I.O.S.

BENTHIC BOUNDARY LAYER — IOS MODELLING PROGRAMME INTERIM REPORT MARCH 1983

by
K.J. RICHARDS

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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 OCEANOGRAPHIC SCIENCES

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INSTITUTE OF OCEANOGRAPHIC SCIENCES

WORMLEY

Benthic boundary layer - IOS Modelling Programme

Interim Report, March 1983

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Ocean disposal of high level radioactive waste
A research report prepared for the Department
of the Environment

I.O.S. Report No. 162

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DEPARTMENT OF THE ENVIRONMENT

RADIOACTIVE WASTE MANAGEMENT

RESEARCH PROGRAMME 1983 /84

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Report Title: Benthic Boundary Layer - IOS Modelling Programme
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Abstract

Numerical models have been developed to study the factors which control the height of the benthic boundary layer in the deep ocean and the residence time of fluid and hence a tracer within it.

In one model, the effects of steady and unsteady currents and variations in fluid density are examined. In conditions similar to those observed in the abyssal regions of the E.N. Atlantic the model predicts an average bottom layer height of 35 m, close to the value observed. Furthermore the layer thickness responds to a sudden change in flow conditions in about three days.

In a second model the effects of spatial variations in currents is examined. Due to convergences and divergences produced by these variations, the height of the bottom mixed layer is distorted, exceeding 100 m in some regions and decreasing below 10 m in others. Where the thinning is large mixing results in warm patches flanked by benthic fronts. Many of the features predicted by the model are observed in the deep ocean.

It is proposed that within the warm regions, which occupy 10 to 20% of the horizontal area of the flow, the bottom mixed layer is exchanged within the ocean above. The residence time of a tracer released within the bottom mixed layer, average value 100 days, is predicted to vary considerably - between 20 and 800 days.

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 necessarily 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 dispersal of radionuclides introduced into the benthic boundary layer (BBL). This layer, adjacent to the seabed and varying from 10-100m in thickness is caused by friction between the moving waters of the main ocean and the stationary ocean bottom. Within it 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 the BBL the density decreases with height and vertical exchange is suppressed.

The Natural Environmental 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. 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 rotation of the earth has a strong influence on currents within the ocean. Away from boundaries and regions of strong currents the flow tends to be horizontal and to follow contours of constant pressure. Close to the ocean floor the flow is retarded allowing some flow to cross pressure contours. The direction of the flow changes with height. Very close to the surface it is approximately 10° to the left of the flow away from the surface. This region is referred to as the Ekman layer. 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.

A distinction must be made between the height of the mixed layer and the height to which the flow is affected by the presence of the boundary, the latter called the momentum boundary layer. As will be shown in this report, in cases where the flow varies horizontally the height of the mixed layer will be distorted and may be many times thicker than the height to which turbulence can penetrate.

Until recently observations of the bottom mixed layer of the ocean have been limited. But measurements of temperature and salinity showed a mixed layer often several times that expected by existing models[1]. Armi and D'Asaro[2] studied the bottom mixed layer at a site in the W. Atlantic and found the height of the mixed layer to vary between 5 and 60m over horizontal distances of 20 km and periods of 15 days. An observational programme was carried out at IOS[3] to study the flow and density structure in the E. Atlantic on the Madeira abyssal plain. The much weaker stratification in this region makes it difficult to detect the presence of a mixed layer. However, by a careful analysis of temperature measurements it has been possible to deduce that the average height of the layer is approximately 30m, becoming less than 10m on some occasions and greater than 100m on others.

The aim of the modelling programme has been to study some of the processes occurring close to the sea bed and to provide a theoretical framework with which to help interpret and extend the results obtained from the observational programme. Two approaches have been taken. The first follows that of previous work and investigates the development of the mixed layer under a horizontally uniform current. A sophisticated turbulence model has been used to study this problem[4]. As the model only considers the vertical structure of the mixed layer it is referred to as a one-dimensional model. The model provides estimates of the expected height of the layer and how long it will take to reach this height together with the vertical variations of the flow and turbulence quantities.

Although an improvement on previous work the model has been found to be inadequate in predicting the height of the mixed layer by subsequent observational work[3]. The observations show that the height of the mixed layer is not correlated with the strength of the flow above the layer as is implied in a one-dimensional model. A second approach has therefore been taken to try and account for this discrepancy betwen theory and observation. Horizontal variations in the strength and direction of the current are taken into account. These variations will cause convergences and divergences of the flow within the mixed layer. The mixed layer will be thickened and thinned, respectively.

A major contribution to the horizontal variation in currents in the deep ocean is from eddies which have diameters 50-200 km and speeds of a few centimetres per second. They are commonly referred to as mesoscale eddies. Over the Madeira abyssal plain[5] mesoscale eddies were found to have a diameter of approximately 40 km and an average speed of 1 to 2 cm s^{-1}. A numerical model has been developed to study their effect on the mixed layer[6]. The model provides estimates of variations in both the height and temperature of the mixed layer. The results are in accord wth observations and can be used to study the horizontal dispersion of a tracer.

One-dimensional model of the bottom mixed layer

The current close to the sea bed has three main components, the lunar (semi-diurnal) tide, inertial oscillations and a slowly varying flow resulting from mesoscale eddies[3]. On the Madeira abyssal plain these have periods of 12.4 hours, 22 hours and 50 to 100 days respectively. Because of the relatively short development time of the mixed layer (a few days) the time variation of the mesoscale motions can be ignored when discussing the vertical structure of the bottom layer. The unsteadiness of the flow at the tidal and inertial frequencies, however, does have to be taken into account.

The height of the boundary layer will be dependent upon the Earth's rotation, the distribution of density and the unsteadiness in the flow. A model has been developed of the vertical structure of the boundary layer to include these effects[4]. Because of the nature of turbulent flow additional assumptions must be made: a so-called 'second-order' turbulence closure scheme has been selected in which transport equations are used to determine the individual turbulence properties. Such models have been successfully applied to the atmospheric boundary layer[7].

The simplest case to consider is that of a steady flow with a density that does not vary with height. The results for a flow of 5 cm s^{-1} at a latitude of 30° are shown in figure 1. The boundary layer has reached an equilibrium and its height remains constant with time. The velocity components U,V and flow direction ϕ all vary with height above the bottom. Near the bottom the flow direction is 13° to the left of the flow well above the bottom. The profiles of turbulent stresses $\overline{uw}$, $\overline{vw}$ and the turbulent kinetic energy, k, indicate that the boundary layer is restricted to a height of approximately 18m.

In modelling an unsteady current the flow well above the bottom is assumed to oscillate with a period T. Results for the semi-diurnal tide with a period of 12.4 hours and maximum velocity 5 cm s^{-1} are shown in figure 2. The turbulent kinetic energy, k, is plotted as a function of height for a number of phases of the tide. Also shown for comparison is the result for the steady case. The boundary layer height is reduced from that of thesteady case to approximately 12 m.

The height of the boundary layer is plotted as a function of the frequency of the flow in figure 3. Near the inertial frequency there is a large increase in the height of the boundary layer. When the flow oscillates at the inertial frequency a resonance occurs and the Earth's rotation no longer limits the height of the boundary layer. The height will be dependent on the density stratification.

The density stratification is characterised by the buoyancy frequency $N=[-g \ d\rho/dz/\rho]^{1/2}$, where g is the acceleration due to gravity and ρ the density of the fluid. The buoyancy frequency is the natural frequency at which a stratified fluid will oscillate in the vertical. Typical values of N are $7x10^{-4}$ s^{-1} for the area studied by Armi and D'Asaro in the W. Atlantic and approximately $2x10^{-4}$ s^{-1} or less for the area studied by Saunders in the E. Atlantic. The development of the boundary layer from an initial state in which density increases linearly with height above the bottom has been studied. The results for a typical case with $N=10^{-3}$ s^{-1} and a steady current of 5cm s^{-1} are shown in figure 4. The time is 3 days from the start of the experiment. A mixed layer of height 13m has developed which is capped by a region of strong density gradient. The height of the profiles of turbulence $\overline{u}^2$, etc. are restricted to this layer. As the layer thickens the density gradient strengthens and will inhibit further mixing. This will reduce the growth rate of the height of the layer. The height of the mixed layer is plotted in figure 5 as a function of time for three values of $N=3x10^{-4}$, 10^{-3} and $3x10^{-3}s^{-1}$. Larger values of N indicate stronger stratification. Also shown are the results for a tidal current for the two cases $N=3x10^{-4}$ and $10^{-3}s^{-1}$. The mixed layer grows more slowly under a tidal current than a steady current. The height of the layer for the tidal case is approximately 25% less than that of the steady case for both values of N considered.

The maximum height of the mixed layer is given approximately by $h_o=0.1\ U(f/N)^{1/2}/f$ where U is the average speed of the flow and f the inertial frequency ($\simeq 10^{-4}s^{-1}$). After this height the growth rate predicted by the model is very small because internal waves now efficiently radiate energy away that was formerly available for increasing the layer depth[4]. The results should therefore also apply when inertial currents are present. The predicted height for the Madeira abyssal plain is 35m, close to the average value observed. It is noted that this height is approximately twice that suggested by Weatherly and Martin[8]. They use a criterion based on the local density gradient and velocity shear which limits the amount of turbulent mixing in the presence of a density gradient. Their mixed layer reaches a critical height at which entrainment into the layer is halted. The results of the present model show that, although local shear production of turbulence is suppressed, diffusive effects enable the mixed layer to continue growing past the critical height predicted by Weatherly and Martin.

The time development of the mixed layer is given approximately by $h=h_o(1-e^{-at})$ where $1/a \simeq 3$ days. The equation approximately fits the results of the model for all three values of N considered.

Model of the interaction of mesoscale eddies with the bottom mixed layer

The one-dimensional model discussed in the previous section provides estimates of the time it takes for a mixed layer to develop and the vertical variation of the flow speed and turbulence quantities within the layer. However, as mentioned in the Introduction, such a model cannot account for the observed variation in time of the mixed layer height. A model has been developed at IOS[6] to investigate the effects of mesoscale eddies on the height of the mixed layer and in particular to give a prediction of the expected horizontal and time variations of the layer.

Rather than use a model of a particular area of the ocean for which there is insufficient data, an idealised model is used. Within a box 500 km square (see figure 6) 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 has 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 bottom mixed layer. An eddy field is prescribed in the uppermost layer. This interacts with the second layer which in turn interacts with the mixed layer. Various statistics of the flow, such as eddy speeds and sizes and mixed layer height are predicted. Similar models have been successful in predicting the statistics of eddies in the ocean[9].

When the mixed layer is thinned due to the action of eddies, mixing will take place across the top of the mixed layer. Fluid will be entrained into the mixed layer leading to an increase in the average height. To counteract this, fluid is lost from the mixed layer either through separation of the layer in a manner described by Armi or D'Asaro[2] or by ejection of fluid at fronts[3]. Includingthese effects in the model is diffcult due to the present lack of understanding of such events. As a compromise a constant detrainment rate is prescribed over the whole region i.e. fluid is assumed to escape from the mixed layer at a constant rate. The detrainment rate is dependent upon the exchange time of the layer, i.e. the average time a fluid particle is expected to remain within the layer. Measurements of radon 222 and the geothermal heat flux give a lower and upper bound on its value. They suggest that the exchange time is between 4 and 600 days[2]. From their measurements of detached mixed layers Armi and D'Aasaro[2] estimate the exchange time to be roughly 100 days. This value has been used in the model.

A number of experiments have been performed. The introduction of the mixed layer in the model has been found to have important consequences for the dynamics of the interior of the ocean[6,10]. The results presented here are from one experiment with emphasis given to height of the mixed layer.

The mixed layer height is initially set to a constant value, h_o, over the region. This height is also taken to be the height below which entrainment takes place. The mean height of the layer will increase with time until the entrainment due to the action of the eddies balances the detrainment. The value of h_o has been chosen so that the mean height that the layer attains is comparable to that observed in the ocean. For the experiment reported here h_o is taken to be 10m.

Typical flow patterns in the first and second layers and the mixed layer height are shown in figure 7. The eddies in the second layer have an average speed of 4 cms^{-1} and have a length scale of 50 km. The mixed layer height has small scale intense features with regions of large gradient. These features are advected by the flow above with the occasional emergence or disappearance of new maxima or minima. The shaded regions are areas where the mixed layer height is less than its initial value h_o. They occupy approximately 10 to 20% of the total area. The mean height of the mixed layer has increased to 32m.

A horizontal cross section of the mixed layer height is shown in figure 8. This shows large variations in the height on horizontal scales down to 30 km. There is a region where the height of the layer vanishes and another where it has become very thin. These are regions where convergence in the flow above is sufficiently intense that it thins the layer more quickly than the layer is thickened by mixing.

Entrainment of the warmer fluid above the bottom mixed layer into the bottom layer will cause an increase in its temperature. This will occur in regions where the mixed layer height is below its equilibrium value, h_o, and entrainment is taking place. The evolution of the temperature of the mixed layer was studied by setting the temperature difference between the mixed layer and the flow above to be a nominal 10 m$^{\circ}$C. The temperature of the mixed layer after 75 days is shown in figure 9. Areas of warmer water are surrounded by regions of strong temperature gradients which are very persistent. The mixed layer height and temperature are shown as a function of time in figure 10 for a single location. The height varies over a period of approximately 20 days. There is a sharp increase in the temperature at day 37 when the depth of the mixed layer becomes very small. Episodes of a similar structure and duration are seen in the temperature records of Armi and D'Asaro[2]. It is posible that the fronts observed by Thorpe[11] could have been formed by this process. The temperature difference of 4 m$^{\circ}$C observed at a typical front requires a vertical downward displacement of approximately 50m.

The observations of Armi and D'Asaro[2] showed the existence of interior layers uniform in temperature above the bottom mixed layer. There is evidence to suggest that these interior layers are formed by the detachment of the bottom mixed layer and may be the principal mechanism for fluid to escape from the bottom layer. The warm patches of bottom mixed layer produced by the action of eddies in the model are likely places of bottom layer detachment. These patches are lighter than the surrounding mixed layer and may be lifted off the bottom by buoyancy forces. The residence time for fluid to remain within the bottom layer will therefore be dependent on the length of time it takes a fluid particle to come into contact with a warm patch. It is postulated that a fluid particle entering a warm area of the bottom mixed layer will escape from the layer. Using the model a number of particles placed in the bottom mixed layer were tracked and the time noted when they first entered an area of possible detachment. It was found that the average residence time of the particles placed initially outside a detachment area was approximately 800 days. As it is uncertain whether all warm patches will detach from the bottom this time should be treated as a lower bound on the residence time. The residence time for fluid in the deeper, colder parts of the mixed layer is therefore much greater than the average residence time for all particles of 100 days.

Implications for the dispersion of a tracer

The nature of the flow within the bottom mixed layer and the detachment of the mixed layer from the bottom have important consequences for the initial dispersion of a tracer and for the concentrations of that tracer expected close to the source. Turbulence within the mixed layer will mix the tracer vertically. The concentration will be uniform throughout the depth of the mixed layer 1 to 10 days after the release. Thereafter the tracer will be spread horizontally within the mixed layer until it encounters a region where fluid can escape from the bottom. Observations indicate that a primary mechanism for escape is the detachment of the mixed layer. The modelling suggests that areas of possible 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. How frequently the tracer comes into contact with one of these areas depends on the nature of the release. For a tracer released continuously from a fixed point, areas of mixed layer which may detach will be carried across the site. The period between the arrival of these areas is 40-100 days (see figure 10). On the other hand, where a puff of tracer is released more-or-less instantaneously, the residence time within the mixed layer is dependent upon the depth of the layer at the moment of release. If the layer is shallow and warm the layer may detach from the bottom taking the tracer with it. If on the other hand the mixed layer is deep then the tracer may be carried by the flow for a considerable time (800 days or more) with little or no escape to the flow above.

When the tracer has escaped from the bottom mixed layer it will be dispersed by the flow above. The flow field predicted by the numerical model can be used to study this dispersion. Preliminary experiments have been performed by tracking particles in the flow field. The results are in agreement with those obtained by Saunders[3] who used a similar technique with field measurements. The particles in the experiment were placed initially 15 km apart. The trajectory calculations show that on average the separation between the particles grows approximately exponentially with time, $R^2=R_o{}^2 \exp \alpha t$, where R_o is the initial separation and α^{-1} is between 15 to 30 days. Once the particle separations are close to the size of the eddies (approximately 50 km) the rate of increase in R^2, the square of the average particle separation, becomes constant with time and the spreading of the particles can be described with a constant diffusivity. The diffusivity was found to be approximately $1 \times 10^6 cm^2 s^{-1}$ for the eddy field used in the experiments. In a cloud of tracer with a diameter of 100 km the tracer concentration will halve in about 60 days.

Conclusions and recommendations for further work

A number of processes controlling the height and horizontal variation of the bottom mixed layer have been studied. Both the modelling programme and the observational programme have highlighted the importance of benthic fronts and the detachment of the mixed layer from the bottom. The numerical model described in this report provides estimates of the residence time of fluid within the bottom mixed layer and the spreading rates of a tracer both within the mixed layer and outside the mixed layer. With this information estimates can be made of the concentration of a tracer close to a source for both a continuous release and an instantaneous release. These calculations will be made in the near future.

To have confidence in the model results they have to be carefully tested with observations. The statistics of the eddies in the model can be matched to those observed. The spreading rates predicted by the model compare favourably with observations. Validation of the model predictions of the formation of new mixed layers which may detach from the bottom is more difficult. Efforts to measure the thickness of the mixed layer on the Madeira abyssal plain have been hampered by the weakness of the temperature signal. It is hoped that the experiment planned by IOS for the summer of 1983, which will be in a region of stronger density gradient and stronger flows, will yield more information on the structure of the mixed layer.

So far, topography has not been included in the model. Not only will topography affect the mesoscale eddy field but separation of the flow may take place leading to a much deeper mixed layer. The inclusion of topography in the model without flow separation is straightforward and is planned for the near future. Flow separation is much more difficult and will require a combination of numerical, laboratory and field experiments to examine the implications for mixing in the deep ocean.

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Figure headings

Figure 1 Vertical profiles of mean velocity components, U,V, direction, ϕ, horizontal turbulent stresses $\overline{uw}$, $\overline{vw}$ and the turbulent kinetic energy, k, for a current of 5 cm s^{-1} at a latitude of 30°.

Figure 2 Profiles of the turbulent kinetic energy for a tidally driven flow at a number of phases of the flow. The dashed curve is the corresponding steady case.

Figure 3 Height of the boundary layer as a function of the frequency of the flow.

Figure 4 Profiles of the turbulent stress component $\overline{uw}$, the variance components $\overline{u}^2$, $\overline{v}^2$ and $\overline{w}^2$ and the mean (non-dimensional) temperature θ, for a stably stratified steady flow of 5 cms^{-1} with the buoyancy frequency $N=10^{-3}s^{-2}$.

Figure 5 Plot of the mixed layer height for a stably stratified steady (solid curve) and tidal (dashed curve) flow as a function of time for three values of the buoyancy frequency $N=3x10^{-4}$, 10^{-3} and $3x10^{-3}s^{-1}$.

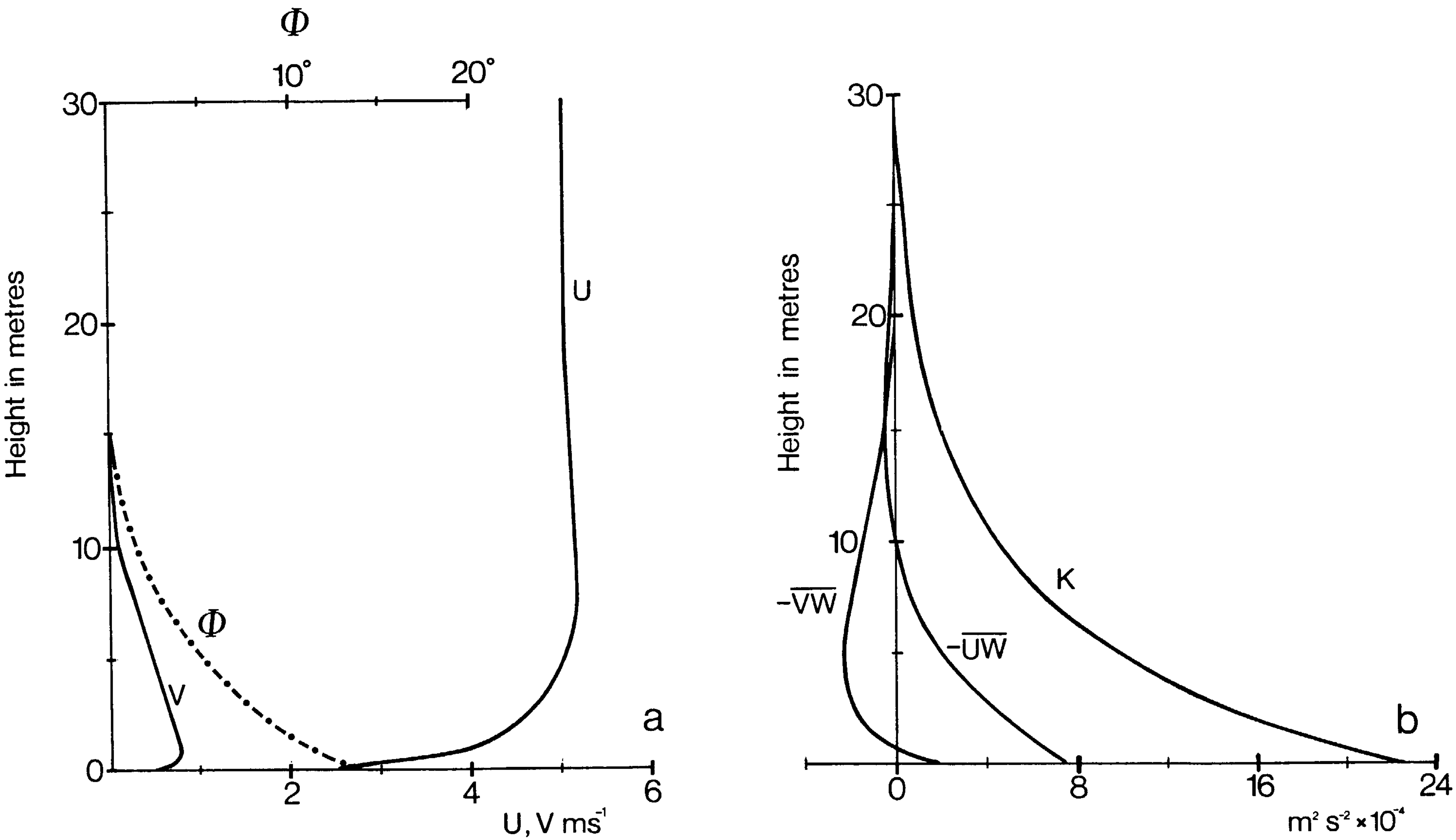
Figure 6 Sketch of the regions of flow in the numerical model.

Figure 7. 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 cm s^{-1}. The shaded regions in the map of h indicate areas where h is less than its equilibrium height. The contour interval for h is 12m.

Figure 8 A typical horizontal cross section of the mixed layer height taken from figure 7.

Figure 9 Map of the temperature of the mixed layer after 75 days. The contour interval is 1 m°C.

Figure 10 Plot of the mixed layer height and temperature as a function of time at a fixed point in the flow.



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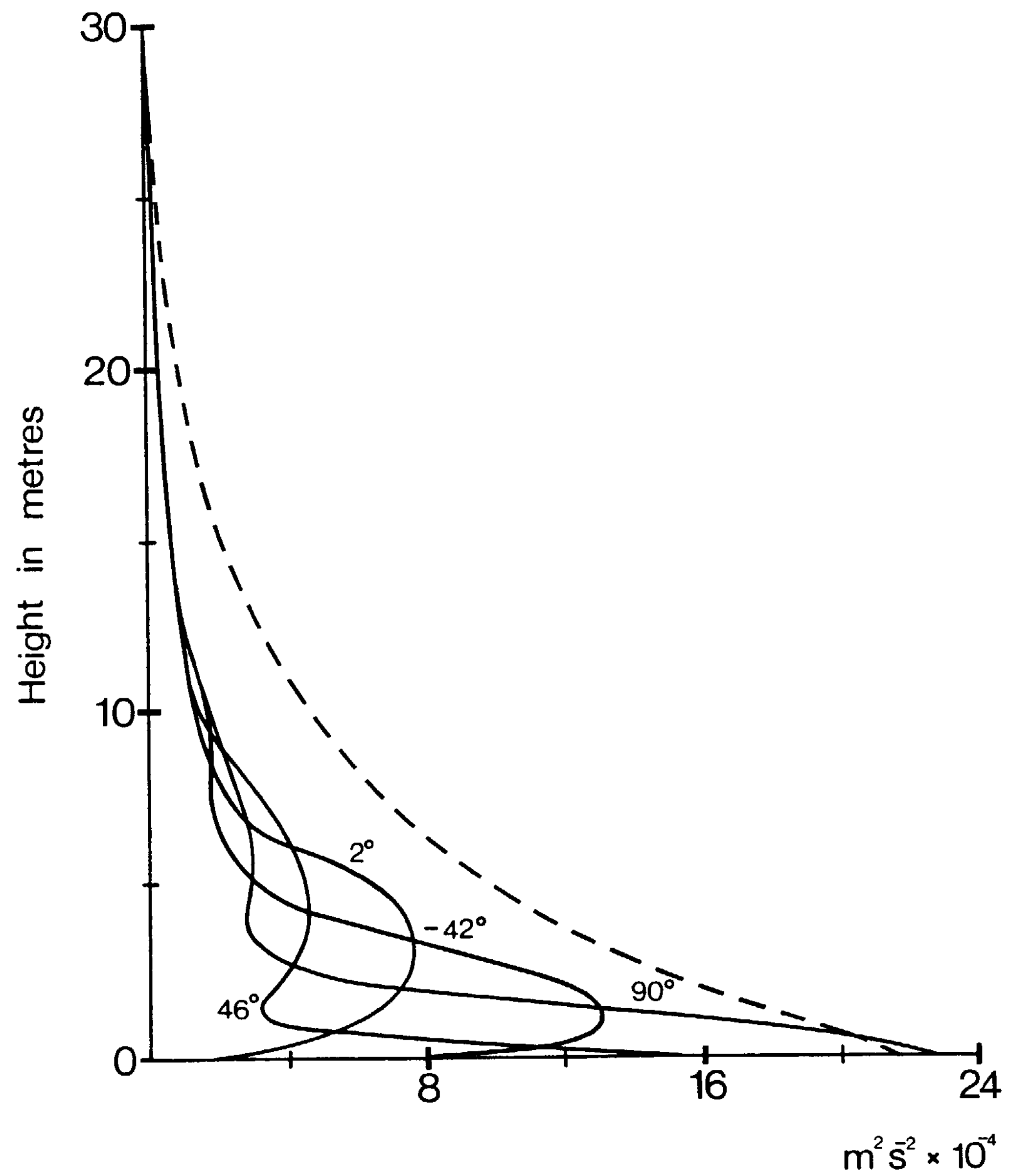

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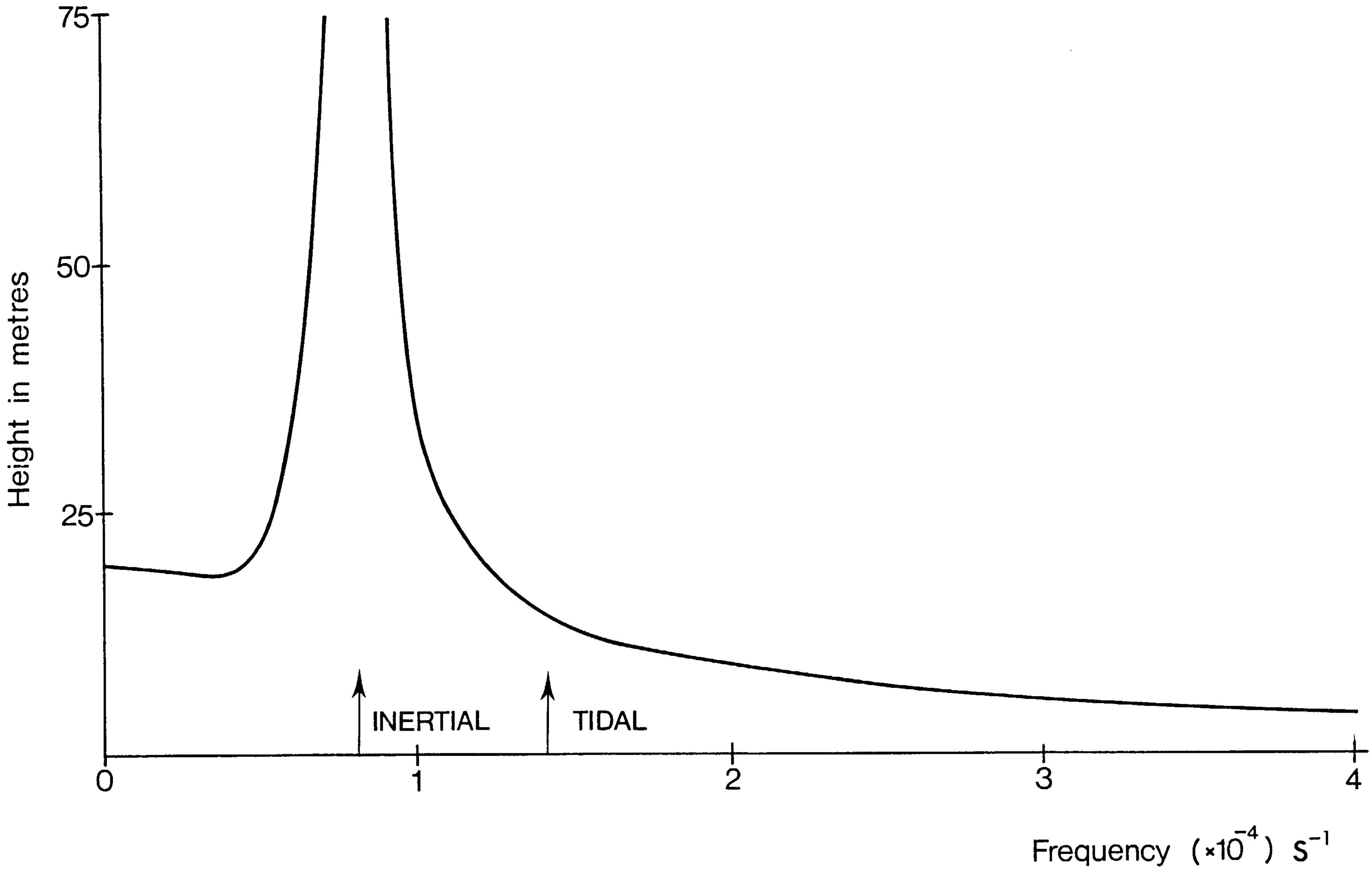

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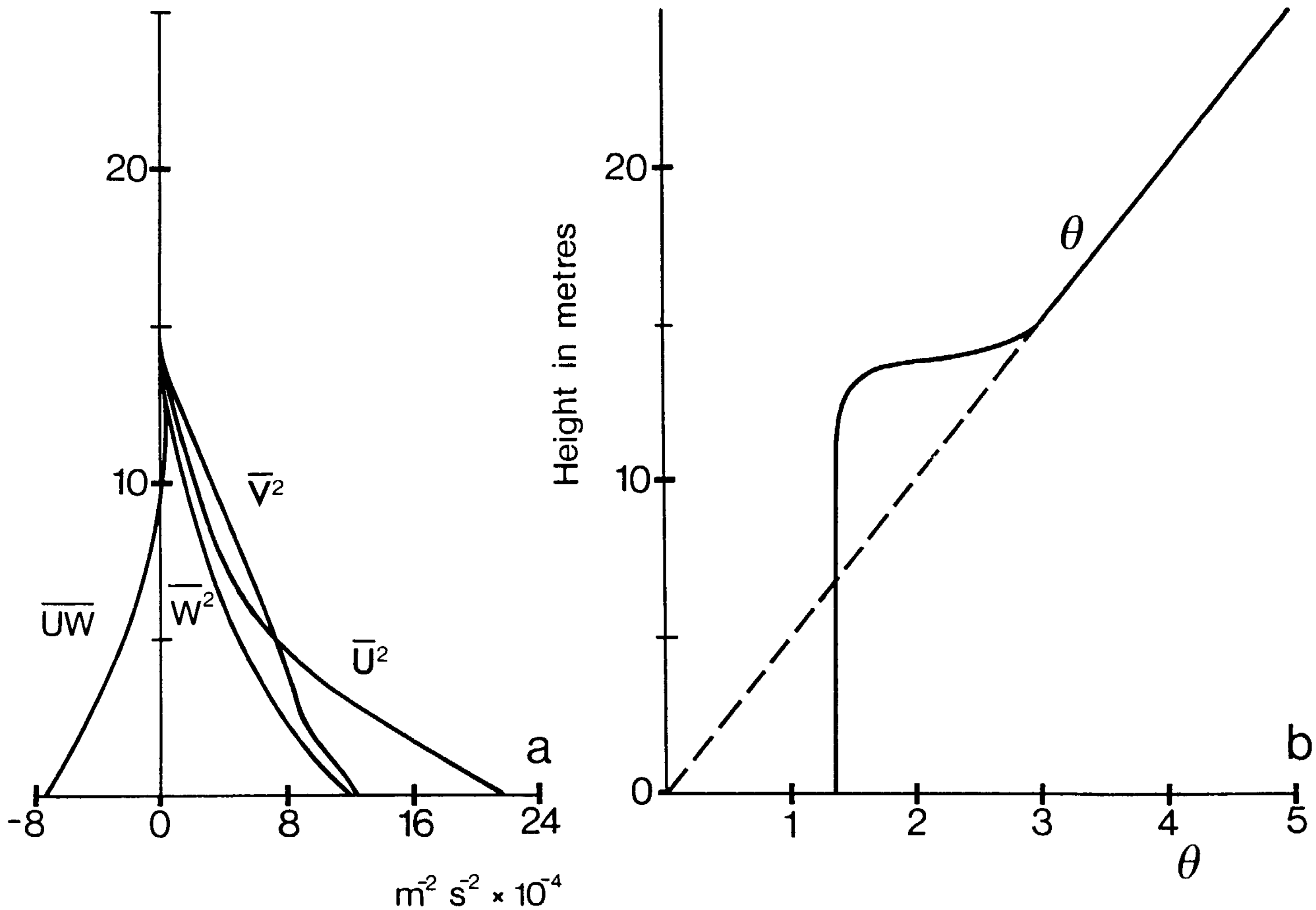

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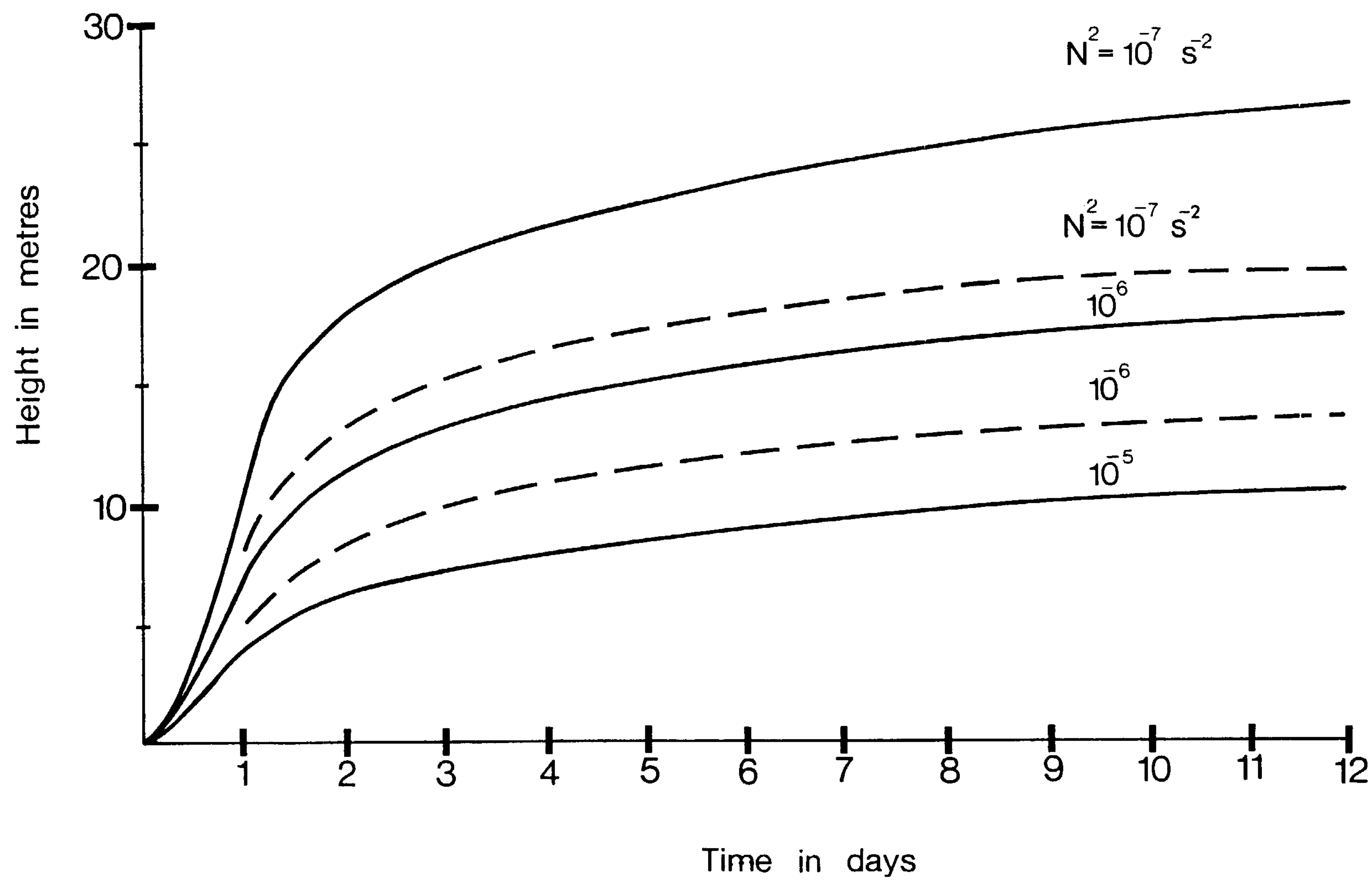

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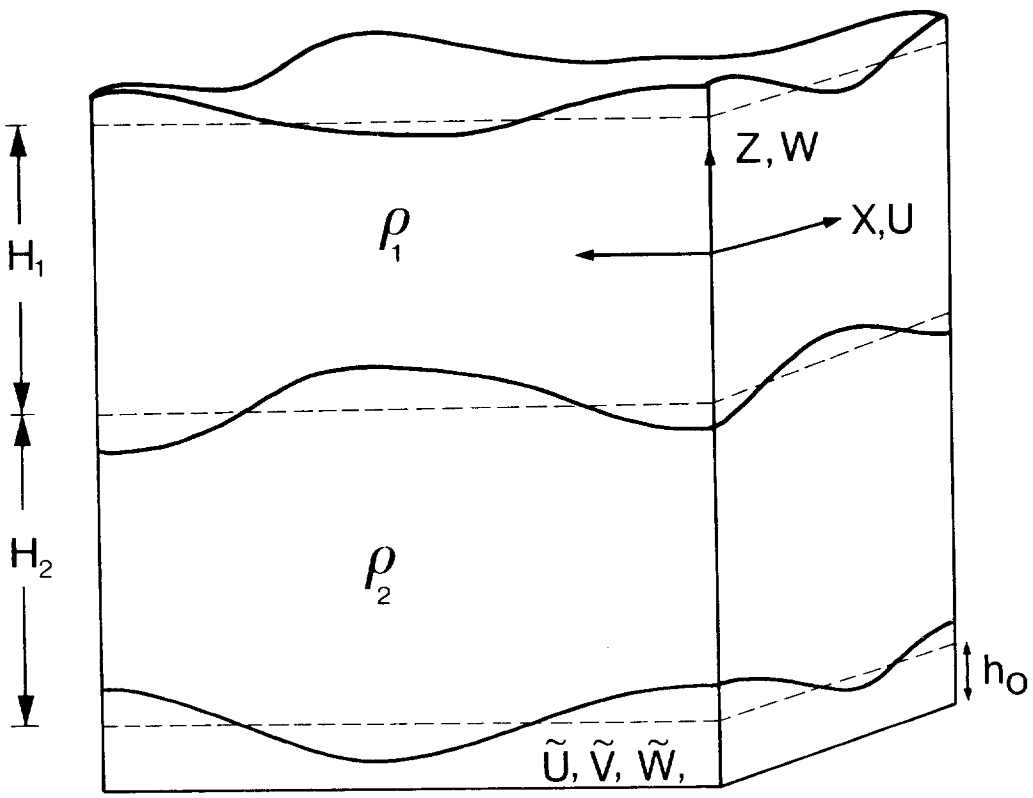

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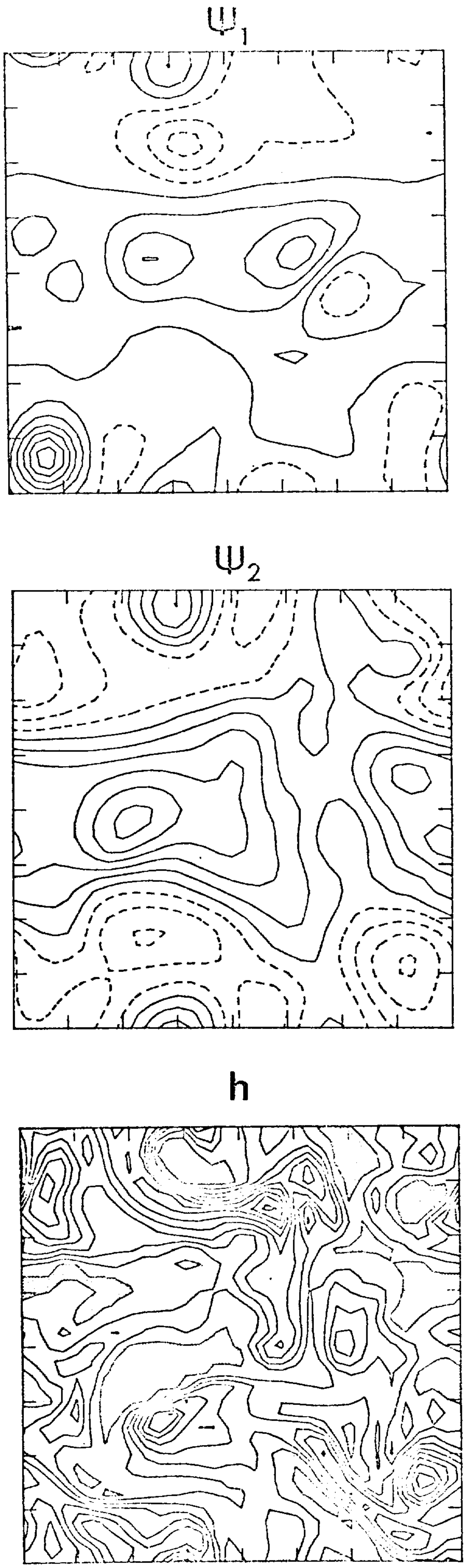

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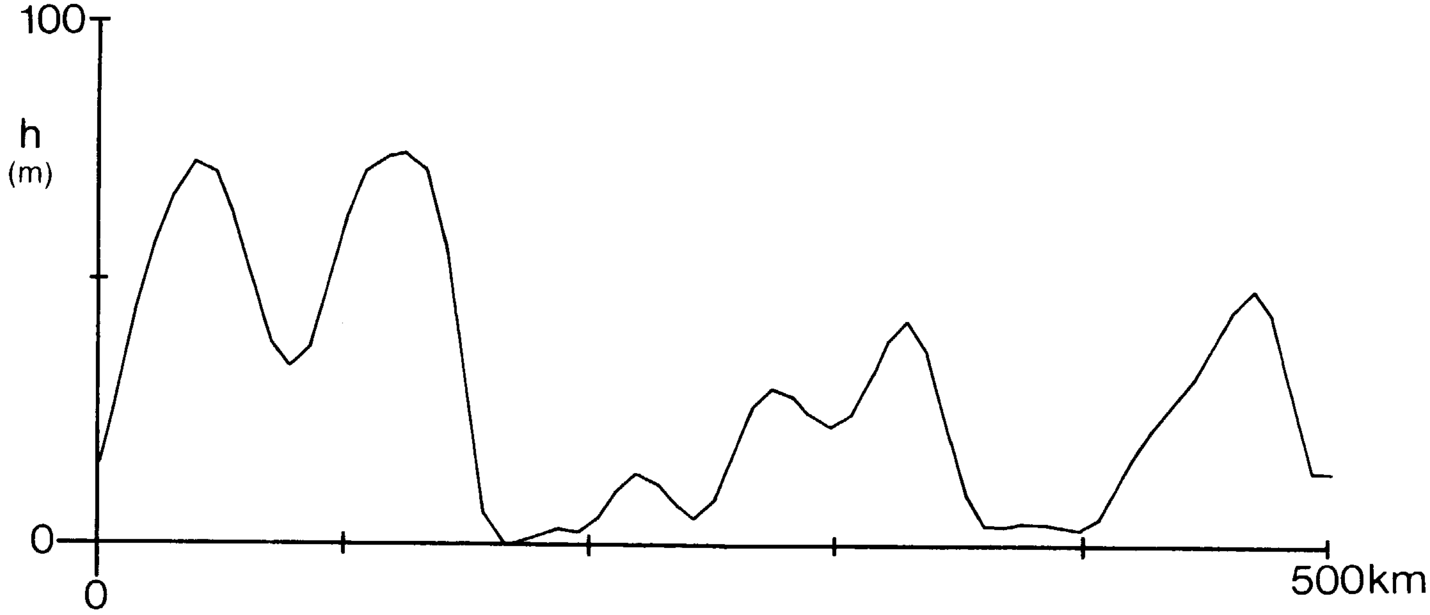

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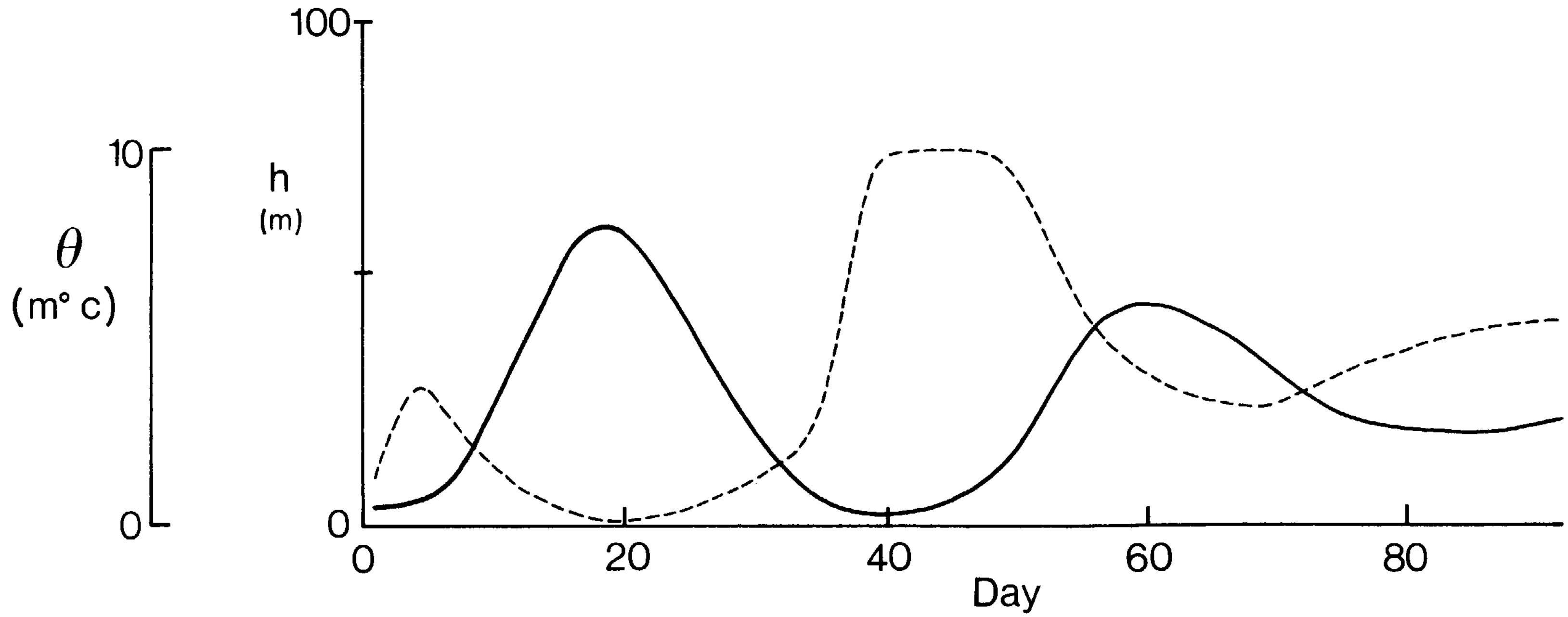

Figure 10 Plot of the mixed layer height and temperature as a function of time at a fixed point in the flow.