NORSK POLARINSTITUTT

RAPPORTSERIE

NR. 80 - OSLO 1993

Engedahl H, Proshutinsky A.Yu., & Ådlandsvik B.

SOVIET - NORWEGIAN OCEANOGRAPHIC PROGRAMME 1988 - 1992

SNOP Numerical EXperiment (SNOPNEX) MODEL COMPARISON

NORSK POLARINSTITUTT

RAPPORTSERIE

NR. 80 - OSLO 1993

Engedahl H.[1], Proshutinsky A. Yu.[2], & Ådlandsvik B.[3]

SOVIET - NORWEGIAN OCEANOGRAPHIC PROGRAMME 1988 - 1992

SNOP Numerical EXperiment (SNOPNEX) MODEL COMPARISON

[1] The Norwegian Meteorological Institute (DNMI), Oslo, NORWAY.
[2] The Arctic and Antarctic Research Institute(AARI), St. Petersburg, RUSSIA.
[3] The Institute of Marine Research (IMR), Bergen, Norway.

ISBN 82-7666-049-5
Printed March 1993

CONTENTS. PAGE

Abstract 4

1. Introduction. 5

2. A brief description of the participating ocean models. 6

2.1 The AARI-model. 6

2.2 The ECOM-3D model. 6

2.3 The ZCOORD model. 7

3. Description of the test cases. 9

3.1 Barotropic test case (SNOPNEX1). 9

3.2 Baroclinic test case (SNOPNEX2). 11

4. Results and evaluation. 13

4.1 The barotropic test case (SNOPNEX1). 13

4.1.1 The AARI-model. 13

4.1.2 The ECOM-3D model. 13

4.1.3 The ZCOORD model. 14

4.1.4 Comparison and evaluation of the results. 14

4.2 The baroclinic test case (SNOPNEX2). 15

4.2.1 Stationary analytical linear shallow-water solution. 15

4.2.2 The AARI-model. 16

4.2.3 The ECOM-3D model. 17

4.2.4 The ZCOORD model. 18

4.2.5 Comparison and evaluation of the results. 19

5. Conclusions. 22

Acknowledgements. 22

References. 23

Figures. 26

Barotropic test case (SNOPNEX1).

The AARI-model. 28

The ECOM-3D model. 32

The ZCOORD model. 36

Baroclinic test case (SNOPNEX2).

The AARI-model. 40

The ECOM-3D model. 43

The ZCOORD model. 46

Abstract.

Two Norwegian and one Russian scientific institute each provided a baroclinic three-dimensional numerical ocean model to be used in test experiments. The three different ocean models were run in one barotropic and one baroclinic idealized test case to compare their results and performance.

All three models worked well in the barotropic test case. Regarding the more demanding baroclinic test case, some discrepancies occurred. A large part of the observed differences in the model results may be explained by different set up of the models, together with the formulation of the baroclinic test case.

Thus, on the basis of the performed test runs, it is somewhat difficult to put up a "ranking list" between the three models. We believe that further experiments, both with idealized test cases and with more realistic ocean settings, are necessary to reveal the actual potential of all three ocean models.

1. Introduction.

The Soviet-Norwegian Oceanographic Programme (SNOP) was initiated in 1988 as a joint project between Soviet and Norwegian research institutions under an agreement between the USS State Committee of Science and Technology (GKNT), and the Norwegian Research Council for Science and Humanities (NAVF).

The aim of the programme was to improve the understanding of the Arctic or near-Arctic waters through joint cruises in the actual areas together with theoretical studies.

One branch of the theoretical work was numerical ocean modelling. During the SNOP-meeting in St. Petersburg in june 1990, a subtask under SNOP was initiated, called SNOPNEX, i.e. SNOP Numerical EXperiment.

The objective of SNOPNEX was to compare the already existing numerical ocean models at the participating Soviet and Norwegian institutions. This was achieved by running specified idealized test cases with the models, and then compare and evaluate the results.

The participating institutions and models were :

* The Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia, with a three-dimensional baroclinic ocean model based on the primitive equations, henceforth called the AARI-model.

* The Norwegian Meteorological Institute (DNMI) in Oslo, Norway, with a three-dimensional primitive equation model denoted ECOM-3D.

* The Institute of Marine Research (IMR) in Bergen, Norway, with a three-dimensional primitive equation model named ZCOORD.

In Part 2 of this report, brief descriptions of the different models are given. In Part 3 the idealized test cases are introduced and described. Part 4 contains the results from the test cases together with an evaluation. Part 5 yields the conclusions.

2. A brief description of the participating ocean models.

2.1 The AARI-model.

The three-dimensional baroclinic primitive equation ocean model at AARI is based on the work of Killworth et al. (1987). For the model to produce satisfactory solutions of baroclinic problems, it was necessary to include advective (non-linear) terms in the heat and salt transfer equations. This was achieved by using a procedure based on Boris and Book (1973) and Zalesak (1979).

A time splitting procedure is applied, in which the fast propagating external gravity waves and the more slowly moving internal gravity waves are treated separately. Thus, the changes in the sea surface elevation by the external gravity waves are computed from the "shallow water equations" using a relatively short time step. The more slowly moving processes determined by the internal gravity waves, are simulated by three-dimensional primitive equations for momentum, heat and salt balance, using a much longer time step. The procedure of "coupling" the computed "barotropic" and "baroclinic" velocities, which is necessary to determine the unknown currents, is analogous to the procedure used in the model of Bryan (1969).

The AARI-model uses finite differences. The "shallow water" equations are discretized on an Arakawa lattice C grid, while the three-dimensional primitive equations are discretized using the lattice B grid. In the vertical the z-coordinate is used (level model).

The integration procedure for the internal mode contains an explicit/implicit algorithm for the Coriolis terms, see Bryan (1969), otherwise an explicit scheme is used. Regarding the external mode, an explicit scheme is applied, except for the bottom friction where an explicit/implicit scheme is used.

2.2 The ECOM-3D model.

The present ocean model at the Norwegian meteorological institute (DNMI) is called ECOM-3D. The ECOM-3D model is a three-dimensional ocean circulation model created by Alan F. Blumberg and George L. Mellor around 1977. Subsequent contributions have been made by Leo Oey, Jim Herring, Lakshmi Kantha, Boris Galperin and others. Institutionally, the model was developed and applied to oceanographic problems within the Atmospheric and Oceanic Sciences Program of Princeton University and Dynalysis of Princeton. The following is just a brief description of the model and the reader is referred to the papers of Blumberg and Mellor (1987), and Mellor (1989), for a more thorough explanation. Other papers also describing this model are contained in the reference section. Description of the implementation and testing of the model at DNMI together with some results are given in Martinsen et. al. (1990) and Slørdal et. al. (1991).

The basis equations of the model are the non-linear primitive equations describing the velocity field, the surface elevation and the salinity and temperature fields. The following two simplifying approximations are used : First, it is assumed that the weight of the fluid identically balances the pressure, i.e. the hydrostatic approximation. Secondly, density differences are neglected unless the differences are multiplied by gravity, i.e. the Boussinesq approximation.

The vertical mixing coefficients are calculated by using a second order turbulence closure sub-model, Mellor and Yamada (1982). This sub-model characterizes the turbulence by prognostic equations for the turbulent kinetic energy and the turbulent macroscale.

The ECOM-3D is a sigma-coordinate model, i.e. the vertical coordinate σ is scaled by the water column depth $\eta + H$:

$$\sigma = \frac{z - \eta}{\eta + H}$$

Here, η is the sea surface elevation and H is the depth.

In the horizontal the model equations were originally formulated in curvilinear coordinates. In SNOPNEX the option for Cartesian coordinates was used.

The governing equations contain both the fast moving external gravity waves and the slow moving internal gravity waves. It is desirable in terms of computer economy to separate out the vertically integrated equations (external mode) from the "vertical structure" equations (internal mode). This technique, known as mode splitting (see Simons, 1974; Madala and Piacsek, 1977) permits the calculation of the free surface elevation with little sacrifice in computational time by solving the volume transport separately from the vertical velocity shear. The volume transport (external mode) equations are obtained by integrating the continuity equation and the momentum equations over the depth and thereby eliminate all vertical structure. The resulting set of equations are then integrated forward in time with a short time step. In this way the external mode equations provides the sea surface elevation gradients for insertion into the original equations which may be computed with a much longer time step. Note that the external mode equations are not subtracted from the original equations to form the more conventional mode set as, for example in Bryan (1969), or Wang (1982).

In the horizontal the equations are solved by finite differences on an Arakawa C-grid. The discretization in the vertical is also staggered, and the σ-levels may be unevenly distributed.

The time integration scheme is explicit in the advection terms and in the horizontal part of the diffusion terms, i.e. Leap-frog scheme in the advection terms and forward scheme in the diffusion terms. The vertical diffusion term is implicit, i.e. backward scheme.

Because of the spurious computational mode of the Leap-frog scheme, the model makes use of a weak time filter, Asselin (1972).

In order to increase the allowed time step slightly, the Shuman pressure gradient averaging technique has been invoked, see Schoenstadt and Williams (1976).

2.3 The ZCOORD model.

The ZCOORD model is based on the SINMOD model. The SINMOD model was designed and coded by Dag Slagstad (SINTEF, div. of automatic control). A description of this model in an early stage is given in Slagstad (1987). The model was later refined by Slagstad and Kjell Støle-Hansen at the same institution. Some results from the model are given in Slagstad et. al. (1990).

Starting in 1990 Jarle Berntsen at IMR, Harald Engedahl at DNMI, and Bjørn Ådlandsvik at IMR have worked with the SINMOD model. During this work the model-version has diverged from the SINTEF's own version and it is now denoted ZCOORD. A detailed description of ZCOORD is given in Ådlandsvik and Engedahl (1991).

Like the ECOM-3D model, ZCOORD is a three-dimensional non-linear baroclinic, primitive equations model. In the vertical direction the discretization is done by fixed levels in real depth (Z-coordinates). This is different from the sigma-coordinates of ECOM-3D. Another difference is the treatment of vertical mixing, which in ZCOORD is calculated by a simple mechanism using the Richardson number defined by

$$Ri=-\frac{g\left(\frac{\partial\rho}{\partial z}\right)}{\rho_0\left\|\frac{\partial\vec{u}}{\partial z}\right\|^2}$$

Three different states are recognized: the instable, the stable turbulent and the nonturbulent state. The eddy viscosity (ν) is constant in each of these states. Thus,

$\nu = 600 \times 10^{-4} m^2 s^{-1}$, if $Ri < 0$
$\nu = 100 \times 10^{-4} m^2 s^{-1}$, if $0 < Ri < 0.65$
$\nu = 0.01 \times 10^{-4} m^2 s^{-1}$, if $Ri > 0.65$.

The horizontal eddy viscosity is kept constant in time and space.

Numerically, the ZCOORD model uses a conventional time splitting procedure based on Berntsen et. al. (1981). By this method the model is split into two modes. The external (barotropic) mode is two-dimensional and includes the sea surface elevation and depth integrated currents. The internal ("baroclinic") mode contains the deviation from the vertical mean currents and the salinity and temperature equations.

Horizontally the discretization is done by introducing finite differences on an Arakawa C-grid. An explicit forward-backward scheme is used to solve the momentum equations. The salinity and temperature equations are solved by an upstream method. The vertical diffusion terms are implicit.

3. Description of the test cases.

3.1 Barotropic test case (SNOPNEX1).

General remarks.

The model domain consists of a straight channel 5000km long and 1000km wide. On one side of the channel there is a flat shelf with a depth of 300m. The width of the shelf is 200km. Out from the shelf, the depth increases linearly from 300m down to 3000m over a distance of 200km; see Fig.3.1.

Over the shelf area an idealized wind stress field is applied. The field has a Gaussian shape in the direction along the channel, and decays exponentially away from the coast; see under point b) in the detailed specification below.

The grid resolution is set to 50km both along and across the channel.

Detailed specifications.

Model domain : As specified in Fig.3.1.

a) Initial condition (t=0) : The sea starts from rest, i.e. sea surface elevation $\eta(x,y,0) = 0$, depth mean velocity components $u_m(x,y,0)$, $v_m(x,y,0) = 0$.

b) Forcing : By idealized wind stress,

$$\tau_x = \tau_0 \cdot \exp\left[\frac{-\left(x-\frac{L}{3}\right)^2}{4L_s^2}\right] \cdot \exp\left[\frac{-y}{2L_s}\right]$$

$$\tau_y = 0$$

$\tau_x = \tau_y = 0$ for $t > 48$ hours.

$\tau_0 = 0.4$ Pa

$L_s = 200$ km

$L = 5000$ km

c) Boundary conditions : At open boundaries : Cyclic.
At rigid boundaries (coast) : No flux (i.e. $v = 0$).

d) Length of simulation : 7 days = 168 hours.

e) Output for intercomparison :

- Contour plots of sea surface elevation every 24 hours. Contour interval proposed to be 1 cm.

- Time series of the sea surface elevation at the grid point closest to the coast y=0 at x=3500km. Output every hour.

f) Bottom stress : Quadratic. Friction coeff. = 0.0025.

g) Horizontal eddy viscosity : A = 0.

h) Coriolis parameter : $f = 1.3 \times 10^{-4} s^{-1}$.

i) Density : $\rho = 1026.0\ kgm^{-3}$.

j) Gravitational acceleration : $g = 9.81\ ms^{-2}$.

k) The modellers shall perform calculations of the kinetic energy per unit mass (E_k), the available potential energy per unit mass (E_p), and the combined energy per unit mass ($E_k + E_p$). Results are to be presented as time series summed up over all grid points carrying η. Thus, if staggered grid, u and v have to be interpolated to the η-points before the energy is calculated. Output every hour. The energies are defined as follows :

$$E_p = \frac{1}{2} g \sum_i \sum_j \eta^2_{i,j}$$

$$E_k = \frac{1}{2} \sum_i \sum_j H_{i,j} (u_{m_{i,j}}{}^2 + v_{m_{i,j}}{}^2)$$

Here u_m and v_m are depth mean currents, and H is the depth.

l) A linear model shall be used (i.e. no advection terms should be included).

3.2 Baroclinic test case (SNOPNEX2).

General remarks.

The model domain consists of a straight channel of infinite length, but with a width of 600km. On one side of the channel there is a shelf with a uniform depth of 300m. The width of the shelf is 200km. Out from the shelf the depth increases linearly from 300m down to 3000m over a distance of 200km; see Fig.3.2.

In the direction along the channel a uniform wind stress is applied; see under point c) in the detailed specification below. Because of the uniform wind stress, it was assumed that this problem may be solved by using a two-dimensional model in the plane across the channel.

The stratification is made up by three layers : The upper layer from 0 to 50m with a constant density, an intermediate layer in which the density increases linearly with depth from 50m down to 550m, and a bottom layer from 550m to 3000m with a constant density; see under point a) in the detailed specification below.

Detailed specifications.

Model domain : As specified in Fig.3.2.

a) Initial condition (t=0) : The sea starts from rest, i.e. sea surface elevation $\eta(x,y,0) = 0$, current components $u(x,y,z,0)$, $v(x,y,z,0) = 0$.

Initial density distribution :

ρ_1 = 1026.0 kgm^{-3} $-50m < z < 0m$
ρ = linear increase $-550m < z < -50m$
ρ_2 = 1027.5 kgm^{-3} $-3000m < z < -550m$

(Optionally, to obtain the density distribution from the equation of state, only the salinity shall be changed. In all grid points a constant temperature of 4°C shall be used.)

b) Resolution : Horizontal grid spacing proposed to be 4km. 8km is acceptable if problems. The vertical resolution is to be decided individually by the involved modellers.

c) Forcing : By idealized wind stress,

$\tau_x = 0.4$ Pa, and

$\tau_y = 0$ throughout the simulation.

d) Boundary conditions : Optionally if a "cross-channel slice" 3-D model is used; Cyclic on the open boundaries. Otherwise, no flux across the coasts (i.e. $v = 0$).

e) Length of simulation : 30 days = 720 hours.

f) Output for intercomparison :

- Cross-shore sea surface elevation (slope along y-axis) after 30 days. The max. and min. values should be written on the plot.

- Cross-section plots in the y,z-plane after 30 days with contour lines of σ_t or specific density (= actual density - 1000 kgm^{-3}), along-shore (u) and cross-shore (v) velocity. Contour interval for density : 0.1, for u : $0.1ms^{-1}$, for v : $0.05ms^{-1}$.

- Time series of surface elevation at the grid point closest to the coast on both sides of the channel. Output every hour.

g) Bottom stress : Quadratic. Friction coeff. = 0.0025.

h) Horizontal eddy viscosity : $A = 10m^2s^{-1}$.

i) Coriolis parameter : $f = 1.3 \times 10^{-4}s^{-1}$.

j) Gravitational acceleration : $g = 9.81ms^{-2}$.

k) Eddy viscosity, vertical : Depends on the model.

l) Computations shall be performed with fully non-linear equations.

4. Results and evaluation.

4.1 The barotropic test case (SNOPNEX1).

4.1.1 The AARI-model.

Set up.

To run this experiment, a separate barotropic model was developed. This barotropic model is practically identical to the "barotropic" part of the three-dimensional primitive equation model at AARI, i.e. the AARI-model.

The specified model domain was defined by 100 x 20 grid points. A time step of $\Delta t = 100$ seconds was used. The calculation time on the computer for this test case was about 20 minutes.

A brief description of the results.

Based on earlier experience with the same kind of test case, the model produced highly satisfactory results. The applied wind forcing generates shelf-waves. This solution is gradually damped by the bottom friction after the wind was shut off at 48 hours of simulation.

All specified plots from the AARI-model for SNOPNEX1 are shown in Figs. 4.1.1a-k.

4.1.2 The ECOM-3D model.

Set up.

The model was run in a two-dimensional mode. The non-linear advective terms were <u>not</u> excluded in the computations. This was because the model does not have a "switch" which easily turns off these terms. However, earlier experience has revealed that these terms contribute very little to the solution in this case.

The model domain was defined by 101 x 22 grid cells.

The CFL-criterion for the leap-frog scheme is :

$$\Delta t \leq [\Delta x/2(2gH)^{1/2}]$$

With a maximum depth of 3000m, this gives $\Delta t \leq 103$ seconds. A time step of $\Delta t = 60$ seconds was used.

The 7 days calculation was performed on a CRAY X-MP computer. The total job-time was approximately 80 seconds.

A brief description of the results.

Like the AARI-model, the ECOM-3D model also showed excellent results in this case. The wind forcing caused piling up of water towards the shallow coast generating shelf-waves. Due to the applied bottom friction, the solution was gradually damped after the wind was shut off.

All specified plots from the ECOM-3D model for SNOPNEX1 are shown in Figs. 4.1.2a-k.

4.1.3 The ZCOORD model.

Set up.

This case was run using only the external two-dimensional mode of the ZCOORD model. The non-linear option of the model was turned off.

The computational domain was defined by 102 x 20 grid cells.

The CFL-criterion for the forward-backward scheme says $\Delta t \leq [\Delta x/(2gH)^{1/2}]$. Here the maximum depth H = 3000 m. This gives $\Delta t \leq 204$ seconds. A time step $\Delta t = 150$ seconds was used.

The 7 days simulation was performed on a SUN SPARCstation 2 and took 10.5 CPU-minutes.

A brief description of the results.

Also the ZCOORD model did produce very nice results in this test case. Again, the shelf-wave solution is gradually damped by the applied bottom friction after the wind forcing was turned off.

All specified plots from the ZCOORD model for SNOPNEX1 are shown in Figs. 4.1.3a-k.

4.1.4 Comparison and evaluation of the results.

All three models showed very similar and realistic results in this test case. As expected, the advective (non-linear) terms, which were included in the ECOM-3D model, contributed very little to the solution.

The wind forcing caused a pile up of water towards the shallow coast. All models simulated a shelf wave with a maximum amplitude of approximately 8 cm, and travelling with a speed of approximately 20 ms^{-1}. As an estimate, the phase speed of the long shelf waves is proportional to the Coriolis parameter times the width of the shelf (Martinsen et al. 1979). With a shelf width of 200km, as in SNOPNEX1, the estimated phase velocity is approximately 25 ms^{-1}, in good agreement with the model results. Thus, the shelf-waves propagated through the model domain in about 70 hours, which is also reflected in the time series of surface elevation from the three models in Figs. 4.1.1h, 4.1.2h and 4.1.3h.

Some discrepancies between the ZCOORD model and the two other models may be seen in the time series of the total model energy in Figs. 4.1.1k, 4.1.2k and 4.1.3k. The ZCOORD model gave values which were approximately 10 % lower than the values from the AARI-model and the

ECOM-3D model.

4.2 The baroclinic test case (SNOPNEX2).

4.2.1 Stationary analytical linear shallow-water solution.
(Derived by B. Ådlandsvik at IMR)

The forced linearized shallow water equations consist of the momentum equations

$$\frac{\partial U}{\partial t} - fV = -gH\frac{\partial \eta}{\partial x} + \frac{1}{\rho}(\tau^x{}_{sur} - \tau^x{}_{bot}) \tag{1}$$

$$\frac{\partial V}{\partial t} + fU = -gH\frac{\partial \eta}{\partial y} + \frac{1}{\rho}(\tau^y{}_{sur} - \tau^y{}_{bot}) \tag{2}$$

and the continuity equation

$$\frac{\partial \eta}{\partial t} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y} \tag{3}$$

Here $U = Hu$ and $V = Hv$ are the depth integrated current components. In this test case $\partial/\partial x = 0$ and we search the stationary solution with $\partial/\partial t = 0$. The continuity equation (3) then becomes

$$\frac{\partial V}{\partial y} = 0$$

This implies $V = 0$ because there is no flux through the coasts. With the shallow water assumption this gives $v = V/H = 0$.

In the test case $\tau^y{}_{sur} = 0$ and $\tau^x{}_{sur} = \rho\alpha$. The bottom stress is quadratic. Since v = 0, the bottom stress simply becomes $\tau^y{}_{bot} = 0$ and $\tau^x{}_{bot} = c\rho u^2$. The momentum equations (1) and (2) then simplifies to

$$0 = \alpha - cu^2$$

$$fU = -gH\frac{\partial \eta}{\partial y}$$

It follows that

$$\frac{\partial \eta}{\partial y} = -\frac{f}{g}\left(\frac{\alpha}{c}\right)^{\frac{1}{2}}$$

In particular, the surface slope is independent of the depth.

In this test case $\alpha = 0.4/1027 = 3.9 \times 10^{-4} m^2 s^{-2}$ and $c = 2.5 \times 10^{-3}$. With $f = 1.3 \times 10^{-4} s^{-1}$ and g =

9.81 ms^{-2}, we get

$$\frac{\partial\eta}{\partial y} = 5.2 \times 10^{-6}$$

The half-width of the channel is 300km and this gives a sea surface elevation of 1.55m close to the coast.

In the three-dimensional solution there is an Ekman current towards the shelf. This is compensated by a counter current below. Thus, the bottom stress term $-\tau^{y}_{bot}$ points towards the shelf and must be balanced by a larger sea surface slope. Since the strength of the undercurrent depends on depth, the surface slope will be slightly larger over the shelf than over the deep sea areas. With stratification the up/down-welling contributes to the pressure. This is balanced by a larger sea surface slope, confined within a distance of the order of the baroclinic (internal) Rossby radius from the coast.

4.2.2 The AARI-model.

Set up.

The test calculations were performed without the non-linear terms in the momentum equations. The salt advection, regarded as the most important mechanism for reproducing the physical processes in an ocean basin with a bottom relief, was retained. A modified non-linear method of flux correction based on Boris and Book (1973) and Zalesak (1979), was applied for the advection terms in the salt equation (the so called Flux-Corrected Transport Algorithm). This method removes the dispersible "ripples" (which prevent a higher -order approximation to the continuous case) that occur with small numerical viscosity. The computations were performed in a vertical cross-shore plane (e.g. two-dimensional). Therefore, along-shore variations were not simulated.

In the computations, the optional grid size of 8km was used (standard was set to 4km). Thus, the "baroclinic" mode calculations was performed with a time step of 1 hour, while the simulation of the "barotropic" mode demanded a time step of 30 seconds. The test case was run on an IBM PC/AT 386 computer, and required about 5 hours of CPU time.

A brief description of the results.

After 30 days of simulation the sea surface elevation has not yet reached a steady state. The sea level height at the shallow coast was approximately 1.45m (down-welling), and about -1.23m at the deep coast (up-welling) (Fig.4.2.2a).

The value of the derivative of the cross-shore sea elevation relief changed over the various areas. It was almost constant over the deep ocean (straight line), and increased linearly over the slope region (parabolic shape). The "barotropic" mode (i.e. depth averaged) velocities showed a maximum of about 0.4ms^{-1} over the shelf slope.

The cross-shore density field (Fig.4.2.2b) showed the existence of two areas with down-welling. The strongest down-welling occurred over the slope region. The down-welling at the shallow coast was much weaker. From estimates, the model-produced up-welling and the associated current at the deep coast, was too small (difficult to detect up-welling in the cross-shore plot of the density).

The maximum along-shore velocities were situated above the slope and reached a value of approximately $0.5ms^{-1}$. The cross-shore current had a maximum of about $0.1ms^{-1}$ in the surface Ekman layer.

All specified plots from the AARI-model for SNOPNEX2 are shown in Figs. 4.2.2a-e.

4.2.3 The ECOM-3D model.

Set up.

Since the model has no option for running a 2-D cross section (y,z-plane), it was run in the full three-dimensional mode introducing a cross-shore "slice" with the thickness of 52km along the x-axis. Thus, horizontally 16 x 158 grid cells were applied. In the along-shore direction (x-axis) 3 grid cells are used to administrate the cyclic open boundary condition. The grid size was 4km.

For practical reasons 7 grid points on land were defined at the deep sea coast, and 1 point on the shelf side coast.

In the vertical, 10 σ-levels were used with level interfaces at 0, 20, 50, 150, 250, 350, 450, 550, 1000, 1500 and 3000 meters off the shelf. Because of the terrain-following σ-coordinate, this corresponds to interfaces at 0, 2, 5, 15, etc. meters on the shelf.

The external time step was set to 5 seconds (the CFL-criterion gave approximately 8.3 seconds), and the internal time step was set to 20 seconds. However, an internal time step of approximately 180 seconds (3 min.) should have been sufficient in this case from the estimates of the internal wave speeds and the present maximum advective (current) speed. This very short internal time step was used here to assure that the internal CFL-criterion was not violated. The rather strong specified wind forcing, which corresponds to a constant wind of approximately $20ms^{-1}$ (strong gale) throughout the simulation period of 30 days, will set up strong baroclinic currents parallel to the coasts. These currents may be baroclinic unstable.

Instead of using a constant horizontal eddy viscosity of $A = 10\ m^2s^{-1}$, the model originally uses the Smagorinsky (1963) formula

$$A = C\Delta x\Delta y\left[\left(\frac{\partial u}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right]^{\frac{1}{2}}$$

This was used in SNOPNEX2 with $C = 0.1$.

The vertical eddy viscosity was calculated by the invoked turbulence closure scheme (Mellor and Yamada, 1982).

Because of an already implemented procedure in handling the wind forcing, the model actually spins up the wind from zero to it's full strength during the first 6 hours of simulation.

This test case was run on a CRAY X-MP computer, and the model used approximately 3 hours of

CPU time.

A brief description of the results.

The channel was made as long as 16 grid points in the x-direction, of which 13 points are active (i.e. 52km). After 30 days small *along-shore* gradients were seen in the results, and they may be explained by baroclinic instabilities, see section 4.2.5.

After 30 days the sea surface elevation had increased from zero to about 1.6m at the shallow coast, and it had decreased down to about -1.6m at the deep coast (Fig.4.2.3a).

The time series of the sea surface elevation (Fig.4.2.3e) also reflect the effects from the spin-up of the wind forcing during the first 6 hours (compare with the same figures from the AARI-model and ZCOORD). The time series also show that the sea level was adjusted faster at the shallow coast.

The plot of the density profile across the channel after 30 days (Fig.4.2.3b) shows rather strong down-welling at the shallow coast and over the shelf brake, and up-welling at the deep coast. At the shallow coast, the surface water reached down to the sea floor. Wave-like features are seen in the density profile between the depth of 500-1000m. These may be due to internal waves.

The cross section plot of the along-shore velocity (u) (Fig.4.2.3c) shows a maximum of approximately 1.3ms^{-1} at the deep coast after 30 days, and a maximum of approximately 0.5ms^{-1} at the shallow coast. These maxima are found in the 10m depth, i.e within the Ekman layer. There is also a local maximum of about 0.7ms^{-1} just outside the shelf break because of down-welling in that region.

Regarding the cross-shore current component (v) after 30 days (Fig.4.2.3d), there is a minimum of about -0.15ms^{-1} at the shallow coast, and about -0.35ms^{-1} at the deep coast.

All specified plots from the ECOM-3D model are shown in Figs. 4.2.3a-e.

4.2.4 The ZCOORD model.

Set up.

This case was run with the non-linear option turned on. Horizontally 16 x 160 grid cells with a grid size of 4km were used. On both sides of the channel 5 grid points on land were specified. Thus, as for the ECOM-3D model, the ZCOORD model was run in a three-dimensional mode.

Vertically 10 levels were used, with level interfaces at 0, 20, 50, 150, 250, 350, 450, 550, 1000, 1500 and 3000 meters. The initial density stratification was specified through the equation of state by the salinity and a constant temperature of 4°C.

The external time step was 10 seconds, and the internal 600 seconds.

However, the model could not cope with the specification of A = 10m^{2}s^{-1} for the horizontal eddy viscosity. In this case instabilities developed. A mixing coefficient of A = 1000 m^{2}s^{-1} (which is unrealistic !) had to be used for both density fields and momentum.

This test case was run on a SUN SPARCstation 2 and required 14 CPU-hours.

A brief description of the results.

The channel was made as long as 13 grid cells to check that no along-shore gradients developed. This part was successful, no such gradients developed, even in the unstable case with a horizontal eddy viscosity of $A = 10 m^2 s^{-1}$.

The formulation used for the vertical mixing prevents statical instabilities from developing by using a high value of the vertical mixing coefficient in this case ($\nu = 600. \times 10^{-4}\ m^2 s^{-1}$). The result of this is seen on the density plot where the contours are almost vertical in the up-welling and down-welling regions (Fig.4.2.4b).

The along-shore velocity plot (Fig.4.2.4c) shows a maximum of approximately 0.55 ms^{-1} and a minimum of approximately 0.25 ms^{-1}. The cross-shore current shows a maximum in the surface Ekman layer of approximately -0.17 ms^{-1} (Fig.4.2.4d). Unfortunately, because of the scale on the plots, the Ekman layer appears as very thin on the presented figures. There is some noise in the plotted values where this current component is close to zero.

The time series (Fig.4.2.4e) show that the sea level adjusts faster at the shallow coast, but after 30 days the sea surface slope is nearly constant.

All specified plots from the ZCOORD model are shown in Figs. 4.2.4a-e.

4.2.5 Comparison and evaluation of the results.

The reliefs of the sea surface elevation across the channel are shown in Fig.4.2.2a, Fig.4.2.3a and Fig.4.2.4a for the AARI-model, the ECOM-3D and the ZCOORD model respectively. The results are quite similar, especially for the AARI and the ZCOORD models. While the surface slope from the AARI and ZCOORD models showed almost no variations over the shelf slope, the result from the ECOM-3D model clearly showed changes in the surface level gradient, both close to the coasts and over the shelf break. This is just the regions where the up- and down-welling takes place. Thus, the results from the ECOM-3D model agree well with the discussion of the analytical solution in section 4.2.1. This discussion concluded that the gradient in the sea surface level should vary over the up- and down-welling areas. The variation takes place over a distance corresponding to the baroclinic (internal) Rossby radius.

The more smooth solution from the ZCOORD model may be explained by the large applied horizontal eddy viscosity. However, the similar response from the AARI-model is more difficult to explain. One reason might be the fact that the AARI-model was run with a grid resolution of 8km, while the two other models used a resolution of 4km. The actual baroclinic (internal) Rossby-radius in this test case is approximately 15km, and this is not properly resolved on a 8km grid.

The minimum value of sea level at the deep coast from the AARI-model was -1.25m, from the ZCOORD model -1.5m, and from the ECOM-3D model -1.6m. At the shallow coast, the maximum value from the AARI-model was 1.44m, from the ZCOORD model 1.69m, and the value from the ECOM-3D model was 1.6m. These results from all three models agreed well with the analytical solution derived in section 4.2.1. The numerical quantity of sea level showed equal values at the shallow and deep coast in the ECOM-3D model, while both the AARI-model and the ZCOORD model gave a higher value at the shallow coast (14% increase for AARI and 12% for ZCOORD). On a larger scale, an asymmetrical solution as in the AARI- and the ZCOORD model, is quite realistic. However, the baroclinic dynamics introduced because of the up- and down-welling, should cause changes in the gradient of the sea level over the up- and down-welling areas. These changes are significant only in the results from the ECOM-3D model, and explain the more "symmetric" form of the sea level relief from that model.

Regarding the time series of sea level at the coasts from the three models in Fig.4.2.2e for the AARI-model, in Fig.4.2.3e for the ECOM-3D and in Fig.4.2.4e for the ZCOORD, they show very much the same results. The largest deviations are seen in the first 6 hours of simulation time because of the linear spin-up of the wind forcing in ECOM-3D.

Looking at the cross section plots of density from the models in Fig.4.2.2b for the AARI-model, in Fig.4.2.3b for ECOM-3D and in Fig.4.2.4b for ZCOORD, the AARI-model and ZCOORD seem to smooth out the up- and down-welling regions at the channel's coasts, when compared to the result from the ECOM-3D model. As mentioned above, regarding ZCOORD this is due to the rather high and constant values of both vertical and horizontal viscosity used in that model. In the ECOM-3D model the vertical mixing coefficients are continuously updated by a turbulence closure scheme, and the horizontal eddy viscosity is computed by the Smagorinsky formula which depends on the velocity field. For the AARI-model the rather smooth solution may be due to the poor resolution of the baroclinic (internal) Rossby-radius because of the applied grid size of 8km (instead of 4km).

The features which were seen in the cross section density plots, are also reflected in the cross section plots of the along-shore (u) and cross-shore (v) current components. The along-shore components are shown in Fig.4.2.2.c for the AARI-model, in Fig.4.2.3c for the ECOM-3D, and in Fig.4.2.4c for the ZCOORD model. The cross-shore components are shown in Fig.4.2.2d, Fig.4.2.3d and Fig.4.2.4d respectively. Again, The AARI-model and ZCOORD produced a much more smooth picture. The regions of up- and down-welling were more sharply defined in the ECOM-3D model. This also explains why the current speeds, especially regarding the along-shore component (u), were higher in the ECOM-3D model than in the two other models.

In general, because of the high (and even unrealistic) horizontal and vertical viscosity which were applied in the ZCOORD model, the results from this model should be regarded as rather artificial. However, the fact that the results from the AARI-model looked very much the same as the results from the ZCOORD model (rather smooth), can not be explained by any applied strong viscosity in the AARI-model. Actually, the Flux Correcting Algorithm was used in the AARI-model because of the rather weak viscosity which was applied in that model. On the other hand, the AARI-model used the optional grid size of 8km, instead of 4km. With an estimated baroclinic (internal) Rossby-radius of about 15km, this grid resolution is too coarse to properly resolve the baroclinic dynamics like up- and down-welling. Regarding the results from the ECOM-3D model, although producing more sharply defined regions of up- and down-welling, the results also show features which may indicate that instabilities are developing in the solution.

In fact, this test case was somewhat poorly designed. The rather strong wind forcing over the specified period of 30 days is due to set up very strong up- and down-welling at the coasts, and thereby large gradients in the density field. This results in creation of strong baroclinic along-shore currents. These strong currents are most likely baroclinic (or dynamically) unstable. In fact, both the ECOM-3D model and especially the ZCOORD model had problems in properly handling this test case by using the specified parameters defined in section 3.2. Because the advective (non-linear) terms were omitted in the momentum equations in the AARI-model, this model was not affected by the problem of baroclinic unstable currents.

That baroclinic instabilities do occur, may be seen from Fig.4.2.5 which shows the current and the density fields at 100m depth over a portion of the shelf closest to the coast. It shows the situation after 18 days of simulation time. The result is from the ECOM-3D model. As seen from the figure, wave-like features are developing in both the current and the density field. Further analysis showed that the amplitude of these disturbances increased with time. We assume that these observed disturbances are due to baroclinic instabilities.

The original physical set up of this test case was formulated to seek a stationary solution which was uniform in the along-shore direction. However, the above indicates that the physical set up of this problem was not well posed, and that it has to be redefined if further model comparisons are to be carried out.

5. Conclusions.

Three baroclinic three-dimensional numerical ocean models were tested in two idealized test cases with wind forcing and topography, one barotropic case and one baroclinic. All three participating models performed an excellent job in the barotropic test case. However, in the baroclinic test case some discrepancies in the performance occurred. The baroclinic test case was more demanding, and the results are more sensitive to the actual model set up. However, the baroclinic test case was most likely not well posed (no model managed to reach a steady state), and it will have to be reformulated if a similar comparison should be made in the future. Further idealized test-experiments are regarded to be useful. However, to reveal the actual potential of the different models, they should also be applied for more realistic simulations.

Acknowledgements.

The Norwegian part of SNOP is supported by the Norwegian Research Council for Science and Humanities (NAVF).

The work carried out at the Norwegian Meteorological Institute (DNMI) during SNOP was a part of the project "Three-dimensional ocean modelling", which was sponsored by the NAVF.

The authors would like to thank Dr. E.A. Martinsen at DNMI for his valuable scientific contributions during the preparation of this report.

References.

ASSELIN R., 1972
Frequency filters for time integrations.
Mon. Weather Rev., 100, pp 487 - 490.

BERNTSEN H., KOWALIK Z., SÆLID S. and SØRLI K., 1981
Efficient numerical simulation of ocean hydrodynamics by a splitting procedure.
Modelling, Identification and Control, 2, pp 181 - 191.

BLUMBERG A. F. and MELLOR G. L., 1987
A description of a three-dimensional coastal ocean circulation model.
Three-dimensional Coastal Ocean Models, Vol 4, edited by N. Heaps, pp 208.
American Geophysical Union, Washington D.C.

BORIS J.P. and BOOK D.L., 1973
Flux-Corrected Transport I: SHASTA - A Fluid Transport Algorithm that Works.
J. Comp. Phys., No.11, pp 38 - 69.

BRYAN K., 1969
A numerical method for the study of the circulation of the world ocean.
J. Comput. Phys., 4, No.3, pp 347 - 376.

KILLWORTH P.D. et al., 1987
A free-surface Bryan-Cox-Semtner model.
J. Phys. Oceanogr., Vol.17, No.7.

MADALA R. V. and PIACSEK S. A., 1977
A semi-implicit numerical model for baroclinic oceans.
J. Comput. Phys., 23, pp 167 - 178.

MARTINSEN E.A., GJEVIK B. and RØED L.P., 1979
A Numerical Model for Long Barotropic Waves and Storm Surges along the Western Coast of Norway.
J. Phys. Oceanogr., Vol.9, No.6, pp 1126 - 1138.

MARTINSEN E.A., SLØRDAL L.H. and ENGEDAHL H., 1990
MetOcean Modelling Project (MOMOP), Phase 2.
Data Report : Joint presentation of the test cases.
Technical Report No. 87, The Norwegian Meteorological Institute.

MELLOR G. L., 1989
Documentation for a three-dimensional, primitive equations, numerical ocean model.
Internal report, 41 pages.
Atmospheric and Oceanic Sciences Program, Princeton University, Princeton.

MELLOR G. L. and YAMADA T., 1982
Development of a turbulence closure model for geophysical fluid problems.
Rev. Geophys. Space Phys., 20, No.4, pp 851 - 875.

SCHOENSTADT A. L. and WILLIAMS R. T., 1976
The computational stability properties of the Shuman pressure gradient averaging technique.
J. Comput. Phys., 21, pp 166 - 177.

SIMONS T. J., 1974
Verification of numerical models of Lake Ontario, Part I. Circulation in spring and early summer.
J. Phys. Oceanogr., 4, pp 507 - 523.

SLAGSTAD D., 1987
A 4-Dimensional Physical Model of the Barents Sea.
SINTEF report STF48 F87013.

SLAGSTAD D., STØLE-HANSEN K. and LOENG H., 1990
Density driven currents in the Barents Sea calculated by a numerical model.
Modelling, Identification and Control, 11, pp 181 - 190.

SLØRDAL L.H., MARTINSEN E.A. and ENGEDAHL H., 1991
MetOcean Modelling Project (MOMOP), Phase 2.
Final Report : Sensitivity tests and pre-operational simulations.
Technical Report No. 88, The Norwegian Meteorological Institute.

SMAGORINSKY J., 1963
General circulation experiments with the primitive equations,
I. The basic experiment.
Mon. Weather Rev., 91, pp 99 - 164.

WANG D. -P., 1982
Development of a three-dimensional, limited-area (island) shelf circulation model.
J. Phys. Oceanogr., 12, pp 605 - 617.

ZALESAK S.T., 1979
Fully multidimensional flux-corrected transport algorithm for fluids.
J. Comput. Phys., Vol31, No3, pp 335 - 362.

ÅDLANDSVIK B. and ENGEDAHL H., 1991
Documentation of a Three Dimensional Baroclinic Sea Model.
Technical Report 16, Institute of Marine Research, Centre for Marine Environment, Norway.

FIGURES

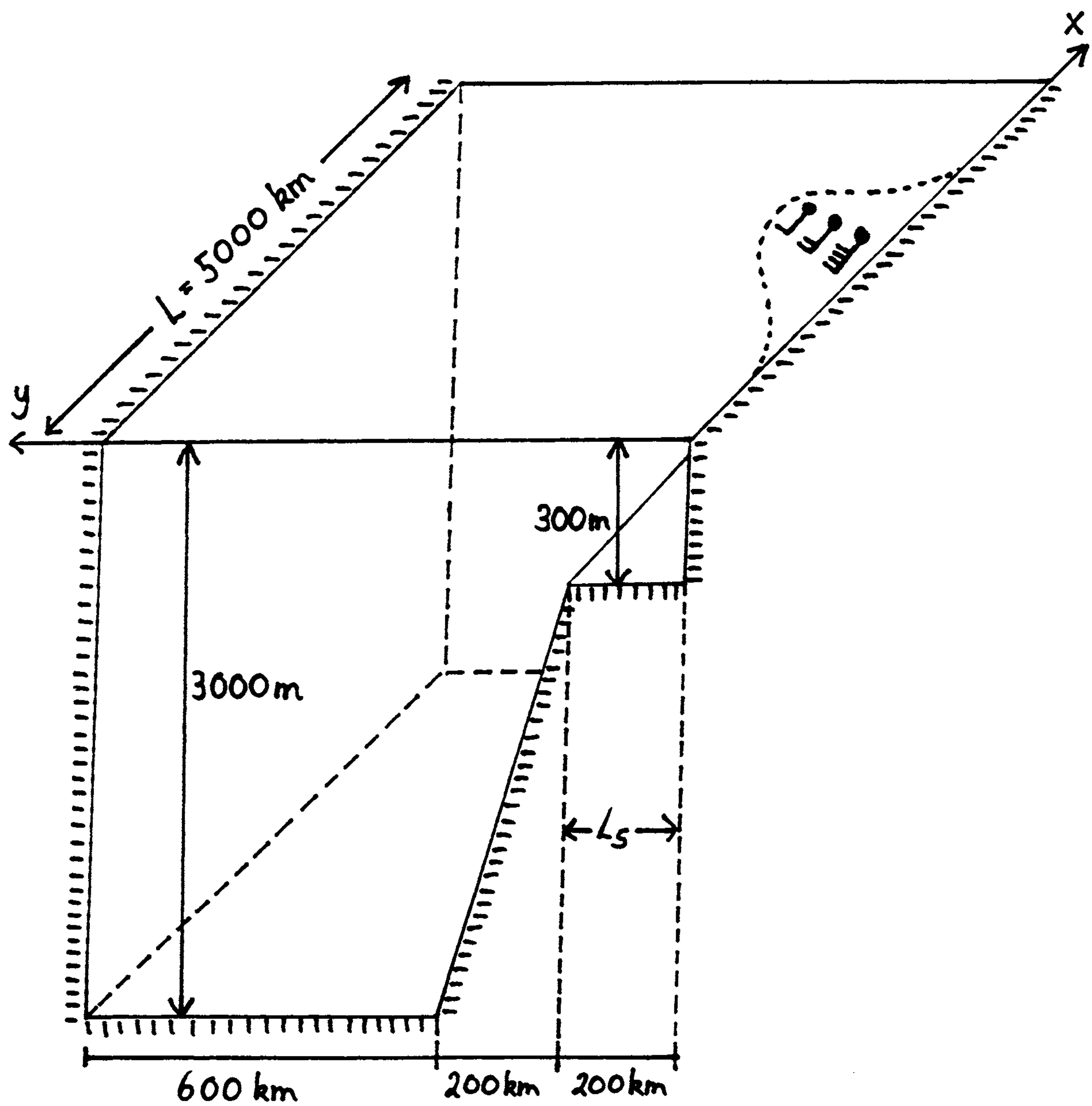

Fig.3.1 : The model domain and bathymetry for the barotropic test case (SNOPNEX1).

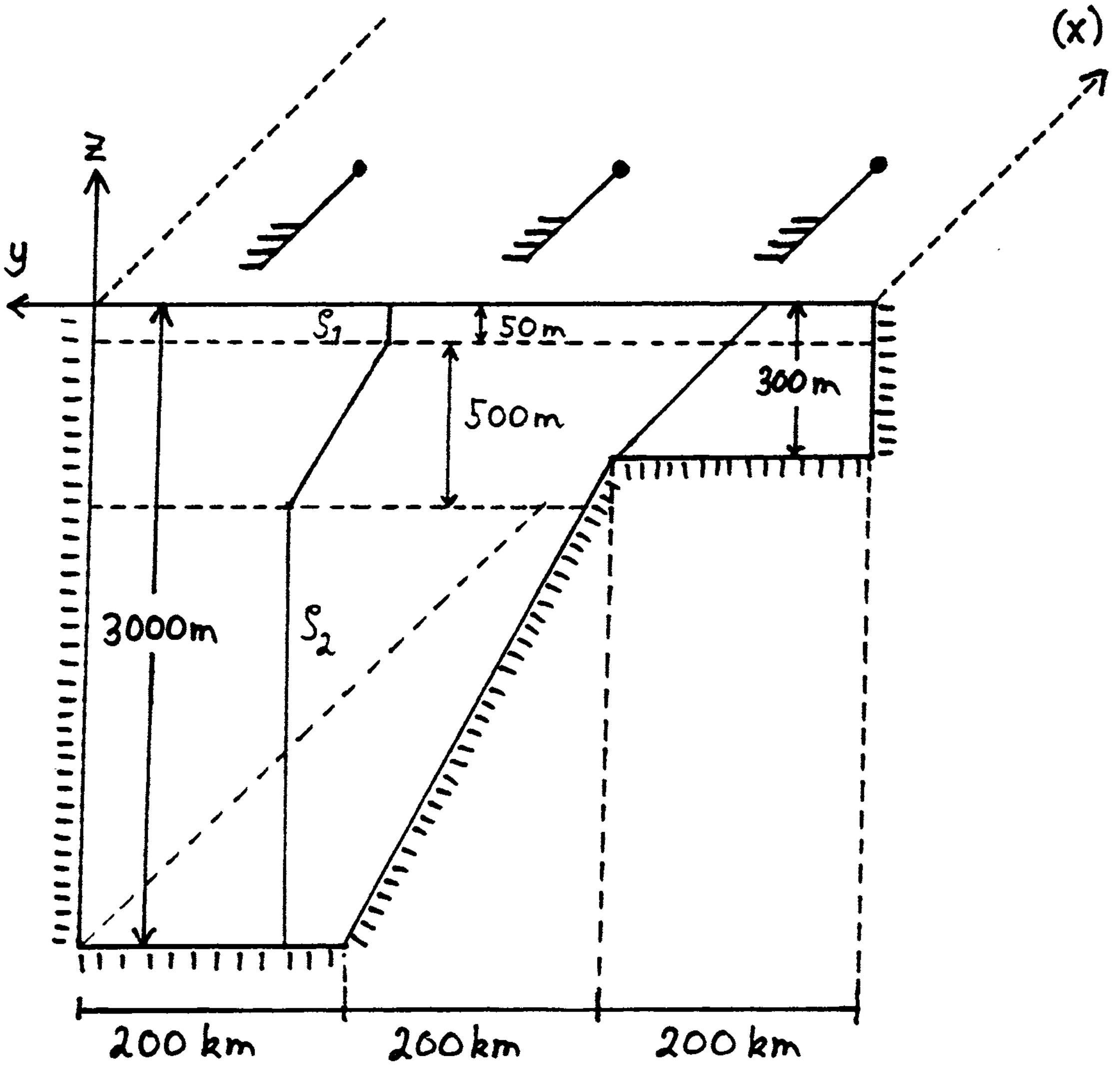

Fig.3.2 : The model domain and bathymetry for the baroclinic test case (SNOPNEX2).

Barotropic test case
(SNOPNEX1)

The AARI-model

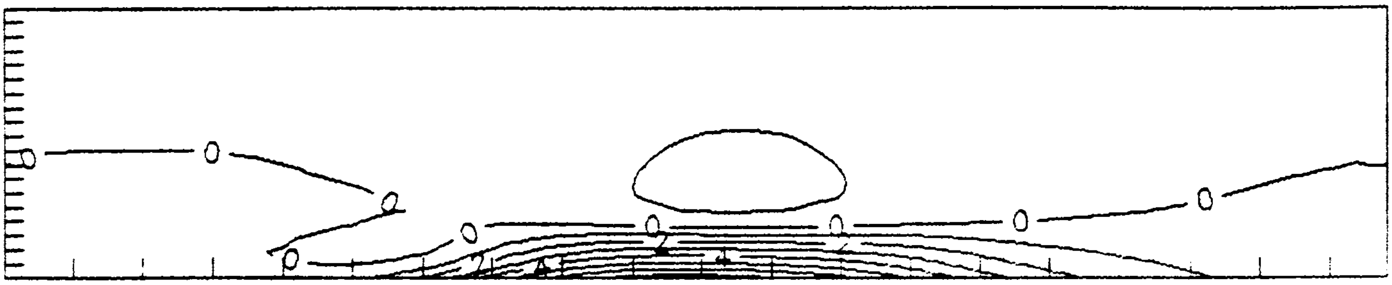

Fig.4.1.1a : Contours of sea surface elevation after 24 hours of simulation time. Unit: cm. **AARI-model.**

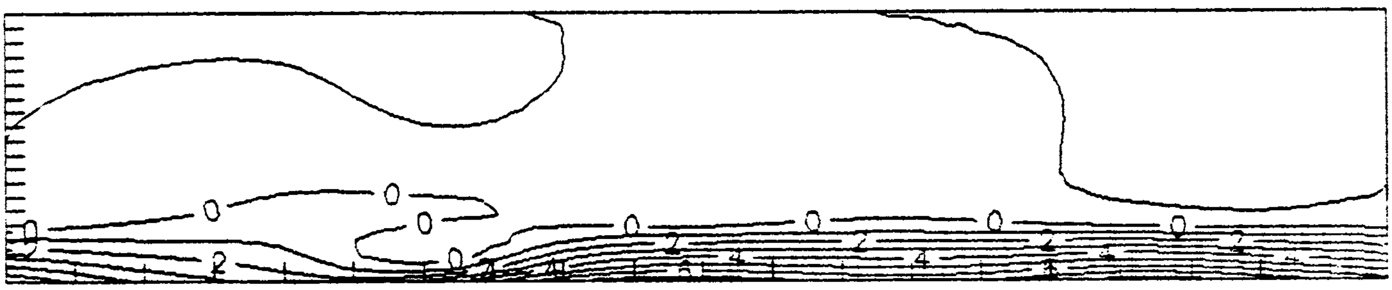

Fig.4.1.1b : Contours of sea surface elevation after 48 hours of simulation time. Unit: cm. **AARI-model.**

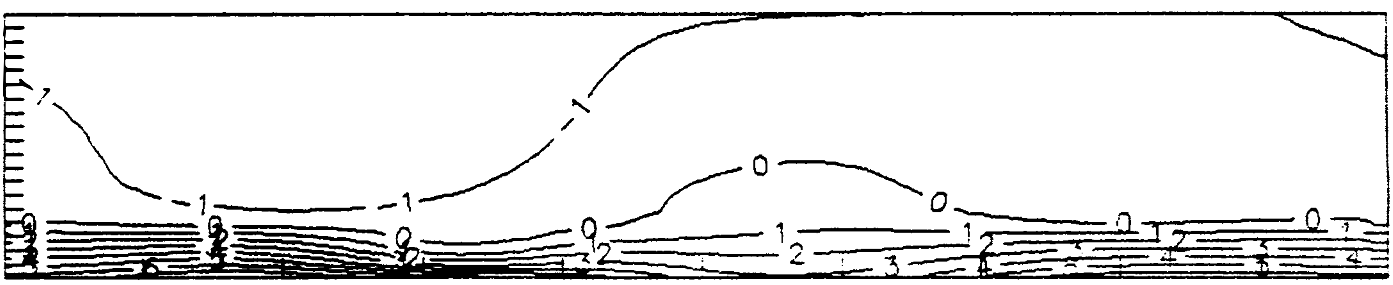

Fig.4.1.1c : Contours of sea surface elevation after 72 hours of simulation time. Unit: cm. **AARI-model.**

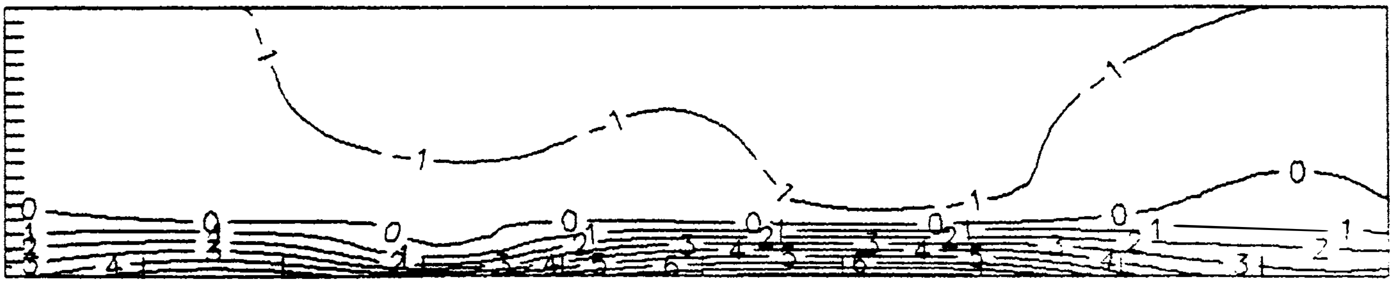

Fig.4.1.1d : Contours of sea surface elevation after 96 hours of simulation time. Unit: cm. **AARI-model.**

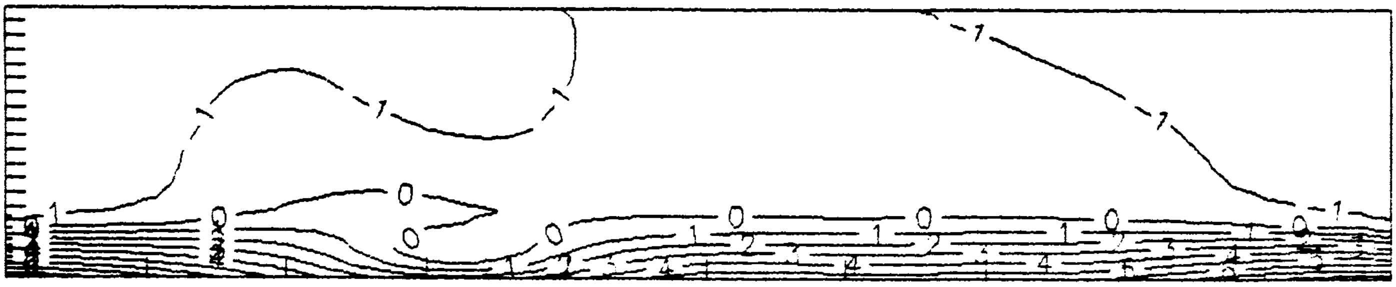

Fig.4.1.1e : Contours of sea surface elevation after 120 hours of simulation time. Unit: cm. **AARI-model.**

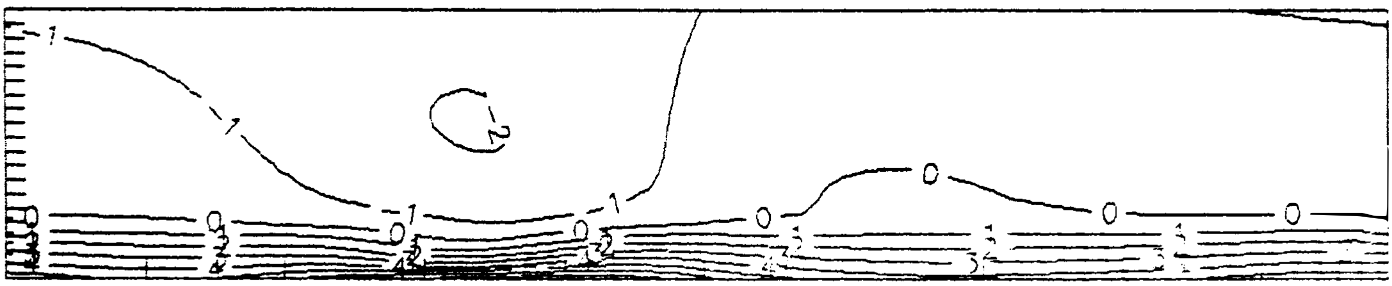

Fig.4.1.1f : Contours of sea surface elevation after 144 hours of simulation time. Unit: cm. **AARI-model.**

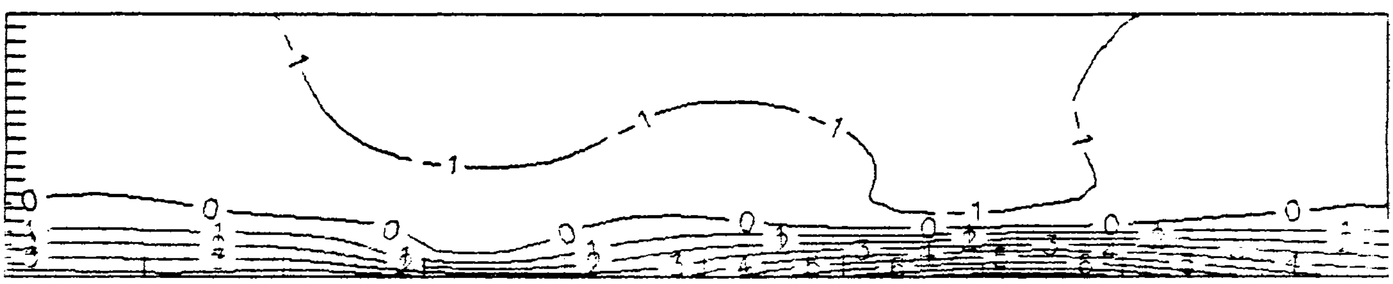

Fig.4.1.1g : Contours of sea surface elevation after 168 hours of simulation time. Unit: cm. **AARI-model.**

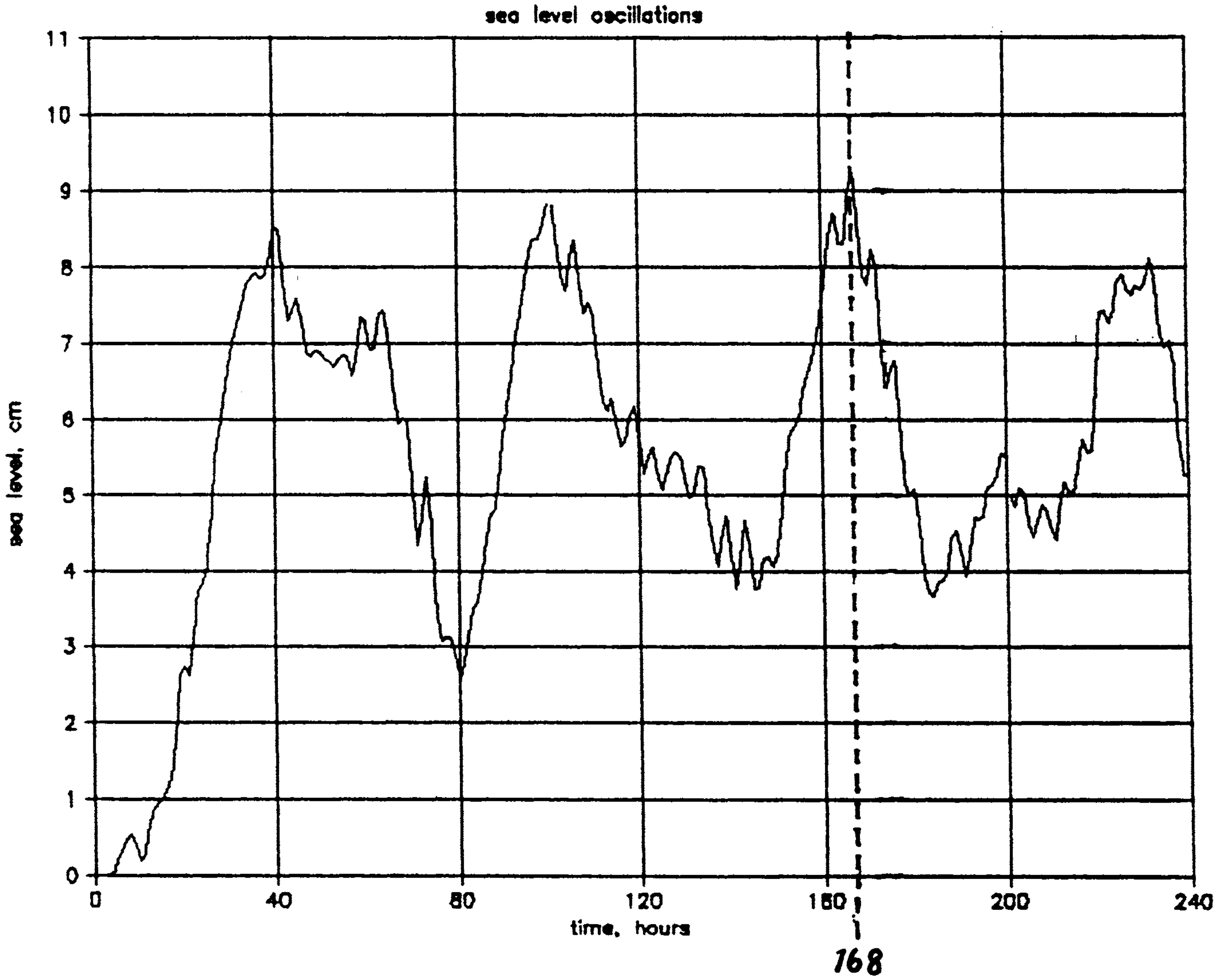

Fig.4.1.1h : Time series of sea surface elevation at the shallow coast (shelf side, y=0) at x=3500km. Unit: cm. **AARI-model.**

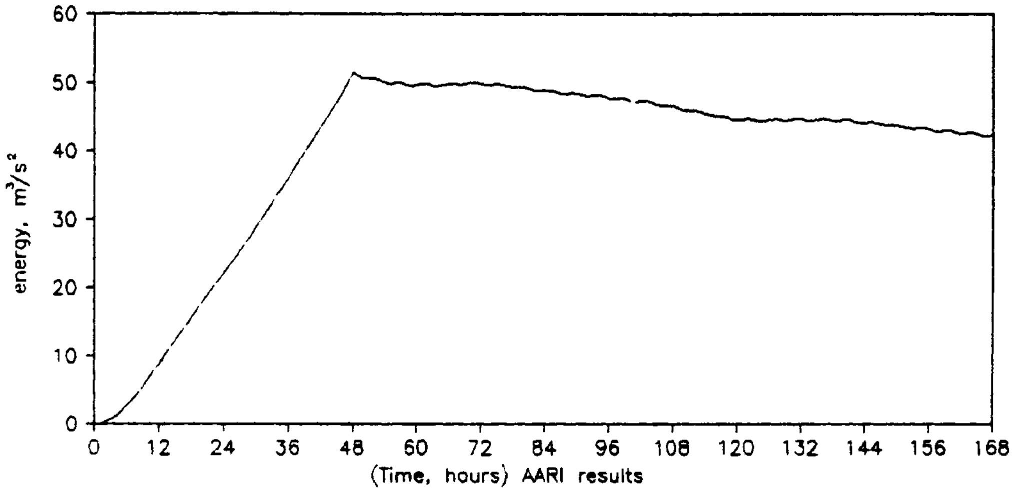

Fig.4.1.1i : Time series of kinetic energy per unit mass summed up over all grid points: E_k. Unit: m^3s^{-2}. **AARI-model.**

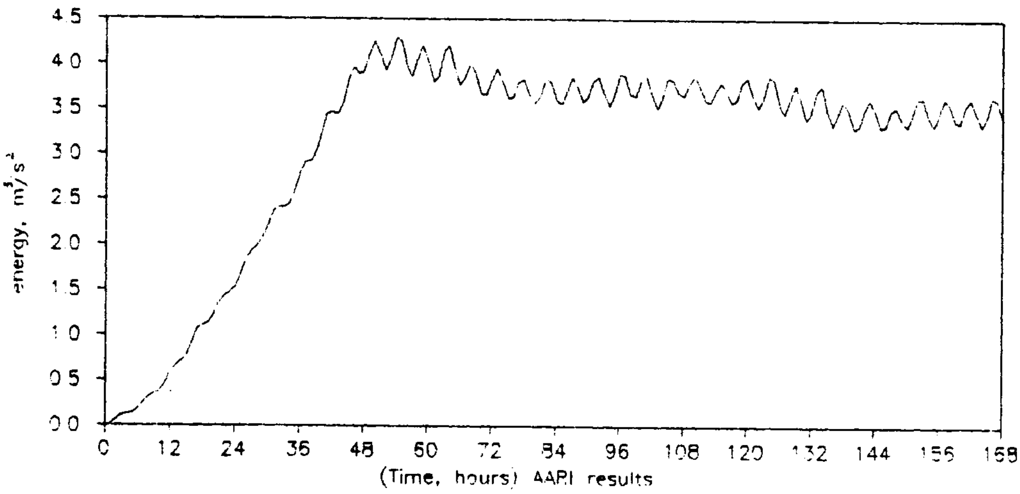

Fig.4.1.1j : Time series of available potential energy per unit mass summed up over all grid points: E_p. Unit: m^3s^{-2}. **AARI-model.**

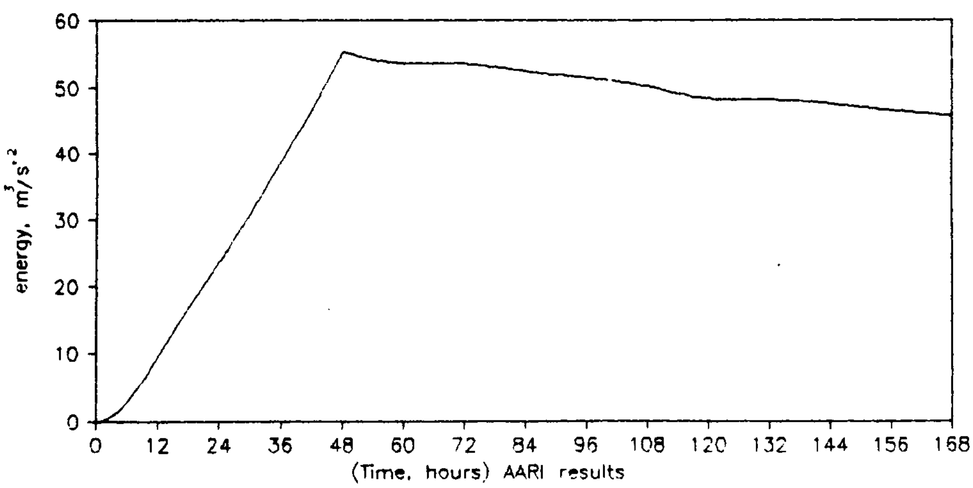

Fig.4.1.1k : Time series of combined energy per unit mass summed up over all grid points: E_k+E_p. Unit: m^3s^{-2}. **AARI-model.**

The ECOM-3D model

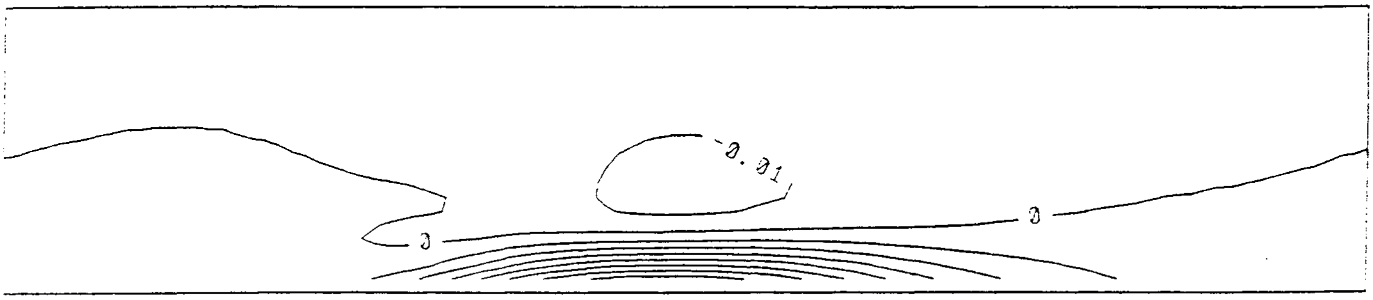

Fig.4.1.2a : Contours of sea surface elevation after 24 hours of simulation time. Unit: meter. **ECOM-3D model.**

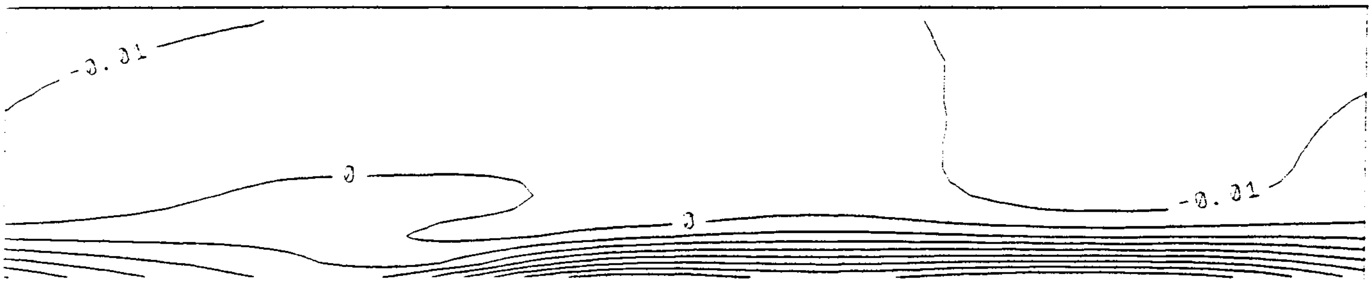

Fig.4.1.2b : Contours of sea surface elevation after 48 hours of simulation time. Unit: meter. **ECOM-3D model.**

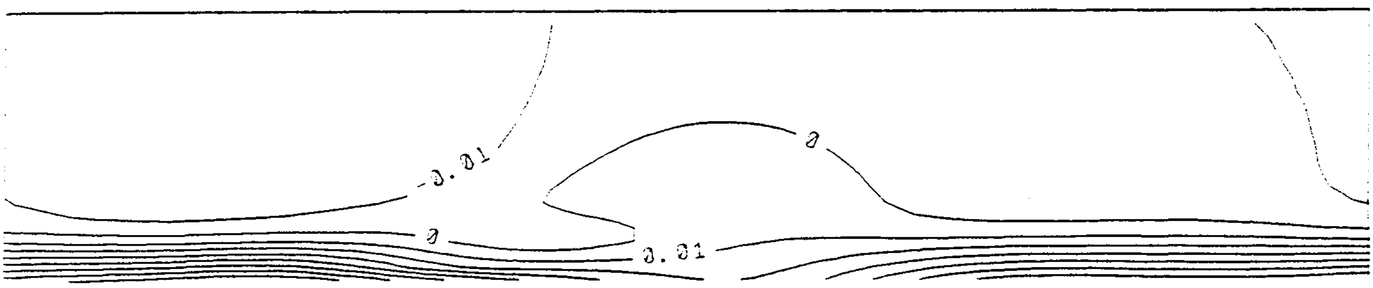

Fig.4.1.2c : Contours of sea surface elevation after 72 hours of simulation time. Unit: meter. **ECOM-3D model.**

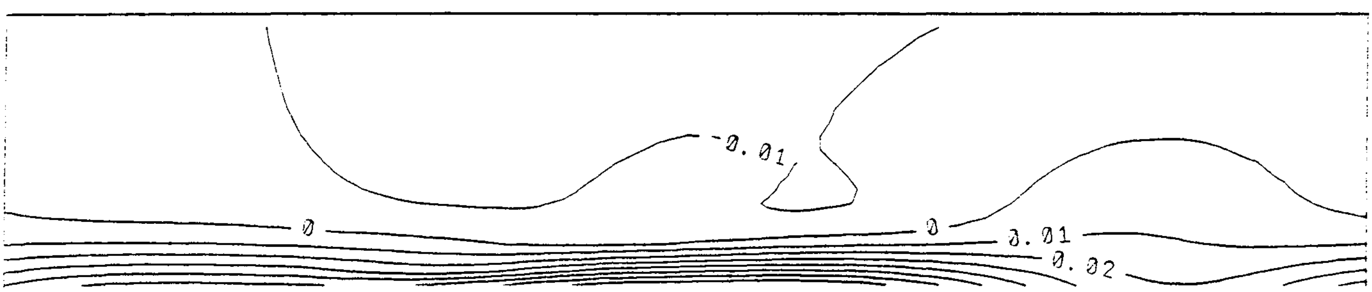

Fig.4.1.2d : Contours of sea surface elevation after 96 hours of simulation time. Unit: meter. **ECOM-3D model.**

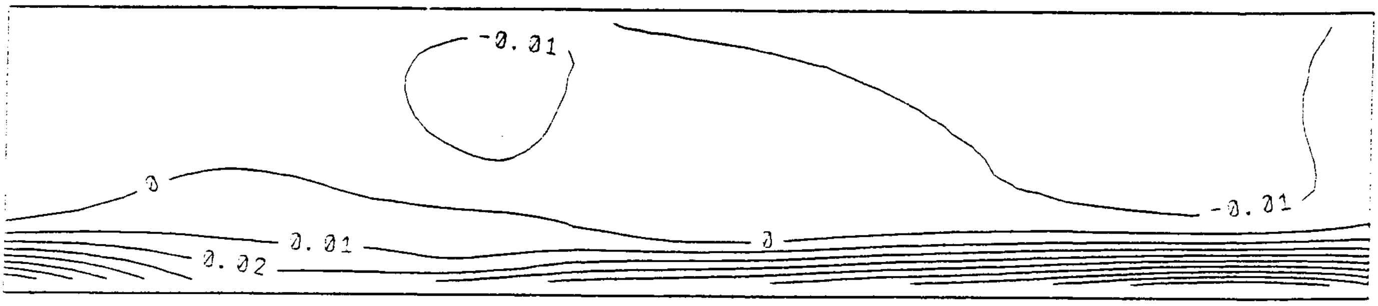

Fig.4.1.2e : Contours of sea surface elevation after 120 hours of simulation time. Unit: meter. **ECOM-3D model.**

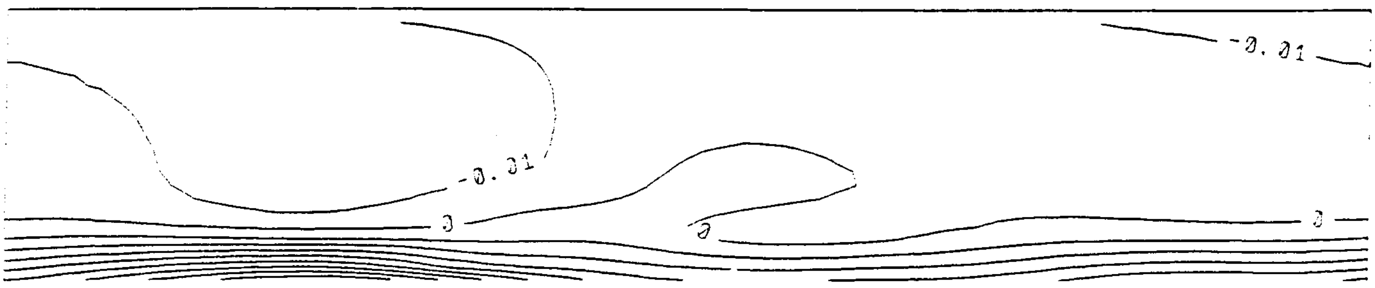

Fig.4.1.2f : Contours of sea surface elevation after 144 hours of simulation time. Unit: meter. **ECOM-3D model.**

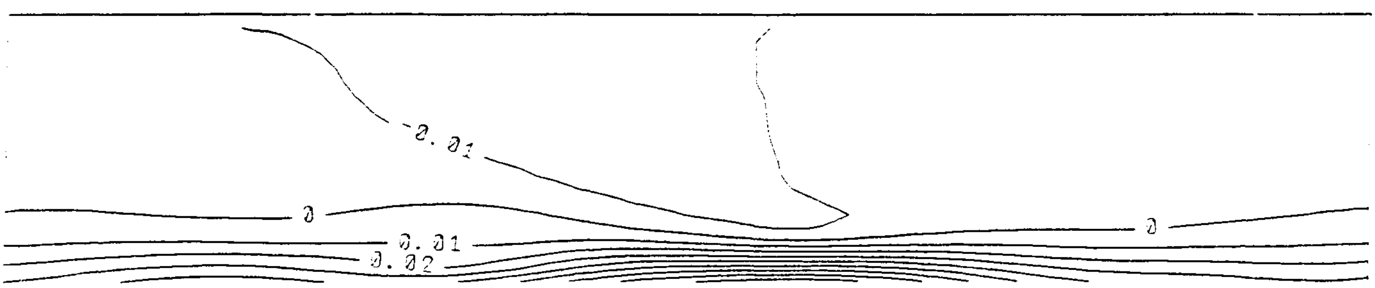

Fig.4.1.2g : Contours of sea surface elevation after 168 hours of simulation time. Unit: meter. **ECOM-3D model.**

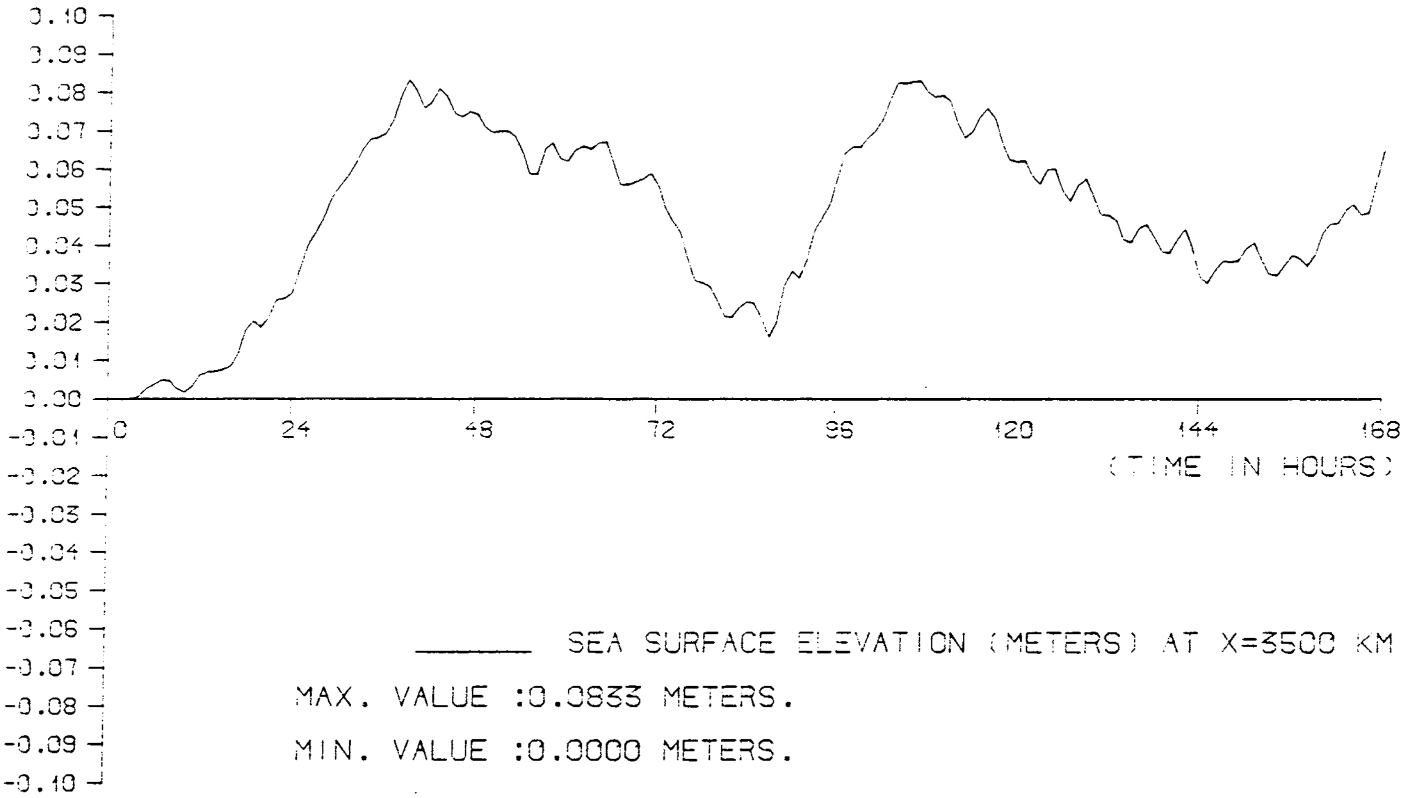

Fig.4.1.2h : Time series of sea surface elevation at the shallow coast (shelf side, y=0) at x=3500km. Unit: meter. **ECOM-3D model.**

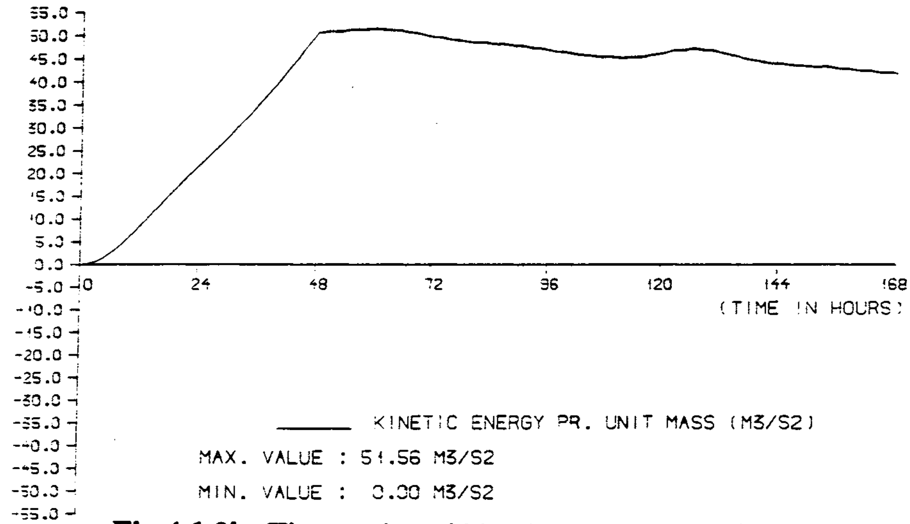

Fig.4.1.2i : Time series of kinetic energy per unit mass summed up over all grid points: E_k. Unit: m^3s^{-2}. **ECOM-3D model.**

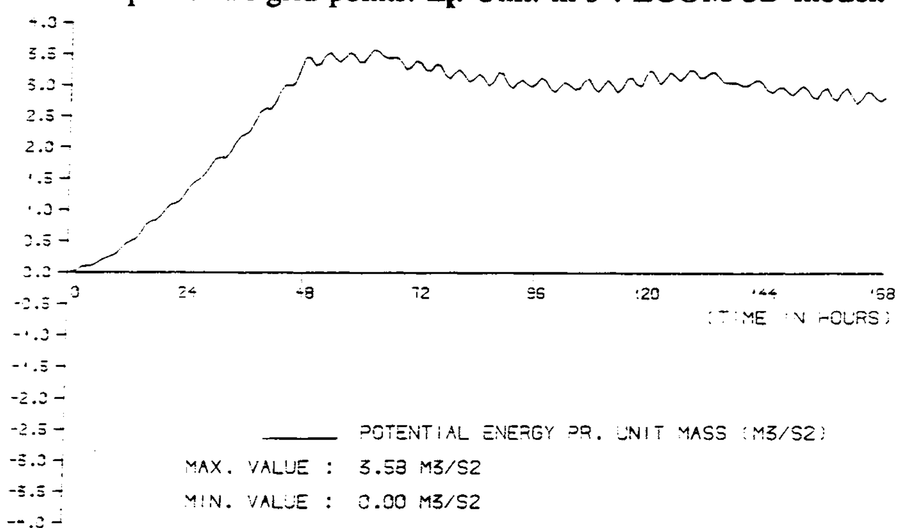

Fig.4.1.2j : Time series of available potential energy per unit mass summed up over all grid points: E_p. Unit: m^3s^{-2}. **ECOM-3D model.**

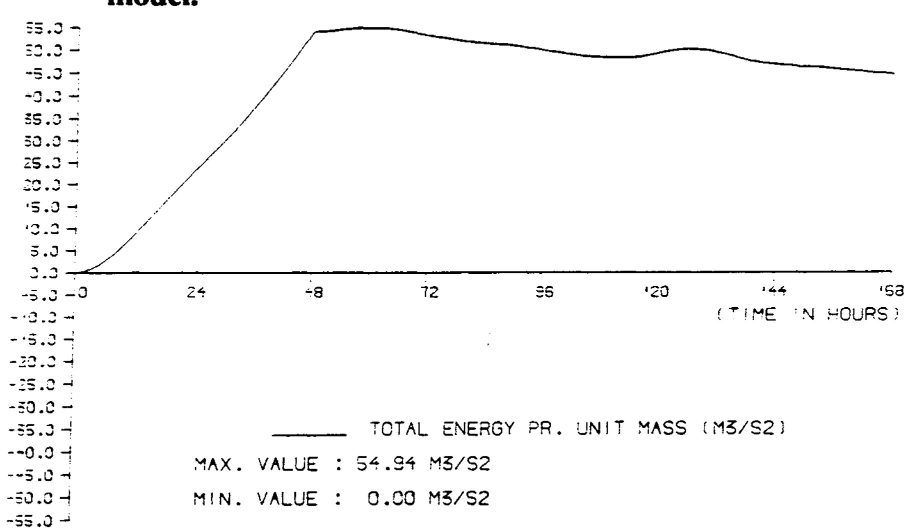

Fig.4.1.2k : Time series of combined energy per unit mass summed up over all grid points: E_k+E_p. Unit: m^3s^{-2}. **ECOM-3D model.**

The ZCOORD model

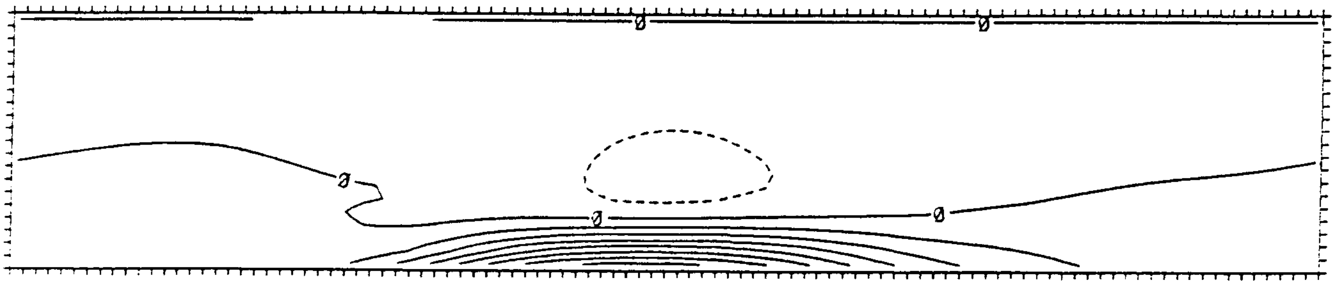

Fig.4.1.3a : Contours of sea surface elevation after 24 hours of simulation time. Unit: cm. **ZCOORD model.**

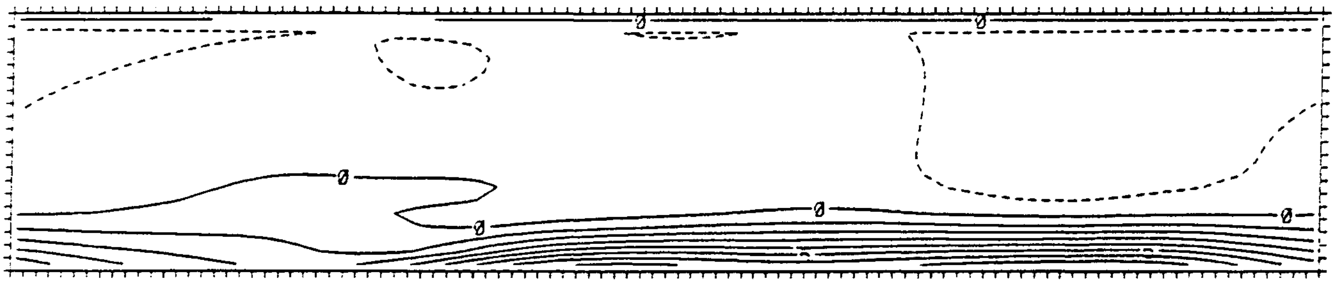

Fig.4.1.3b : Contours of sea surface elevation after 48 hours of simulation time. Unit: cm. **ZCOORD model.**

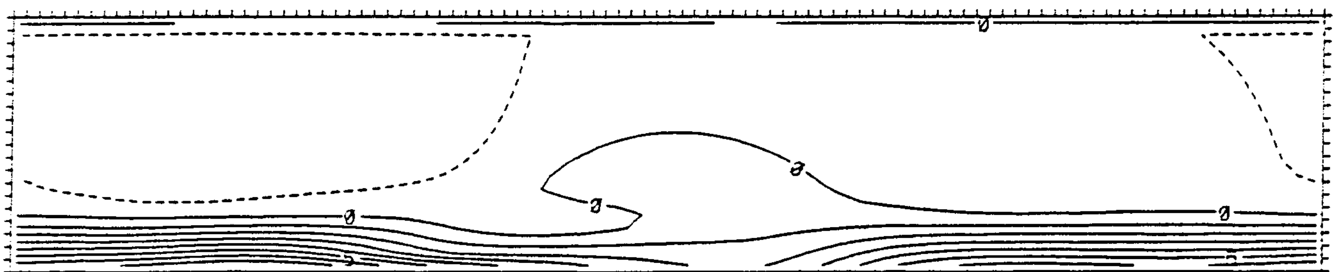

Fig.4.1.3c : Contours of sea surface elevation after 72 hours of simulation time. Unit: cm. **ZCOORD model.**

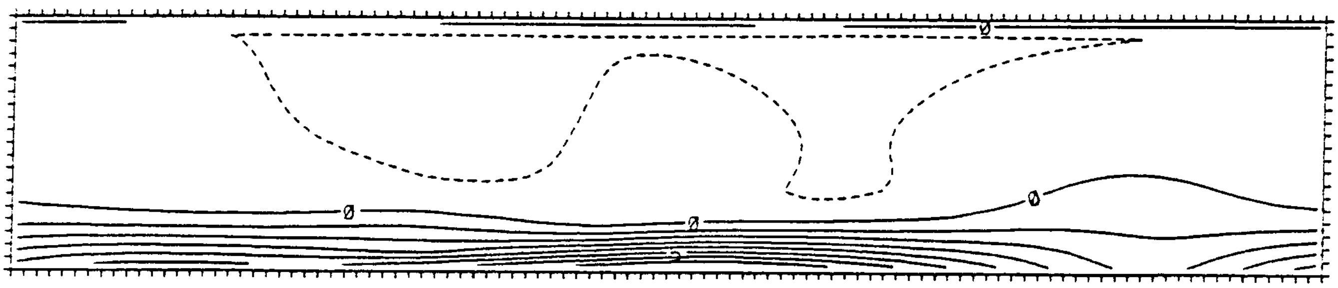

Fig.4.1.3d : Contours of sea surface elevation after 96 hours of simulation time. Unit: cm. **ZCOORD model.**

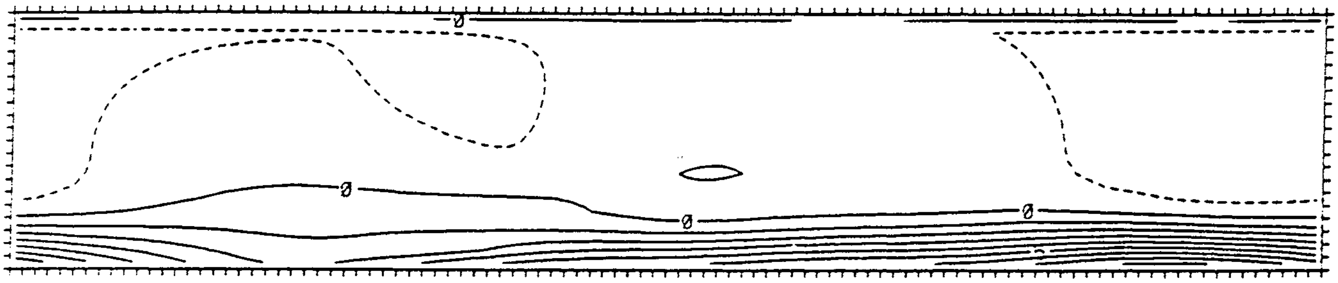

Fig.4.1.3e : Contours of sea surface elevation after 120 hours of simulation time. Unit: cm. **ZCOORD model.**

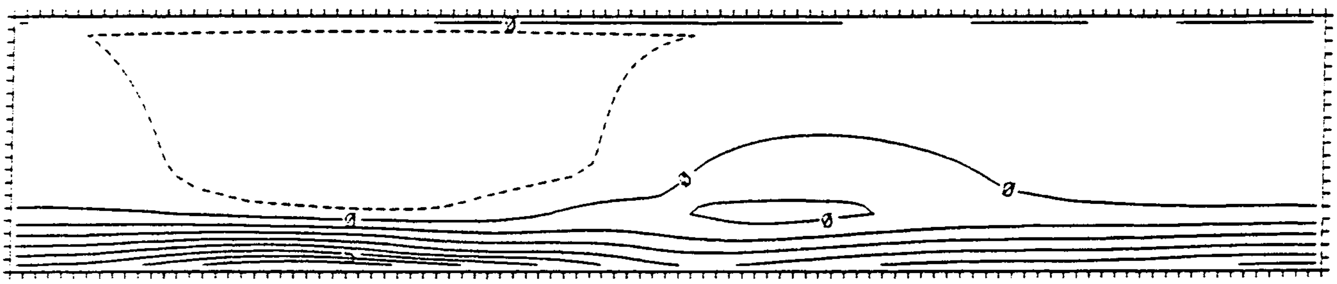

Fig.4.1.3f : Contours of sea surface elevation after 144 hours of simulation time. Unit: cm. **ZCOORD model.**

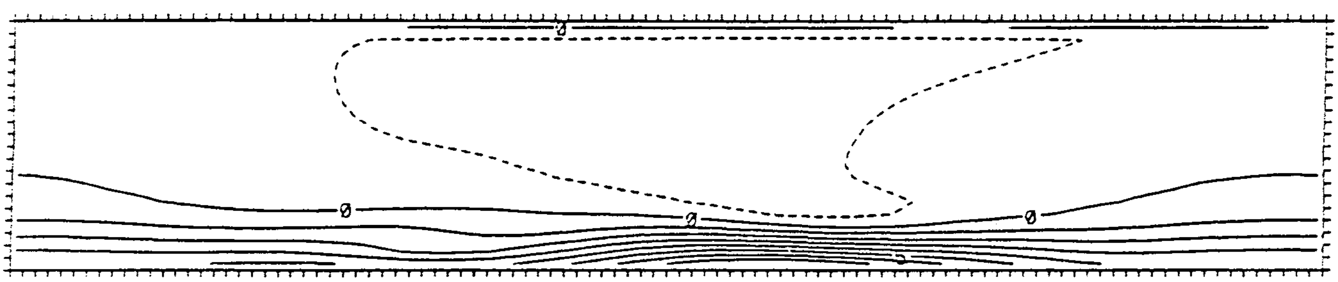

Fig.4.1.3g : Contours of sea surface elevation after 168 hours of simulation time. Unit: cm. **ZCOORD model.**

Fig.4.1.3h : Time series of sea surface elevation at the shallow coast (shelf side, y=0) at x=3500km. Unit: cm. **ZCOORD model.**

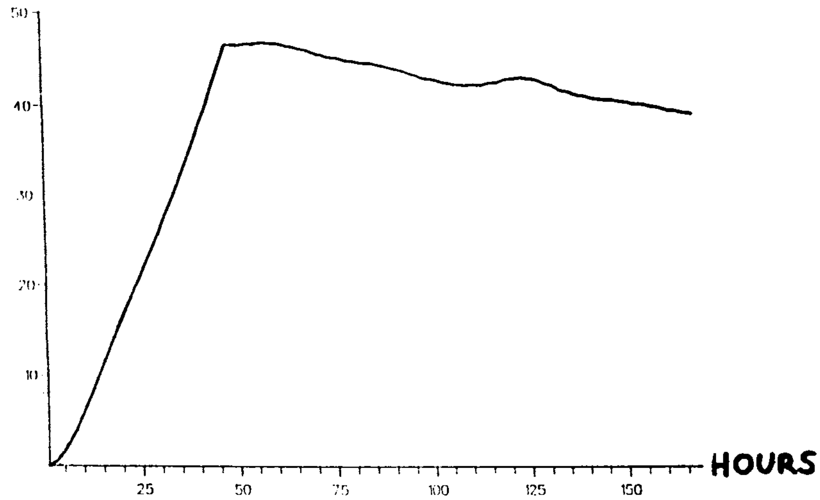

Fig.4.1.3i : Time series of kinetic energy per unit mass summed up over all grid points: E_k. Unit: m^3s^{-2}. **ZCOORD model.**

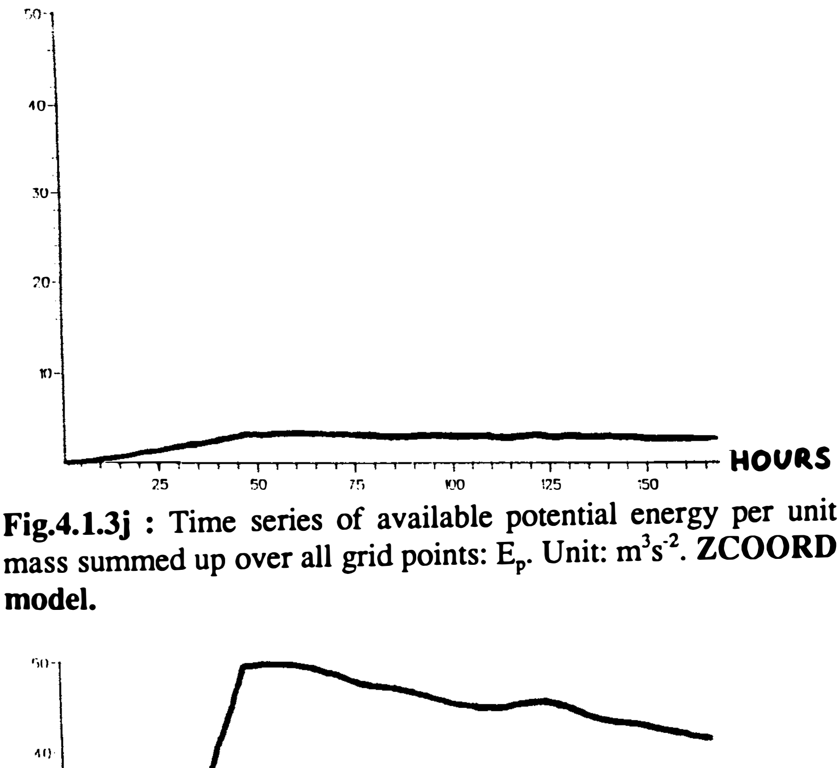

Fig.4.1.3j : Time series of available potential energy per unit mass summed up over all grid points: E_p. Unit: m^3s^{-2}. **ZCOORD model.**

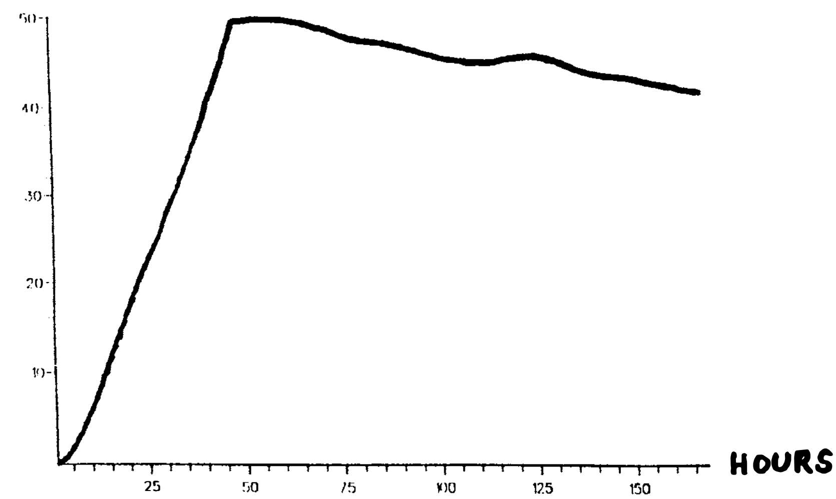

Fig.4.1.3k : Time series of combined energy per unit mass summed up over all grid points: E_k+E_p. Unit: m^3s^{-2}. **ZCOORD model.**

Baroclinic test case (SNOPNEX2)

The AARI-model

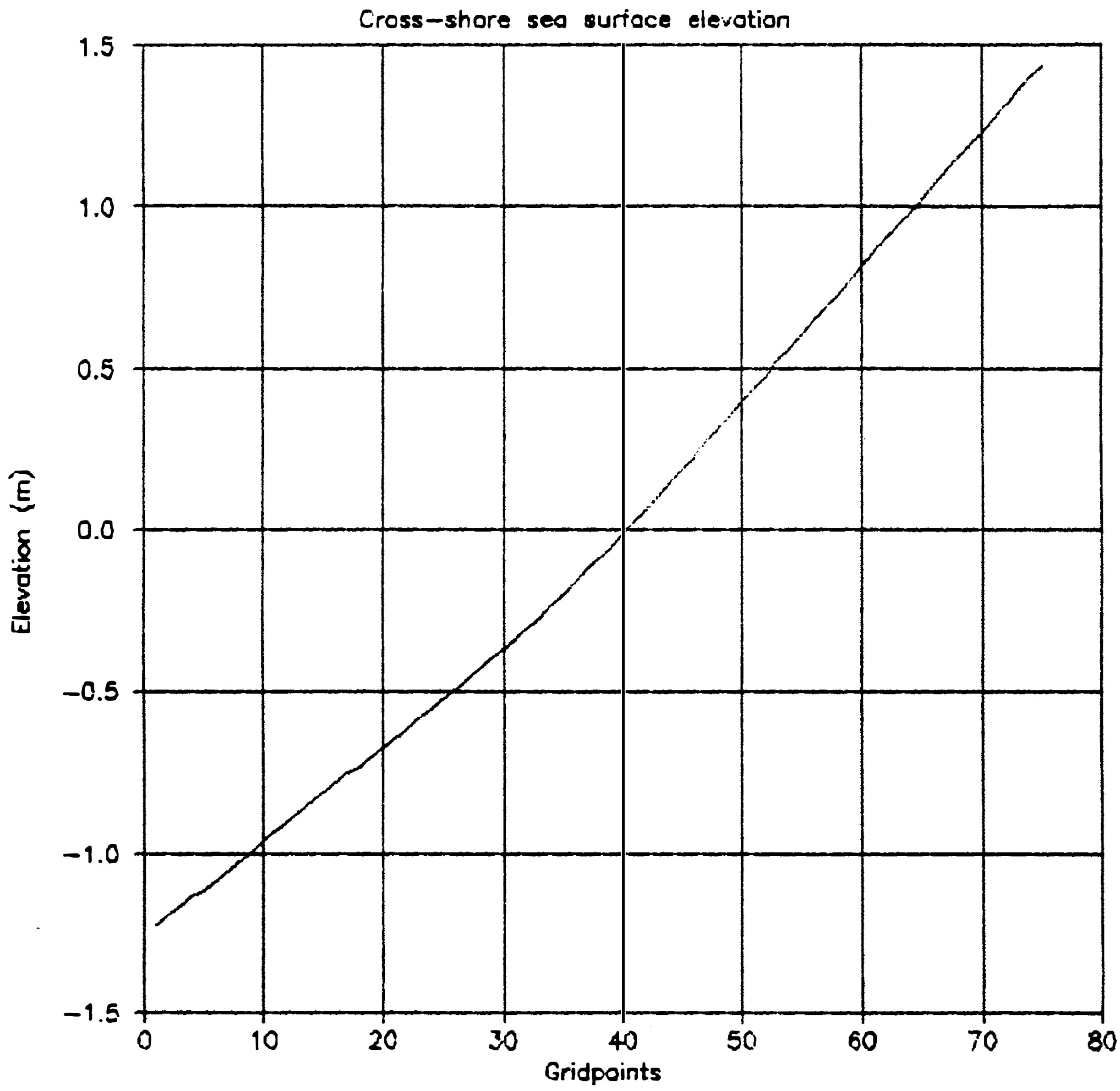

Fig.4.2.2a : Cross shore-sea surface elevation, i.e. slope along y-axis, after 30 days (720 hours). Unit: meter. **AARI-model.**

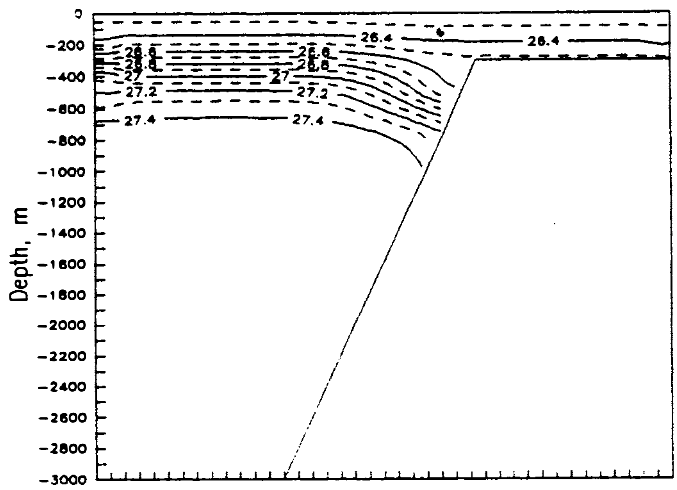

Fig.4.2.2b : Cross section in the y,z-plane after 30 days showing contour lines of specific density, i.e. actual density - 1000kgm^{-3}. **AARI-model.**

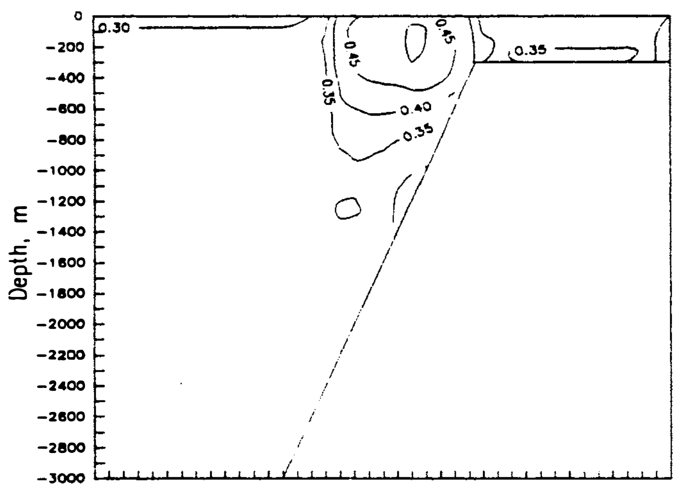

Fig.4.2.2c : Cross section in the y,z-plane after 30 days showing contour lines of along-shore current component (u). Unit: ms^{-1}. **AARI-model.**

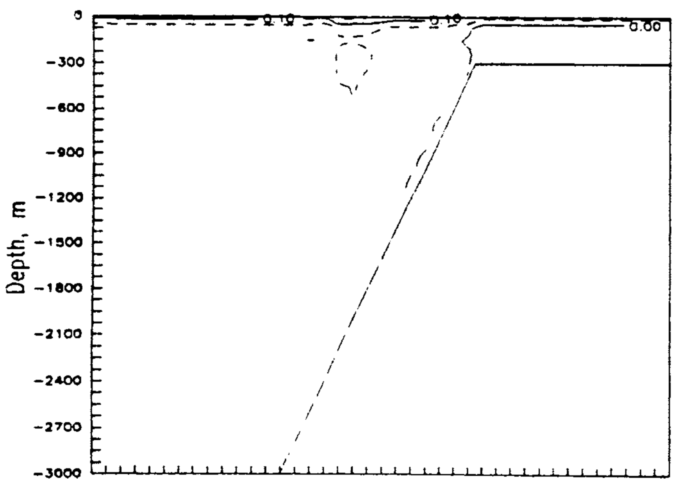

Fig.4.2.2d : Cross section in the y,z-plane after 30 days showing contour lines of cross-shore current component (v). Unit: ms^{-1}. **AARI-model.**

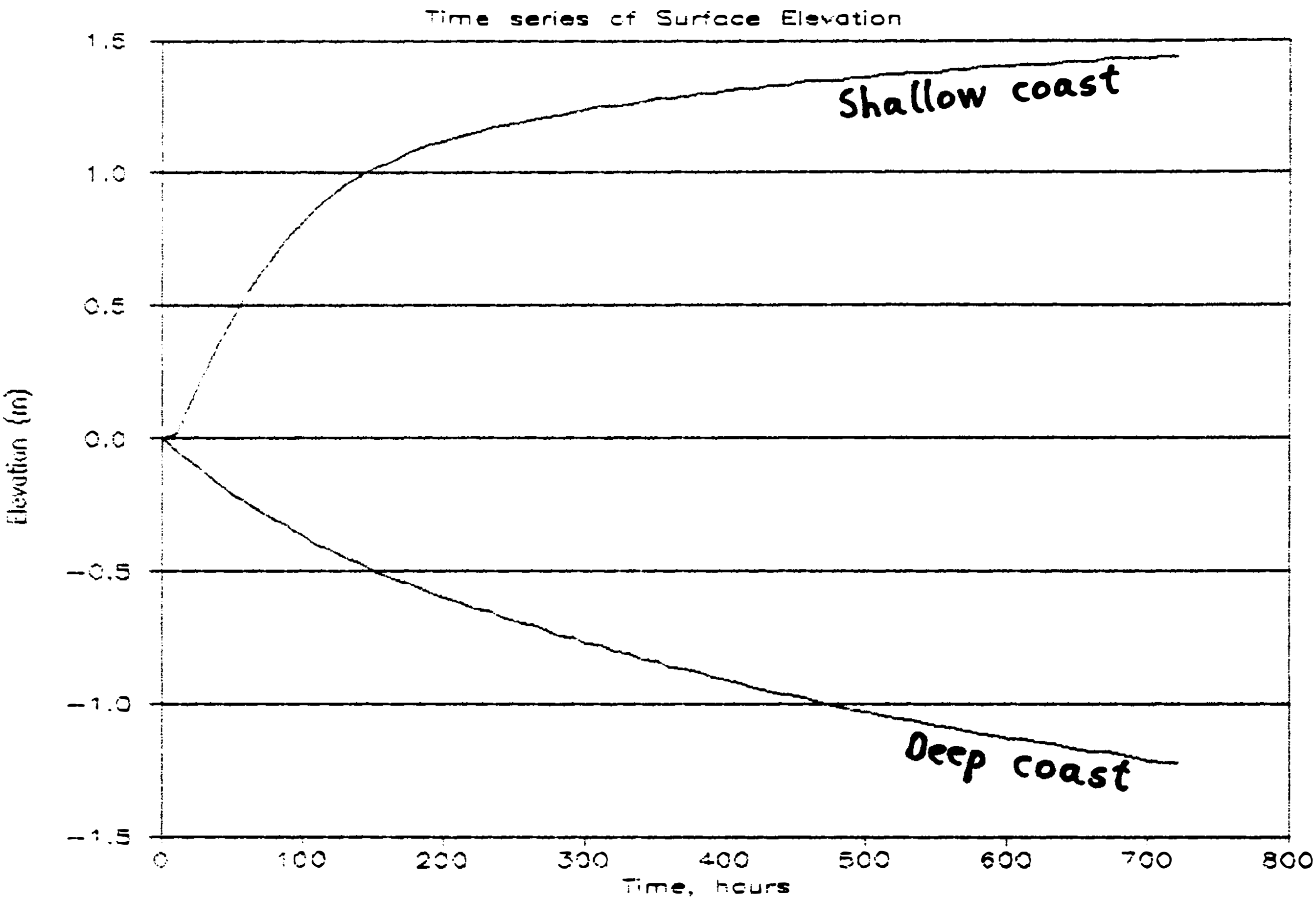

Fig.4.2.2e : Time series of surface elevation at the grid point closest to the coast on both sides of the channel. Unit: meter. **AARI-model.**

The ECOM-3D model

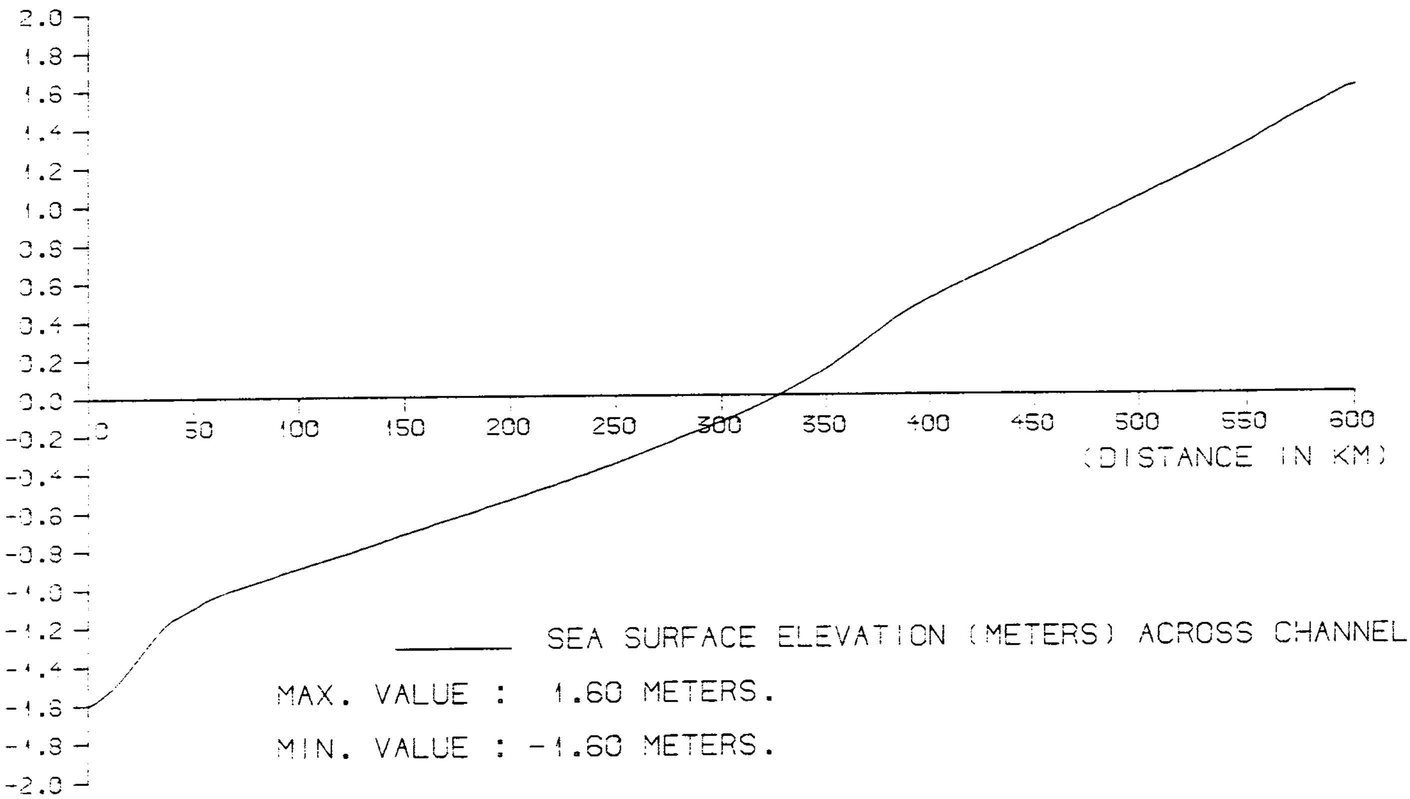

Fig.4.2.3a : Cross-shore sea surface elevation, i.e. slope along y-axis, after 30 days (720 hours). Unit: meter. **ECOM-3D model.**

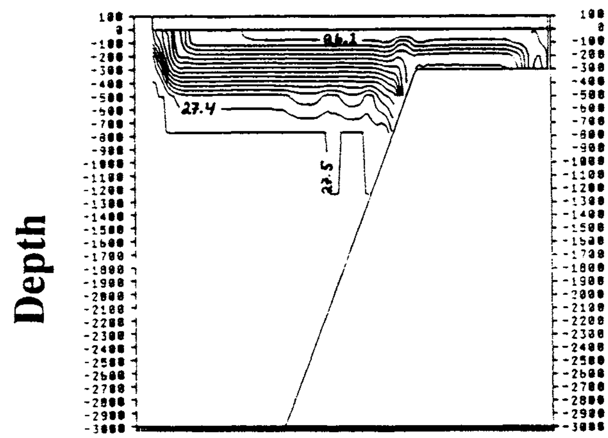

Fig.4.2.3b : Cross section in the y,z-plane after 30 days showing contour lines of specific density, i.e. actual density - $1000 kgm^{-3}$. **ECOM-3D model.**

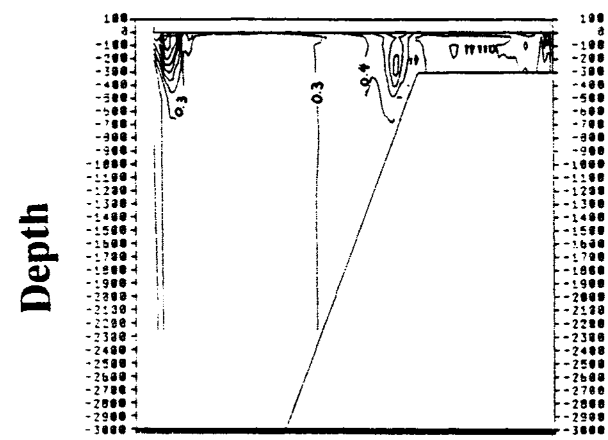

Fig.4.2.3c : Cross section in the y,z-plane after 30 days showing contour lines of along-shore current component (u). Unit: ms^{-1}. **ECOM-3D model.**

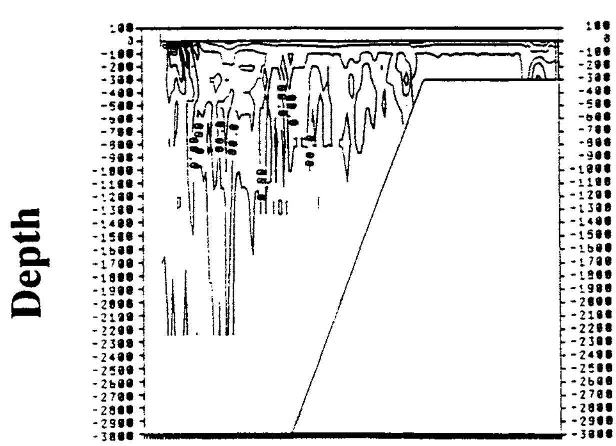

Fig.4.2.3d : Cross section in the y,z-plane after 30 days showing contour lines of cross-shore current component (v). Unit: ms^{-1}. **ECOM-3D model.**

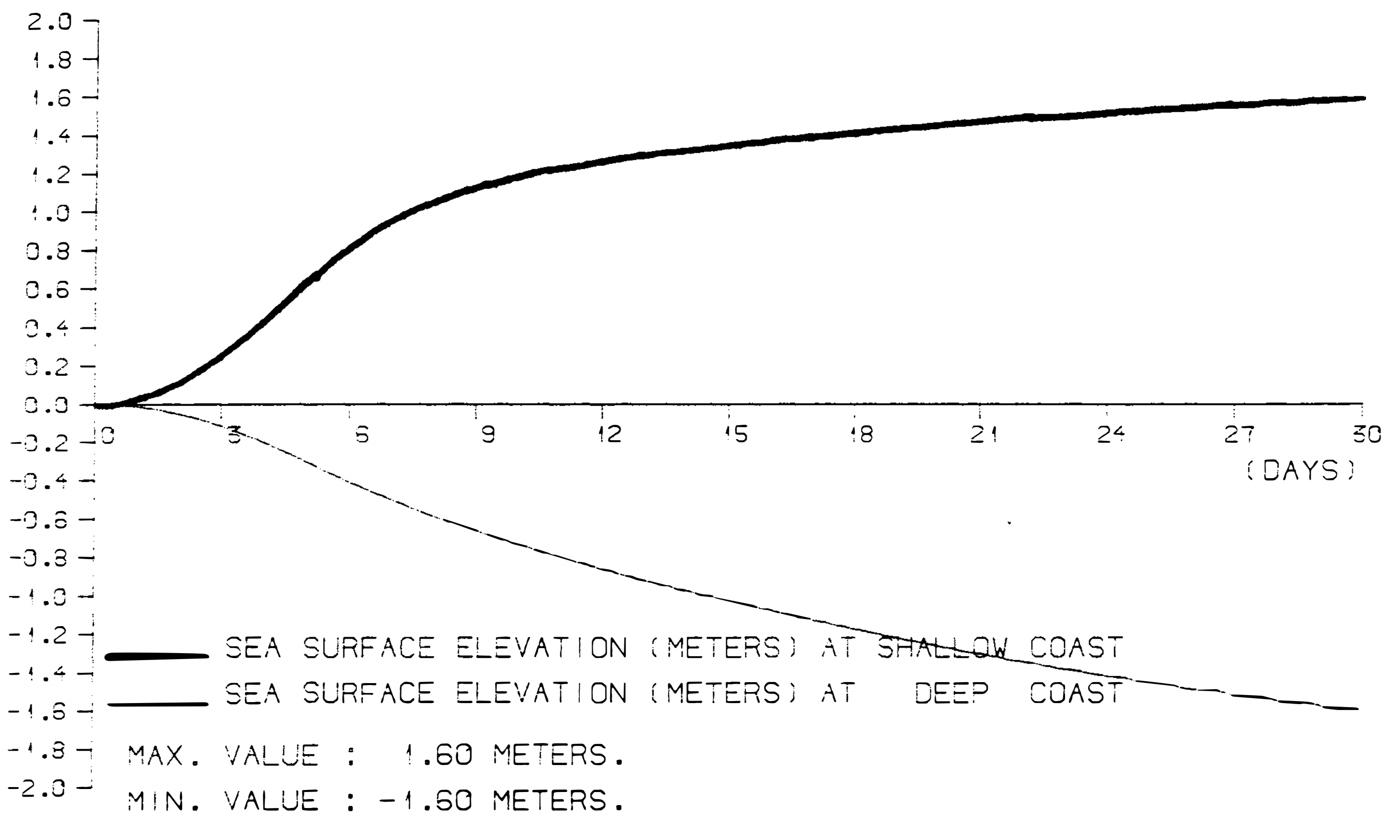

Fig.4.2.3e : Time series of surface elevation at the grid point closest to the coast on both sides of the channel. Unit: meter. **ECOM-3D model.**

The ZCOORD model

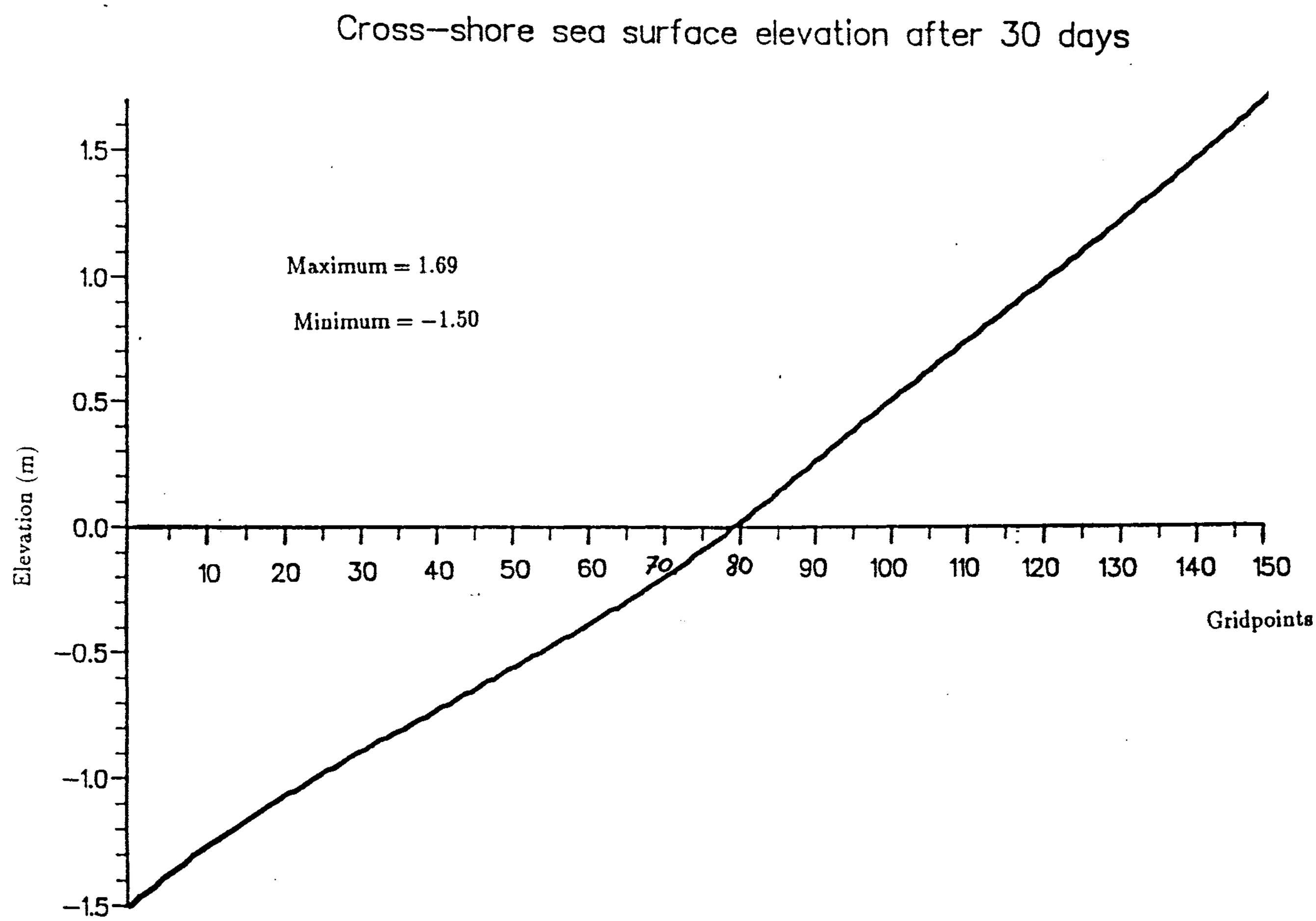

Fig.4.2.4a : Cross-shore sea surface elevation, i.e. slope along y-axis, after 30 days (720 hours). Unit: meter. **ZCOORD model.**

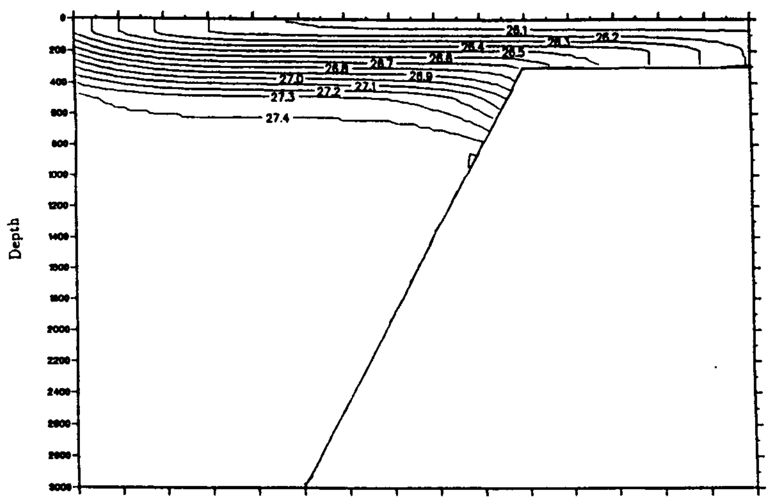

Fig.4.2.4b : Cross section in the y,z-plane after 30 days showing contour lines of specific density, i.e. actual density - 1000kgm^{-3}. **ZCOORD model.**

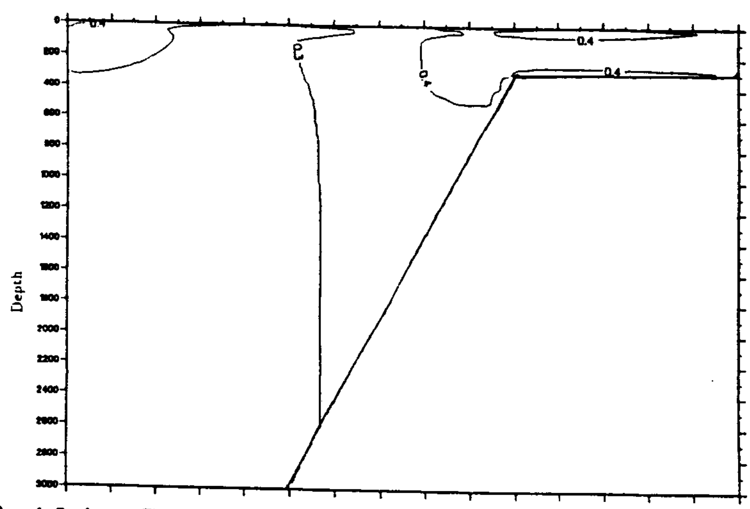

Fig.4.2.4c : Cross section in the y,z-plane after 30 days showing contour lines of along-shore current component (u). Unit: ms^{-1}. **ZCOORD model.**

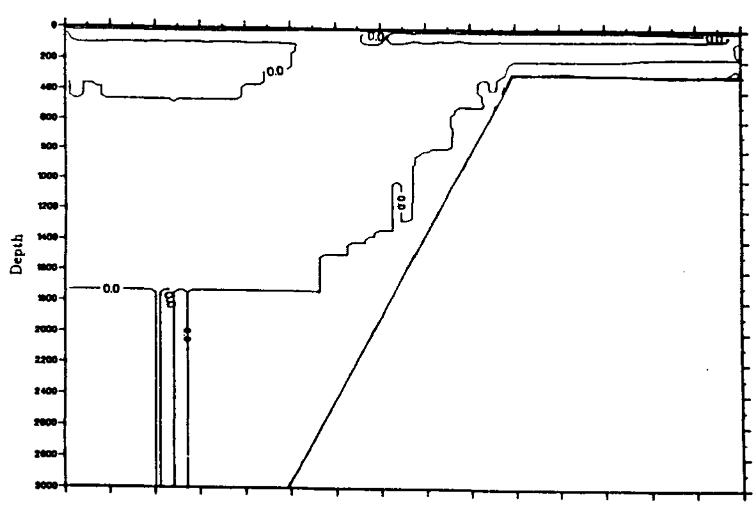

Fig.4.2.4d : Cross section in the y,z-plane after 30 days showing contour lines of cross-shore current component (v). Unit: ms^{-1}. **ZCOORD model.**

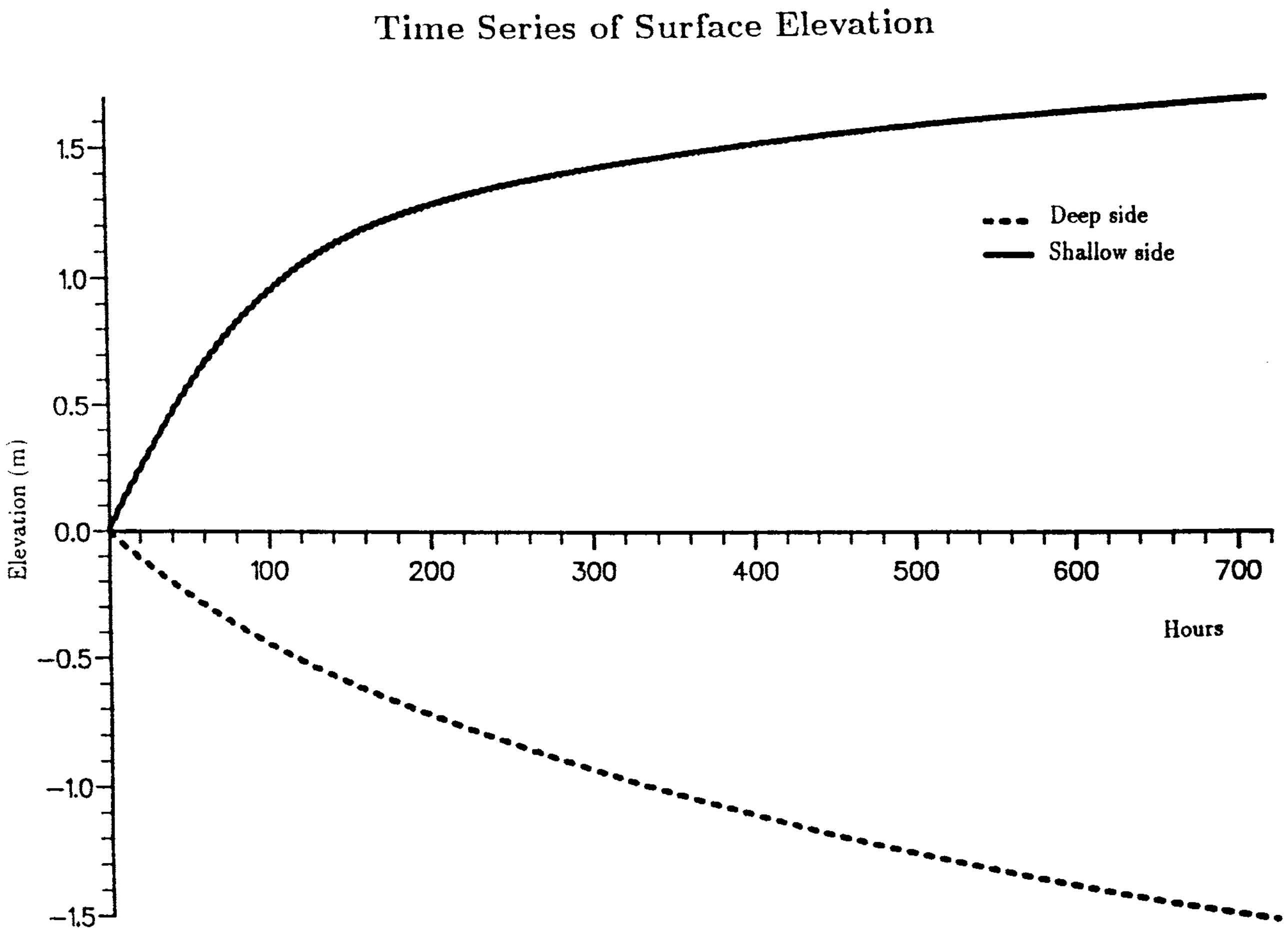

Fig.4.2.4e : Time series of surface elevation at the grid point closest to the coast on both sides of the channel. Unit: meter. **ZCOORD model.**

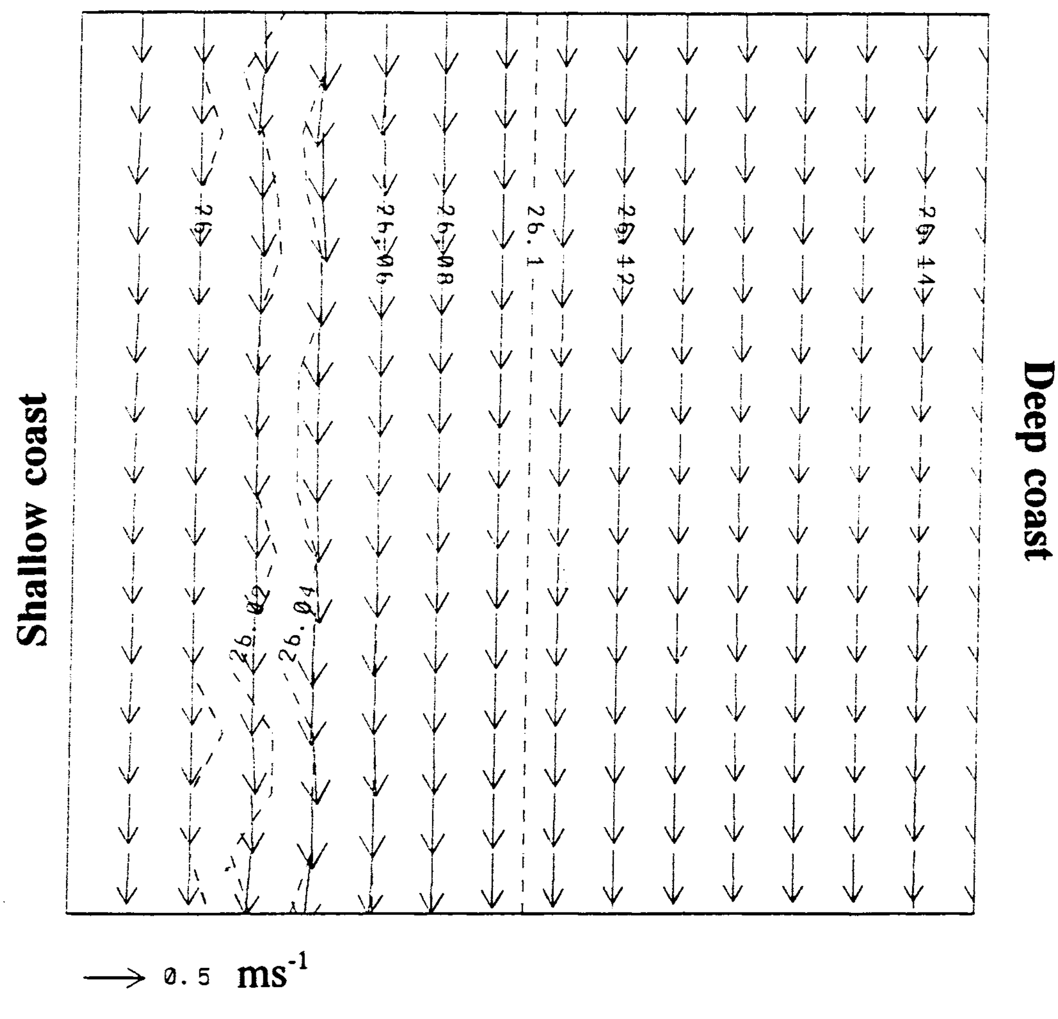

Fig.4.2.5 : Arrow-plot of current in ms^{-1} and contour plot of specific density (dashed lines) at 100m depth after 18 days (432 hours). The plot shows the situation over the portion of the shelf closest to the shallow coast. **ECOM-3D model.**