NUMERICAL SIMULATIONS OF FLOW AND SALINITY DISTRIBUTIONS IN ÖRESUND

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ABSTRACT

Numeral simulations of the flow and salinity distributions in Öresund, which is the sound between Sweden and Denmark, are presented. The purpose of the simulations is to assess the impact of a bridge, that is under construction, over Öresund. The numerical model is fully three-dimensional, employs an advanced turbulence model and uses a body-fitted coordinate system. Simulations, covering several months, have been carried out and results have been compared with field measurements; good agreement is generally obtained. In this paper the calibration of the model will be in focus.

1. INTRODUCTION

A fixed link is currently being built between Sweden and Denmark. This is one of the major civil engineering projects in Scandinavia presently and the environmental impacts of the bridge have been carefully evaluated. One of these impacts concerns the salt water, originating from the North Sea, that passes through Öresund and eventually forms the bottom water of the Baltic. It was decided that advanced numerical simulation studies were needed to assess if the salt water inflow would be reduced or modified, due to the bridge piers and two artificial islands. The purpose of the present paper is to give a brief description of these simulations.

The main features of Öresund, see Figure 1, can be summarised as follows. Brackish water from the Baltic meets salt water from the North Sea and an estuarine circulation is set up. Variations of this basic pattern, for example a homogeneous density field, are frequent depending on the pressure difference between the north and south boundary of Öresund. The pressure difference is caused by the difference in free surface elevation and it is this pressure gradient that mainly governs the flow; direct windstress is of secondary importance.The length of Öresund is about 80 km, the width 20 km and the depth typically 20 metres.
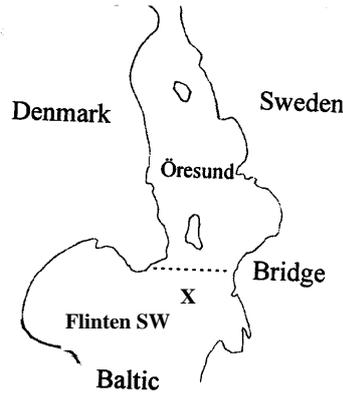
Figure 1. Schematic outline of Öresund

A mathematical model that can describe the transient flow and salinity distributions in Öresund needs to possess the following characteristics. It should solve the basic momentum equations, employ an advanced turbulence model (like the k-ε model with buoyancy damping) and solve the salt and mass balance equations. Advanced grid techniques, like multiblock and fine grid embedding in a three-dimensional body-fitted coordinate system, are needed in order to resolve local features (for example dredging). Such a model has been set up and simulations, based on measured pressures at boundaries and meteorological data, covering several months have been carried out.

In the following section the details of the mathematical model will be given and after that simulation results, including comparisons with field measurements, are discussed. Finally some conclusions are formulated.

2. MATHEMATICAL MODEL

It will be assumed that the flow can be regarded as incompressible and that density variations can be handled by the Boussinesq approximation, i.e. density variations are only significant in the gravitational term. It will further be assumed that molecular friction can be neglected and that turbulent friction can be parameterized with the eddy viscosity concept. Within these assumptions we may formulate the conservation equations for mass and momentum as follows:

$$\text{Momentum:} \qquad \frac{DU_i}{dt} = -\frac{1}{\rho}\frac{\partial P}{\partial X_i} + \frac{\partial}{\partial X_j}\left(\nu_T \frac{\partial U_i}{\partial X_j}\right) + F_i \qquad (1)$$

$$\text{Mass:} \qquad \frac{\partial U_j}{\partial X_j} = 0 \qquad (2)$$

where $U_i (= U, V, W)$ is velocity, P pressure, ρ density, ν_T kinematic turbulent viscosity and F_i forces due to gravity and Coriolis effect.

The salinity, S, is determined from the following conservation equation:

$$\frac{DS}{dt} = \frac{\partial}{\partial X_j}\left(\frac{\nu_T}{\sigma_T}\frac{\partial S}{\partial X_j}\right) \tag{3}$$

where σ_T is a turbulent Prandtl/Schmidt number (put to 2.5).

The kinematic eddy viscosity was calculated from the standard $k-\varepsilon$ model, see Rodi (1986), including terms for production/destruction due to buoyancy effects. All coefficients in the turbulence model were set according to the recommendations by Rodi (1986). Due to space limitations the reader is referred to Rodi (1986) for the set of equations giving the $k-\varepsilon$ model.

Finally an equation of state is needed to relate salinity to density:

$$\rho = \rho_0(1+\alpha S) \tag{4}$$

where ρ_0 is a reference density (=1000 kg/m^3) and α an expansion coefficient $\left(=8\times10^{-4}\right)$. The general equation solver PHOENICS (Spalding 1981) was used to solve the set of equations formulated.

3. RESULTS

The computational domain is specified using a body-fitted coordinate system, see Figure 2. The basic grid (55 cells north-south, 29 cells east-west and 15 cells in the vertical) has in total 23 925 cells. Boundary conditions were given as measured water levels and salinity profiles north and south of Öresund and windstress from meteorological data sets. Bottom stress was calculated from a log-law with a calibrated bottom roughness coefficient.

Time series of velocity and salinity are available from several measuring points in Öresund. Part of these were used to calibrate the model; mainly tuning the bottom roughness length and the turbulent Prandtl/Schmidt number. The remaining part of the time-series were used for predictions, i.e. no tuning of the model was allowed in these comparisons. Examples of results from the calibration of the model are given in Figures 3 and 4. The position of the measuring station chosen, Flinten SW, is shown in Figure 1. Comparisons of the timeseries of velocity are shown in Figure 3; a time period of 20 days in 1997 is used in this case. The agreement is very close indeed. The corresponding comparisons for salinity are shown in Figure 4. Also this comparison is regarded as most satisfying. It should be pointed out that the salinity at a certain point reflects all upstream events; hence if the model predicts complete vertical mixing at a certain upstream position this will affect the comparison in the point in question. It is thus much more difficult to get good agreement for salinity, as compared to velocity.
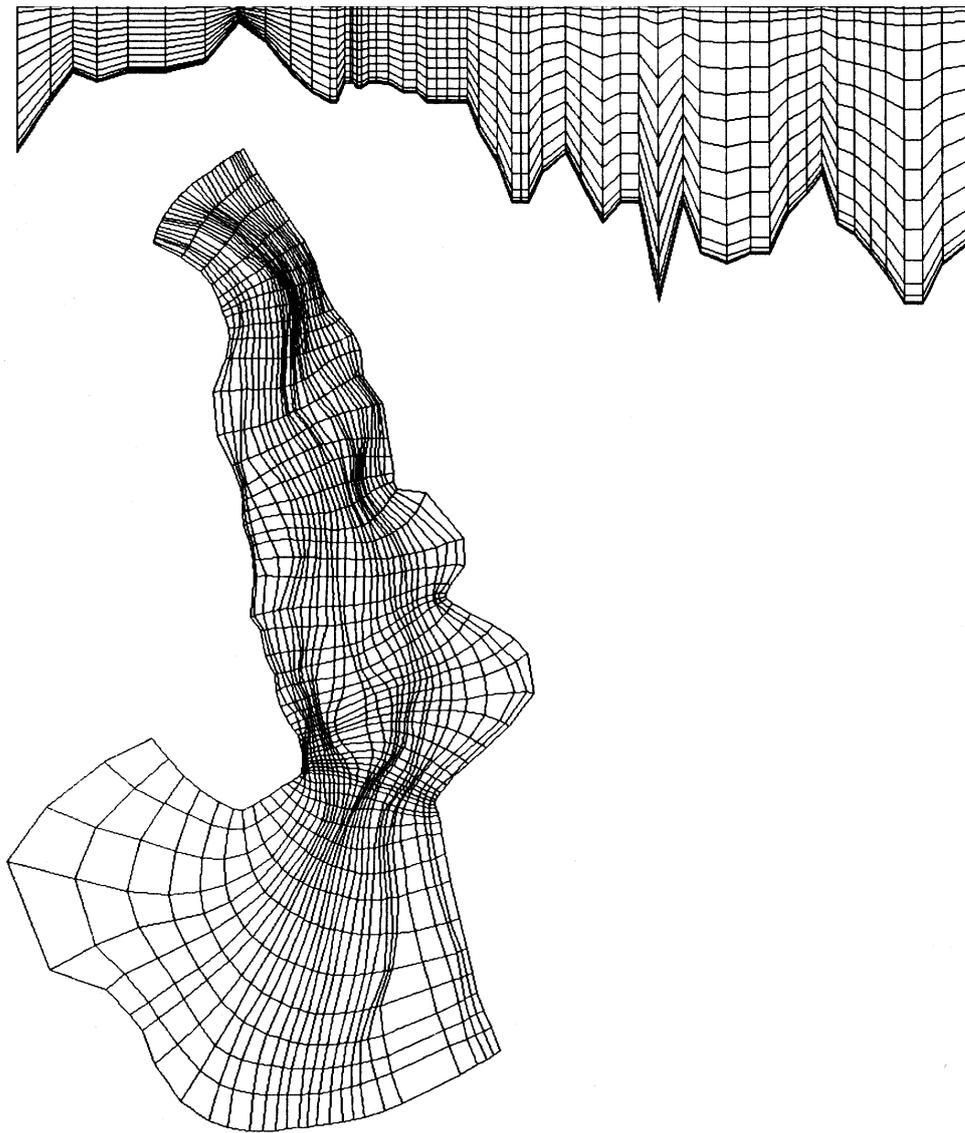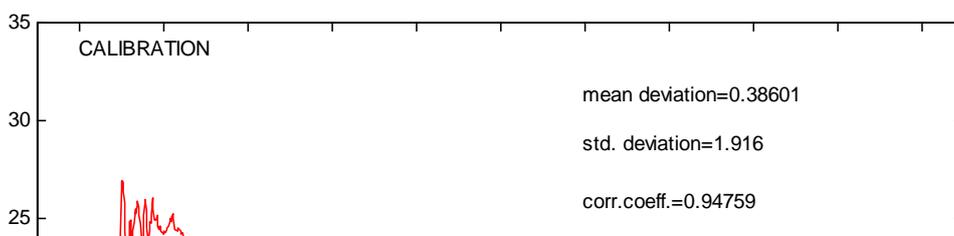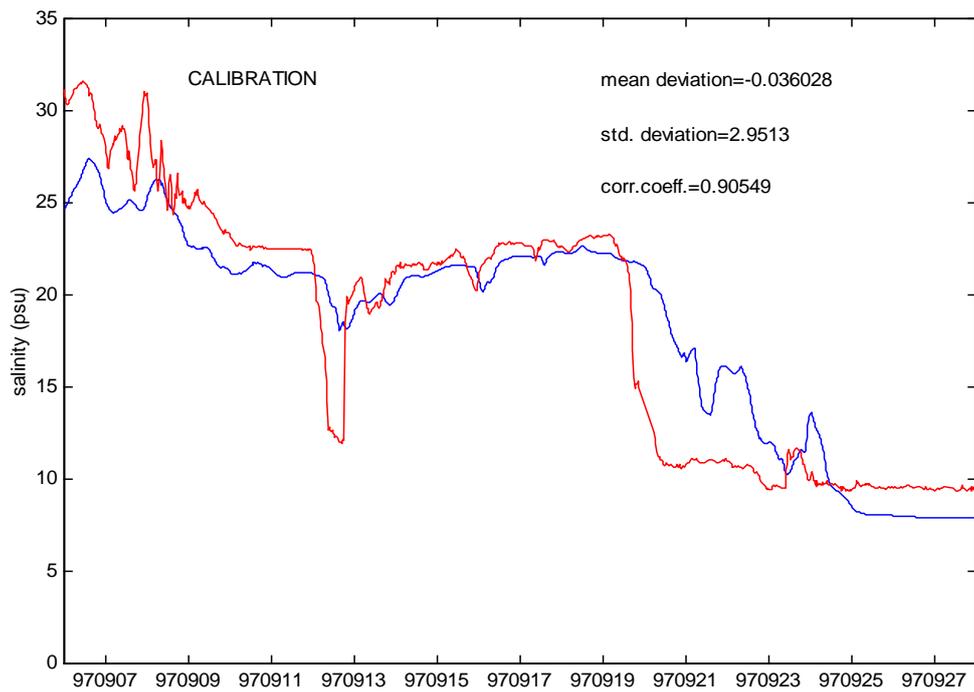
Figure 2. Computational grid. A vertical (top) and horizontal (bottom) section.
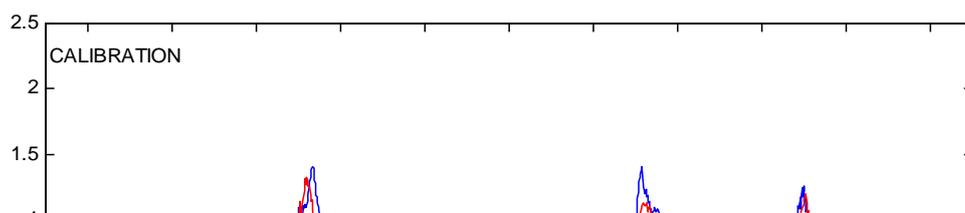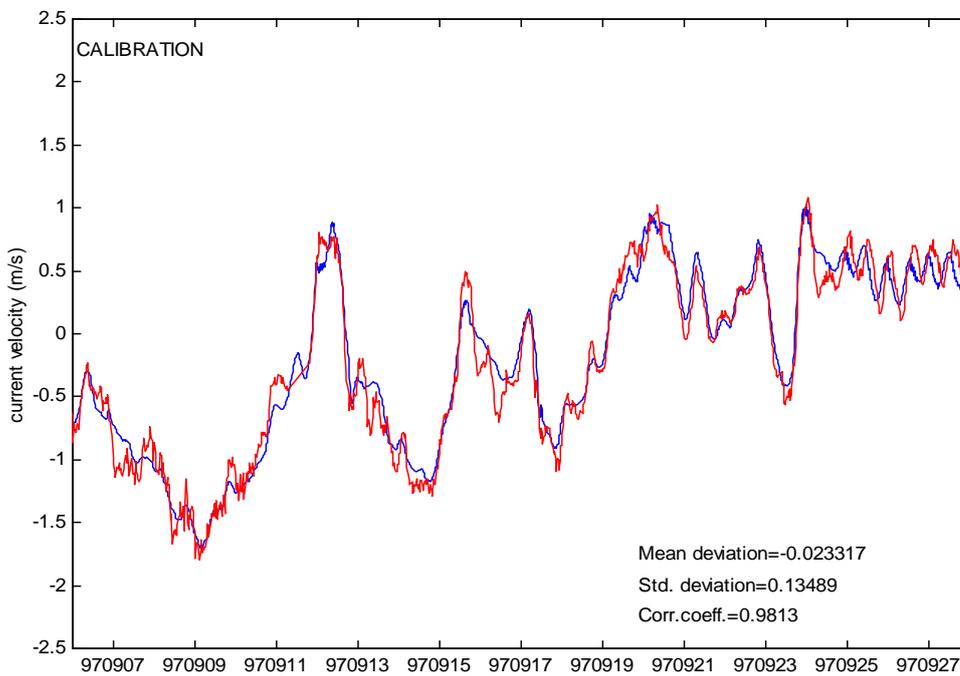
Figure 3. Comparison of velocity time series (measured red) at Flinten SW for a period of 20 days in 1997. Upper figure shows velocities at the surface while the lower one is for a depth of 5 metres.
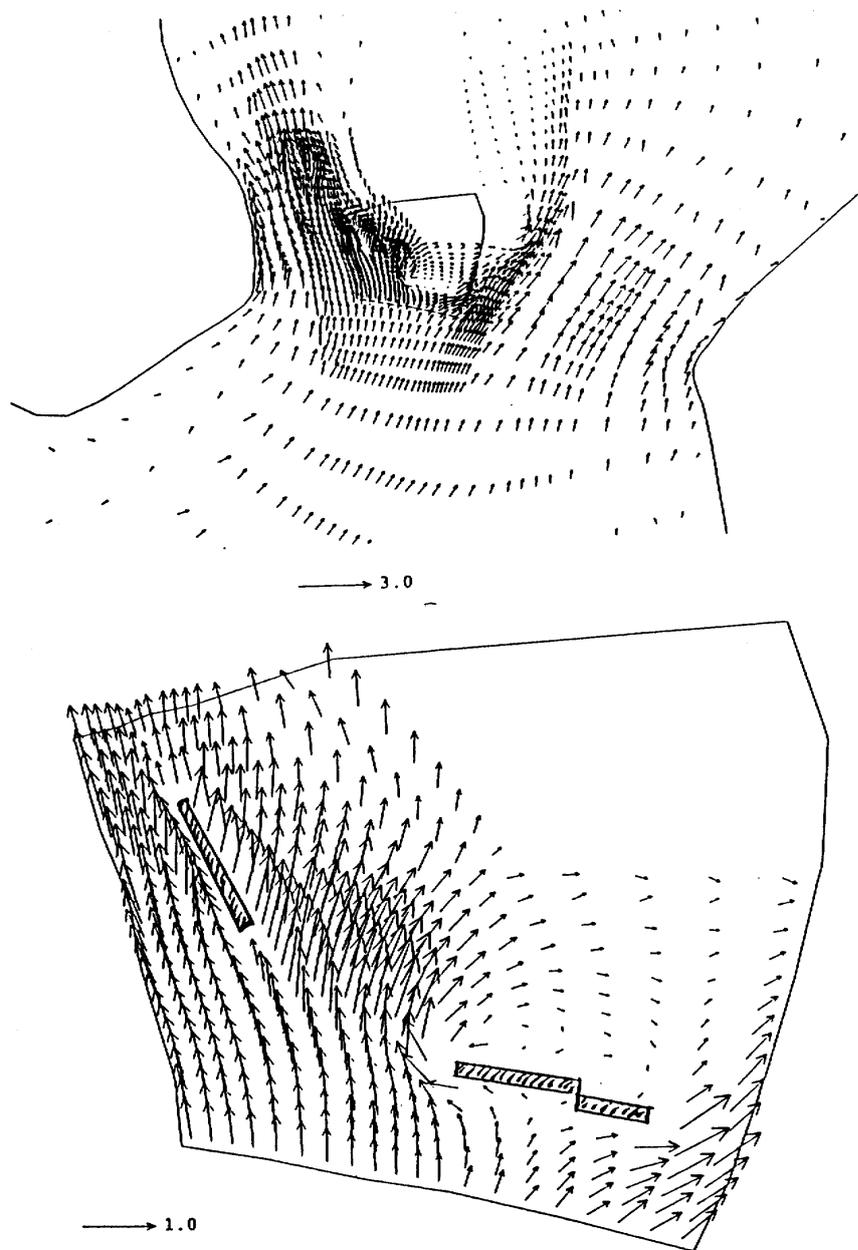
Figure 4. Comparison of salinity time series (measured red) at Flinten SW for a period of 20 days in 1997. Upper figure shows conditions at a depth of 3 metres, while the lower one is for a depth of 9 metres.
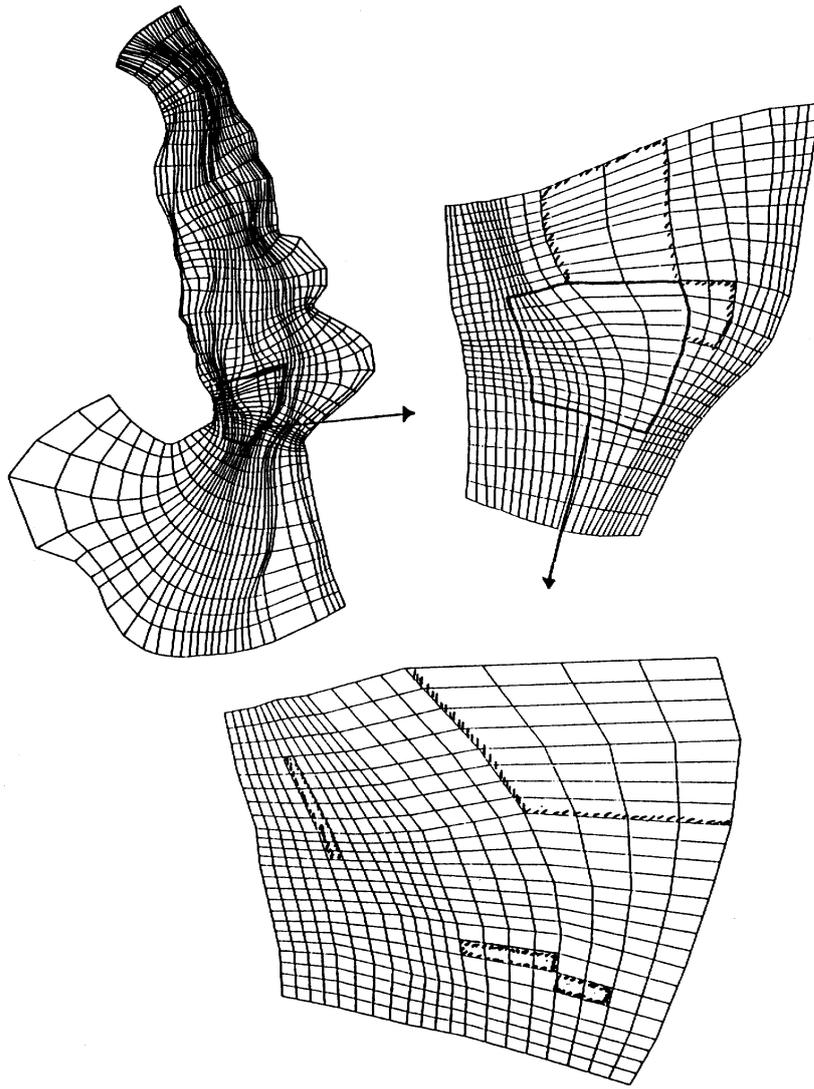
Figure 5. Standard grid for Öresund and two embedded grids.

Figure 6. Flow-vectors at a mid-depth position for north-going flow in Öresund.

The Öresund Link will start as an immersed tunnel at the Danish side and end as a bridge at the Swedish side. Two artificial islands will connect the tunnel to the bridge. It is of interest to study the blocking effect of the islands and, eventually, also optimise the shape of the islands. Such simulations call for a grid-refinement technique. The PHOENICS code offers a powerful technique for multi-block and fine-grid embedding. This technique is used to get a succession of fine grids around the artificial islands. In Figure 5 the grid and the two embedded grids are shown. In the finest grid the two islands are shown as blocked out cells. The finer grids were generated by splitting a cell in the coarse net into four cells, thus doubling the horizontal resolution by each finer grid. In the finest grid the gridspacing is of the order of 100 metres.

Predicted flow fields for the two embedded grids are shown in Figure 6. As can be seen a recirculation is predicted behind one of the islands.

These are some sample results of the simulations carried out to assess the environmental impact of the Öresund Link. A complete account of the simulations can be found in Svensson et al (1994) and Svensson (1999). In these reports it is concluded that the Öresund Link can be built without negative impact on the salt water transport into the Baltic.

4. CONCLUDING REMARKS

The flow and salinity distributions in Öresund are not easily predicted as a number of complex processes (stratification, Coriolis effects, transient boundary conditions, etc.) are significant. The simulation model presented has however been shown to provide a realistic description of most of the dynamical effects that need to be considered in the Öresund Link project. More specifically, our experiences from the project can be summarised as:

- A numerical model is the *only* tool (due to the Coriolis effect and complex boundary conditions) that can be used to assess the impact of the bridge.

- State of the art techniques (bodyfitted grid with local refinements, advanced turbulence model, higher order numerical schemes, etc) are needed to get acceptable results.

- Field measurements are essential in order to calibrate and validate the model. By careful calibration of the bottom roughness coefficient, very close agreement with field measurements can be obtained.

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