Simulations of water flow, transport and temperature in the Oder (Szczecin) Lagoon

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Summary

The Oder (Odra) river is the most important nutrient source and pollutant for the south-western Baltic Sea. The adjacent German-Polish coastal waters, especially the large, shallow Oder (Szczecin) Lagoon therefore suffers from severe eutrophication and water quality problems. The water quality of the lagoon is a key factor for sustainable development and management of the region. The European Water Framework Directive has the aim to ensure a good water quality in all aquatic systems in the member states of the European Community. The implementation of this directive in the Oder lagoon raises several questions: How does the transport of the Oder river water in the lagoon looks like? How intensive is the exchange of water between the two large parts, the Grosses Haff (Wielki Zalew) and the Kleines Haff? Can the lagoon be considered as one water type? Are measures within the lagoon possible to improve the insufficient water quality? Models are important tools to answer these Questions. We present a simple and flexible two-dimensional flow model Femflow 2D that can tackle these questions and support the decision making process. The model is applied to several wind conditions and the spatial temperature development is simulated. The work was carried out as part of the project SIBIK. Aim of the project was to link satellite images and modelling to support coastal monitoring along the German Baltic coast.

1 Flow modelling tool - Femflow2D

The vertically integrated equations of motion and continuity, widely known as “shallow water equations”, are frequently used to describe the dynamics of flow in shallow well mixed water areas (WEIYAN 1992). These equations form the basis of the simulation package FEMFLOW2D. The model runs under Windows 95/98/NT operating system and has a user-friendly graphical interface (Fig.1). Among other features, an interpolation module to prescribe spatially variable model parameters, like bottom roughness or wind field, a particle tracking block and simple animation tools are available.

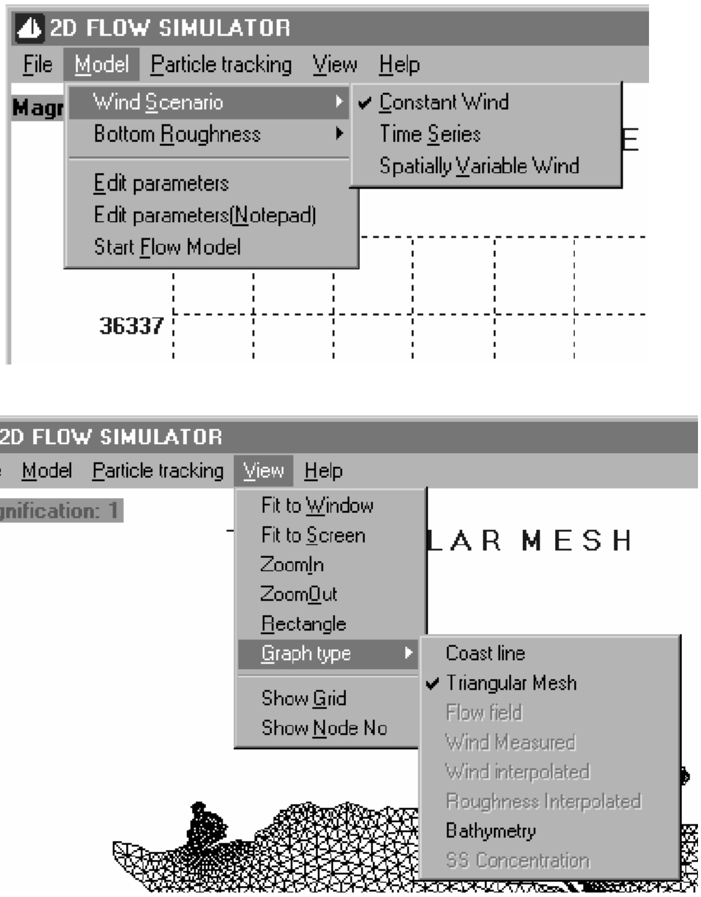
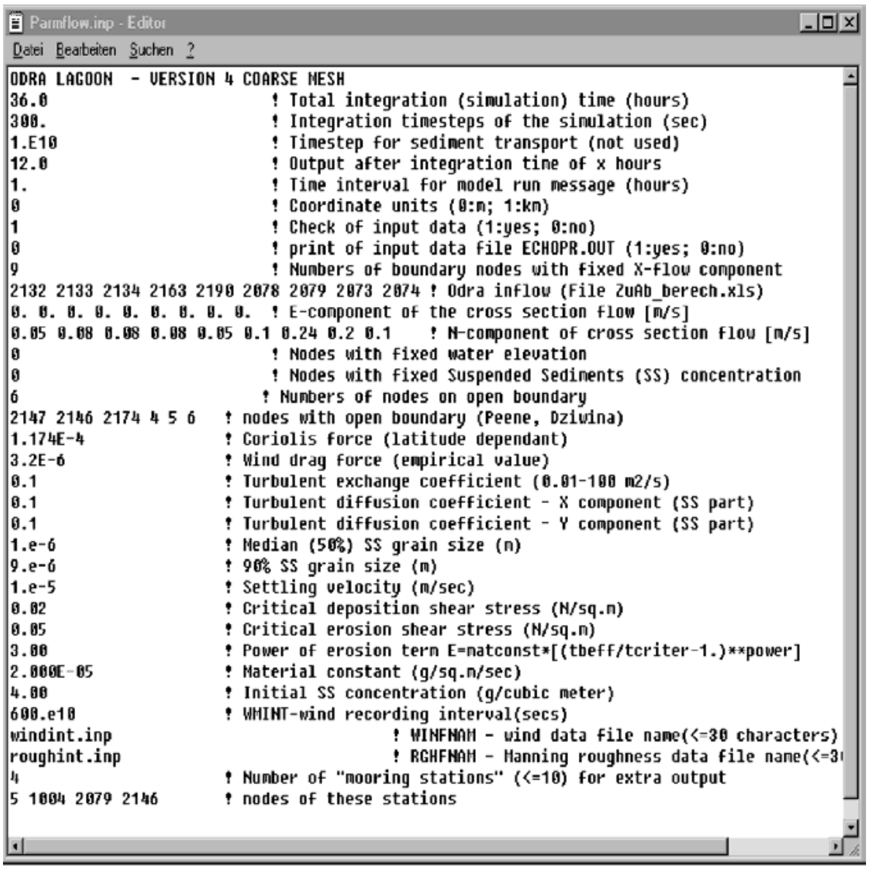


Figure 1: Graphical user interface of FEMFLOW2D.

All model parameter can be edited directly in a simple file or in special user interface. The file shown in Fig. 2 gives an example of an input file used for simulations of the Oder flood. In this example the discharge was kept constant during time and a non-uniform discharge of the Oder into the lagoon was applied.



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Parmflow.inp - Editor
Datei  Bearbeiten  Suchen  ?
ODRA LAGOON  - VERSION 4 COARSE MESH
36.0                       ! Total integration (simulation) time (hours)
300.                       ! Integration timesteps of the simulation (sec)
1.E10                      ! Timestep for sediment transport (not used)
12.0                       ! Output after integration time of x hours
1.                         ! Time interval for model run message (hours)
0                          ! Coordinate units (0:m; 1:km)
1                          ! Check of input data (1:yes; 0:no)
0                          ! print of input data file ECHOPR.OUT (1:yes; 0:no)
9                          ! Numbers of boundary nodes with fixed X-Flow component
2132 2133 2134 2163 2190 2078 2079 2073 2074 ! Odra inflow (File ZuAb_berech.xls)
0. 0. 0. 0. 0. 0. 0. 0. 0.  ! E-component of the cross section flow [m/s]
0.05 0.08 0.08 0.08 0.05 0.1 0.24 0.2 0.1    ! N-component of cross section flow [m/s]
0                          ! Nodes with fixed water elevation
0                          ! Nodes with fixed Suspended Sediments (SS) concentration
6                         ! Numbers of nodes on open boundary
2147 2146 2174 4 5 6   ! nodes with open boundary (Peene, Dziwina)
1.174E-4               ! Coriolis force (latitude dependant)
3.2E-6                 ! Wind drag force (empirical value)
0.1                    ! Turbulent exchange coefficient (0.01-100 m2/s)
0.1                    ! Turbulent diffusion coefficient - X component (SS part)
0.1                    ! Turbulent diffusion coefficient - Y component (SS part)
1.e-6                  ! Median (50%) SS grain size (m)
9.e-6                  ! 90% SS grain size (m)
1.e-5                  ! Settling velocity (m/sec)
0.02                   ! Critical deposition shear stress (N/sq.m)
0.05                   ! Critical erosion shear stress (N/sq.m)
3.00                   ! Power of erosion term E=matconst*[(tbeff/tcriter-1.)**power]
2.000E-05              ! Material constant (g/sq.m/sec)
4.00                   ! Initial SS concentration (g/cubic meter)
600.e10                ! WHINT-wind recording interval(secs)
windint.inp                           ! WINFNAM - wind data file name(<=30 characters)
roughint.inp                          ! RGHFNAM - Manning roughness data file name(<=3
4                      ! Number of "mooring stations" (<=10) for extra output
5 1004 2079 2146       ! nodes of these stations
```

Figure 2: Parameter input file of FEMFLOW2D.

The flow model is the basis of future model developments concerning spatial highly resolved short term predictions. Some characteristics of the finite element solution: The system of shallow water equations is discretized with the modified UTNES scheme (1990) which is characterized by a semi-decoupling algorithm. The continuity equation is rearranged to Helmholtz equation form. The upwinding TABATA method (1977) is used to approximate convective terms. For details see PODSETCHINE & SCHERNEWSKI (1999).

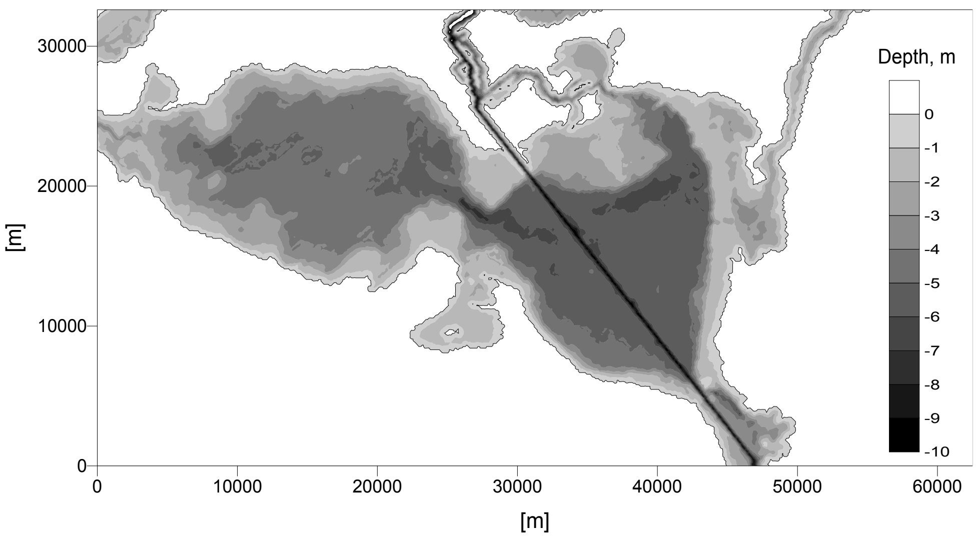


Figure 3: Bathymetry of the Oder Lagoon. Data supplied by K. Bruckmann, Greifswald.

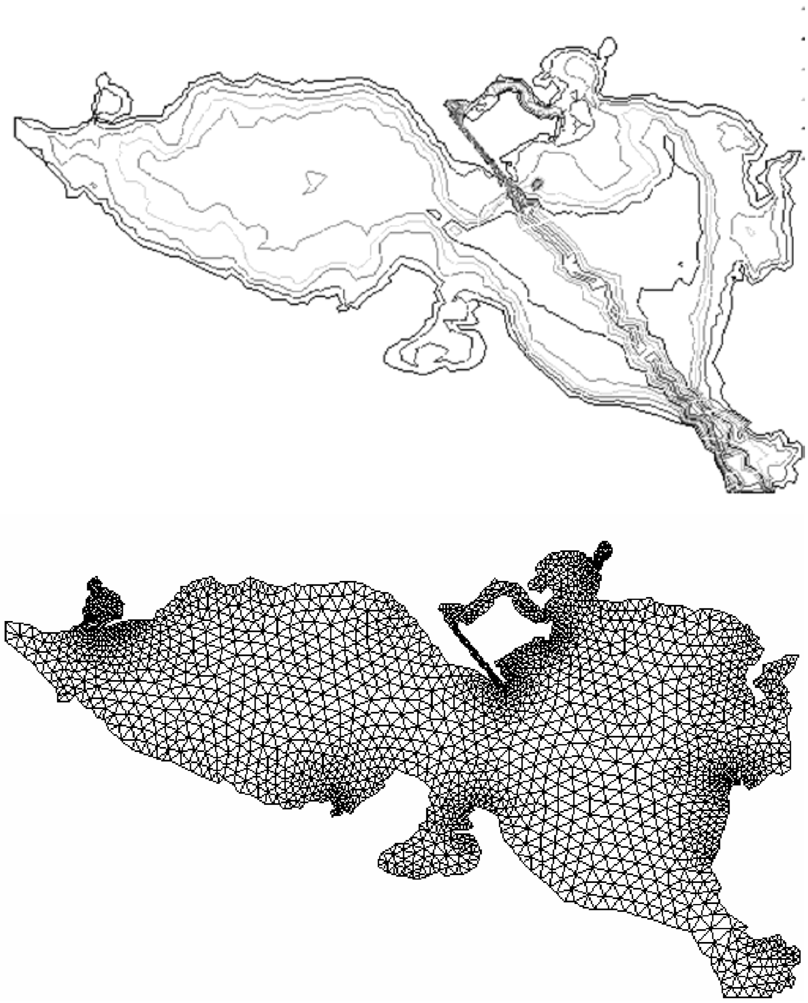


Figure 4: Triangular mesh and model bathymetry used for flow calculations in the Oder Lagoon (graphical output generated with FEMFLOW2D).

The bathymetry of the Oder lagoon is available on the basis of detailed depth information in 100*100 m grids supplied by K. Bruckmann, Greifswald (Fig. 3). In the first step a linear triangular mesh of 2240 nodes and 3845 elements covering the Oder lagoon was generated (Fig. 4) and linked to depth information. The resulting bathymetry, used in the model, is shown in Fig. 4. This grid density with a slightly simplified bathymetry was chosen to keep the computation time reasonable. During the Oder flood in summer 1997 a total simulation period of 20 days with simulation time steps of 5 minutes were used for flow field calculations. A Manning roughness coefficient of 0.015 m-1/3s, a horizontal diffusion coefficient equal to 0.01 m2s-1 and a Coriolis parameter of 1.174 *10-4s-1 were applied. The model runs were made on a PC workstation under Windows NT 4.0 operating system.

1.1 Average flow and transport situations in the Oder Lagoon

During the project SIBIK (Satellitengestützten Interpretations- und Bewertungsinstrumentes für das Küstenmonitoring) several flow and transport simulation were carried out. Aim was to provide satellite images as well as flow model results for an improved coastal monitoring as well as an improved analysis of surface water processes. The Oder Lagoon was one focus region for these investigations. In average wind from between south-west and west is dominating in this region. This dominance increases if only strong wind events are considered. The annual dynamic of the

Oder river discharge into the lagoon is not very pronounced and in all following simulations a water discharge of 300 m³/s was assumed.

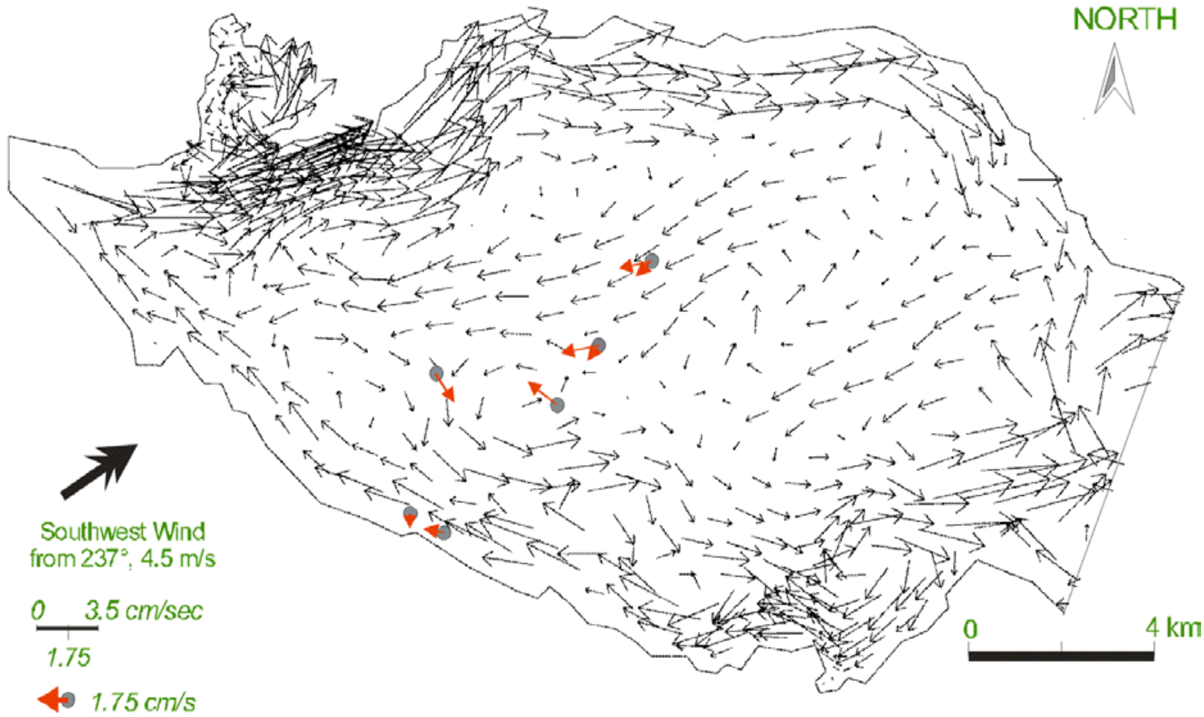


Figure 5: Average two-dimensional flow field during 14. August situation. field as well as measured depth-averaged currents in the Szczecin Lagoon (Kleines Haff) on August 14, 2001 (SCHERNEWSKI et al. 2002).

For August 14, 2001 detailed flow measurements from 3 independent sources were available and allowed the model validation. Several cross sections measurements with an Acoustic Doppler Current Profiler (ADCP), installed on a small boat, were carried out in the Kleines Haff. On several stations the boat anchored and measured detailed vertical current profiles. Additionally wind data was collected and the sheltering effect of coastal vegetation was taken into account in the simulations. In Fig. 5 the depth-averaged current values for these 4 stations are given. Close to the shore, vertical current profiles with an inductive current-meter ISM 2000 were taken and the 2 stations with the largest distance to the shore are presented, too. Altogether the measured and simulated flow data are in good agreement. Close to the German/Polish border a fixed station by GKSS, Geestacht measures current time series. This data is not shown but in good agreement with our simulated flow field, too (SCHERNEWSKI et al. 2002).

Figure 6 shows average flow fields in the Oder lagoon under different constant wind conditions. Figure 7 visualizes the transport of water resulting from these flow field. It was assumed that passive particles are moving with the currents for 60 days. One has to keep in mind that in reality a constant wind situation hardly ever lasts longer than a week.

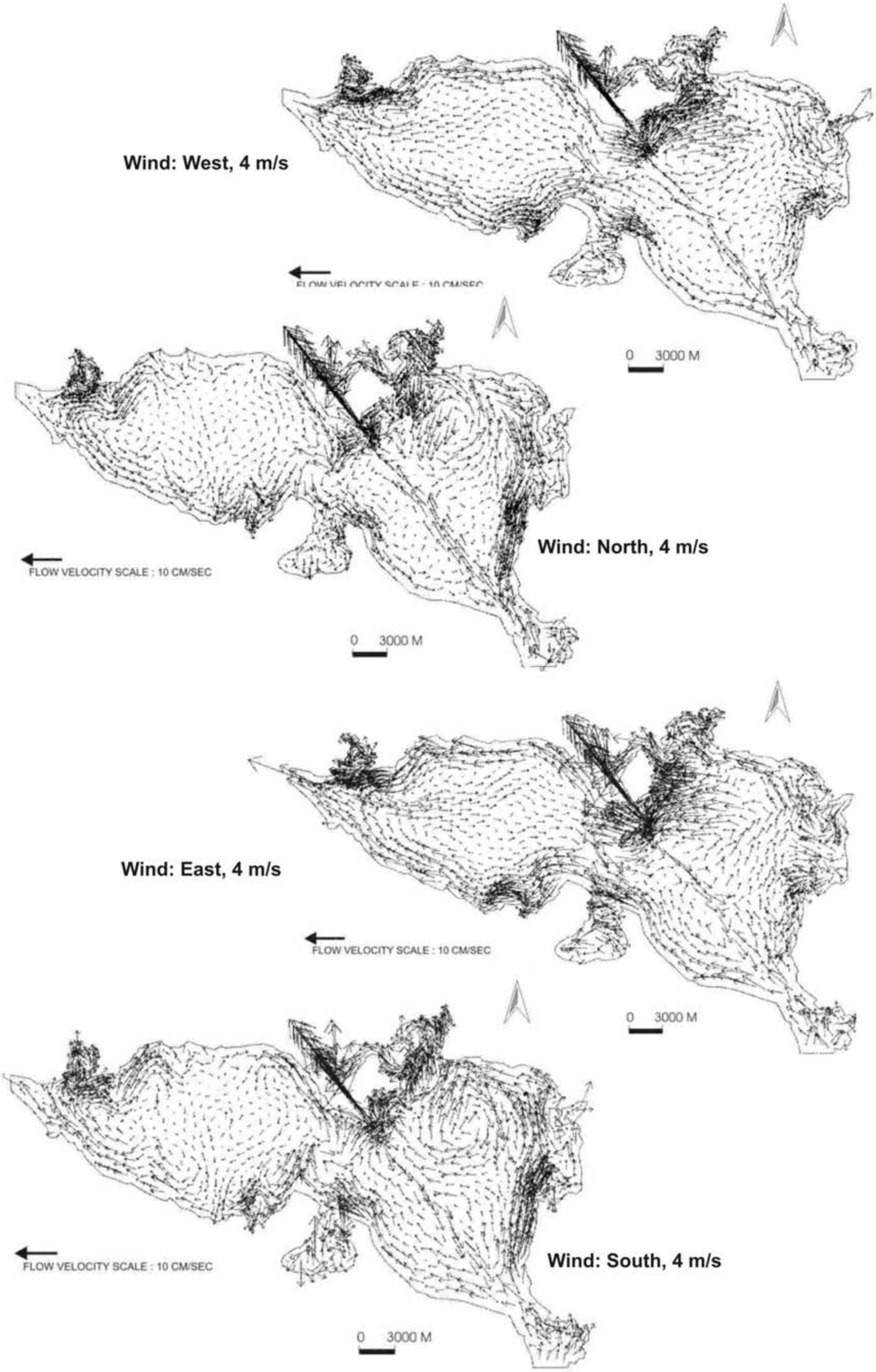
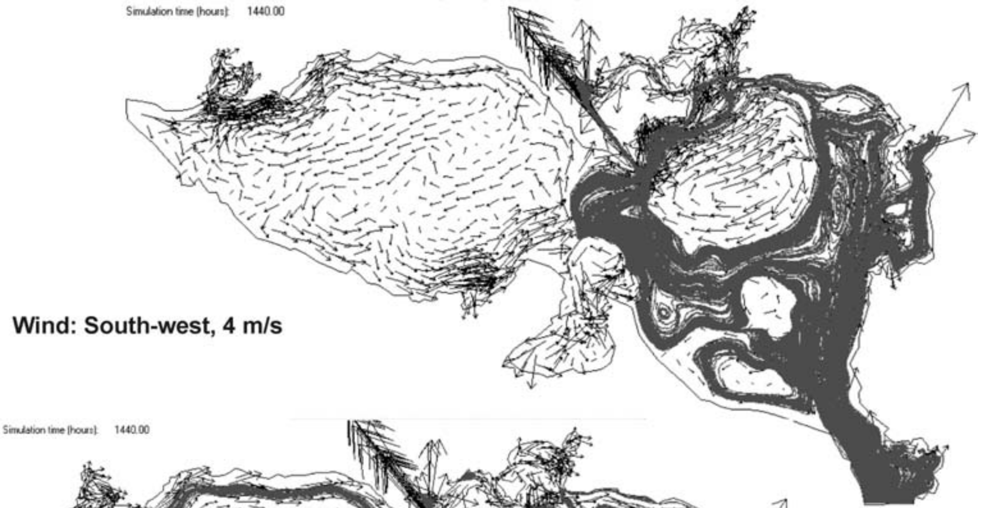
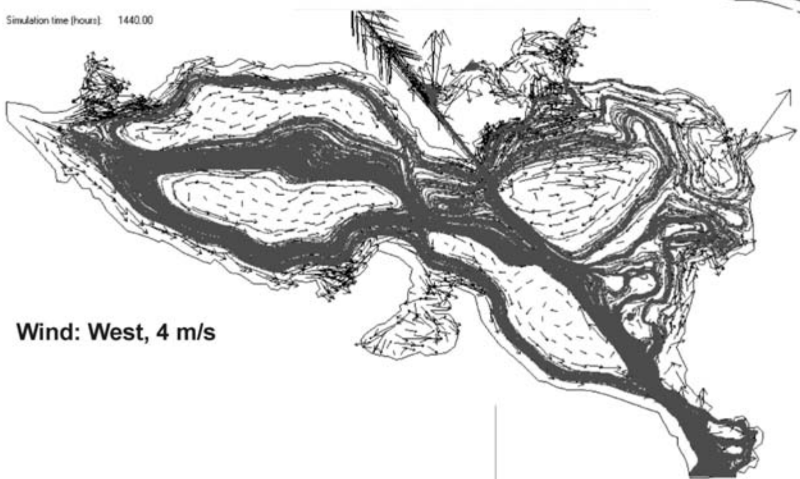
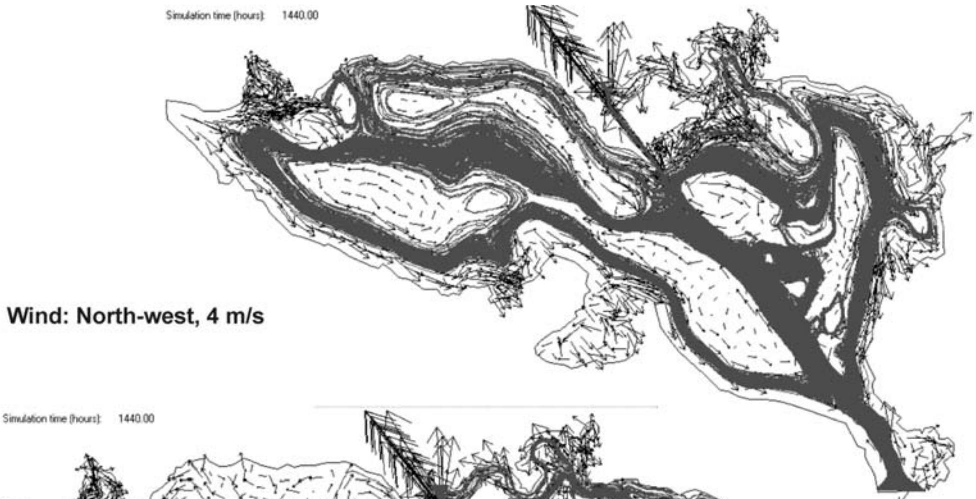
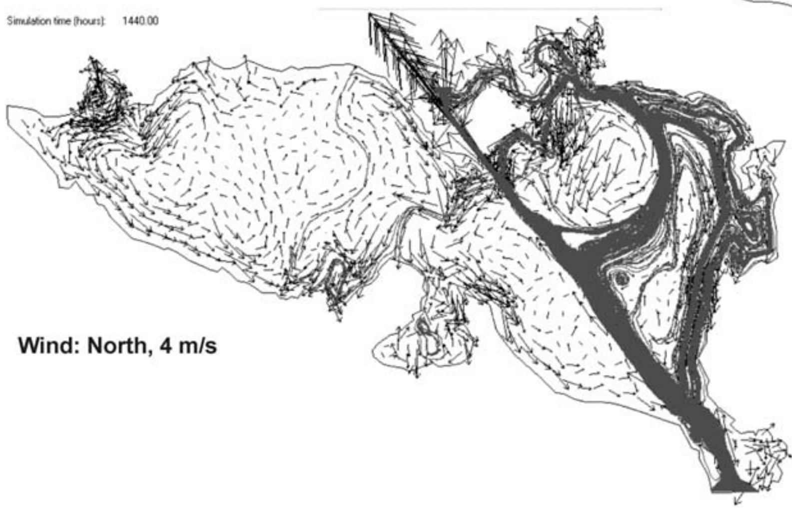


Figure 6: Depth averaged flow field in the Oder lagoon under different constant wind conditions.


Simulation time (hours): 1440.00
Wind: South-west, 4 m/s


Simulation time (hours): 1440.00
Wind: West, 4 m/s


Simulation time (hours): 1440.00
Wind: North-west, 4 m/s


Simulation time (hours): 1440.00
Wind: North, 4 m/s

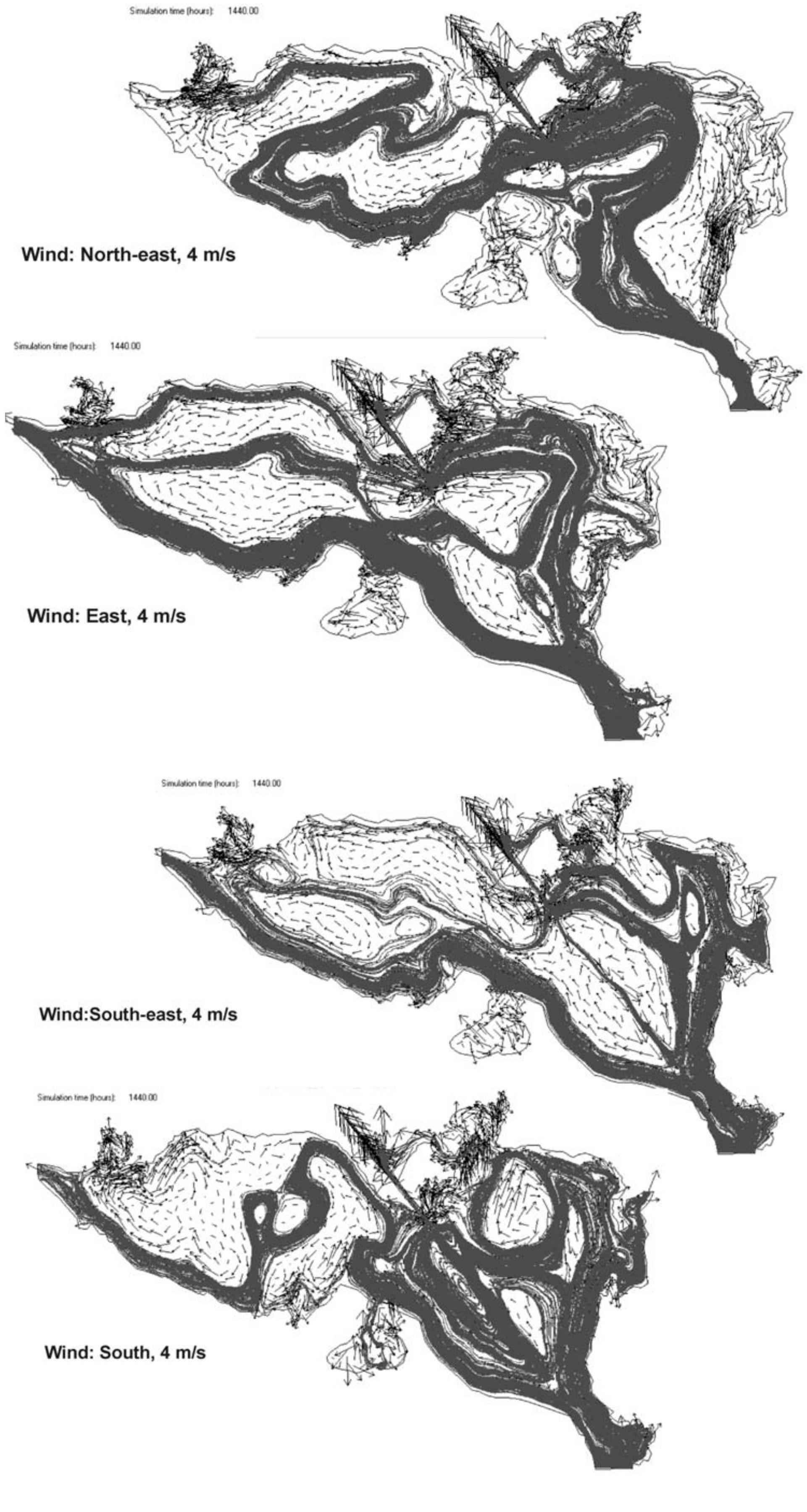


Figure 7: Trajectories of passive particles moving 60 days with depth averaged flow fields

The flow simulations can be summarised as follows:

- The model is two-dimensional and the shown flow velocities are averages from the surface down to the bottom.
- The spatial resolution of the model grid is sufficient for a system with a simple morphometry, like the lagoon. Important eddies and structures are well visible.
- The flow measurements are well in agreement with the simulations. The assumption of an uniform flow is reasonable for a shallow system like the Oder lagoon and reflects the average transport conditions well. Despite that, measurements clearly show that the water column often is divided into layers with different flow velocity and direction.
- Near the coast wind sheltering effects due to the coastal vegetation play an important role. The model is able to reflect these effects, if a detailed knowledge about the wind field is available. Seheltering effects depend on the wind speed and direction but are always to some extent visible. Without taking these effects into account, discrepancies between measured and simulated flow fields are the consequence. The assumption of a spatially uniform wind field (Fig. 6 and 7) is a simplification.
- In the major shallow and coastal parts of the lagoon the depth-averaged flow field and the wind have the same direction. The flow velocity is around 0.5 % to 1 % of the wind speed. In central parts, especially of the Kleines Haff, the average flow is directed against the wind. In these regions the surface layer is moving with the wind, too. A strong compensation flow against the wind direction is found in deeper water layers. In average, a weak current against the wind results from both opposing processes.
- Within the first kilometres off the coastline measurement indicate a large number of variable and relatively small eddies. It is very likely, that these eddies efficiently increase the exchange of water and nutrients between the red belts and the open water. Due to the spatial resolution of the model grid the eddies are not visible in the shown model simulations.
- In the western bay, the Kleines Haff, we find large eddies with a diameter of several kilometres, which act as a trap for drifting suspended substance and phytoplankton. These eddies are well reflected in satellite images and cause a significant spatial heterogeneity in the lagoon.
- These large eddies are comparatively stable and maintain even if the wind direction changes. Due to the persistence of the eddies, a more or less stable spatial heterogeneity is likely and effects the results of the water quality monitoring in the lagoon.
- Northerly and south-westerly winds favour a direct transport of Oder river water into the Baltic Sea. During southerly and westerly winds situations larger amounts of polluted Oder river water enter the western bay, the Kleines Haff. The wind and flow situation has a significant effect on the results of water quality data collection.
- Under usual discharge conditions, the effect of the Oder river on the flow field is restricted to an area close to the river mouth. In nearly all parts of the lagoon and even under low wind, the flow field is dominated by wind.

2 Spatial temperature development

Water temperature is one of the most important parameter that effects nearly all processes in a water body. Especially in large shallow systems, like the lagoon, significant spatial differences in water temperature are possible. As a result biological and chemical processes may have different intensities in different regions of the lagoon. Therefore one recent extension of the model includes a temperature block. A two-dimensional depth-averaged unsteady temperature equation can be written as (BENQUE et al., 1982):

$$\frac{\partial HT}{\partial t} + \frac{\partial (uHT)}{\partial x} + \frac{\partial (vHT)}{\partial y} = div(KHgradT) + \frac{\alpha (T - T_a)}{\rho_0 C_p} \quad , \qquad (1)$$

where H =H(x,y,t) is the water depth, u,v are components of depth-averaged velocity vector, K is the dispersion coefficient, $\rho_0 \cong 10^3$ kgm^{-3} is water density, C_p $\cong 4.187 \times 10^{-3}$ J kg^{-1} $^{\circ}C^{-1}$ is a specific heat capacity of water, T is water temperature ($^{\circ}$C), T_a is air temperature ($^{\circ}$C), α is the bulk heat exchange coefficient (W m^{-2} $^{\circ}C^{-1}$). It is estimated using an empirical dependence on wind speed W, ms^{-1} (ASHTON, 1982):

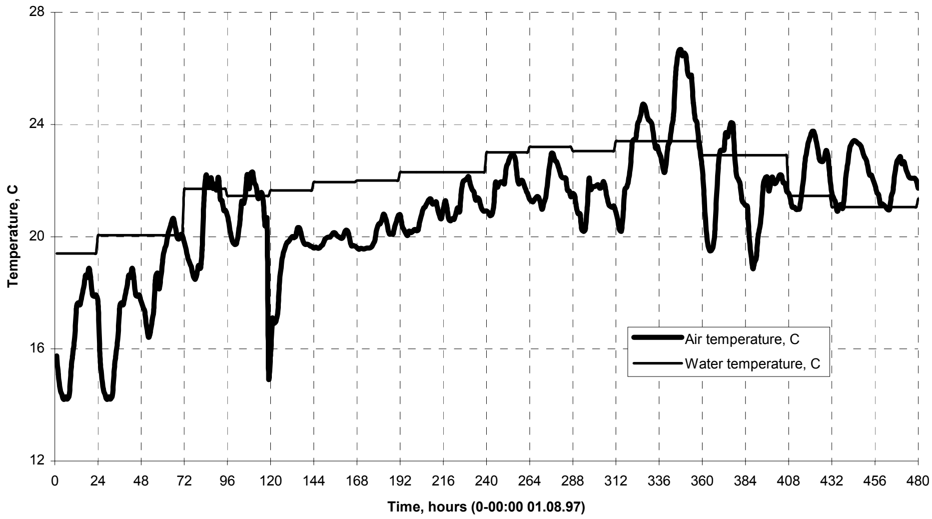
$$\alpha = 5.7 + 3.8W \qquad (2)$$

A no-flux boundary condition was applied along the solid boundary. The observations of time-varying inflowing water temperature in river Oder altogether with estimated values of inflowing mean cross-section velocity (T. NEUMANN, pers. com.) and time-series of wind in the Pomeranian Bight were used to drive the combined flow and temperature model.

Simulation results show that the temperature regime of the Oder lagoon is strongly influenced by air temperature variations. The dependence of the bulk heat transfer coefficient on wind speed (formula 2) additionally accelerates the response of depth-averaged water temperature to changes in atmospheric conditions. This is clearly reflected in Fig. 10b showing simulated time-series of water temperature in different parts of the lagoon. Shallow near coastal areas exhibit higher and faster changes than deeper parts located in the vicinity of the navigational channel.

During night the spatial temperature differences in the lagoon are significant lower than during day. In August 1997, for example the spatial temperature difference exceeded 2°C during the day and was below 1 °C in the night (Fig.11). Due to the flood the flow velocity in the lagoon was much higher compared to other years and spatial water exchange increased. Under common summer conditions we can expect significant higher spatial temperature differences.

a)



b)

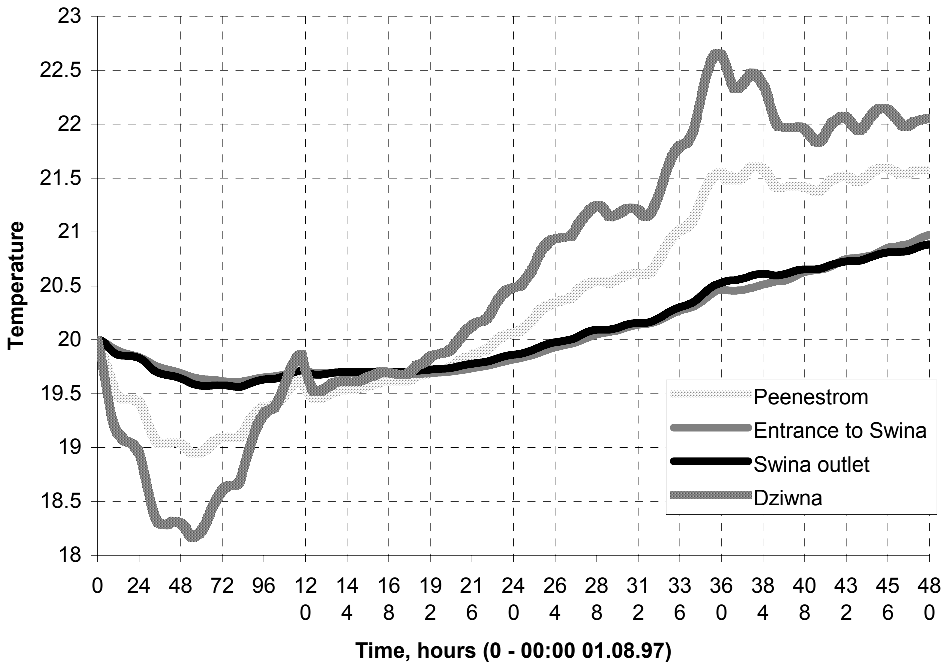


Figure 8: The Oder Lagoon between 1. August and 20. August 1997.
a) Measured air temperature and simulated and water temperature,
b) simulated water temperatures in different areas of the lagoon.

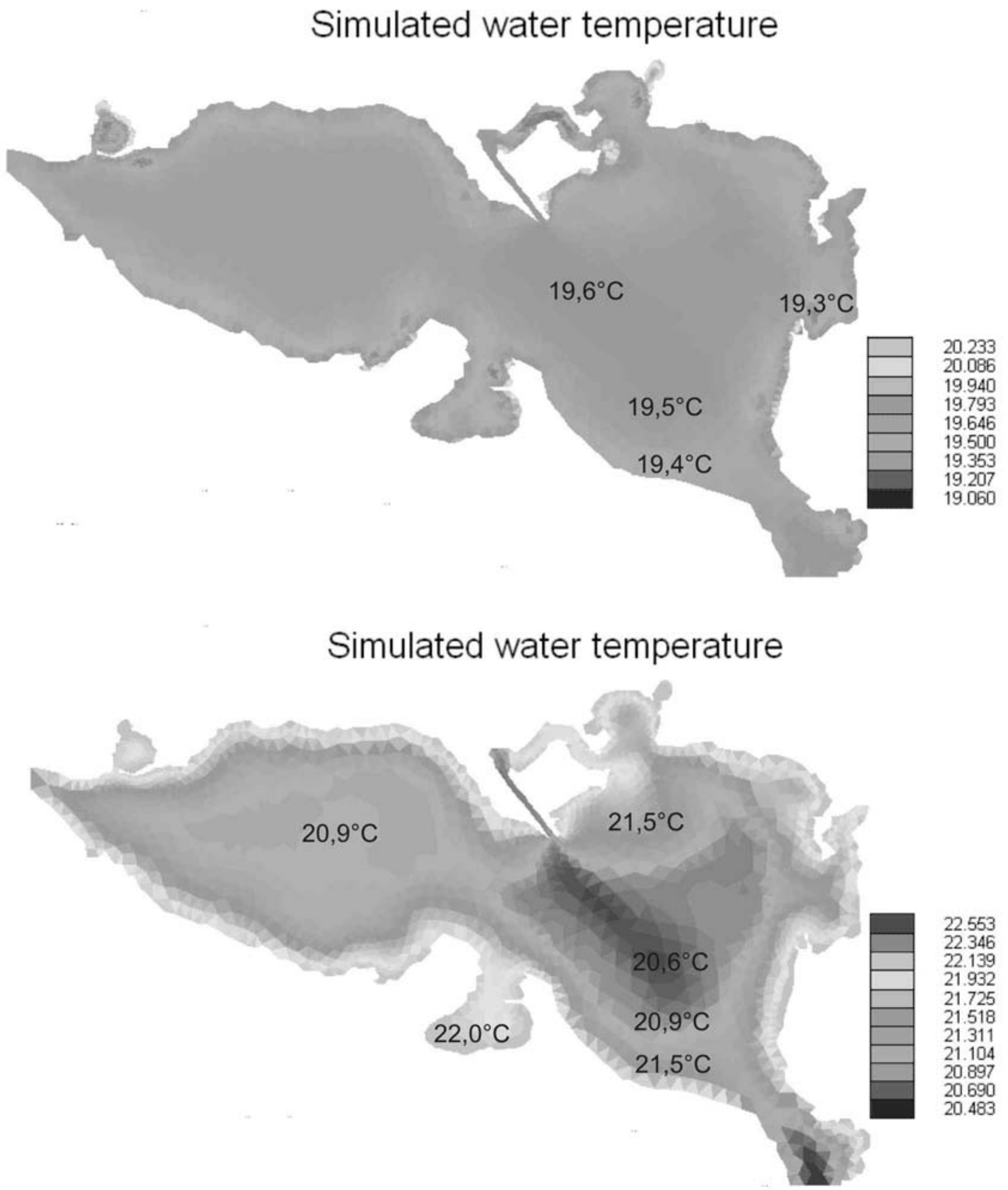


Figure 9: Spatial temperature distribution in the Oder lagoon during the Oder flood 1997 on 6. August midnight (top) and 21. August midnight (bottom).

Acknowledgement

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Literature

BENQUE, J.-P., HAUGEL, A., VIOLLET, P.-L., 1982: Engineering Applications of Computational Hydraulics. Volume **II**, Pitman Advanced Publishing Program, p.160

FENNEL, W. & NEUMANN, T. 1996: The mesoscale variability of nutrients and plankton as seen in a coupled model. Dt. Hydrogr. Z. **48**, 1: 49-71.

MOHRHOLZ, V. & LASS U., 1998: Transports between Oderhaff and Pomeranian Bight – a simple barotrophic box model. Dt. Hydrogr. Z. **50**, 4: 371-383.

NEUMANN, T., submitted: Towards a 3D-ecosystem model of the Baltic Sea. Journal of Marine Systems.

PODSETCHINE, V. & SCHERNEWSKI, G., 1999: The influence of spatial wind inhomogeneity on flow patterns in a small lake. Wat. Res. **33**, 15: 3348-3356.

REGIONALER PLANUNGSVERBAND VORPOMMERN, 1998: Regionales Raumordnungsprogramm Vorpommern. Greifswald: Amt für Raumordnung p.225.

ROSENTHAL, W., WOLF, T., WITTE, G., BUCHHOLZ, W. & RYBACZOK, P., 1998: Measured and modelled water transport in the Oder Estuary for the flood period July/August 1997. Dt. Hydrogr. Z. **50**,2/3: 215-230.

SCHERNEWSKI, G., PODSETCHINE, V., ASSHOFF, M., GARBE-SCHÖNBERG, D. & HUTTULA, T., in press: Spatial ecological structures in littoral zones and small lakes: Examples and future prospects of flow models as research tools. Arch. Hydrobiol. Advances Limnol.

SCHERNEWSKI, G., DANNOWSKI, R., HUMBORG, C., MAHLBURG, S., MÜLLER, C., POLLEHNE, F., STEIDL, J. & WALLBAUM, V., accepted: Interdisziplinäre Forschung zum Küstenzonenmanagement: Erfahrungen und Perspektiven am Beispiel der Oder. Bodden.

SCHERNEWSKI, G., T. HUTTULA, W.-D. JÜLICH, V. PODSECHIN & I. TEJAKUSUMA, 2002: Water quality problems in Baltic coastal waters: The Oder river as a source of human pathogenic viruses. Proceedings of the International Conference 'Sustainable Management of Transboundary Waters in Europe', UNECE, 21 - 24 April 2002, Miedzyzdroje, Poland, 341-345

SIEGEL, H., GERTH, M. & SCHMIDT, A., 1996: Water exchange in the Pomeranian Bight investigated by satellite data and shipborne measurements. Cont. Shelf. Res. **16**, 14: 1793-1817.

SIEGEL, H., MATTHÄUS, W., BRUHN, R., GERTH, M., NAUSCH, G., NEUMANN, T. & POHL, C., 1998: The exceptional Oder flood in summer 1997 - distribution patterns of the Oder discharge in the Pomeranian Bight. Dt. Hydrogr. Z. **50**, 2/3: 145-167.

SIEGEL, H., GERTH, M.& MUTZKE, A., 1999: Dynamics of the Oder river plume in the southern Baltic Sea: satellite data and numerical modelling. Cont. Shelf Res. **19**: 1143-1159.

TABATA, M., 1977: A Finite element approximation corresponding to the upwinding finite differencing. Mem. Numer. Math., **4**, 46-63.

UTNES, T., 1990: A finite element solution of the shallow-water wave equations. Appl. Math. Modelling, **14**(1), 20-29.