CHAPTER 64

A Barotropic 3D-Model for the Study of Currents around the Atlantic Coast of the Iberian Peninsula.

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Abstract

We intend to present a brief description of the fundamentals of a barotropic version of the 3D numerical model of the Institut für Meereskunde-Hamburg altogether with some results concerning the application of the model to the simulation of tidal currents in the spanish atlantic waters.

1 Introduction

In 1984 the Climate Marine Program (PCM) of the spanish Directorate of Ports and Coasts decided to get involved into the modelling of sea currents induced by tides and winds at the waters surrounding the Iberian Peninsula and the Canary Islands.

The main motivation was the scarcity of data of this kind all along the spanish coastline, as well as the need for numerical tools as a help in the study of local coastal problems.

We also consider its use as a support for navigation and fishery activities and data banking assimilation. P.C.M. established this year an agreement of technical assistance with two german institutions: the G.K.S.S.-Forschungzentrum at Geesthacht and the Institut für Meereskunde in Hamburg (IFM).

The purpose of this agreement was the implementation of a barotropic version of the 3D model developed by the IFM in the area of interest for PCM.

The strategy comtemplated two stages.

The first one accomplished the implementation of a large scale barotropic model for tidal and wind induced dynamics.

A winter episode has been simulated. And charts of tidal and wind induced currents have been produced. This model will also provide consistent boundary conditions for smaller scale regional models.

PCM in a second stage will apply the model to smaller scale areas incorporating new features of the original version such as the baroclinic pressure gradient.

2 Model Description

The barotropic three dimensional numerical model is

based on a two-time level semi-implicit scheme.

Momentum equations in S-E and W-E directions as well as the continuity equation have been vertically integrated for each of the horizontal layers in which the water column is divided.

For the layer of thickness "h" the equations are:

- Momentum balance

$$\frac{\partial U}{\partial t} - fV + gh\frac{\partial \tau}{\partial x} = X + \Delta\left[A_v \frac{\partial}{\partial z}\left(\frac{U}{h}\right)\right]$$

$$\frac{\partial V}{\partial t} + fU + gh\frac{\partial \tau}{\partial y} = Y + \Delta\left[A_v \frac{\partial}{\partial z}\left(\frac{V}{h}\right)\right]$$

- Mass balance

$$0 = \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \Delta W \Leftrightarrow \frac{\partial \tau}{\partial t} = -\left(\frac{\partial \overline{U}}{\partial x} + \frac{\partial \overline{V}}{\partial y}\right)$$

U, V - Horizontal components of transport for the layer

$\overline{U}, \overline{V}$ - Horizontal components of transport for the whole water column. (Vertically Integrated)

ΔW - Vertical velocity difference between top and bottom of the layer

τ - Free surface elevation.

f - Coriolis parameter.

g - Acceleration of gravity

A_v - Vertical eddy viscosity coefficient.

The most important terms involved in the equations have been explicitly pointed out:

- Local Inertia terms
- Coriolis force
- External horizontal pressure gradient
- Vertical diffusion terms expressed through the eddy viscosity analogy.

Additional terms like those of horizontal diffussion and advection are indicated by the letters X, Y.

The main features of the numerics can be summarized as follows (Backhaus 1983, 1985):

a) In order to avoid instabilities arising from a forward-in-time approximation of the Coriolis terms a second order approximation has been used for those terms. This introduces a coupling of spatial derivatives of the free surface elevation in both momentum equations through a rotation operator.

By doing this aditional boundary conditions need to be defined when computing cross derivatives of the free surface elevation in the vecinity of solid boundaries.

b) Advective and horizontal diffussion terms are solved explicitly. Advective terms are updated in a lagrangian way by means of a vector - upstream scheme.

c) A semiimplicit treatment of the free surface elevation has been used in all terms involving this variable.

This allows the scheme to get free of the stringent limitation for the time-step given by the Courant-Friedrichs-Lewy stability criterium, as would be the case if the external gravity waves were approximated in an explicit way $\left(\Delta t < \Delta L/\sqrt{2gh}\right)$.

d) The model considers the horizontal eddy viscosity coefficient as time and space dependent.

An implicit additional system have been introduced for the vertical diffussion terms.

This have been done because once that grid size and layer thickness have been fixed, the stability criterium for an explicit approximation of those terms would represent an artificial upper limit for the vertical eddy viscosity coefficient $\left(A_v < \Delta z^2/(2\Delta t)\right)$.

As a consecuence, unrealistic description of the flux could take place when a high rate of vertical momentum transfer is required, as would be the case when severe wind forcing is beeing simulated.

e) A semi-implicit formulation for the quadratic bottom stress is introduced for the sake of numerical stability.

f) Spatial derivatives are centered in time (Crank-Nicholson approach) which leads to a scheme essentially neutral with regard to damping of amplitudes.

The sequence of advancing one time-step proceeds in this way:

First, the horizontal elliptic system for the free surface is obtained by replacing the momentum divergence terms in the vertically integrated equation of continuity (vertical diffussion terms cancel out).

The system is solved by means of an iterative procedure (succesive over-relaxation algorithm).

Once that the free surface elevation at the new time level is known, an interim solution for transports can be computed from the pressure gradient terms and all others terms explicity treated.

Finally, the vertical implicit system involving layer

transports for each water column is established. The equation system is solved by means of a gaussiam algorithm.

Boundary conditions are introduced into the model via the coefficients of the free surface elevation system.

Open boundary tidal constants for several harmonics are obtained from the global oceanic model of Schwiderski (1º size).

3 Details of the Model

The horizontal grid used for the model is of the type Arakawa-C. It has the pressure points and transport points half a grid size apart. (Fig. 1)

The horizontal grid size is 12' in latitude and 20' in longitude which means an approximate medium length for the area of about 25 Km.

The real topography for the area has been considered, after an smoothing process up to a depth of 5 Km. (Fig. 2)

The water column has been divided into six vertical layers.

The layer boundaries are: 30, 100, 200, 600, 1500, 5000 meters. The bottom layer thickness accommodates to the sea bottom.

The time step is 20 minutes which gives a CFL factor of about 13.

The performance of the model on an IBM 3090-150 computer is 1 day simulation equivalent to 3.5 CPU minutes.

4 Results

Verifications runs have been carried out with single tidal harmonic components: M2 and S2.

After obtaining stationarity the results of amplitude and phase were compared with the observed ones for points placed along the coast and in the deep sea zone (tidal gauges).

The model behaves very well, producing results very close to the observed ones as it is shown in the graphics included. (Fig. 3)

In order to attain the stationarity of the fortnight spring-neap cycle the model was run for several months with those two tidal harmonics.

A medium factor of about two has been obtained when comparing the tidal ranges of spring to neap tides. (Fig. 4)

At first glance, from the huge ranges obtained high velocities could be expected in the area. This is only true in

the near shore of Bay of Biscay, for as the main part of the domain is deep sea the velocities in the surface layer for the spring hypothesis are less than 0.2 Knots. (Fig. 5)

The graphic output for this spring-neap tidal analysis has been made by drawing the tidal ellipses for several points in the area. (Fig. 3)

The tidal ellipses represent the curve described by the extremity of the velocity vector of each point along a tidal cycle refered to an arbitrary zero time (Highwater at Cadiz)

As, in the Bay of Biscay the velocities are much greater than in the rest of the domain the tidal ellipses in this zone have been removed for the sake of clarity. (Fig. 7, 8)

An interesting feature of the tidal ellipses pattern is the change of sense of rotation from clockwise in the shelf of the Bay of Biscay to anticlockwise in the rest of the area. (Fig. 6)

Other intering points to be mentioned are the two distorted north-south oriented tidal ellipses along the iberian coastline which coincide with two topographic bumps in this zone; and the distorted shapes of tidal ellipses polarized in N-E direction in the area of Madeira and Canary Islands.

This last point requires further explanation, but it seems coincident with the observed pattern in the Canary Islands. (Fig. 6)

There is no observed change of sense of rotation for the ellipses along the water column. The huge thickness (3.5Km) of the bottom layer can overshadow this feature. The most noticeable effect of friction is on the Bay of Biscay shelf where it causes the transition to more open ellipses. (Fig. 6, 7, 8)

5 Conclusions

. Fine scale barotropic 3-dim. model set up and verified

. Sea - level variation within 5 - 10% of observed values.

. Not expected large variation of tidal ellipses (shape sense of rotation and alignment with topography)

- Madeira/Canary Is.: currents almost linearly polarized.
- Bay of Biscay: change from anti-clockwise to clockwise rotation
- Off Iberian peninsula: topographic bumps induced rectilinear distortion of ellipses
- Bay of Biscay shelf: friction caused transition to more open ellipses

. Model output:

- Simulation of a winter episode involving the five most significant partial tides (M2, S2, N2, O1, K1) and actual wind stress. The latter obtained from six-hourly surface pressure field from the ECMWF.
- Production of Tidal Atlas for water levels and currents
- Boundary values for finer scale regional models (e.g. fisheries, pollution, ...)

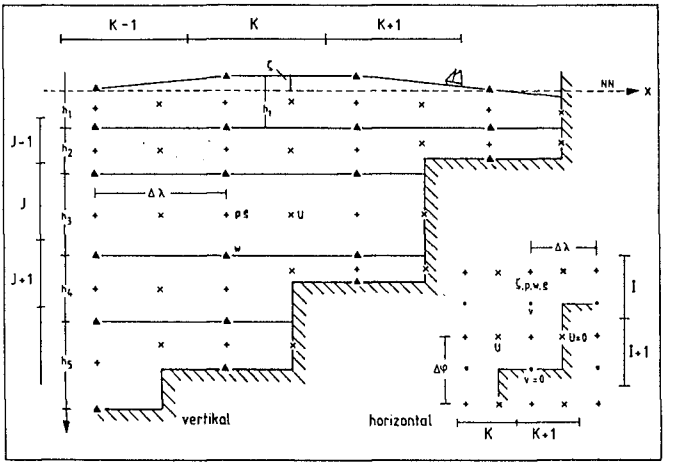
. Develop regional barotropic models

. Develop large scale/regional baroclinic models

6 References

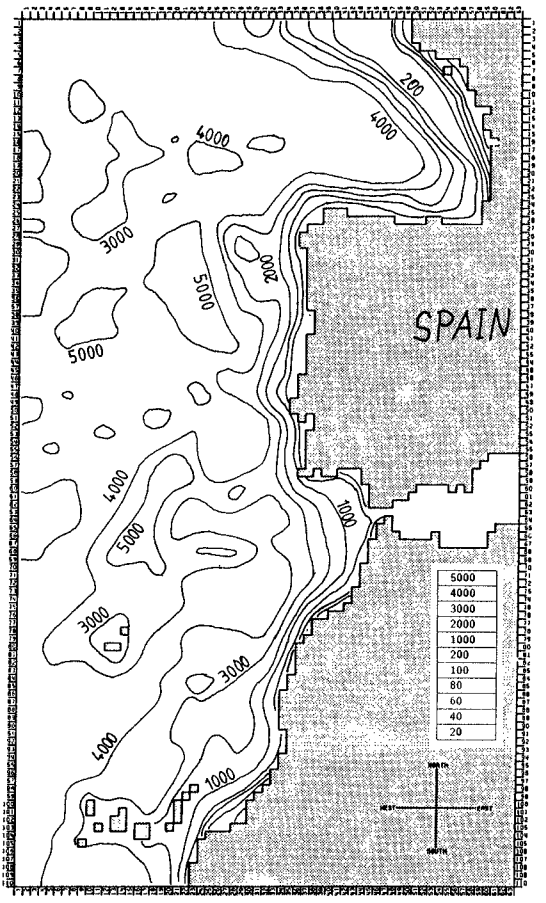
A three dimensional model for the simulation of shelf sea dynamics. Prof. Jan O. Backhaus, Institut für Meereskunde, University of Hamburg.

Fig.1.-

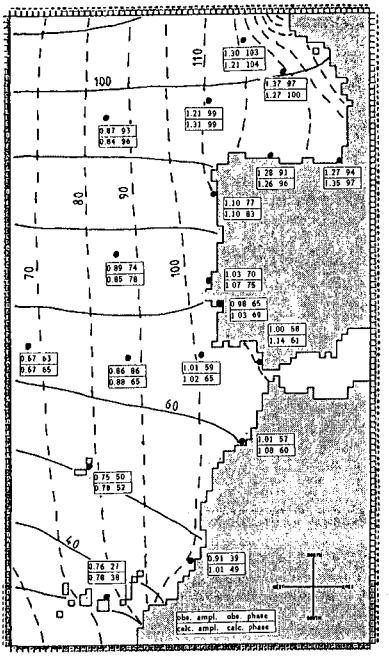


Horizontal and vertical computational grid. U, V - momentum components (east, north), w - velocity component (positive up), p - (internal) pressure, ρ - density, ζ - surface elevation, h_i - layer thickness, NN - mean sea level

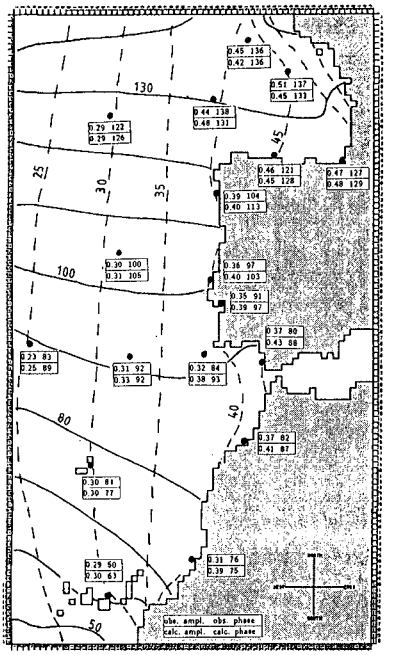
Fig.2.-



Topography of model area (meters)



M_2 tide: amplitude (cm) and tidal phase (degrees), referred to moon's transit at Greenwich. Boxes: comparison of observed and computed values (see explanation at bottom of figure)



S_2 tide: amplitude (cm) and tidal phase (degrees), referred to moon's transit at Greenwich. Boxes: comparison of observed and computed values (see explanation at bottom of figure)

Fig. 3.-

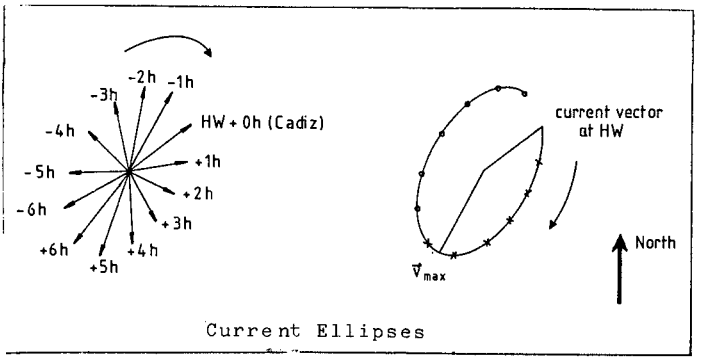
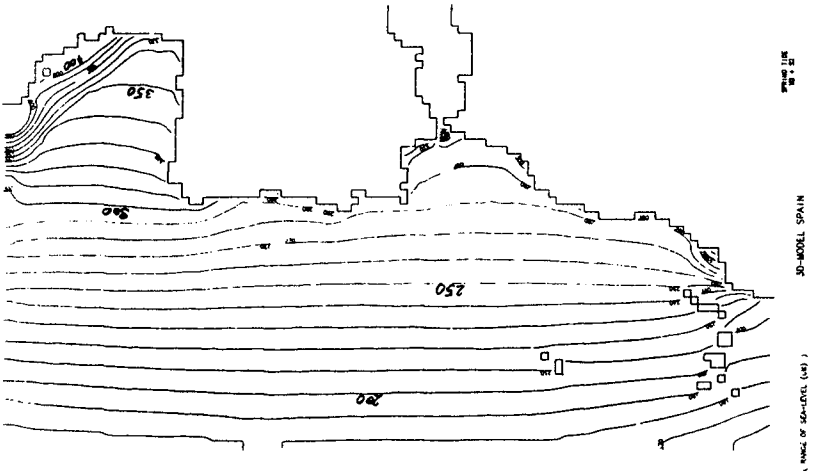
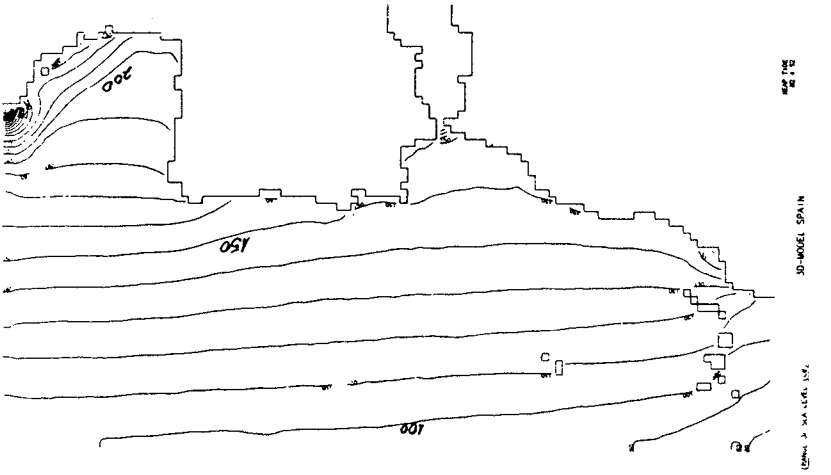


Fig. 4.-

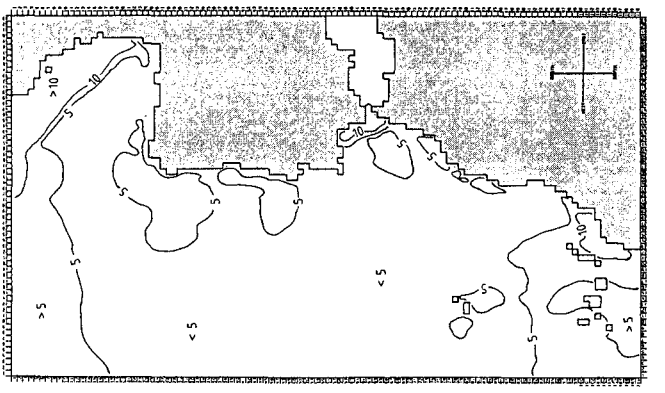


Spring Tide. Range of sea level (cm)



Neap Tide. Range of sea level (cm)

Fig. 5.-



CURRENTS

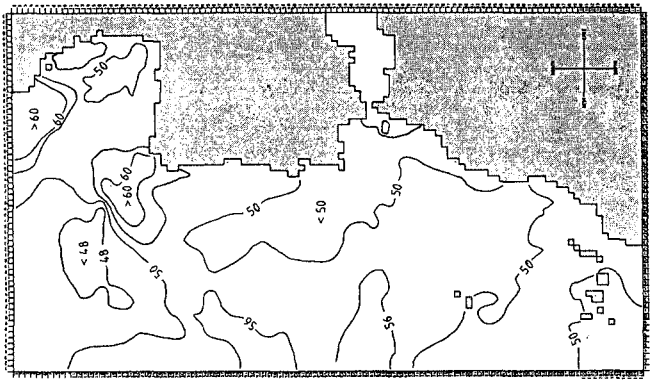
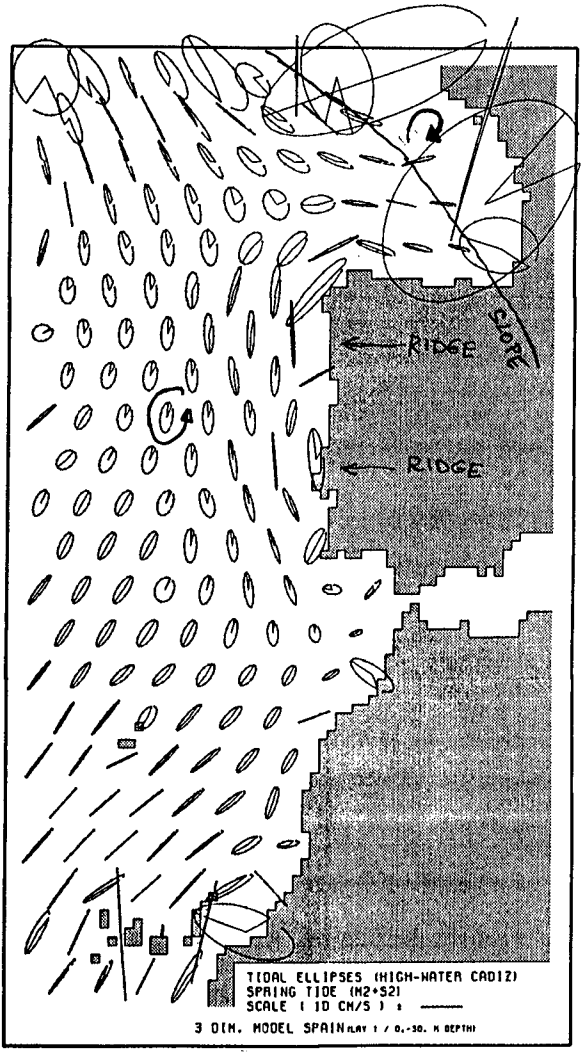
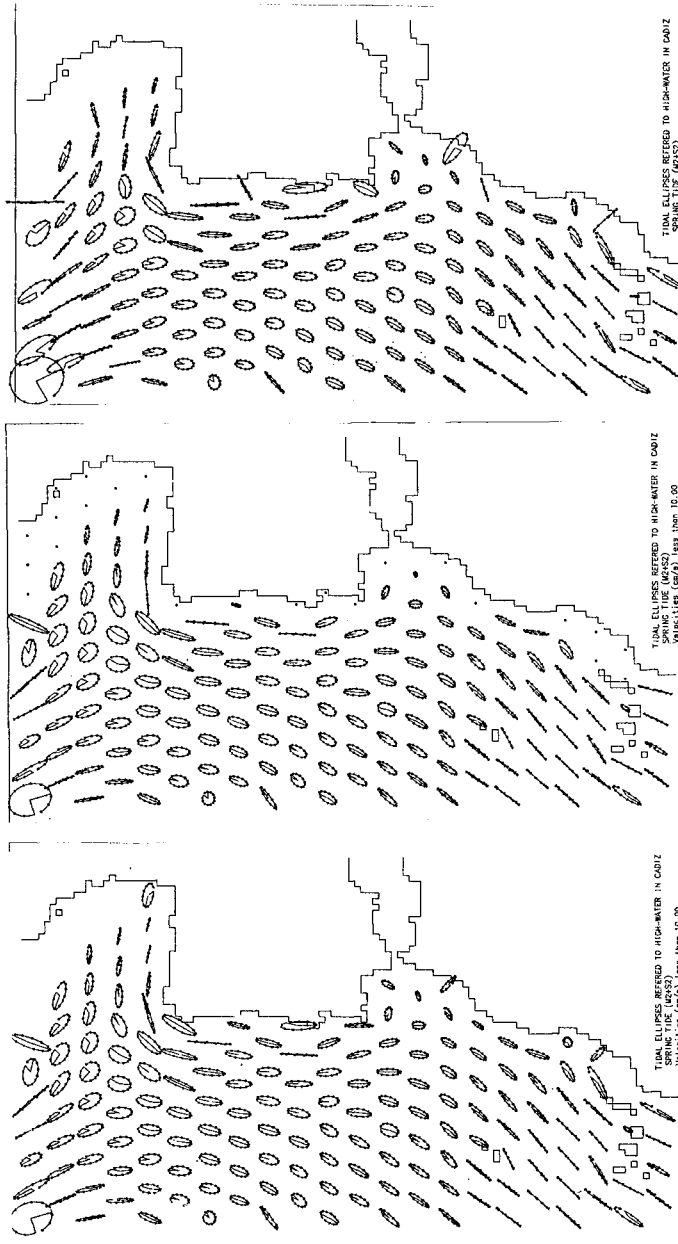


Fig. 6.-



Spring tide: current ellipses (referred to high - water at Cadiz) surface layer

Fig. 7.- SPRING TIDE



Surface Layer

Bottom Layer

Vertically Integrated

Fig. 8.- NEAP TIDE