I.O.S.

DISPERSION OF TRACERS BY THE OCEANIC EDDY FIELD

MODELLING PROGRAMME, INTERIM REPORT, APRIL 1986

BY

K.J. RICHARDS

REPORT NO. 229

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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

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Report Title: Dispersion of tracers by the oceanic eddy field - modelling progamme. Interim Report, April 1986.

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Abstract (100-200 words as desired)

A numerical model has been developed to study the dispersion of tracers by the oceanic eddy field.

The present study is designed to investigate the horizontal and vertical structure of the eddies and how this structure is influenced by the bottom topography. It is found that hills and valleys have a strong effect on the eddies above them. The flow close to the bottom has a tendency to be steered by the height contours. The surface and bottom flows become decorrelated and the vertical variation of the kinetic energy of the eddies is increased with higher topographic features.

Topographic effects are large even for small hills and valleys (height 50 m or less) which suggests that topography needs to be taken into account in any study of oceanic eddies for practically all regions of the ocean.

Keywords: 129,299 - Ocean circulation/dispersal, DoE sponsored research.

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.

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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 mechanisms of dispersal of radionuclides in the water column by large scale (100 km) oceanic eddies. In this particular study the role bottom topography has to play in influencing the horizontal and vertical structure of the eddies is investigated.

The Natural Environment Research Council, through the Institute of Oceanographic Sciences, has a contract with the Department of the Environment (DOE, PECD7/9/216) to examine the diffusion of tracers by the oceanic eddy field 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 in the water column in order that realistic predictive models can be developed.

Introduction

The topography of the ocean bottom is comprised of features on many diferent length scales from the geometry of the ocean basin down to sand ripples of a few centimetres wavelength. Topographic features influence the flow of water about them to a greater or lesser extent depending on their horizontal lengthscale and vertical height. The greater the horizontal lengthscale the greater the depth of flow affected by the topography and the more the flow is influenced by the Earth's rotation. In the deep ocean rotational effects are important on lengthscales of order a kilometre and longer. As the lengthscale increases there is a tendency for the flow to be steered along depth contours.

On a basin scale the wind driven circulation is shaped by the coastlines. The presence of continental slopes and the mid-Atlantic ridge significantly affected the dynamics of the flow[1,2]. Deep flows, say deeper than 4000 m, are confined to smaller basins connected by narrow sills (see example figure 1 of Saunders and Richards[4]). Here too the sloping edges of the basins (slope $O(10^{-2})$) will influence the flow. The 'so called' abyssal plains within the deep basins are not free from topography. Abyssal hills are present on horizontal lengthscales from a few to tens of kilometres and height order a hundred metres[5,6]. The statistics of observed abyssal hills, principally in the Pacific, has been calculated by Bell[7,8]. An example of a group of three abyssal hills is given by Saunders[9]. Observations[10,11] show that abyssal hills affect the flow above them in general accordance with simple theory (see Hogg[12] for a review of theory and observations).

The aim of the present study is to investigate the role of topography in the dispersion of a tracer in the deep ocean. Topography can affect dispersion in two ways. Firstly, the flow near the sea bed, the boundary layer, can separate. Recent laboratory experiments have investigated the effect of rotation on boundary layer separation[13,14]. Material within the boundary layer will escape into the interior of the ocean. Estimates of the residence time of a tracer within the boundary layer[15] suggest that this may be a primary means of escape. Alternatively, material in the interior of the ocean may be advected towards an abyssal hill or slope, enter the boundary layer where it is mixed across isopycnal surfaces and subsequently ejected[16]. Observations of radon 222[17] and suspended particles[18] show the existence of newly separated layers from a sloping boundary but more work is needed on the precise nature and efficiency of the process.

The second way in which topography can affect dispersion is through its influence on the dynamics of the flow above the topography. It is in this aspect of the problem to which the present study is addressed. The work reported on here investigates the effect of abyssal hills on the structure of currents due to mesoscale eddies. Mesoscale eddies form a major contribution to current in the deep ocean. In the deep N.E. Atlantic[19] eddies have a diameter of approximately 50 km and an average speed of 1 to 2 cm s^{-1}. The second part of the problem, the dispersion of a tracer due to these currents, will be dealt with in a later report.

There are two questions to be asked. The first is how does topography affect the vertical structure of the flow? Numerical simulations of mesoscale eddies over a flat bottom (see Haidvogel[20] for a review) show that through non-linear interactions there is a tendency for the flow to become uniform with depth and the energy in the system to go into long horizontal lengthscales. In general terms this process is independent of the forcing mechanism producing the eddies such as an unstable mean flow[21] or a forcing restricted to upper levels balanced by bottom friction[22]. The implication is that the kinetic energy of low frequency motions in the ocean (period greater than one or two days) should alter little with depth. This is at variance with observations[23] which show for example in the western basin of the N. Atlantic a very marked decrease with depth of eddy kinetic energy. Even in the eastern basin where the eddy energy is much reduced there is a factor five or more difference between surface and bottom values. As will be shown in this report and elsewhere[24] the presence of bottom topography inhibits the tendency for the flow to become uniform with depth and produces a vertical variation of kinetic energy more in line with observations.

The second question, which has strong implications for tracer dispersion, is to what extent is the flow steered by the topography? If the flow is predominantly along depth contours then mixing along the slope will be greater than across the slope. The evolution of mesoscale eddies above topography in the absence of forcing and strong dissipation has been studied for both the case where the density is assumed constant[25] and where the density varies with depth[24]. For the former the final state is one in which the flow follows the longer lengthscale features of the topography and is swept across small-scale hills and valleys. In a vertically stratified ocean the state to which the flow will develop is very dependent on the energy of the flow and the horizontal lengthscale of the eddies. However there very often remains an appreciable amount of cross slope flow at all scales. An example of observed strong cross slope flow is given in figure 3 of Saunders and Richards[4].

The numerical model used in the study is briefly described in the following section. For a given forcing, the affect of varying the height and horizontal scale of the topography on the structure of mesoscale eddies in the ocean is investigated. A fuller description of the model and interpretation of results will be given in Richards[26].

The Model

In order to study the dynamics of mesoscale eddies it is convenient to idealise the problem and consider a small region of the ocean, or box, which is assumed to be embedded in a larger region where the character of the eddies is horizontally uniform. The flow is then assumed to be periodic over the size of the box, here taken to be a 1000 km square. An eddy travelling out of one side of the box comes in on the opposite site (see for example figure 3). The effect of varying parameters such as the forcing or height of the topography on the statistical properties of the mesoscale eddies can be ascertained. Such models are referred to as periodic or process models[20].

The model is based on the quasi-geostrophic equations. These are a set of equations that are derived from the full set of equations describing all motions in the ocean under the assumption that the vorticity (local spin) of the fluid is small compared to the spin of the Earth. It is believed that quasi-geostrophic theory provides a reasonably accurate description of motions on the lengthscale of mesoscale eddies and upwards.

The equations of the model are solved numerically by using a combination of horizontal spectral and vertical modal techniques. Variables such as velocity are then described by a sum of continuous functions in all three spatial dimensions. This is in contrast to conventional models which defined variables at a number of discrete points (grid points) in the horizontal and divide up the flow in the vertical into a small number of levels or layers. In the present model the flow is defined in the horizontal by a sum of sine and cosine functions, the natural choice for a periodic box. In the vertical the flow is decomposed into its normal modes, that is a set of functions that describe the vertical structure of the response of the ocean to perturbations. The first mode, the barotropic mode, is constant with depth. The remaining modes, the baroclinic modes, vary in the vertical and become more and more 'oscillatory'. For an ocean with a constant density gradient the baroclinic modes are cosine functions. The normal modes for the density structure typical of the eastern N. Atlantic are shown in figure 1. The flow at any depth is found by summing over the normal modes. In a non linear flow the normal modes will interact, each mode interacting with pairs of modes. For any modelling study only a finite number of modes can be retained. The results presented here were obtained using the first three modes.

The use of spectral and modal techniques have a number of advantages over grid point and layer models. These are as follows:

Spectral Methods

(i) have a high convergence rate and thus require fewer degreees of freedom, i.e. number of functions vs. grid-points. Typically a spectral model requires a factor of four (in two dimensions) fewer 'points' than a grid-point model to achieve the same accuracy.

(ii) boundary conditions are satisfied exactly.

(iii) derivatives are evaluated exactly - waves in the system will propagate accurately.

Modal Methods

(i) any vertical density structure can be easily treated. The flow field has a continuous vertical distribution so that the effects of a vertically varying flow on tracer dispersion can be studied.

(ii) the model will give accurate results when two or more physical processes are present, e.g. in the present study bottom topography and non-linearity. This is not true of layer models.

(iii) the model is rich in modal interactions.

The eddy field in the model is forced by prescribing an input of energy at a range of lengthscales in the upper levels of the model ocean. These eddies interact with themselves and the flow at depth which in turn interacts with the bottom topography. Energy is taken out primarily by bottom friction thus producing a flow of energy from the surface to the bottom of the ocean. The forcing is rather ad hoc but was preferred to other perhaps more physically realistic forcings which present a number of drawbacks. For example if eddies are produced by an unstable mean flow a large number of normal modes (greater than 20) are required to model the instability (Hua, private communication). Once the eddies have been formed it is expected that their dynamics are not unduly affected by te precise mechanisms of their generation. Other studies seem to support this. The model is run until the flow reaches a statistical equilibrium, typically 1 to 2 years of integration. The structure of the flow is then analysed. The strength of the flow can be altered by adjusting the strength of the forcing.

Effect of topography on oceanic eddies

To illustrate the role topography plays in shaping the flow above it, results are presented for a rough ocean bottom shown in figure 2. This is a random collection of hills and valleys on a number of lengthscales. The statistics of the topographic features have been chosen to be broadly similar to those of the ocean bottom without trying to model any particular region. The lengthscale of the smaller scale hills is approximately 50 km. The root mean square height of the topography has been varied from zero (a flat bottom) to 800 m. The depth of the ocean is taken to be 5000 m and the density structure assumed to have a constant gradient. This latter choice was made so as to ease the task of understanding the dynamics of the flow (there are many fewer interactions betwen the vertical modes when the density gradient is constant with depth then for a more realistic density gradient). In fact experiments using a density structure similar to that of the eastern North Atlantic show similar characteristics to the results presented here.

Typical flow patterns at the surface and at the bottom of the ocean are shown in figure 3 for a case where the height scale of the topography is 500 m. This is an instantaneous picture of the flow. There is a striking difference between the upper and lower flows. At the surface the eddies are large, having a diameter of approximately 200 km. The r.m.s. speed of the flow is 5 cm s^{-1}. There is a slight elongation of the eddies in the east-west direction. The flow close to the bottom is completely different. Here the flow is on a much smaller scale. The r.m.s. speed is reduced to 2 cm s^{-1}. Comparison with the topography (figure 2) shows that the direction of the flow is influenced by the depth contours but not completely controlled by them. For this case the ratio of the energy along depth contours to that across is 3. The flow varies with time. Figure 4 shows the value of the streamfunction, which is related to the pressure, at the top of the hill marked A in figure 2 as a function of time. When the streamfunction is positive, (high pressure) the flow is clockwise around the hill, when it is negative the flow is anti-clockwise. The direction of the flow is seen to alternate between clockwise and anti-clockwise with a period of approximately 100 days. This behaviour is typical of the flow around the hills and valleys generally in the model.

A vertical cross section of the flow is shown in figure 5. This clearly shows the vertical extent of the influence of the topography, it being roughly 1000 m in this instance. This height scale compares well with the height scale, h, predicted by linear theory namely $h=fL/N$ where f is the Coriolis parameter, N the buoyancy frequency of the fluid and L the horizontal lengthscale of the topography. Increasing the lengthscale or decreasing the buoyancy frequency will increase the height of influence of the topography.

The time mean flow is shown in figure 6. Because of the long period oscillations in the flow a long averaging time is needed. In this case the mean was taken over 4 years. Again the flow at the surface and bottom are very different. At the surface the mean flow is predominantly in the east-west direction. At the bottom the flow is predominantly along depth contours. The r.m.s. speed is 0.7 cm s^{-1}. Now the ratio of energy along the depth contours to that across is 30. The flow around hills is clockwise and around valleys is anti-clockwise. An interesting feature of the flow is that the strongest mean flow is not necessarily around the biggest topographic features. For instance the deep valley at the bottom centre of figure 2 produces only a small mean circulation around it whereas the strongest flow is around the shallow valley in the centre. This is probably due to the larger scale topography 'trapping' eddy energy in certain regions causing a build-up of energy over the smaller features in that region.

The effect of varying the height of the topography is shown in figure 7, by plotting the kinetic energy of the flow against depth for six different topographic heights, with the height doubling each time. For a flat bottom ocean the ratio of the kinetic energy at the surface to that at the bottom is 2.5. Even with the smallest topography considered, h=50 m, this ratio is increased to 4.2. Above h=200 m increasing the height of the topography has less and less effect on the vertical structure of the flow, and the topographic effect appears to become 'saturated'. The ratio of surface to bottom kinetic energy reaches a maximum of approximately 10. The bottom flow is increasingly steered by the topography as the height is increased. When h=800 m the ratio of the kinetic energies of the along to across depth contour flow is 20.

The horizontal length-scale of the topography is very important in determining the structure of the flow. A number of experiments were carried out with an ocean bottom similar to that shown in figure 2 but with a high pass filter applied to it to remove the small-scale hills. This resulted in a more gently rolling topography. Without the small-scale hills the eddies near the bottom are freer to move and do not remain stationary above topographic features. The along to across ratio of the flow is decreased by a factor of approximately 0.75. A mean flow along depth contours is again produced but this time driven by the interaction of the bottom eddies with the sloping bottom.

The results reported on here have concentrated on an ocean with a constant density gradient. Experiments with a density profile such as shown in figure 1 which is typical for the eastern North Atlantic show similar characteristics to those described above, most notably the decoupling of the upper and lower flows, the steering effect of the topography on the bottom flow and an increase in the vertical variation of kinetic energy with topographic height. The byoyancy frequency of the ocean is smaller at depth (see figure 1). The height of influence of the topography will therefore be increased above that found for the constant density gradient ocean. In fact for the topography shown in figure 2 the height of influence for a 'real' ocean was found to be 2500 m (compare this with figure 5). The ratio of the kinetic energy at the surface and the bottom is also increased, it being 17.5 with h=200 m.

Implications for the dispersion of a tracer

The results presented above can be used to suggest the effect topography will have on the dispersion of a tracer, in the deep ocean. These effects will become important at depths of 2000 m and deeper.

Since the dispersion rate scales on the kinetic energy of the eddies the preference for the flow to be along depth contours rather than across implies that dispersion will be greater along slopes than across leading to an elongation of a tracer cloud along the slope. With the r.m.s. height of the topography h=200 m the ratio of along to across slope eddy energy was found to be 3. The aspect ratio of the cloud will then be approximately 1.7. For higher topographies this aspect wil be roughly 4.5.

Steady flow over an isolated hill can form what is referred to as a Taylor column over the hill. This is a region of the flow where the streamlines are closed and which is isolated from the rest of the flow. Tracer material in such a region would be effectively trapped over the hill and undergo little or no dispersion. In the unsteady eddying flows investigated no permanent isolated regions were found to exist. However the features shown in figure 3 above individual hills and valleys do persist for periods up to 100 days and more. The effect of these persistent features on the dispersion of a tracer needs to be investigated.

Perhaps the most important feature of mesoscale eddies above topography is the existence of mean flows along depth contours driven by the eddies. The energy of the mean flow can be a not insignificant fraction of the total flow. For instance the ratio of mean to total energy of the flow shown in figure 3 is 0.3. This will further increase the along slope dispersion of a tracer and in some areas may dominate the dispersion. On a basin scale an eddy diffusivity of 10^6 cm^2 s^{-1} implies a tracer will take approximately 20 years to spread through a region of side 1000 km. An along slope mean current of 0.5 cm s^{-1} would cross the basin in 5 years with substantially higher concentrations.

Conclusion and recommendations for further work

Topography has been shown to have a great influence on mesoscale eddies in the ocean and that its presence controls to a great extent the structure of the flow throughout the water column. The horizontal lengthscale of the topography has been found to be particularly important. The existence of small scale hills, of the same size or smaller than the eddies, affect both the dynamics and the shape of the flow within 2000 to 3000 m of the ocean bottom. The topographic effect is large even for surprisingly low hills and shallow valleys, that is when the height of the hills to the total depth of the ocean is of order 1/100 or less.

In future work it is planned to use the numerical model to study the dispersion of a tracer by mesoscale eddies in the presence of topography. This will be achieved by a combination of tracking particles in the flow and studies of the dispersion of a cloud of tracer.

The studies to date have not been focussed on a particular region of the ocean. The IOS observational programme has produced valuable data sets from current meter arrays and deep neutrally buoyant floats for a number of locations. In future studies it is intended to use density profiles and topographic features typical of the regions concerned so that more can be gained from the comparison of theory and observation. Of particular interest are the neutrally buoyant SOFAR float tracks. These provide data to test the numerical model. In return model studies will be used to suggest ways in which to best analyse the float data and to ascertain how much information can be obtained from a small number of float tracks of limited duration in a turbulent medium. The model studies will also be used to examine the differences between Eulerian (taken at a fixed point - current meters) and Lagrangian (following fluid particles - floats) methods of measurement.

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Figure Legends

Figure 1 Typical profile of the buoyancy frequency $N = -g \frac{d\rho}{dz} / \rho$ for the Eastern N. Atlantic and the associated barotropic and baroclinic normal modes for the horizontal flow.

Figure 2 The bottom topography used in the experiments. The r.m.s. height of the topography is 200 m.

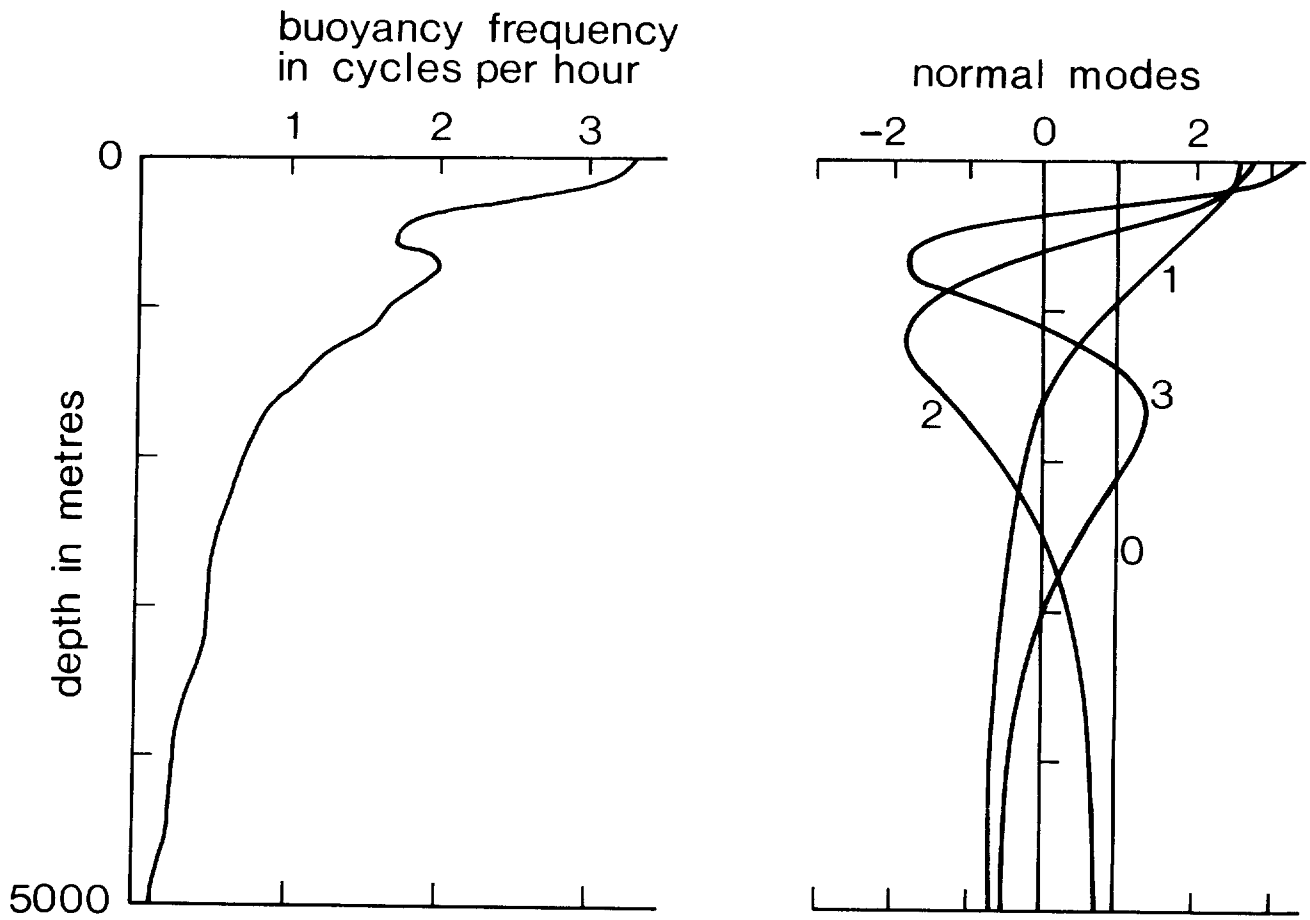
Figure 3 Instantaneous stream function maps for the flow at the surface and bottom of the model ocean. The average speed at the surface is 5 cm s^{-1} and at the bottom is 2 cm s^{-1}.

Figure 4 Plot of the streamfunction (related to pressure) against time on the top of hill A marked in figure 2.

Figure 5 Vertical section of the flow. Note the height of influence of the topography is approximately 1000 m.

Figure 6 Mean streamfunction maps for the flow at the surface and bottom of the model ocean taken over 4 years. The average speed of the mean current around the topography at the bottom is 0.7 cm s^{-1}.

Figure 7 Plot of the kinetic energy of the eddies against depth for six different heights for the topography.



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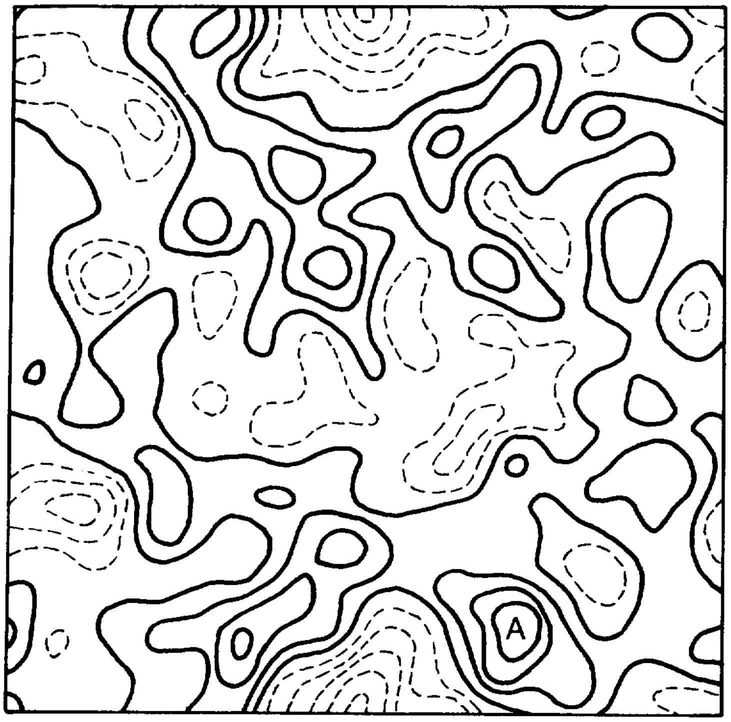

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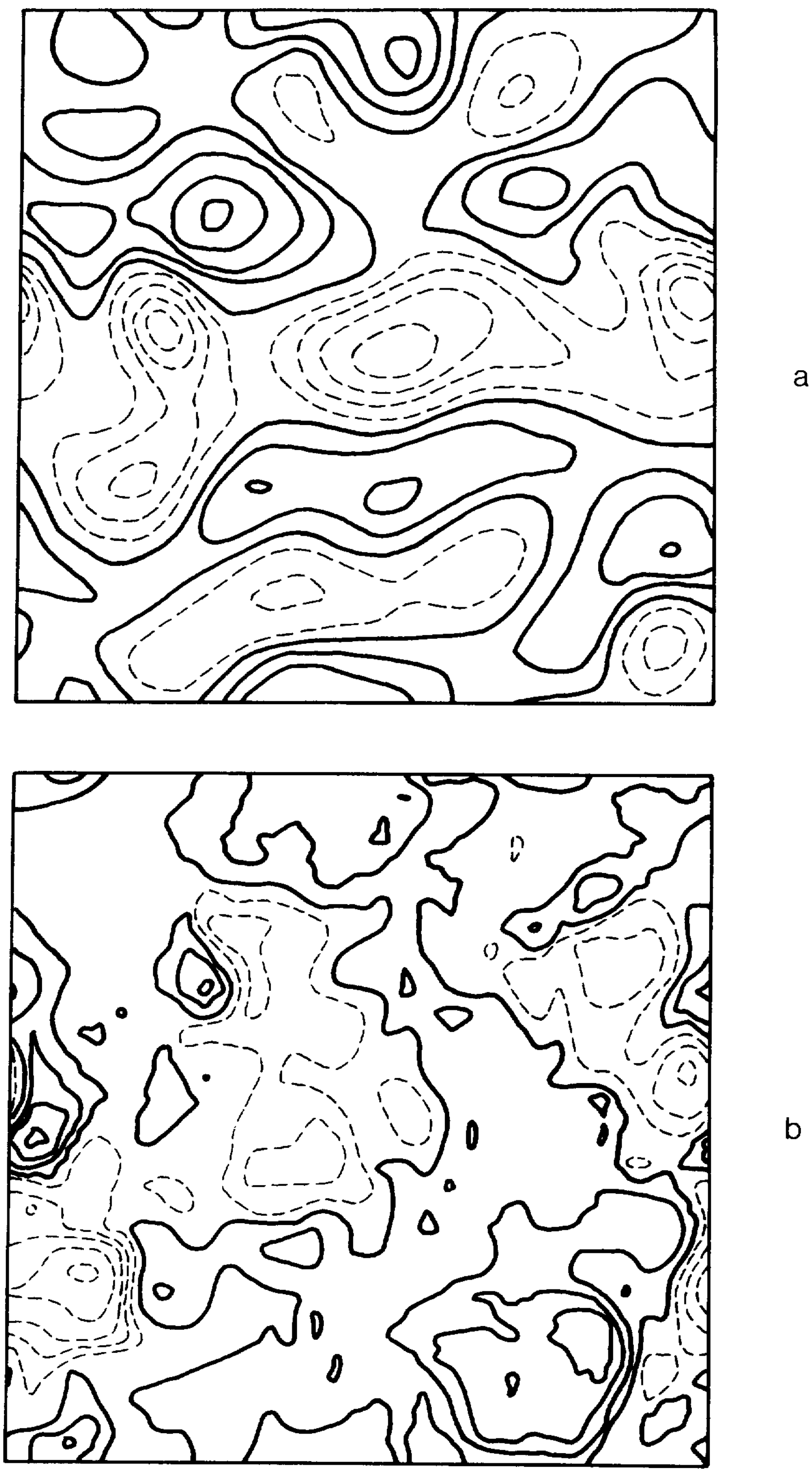

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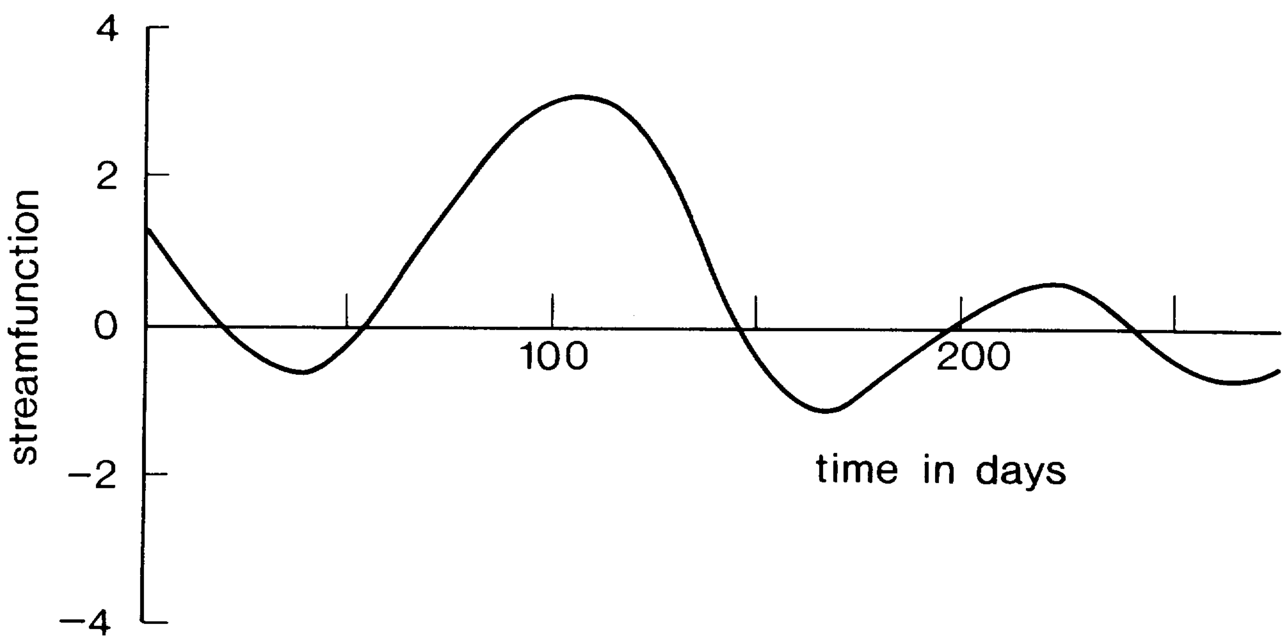


Figure 4 Plot of the streamfunction (related to pressure) against time on the top of hill A marked in figure 2.

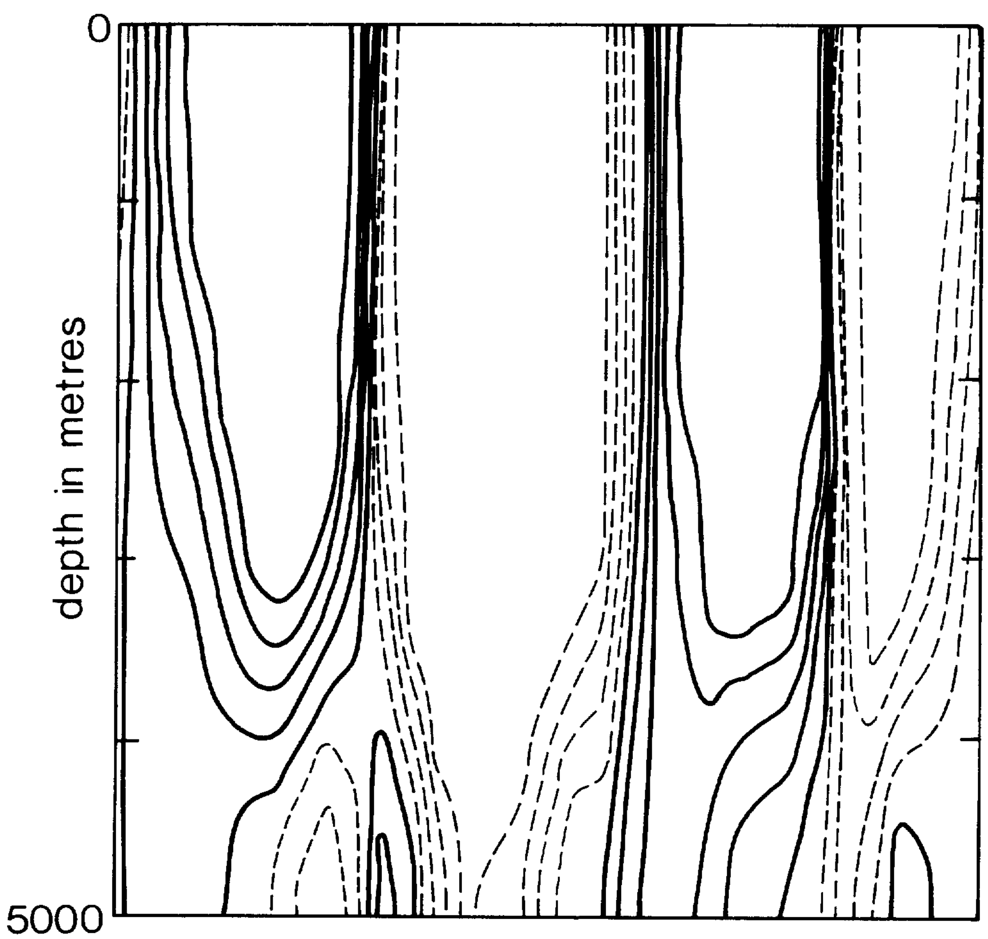
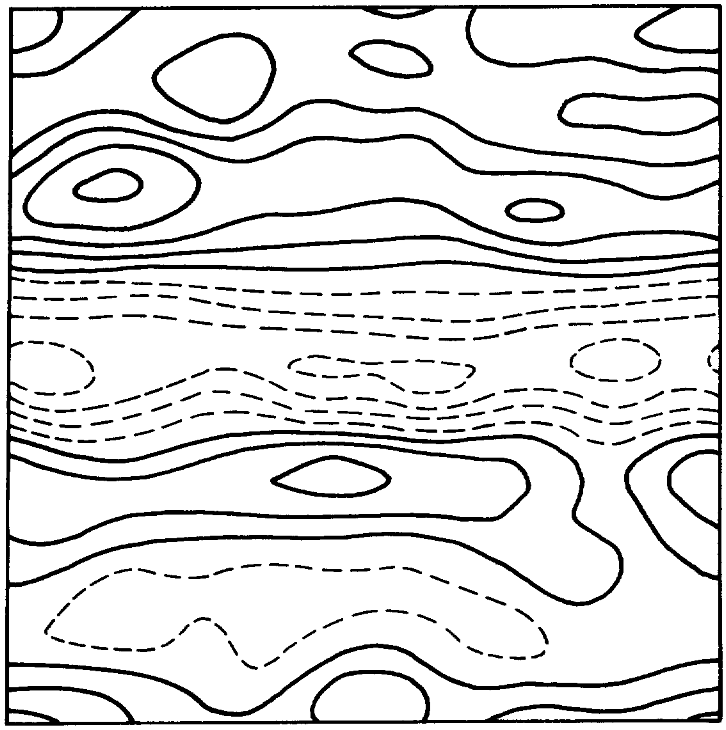


Figure 5 Vertical section of the flow. Note the height of influence of the topography is approximately 1000 m.



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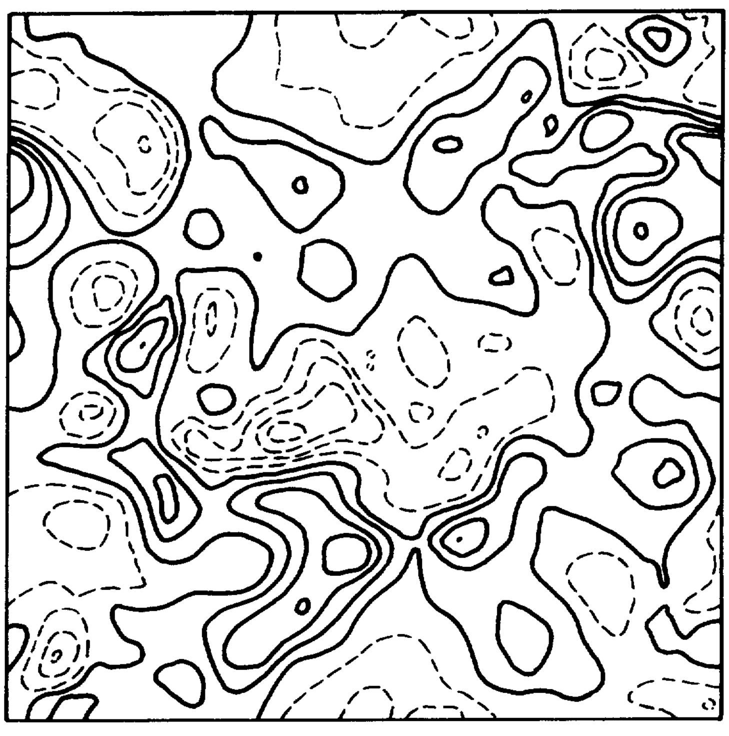

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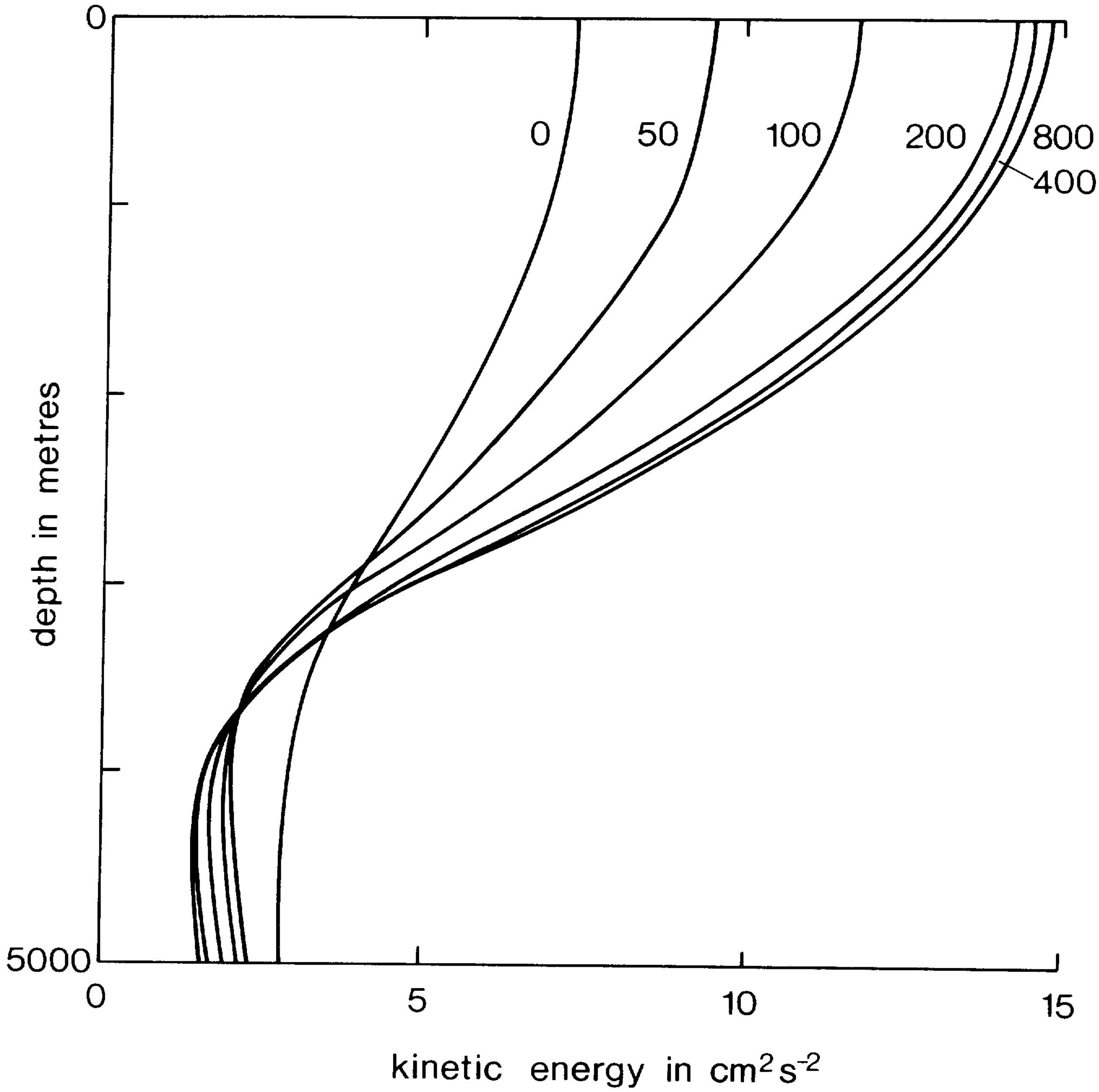
Figure 6 Mean streamfunction maps for the flow at the surface and bottom of the model ocean taken over 4 years. The average speed of the mean current around the topography at the bottom is 0.7 cm s^{-1}.



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