I.O.S.

BENTHIC BOUNDARY LAYER MODELLING STUDIES

INTERIM REPORT, MARCH 1984

BY

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OCEAN DISPOSAL OF HIGH LEVEL RADIOACTIVE WASTE
A RESEARCH REPORT PREPARED FOR THE DEPARTMENT
OF THE ENVIRONMENT

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF
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Benthic boundary layer modelling studies

Interim Report, March 1984

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DEPARTMENT OF THE ENVIRONMENT RADIOACTIVE WASTE MANAGEMENT

RESEARCH PROGRAMME 1983/84

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Abstract

A numerical model has been developed to study the factors which control the height of the benthic boundary layer in the deep ocean and the dispersion of a tracer within and directly above the layer. This report covers tracer clouds of horizontal scales of 10-100km.

The dispersion of a tracer has been studied in two ways. Firstly, a number of particles have been introduced into the flow. The trajectories of these particles provide information on dispersion rates. For flow conditions similar to those observed in the abyssal N.E. Atlantic the diffusivity of a tracer was found to be $5x10^6 cm^2 s^{-1}$ for a tracer within the boundary layer and $8x10^6 cm^2 s^{-1}$ for a tracer above the boundary layer. The results are in accord with estimates made from current meter measurements.

The second method of studying dispersion was to calculate the evolution of individual tracer clouds. Clouds within and above the benthic boundary layer often show quite different behaviour from each other although the general structure of the clouds in the two regions were found to have no significant differences.

Keywords:
299 93, 94, 125, 155

This work has been commissioned by the Department of the Environment as part of its radioactive waste management research programme. The results will be used in the formulation of Government policy, but at this stage they do not necessary represent Government policy.

Contents

PREFACE

The research described in this report is concerned with a small part of the scientific assessment of the feasibility of the disposal of heat generating radioactive waste (HGW) into the deep sea environment. A presentation is given of research aimed at understanding the initial mechanisms of dispersion of radionuclides introduced into the benthic boundary layer (BBL) of the deep ocean. This layer, adjacent to the seabed and varying from 10-100m in thickness is caused by friction between the moving ocean water and the stationary ocean bottom. Within the BBL turbulent mixing is sufficiently strong that the properties such as density (and by analogy a radionuclide source term), are rendered uniform in the vertical. Above it the density decreases with height and vertical exchange is suppressed.

The Natural Environment Research Council, through the Institute of Oceanographic Sciences, has a contract with the Department of the Environment (DOE, DGR481/176) to examine processes within the BBL both by direct measurement within the deep ocean and also by numerical modelling (DoE Report No. 83-070). The emphasis of the investigations has been placed on studying the processes relevant to radionuclide dispersal within the BBL in order that realistic predictive models can be developed.

Introduction

The benthic boundary layer is the region of flow in the ocean adjacent to the sea floor. Because of vertical shear the flow will be turbulent. The turbulence will mix properties such as temperature and salinity to produce a homogeneous layer some tens of metres thick. The layer is sometimes capped by a region of strong density gradient inhibiting exchange of properties between the mixed layer and above. Turbulence generated at the bottom will be restricted to this layer.

Mathematical models of the vertical and horizontal structure of the benthic boundary layer have been developed and have been reported by Richards[1]. Many of the features predicted by the models are observed. One of the main conclusions of that report is the control by mesoscale eddies of the height of the benthic boundary layer. Mesoscale eddies have diameters 50-200 km, speeds of a few centimetres per second and are the major source of flow variation in the deep ocean. Due to convergences and divergences produced by these variations, the height of the benthic boundary layer is distorted, exceeding 100m in some regions and decreasing below 10m in others. Benthic fronts are formed and the mixed layer may detach from the bottom.

The present report concentrates on the dispersion of a tracer both within the benthic boundary layer and immediately above it. After the release of a tracer in the benthic boundary layer turbulence within the layer mixes the tracer vertically and the concentration becomes uniform throughout the depth of the layer within 1 to 10 days. Thereafter the tracer spreads horizontally under the the action of mesoscale eddies. The eddies stretch and distort a cloud of tracer causing the cloud to disperse at a far greater rate than the shear generated turbulence within the layer. The tracer remains in the boundary layer until it moves into a region where it can escape. Observations indicate that one mechanism for escape is the detachment of the bottom mixed layer. The modelling work suggests that areas of detachment are created by the interaction of the bottom layer with eddies and that these areas occur over 10-20% of the total horizontal area of the mixed layer. Other mechanisms for escape are the ejection of fluid at fronts[2] and the mixing around abyssal hills. Once the tracer has escaped from the bottom layer it continues to be dispersed by mesoscale eddies. Outside the bottom layer such dispersion occurs primarily along constant density surfaces. The mixing rate of a tracer through density surfaces is much less[3].

Estimates of the dispersion rates in the deep ocean on horizontal scales of 1-20 km have been made by Saunders[2,4] using current meter measurements and free-drifting float observations. The numerical experiments reported here compliment the estimates of Saunders and extend the scales covered to 100-200km.

The numerical model of Richards[1,5] provides predictions of the flow within and immediately above the benthic boundary layer due to a field of mesoscale eddies. The dispersion of a tracer is studied in two ways. The tracks of a number of particles placed both within the benthic boundary layer and above it have been calculated using the predictions of the flow by the model. The statistics of these particle tracks then give estimates of dispersion rates in the different flow regions. The second and complimentary method is to calculate what happens to a single cloud of tracer under such flow conditions. This approach not only provides estimates of the spreading rates of the tracer but also gives information on the expected shape of the cloud and how 'streaky' it may become.

Two distinctly different flow regimes have been used for this study. The results will be reported in Richards[6]. Here, the results for the case most like the flow in the Madeira abyssal plain as observed by Saunders[2] will be presented.

The numerical model

The model is of a 500 km square piece of ocean (figure 1). The flow is assumed to be periodic in both horizontal directions so that an eddy travelling out of one side of the box comes in on the opposite side. In the vertical the model is divided into three layers. The upper two layers model the ocean interior. Their depths H_1 and H_2, and densities, ρ_1 and ρ_2 are chosen so that the dynamics of the model approximate to the dynamics of the real ocean. The lowest layer is the benthic boundary layer. An eddy field is prescribed in the uppermost layer. This interacts with the second layer which in turn interacts with the boundary layer. Various statistics of the flow, such as eddy speeds and sizes and mixed layer height are predicted. The model is described in full detail in Richards[5].

Typical flow patterns in the first and second layers and the mixed layer height are shown in figure 2. The eddies in the second layer have an averaged speed of 4 cm s^{-1} and have a length scale of 50 km. These velocity and length scales are in accord with the measurements of Saunders[4] on the Madeira abyssal plain. The mixed layer height has small scale intense features with regions of large gradient. These features are advected by the flow. In the dispersion studies described in the following two sections particles or a tracer placed in the benthic boundary layer are assumed to be advected with the vertically averaged velocity of the layer. When the layer is deep this velocity is close to the velocity of the flow above the layer. When the layer is thin particles in the bottom layer will be advected more slowly than those above the layer and, as will be shown, this leads to a reduced dispersion rate within the bottom layer.

The vertical shear in the advection velocity of a tracer in the bottom layer will lead to an enhanced horizontal diffusion of the tracer over and above that due to the turbulence in the layer (see Smith[7]). However, it is estimated that this shear enhanced diffusion is small compared to the dispersion due to the mesoscale eddies.

Dispersion of particles

The procedure for calculating particle tracks in the model was as follows. At a given time in a run of the numerical model an array of particles was placed in the second and bottom layers of the model representing particles just above and within the benthic boundary layer respectively. The array contained 289 particles. The initial separation of the particles was 16 km and the array covered a quarter of the total area of box. The model was then run on for a further 90 days and the tracks of the individual particles through the box calculated. Five such runs were performed giving a total of 1445 particle tracks in each layer. The statistics of the particle tracks were calculated using this ensemble of runs.

An example of six particle tracks above and within the benthic boundary layer are shown in figure 3. These tracks were chosen to demonstrate how different the dispersion of particles above and within the boundary layer can be rather than to be representative of all the tracks calculated. The particles above the boundary layer disperse with their maximum separation increasing by a factor of eight after 90 days. The tracks of the particles within the boundary layer are completely different. After a short while the particles become trapped in a small intense eddy and at the end of 90 days are closer together than when they started. These particle tracks highlight the need for a large number of particles to obtain reliable statistics as was found by Saunders[4].

The particle tracks can be analysed in two ways, either individually or by looking at pairs of particles and calculating the separation between them. Since the second way relates to the dispersion of a cluster or cloud of tracer the statistics of the particle pairs are reported here.

In the array of 289 particles there are 545 particle pairs with an initial separation R_o, of 16 km. The separation between these particle pairs, R, was calculated as a function of time after release and the average of the squared separation $< R^2 >$ taken over all particle pairs. The particle pair separation is shown in figure 4. After a short initial period the particle pair separation on average grows exponentialy with time, i.e. $R^2=R_o^2 \exp \alpha t$ with $\alpha^{-1}=11$ days for particles above the boundary layer and $\alpha^{-1}=13$ days for particles within the boundary layer. The range of particle pair separations for which this is true is 18 km to 60 km. For greater particle pair separations the rate of increase in the separation is reduced. After 90 days the average particle pair separation is 125 km for particles outside the boundary layer and is 100 km for particles inside the boundary layer. The average concentration of a tracer will fall by a factor of 64 outside and 40 inside the boundary layer in this time.

A measure of the effective diffusivity of the mesoscale eddies, K, is given by $\frac{1}{4}\frac{d}{dt}\langle R^2 \rangle$. The effective diffusivity is plotted against time in figure 5. At the time of release with the particle pair separation, $\langle R^2 \rangle^{1/2}=16$ km the diffusivity $K=2.5\times10^5 cm^2 s^{-1}$. The diffusivity increases with time and reaches a maximum value of $K=8\times10^6 cm^2 s^{-1}$ for particles above the boundary layer and $K=5\times10^6 cm^2 s^{-1}$ for particles within the boundary layer. When the particle pair separations are larger than the eddy size the diffusivity will become constant with time. This happens in the boundary layer when $\langle R^2 \rangle^{1/2}$ is greater than 70 km. Above the boundary layer the diffusivity levels out when $\langle R^2 \rangle^{1/2}=100$ km. The decrease in K for later times is due to some of the particle pair separations becoming comparable to the box size and the motions of the particles becoming correlated. The values of the diffusivity of a tracer obtained from the numerical model are similar in magnitude to the estimates obtained from current meter measurements by Saunders[2].

The results from the numerical experiments reported here show on average only a small difference between the diffusion of particles above the boundary layer and particles within the boundary layer even though there are quite dramatic differences in some individual cases. Experiments have also been performed with a somewhat different flow regime where there is a strong interaction between the boundary layer and the flow above. In this case the effective diffusivity of a tracer in the boundary layer was found to be ten times less than the diffusivity above the boundary layer.

In calculating the tracks of particles placed in the benthic boundary layer it has been assumed that the particles remain in the boundary layer. In practice some of these particles will escape from the boundary layer when fluid is lost from the layer either through the detachment of the layer from the bottom or by the ejection of fluid at fronts. The numerical model predicts likely places of boundary layer separation[1]. These are warm patches of the boundary layer caused by first a thinning of the layer due to the action of the eddies followed by an entrainment into the layer of the warmer fluid above the layer. These patches are lighter than the surrounding boundary layer and may be lifted off the bottom by buoyancy forces. It is postulated that a particle entering such an area will escape from the bottom layer. The time was noted when each particle first entered an area of possible detachment. Fifteen per cent of particles were immediately lost as they were placed initially in a warm patch. The number of particles remaining in the boundary layer, N, is plotted against time in figure 6 for four different experiments. The scatter in the points is large. They do however show a decrease in N with time. After 90 days only 10% of particles have been lost. Extrapolating these results to later times gives an estimate of 800 days for the average residence time of particles in the boundary layer. This slow decrease in particle numbers will not significantly affect the statistics obtained from the particle trajectories over 90 days. In 800 days, with a diffusivity of $5 \times 10^6 cm^2 s^{-1}$, the tracer cloud will have a diameter of 400 km with two thirds the tracer having escaped out of the boundary layer.

Dispersion of a tracer cloud

A number of experiments have been performed where the evolution of a cloud of tracer is calculated. Two such experiments are reported here with the cloud above and within the boundary layer. The clouds were released at the same time and in the same horizontal position. The initial cloud radius was 16 km. To model the scales of motion that are unresolved by the numerical model a background diffusivity is introduced. This background diffusivity is set at the lowest value that will produce numerically stable results. For the experiments reported here this is $4x10^5 cm^2 s^{-1}$. The evolving clouds are shown in figures 7 and 8. The centre of mass of each cloud has been moved to the centre of the plot. The mesoscale eddies stretch and contort the cloud. The cloud above the boundary layer has been stretched out in a predominantely E-W direction with a piece of the cloud shed to the SE. The centre of mass of the cloud has moved 140 km to the west. The maximum concentration in the cloud has been reduced by a factor of 9.5 from its initial value. The mean radius of the cloud has increased to 98 km. With the background diffusivity alone the radius would only have increased to 30 km. The orientation of the cloud in the boundary layer is N-S with a piece of the cloud shed to the west. The centre of mass has moved 40 km to the northwest. The maximum concentration has been reduced by a factor of 7.3 and the mean radius increased to 72 km. Although there are differences in the orientation and sizes of the two clouds there is no significant differences in their structure, i.e. one is not more 'streaky' than the other. More experiments are required to make a firmer statement.

Conclusion and recommendations for further work

The particle dispersion and tracer cloud experiments reported here provide estimates of dispersion rates on the 10-100 km scale in and above the benthic boudary layer. The results are in accord with the estimates of Saunders[2] using current meter measurements. Direct measurement of dispersion in the ocean on this and longer scales requires the use of long-range free-drifting floats. The use of these floats by IOS is planned for the near future. The numerical model will be used to access the representativeness of the results obtained using a limited number of float trajectories.

The numerical model predicts that the average length of time for a fluid particle to remain in the benthic boundary layer is approximately 800 days. In this time the fluid particle will have travelled several hundred kilometers and is very likely therefore to come into a region of topography. The flow around an abyssal hill is likely to separate leading to enhanced mixing and thus providing a means of escape for the fluid particles and reducing the residence time of the particle in the boundary layer. Laboratory experiments to examine the implications of flow separation around hills for mixing in the deep ocean will be carried out in the near future.

The question of how streaky a cloud of tracer will become has not been fully answered. The present results are limited by the horizontal resolution of the numerical model. Experiments with a higher resolution model are planned. Topography will affect the dispersion of a tracer outside the benthic boundary layer on scales of 100 km and greater. Topography will be included in future runs of the numerical model.

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Figure captions

Figure 1 Sketch of the regions of flow in the numerical model.

Figure 2 Typical streamfunction maps for the flow in the upper two layers Ψ_1, Ψ_2 and the mixed layer height, h. The flow is along the contours of Ψ_1 and Ψ_2. The average speed of the flow in the upper two layers is 4 cms^{-1}. The contour interval for h is 12m.

Figure 3 Particle trajectories for particles placed above the boundary layer, (a), and within the boundary layer, (b).

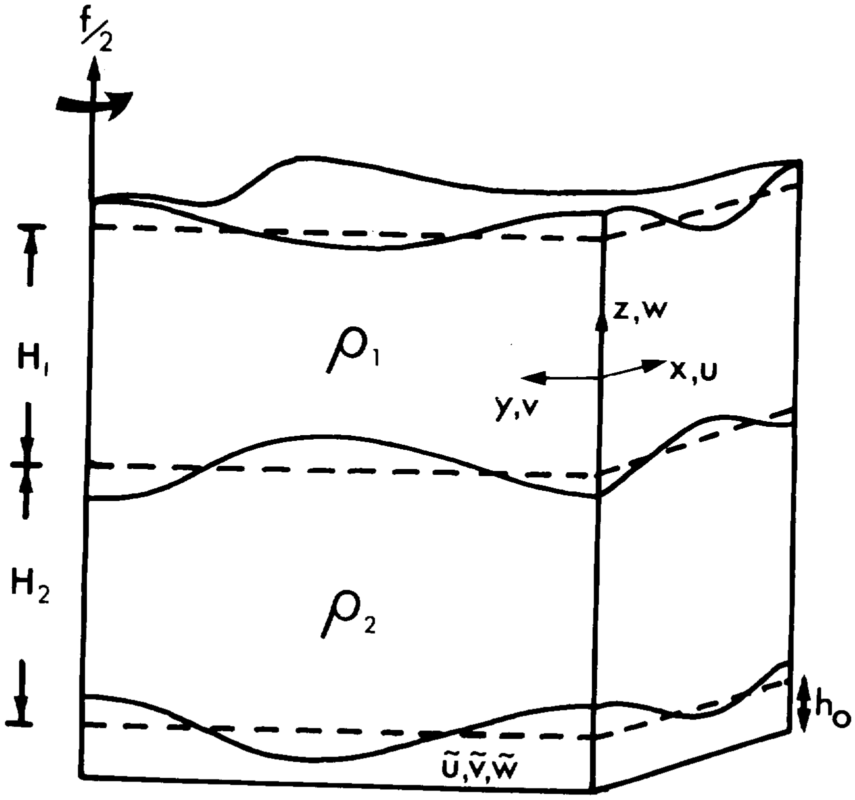
Figure 4 Plot of the natural logarithm of the mean squared separation of particle pairs $<R^2>$ over the square of the initial separation, Ro^2, for particles above (1), and within (2), the boundary layer. The initial separation of pairs, Ro, is 15.6km.

Figure 5 Plot of the rate of change of the mean squared separation of particle pairs against time for particles above, (1), and within, (2), the boundary layer. The effective diffusivity, K, is equal to $\frac{1}{4}\frac{d}{dt}<R^2>$.

Figure 6 Plot of the natural logarithm of the number of particles remaining in the benthic boundary layer, N, over the initial number, No, against time. The initial number, No, is the number of particles not placed initially in a region of boundary layer detachment (see text).

Figure 7 Evolution of a tracer cloud above the benthic boundary layer. The time interval between each plot is 18.4 days. The centre of mass of the cloud has been moved to the centre of each plot.

Figure 8 As for figure 7 except for tracer cloud within the benthic boundary layer.



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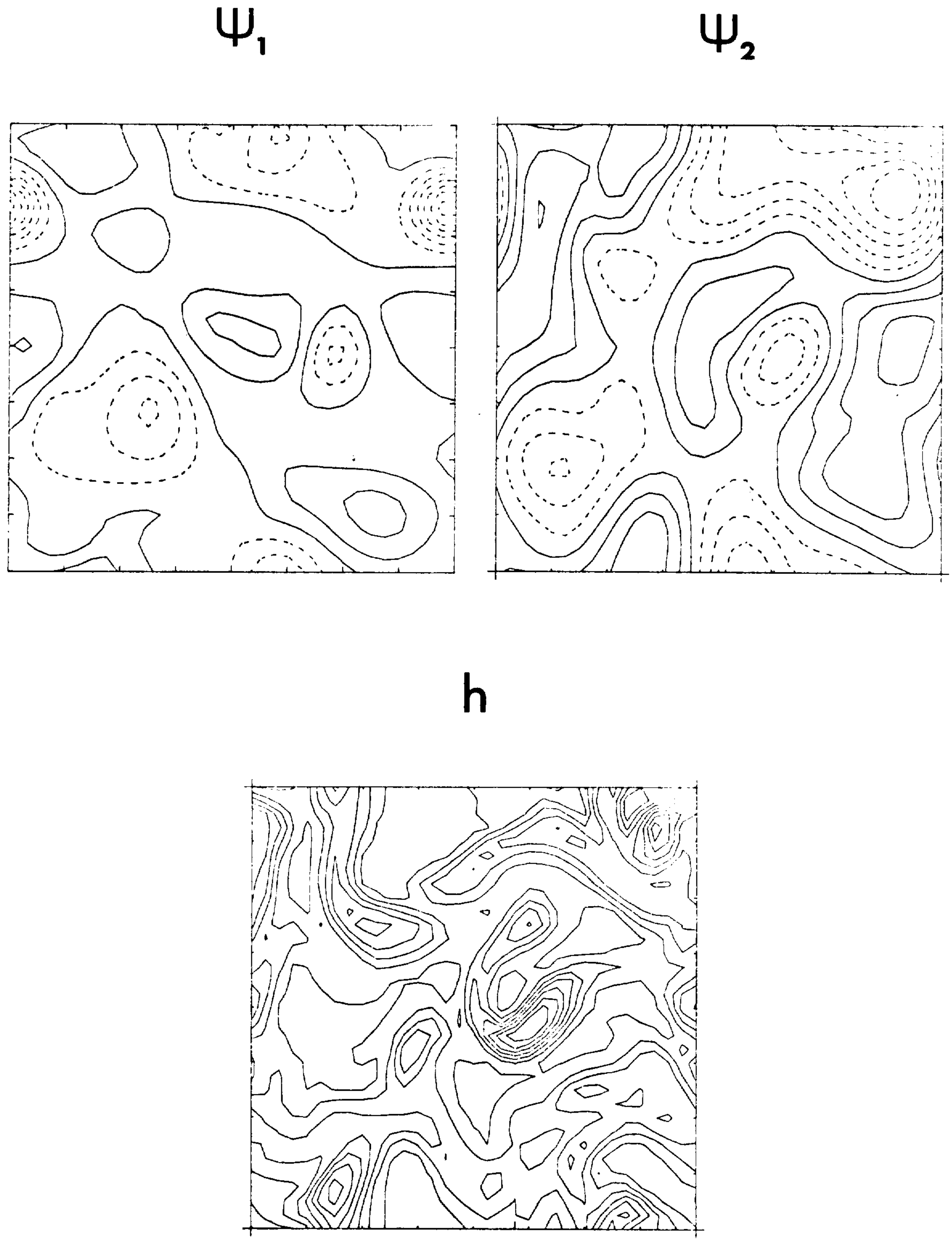

Figure 2 Typical streamfunction maps for the flow in the upper two layers Ψ_1, Ψ_2 and the mixed layer height, h. The flow is along the contours of Ψ_1 and Ψ_2. The average speed of the flow in the upper two layers is 4 cms^{-1}. The contour interval for h is 12m.

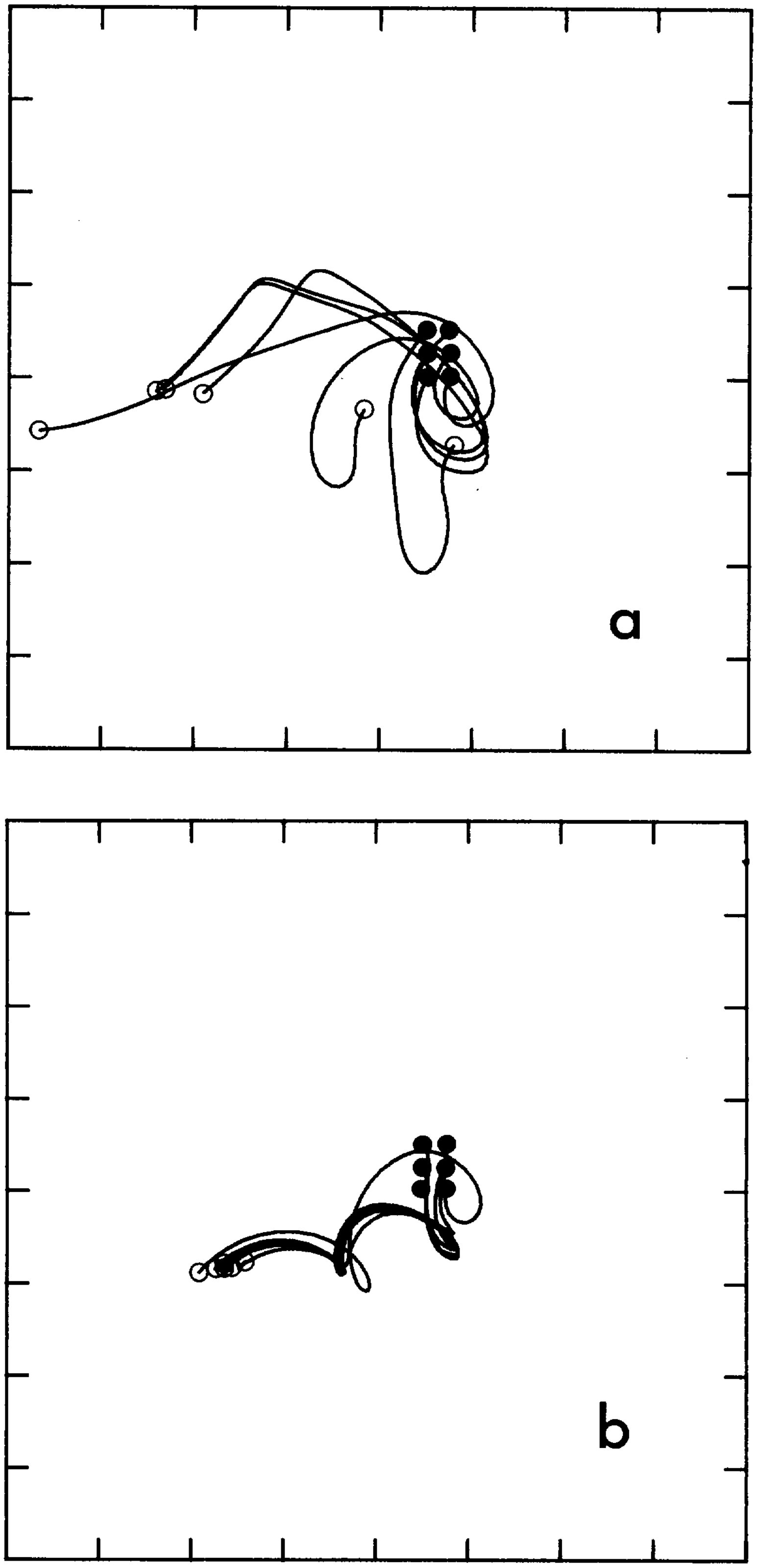

Figure 3 Particle trajectories for particles placed above the boundary layer, (a), and within the boundary layer, (b).

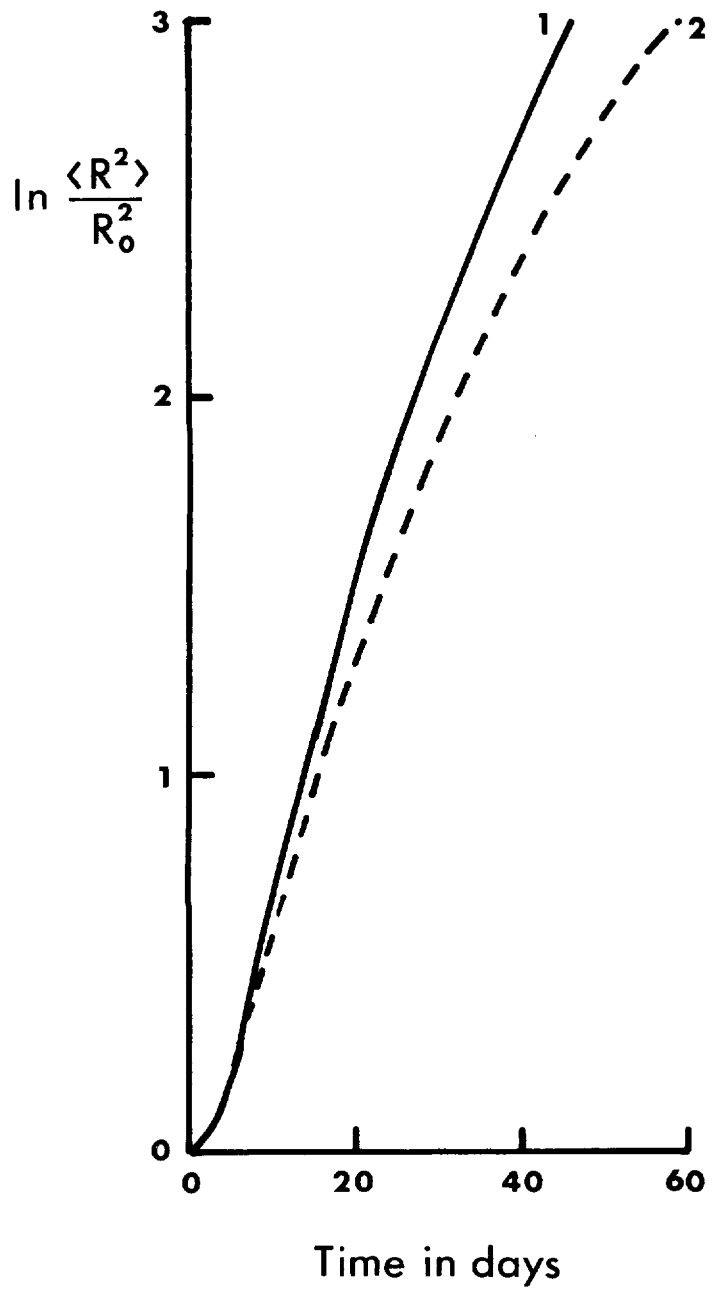

Figure 4 Plot of the natural logarithm of the mean squared separation of particle pairs $\langle R^2 \rangle$ over the square of the initial separation, Ro^2, for particles above (1), and within (2), the boundary layer. The initial separation of pairs, Ro, is 15.6km.

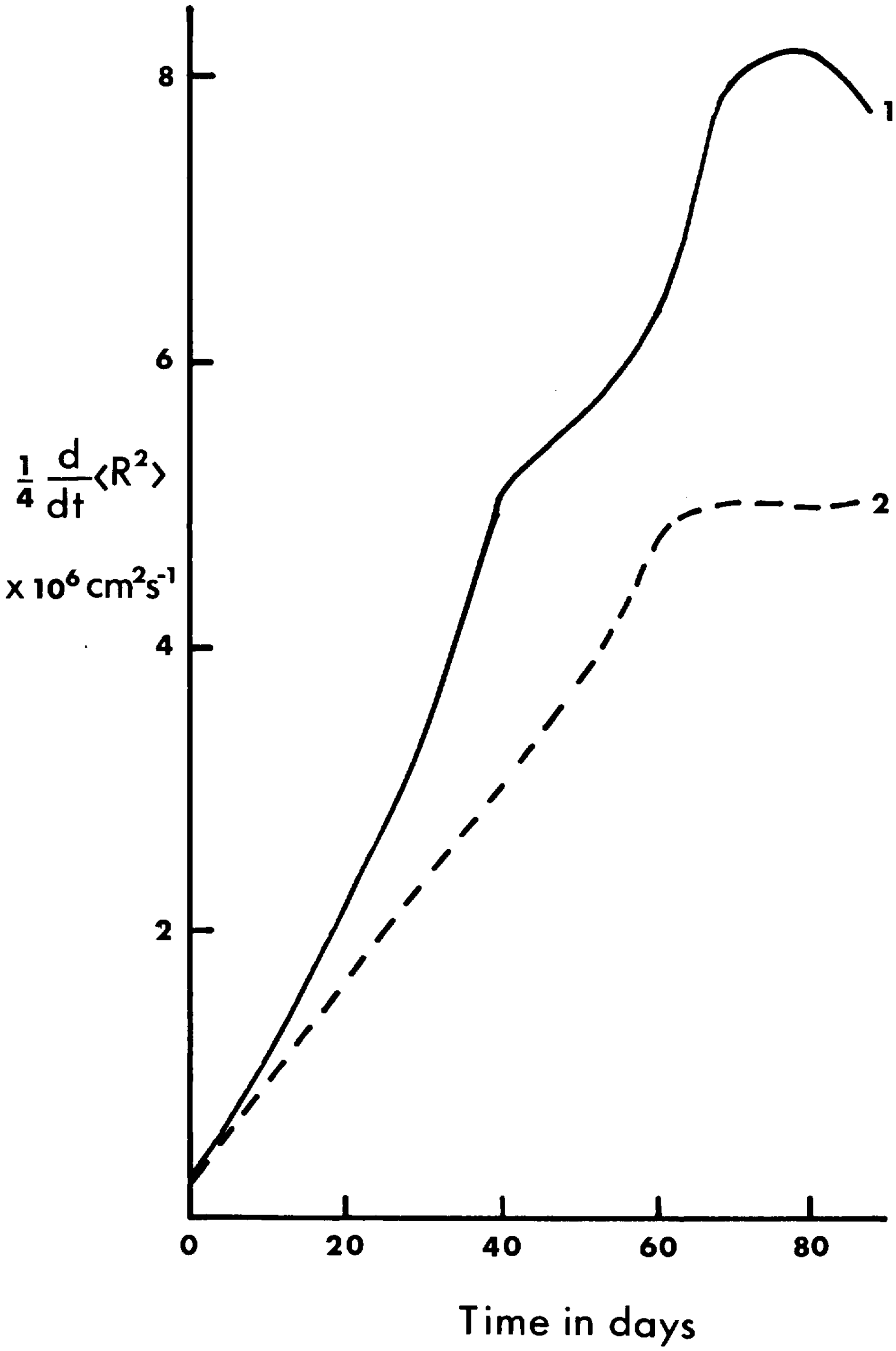

Figure 5 Plot of the rate of change of the mean squared separation of particle pairs against time for particles above, (1), and within, (2), the boundary layer. The effective diffusivity, K, is equal to $\frac{1}{4}\frac{d}{dt}<R^2>$.

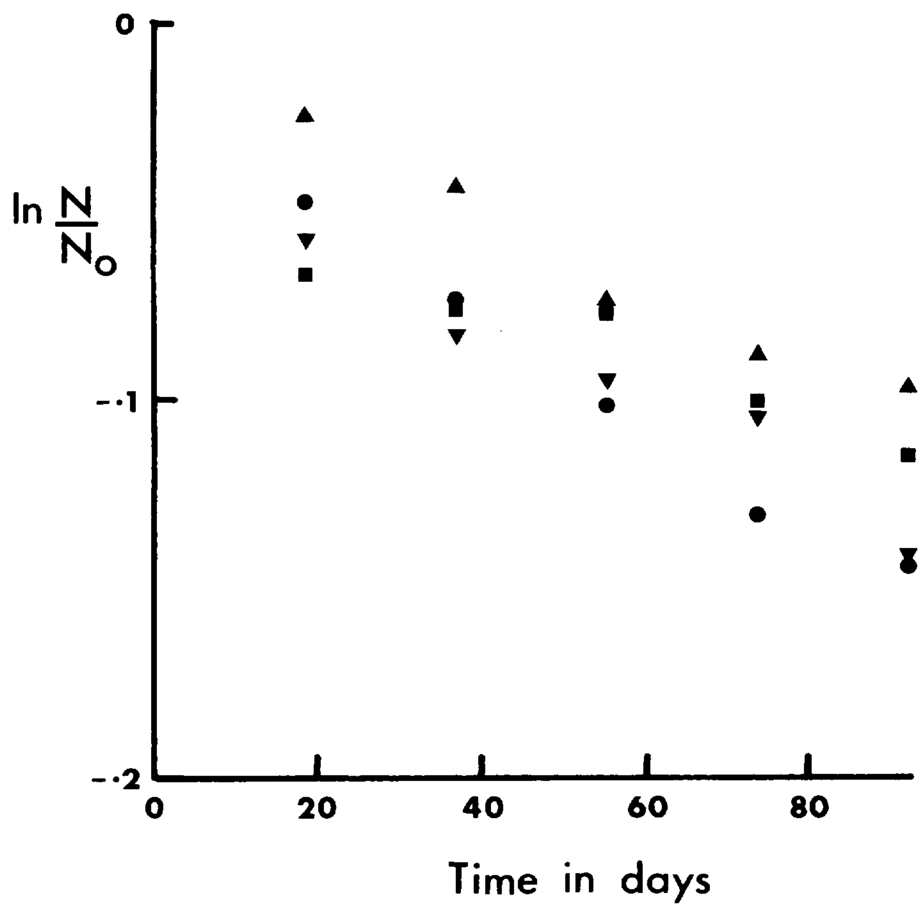

Figure 6 Plot of the natural logarithm of the number of particles remaining in the benthic boundary layer, N, over the initial number, No, against time. The initial number, No, is the number of particles not placed initially in a region of boundary layer detachment (see text).

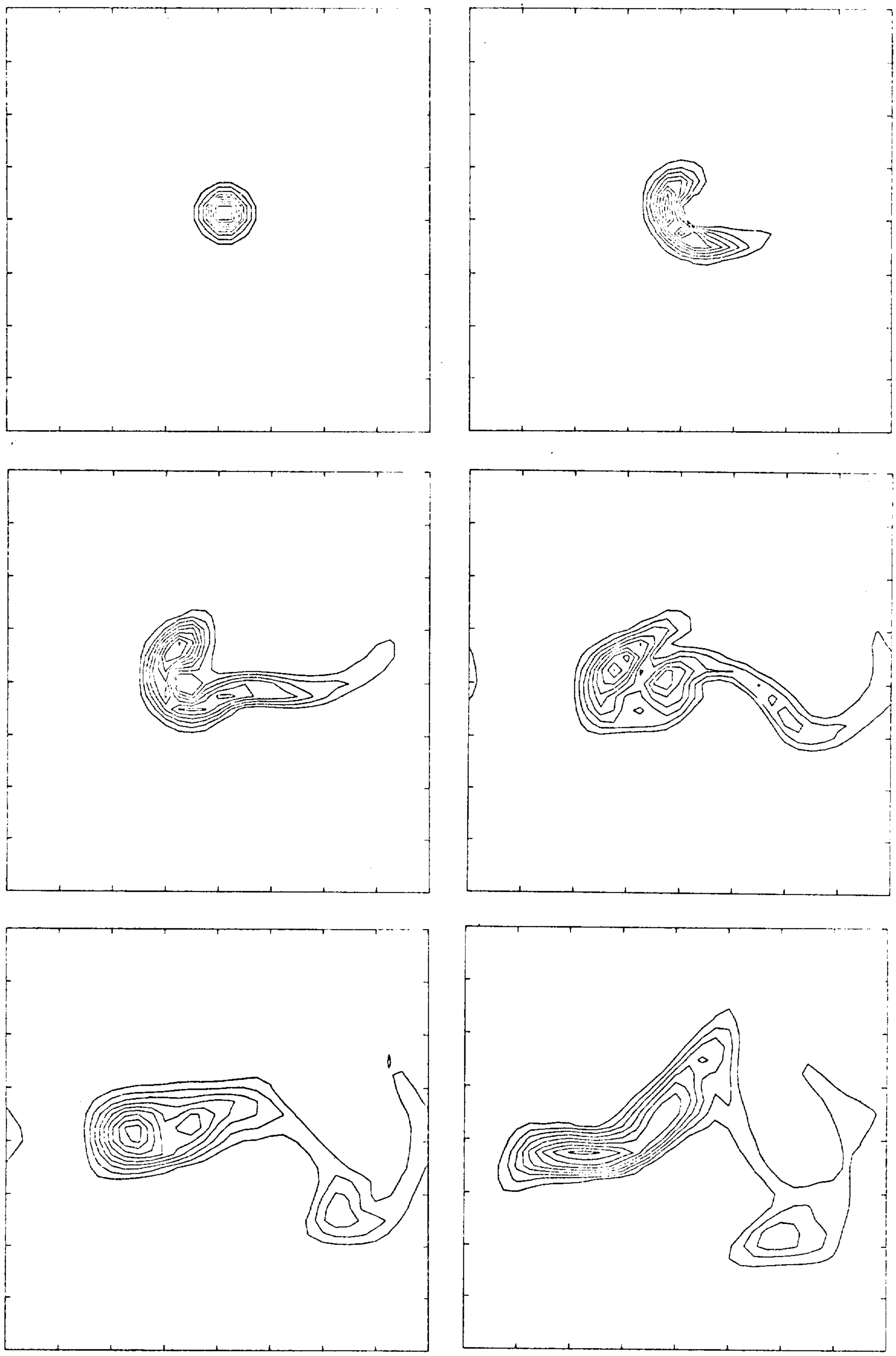

Figure 7 Evolution of a tracer cloud above the benthic boundary layer. The time interval between each plot is 18.4 days. The centre of mass of the cloud has been moved to the centre of each plot.

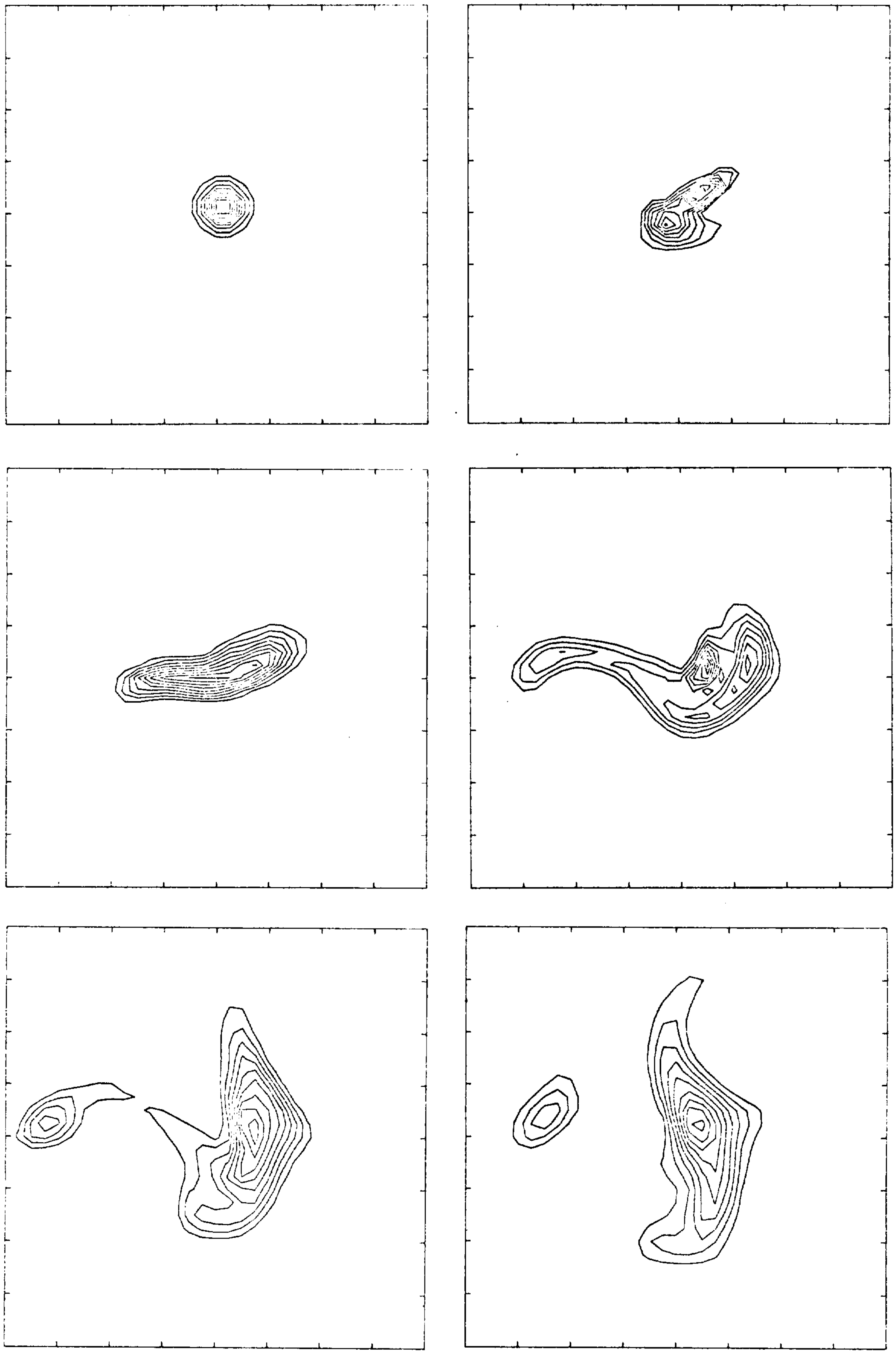

Figure 8 As for figure 7 except for tracer cloud within the benthic boundary layer.