The Vistula river discharge front – surface observations

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Plume front
Surface water properties
River Vistula

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Abstract

The spreading of Vistula river water has been studied on the basis of surface spatial distributions of water properties. The horizontal divergence field of the gradient of a given property is analysed to find the main directions of surface water transport. This shows that advection in the direction perpendicular to the frontal line is weak. Examples of salinity, temperature (AVHRR/SST), density and nutrient concentration fields in the area adjacent to the river mouth are discussed.

1. Introduction

The hydrology of the Gulf of Gdańsk (Fig. 1) is influenced by both Baltic Sea waters and those of terrestrial origin, among which the Vistula (Wisła) is of the greatest significance. The role that the Vistula plays in the variability of the physical and chemical parameters in this region has been described in many papers *e.g.* Bojanowski (1981), Cyberska and Trzosińska (1984), Majewski (1972), Krężel and Cyberski (1993). Nevertheless, the problem of the hydrological front itself has not been taken up explicitly; however, it is clearly a zone where dynamic freshwater spreading is strongly marked by the presence of large horizontal gradients of water properties.

The discharge front forms at the border of the river-water plume where buoyant spreading is retarded by friction with and entrainment from the underlying water (Garvine, 1974; Bowman and Iverson, 1978). The spreading of the Vistula water and, therefore, the location of the front depends on the overall water circulation in the Gulf of Gdańsk (Kowalik and Wróblewski, 1971), local wind conditions and the rate of Vistula water outflow (Cyberska and Krzymiński, 1988). The aim of this study is to investigate the relation between the location of the surface-plume frontal zone and the direction of Vistula water transport. Preliminary results of the work were

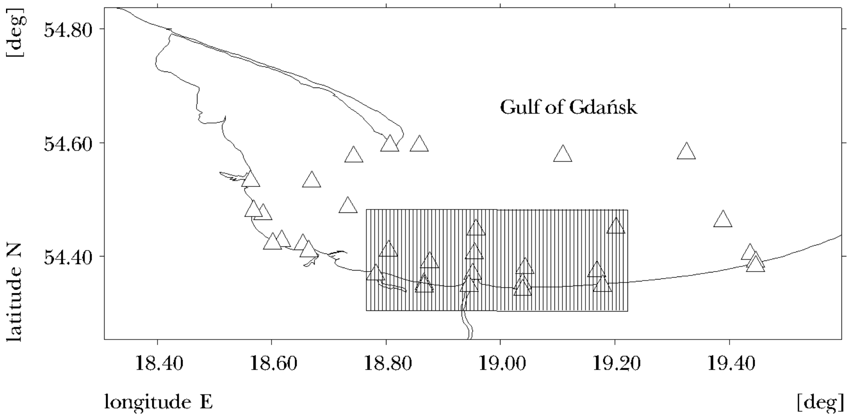


Fig. 1. △ location of sampling stations in the study area

presented at the 19th Conference of Baltic Oceanographers (Matciak and Nowacki, 1994).

2. Data preparation

Satellite data as well as *in situ* data were used to make maps of water temperature, salinity and density. Surface temperature data were obtained by means of the Advanced Very High Resolution Radiometer (AVHRR) carried aboard NOAA polar-orbiting satellites. The raw satellite data were processed at the Physical Oceanography Department of Gdańsk University. STD and chemical measurements were made at sampling stations covering an area of 50 km in width, the seaward border of which is 20 km from the shoreline (Fig. 1). Salinity and temperature were measured with an automatic probe and density was calculated in accordance with UNESCO algorithms; the analyses of chemical compounds were carried out by methods described in the Guidelines for the First Stage of the Baltic Monitoring Programme (Baltic Marine Environment, 1980). The use of satellite images provides an opportunity to obtain maps of surface temperature represented on a regular grid. Mean temperatures from the pixel are allocated to grid points with a spatial step of about 1 km. Similar maps based on *in situ* measurements were obtained by means of Kriging interpolation (Davis, 1986) with a gridstep of 1.85 km (1 Nm). Additional empirical data, including current velocities, come from the Vistula river cone area (4 × 4 km) (Nowacki and Urbański, 1980), where the gridstep was taken to be *ca* 0.2 km. The data prepared in this way were used to estimate the horizontal divergence field of the gradient of a given parameter $c : \partial^2 c/\partial x^2 + \partial^2 c/\partial y^2$; the divergence is further denoted by $\Delta_h\, c$, and evaluated by using a finite-difference approximation. The results of computations are smoothed in the sense that successive derivatives are the arithmetic mean of the derivatives from neighbouring grid points.

3. Method

It is characteristic of all the situations investigated, no matter which parameter is taken for computations, that the lines of zero horizontal divergence coincide with the areas having the largest gradients and high absolute values of $\Delta_h c$, separating areas of divergence of the opposite sign. In particular, if $\partial^2 c/\partial x^2$ and $\partial^2 c/\partial y^2$ take maxima, then $|\nabla_h c|$ also takes a maximum; if one of these partial derivatives takes a maximum and its spatial changes dominate the changes of the other, resulting in $\Delta_h\, c = 0$, $|\nabla_h c|$ takes a maximum with reference to the x or y axis. Thus, the disappearance of the horizontal divergence is expected to accompany the frontal structures. Obviously, the isoline of zero divergence also appears where the changes in a given parameter are negligibly low in comparison with the frontal line zone.

The interpretation of the results is based on a stationary (the sea surface is taken to be horizontally flat and time-invariable), simplified advection-diffusion equation for a conservative property of water at the sea surface:

$$u\frac{\partial c}{\partial c} + v\frac{\partial c}{\partial y} = k_h\,\Delta_h\,c + \frac{\partial}{\partial z}\left(k_v\frac{\partial c}{\partial z}\right), \tag{1}$$

where u, v are the components of the current velocity along the x and y axis, and k_h and k_v are the horizontal and vertical coefficients of the eddy diffusivity respectively. It is assumed here that the process of horizontal mixing is isotropic, but the value of k_h need be constant only in the area around a grid point where the second order spatial derivatives are calculated. The equation involving the relative density ($c = \sigma$) can be obtained from the continuity equation of an incompressible fluid or by combining the linear effects of salinity and temperature changes on density (see *e.g.* Garrett and Horne, 1978). In both cases cabbeling is ignored, as it requires the process of eddy stirring to be followed by molecular mixing, which is usually neglected in the turbulent flow equation.

For the zone where $\Delta_h c$ disappears from the right-hand side of eq. (1), only the term describing vertical diffusion in the thin surface water layer remains. As this is a place where the pycnocline reaches the surface, vertical mixing must be strongly reduced, and the scalar product $\vec{\nabla} \circ \nabla_h c$ reaches a minimum. This means that the surface advection of the parameter under investigation in the direction perpendicular to its isolines is weak. Here there are two possibilities: either the vector of the horizontal surface current velocity is nearly perpendicular to the vector of gradient c, or the vector $\vec{\nabla}$

is small or even equal to zero. The latter case may be a manifestation of an important feature of discharge front dynamics when the riverine waters sink at the frontal line, and flow on along the pycnocline (Garvine, 1974).

4. Results and discussion

Frontal zones in seas can be described by a variety of physical and chemical properties of water (Fedorov, 1986). The best indicators of the spread of riverine waters in the sea are density and salinity, for the driving buoyant force is mainly due to the salinity/density difference. The spatial distributions of these two parameters in the study area are very similar after the same interpolation procedure has been used. On the other hand, remote sensing is a much more efficient technique for mapping sea surface properties than *in situ* sampling. However, at the present state of the art, only temperature among the parameters describing the seawater state can be successfully interpreted from satellite pictures.

Comparison of the fields of surface relative density and current velocity (Figs. 2, 3) seems to confirm that fronts are zones through which advection is weak. This is in accordance with the fact that the isolines of a given passive water property tend to lie parallel to the streamlines in the convergent zone if the initial angle between them is less than 45°, and that the isolines are finally compressed to form an area of large gradients (Fedorov, 1986). The density front may appear very close to the river mouth, restricting laterally the main stream of freshwater flow. It is clearly seen on divergence maps that the zero lines follow the direction of the frontal zones, and that the vectors of current velocity in the main stream are parallel to them. Beyond the main stream the current velocity field is very complex. Smaller frontal structures and convergence zones can be observed, as in Fig. 3, and are accompanied by zones of vanishing horizontal divergence.

It must be mentioned that the quality of some of the results presented in this paper depends on the location of the sampling stations, and on the interpolation method, which is considered to be one of the most objective and is commonly used to describe various spatial phenomena. Satellite photographs of the sea surface provide a more accurate picture of the temperature field (Figs. 4, 5) because of the greater spatial density of measurements, so this method may be particularly useful if the temperatures of the river and the receiving waters differ significantly, *i.e.* in autumn and spring.

Taking into consideration the whole study area, the frontal line of the Vistula can be divided into three parts. Two of them are directly adjacent to the shore on either side of the river mouth, whereas the third one occurs

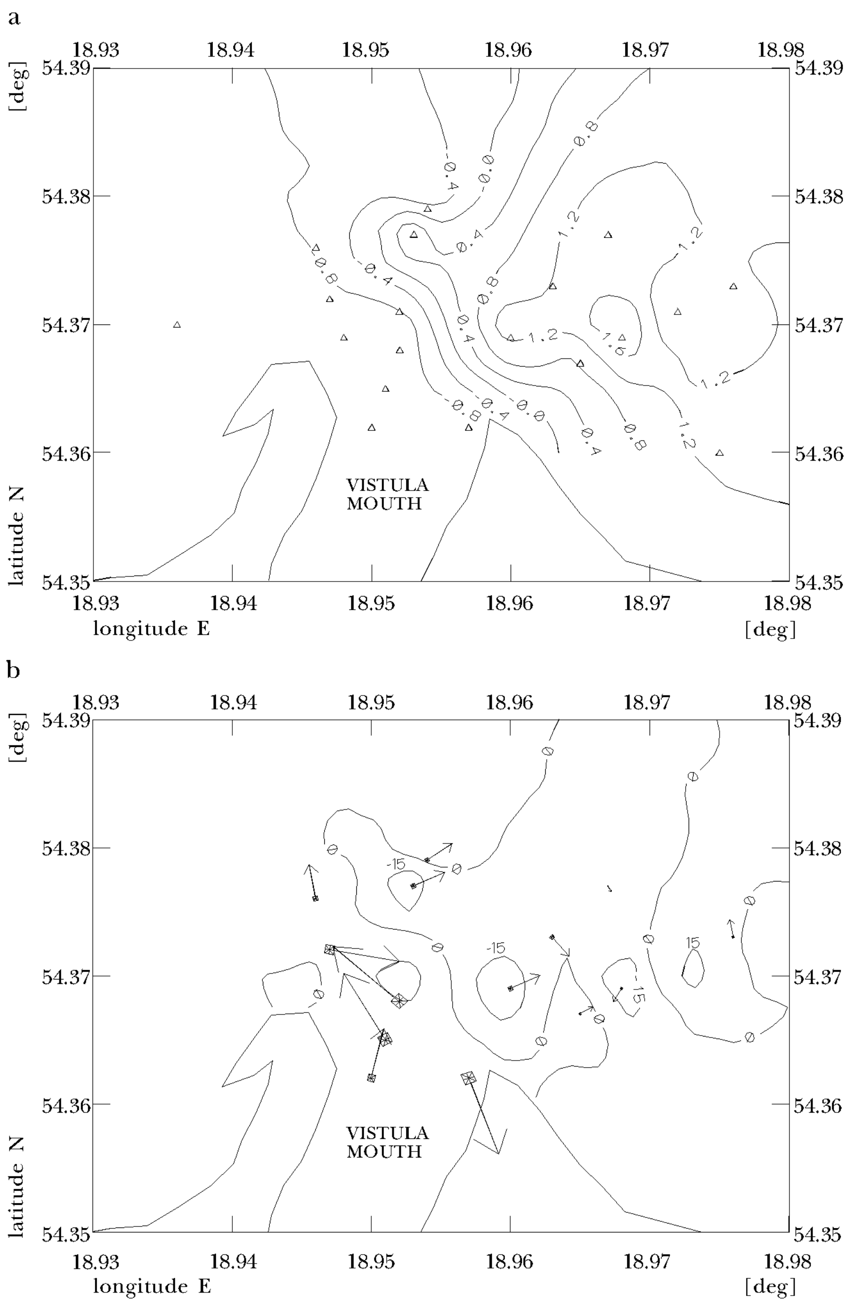
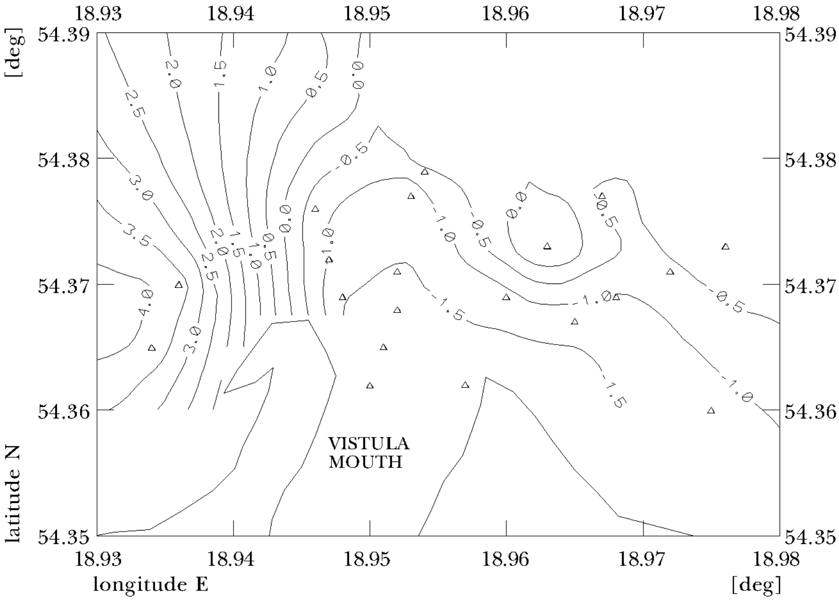


Fig. 2. Surface spatial distributions in the area of the Vistula river cone on 12.07.1977: relative density, △ location of sampling stations (a), horizontal divergence of density $[(0.2\ \mathrm{km})^{-2}]$, → surface-current velocity vector: the lengths of the vectors are linearly scaled in the interval between 0.5 and 0.05 $[\mathrm{m\ s^{-1}}]$ (b)

a



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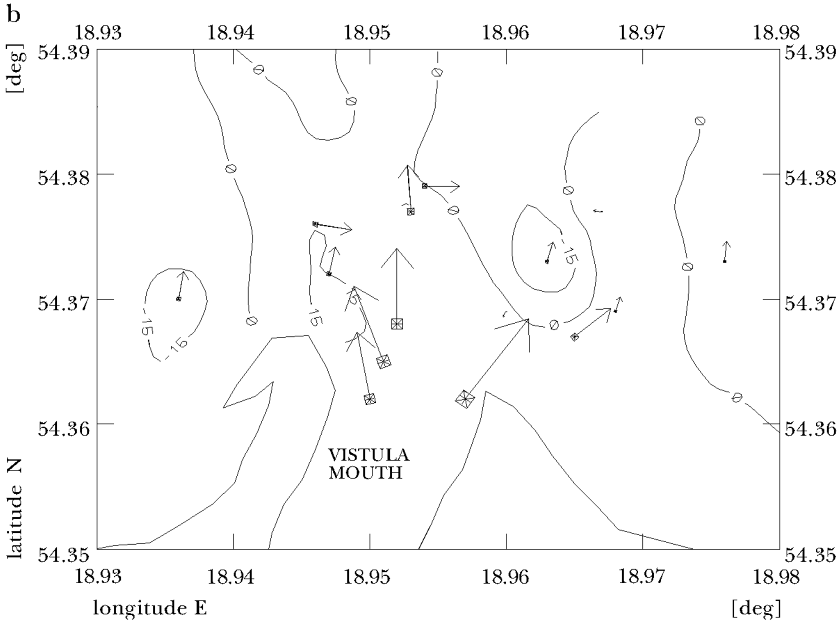

Fig. 3. Surface spatial distributions in the area of the Vistula river cone on 14.07.1977: relative density, △ location of sampling stations (a), horizontal divergence of density $[(0.2\ \mathrm{km})^{-2}]$, → surface-current velocity vector: the lengths of the vectors are linearly scaled in the interval between 0.5 and 0.05 $[\mathrm{m\ s^{-1}}]$ (b)

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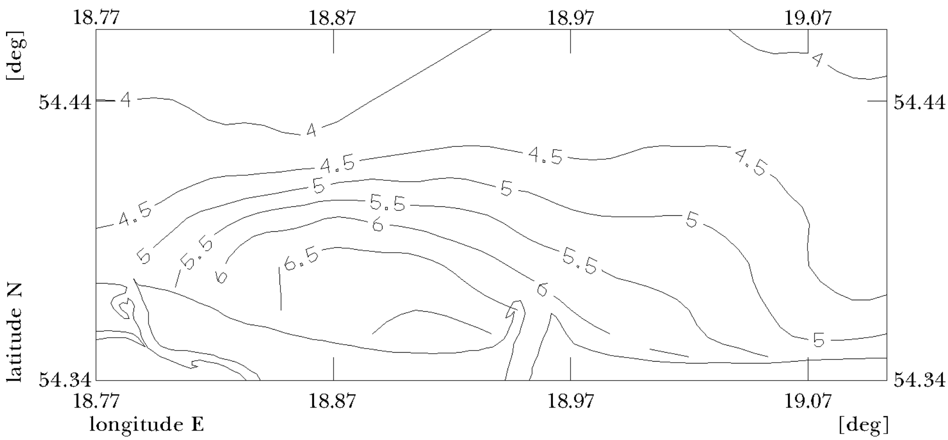

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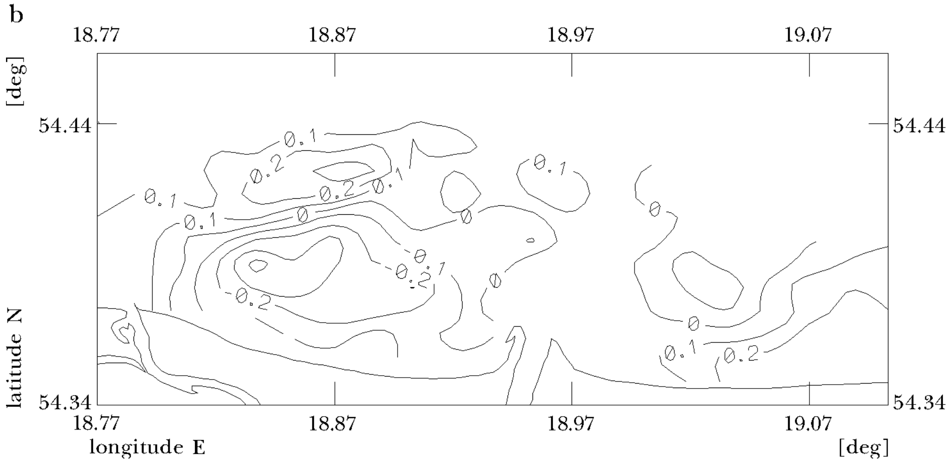


Fig. 4. Surface spatial distributions on 6.04.1990 (10.40 GMT): temperature (AVHRR) [°C] (a), horizontal divergence of temperature [°C (1.85 km)$^{-2}$] (b)

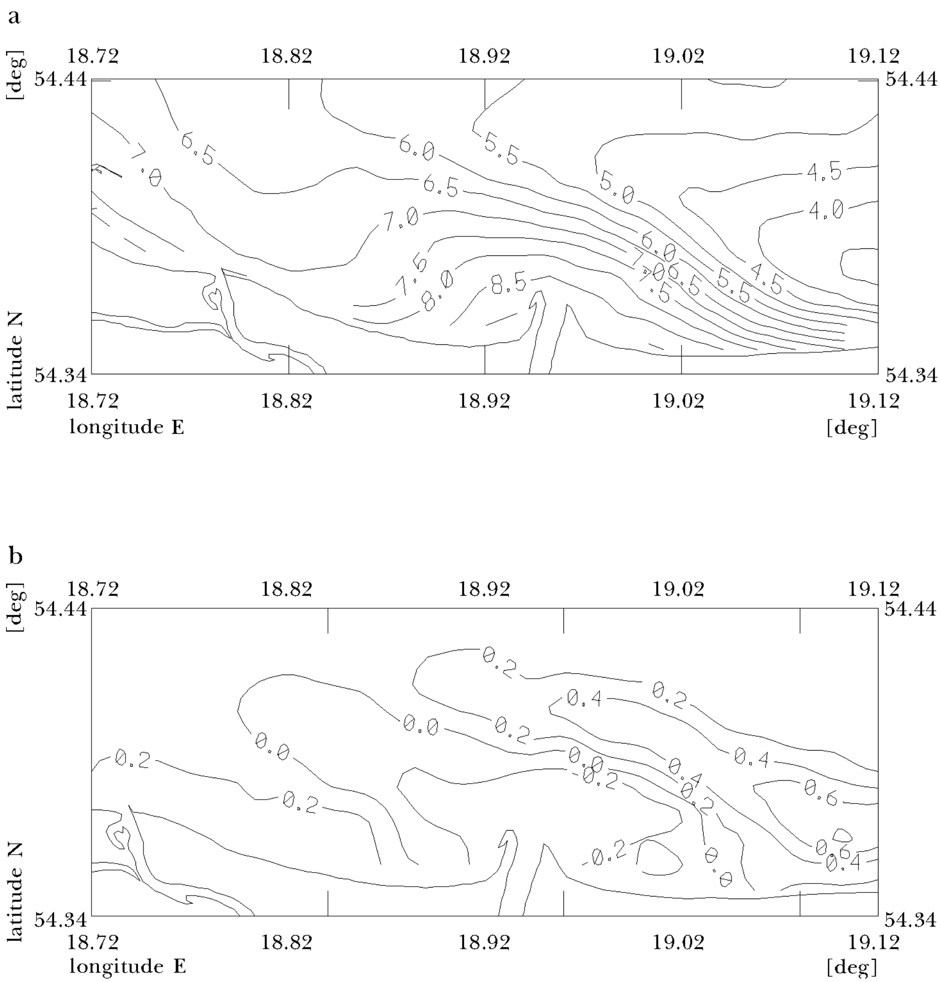
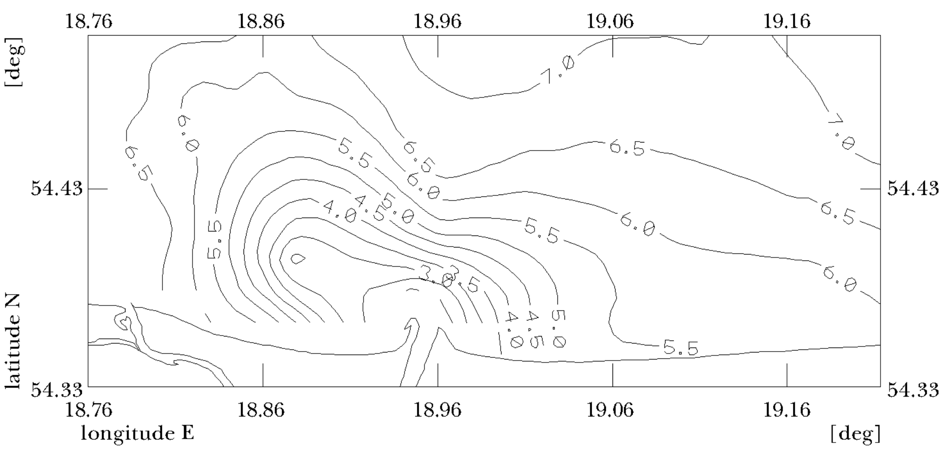


Fig. 5. Surface spatial distributions on 10.05.1988 (8.15 GMT): temperature (AVHRR) [°C] (a), horizontal divergence of temperature [°C (1.85 km)$^{-2}$] (b)

a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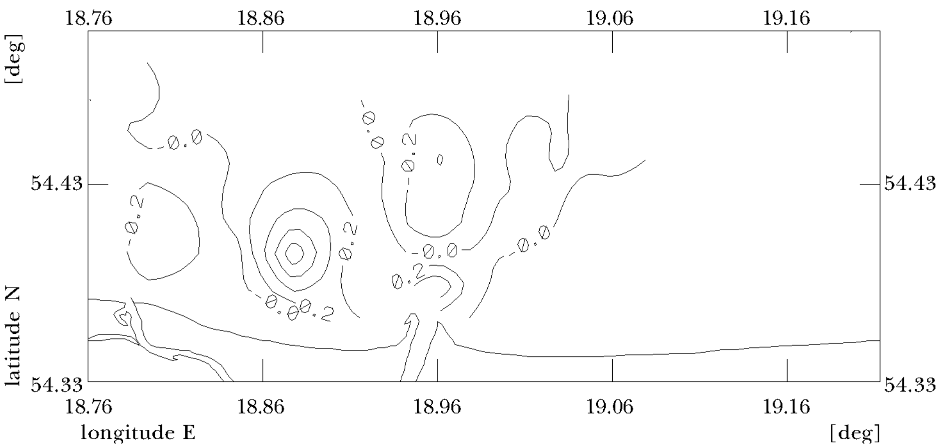
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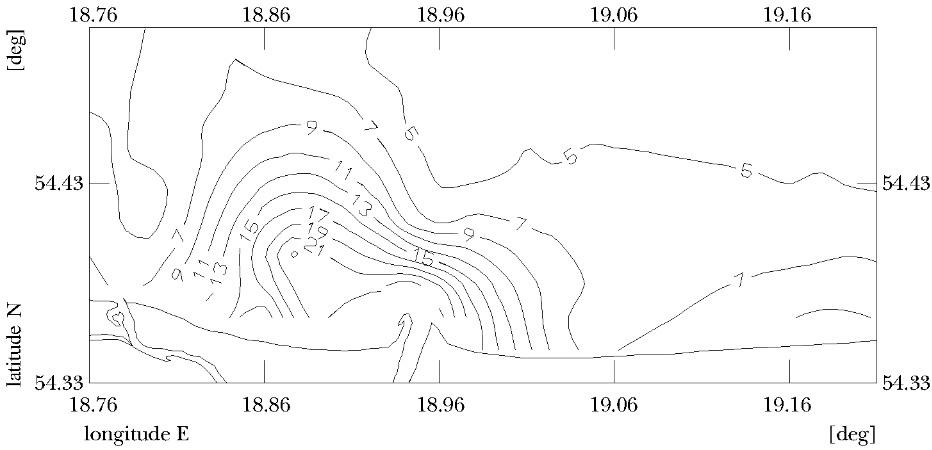
c



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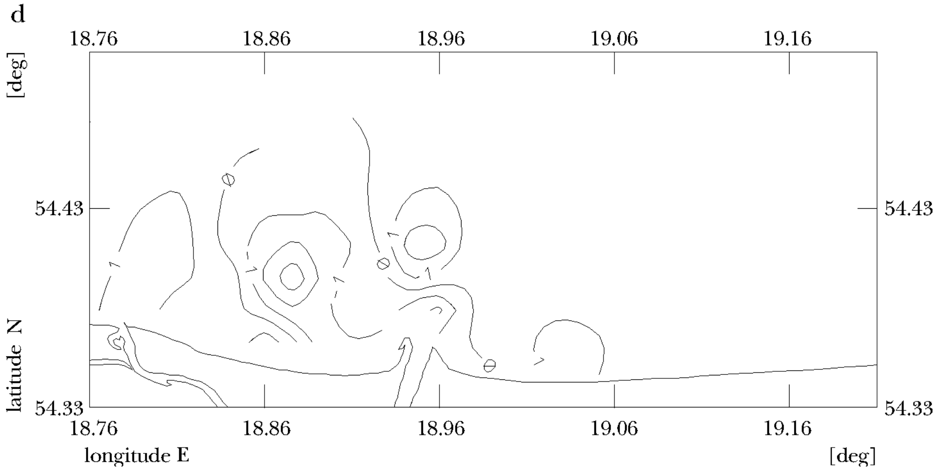
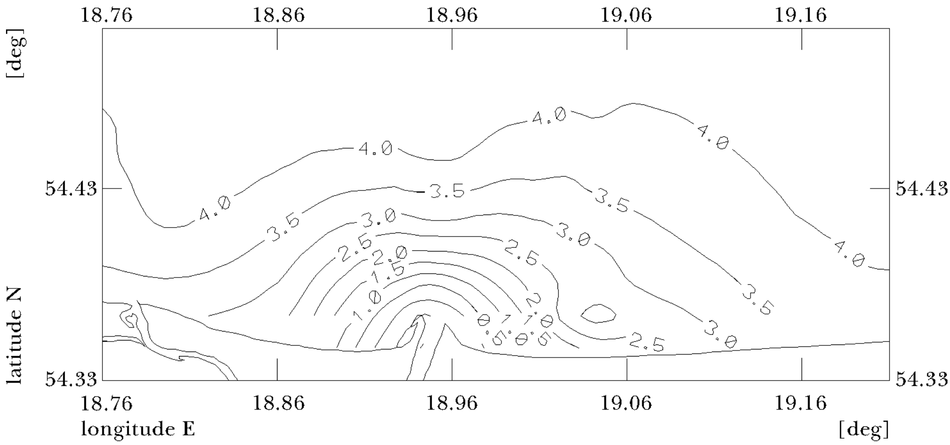


Fig. 6. Surface spatial distributions on 18–19.09.1989: salinity [psu] (a), horizontal divergence of salinity [psu (1.85 km)$^{-2}$] (b), silicon [μmol dm^{-3}] (c), horizontal divergence of silicon [μmol dm^{-3} (1.85 km)$^{-2}$] (d)

a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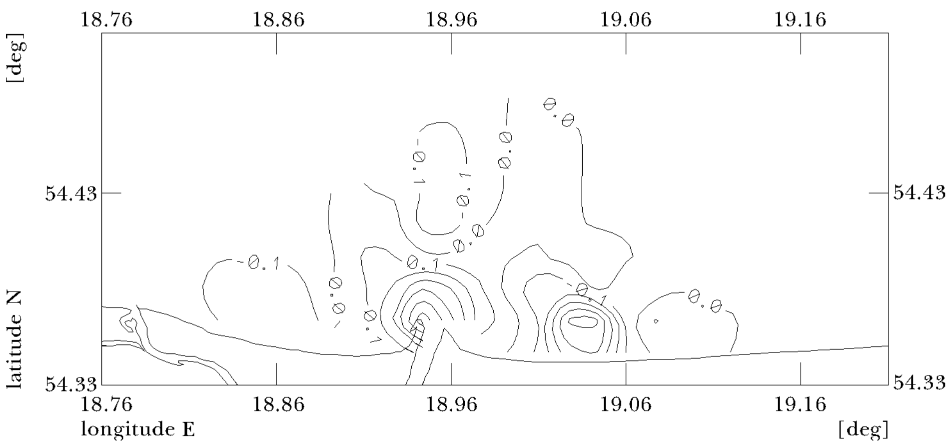
b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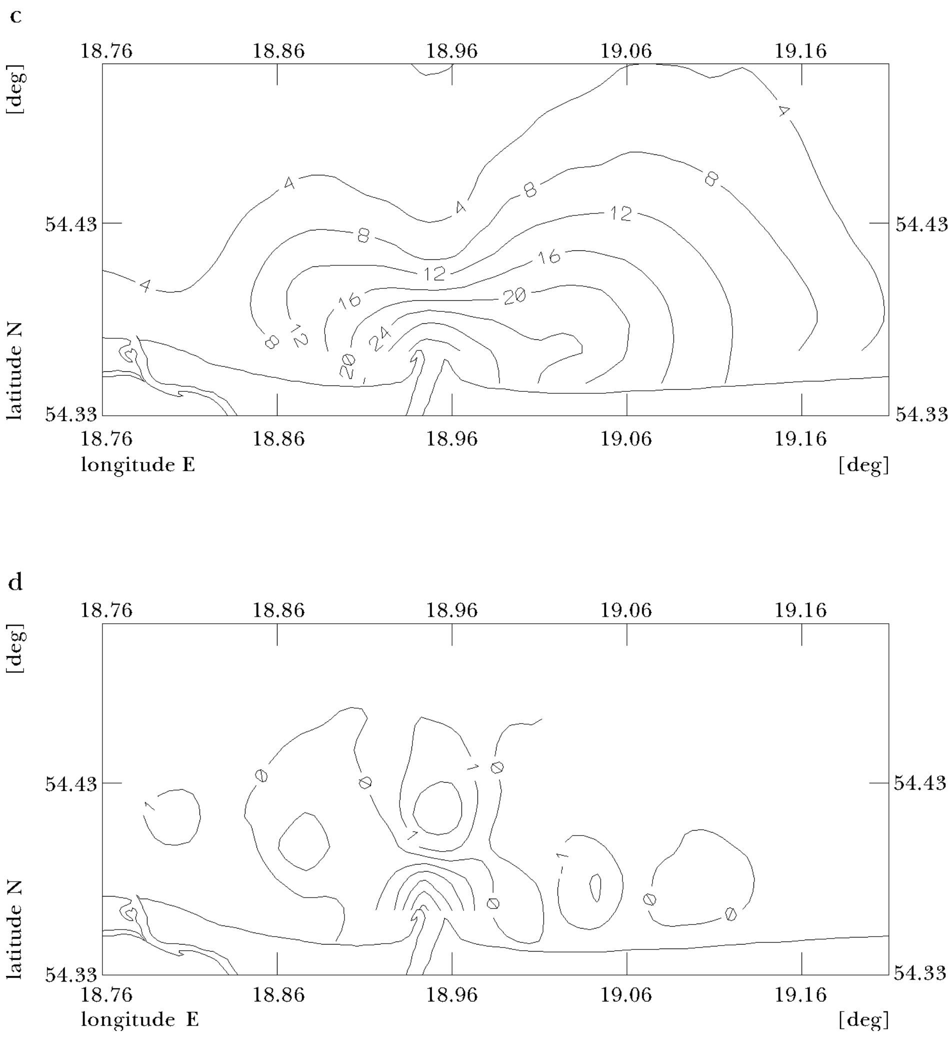

Fig. 7. Surface spatial distributions on 28.07.1986: salinity [psu] (a), horizontal divergence of salinity [psu (1.85 km)$^{-2}$] (b), phosphate [μmol dm^{-3}] (c), horizontal divergence of phosphate [μmol dm^{-3} (1.85 km)$^{-2}$] (d)

at a certain distance from the coast. This configuration depends on the external factors, *e.g.* wind conditions, acting on the system during a given period of time. In calm weather, with a windspeed below 4 m s^{-1}, the situation may be as in Figs. 6, 7, when the northward river flow forks at a distance of 3.5–5.5 km from the coast into two streams going north-westwards and north-eastwards. The divergence maps show that freshwater spreading northwards and along the shore is to some extent limited, so in the main it is a relatively small coastal area that is strongly influenced by the river water. The presence of the observed frontal zones between the river and ambient waters is confirmed by the spatial distribution of silicon concentration (Figs. 6c, 6d) and phosphate concentration (Figs. 7c, 7d). It is also possible that river waters may be trapped in the areas between the coastal and frontal lines, remaining there for a lengthy period of time (Figs. 4, 5). Such a situation favours the accumulation of substances carried by Vistula water.

Summing up, it seems that during calm weather, Vistula river water cannot spread over a great area and accumulate near the river mouth. The aerial extent of the freshwater plume can be estimated on the basis of the divergence field of the water surface properties and the frontal line location. More general conclusions can be formulated after a statistical analysis of the surface front location over a longer period of time. This would also contribute to a better understanding of the chemical and biological processes in the area.

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