Papers

Transport of the Odra river waters and circulation patterns in the Pomeranian Bay*

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Abstract

During several cruises of r/v 'Oceania' in different seasons of 1993–1997 detailed investigations of the Pomeranian Bay were carried out with particular attention to the vicinity of the Odra river mouth. On the basis of CTD soundings as well as quasi-continuous profiling by means of a towed CTD probe, the thermohaline fields were analysed in order to determine the pattern of riverine water transport. The characteristic flow paths under different meteorological conditions were identified, Ekman transport of freshened waters being found to prevail along the coasts of the Pomeranian Bay. Physical phenomena such as the pulsating outflow of the river Odra and the formation of isolated plumes of freshened water were observed. The vertical and horizontal extents as well as the lifetime and speed of movement of the plume-like structures were estimated. A typical plume was a few km in diameter and there were steep horizontal and vertical salinity gradients at the boundaries. As the plume moved away from the mouth, it was transformed and finally vanished. There was strong wind mixing and entrainment into underlying, more saline water at some distance from the channel mouth. Hydrological fronts between riverine and ambient waters frequently formed. Numerous intrusions were found in the temperature and salinity profiles in the frontal zones. The freshwater fraction in the entire volume

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of the bay waters was estimated for different hydrological situations, the highest values being obtained for the period following the flood event of summer 1997. Under favourable wind conditions, dense, saline waters flowing in from the Arkona and Bornholm Deeps were present in the near-bottom layer at the edges of the bay. Anomalously, waters of higher salinity were found in the Pomeranian Bay in November 1997 as a result of a minor inflow from the Danish Straits.

1. Introduction

The freshwater buoyancy input resulting from river run-off always creates a particularly subtle and complex physical regime radically different from other parts of shelf seas. For that reason, systems that have been termed ROFIs (Regions of Freshwater Influence) have become the object of detailed observations as well as modelling efforts in recent years. The classification introduced by Simpson (1997), based on the configuration of the coastline into which river water flows, distinguishes four types of regions: open, corner, gulf, and gulf with sill. In the simplest situation, river discharge enters the sea from a straight coast and is constrained by the Coriolis force to flow parallel to the coast. In a gulf the freshwater flow pattern is the combined effect of the classical longitudinal estuarine circulation and the Earth's rotation, varying considerably with particular topographies (Fujiwara *et al.* 1997). Wind and river runoff are the dominant factors for the onset and breakdown of stratification in a region influenced by freshwater. In all these systems the spreading flow and associated undercurrents tend to stratify the water column. This tendency is opposed by mechanical stirring resulting from tides, waves and wind (Simpson 1997). Attempts have been made to explain the behaviour and shape of riverine plumes on the basis of numerous analytical and numerical models supported by field studies (*e.g.* Chao & Boicourt 1986, Garvine 1987, Chao 1988, O'Donnell 1990). Chao and Garvine both showed that freshwater plumes have an Ekman-like response to forcing by a local coastal wind, causing the flow to run parallel to the shore with the coast to the right. But Garvine's model also suggested that small-scale plumes (where the Coriolis force is secondary to the advective terms) lack the Coriolis-induced deflection. In such a case, a plume can be transported in the direction of the ambient current and delineated on the upstream side by a strong frontal boundary.

The pulsating Odra (Oder) river discharge and the resulting circulation patterns show a distinct analogy with the Rhine region of freshwater influence, widely investigated by different authors (*e.g.* de Ruijter *et al.* 1997, Luyten 1997). The tide moving into the Rhine estuary modulates the outflow and may reverse the flow of river water upstream. As a result, riverine water discharged during the previous tidal cycle is 'pinched-off' at the river mouth and exits to the shelf as an isolated blob. Trains of freshwater lenses are driven in a coastal jet that is strongly deformed and mixed, especially under the influence of winds. The halting of the river discharge at some stage and a sufficiently large separation of consecutive pulses are the two principal criteria governing such a pulsating outflow as opposed to a continuous one. In case of the Pomeranian Bay, variations in sea-surface level due to local winds are the factor controlling this pulse discharge.

Fennel & Mutzke (1997) investigated the dynamics of river plumes in a stratified non-tidal sea in detail on the basis of a linear analytical theory and simulations with a numerical primitive equation model. They found that the response pattern to a sudden commencement of river runoff consisted of two parts. First, a freshwater bulge was formed right in front of the river mouth and set up a coastal current carrying the freshwater along the shore as a result of baroclinic Kelvin wave propagation. The combined effect of buoyancy and wind forcing revealed that the plume pattern is strongly affected by on- and offshore Ekman transport. Dispersion and entrainment of freshwater is strongest during upwelling winds, while downwelling conditions tend to maintain the plume. These theoretical findings are in good agreement with the situations observed in the vicinity of the Odra estuary, where offshore Ekman transport has often caused the plume to become detached from the coast, whereas onshore Ekman transport has confined the plume to an area near the river mouth.

The sharp horizontal salinity and density contrasts, one or two orders of magnitude greater than the horizontal gradients in the open ocean, are characteristic of all river discharge fronts. They are manifested by bands of foam and flotsam as well as by changes in the colour and transparency of the water. The band of foam is usually a sign of flow convergence at the front, and this front restricts the maximum extent of the freshwater plume at the surface (Fedorov 1983). The horizontal scale of the front is usually a few times the thickness of the buoyant layer. Significant downwelling was observed within the frontal area of maximum surface convergence (O'Donnell *et al.* 1998). Downwelling and convergence at the front establish the mechanism entraining the ambient saline water under the front. Losses of freshwater due to vertical entrainment can be compensated by the constant addition of water to the plume from the river discharge or, when the river outflow is temporarily blocked, can result in the destruction of the plume and decrease the front's sharpness.

Furthermore, a feature typical of ROFI systems is the switching, over short time scales, between vertically mixed and stratified conditions in response to changes in the intensity of stirring by winds and wave motion and to variability in the river run-off (Simpson 1997). Interactions between the density-driven flow and the mixing mechanism depend on the topography and magnitude of forcing, which are significantly variable in the Pomeranian Bay.

The present work seeks to understand and describe the circulation patterns resulting from freshwater discharge into the Pomeranian Bay and modified by external factors, principally wind forcing, bottom topography and the lie of the coastline. The various sections describe the study area, the methods and measurements, analyse the flow pattern under different wind conditions with respect to the seasonal variability of the thermohaline fields, and examine the shape, behaviour and structure of the freshwater plumes and fronts in greater detail. Two specific situations illustrating the influence of the most important factors – riverine water input and exchange with adjacent open seawaters – are dealt with later. Finally, some conclusions based on the results of our five-year-long studies are discussed.

2. Study area

Located off the Polish and German coasts, the Pomeranian Bay covers an area of about $6000\,\mathrm{km}^2$ (together with adjacent open waters, about $8300\,\mathrm{km}^2$). To the north it adjoins the deep-water Arkona and Bornholm Basins, separated by the shallow Adler Bank extending southwards from Bornholm. At the edge of the Pomeranian Bay, between these shallows and the Odra Bank, which occupies a central position in the bay, there is a trench affording a connection between these two deep basins. Owing to the broad Odra Bank and the complex network of shallow water passages along the coasts ($< 10\,\mathrm{m}$ deep), the average depth in the Pomeranian Bay is *ca* 13 m. Even though some 80% of the bay area is less than 20 m deep, the bottom topography is very complicated. Also of importance is the fact that the flow pattern in the Pomeranian Bay is affected by the elongated bottom depression along the eastern coast of Rügen and the shallow bank off this coast stretching from the mouth of the Greifswalder Bodden towards the small island of Greifswalder Oie.

The waters of the river Odra enter the Pomeranian Bay via the Szczecin Lagoon. This has a retention time of several weeks and acts as a buffer to river water transport. Direct river outflows into the bay are relatively insignificant: $< 10\%$ of the total river discharge. Majewski (1974) estimated the total river discharge into the Pomeranian Bay for the years 1951–1960 at $560\,\mathrm{m}^3\,\mathrm{s}^{-1}$, *i.e.* $17.6\,\mathrm{km}^3$ per year. If one compared this value with the relatively small volume of the bay ($73\,\mathrm{km}^3$), it is obvious that riverine water is of great significance to the hydrological conditions in the Pomeranian Bay. Other estimates from recent years yield slightly higher river discharge values (calculations based on data published by Niemirycz 1994, Niemirycz

& Borkowski 1995, 1996, 1997, Heybowicz *et al.* 1998). The mean annual discharge of the Odra during the measurement period (1993–1997) was estimated at $632\,\mathrm{m^3\,s^{-1}}$, a figure well in excess of the long-term mean (1971–1990) of $574\,\mathrm{m^3\,s^{-1}}$. The maximum outflow of riverine water was recorded during the 1997 flood, when instantaneous values of around $3200\,\mathrm{m^3\,s^{-1}}$ were reached.

There are also significant seasonal differences in the river discharge during the year. Mean monthly outflows can vary widely: *e.g.* in 1994 the Odra discharge in April and May was $> 1400\,\mathrm{m^3\,s^{-1}}$ while in August it dropped to $< 400\,\mathrm{m^3\,s^{-1}}$. In general, some 2/3 of the entire annual volume of freshwater enters the sea between January and May (Majewski 1974), whereas during the second half of the year (summer, autumn) river water outflow is relatively low (usually no greater than $500\,\mathrm{m^3\,s^{-1}}$).

Water exchange between the Szczecin Lagoon and the Pomeranian Bay is established through a system of three straits: the Peene, Świna and Dziwna. The Świna, a relatively short (16.3 km) but deep channel situated centrally at the head of the Pomeranian Bay, is the main route of river water outflow. At a rough estimate, the Świna carries around 75%, the Peene 15% and the Dziwna 10% of Odra waters to the sea (Majewski 1980). These values appear to be tentative because of the considerable variability in the inflow/outflow conditions in the straits. These depend on forces directly affecting the free surface of the water as well as the horizontal pressure gradient due to barotropic (slopes between strait ends, tides, seiches, storm surges, changes in river discharge, etc.) and baroclinic (difference in density of water at the strait ends) gradients.

The difference in water levels between the Szczecin Lagoon and the Pomeranian Bay, inducing flow through the straits, is due mainly to random storm surges resulting from the atmospheric circulation over the Baltic Sea or locally over the bay (Robakiewicz 1993). The nature of the flow in the Świna varies significantly: when the slope between the ends of the channel is more than 0.05 m, a barotropic gradient dominates and there is an outflow of riverine water (or inflow of seawater into the strait) along the whole vertical profile. But in more than 50% of cases, the difference between the water levels in the Lagoon and the Pomeranian Bay is small (no greater than 0.05 m). Then, pure outflow or inflow conditions are observed alongside a bilaminar and bidirectional baroclinic flow. The inflow of saline water into the deeper layers and the outflow of fresh and mixed water in the upper layer cause salt wedges to form in the channel. Variations in flow velocities are significant, with periods ranging from a few minutes to tens of hours. Considerable variations in flow conditions from outflow to inflow passing through bidirectional flow were reported in the Świna by Jasińska *et al.* (1996) with time intervals of a few hours. The main consequence of the complicated and unsteady nature of river water transport through the straits (especially through the Świna) is that Odra river water enters the Pomeranian Bay not continuously but in the form of discrete pulses, a fact which exerts a considerable influence on circulation patterns.

3. Methods and measurements

During five years of research in the Pomeranian Bay (1993–1997) eleven cruises on board r/v 'Oceania' were organised to carry out the field studies in the bay area and adjacent waters of the open sea. The Polish investigations, aimed at studying the influence of the river Odra on the ecosystem of the Pomeranian Bay, were carried out in parallel with the German TRUMP project (Transport und Umsatz in der Pommerschen Bucht). The first pilot expedition took place in September 1993. Based on a preliminary understanding of the structure of the thermohaline fields, a radial grid of stations was set up to cover the whole bay area together with neighbouring deep regions of the Baltic Sea. During successive cruises this radial grid, consisting of five 'rays' converging at the river mouth (Fig. 1), was measured initially in order to predict the direction and range of riverine water transport. Subsequently, measurements were conducted over the fine scale grids (with a horizontal resolution of 1–2 Nm), which were arranged

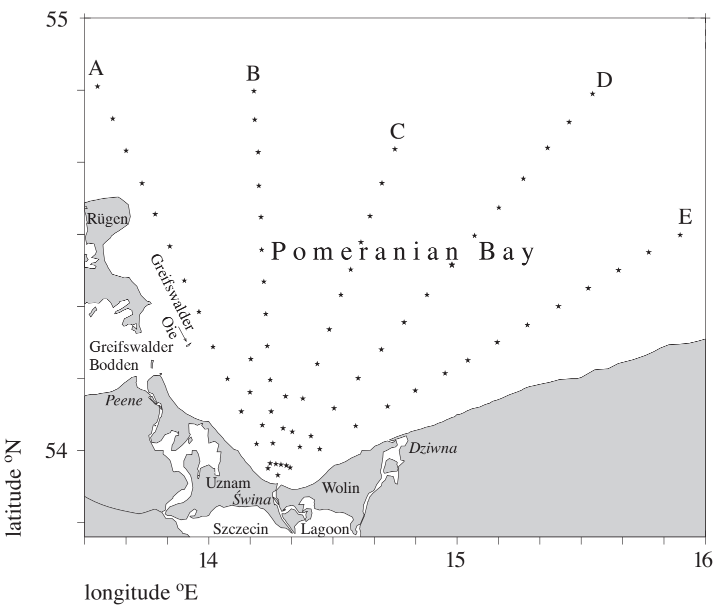

Fig. 1. Location of the radial station grid in the Pomeranian Bay in 1993–1997

for detailed observations of the small-scale structures (isolated plumes, hydrological fronts, etc.) The most interesting findings were investigated with high spatial resolution along transects, where readings were taken with a towed undulating CTD probe ('tow-yowed' probe). The field studies were performed during different seasons (except midsummer), but special attention was paid to spring and autumn months. A summary of the research campaigns and the measurements is given in Table 1.

Table 1. Research cruises carried out by the Institute of Oceanology PAS in the Pomeranian Bay in 1993–1997

Cruise No.	Date	Radial grid	Fine-scale grids	High resolution transects
1	20.09.93–03.10.93	yes	no	no
2	05.05.95–20.05.95	no	yes	no
3	23.09.95–28.09.95	no	yes	no
4	03.10.95–09.10.95	yes	yes	no
5	05.02.96–16.02.96	yes	no	no
6	23.04.96–03.05.96	yes	yes	yes
7	11.09.96–22.09.96	yes	yes	yes
8	09.04.97–21.04.97	yes	no	no
9	10.08.97–18.08.97	yes	yes	no
10	31.08.97–05.09.97	yes	no	no
11	10.11.97–29.11.97	yes	no	yes

Temperature and salinity data were collected by means of two CTD probes: Guideline 8770 and Seabird 9/11+. The rough data were processed and averaged at the 0.5 m horizons.

A purpose-built structure was used to hold the typical CTD, the Guideline 8770 in our case, and could be winched into and out of the water. The speed of this movement, and thus the frequency of profiling and the distance between profiles, also depended on the vessel's speed, the rpm of the winch, the weight attached to the carrier and the sampling depth. In most cases the usual speed of 3–4 knots allowed vertical profiles to be obtained every 100–200 m in the shallow waters of the Pomeranian Bay (depths of a dozen or so metres or less). Every sounding was precisely positioned by a differential GPS system. Distributions of salinity and temperature were presented in real time, which enabled the measurements to be fitted to the ongoing situation.

Meteorological observations, *i.e.* a full set of standard parameters (air temperature, wind speed and direction, atmospheric pressure, humidity, cloud cover) were made every 3 hours during the entire measurement periods.

4. Thermohaline fields

The horizontal distributions of temperature and salinity fields in the Pomeranian Bay area display a characteristic seasonal variability, which is modified by the influence of the variable Odra discharge and wind forcing (Majewski 1974, Beszczyńska-Möller 1995). Although buoyancy input from the riverine waters tends to induce stratification, mixing due to wind stress and wave motion contribute significantly to the dissipation of the vertical salinity and temperature gradients in the shallow bay waters. The spatial distribution of these properties is closely dependent on the wind strength and direction, both through wind-induced surface mixing and advection by wind-driven surface currents. In most cases the potential density σ_t field corresponds closely to the salinity distribution because of the insignificant input from spatial or vertical differences in temperature.

In general there are some discrepancies arising from seasonal variability, especially in the horizontal distribution of temperature (Fig. 2). During the late autumn and winter months, the substantial heat losses from the shallow waters of the inner Pomeranian Bay cause them to become cooler than the open waters, *e.g.* October 1995, February 1996, November 1997. Moreover, if the outflow from the river mouth is examined, the riverine water is found to be cooler than the adjoining waters at the head of the bay. During spring the inshore waters begin to heat up rapidly and river discharge starts to carry a warmer mass of water. Hence the pattern of isotherms is reversed: the temperature is highest near the river mouth and coastal shallows, and drops towards the open part of the bay, *e.g.* April 1996, April 1997, and May 1995 (not shown on Fig. 2).

The minimum temperature noted in the Pomeranian Bay was below 0°C, and was recorded in February when most of the bay was covered by fast ice. Maximum temperatures (20–23°C) were recorded in late summer/early autumn (August 1997, September 1997). They were higher than the long-term mean for the summer months because of the combined influence of the large amount of relatively warm riverine waters entering the bay during the flood event and the high air temperatures. The horizontal temperature gradient did not normally exceed 2°C over the entire Pomeranian Bay. Only during spring warming and autumn cooling and the simultaneous intensive influx of freshwater were spatial differences of surface temperature higher than 5–6°C recorded. Vertical temperature gradients were related mainly to the riverine water flow and, at the edges of the bay, to the influence of open-sea waters, where a stratification typical of the deep regions of the Baltic Sea was established.

Seasonal changes in salinity distribution were the effect of the variable intensity of the Odra discharge and the variable supply of Pomeranian Bay

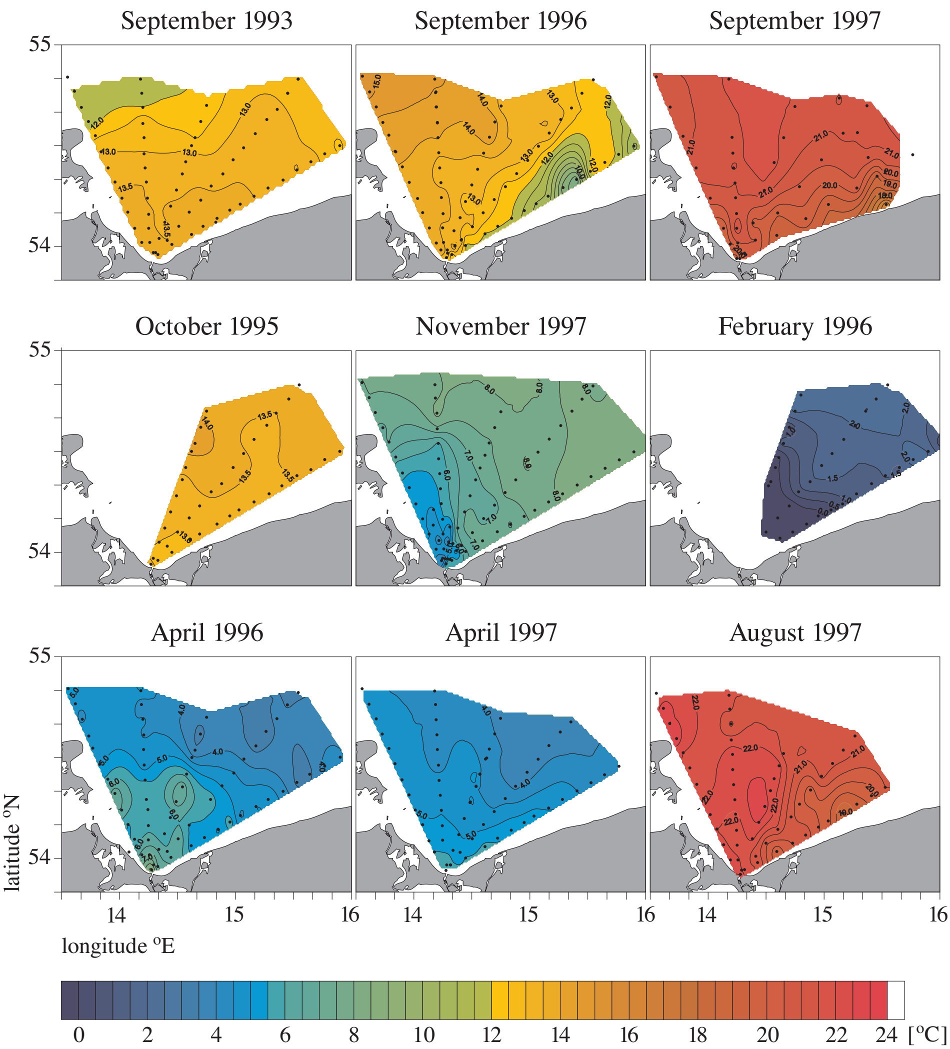

Fig. 2. Distributions of surface temperature [°C] in the Pomeranian Bay in different seasons 1993–1997

waters with highly saline water from the adjacent open-sea area (Fig. 3). In general, the drop in salinity was highest in the spring months, when the riverine outflow to the bay was at its most intensive. During the measurement period 1993–1997, the highest Odra discharge values were recorded between March and May, with the exception of the flood event in August 1997. The salinity in the nearest neighbourhood of the river mouth decreased significantly during strong outflow pulses, dropping to about 4–5 PSU in the main flow of riverine water; however, values < 2 PSU were also recorded in isolated cases. The range of freshwater influence on the

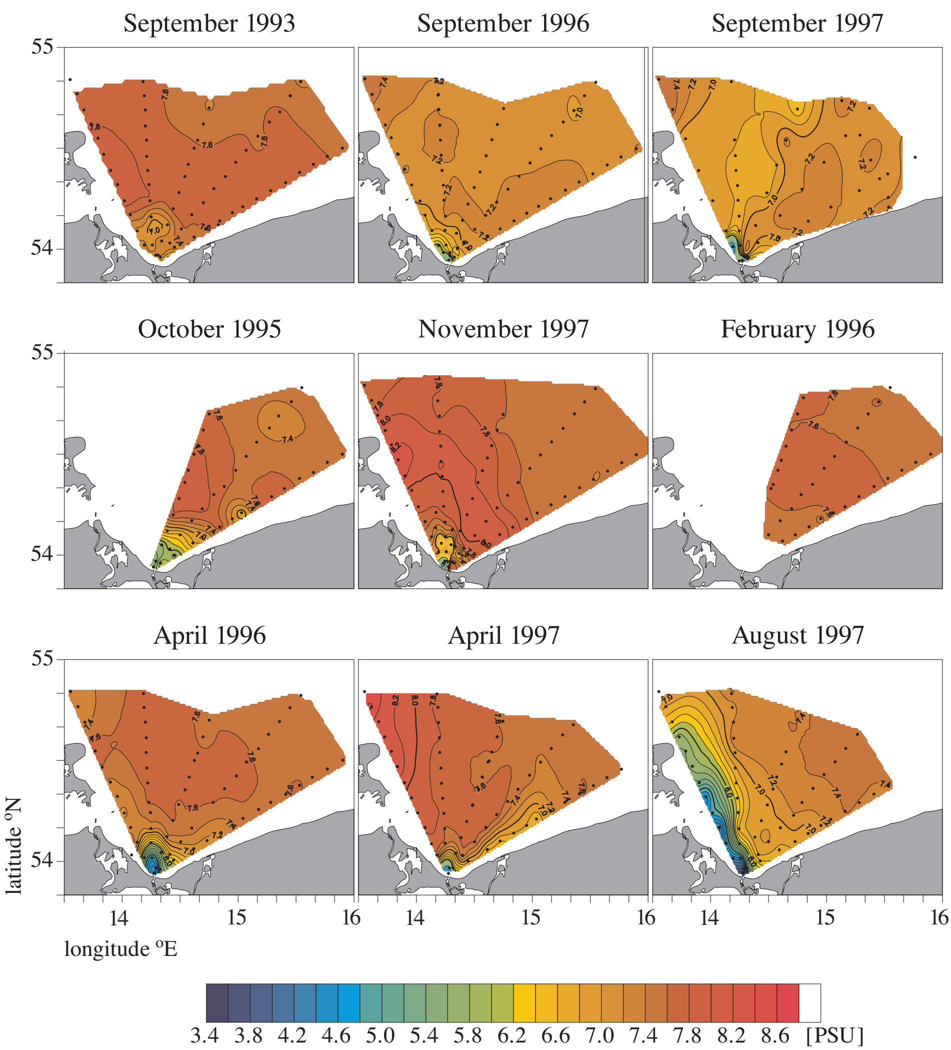

Fig. 3. Distributions of surface salinity [PSU] in the Pomeranian Bay in different seasons 1993–1997

salinity field in the Pomeranian Bay was closely dependent on the volume of it entering the bay, and also on wind forcing, which affected advective transport and mixing.

The surface salinity in the central and outer area ranged between 7.4 and 7.8 PSU, except when the influence of the open-sea waters was dominant in much of the bay (*e.g.* April 1997, November 1997) and the salinity rose to 8.2 PSU and more. If a freshwater plume developed at the same time in the inner basin, the differences in salinity over the whole Pomeranian Bay area could exceed 4–5 PSU.

Within the deep layers, the spatial distribution of salinity was more uniform, varying in the 7–8 PSU range. Inflows of highly saline waters from adjacent deep basins, the Arkona Basin to the west and the Bornholm Basin to the east, caused a substantial rise in salinity in the near-bottom layer along the edges of the bay. The highest values were recorded towards the Arkona Basin (>17 PSU) while deep waters from the direction of the Bornholm Basin, though slightly less saline, penetrated farther into the bay.

In general, when the influence of wind on the circulation scheme is not taken into consideration, some typical patterns in the thermohaline fields as a result of seasonal variability can be distinguished. During the spring months the Pomeranian Bay waters are subject to the strong influence of the Odra river discharge. Spreading freshwater gives rise to steep horizontal temperature and salinity gradients. The pattern of surface isohalines is then latitudinal in the close vicinity of the outlet, but farther out to sea they lie parallel to the coastline. In autumn and winter the bay waters are more affected by the open sea, and the isohalines run longitudinally. On the other hand, such exact patterns are rarely observed in nature because of the dominant part wind forcing plays in affecting the circulation in the Pomeranian Bay.

5. Circulation patterns under different wind conditions

The wind-driven circulation dominates the flow pattern in the shallow waters of the Pomeranian Bay. The main dynamical processes of the freshwater transport in the bay can be regarded as a linear response to local wind forcing and Ekman current advection (Mohrholz 1998). Depending on the wind direction, onshore or offshore Ekman transport coupled with a compensatory current in the bottom layer generates downwelling or upwelling off the coast. These vertical motions cause density and pressure perturbations, which in turn establish a geostrophically adjusted intense coastal jet in the mixed surface layer. With regard to coastal Kelvin waves, which propagate from the shoreline with the coast to their right, the longshore jet becomes arrested as a result of a Kelvin wave front. The longshore pressure gradient generates a coastal undercurrent beneath the layer directly influenced by wind forcing (Lass & Talpsepp 1993). These two main factors – Ekman transport under local wind forcing and the Kelvin wave field modified by buoyancy input – determine the pattern of freshwater flow in the Pomeranian Bay.

The prevailing circulation over the Pomeranian Bay is westerly, but easterly wind situations are also frequent. The dominance of wind directions parallel to the Polish coast is distinctive (Majewski 1974). Long-term wind data quoted by Robakiewicz (1993) indicate that the prevailing winds during the autumn and winter months are from the south and south-west (about 50% between September and February), while wind directions from the NW–NE sector are more frequent in late spring and summer. This tendency was confirmed by an analysis of wind directions during the measurement period (1993–1997) based on data from Świnoujście (Miętus 1995, Kierzkowski & Miętus 1996, Malicki & Miętus 1997, Miętus & Owczarek 1998). The overwhelming predominance of westerly and south-westerly winds in autumn and winter was coupled with the prevalence of north-easterly and easterly winds in the summer months. Data series from Arkona (1980–1990) analysed by Mohrholz (1998) also show similarities in the distribution of the wind direction with a very distinct prevalence of easterly and especially westerly winds.

To conclude, the flow of freshened, riverine water under the prevailing wind conditions should be manifested as a coastal current parallel to the coasts of the Pomeranian Bay resulting from on- or offshore Ekman transport. The circulation patterns observed in the Pomeranian Bay on the basis of the horizontal distributions of salinity and temperature (Figs. 2 and 3) are in good agreement with the foregoing assumption. When winds are westerly, a strong but relatively narrow current of Odra freshwater forms an intensive coastal jet along the eastern coast of the bay (the situation obtaining in April 1997 and rather less distinctly in April 1996). In this first case the maximum width of the main longshore flow was several km, although a drop in salinity was noticeable along the extensive Polish coastline, thereby providing evidence that the coastal jet was being sustained and intensified. In the second case the coastal current was not so distinctive, probably because of an earlier stage in the riverine water outflow, which was confined to the form of a freshwater bulb in the vicinity of the mouth. The flow of less saline water from the Greifswalder Bodden towards the inner part of the bay was also noted.

When winds are from the east, the broad stream of freshwater is directed along the western coasts of the Pomeranian Bay. The most evident case was observed in August 1997 when a very strong coastal stream of freshwater heading north-west reached the open sea. Nevertheless, in a typical situation without extremely high river discharge, a westward coastal flow along the coast of the island of Uznam (Usedom) is established. A stable freshwater plume of significant dimensions then forms to the west of the river mouth (the patterns recorded in September 1996, September 1997 or November 1997). Freshwater transport is blocked by the bottom topography in the neighbourhood of the Greifswalder Oie. Winds backing or veering southerly can force the flow of riverine water farther along the western coasts, resulting in the detachment of freshwater portions and the formation of isolated lenses. Moreover, easterly winds produce offshore Ekman transport and therefore upwelling, which was recorded at the surface in September 1996 as a patch of more saline and colder water off the Polish coast. As was mentioned above, southerly winds can cause freshwater lenses to hive off, which then move northward (the situation in September 1993 is shown in Fig. 4a). On reaching the Odra Bank these buoyant structures usually break up owing to wind mixing and the entrainment of underlying saline waters.

During northerly winds, the outflow from the river mouth is significantly reduced. But if the plume structure of the riverine water manages to develop earlier, onshore winds will push the plume back towards the coast (observations from May 1995 and September 1995 – Figs. 4b and 4c).

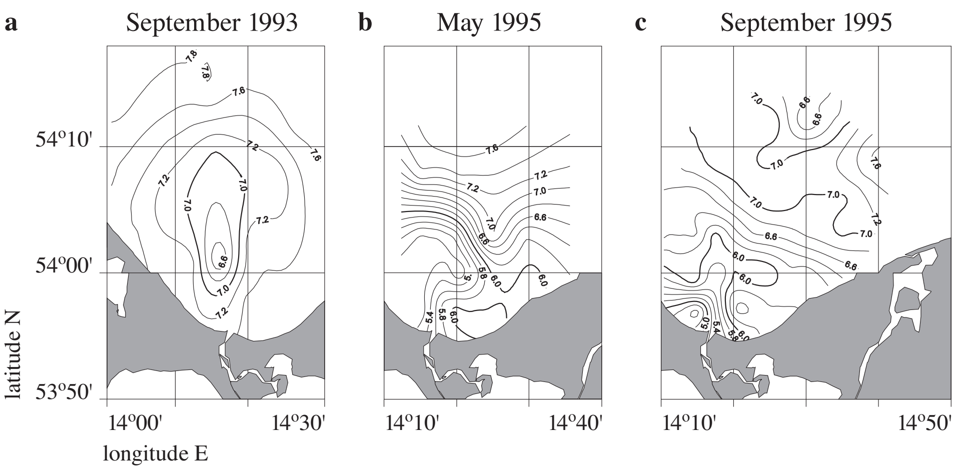

Fig. 4. Distributions of surface salinity [PSU] in the vicinity of the river mouth

Changes in weather conditions and a succession of variable wind directions elicit a rapid response in the form of changes in the circulation and freshwater flow patterns. In April/May 1996, the river plume front was observed to move in various directions during relatively high river discharge. Initially, a comparatively narrow plume of water of salinity < 5 PSU was transported offshore by weak south-easterly and southerly winds (Fig. 5a). During the following two days this freshened plume was supplied with a new portion of river water from an intensive outflow pulse. Subsequently, the salinity dropped abruptly to < 3.5 PSU in the vicinity of the mouth (Fig. 5b). At the same time, the plume broadened, though still confined by a strong front, and then spread slowly across the whole head of the bay. Evidence of outflow from the Dziwna Strait outlet was visible as a small freshwater patch with a minimum salinity of < 6 PSU. Because of weak wind forcing, the spreading of both plumes was governed by buoyancy

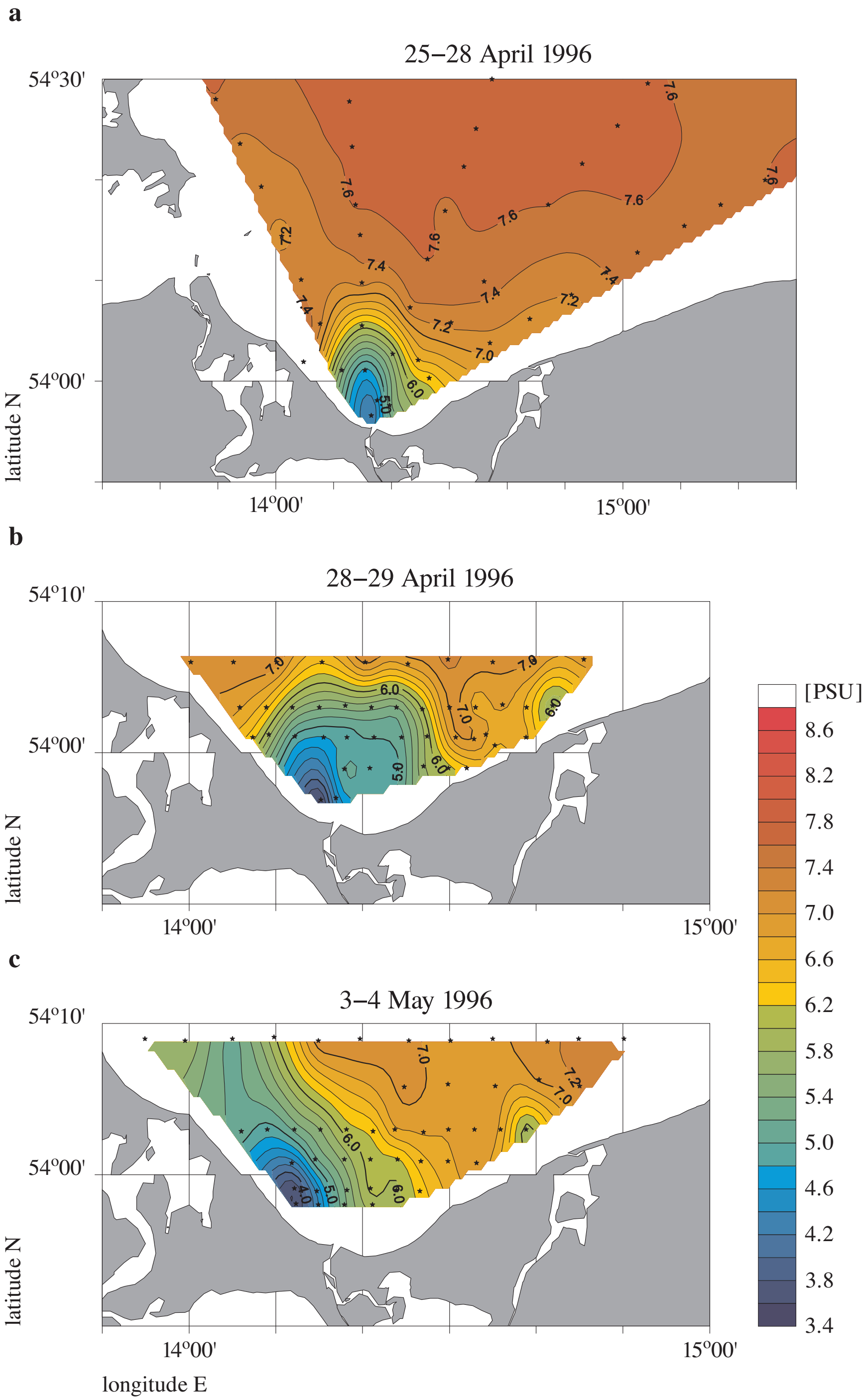

Fig. 5. Distributions of surface salinity [PSU] near the river mouth during three successive stages of the investigation in April/May 1996

forcing in front of the river mouth. After a further three days, during which the wind was rapidly backing easterly, the freshwater flow pattern altered completely (Fig. 5c). A strong coastal jetstream was established along the western shore of the bay and freshwater from the plume was transported in the longshore direction. The pattern of isohalines, which had previously bordered the plume, now ran parallel to the coastline. Riverine water of decreased salinity (< 4 PSU) originating from a long-lasting discharge was also advected along the western coast. The observed variability of the flow indicates that the response time to rapidly changing wind conditions was of the order of one or two days (sometimes tens of hours); the whole circulation pattern can undergo complete reversal in a very short time.

The distribution patterns for different wind directions observed during field measurements are in good agreement with the circulation scheme described on the basis of SST images by Siegel (1994a,b). In particular, the coastal jet along the Polish coast of the Pomeranian Bay established during north-westerly winds and the development of the riverine water plume are clearly visible. With easterly winds, the wide coastal current along the eastern shore is distinctive on the satellite images. Moreover, thermal fronts occurring at the boundaries of different water masses in the bay are noticeable. Mohrholz (1998) showed series of SST images depicting the transport of bay waters influenced by the Odra discharge along the Polish coast. During stable westerly winds this stream can extend as far as the distant Gulf of Gdańsk.

6. Hydrological fronts and freshwater plumes

The pulse-like nature of the Odra river discharge and the strong influence of wind forcing on this freshwater flow produce complex dynamical structures characterised by steep horizontal and vertical salinity gradients. The barotropic box model developed by Mohrholz (1998) enabled the effective water exchange between the Szczecin Lagoon and Pomeranian Bay through all three channels to be estimated. In the Świna and Peene, the effective transport amounted to 65–75% of the total transport during outflow events and 30–40% during inflow situations. They calculated the volume of freshwater discharged from the Świna for three modelled outflow events in June 1994 and obtained a value of 0.12–0.13 km^3. During these outflows the salinity at the Świna mouth dropped to as low as 1 PSU, which is equivalent to the salinity of the riverine water entering the bay. Fluctuations in salinity, nitrates and phosphates in the Świna revealing the sequence of inflow and outflow events were demonstrated by Pastuszak *et al.* (1996). Differences between the surface and near-bottom salinities – *e.g.*

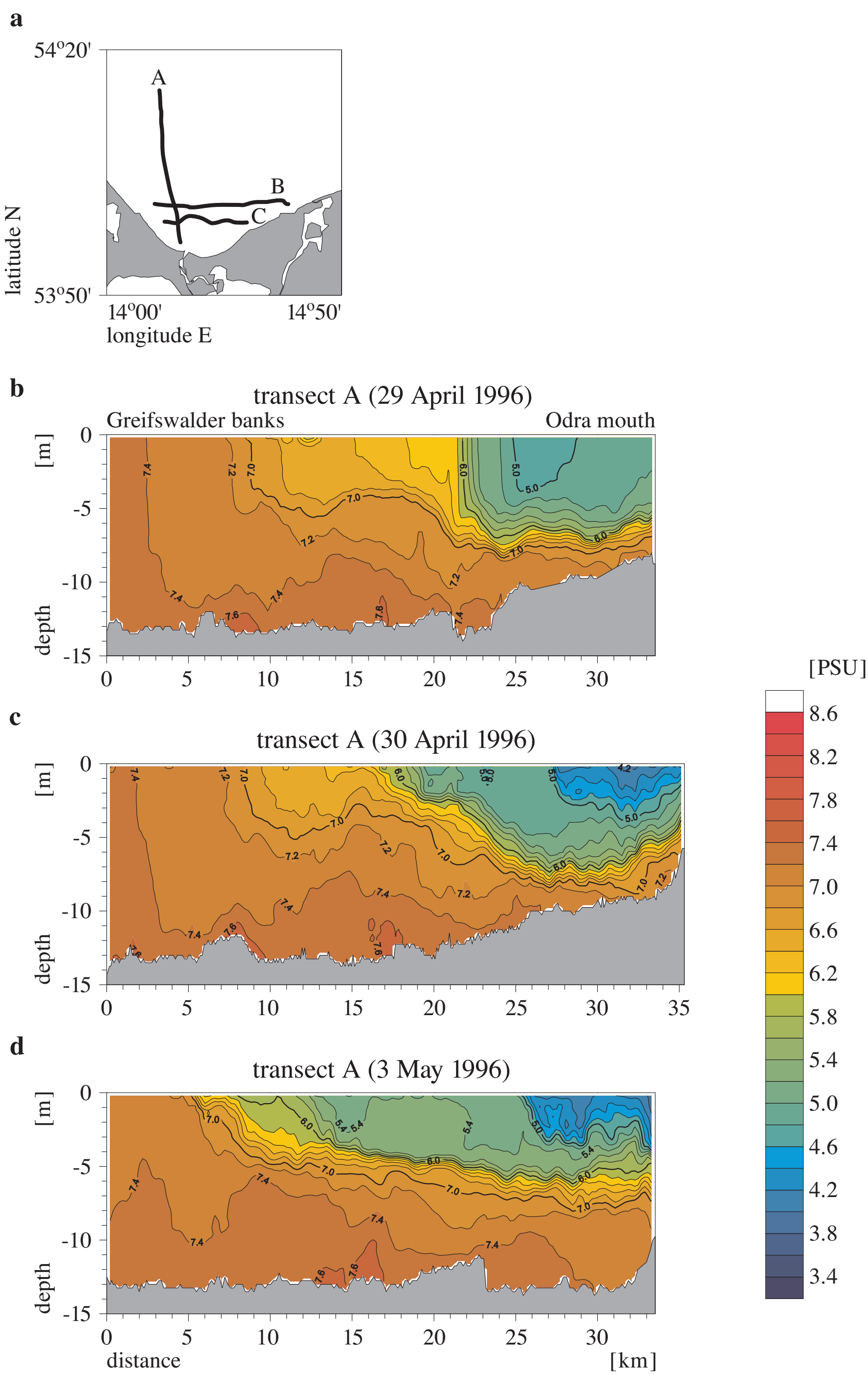

Fig. 6. Distribution of salinity [PSU] along a transect parallel to the riverine water flow, repeated three times in April/May 1996; location of transects in April/May 1996 (a), salinity distributions during three series of measurements (b)–(d)

the salinity at the surface is *ca* 2 PSU while near the bottom it is over 7 PSU – confirmed the bilaminar and bidirectional flow in the channel mouth.

Furthermore, the response of the sea to a sudden freshwater discharge (river outflow event) preceded by a period of blocked river runoff (inflow event) was described in Fennel & Mutzke (1997). The buoyancy patch of freshwater developing in the front of the river mouth resulted in the generation of an anticyclonic eddy in the near field. Eddy formation was assumed to be a weakly non-linear effect of the altered stratification after the spreading of buoyant river water. When the wind-driven circulation is taken into account, winds favourable to upwelling can detach the freshwater plume from the shore as a consequence of offshore Ekman transport.

These theoretical findings based on model calculations are in good agreement with the freshwater flow patterns observed in the Pomeranian Bay. CTD transects with high horizontal resolution turn out to be very useful for investigating the detailed structure of the river plume fronts. Salinity distributions (Figs. 6b, 6c, 6d) along a transect parallel with the riverine water flow (see map in Fig. 6a) were obtained during thrice-repeated

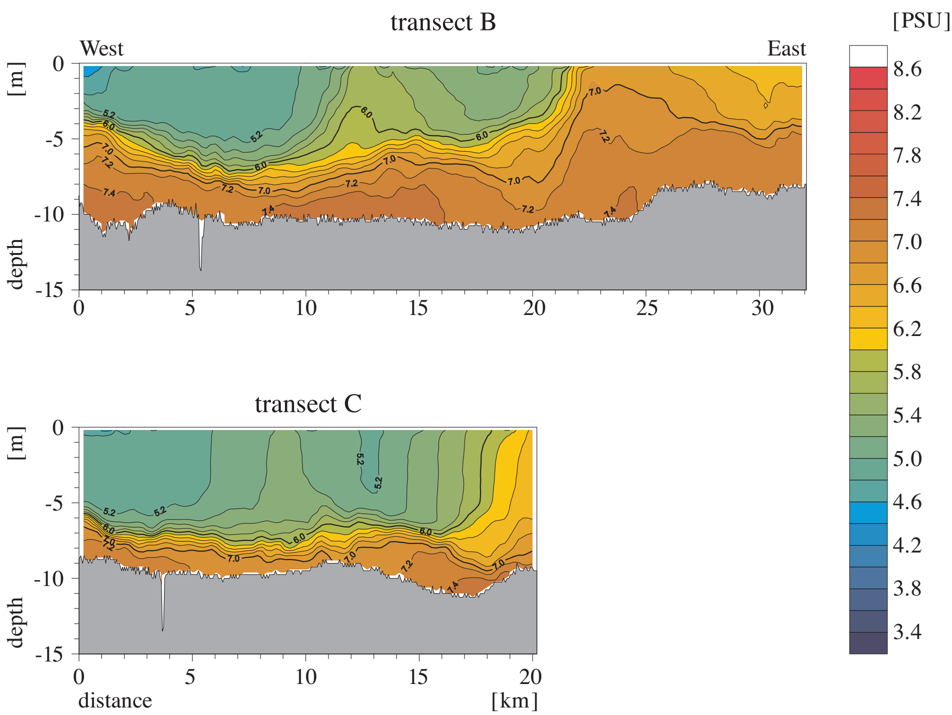

Fig. 7. Distribution of salinity [PSU] at two successive transects across the main river water stream in April/May 1996 (see map at Fig. 6a)

measurements in April/May 1996. The successive stages of the propagating front and transformation of the frontal interface shape could thus be observed. Figs. 7a and 7b illustrate the transverse structure of this offshore transport. The main stream of riverine waters is clearly visible; however, there is also a distinctive stretch of slightly higher salinity (a lower drop as compared with the adjacent bay waters) but surely originating from the river runoff. Disturbances in the vertical temperature profiles (Fig. 8), strongest in the frontal interface area, provide evidence of intrusive processes and intensive mixing probably associated with the downward entrainment of plume water into the underlying, more saline layers.

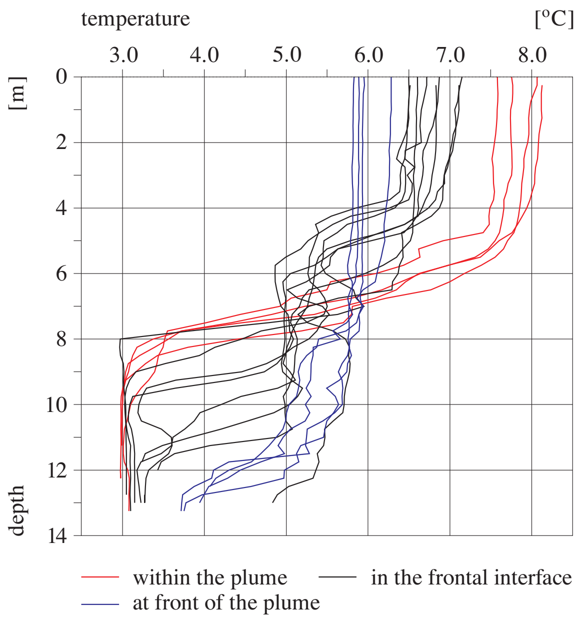

Fig. 8. Vertical profiles of temperature [°C] in different parts of the river plume front obtained in April 1996 in the inner part of the Pomeranian Bay

Analysis of the perpendicular transects disclosed the existence of an isolated lens of riverine water during the first stage of observations. This anticyclonic eddy was almost circular in shape, with a diameter of about 10 km and depth of 5–7 m. The estimated velocity of the baroclinic geostrophic current within the eddy was slightly over $10\,\mathrm{cm\,s^{-1}}$ (Fig. 9). On subsequent days the evolution of the river plume front was observed. The typical structure with nearly constant thickness and a vertical frontal interface changed into an elongated tongue of freshwater. This was an effect of flow intensification in the direction of the density gradient after the wind had backed from southerly to easterly.

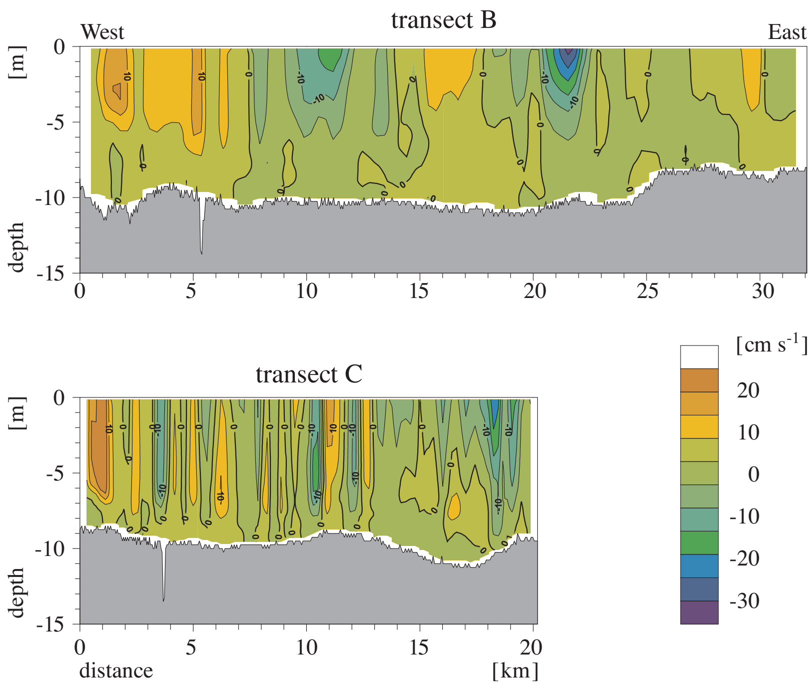

Fig. 9. Distribution of the baroclinic geostrophic current velocity [$\mathrm{cm\,s^{-1}}$] along two successive transects across the main flow of river water in April/May 1996 (see map at Fig. 6a)

Initially, the velocity of the front propagation estimated from the position of isohaline 6 PSU (Table 2) was *ca* 8 $\mathrm{cm\,s^{-1}}$, but fell later to about 3 $\mathrm{cm\,s^{-1}}$. The overall thickness of the river plume varied between 7 and 9 m.

Table 2. Range of isohalines from the river mouth along a transect parallel to the main stream of freshwater; measurements repeated three times in April/May 1996

Isohaline	Transect [km]		
[PSU]	29 April	30 April	3 May
4.2	–	4	0.5
4.8	–	7.5	7.5
5	8	8.5	8.5
6	11	18	26
7	24	26	28
7.4	31	34	>34

Beneath it there was a layer of more saline water (7.0–7.6 PSU) originating from the compensating undercurrent. The vertical gradient between the plume and ambient bay waters attained a maximum value of 1 PSU m^{-1}. The maximum decrease in salinity within the plume was recorded during the second stage of river outflow, and attained a value of 4 PSU at the surface. The isohalines sloped downwards towards the front before rising sharply to the surface at the front. This suggests that there was significant downwelling on the buoyant side of the front. Such downwelling and convergence at the front can establish a mechanism entraining the ambient saline water under the river plume. The volume of freshwater within the plume (salinity < 6 PSU) during the first stage of the flow was roughly estimated at 0.8 km^3.

The pulsating Świna runoff may be seen as a continuous discharge if the resolution of measurements is insufficient to separate the successive outflow events. In the figure showing the distribution of layers with a maximum salinity gradient (a gradient in the direction of maximum salinity difference – Fig. 10) we can distinguish an area of water originating from two successive river discharge pulses.

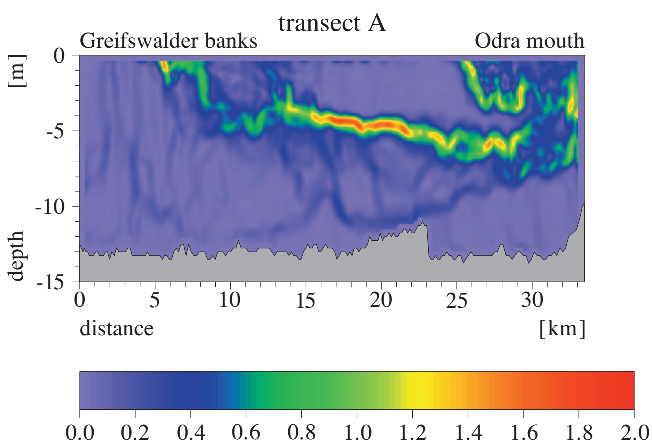

Fig. 10. Distributions of the layer with the maximum salinity gradient along a transect parallel to the main flow of riverine water (example from May 1996; see map at Fig. 6a)

A fast-moving freshwater plume front was found in May 1995, travelling northwards from the river mouth. Two patches of reduced salinity were distinctive in the salinity distribution across this front (Fig. 11a). Furthermore, these structures were found to pass through station ZPP5 durning subsequent stationary measurements (Fig. 11b). The thickness of the freshened

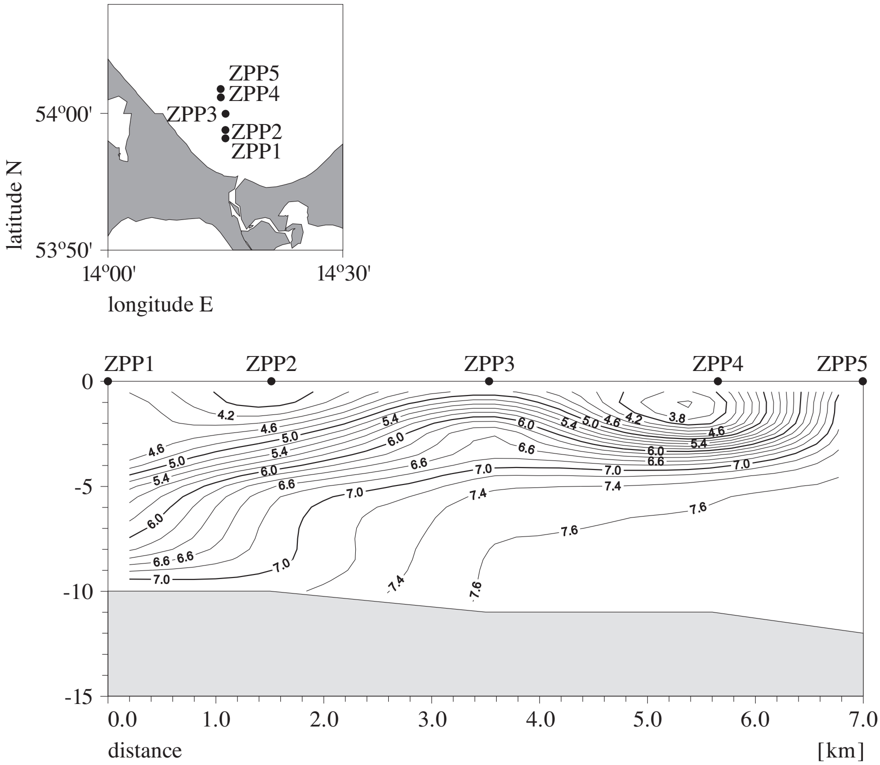

Fig. 11a. Distribution of salinity [PSU] along a transect across the moving front of the riverine water plume measured in the vicinity of the mouth in May 1995

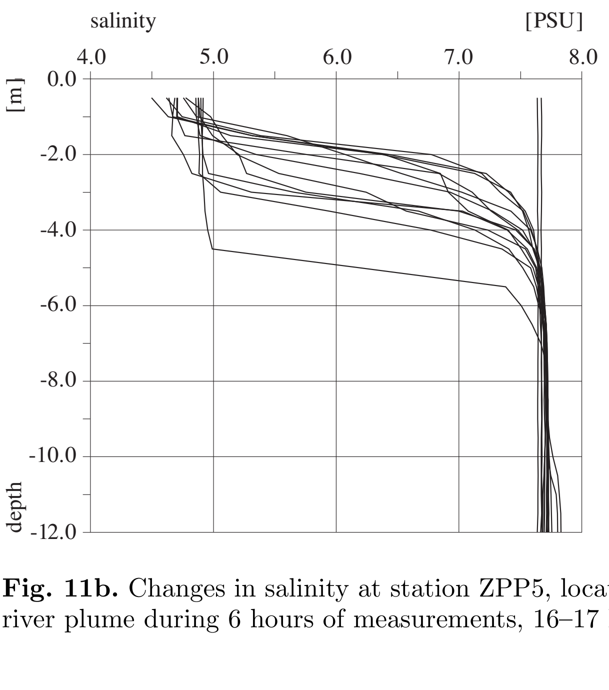

Fig. 11b. Changes in salinity at station ZPP5, located at the front of the moving river plume during 6 hours of measurements, 16–17 May 1995

layer varied between 3 and 6 m. Interestingly, the front at the surface manifested itself as a band of foam and flotsam and also as changes in the water colour. The band of foam turned out to be a sign of flow convergence at the front, which at the surface restricted the maximum extent of the freshwater lens (Fedorov 1983).

7. The consequences of the flood event in summer 1997 and the minor inflow through the Danish Straits in autumn 1997

During the flood period a vast quantity of freshwater flowed into the Pomeranian Bay. The mean monthly Odra discharge was 1320 $m^3 s^{-1}$ in July but 1510 $m^3 s^{-1}$ in August, and the river runoff was then three times as great as the long-term mean (Heybowicz *et al.* 1998). The situation was the reverse of the usual summer pattern, when the riverine water influx usually reaches its lowest level of the year. The weak easterly winds prevailing during the measurements in August 1997 sustained an unusually long and broad longshore stream of freshwater in the western part of the bay. A band

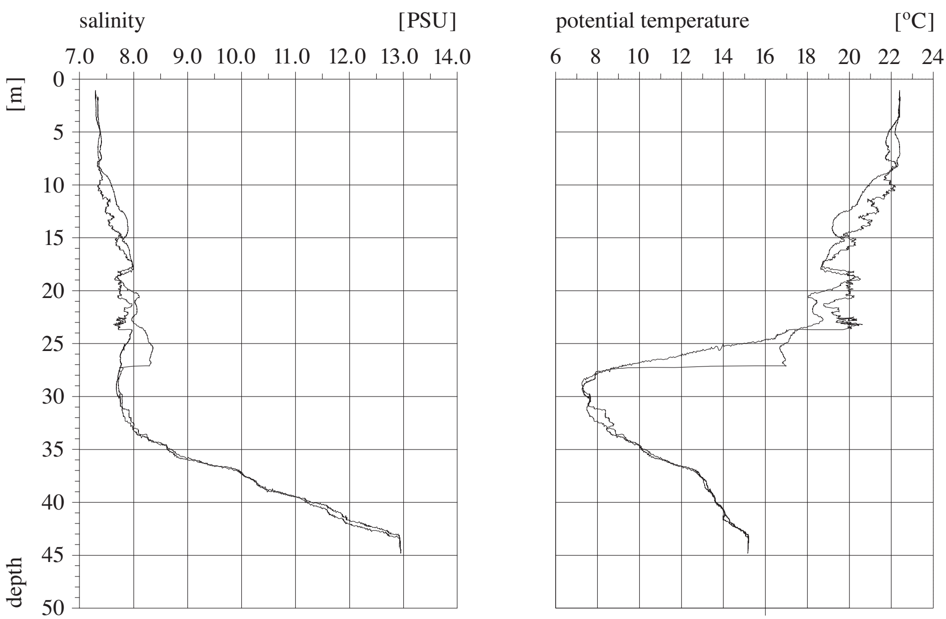

Fig. 12. Vertical profiles of temperature [°C] and salinity [PSU] at two stations (about 0.3 Nm distant from each other) located at the edge of the Pomeranian Bay, taken in the direction of the Arkona Basin and recorded after the flood event in August 1997

of water with salinity below 7 PSU some 30 km wide covered the entire western side of the bay and the pattern of isohalines parallel to the coastline remained unchanged even in the adjacent open-sea waters. The fact that the water was of riverine origin was signalled by the vertical salinity and temperature profiles at the edges of the Arkona Basin in the form of fine-scale disturbances, indicative of intrusive processes and turbulent mixing in the intermediate layer (Fig. 12). The salinity distribution in the vicinity of the river mouth (Fig. 13) disclosed powerful pulses. As a result,

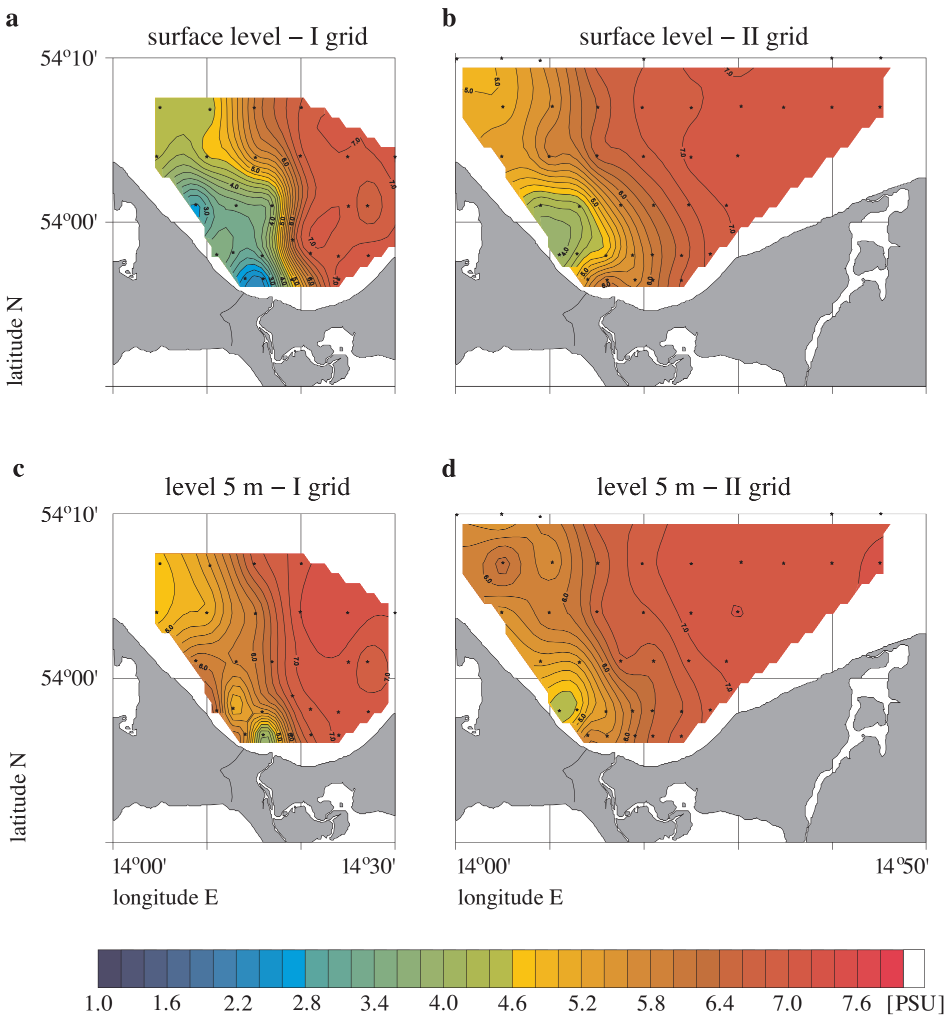

Fig. 13. Distributions of salinity at the surface (a)–(b) and at 5 m depth (c)–(d) during the first (13 August – Figs. a, c) and second (15 August – Figs. b, d) stage

of measurements after the flood event in summer 1997 successive patches of freshwater were carried along by the coastal jet. During the first stage, a bulb of riverine water of salinity < 2.5 PSU developed close to the channel outlet. At the same time, the previously generated plume of salinity < 3 PSU was visible about 10 km farther along the shore. Freshwater plumes were confined to the upper few metres, and the horizontal salinity gradient vanished in the near-bottom layer. The powerful flow of buoyant water, the strong advective current and weak wind mixing (wind speed $< 1\ \mathrm{m\,s^{-1}}$) restricted the downward entrainment of freshwater. As a result, steep vertical salinity gradients developed (> 1 PSU $\mathrm{m^{-1}}$). During the second stage of measurements, the wind was slightly stronger (2–3 $\mathrm{m\,s^{-1}}$). The freshwater bulb became detached from the river outlet and was transported parallel to the coast. Further intensive mixing and downward entrainment of the riverine water were the reason for the increased volume of the plume and its higher salinity as compared with the previously observed structure. Intense offshore transport in the upper layer was coupled with a strong compensatory near-bottom current carrying relatively saline and dense water (Fig. 14).

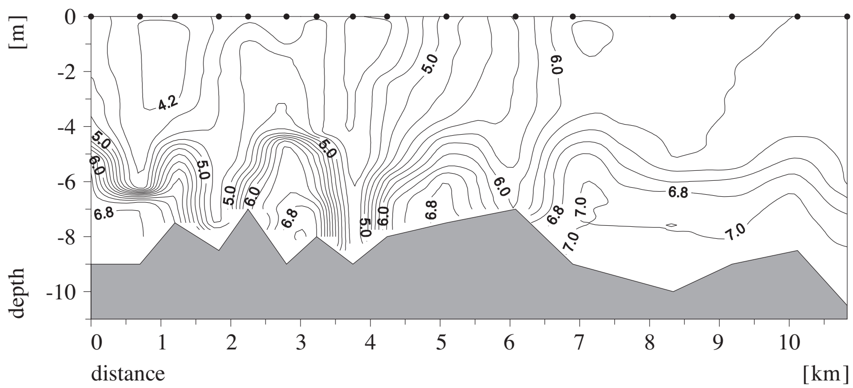

Fig. 14. Distribution of salinity [PSU] along a transect across the main flow of freshwater in August 1997 after the flood

The proportion of freshwater in the Pomeranian Bay volume was estimated by a method adapted from Ketchum (1950). Based on the difference between the background and average salinity in the layer (in our case, the maximum salinity in the layer was assumed to be the background value), this method yielded an estimate of the percentage of freshwater (FI) and freshwater volume (FVF) in the various layers:

$$\mathrm{FWF} = (S_0 - S)/S,$$

$$\mathrm{FI} = \mathrm{FWF}\ 100\%,$$

$$\mathrm{FWV} = \mathrm{FWF}\ \mathrm{V},$$

where
FWF – freshwater fraction,
FI – freshwater index,
FWV – freshwater volume,
S_0 – background salinity in the layer (in this case the maximum salinity in the layer),
S – averaged salinity in the layer.

It is obvious that the highest values in all layers were attained for the flood period in August 1997 (Fig. 15). A somewhat elevated proportion of freshwater in the upper and intermediate layers was also noted for September 1997, after the flood, as compared with the values for autumn months in previous years.

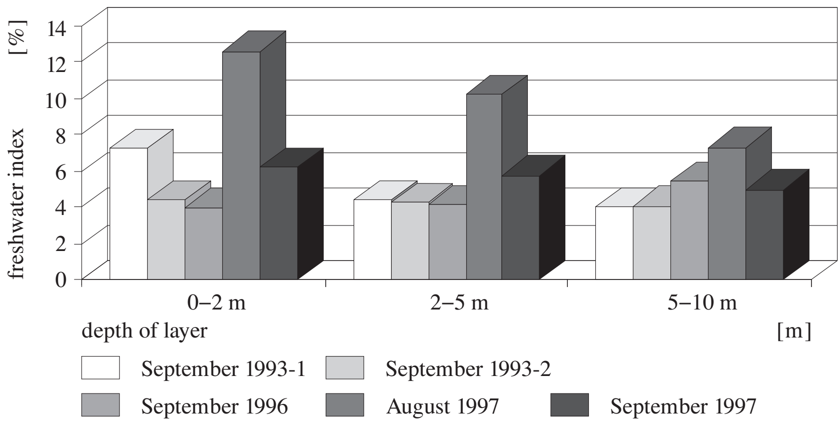

Fig. 15. Proportion of freshwater in the various layers of the Pomeranian Bay estimated from salinity differences

It is interesting to note that the influence of the floodwaters on the Pomeranian Bay water masses ceased completely in late autumn. Even though reduced salinities were still being recorded in much of the bay in September, two months later, in November 1997, the Pomeranian Bay was filled with unusually saline water (Fig. 2). The prevailing influence of the open sea was the effect of a minor inflow of highly saline, near-bottom water from the Danish Straits. Water originating from the Arkona Basin caused a sharp rise in the surface salinity to 7.8 PSU and above (the highest values were > 8.5 PSU). The constraining plume of riverine water was limited to the mouth area in the form of an anticyclonic lens (Fig. 16). The salinity in this eddy-like structure was lower than in the ambient waters, but as a result of mixing with highly saline bay waters, it did not drop below 6 PSU. The relatively warm water transported from the direction of the open sea cooled

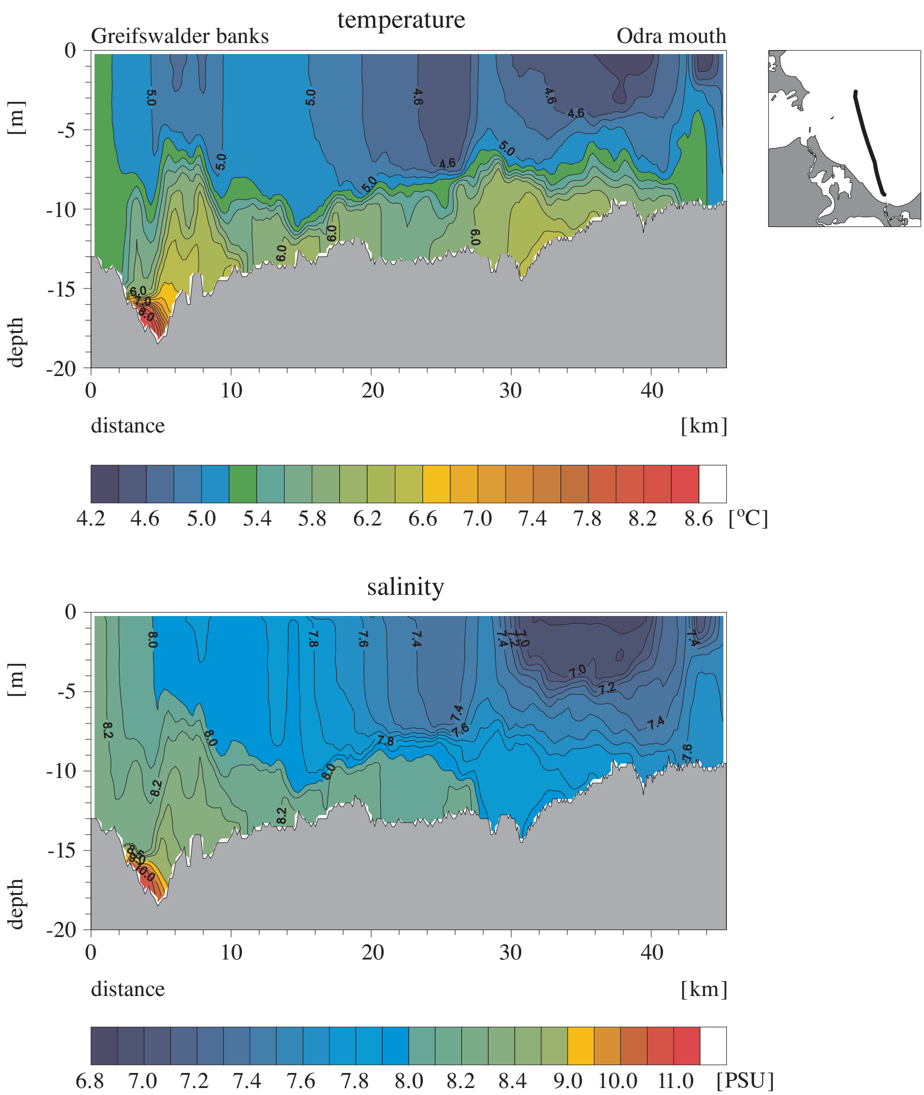

Fig. 16. Distributions of temperature [°C] and salinity [PSU] along a transect parallel to the riverine water flow, recorded after the minor inflow from the Danish Straits in November 1997

rapidly when mixed with colder shallow coastal and riverine waters, in which heat losses were significantly greater. But in a small bottom depression at the latitude of the Greifswalder Bodden, in which the depth was about 18 m, a portion of extremely saline (*ca* 11 PSU) and warm (8.5°C) water was found, which had been transported almost unmixed from the Arkona Basin.

8. Conclusions

The circulation patterns in the Pomeranian Bay have a great influence on the spreading of nutrients and dissolved/suspended matter introduced by the discharge from the river Odra. Although the buffering capacity of the Szczecin Lagoon can reduce the pollution loads carried into the sea, owing to the long retention time in this reservoir (Robakiewicz 1993), the Arkona and Bornholm Basins are the main sinks of the Odra river loads. Exchange between the Odra estuary and the adjacent open waters of the Baltic Sea are entirely dependent on the circulation scheme and transport conditions in the Pomeranian Bay.

Five years of regular field studies, carried on by the Institute of Oceanology PAS, have led to a better understanding of the major factors determining the thermohaline conditions and riverine flow patterns in the bay. The Odra discharge and the influx of open-sea waters were found to be the main sources of the external water masses determining the thermohaline conditions in the Pomeranian Bay. The freshwater discharge provides input of buoyancy and momentum, and determines the plume structure in the vicinity of the river mouth. But the dynamical processes and circulation patterns in the bay are primarily dependent on wind forcing, both through wind-induced mixing and advection by wind-driven currents. The flow of riverine water is additionally governed by the bottom topography and the lie of the coastline. Longshore wind directions, dominant over the Pomeranian Bay, give rise to off- or onshore Ekman transport, which results in up- or downwelling. Coastal currents are established with intensities and stream widths dependent on the flow direction. Seasonal variability is distinguishable in the circulation scheme, the influence of freshwater from the river discharge prevails in the spring months and the effects of influxes from the open sea are dominant during late autumn and winter.

Transport of Odra water in the Pomeranian Bay under different wind directions can be generally described as follows:

- westerly winds – a narrow coastal current is intensified along the Polish coast, carrying the freshwater and spreading it over long distances from the river outlet; this is the most frequent situation, as the prevailing winds are from this direction;
- easterly winds – a broad and less intense stream of riverine water along the German coast; freshwater flow can be blocked by the bottom topography with a tendency for the flow to meander and freshwater lenses to separate; the most frequent pattern during our measurements;

- southerly winds – can counter the blockage of the riverine water plume and transport it farther away from the coast, where it undergoes mixing and entrainment and in most cases disappears;
- northerly winds – block the river discharge from the outlet; the freshwater plume is confined to the nearest neighbourhood of the mouth; steep horizontal gradients develop, thereby establishing sharp fronts between riverine and bay waters.

The pulsating character of the Odra discharge can result in a train of successive freshwater plumes. Steeper horizontal salinity gradients mark the range of the river plume and the position of the front. The front propagates at velocities of up to $10\,\mathrm{cm\,s^{-1}}$; the plume is around a few metres thick, and mostly between 10–20 km across. Water from the river plume is turbulently entrained across the frontal interface and down into the underlying layer of more saline water. Compensatory undercurrents may be the reason for the decoupling between the surface flow carrying low-saline water from the river outlet and the deeper flow of higher-salinity water spreading beneath the river plume in the opposite direction. Offshore Ekman transport, together with restrained river discharge between successive outflow pulses, can lead to the detachment of the separated freshwater plume from the coast and the development of an anticyclonic eddy. Although this latter can transport freshwater over relatively long distances, it gradually disappears when subjected to stirring by wind stress and wave motion.

The Odra waters do not influence the water of the open Baltic Sea directly; nevertheless, the Pomeranian Bay water masses, strongly affected as they are by the riverine freshwater, are transported to the deep Arkona and Bornholm Basins. The circulation patterns in the Pomeranian Bay can sustain or inhibit this transport depending on external factors: the magnitude and type of river discharge and wind forcing.

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