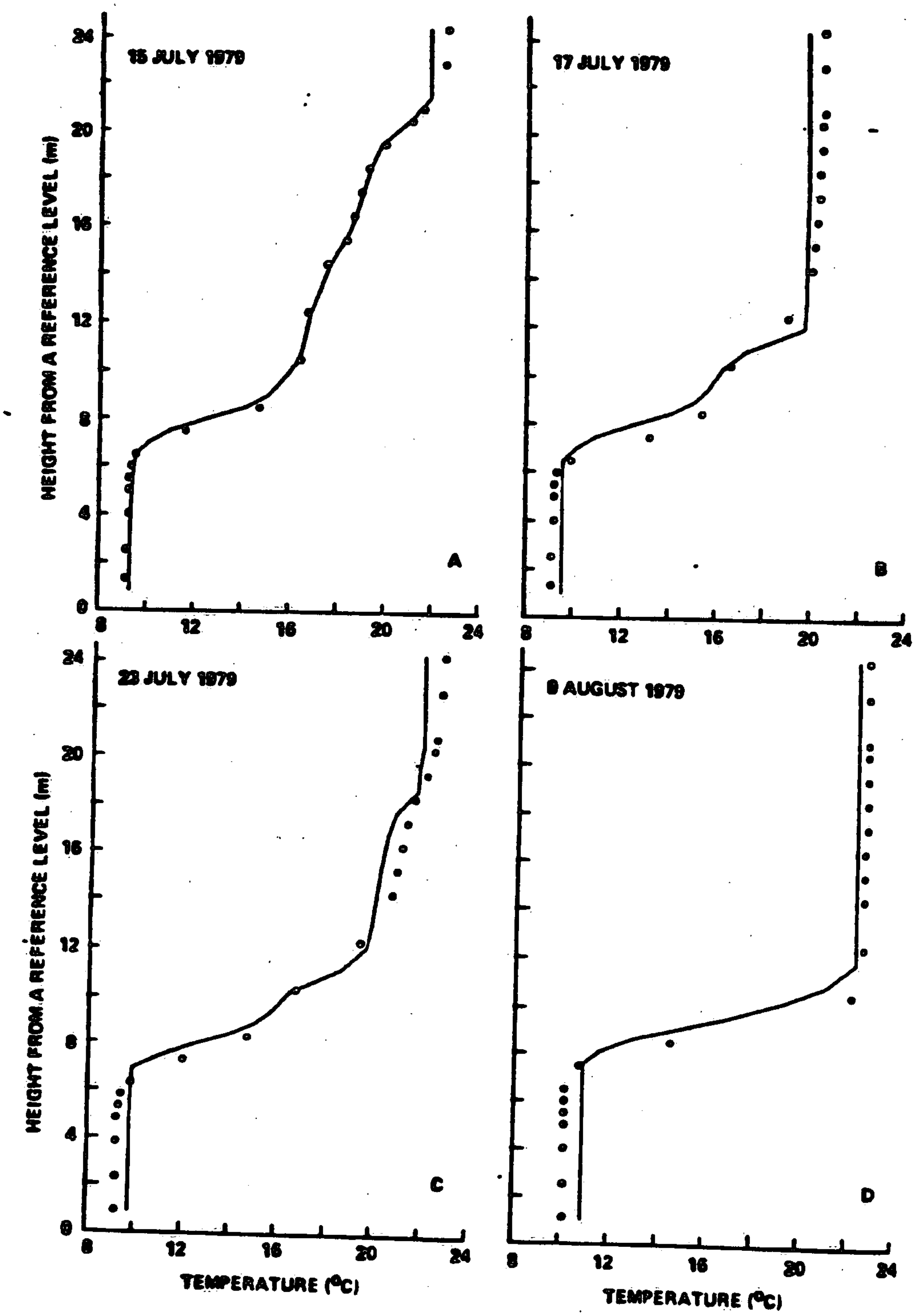

HEAT CONTENT VARIATIONS IN BOTTOM LAYER
TOTAL ADVECTED FLUX IN BOTTOM LAYER
WATTS/M²
-600
-450
-300
-150
0
150
300
450
600
JUNE
JULY
AUGUST
SEPT

FIG 7


15 JULY 1979
17 JULY 1979
23 JULY 1979
8 AUGUST 1979
HEIGHT FROM A REFERENCE LEVEL (m)
HEIGHT FROM A REFERENCE LEVEL (m)
TEMPERATURE (°C)
TEMPERATURE (°C)
A
B
C
D
0
4
8
12
16
20
24
8
12
16
20
24