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# COMPUTER MODELLING OF SEA CIRCULATION PATTERN

## KOMPJUTORSKO MODELIRANJE CIRKULACIJE U MORU

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Hydrodynamic models can be used to reconstruct the representative and characteristic situations. But, in the case of the Adriatic Sea or coastal regions, they can only do so with the expected accuracy if they are sufficiently evolved and complete to deal with all the complexity of the marine area and processes under study. Bathymetric and baroclinic effects, the multiplicity of tidal components and the general atmospheric forcing require fully three-dimensional, non-linear, with variable eddy diffusivity hydrodynamic model. The type of such model, that the author has worked on in Joint Research Center, Ispra (Italy) is also briefly described in the paper.

## INTRODUCTION

Adriatic Sea has been dramatically deteriorating in the last decades. In the near future, the problems will become more acute and will call for a more thorough understanding and a more rational and strict control of the environment.

The marine system however, is extremely complex. Collection of data and their descriptive ordering have appeared to be such a formidable task, that one has often ignored the need for doing more than this.

Although the necessity of prediction has been realized for some time, it is only now that initial efforts in forecast have begun. The basic physical fields of velocity, pressure, density, temperature and salinity are linked; forecasting any of them implies essentially the forecasting of all of them. Additionally, nowcasting and forecasting of the basic fields allows the prediction of associated fields of active and passive dispersion materials (e.g. nutrients, tracers, and pollutants).

A most significant element of the methodology for nowcasting and forecasting generally is systematic field estimation. Here the term system refers to a multicomponent approach, built out of ongoing and historical observation, a validated general dynamical model, and various regional statistics. All estimates have errors, but a combination of two independent estimates can be made, which has an expected error lower than either of two component errors. This technique is efficient and is utilized by engineers under the terminology of optimal estimation. One independent estimate can be derived from observations and another from the dynamical simulations model.

Ocean scientistS are aware that the greatest impact of contemporary technology on their discipline will come from two sources: satellites and supercomputers.

As in other branches of modern physics and engineering, realistic simulation of the marine environment are now becoming possible. The use of such simulation in scientific research (numerical experimentation, sensitivity and process studies, etc.) is thought by many to represent the first major step forward in the basic scientific method since the seventeenth century. Science is now a tripartite endeavor with Simulation added to the two classical components: Experiment and Theory.

*Hydrodynamics and transport phenomena*

In order to analyze the influence of pollution inputs on the water quality of the Adriatic Sea, mathematical modeling techniques have to be used to quantify the transport of pollutants.

The first step in modelling system is the demarcation of the system. The demarcation defines the boundaries of the system and the state variables of the model, and thus determines the nature, place and time of the boundary and initial conditions which will be required.

Ideally, a marine model would be a time dependant 3D-model. A reductions of the dimensions can be achieved by restricting attention to time and space averages, considering for instance quasi steady state models of residuals, cross-section averaged models of estuaries or box-models for completely space averaged ecological variables.

Ideally also, a completely realistic marine model would have an infinite number of state variables. The essence of modeling is the selection of limited number of representative state variables. There must be sufficiently few of them for their evolution equations to be amenable to analysis but enough of them to describe adequately the system's behaviour.

The state space can be divided in several sectors corresponding to hydrodynamical, chemical, biological, etc. processes. One can conceive separate hydrodynamical, chemical and biological models with the necessary input-output links between them.

Hydrodynamical models are by far the most advanced. In a sense, this is rather fortunate because the understanding of hydrodynamical processes is prerequisite to any form of chemical or biological modeling. In the present state of development of marine models, hydrodynamics constitutes the most reliable contribution to the explanation and anticipation of ecological processes.

While chemical and biological models are still frequently limited to interaction box-models describing, by means of differential equations, concentrations and biomasses in a hypothetic homogeneous environment or averaged over large regions of space, hydrodynamical models have evolved to transport-dispersion field-models describing, by means of partial differential equations, the spatial distribution and time evolution of variables determined at all grid points.

The development of hydrodynamical sea models has been made possible by the absence of any significant feed-back from chemical and biological processes on hydrodynamical phenomena: transport and dispersion in the sea determined factors in marine chemistry and biology, but chemical and biological interaction have no appreciable effect on advection and mixing in the sea.

*Author's contribution*

In 1988 in the Joint Research Center of the European Community, Ispra Establishment in Italy, a team for oceanographic computer modelling was organized with a fundamental task to promote better understanding of hydrodynamic and, for a long time, ecological occurrences in the sea. Special emphasis in the activity of this team should be placed on confrontation of the mathematical numeric modeling with activity of processing, production and application of satellite images, especially for the Adriatic Sea, which had already been started there a few years ago.

In the first year of the work in the mentioned team, several series of numerical computations were performed for verification, further development and special real applications of the three computer models, for simplicity called briefly $M_1$, $M_2$ and $M_3$. A detailed description of the results of this study is available in the form of the joint report published a few months ago by the EC Commission under the title:
**"Numerical Verification Exercises with Different Computer Models for Simulating Sea Circulation Pattern"**, by E i f l e r *et al.*, 1990.

In this framework, the author worked on model $M_1$. The related activity is briefly summarized below. For the detailed scientific results, reference is made to the aforementioned technical report, and papers submitted to:

- **Eighth International Conference on Computational Methods in Water Resources,** held in Venice, Italy, June 1990 (Springer-Verlag);
- **Second World Congress on Computational Mechanics**, Stuttgart, August 1990 and
- **Tenth Congress of Yugoslav Association for Hydraulic Research**, Sarajevo, October 1990 (Croatian).

*General Numerical Tests*

Model $M_1$ was developed for the Joint Research Center on a contractual basis by the "Geohydrodynamics and Environment Research (GHER)" - Unit of the University of

Liege. General transport equation is solved for two horizontal components of velocity, temperature, salinity, passive tracer and turbulent kinetic energy. The equations are discretized in time and space by the method of finite differences using generally explicit procedure over time and horizontal coordinates and a special implicit procedure over the vertical direction. Continuity equation gives vertical component of velocity whose integral over the depth gives the local sea level. Nonlinear terms in all the equations are discretized by the upstream differences.

A great member of calculations were made to test the behaviour of this model in different situations. For some specific cases, equations that describe flowing can be also solved analytically. Comparison of the numerical model results with analytic solutions enabled both detailed understanding of the model behaviour and parallel comprehension of the physical essence of some hydrodynamic processes in the sea. Simultaneously, this testing proved to be the first, unavoidable step of a longterm task, all for the purpose to discover and eliminate some mistakes in the code. It also enabled fundamental advancement in the numerical procedure and even in the mathematical model.

The first test was modelling of the sea circulation caused exclusively by horizontal density gradient with a constant coefficient of turbulent viscosity which is assumption of used analytic solution made by B i s h o p and O v e r l a n d , 1977. Circulations with or without Coriolis force were calculated as well as with or without water level inclination. Calculations were performed supposing the start from the state of rest using different values of density gradient, Coriolis parameter and water depth. At the beginning, obtained model results were qualitatively very similar to the analytic ones, but with the absolute difference of about 10 to 60%. After eliminating an accidental fortran error in the original code (replacing matrix names for the viscosity coefficient and for the vertical velocity component in several statements of the subroutine for computation of the velocity component in the direction), the ideal results were obtained, i.e. the perfect agreement with analytic solution for the steady state in the first four or five figures, even for about only twenty elements in the vertical direction. For relatively small water depths of several meters, steady state is being quickly established while, for the depths of, let us say, several tens of meters, a rather long real time is necessary for reaching this state.

The next case was comparing the numerical and the analytic solution for the steady and unsteady circulation occurring in the shallow homogenous sea during constant wind (E k m a n and F r e d h o l m solution). After verification of the model for this case, several examples were made with change in the wind intensity or direction as well as with other variations in the boundary conditions, all for the constant coefficient of turbulent viscosity. Agreement with the mentioned analytic solutions was absolute.

Nonlinear, convective components in the model i.e. their discretization in the numerical model were also tested by comparing it with an analytic solution (H e s s , 1985). Certain small defects were defined, and with some changes in one subroutine, eliminated. After that, almost perfect agreement with the analytic solution was obtained.

In order to test the behaviour of the model for calculations of the sea circulation driven by tide, an analytic solution of forced oscillation in ideal liquid in semi-closed channel was used (I p p e n and H a r l e m a n , 1966). Comparisons were also made for the case of the channel with open end as well as for the case of amplification of the oscillations. Depending on the used numerical mesh, an agreement, ranging from that of few percents up to the perfect one was obtained.

*Vertical Diffusion of Momentum*

The following three specific cases were considered in details:
1. The steady turbulent COUETTE flow simultaneously driven by wind and pressure gradient;
2. The steady EKMAN problem for finite depth and flow, driven also by wind and pressure gradient but with the presence of Coriolis force; and
3. The unsteady EKMAN problem.

For all the three cases, analytic solutions exist and they were used for testing of model behaviour and its verification. For solution of the COUETTE flow, a family of analytically defined profiles of turbulent viscosity (E i f l e r , 1988), based on reliable and detailed experimental measurements, was used, while for the EKMAN problems (with constant viscosity coefficient) available solutions were used - E k m a n , 1905, and H i d a k a , 1933.
Publication fore-mentioned will present complete results of the testings of time and space discretization, introduction of the "universal" and the "ideal" wall-adjacent shape function as well as the results of the numerical stability testings etc.

*Computation of the Wind Driven Circulation in the North Adriatic*

The first step was testing of all the three models behaviour under, as much as possible equal boundary conditions and with a constant viscosity coefficient. Spatially uniform numerical mesh, 70 x 50 x 25 elements, was chosen and uniform wind was supposed, i.e. constant surface shear stress. Time step was chosen to be small enough (for MODEL-1 T = 90 s) so that its diminishing has practically no effects on the solution.
The following step is testing of influences of different models assumptions on the obtained results such as:
- Turbulence model (original version, modifications introduced during the work on the COUETTE and EKMAN problem, and possibly some simpler model of turbulence);
- Nonlinear terms, especially horizontal advection;
- Real wind (at space and time);
- Transport of passive tracer (advective and diffusive) etc.

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## KRATKI SADRŽAJ

Hidrodinamički se modeli mogu koristiti da rekonstruiraju reprezentativne i karakteristične situacije. Medjutim, u slučajevima kao što je Jadransko more ili obalna područja oni se mogu koristiti u tu svrhu a da bi dali očekivanu točnost, pod uvjetom da su dovoljno razvijeni i upotpunjeni kako bi mogli pravilno obuhvatiti svu kompleksnost nekog morskog područja ili procesa koji se izučava. Djelovanja batimetrije

i tlaka zraka, višeslojnost komponenti morskih mijena kao i opće djelovanje atmosferskih prilika traže da taj model bude potpuno trodimenzionalan, nelinearan, hidrodinamički model sa promjenjivom vrtložnom difuznošću. Tip takvog modela na kojem je autor radio u ISPRA Centru u Italiji u kratkim je crtama opisan u ovom radu.