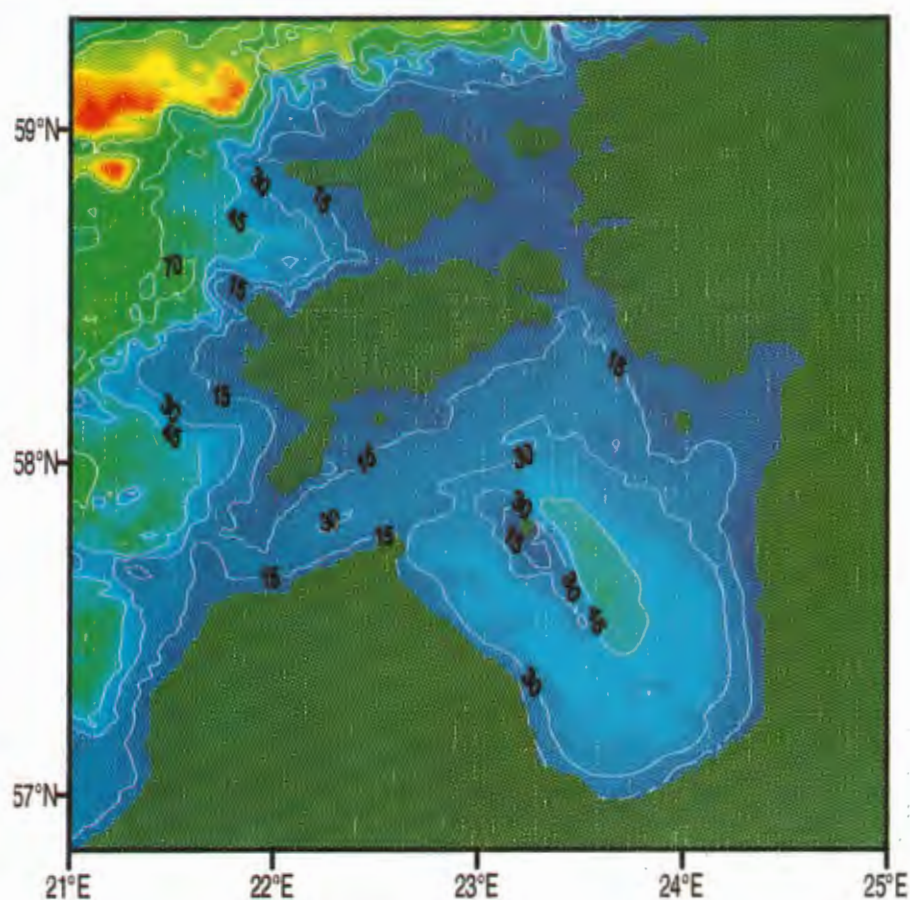


Observations of water exchange, currents, sea levels and nutrients in the Gulf of Riga



Editors
Tarmo Köuts
Bertil Håkansson

Estonian Marine Institute
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Abstract

The Gulf of Riga is one of the main subbasins of the Baltic, coupled through one shallow and one deep (the sill depth in Virtsu is 5 and in Irbe 35 meter) strait. The fresh water flux to the gulf from river Daugava is one of the highest in the Baltic. Nevertheless, the average gulf salinity is close to the surface values of the Baltic proper, showing that the water exchange through the straits are dominating the buoyancy flux. As a result two strong salinity fronts are regularly found, one is close to the river mouth in the southern gulf and the second one in the Irbe Strait area. The frontal zone in Irbe is often S-shaped with inflow along the southern part and a outflow along the northern side. The surface front is strongly variable in position and strength, depending on atmospheric (winds and summer heating) conditions, whereas the deep layer front is almost a stationary phenomenon. Generally, the current structure are organized in two layers and is in geostrophic balance, but superimposed by oscillatory currents with typical diurnal and inertial periods.

In the central part of the gulf - the Ruhnu Deep - southward currents in the near bottom layer prevailed during July and September, 1993. Two meters above bottom high speed bursts were recorded intermittently with velocities up to 25 cm/s. It was found that these bursts were coincident with passing atmospheric low pressure systems, which caused strong fluctuations in the sea level with intensive barotropic currents as a result.

It is expected that the sea level variability also influence the water exchange in the two straits. Long time series at several stations around the gulf show large variability with many fluctuation periods. The most frequent period is the annual cycle with low levels in May to June and high levels in November and December. In addition periods close to 70 days, diurnal and inertial were recorded.

Nutrient concentrations in the gulf and in the Irbe strait showed higher values than those in the Baltic proper and inorganic nutrients correlated well with the thermohaline structures, which was not the case with total nitrate and phosphate. It is believed that the gulf is phosphorus limited whereas the Baltic proper is nitrogen limited, regarding phytoplankton growth. In the Irbe frontal zone, mixing might create a water mass including both nutrients and hence a strong plankton growth potential. However, the observations did not favor this hypothesis.

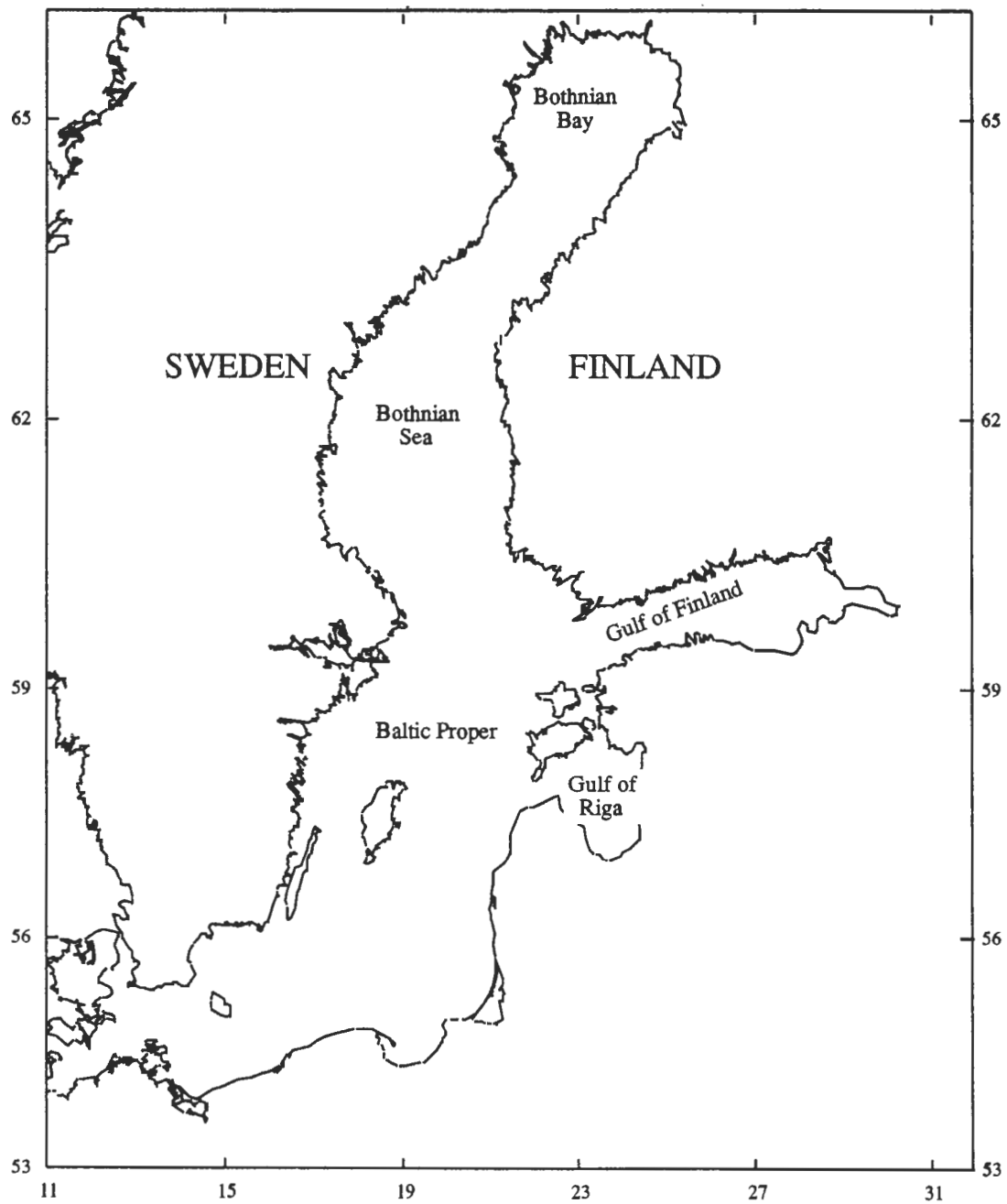
Introduction

The Gulf of Riga is located in the eastern part of the Baltic proper. It is relatively closed, forming a subbasin with its own physical, chemical and biological character. The bottom topography is comparably flat over the whole area. The deepest part, found in the central gulf near the Ruhnu island, is about 55 meter below the sea surface, whereas the sill depth of the western Irbe Strait and the northern Virtsu Strait is 35 and 5 meters, respectively. The volume of the gulf is 410 km^3 and since the annual river runoff amounts to 30 km^3 the fresh water load of the gulf is slightly higher per unit area than the corresponding figure for the whole Baltic. The river Daugava supplies 70 % of the total runoff, to the southern part of the gulf, while the water exchange through the straits supplies another 100 km^3 of Baltic proper surface water. Since the subbasin is shallow only a summer halocline is found in the gulf, when the atmospheric heat input is strong enough to limit the wind mixing to the upper 20 meter. During autumnal atmospheric cooling and increased windinduced mixing, convective overturning completely make the vertical stratification homogeneous. Instead two strong and almost permanent frontal regions are found, one in the Irbe Strait and one in the most southern part of the gulf, offshore the river Daugava. These fronts are most certainly maintained by the converging fresh and salt water fluxes, despite strong wind mixing.

The drainage basin, which area is about 6.8 times larger than the area of the gulf and dominated by agriculture, is influencing both the water balance and the ecology of the gulf. Eutrophication of coastal waters was noticed during the nineteen eighties and there are indications of phosphorus limitation plankton growth. Note however, that the Baltic proper is regarded to be nitrogen limited. Hence, it is expected that a net transport of nitrogen can take place from the gulf to the open Baltic as well as may strong plankton growth in the Irbe Strait frontal zone where both limiting nutrients may be found simultaneously. To quantify the transport of nutrients and pollutants between both the Baltic proper surface water and the Gulf of Riga, it is necessary to find out the dominating processes determining the water exchange and the mixing in the two straits.

These above mentioned indications together with some other strong environmental problems in the Gulf of Riga area, led the Nordic Council of Ministers to initiate the Gulf of Riga Project. The inter-disciplinary programme started with a process-oriented phase in 1993, by focusing on strengthen monitoring and special measurement projects. A close cooperation between Baltic and Nordic scientists was a prerequisite for the whole programme.

This report present data and some preliminary results from the 1993 and 1994 campaign on water exchange properties and nutrient dynamics in the Irbe Strait, deep water currents, sea levels and hydrographic state and circulation characteristics in the southern part of the gulf.



1. Thermohaline structures in Gulf of Riga

by Tarmo Kõuts (Estonian Meteorological and Hydrological Institute)

1.1 Introduction

The program of hydrographic measurements, covering the whole Gulf of Riga in 1993, consisted of four seasonal monitoring cruises performed by the Estonian Meteorological and Hydrological Institute (R/V ORBIIT) and the Latvian Hydrometeorological Agency (R/V VEJAS). Map of visited monitoring stations of both countries is presented on Fig. 1.1. As expeditions took place nearly simultaneously (plus-minus one week), hydrographic parameters can be interpreted together to give a synoptic view on hydrographic state of the Gulf of Riga.

1.2 Measurements

On board of R/V ORBIIT CTD sond Neil Brown Mark III was used to measure sea water temperature and salinity. This sond gives an accuracy of measurements of about 0.01°C for temperature and 0.01 psu (practical salinity unit) for salinity. The salinity sensor, was periodically calibrated by estimation of salinity on high-precision salinometer AUTOSAL, in bottle samples (taken at several depths in various stations). The temperature sensor is usually calibrated 1-2 times per year.

Relevant hydrographic measurements from the R/V VEJAS were performed using inverted thermometers for the sea water temperature and titration for the analysis of the sea water salinity. Water samples for the estimation of salinity were taken analogous to Nansen bottles, water sampler.

1.3 Water masses

The Gulf of Riga is a water basin, connected to the Baltic Proper through two Sounds - Irbe and Virtsu Straits. Sill depths in the transition areas are quite different - about 35m in Irbe and 5m in Virtsu Sound. Due to sills and large fresh water supply from rivers, the salinity of the Gulf is about 1-2 psu less than in the surface layer of the Baltic Proper.

The average annual river runoff into the Gulf is estimated to ~31 km³ (Pastors, 1967). Another fresh water supply from precipitation is minor compared to river runoff and is estimated to about 0.3-0.5 km³ per year (Pastors, 1967).

Saline water input through exchange processes occurring in the Irbe and Virtsu Sounds cause in the Gulf a permanent sea water salinity of about 4.8 - 6.0 psu. According to the measurements and model calculations the larger part of the saline Baltic Proper surface water (typical salinities 7.0-7.8 psu) inflow through the Irbe Straight covering about 70-80% of the total volume flow. Then about 20-30% of the saline water supply occurs through the Virtsu Sound (Petrov, 1979). It should be noted that under some certain wind conditions the water exchange through the Virtsu Straight can increase remarkably (Mardiste, 1964). However, mechanisms causing water exchange and mixing in the transition areas - the Sounds, are still poorly known and several authors rely on water volumes from 184 km³ (Pastors, 1967) to 691 km³ (Petrov, 1979), which participate in the water exchange with the Baltic per year. The exchange processes in the Straits are subject to large variability both in annual and on year to year time scales.

Two main types of vertical thermohaline structures of the water masses can be distinguished in the Gulf of Riga. *Firstly*, well mixed from surface to bottom with salinity around 5.5 psu

and with temperature varying from late autumn values (7-8°C) to typical winter temperatures around (0°C). On a T-S diagram such a water mass is presented dotlike on the graph. In the Gulf of Riga the above described vertical thermohaline structure can usually be observed during the season from late October to the beginning of April, that is after the erosion and before the formation of the seasonal thermocline. Exceptions are transition areas - sounds and river mouths, where more saline water beneath the upper layer occurs and less saline on top of the Gulf's water is observed. Vertically overmixed water masses were observed during the cruises in March and November, CTD profiles from one of these surveys, for example, is presented on Fig. 1.3.

Secondly, the thermohaline structure obtained during summer time a less saline and warmer upper layer (thickness of about 10-15m), a seasonal thermocline (thickness of about 5-7m) and a weakly stratified lower layer (below 25-30m). Typical TS-curves of layered thermohaline structures in the Gulf of Riga were measured during cruises in May and August (see Fig. 1.2). The first plot is showing vertical thermohaline structure just after formation of a seasonal thermocline and second, when temperature of the surface layer reached its maximum and autumn cooling starts afterward. Relevant CTD vertical profiles are presented on Fig. 1.3.

1.4 Variability of thermohaline structures

Maps of spatial distribution of temperature and salinity in the surface and bottom layers are presented in Fig. 1.4 - 1.11 on the basis of data from four monitoring cruises in the Gulf of Riga. Below is presented some results from each survey.

March

The temperature of sea water is quite homogeneous both in horizontal and in vertical directions and temperature differences between the separate parts of the Gulf do not exceed 0.2°C in the surface layer and 0.8°C in the bottom layer (see Fig.-s 1.4 and 1.5). This thermohaline structure is typical for the winter season. The area of more saline and colder water near the eastern slope of the Gulf identifies the presence of saline water intrusions through the Irbe Strait, which then tends to flow as a deep current following the western slope. In the salinity field along the eastern coast of the Gulf of Riga a weak front can be distinguished, extending from the southern coast towards the Virtsu Sound. The front separates the typical Gulf water mass with salinity ~5.5 psu from fresher ($S \sim 5.0$ psu) coastal zone water, being the mixture of the Gulf's and riverine fresh water (mainly the Daugava river). Observed anticlockwise general circulation pattern in the Gulf seems to be quite typical, as is noted also by other authors (Pastors, 1967, Petrov, 1979, Yurkovskis et al., 1993).

May

A well developed seasonal thermocline was observed in the Gulf of Riga laying at the depth of about 8m. The temperature in the surface layer reached 12.5 °C at the eastern side of the Gulf (see Fig. 1.6), which is shallower than the western one. In the southern part a comparably strong temperature anomaly can be observed, which is caused by the spreading of the riverine colder water in the Gulf. Below the seasonal thermocline, the temperature of the sea water remained at about early spring values - 2-3°C (see Fig. 1.7). Such a thermohaline structure represents a typical summer situation. Seasonal thermocline shielding the lower layer from the influence of the direct wind forcing and thus vertical mixing between surface and deep layers is minor then. Under the latter conditions lower layer is more saline and weakly stratified.

A strong frontal zone in the upper layer salinity field was observed in the mouth area of the Daugava river (see Fig. 1.6), which is caused by high river runoff, occurring in May-June

(Pastors, 1967). At this time of the year the seasonal thermocline is already formed, the frontal zone does not extend any more down to the bottom layer. Maximum salinities in the bottom layer were observed in the central and western parts of the Gulf. The first place is in the deepest part of the Gulf and secondly, where the inflowing saline water tends to be located when it has passed the Irbe Strait.

The surface frontal zone between the Gulf of Riga and the Baltic Proper waters was probably far offshore from the Irbe Strait, whereas the deep water front was situated in the Irbe Strait between the Sõrve Peninsula and Cape Kolka (see Fig. 1.7).

August

The surface layer temperature reached its maximum of about 16.5-18°C and its horizontal distribution is quite homogeneous in the central part of the Gulf (see Fig.-s 1.8 and 1.9). The western coastal zone is affected by upwelling due to westerly winds. The upwelling caused a sea water temperature anomaly of about 1°C near the western coast and nearby Cape Kolka even up to 2 °C. This event also influence the distribution of the temperature in the near bottom layer of the Gulf, where cold water extends from the center of the Gulf up to its western slope. Some earlier observations of upwelling near the western coast of the Gulf of Riga and relevant statistics are reported by Zakharchenko and Kostjukov, 1987.

The salinity distribution both in the surface and in the bottom layers is quite homogeneous in the whole area of the Gulf. The frontal zone between the Gulf and the Baltic Proper water is situated in the Irbe Strait in its ordinary location both in the surface and in the bottom layers. (see Fig.-s 1.8 and 1.9). A more detailed description of the dynamics of the frontal zone in the Irbe Strait is given in Chapter 4 of the current report.

November

During the survey in November (see Fig.-s 1.10 and 1.11) a typical late autumn-winter thermohaline situation was observed in the Gulf of Riga. Vertically homogeneous water masses with salinity of about 5.5 psu and temperature around 7 °C extended over the whole area of the Gulf. As the air temperature decrease during the period was very rapid and in addition occurred during strong winds in the area, a fast cooling of the whole water mass of the Gulf took place during the November survey (see Fig. 1.12). In about ten days the temperature in water column at a depth of 30m lowered from 7.5 °C to 4.5 °C (see Fig. 1.12). The horizontal variations of the sea water temperature were in range of about 1.2 °C between the coastal shallow areas and the deep central part of the Gulf. Salinity distribution patterns showed higher values in the northern part of the Gulf both in the surface and near-bottom layers. A weak fresh water anomaly is distinguishable in the mouth of the Daugava river.

1.5 Conclusions

The Gulf of Riga thermohaline structures are related to the variations of fresh water input from the rivers and saline water input through the Straits of Irbe and Virtsu.

A quasipermanent frontal zone, extending across the Irbe Strait between the Gulf of Riga and the Baltic Proper waters, was observed in the thermohaline field during all four surveys in 1993.

A second frontal zone was observed near the mouth of the Daugava River, which is the largest fresh water supply into the Gulf of Riga, giving some 70% of the total fresh water runoff. The strongest low saline anomaly was observed during the seasonal runoff maximum in May-June, when the flow rate of the Daugava increases from about 400 m³/s to 4000 m³/s (Pastors, 1967).

More saline water that enters the Gulf from the Baltic Proper, originates from the levels above the sill depth (30m) between the two basins. As the inflowing water has higher salinity and therefore density, it forms a dense bottom current, which after passing the Irbe Strait in most cases turns to the south and then follows the western coastal slope of the Gulf. Signs of a such inflow pattern, when more saline water was situated along the western coast of the Gulf, were observed during all seasonal surveys.

Future analysis should probably be more concentrated on the analysis of year to year variability of the thermohaline structures on the basis of available hydrographic parameters measured in different years at monitoring stations of the Gulf of Riga.

Acknowledgements

The expedition group of the Estonian Meteorological and Hydrological Institute (leader Mr. Ivo Saaremäe), who performed field activities during Estonian monitoring cruises and Dr. Evgeny Zakharchenko, who made available Latvian Monitoring data, are kindly acknowledged.

References

- Mardiste, H. 1964.** Currents in Moonsund Sound. In: *Proceedings of the Hydrometeoro-logical Service of Estonian SSR*. Tallinn, 2, 70-88.
- Pastors, A. 1967.** Water and heat balance in the Gulf of Riga. In: *Morskie zalivy kak priyomniki stochnykh vod*. Riga, Zinātne 8-20 (in Russian).
- Petrov, B.S. 1979.** Water balance and water exchange between the Gulf of Riga and the Baltic Proper. *Sbornik rabot rizskoi gidrometeorologicheskoy observatorii* 18, 20-40 (in Russian).
- Zakharchenko, E.N., and Kostjukov, J.L. 1987:** Prognosis of upwelling near western coast of the Gulf of Riga, *Sbornik rabot rizskoi gidrometeorologicheskoy observatorii*, 6, 88-95 (in Russian).
- Yurkovskis A., Wulff, F., Rahm, L., Andruzaitis, A., and Rodrigues-Medina, M. 1993.**
A Nutrient Budget of Gulf of Riga; Baltic Sea *Estuarine, Coastal and Shelf Science*, 37.

Monitoring stations Gulf of Riga

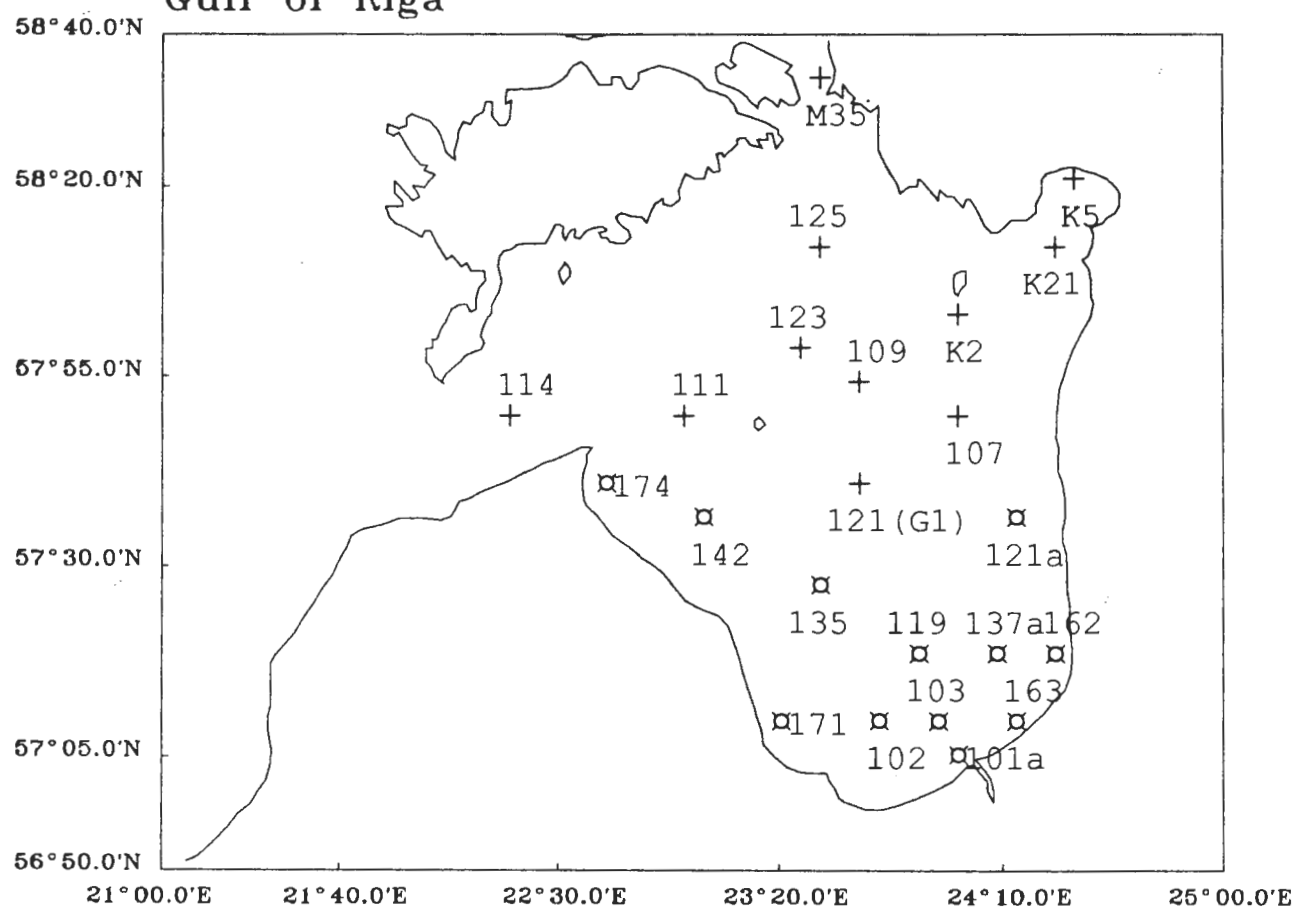


Fig. 1.1 Seasonal monitoring stations in the Gulf of Riga of Estonian Marine Monitoring Program (+) and Latvian Marine Monitoring program (□)

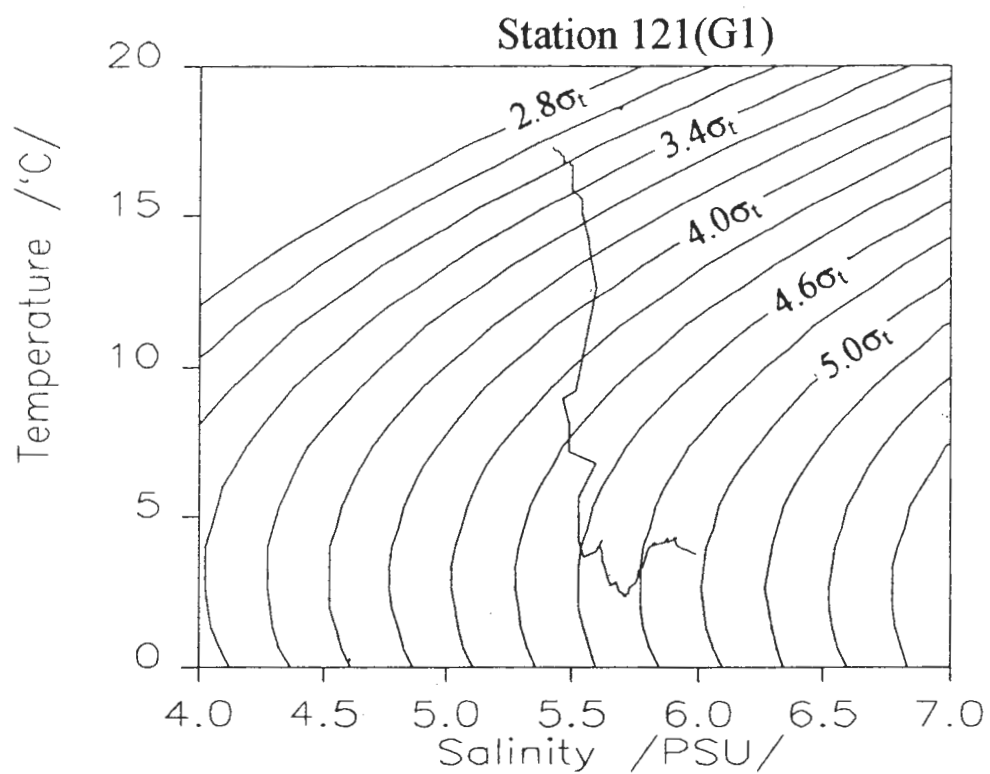
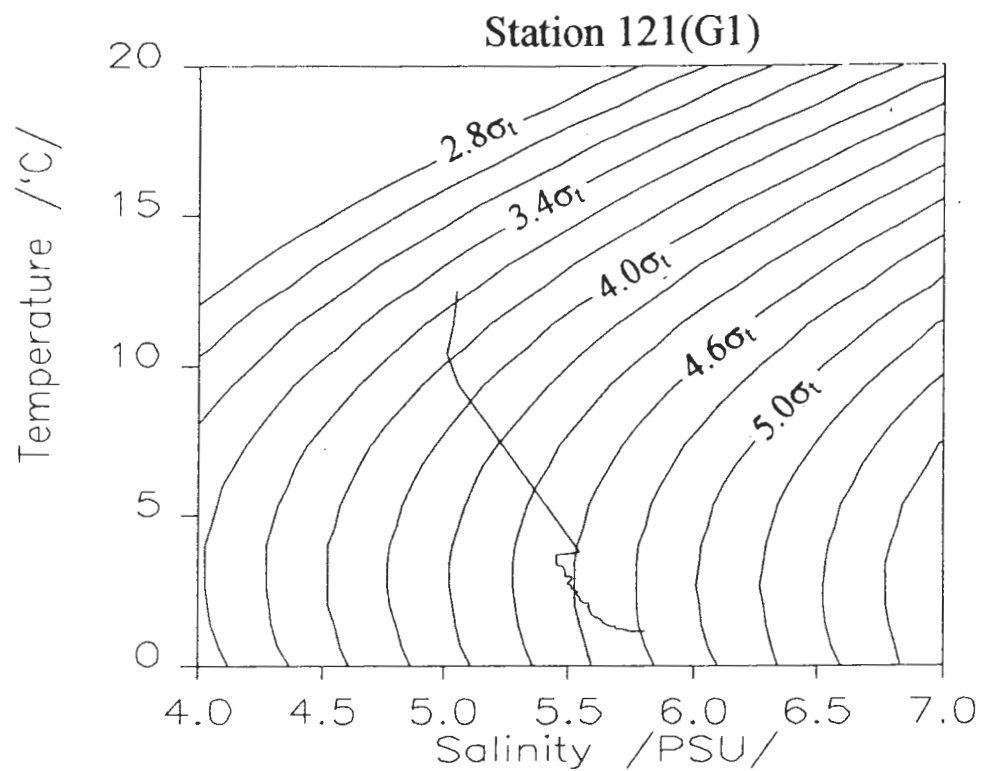
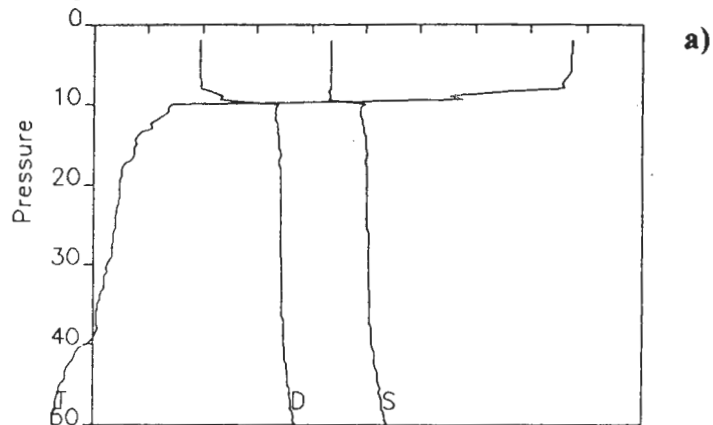
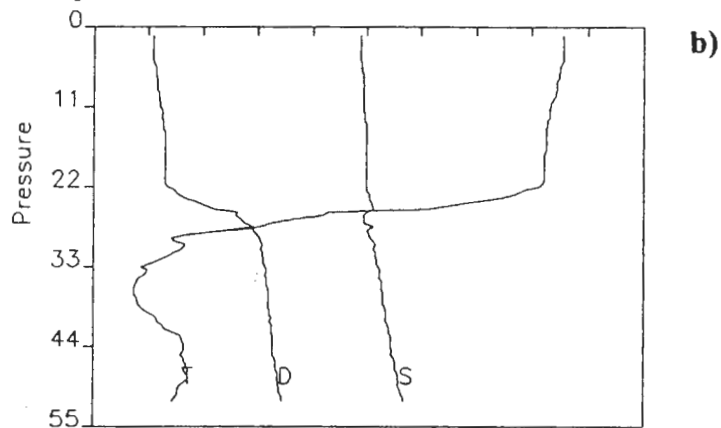


Fig. 1.2 T-S curves representing the Gulf of Riga water mass sampled in May (a) and in August (b), 1993.

R/V ORBIT cruise 1
 Survey 2 CTD - Station 121(G1)
 57 37.0'N 23 37.0'E Date 17/ 5/93 GMT 13.54
 Plotting limits: Temp = 2.0-14.0 Sal = 2.0- 9.0
 Sig-t = 2.0- 9.0



R/V ORBIT cruise 2
 Survey 1 CTD - Station 121(G1)
 57 36.9'N 23 36.9'E Date 16/ 8/93 GMT 21.55
 Plotting limits: Temp = 1.0-20.0 Sal = 2.0- 9.0
 Sig-t = 2.0-10.0



R/V ORBIT cruise 3
 Survey 1 CTD - Station 121(G1)
 57 36.9'N 23 36.9'E Date 2/11/93 GMT 22.51
 Plotting limits: Temp = 5.0- 8.0 Sal = 5.0- 7.0
 Sig-t = 4.0- 6.0

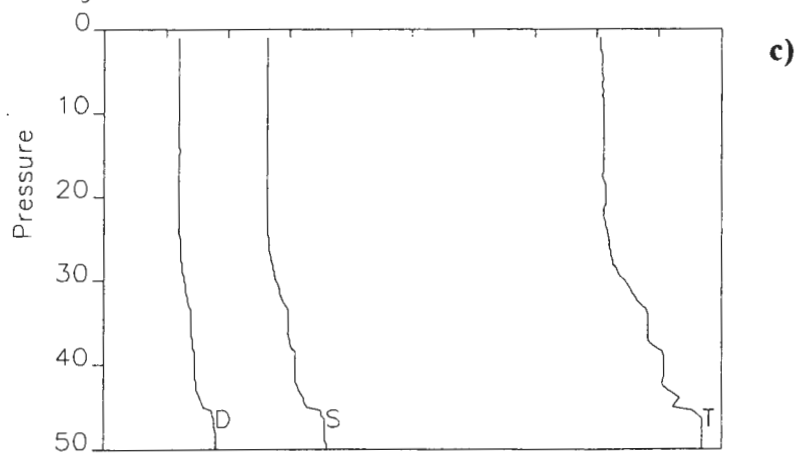


Fig. 1.3 Vertical profiles of hydrographic parameters in the Gulf of Riga typical for spring (a), summer (b) and autumn-winter (c) seasons.

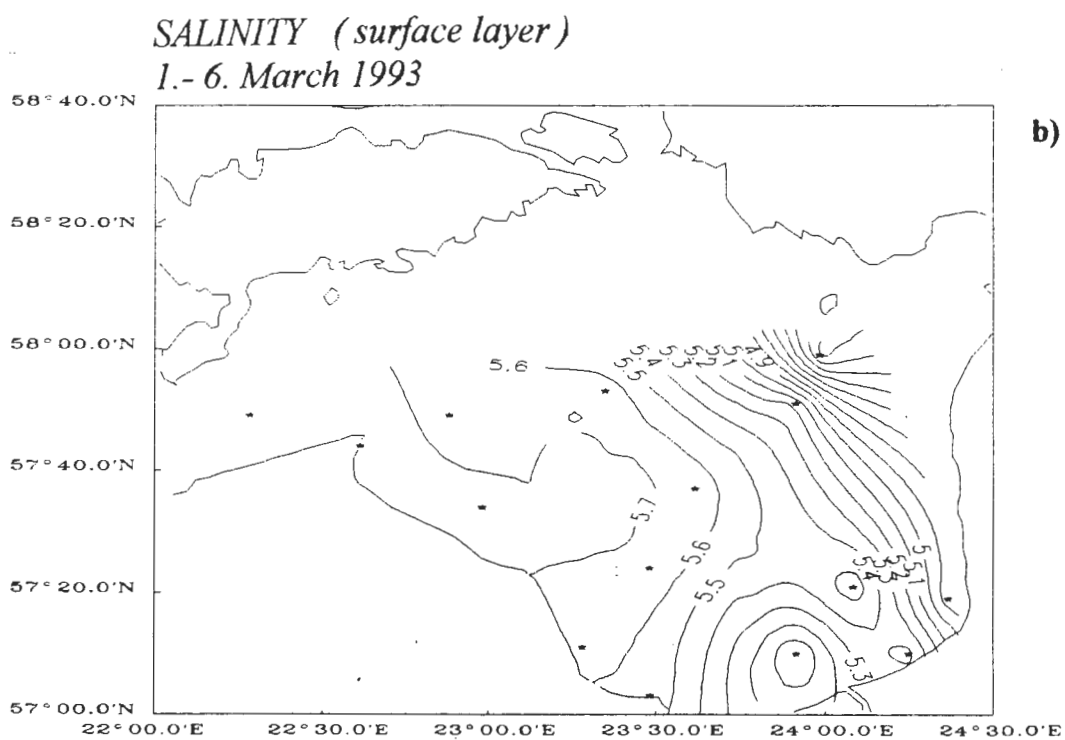
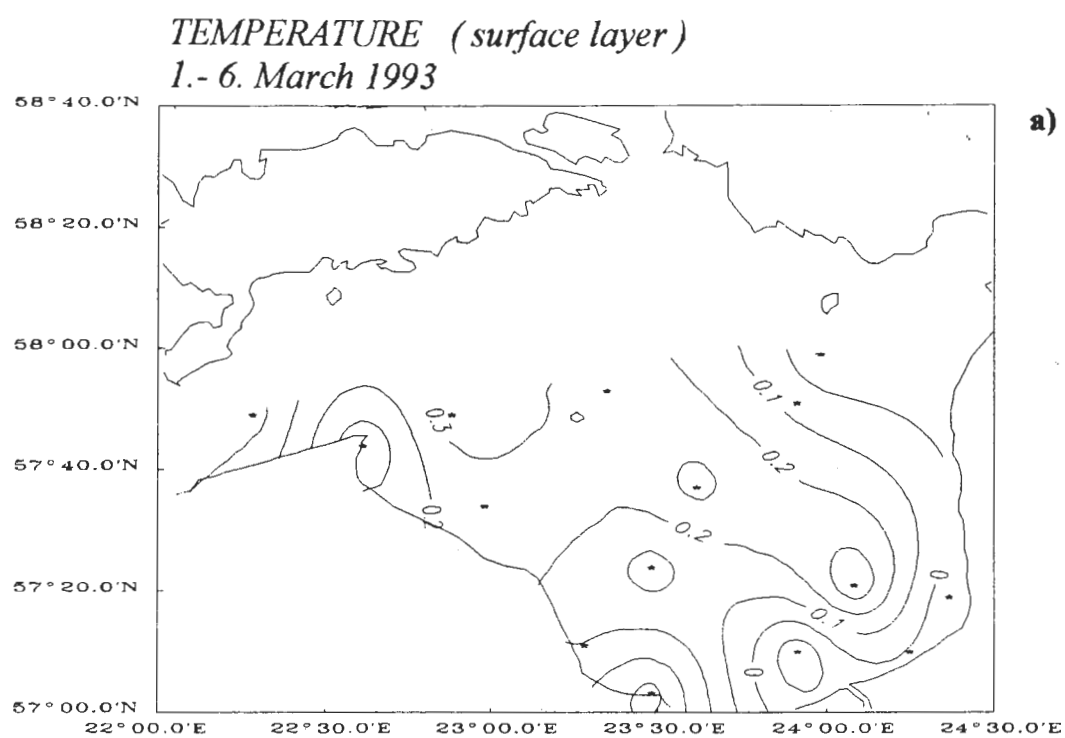
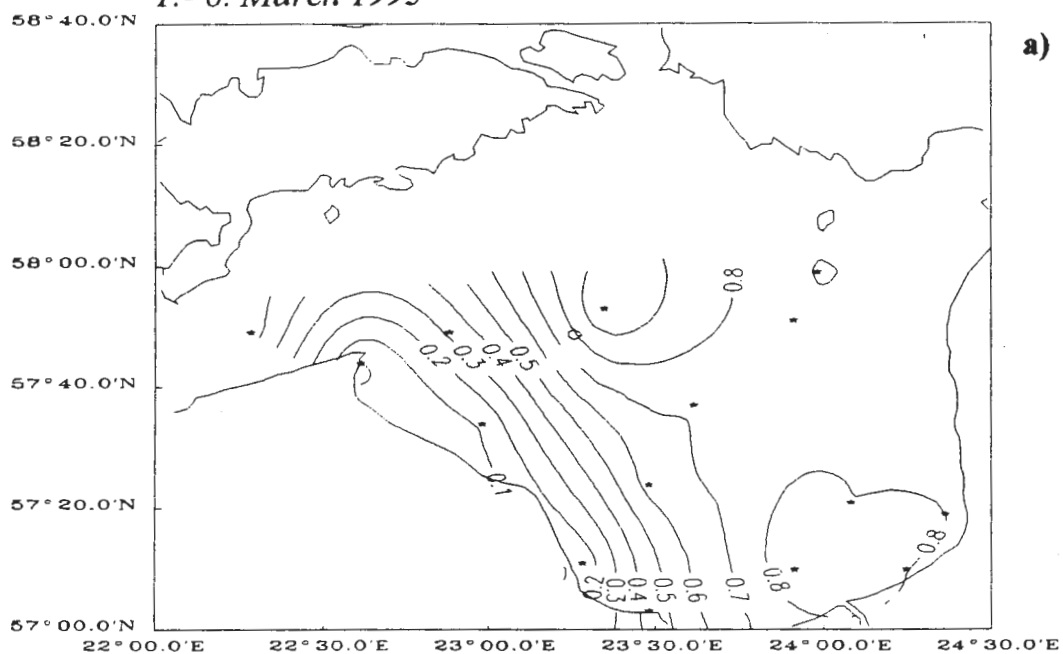


Fig. 1.4 Surface layer temperature (a) and salinity (b) in the Gulf of Riga in March 1993.

TEMPERATURE (bottom layer)
1.- 6. March 1993



SALINITY (bottom layer)
1.-6. March 1993

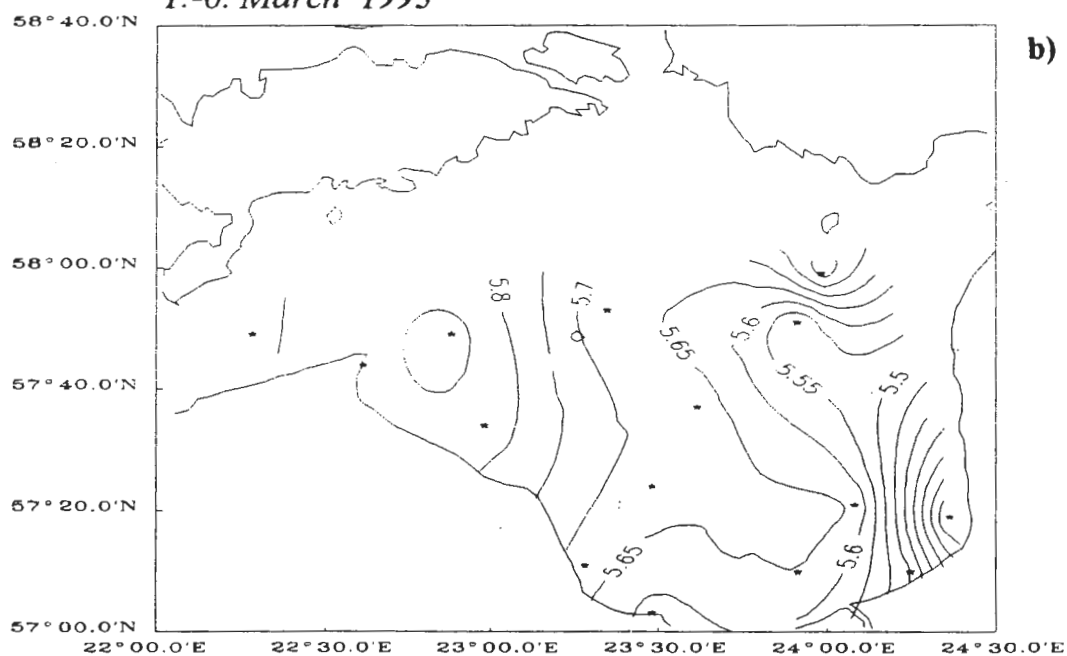
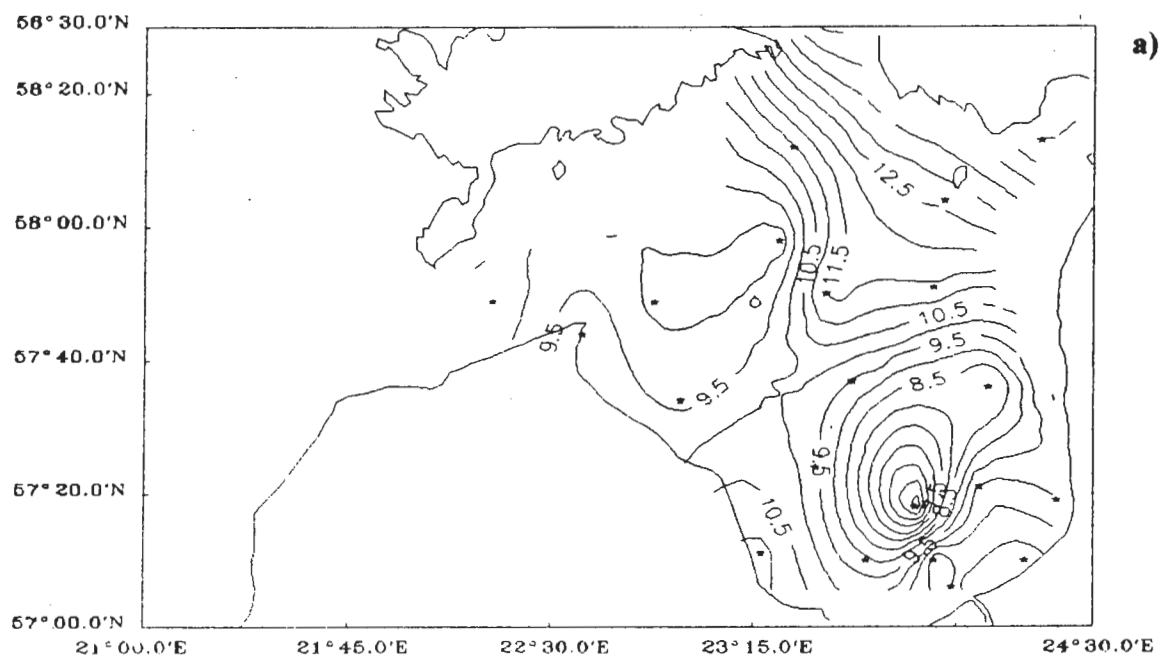


Fig. 1.5 Near-bottom layer temperature (a) and salinity (b) in the Gulf of Riga in March 1993.

TEMPERATURE (surface layer)
10.- 14. May 1993



SALINITY (surface layer)
10.- 14. May 1993

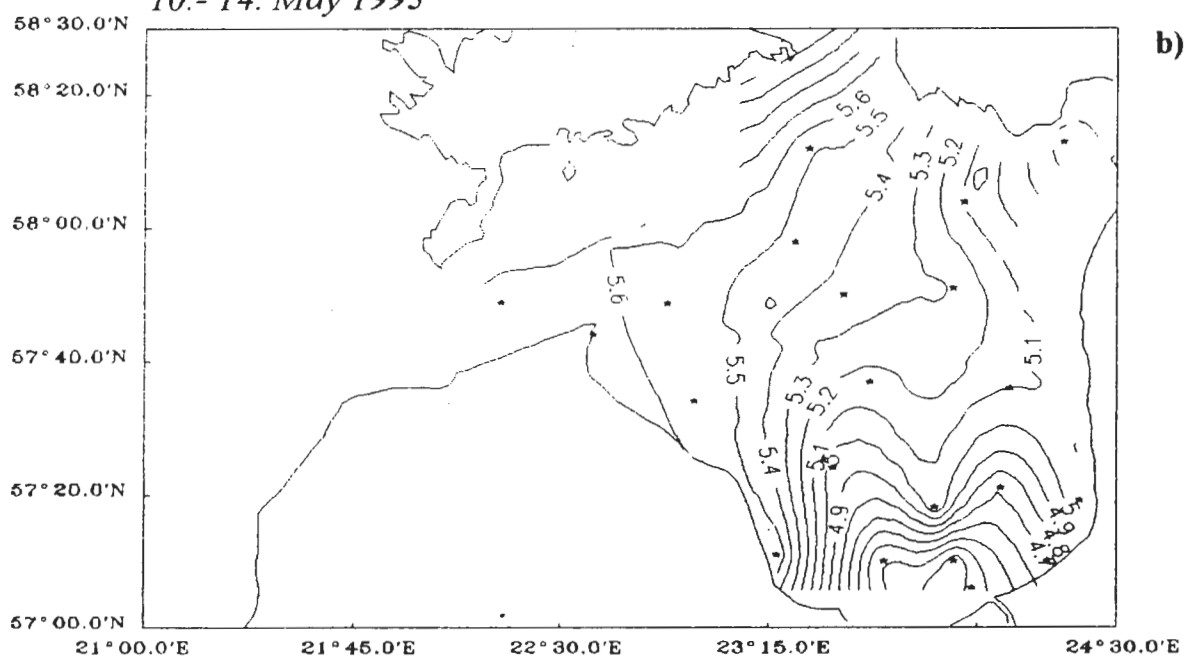


Fig. 1.6 Surface layer temperature (a) and salinity (b) in the Gulf of Riga in May 1993.

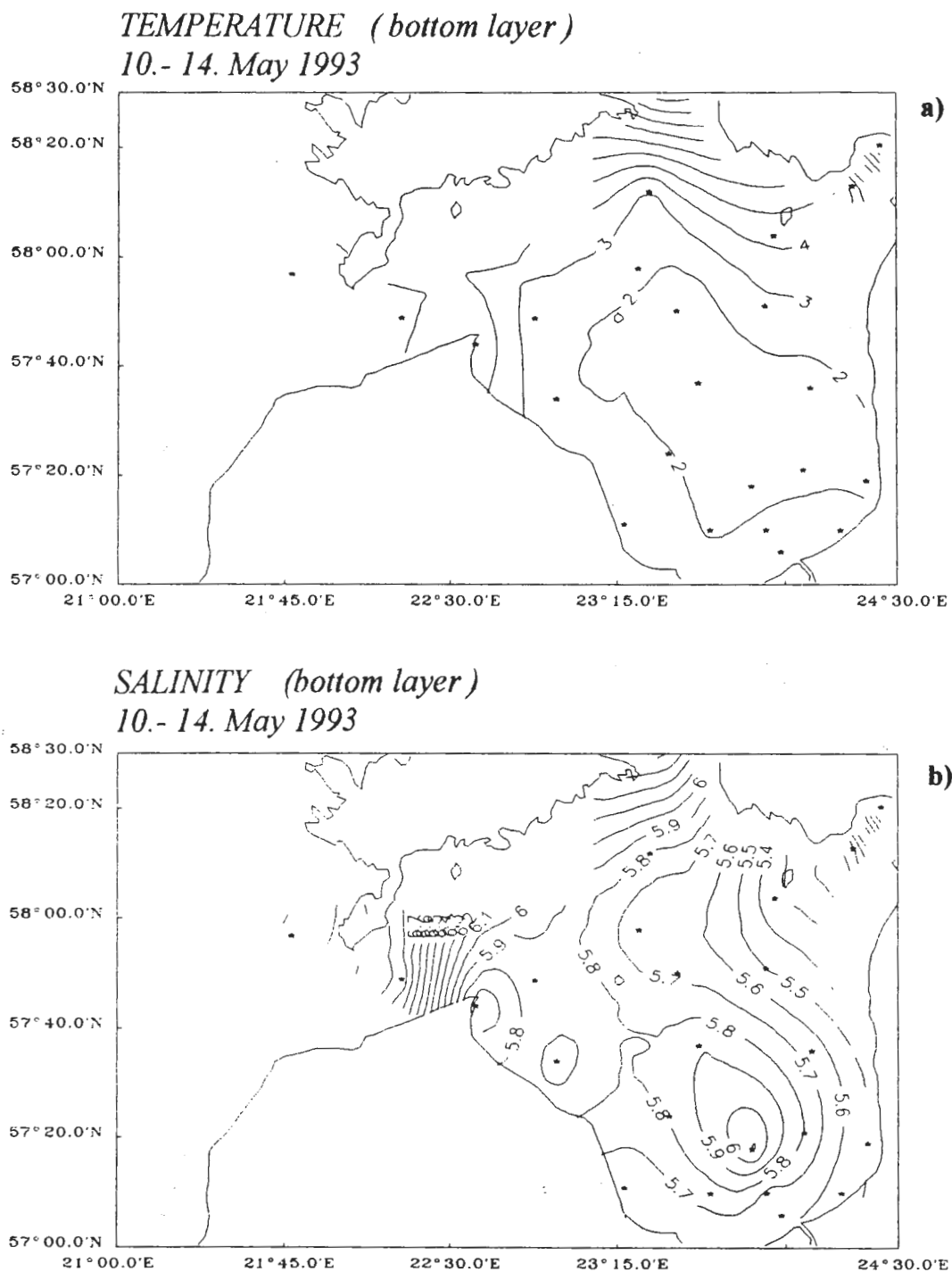
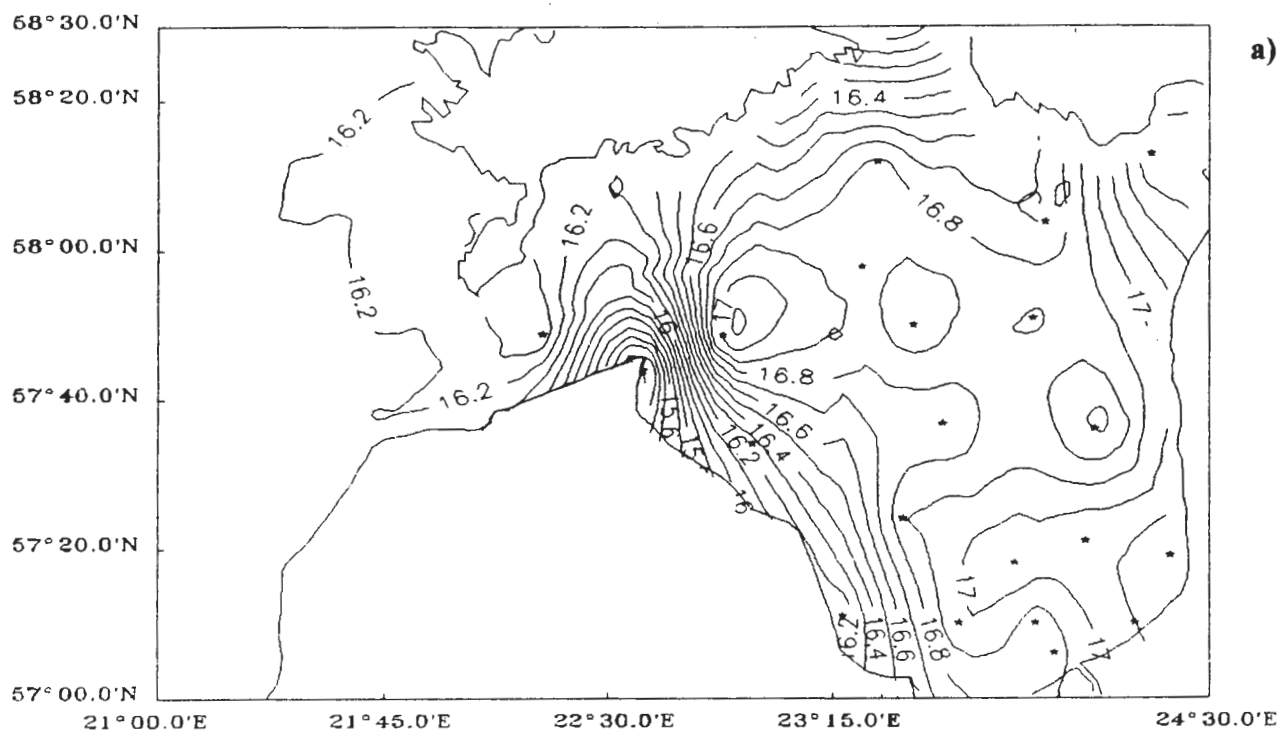


Fig. 1.7 Near-bottom layer temperature (a) and salinity (b) in the Gulf of Riga in May 1993.

TEMPERATURE (surface layer)
12.- 16. August 1993



SALINITY (surface layer)
12. -16. August 1993

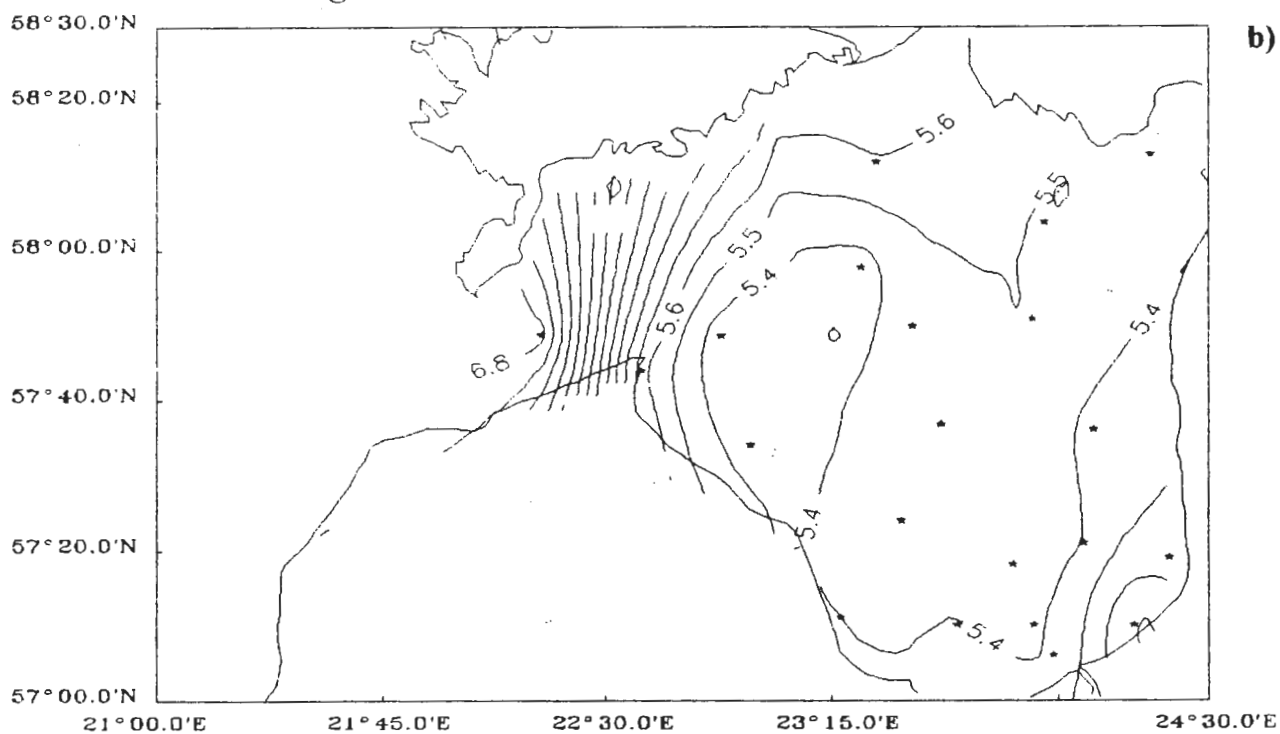
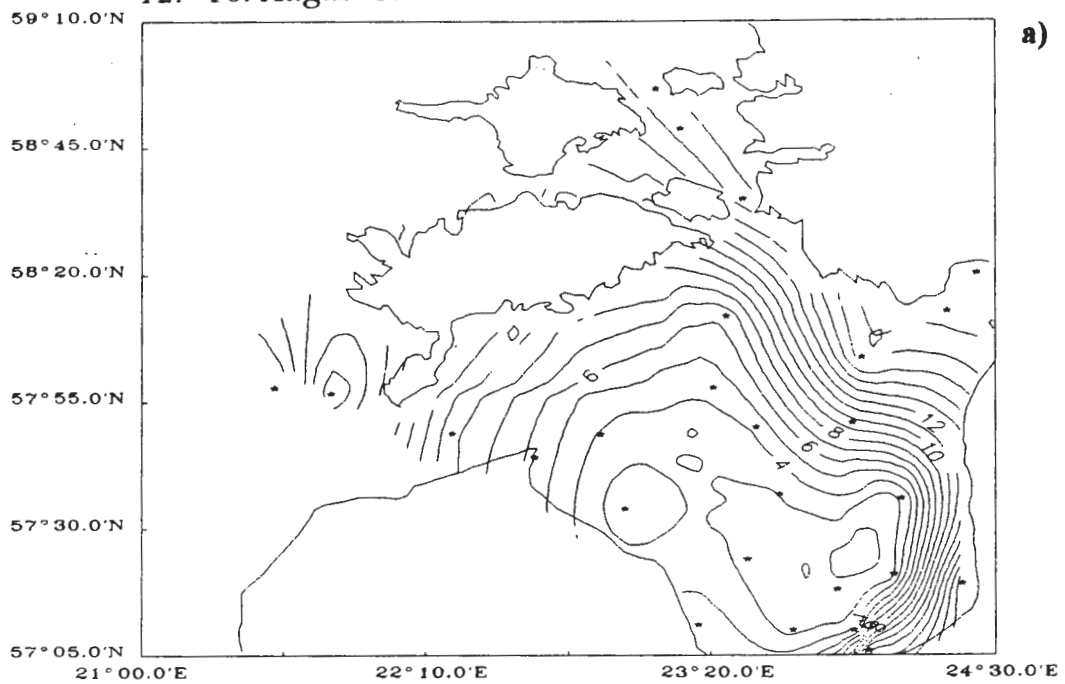


Fig. 1.8 Surface layer temperature (a) and salinity (b) in the Gulf of Riga in August 1993.

TEMPERATURE (bottom layer)
12.- 16. August 1993



SALINITY (bottom layer)
12. -16. August 1993

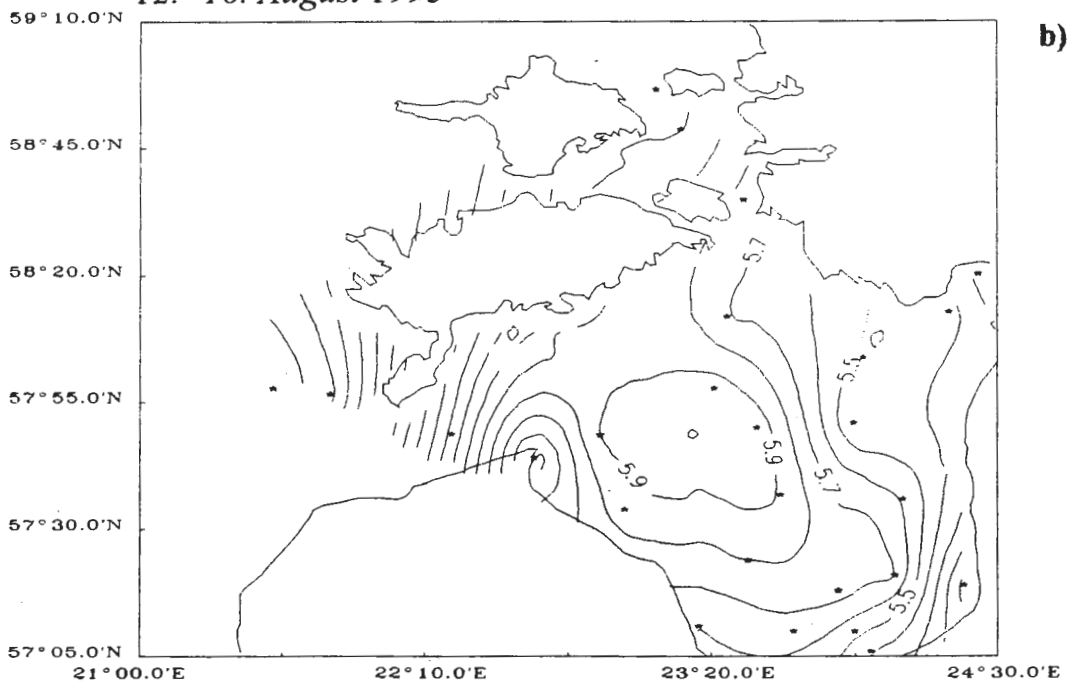
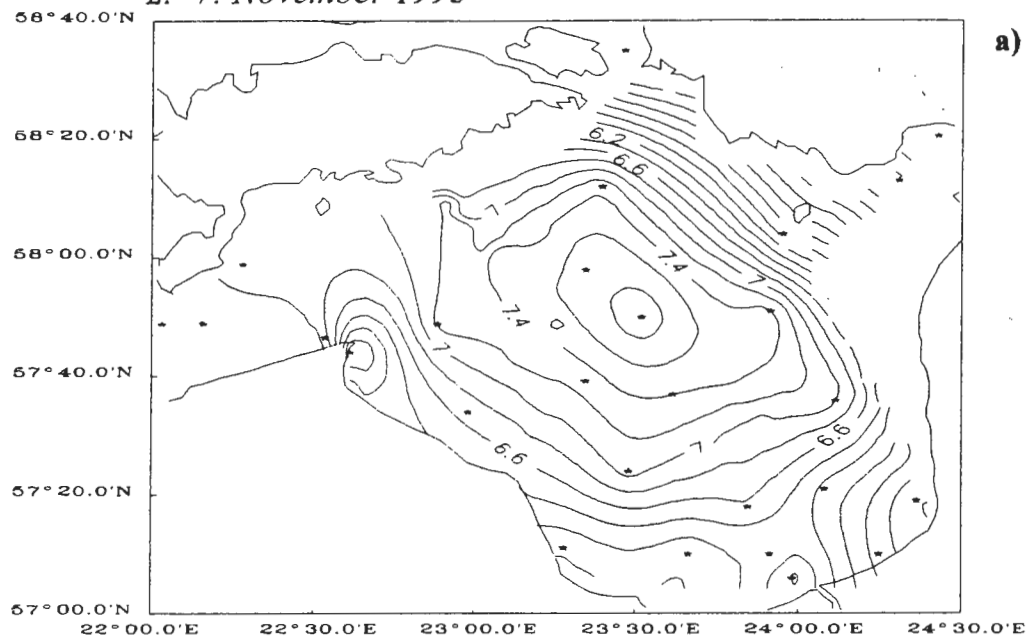


Fig. 1.9 Near-bottom layer temperature (a) and salinity (b) in the Gulf of Riga in August 1993.

TEMPERATURE (surface layer)
2.- 7. November 1993



SALINITY (surface layer)
2.- 7. November 1993

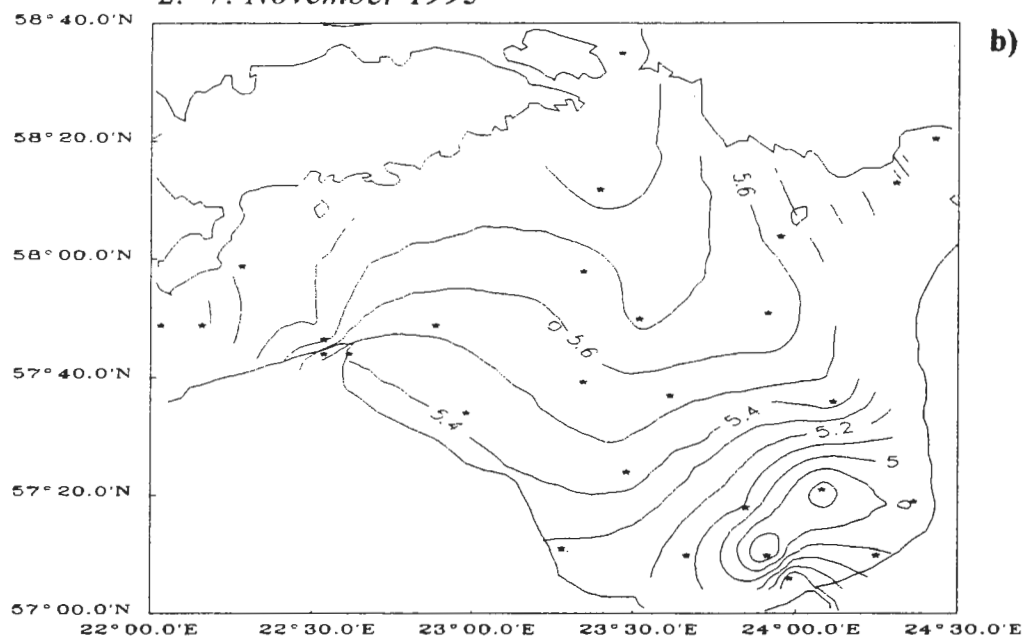


Fig. 1.10 Surface layer temperature (a) and salinity (b) in the Gulf of Riga in November 1993.

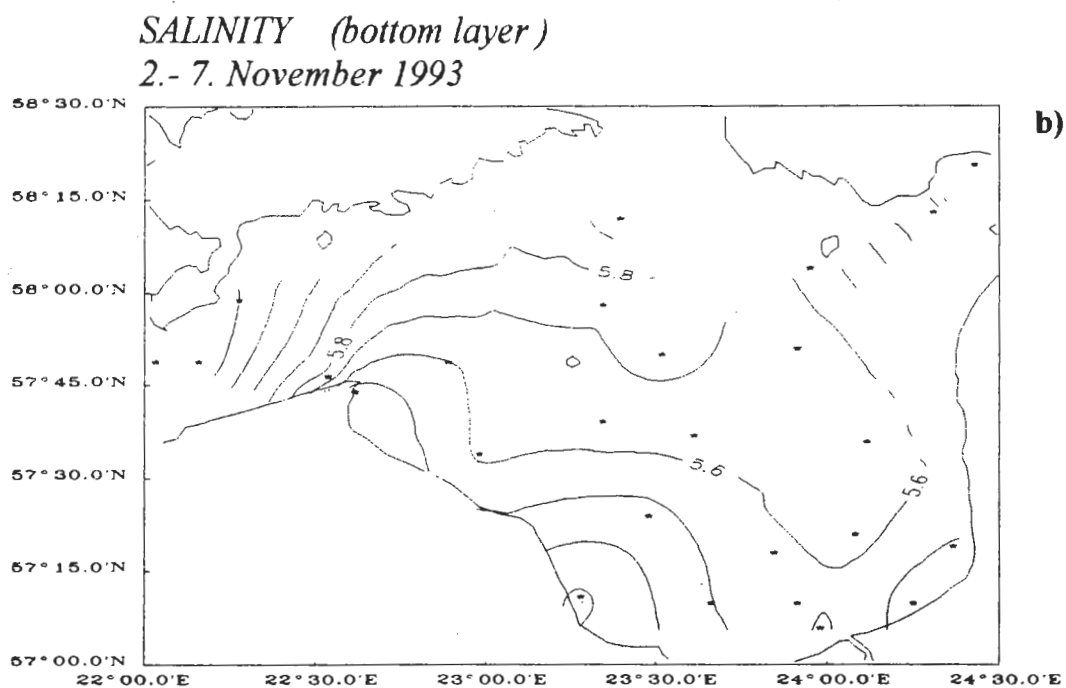
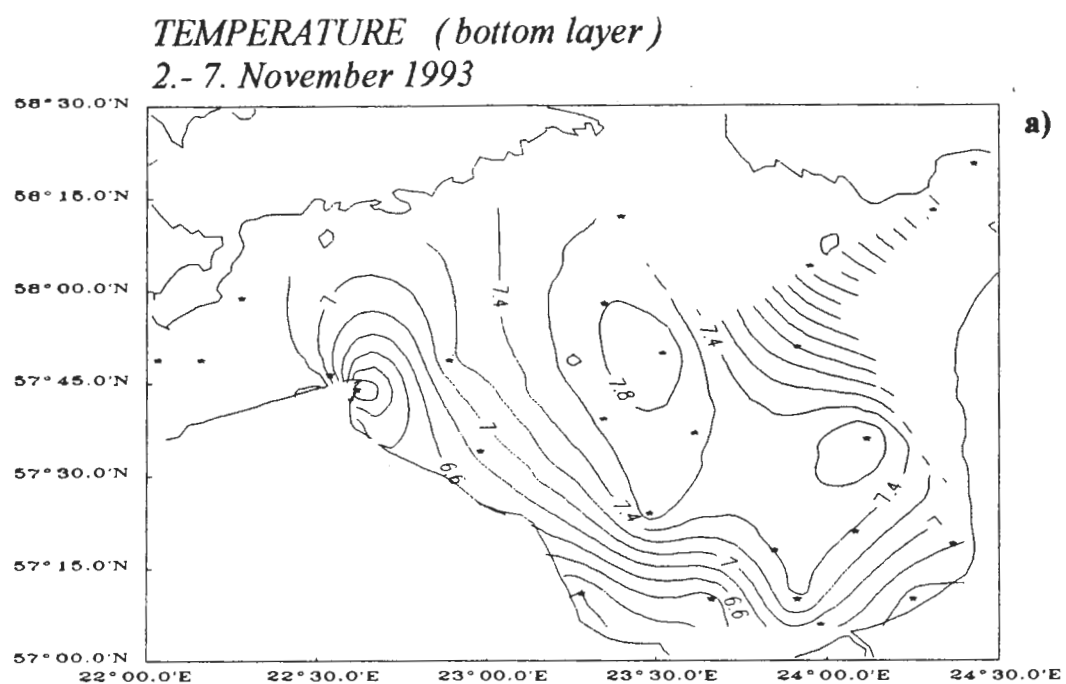


Fig. 1.11 Near-bottom layer temperature (a) and salinity (b) in the Gulf of Riga in November 1993.

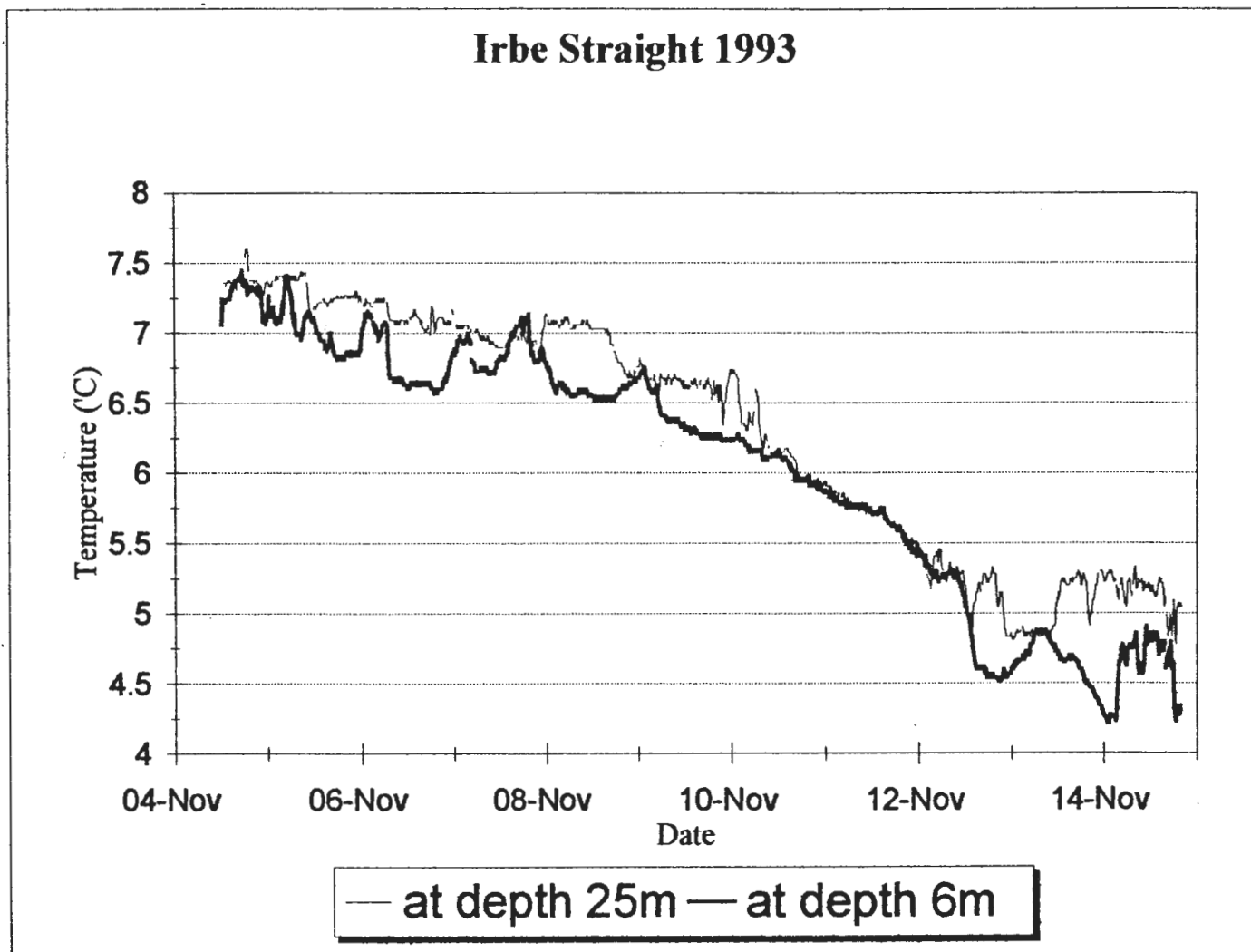


Fig. 1.12 Continuous temperature records measured at mooring station in the Irbe Strait at depths 6m (a) and 25m (b) in November 1993, when intensive cooling of sea water took place. Depth of sea floor in the location of the mooring station is ~30m.

2. On the vertical structure of currents in the Irbe Strait

by Madis-Jaak Lilover (Estonian Marine Institute)

2.1 Introduction

The main part of the water exchange between the Baltic Proper and the Gulf of Riga occurs through the Irbe Strait. Although there are existing several estimates of total water volume exchanged through the strait (see for example Petrov, 1979), the actual processes responsible for the volume and material exchange are still poorly known. Therefore, better knowledge about the vertical structure of currents in the Irbe Strait as well as the physical processes responsible for the structure of currents are needed. The planning of ongoing experimental efforts, the evaluation of obtained data of biological parameters and nutrient dynamics in the transition area, will also benefit from studies of these issues.

- The vertical structure of currents in the Irbe Strait is mainly formed by the following factors:
- atmospheric forcing,
- sea level inclination,
- horizontal density differences,
- tides (shown by Francke, 1984 and Petrov, 1979 in the shallow and narrow channel-like regions of the Baltic Sea)

In the Irbe Strait the 24 hours tidal period (K_1 tide) and the semi-diurnal tidal period (M_1 tide) was observed from the current meter records (Petrov, 1979).

These forces acting all together probably form the complicated vertical structure of currents in this region. The following two layer scheme was suggested by Petrov for typical water exchange: the outflow takes place in the northern part and in the upper layer (down to 10-15 meters) of the southern part of the Strait, the inflow takes place in the deep layer near the southern coast. The salinity measured in the sections perpendicular to the Strait indirectly characterize the vertical structure of currents as well as the horizontal structure. The salinity cross section made during the prevailing eastern wind revealed that the upper layer was divided into two parts (Fig. 2.1) by a strong salinity front (salinity difference of 1 psu). The salinity cross section made during the south wind period revealed also a strong salinity front in the upper layer. Both sections belong most likely to the inflow period near the southern coast of the Strait and to the outflow period near the northern coast. The front region between outflow and inflow waters is rather sharp and its location on the cross transect varies in time. According to these salinity sections the saline water inflow should be measured near the southern coast of the Irbe Strait in two layers and outflow of fresher water near the northern coast of the Strait in order to study the water exchange.

From snapshots of relative current vertical structure profiles (the current vertical structure is measured relatively to the uniformly drifting ship and vehicle body) the clear two layer structure can not be expected because the measurements are contaminated by the motions of higher frequencies, such as tidal and inertial oscillations.

We would like to see from our current vertical structure measurements a snapshot of a layered structure, to assess movement of one layer relatively to another and to use them to determine different physical processes that form the vertical structure of currents in the Strait (for example: near-inertial waves, coastal jets). Therefore, the data are treated trying to answer the following questions. Where is the salinity front situated in the upper layer (in the lower layer)? According to the salinity values is there an inflow or outflow situation in both

layers? What is the movement of one layer relatively to another? How the observed situation corresponds to the wind field?

The aim of our study is to characterize the vertical structure of the currents and the physical processes forming it in the Irbe Strait and in the contact (frontal) zone of the Baltic Proper and the Gulf of Riga waters.

2.2 Equipment and methods

The measurements of vertical profiles of current velocity, temperature and salinity were made using a Neil Brown Instrument Systems (NBIS) Acoustic Current Meter supplemented with NBIS MARK III CTD sensors (ACM/CTD). The profiler ACM/CTD measures two components of horizontal velocity relatively to the vehicle body, vehicle orientation, conductivity, temperature and pressure. The current measurement technique by ACM/CTD is described by Robbins and Morrison (1981). The ACM measures water currents by detecting the differential travel time of acoustic signals propagated in opposite directions along the same fluid path. Acoustic Current Meter sensor geometry and ACM/CTD profiler outline is shown in Fig. 2.2.

The deployment of ACM/CTD required the ship to drift broadside to the wind. The measurements were started when the uniform ship drift was reached. Contamination of the velocity data caused by the ship rolling was reduced by low pass cosine filtering with half filter period of 10 s that exceeds the characteristic period of ship rolling which is 5-6 s. At our main lowering speed of the probe (0.3 m/s) the motions with vertical scales less than 3 meters were filtered out. The velocity components were measured with noise level of 1-2 cm/s depending on the sea roughness. Details of accuracy analysis of the ACM/CTD measurements are presented in Lilover (1987). The CTD sensors accuracy was checked by comparing in situ measurements with high-precise salinometer AUTOSAL analysis of the water samples.

During the November cruise a special measuring technique was used. The CTD profiles were taken during the drop of the profiler but current velocity was measured at 5 meter intervals, when profiler rose up from 25 meter depth to the 5 meter depth. At each depth level a 2 minutes average velocity was calculated.

2.3 Measurements

During three cruises in 1993 to the Gulf of Riga area (in May, in August and in November) two types of measurements of vertical profiles of current velocity and CTD profiles were made using an ACM/CTD probe. In May from 18 to 19 the measurements were performed along the transect II at stations with numbers 77-101 (Fig. 2.3). During the cruises in August (from 22 to 24) and November (from 5 to 7) the current velocity profiles were taken at a single station in the point of intersection of the transects where also the buoy station was located (57°48,9'N, 22°16.9'E). The time series in August was expected to cover 57 hours with an hourly interval, but due to computer failure two data gaps of five and six hours occurred. In November seven profiles of current velocity were measured during 52 hours.

The measurements of current profiles differ in type (spatial, temporal) and in background conditions (different seasons) therefore further analysis is made for each cruise (month) separately.

2.4 Results and discussion

May

With the aim to characterize the vertical structure of currents in the Irbe Straits and in the contact (frontal) zone of the Baltic Proper and the Gulf of Riga waters, the measurements were performed along transect II extending from the mouth area of the Strait to the north-western part of the Gulf, it is from SW to NE.

Weak ENE winds (direction 50°-70°, speed 3-6 m/s) prevailed during the measurements.

According to the detected thermohaline pattern it seems that a saline water inflow situation took place. The more saline Baltic Proper water flowed into the Gulf beneath the outflowing surface water. The salinity front in the surface layer between the two water masses was directed out of the Irbe Strait towards the Baltic Proper. The strong salinity front in the lower layer was accompanied by a weak front in the upper layer between the stations 91 and 88 (at the level of 17 meters the salinity changed from 6.6 to 5.9 psu, the latter is indicator of the Gulf of Riga water Fig. 2.3).

In the middle of the Strait the vertical structure of the current velocity followed the thermohaline structure of three layers: surface mixed layer (down to depth of 8 meters), seasonal thermocline more than 7 meters lower and deep (lower) layer (15-30 meters) (Fig. 2.4a). Assuming that the velocity has minimum value near the bottom, a two layer structure can be distinguished: upper layer down to 10 meters with water flowing along the section out of the Strait and lower layer with water flowing in. This two layer structure can be detected from successive profiles as well (st.93, 94, 95) (Fig. 2.4b).

The velocity vectors have opposite directions at different sides of the front. The current velocity vector has been directed to the south in respect to the bottom layer at the more saline side of the front and to the north (Fig. 2.5) at the side with fresher water.

Therefore a two-layer current structure was observed in the Strait, this structure disappeared outside the Strait. The water in the upper layer was flowing to the south in the west side of the salinity front and to the north direction in the east side.

August

With the aim to characterize evolution of the vertical structure of currents, measurements close to the buoy station in the intersection point of the transects were carried out during 57 hours (Fig. 2.6a). In the beginning of the survey, the wind blew from the W (speed 7 m/s, st.286-305), then turned to the S (speed 7 m/s, st.306-325) and then blew from W again but increased first up to 10 m/s and then up to 14 m/s (st.326-340) in the end of the observation period.

According to the thermohaline structure inflow from the Baltic Sea took place in the upper 20 meters and a compensating outflow of fresher water occurred in the bottom layer. The current velocity measurements averaged over 2.5 days at the buoy station supported that structure indicating a mean inflow velocity of 3.9 cm/s at the level of 10 meters and a mean outflow velocity of 1.3 cm/s at the level of 25 meters (Kouts, pers. comm.). The general outflow was accompanied by the situation with less saline water in the lower layer and more saline water in the upper layer. The lower layer salinity minimum was around 6.0 psu while in the upper layer the salinity value was around 6.3 psu. This salinity inversion was compensated by colder water in the lower layer so that a stable stratification (Fig. 2.7) was preserved.

A salinity front was observed in the surface layer just within the Irbe Strait, where salinity changed from 6.7 to 5.4 psu (Fig. 2.6b).

The along-strait relative current (rotation of 27 degrees of co-ordinate axes was performed) indicated an outflow in the upper layer in respect to the near-bottom layer (that was consistent with the current meter measurements at the mooring station where the current

direction was 220°) during westward wind case (Fig. 2.8 I). Salinity increased in the upper 20 meters (Fig. 2.7 II) during the wind from the south. The cross-transect velocity component indicated the SE-ward current flow in the upper layer relatively to the lower layer (Fig. 2.8 II). This was also consistent with the current direction (150°) at the mooring station.

The rapid increase of wind speed and change of direction destroyed the existing current system (Fig. 2.8 III). Disturbances with vertical scale of 10 meters could be observed in current velocity profiles. During this wind event the upper layer was totally mixed down to 20 meters. Probably alternating of the fresher water with the saline water in the deep layer was caused by meandering of more saline water flow, located not far from the position of measurements (near the southern coast of the Strait) (Fig. 2.8 III).

The fourth wind case (W, 13-14 m/s) was characterized by well-mixed upper layer down to 23 meters and with saline water (6.7 psu) in the near-bottom layer (Fig. 2.8 IV).

A set of TS curves clearly demonstrate the water masses variation during these 2.5 days (Fig. 2.9).

To conclude, the vertical structure of currents was completely rearranged by the increase of the wind speed. Disturbances with vertical scale of 10 meters were observed.

November

With the aim to detect physical processes forming the current velocity field in the Strait seven profiles of relative current velocity with vertical step of 5 meters were measured close to the mooring station during 52 hours (Fig. 2.10a). During the first half of the experiment the wind blew from the NE (speed 7-10 m/s) and afterwards from the E (speed 10 m/s).

According to the current measurements at the buoy station, a weak inflow took place. The current was directed in both layers against the wind. This might be the compensating current since the Ekman transport was during the last week in October out of the Strait (the last week wind blew from the S W-NNE directions according to data from Vilsandi island meteorological station).

The salinity front was observed at about the same location as in August between station of current measurements and the next station to the NE direction (salinity decreased from 6.2 to 5.6 psu) (Fig. 2.10b). In comparison to the situation in August, now the water was more saline in the lower layer than in the upper layer.

According to the measurement series the vertical structure depend on the local wind changes. The rapid NE wind increase during measurements at stations 499 and 505 generated a high velocity shear and perturbations of current velocity with different oscillation periods (Fig. 2.11 component V_c). The successive velocity profiles in the lower layer (below 10 meters) with time discrepancy of 7 hours revealed that the perturbations with vertical scale of 10-15 meters had an opposite oscillation phase (Fig. 2.11 pairs of profiles 505,511; 511,517; 517,523). This indicates the presence of inertial oscillation (the local inertial period is equal to 14 hours) or the influence of semi-diurnal tide. This oscillation period is also indicated by the similarity in the velocity structure at stations 511 and 523, separated in time by 14 hours. An oscillation period of 24 hours can detected from profiles 511 and 529 in the lower layer.

The temperature, salinity and water density fields showed an oscillating character in the lower layer. Water density had local maximum in time with period of 14 hours (Fig. 2.12 profiles 511,523) on the level of 25 meters. The temperature and salinity values were consistent with the oscillation phase of currents (for example see the lower values of temperature and salinity at station 517 where profile V_c is in opposite phase with profiles V_c at stations 511, 523 (Fig. 2.12 and Fig. 2.11)).

The time evolution of temperature, salinity and water density fields supported the observed oscillating pattern of currents.

2.5 Concluding remarks

The along-strait salinity front location as well as the deeper located halocline, which separate the Strait inflow/outflow sections, are highly variable in time and depend to a great extent on wind conditions. The cross-strait salinity front, separating the Baltic Proper and the Gulf of Riga water masses, was found shifted towards the Baltic Proper in May, whereas in the other 3 cruises (in August, in November, in January) just in the Strait.

According to the current profiler measurements the vertical structure of currents was characterized by a two layer structure. Wind speeds greater than 10 m/s seemed to destroy that structure. The current velocity vector had opposite directions at different sides of the front.

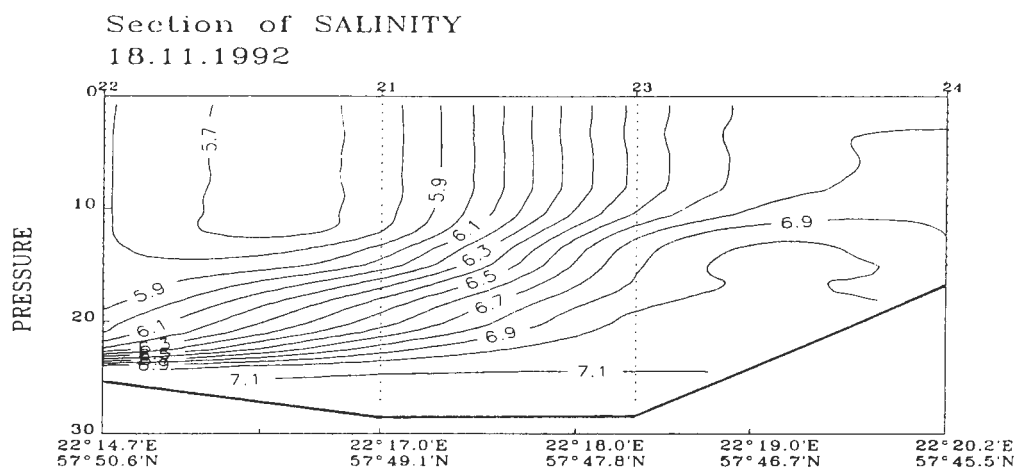
The series of current velocity profiles as well as series of current measurements at buoy stations revealed the presence of oscillations at semi-diurnal, inertial and diurnal periods. The current velocity oscillations were confirmed with oscillations of the thermohaline parameters. However, the current velocity oscillations revealed differently on along-strait component and on cross-strait component. The along-strait current velocity component revealed mainly the diurnal oscillation period, whereas the cross-strait component revealed the inertial (semi-diurnal) oscillation period.

For better separating the periods of oscillations much longer (at least one month) current measurements are recommended. To estimate the inflow and outflow fluxes, the currents should be measured on a cross transect of the Irbe Strait in two layers near the southern coast and at least in one layer near the northern coast.

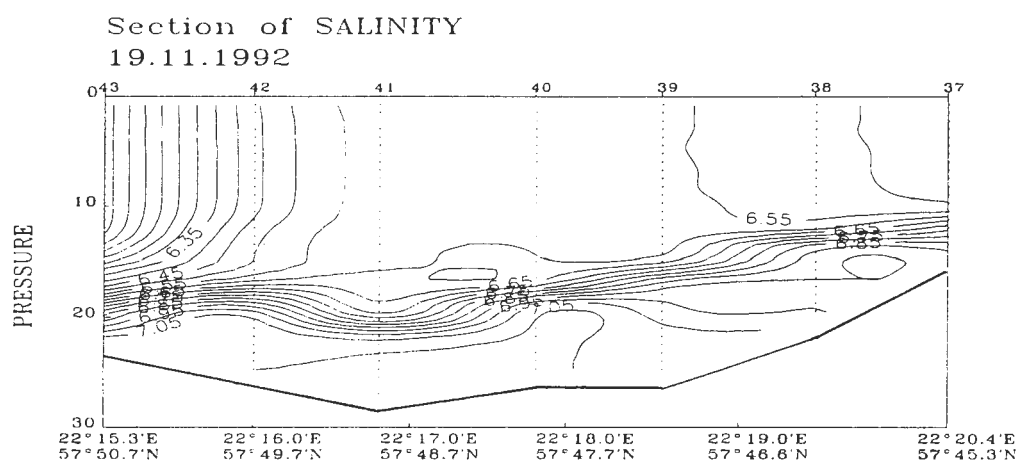
References

- Francke, E. 1984.** A contribution on the investigation of currents in the surface layer in the region of the Darss Sill. Proceedings of the XII conference of Baltic Oceanographers and of the VII meeting of experts on the water balance of the Baltic Sea, 2, 3-19.
- Lilover, M.J. 1987.** Estimation of accuracy of calculations of vertical shear, the Väisälä frequency and the Richardson number using vertical profiler data (in Russian). *Oceanol. Res.*, 40: 117-127.
- Petrov, B.S. 1979.** Water balance and water exchange between the Gulf of Riga and the Baltic proper. *Sbornik rabot rzhskij gidrometeorologicheskij observatorii*, 18, 20-40 (in Russian).

a



b



c

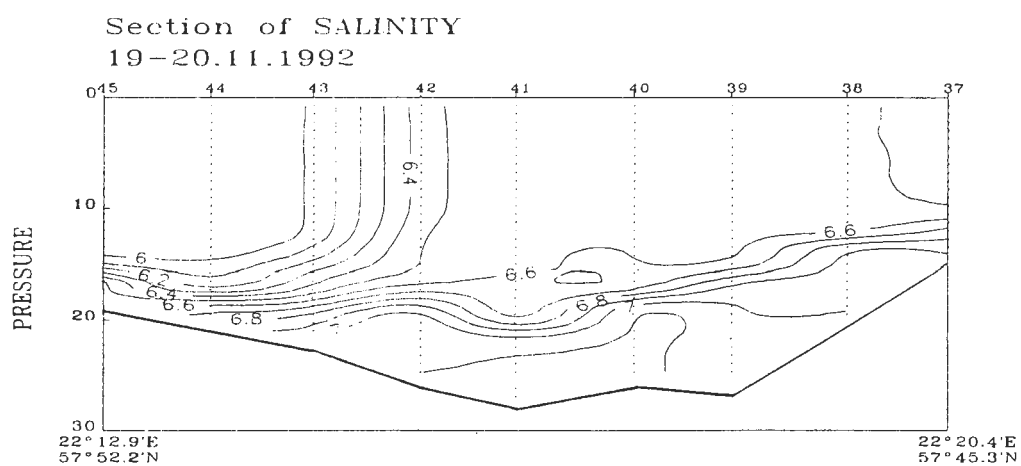
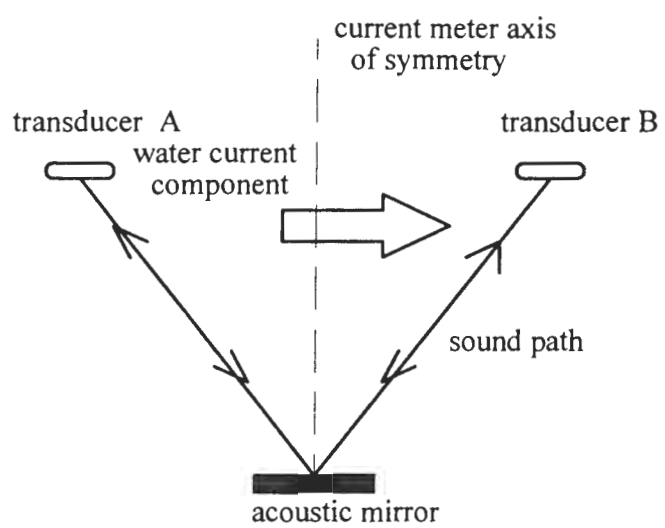


Fig. 2.1. Vertical sections of salinity along the cross transect of the Irbe Strait.
a -east wind prevailed, b -south wind prevailed, c -elongated toward Estonian coast section b.

a



b

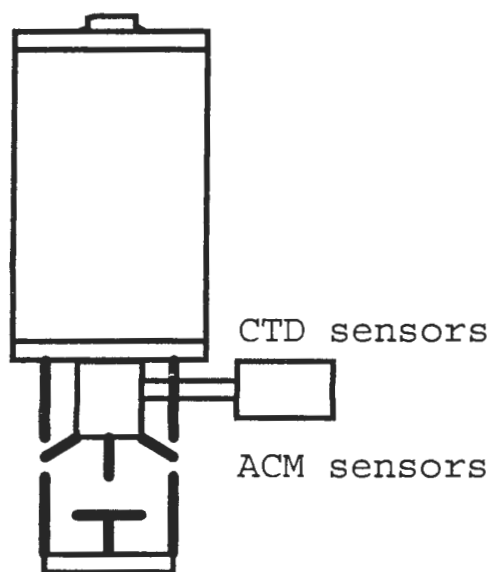


Fig. 2.2. Acoustic Current Meter sensor geometry (a) and ACM/CTD outline (b).

SCHEME OF STATIONS
MAY 17-19.05.1993

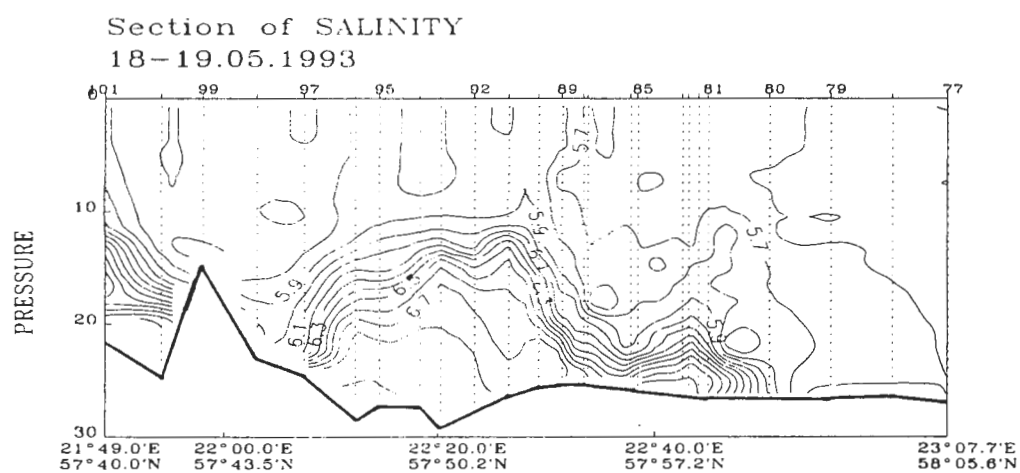
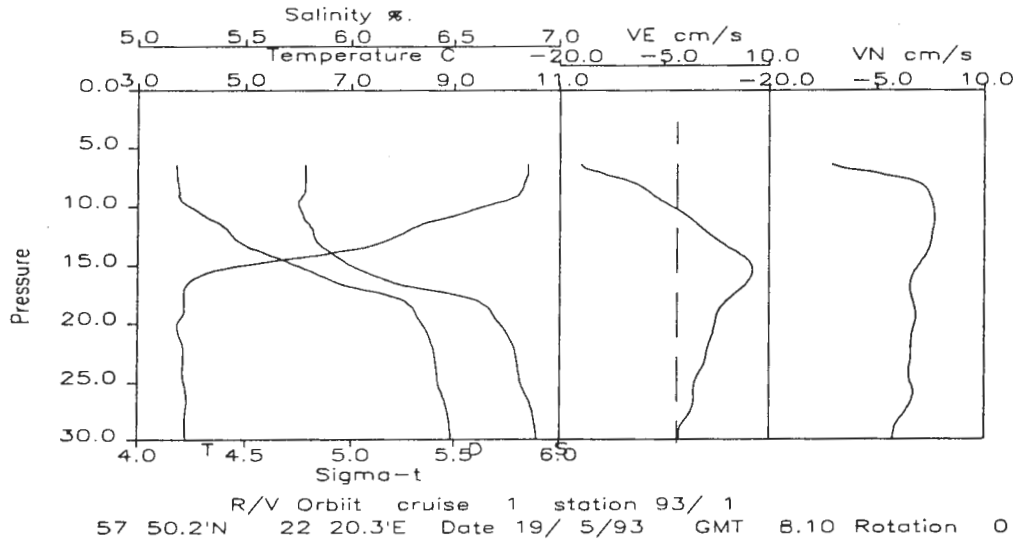


Fig. 2.3. Scheme of stations in May (a). Vertical section of salinity along the transect II (b).

a



b

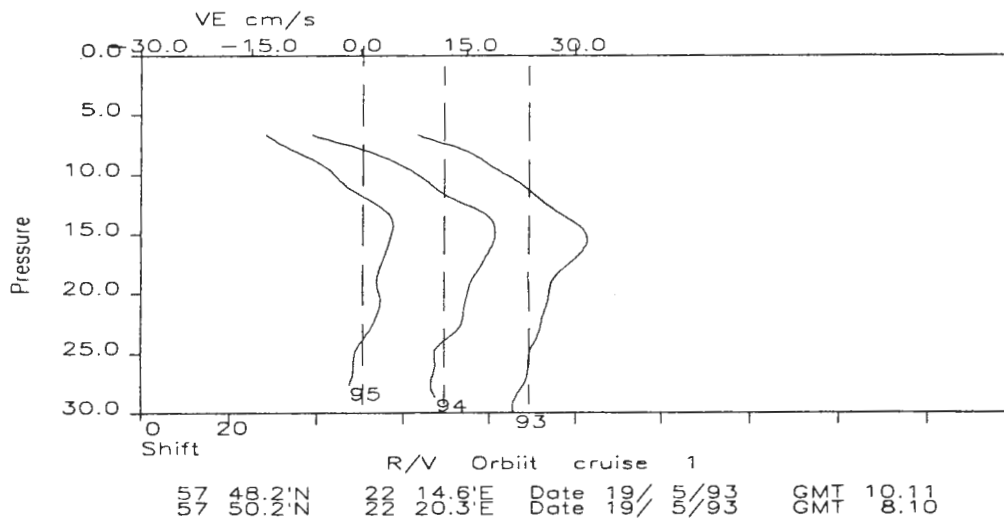
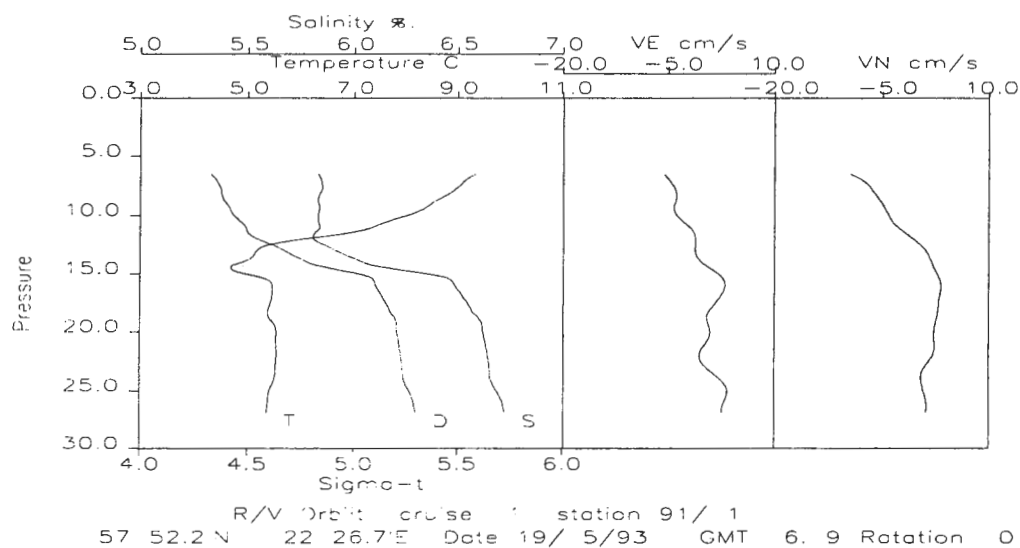


Fig. 2.4. a) Profiles of temperature, salinity, relative density and current velocity east and north components in station 93 (the vertical mean value is subtracted from velocity components).

b) Successive profiles of east component of current velocity at stations 95, 94, 93. The velocity scale is given for profile 95, profiles 94 and 93 are shifted 11 and 22 cm/s respectively.

a



b

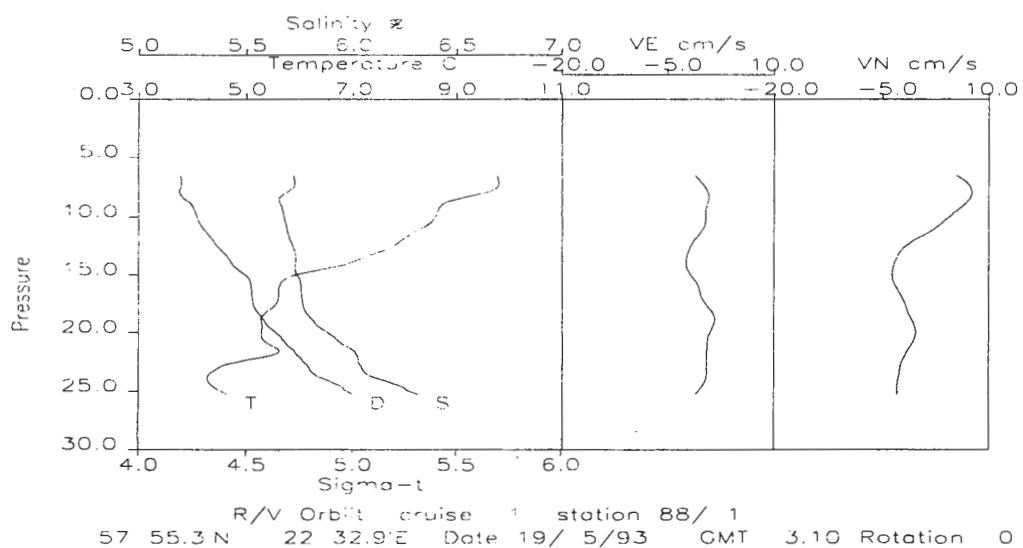
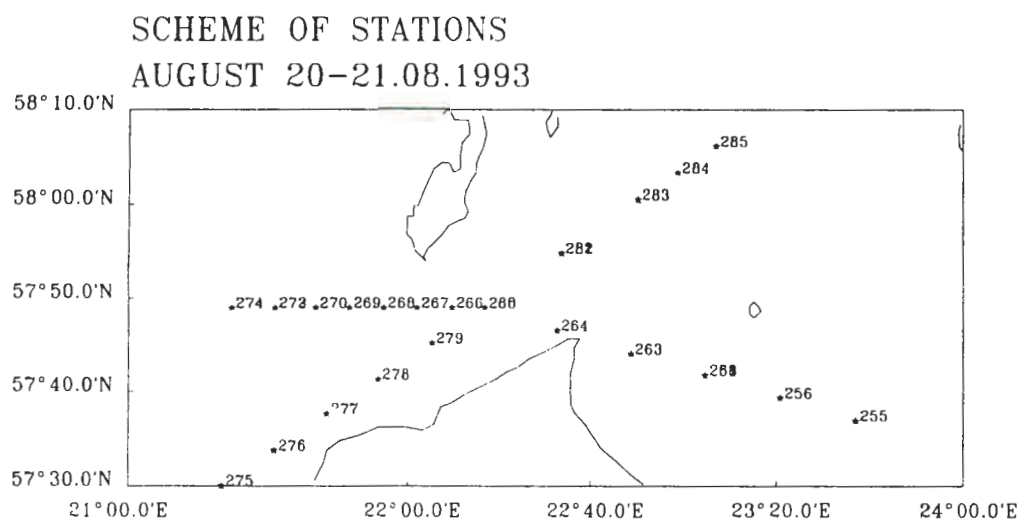


Fig. 2.5. East and north components of current velocity and vertical thermohaline structure in the Irbe Strait side (a) and in the Gulf of Riga side (b) of salinity front near the Cape Kolka.

a



b

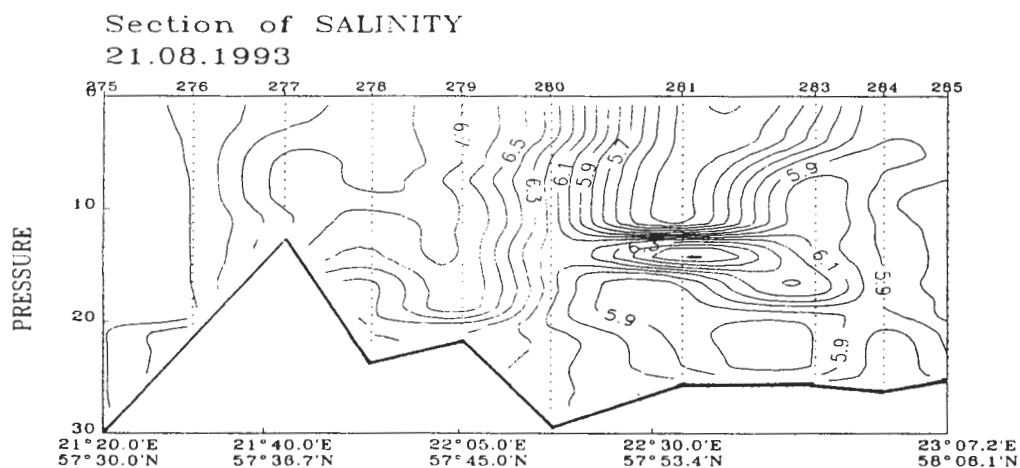


Fig. 2.6. Scheme of stations in August (a). Vertical section of salinity along the transect II (b).

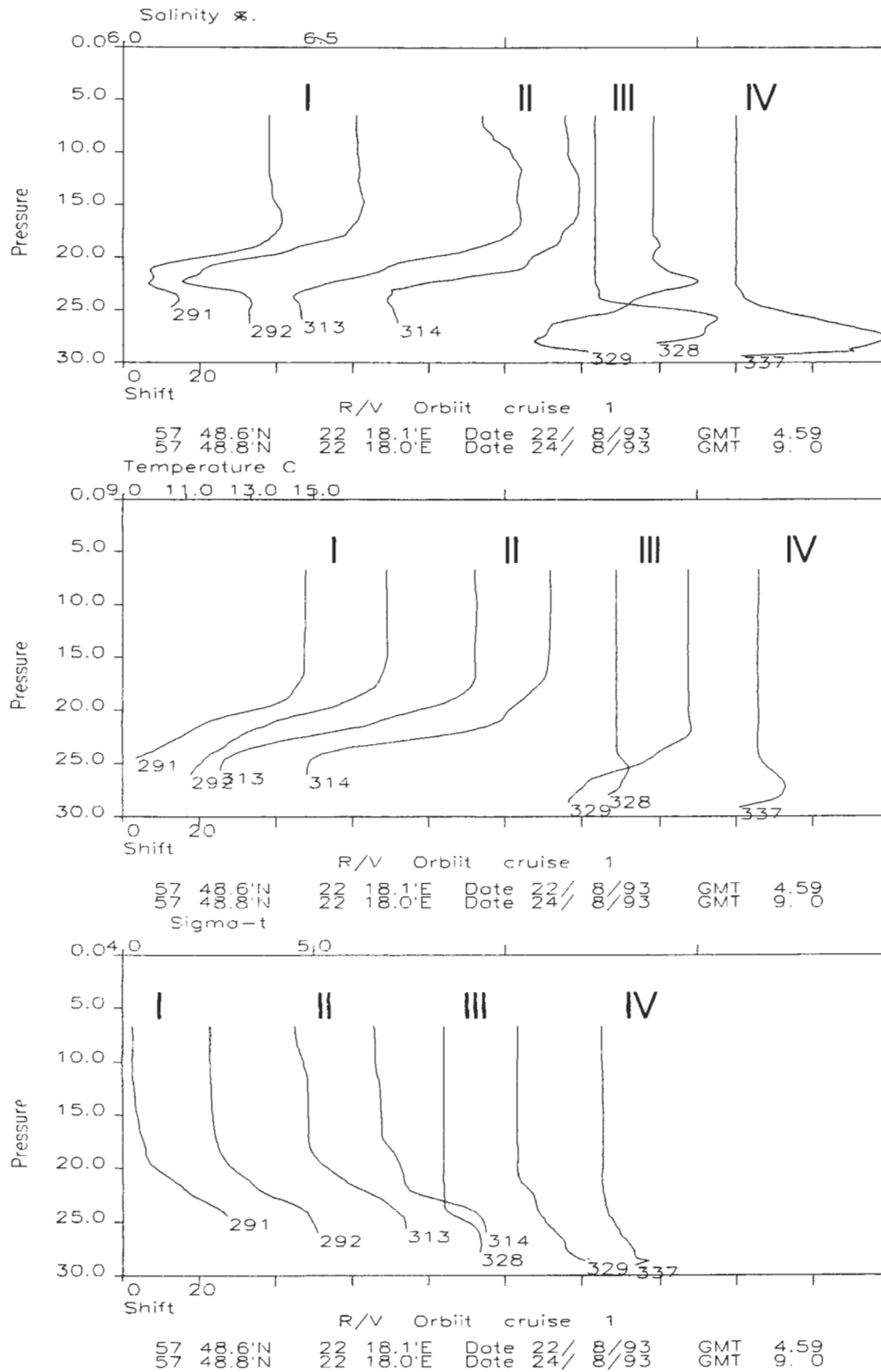


Fig. 2.7. Evolution of salinity, temperature and relative density profiles at four different wind cases at a single location near buoy station in the Irbe Strait in August. The scales are given for profiles at station 291, subsequent profiles are shifted gradually by 0.2 psu, 2.4 °C and 0.4 kg/m³, respectively. The time lag between the sequential profiles is 1 hour.

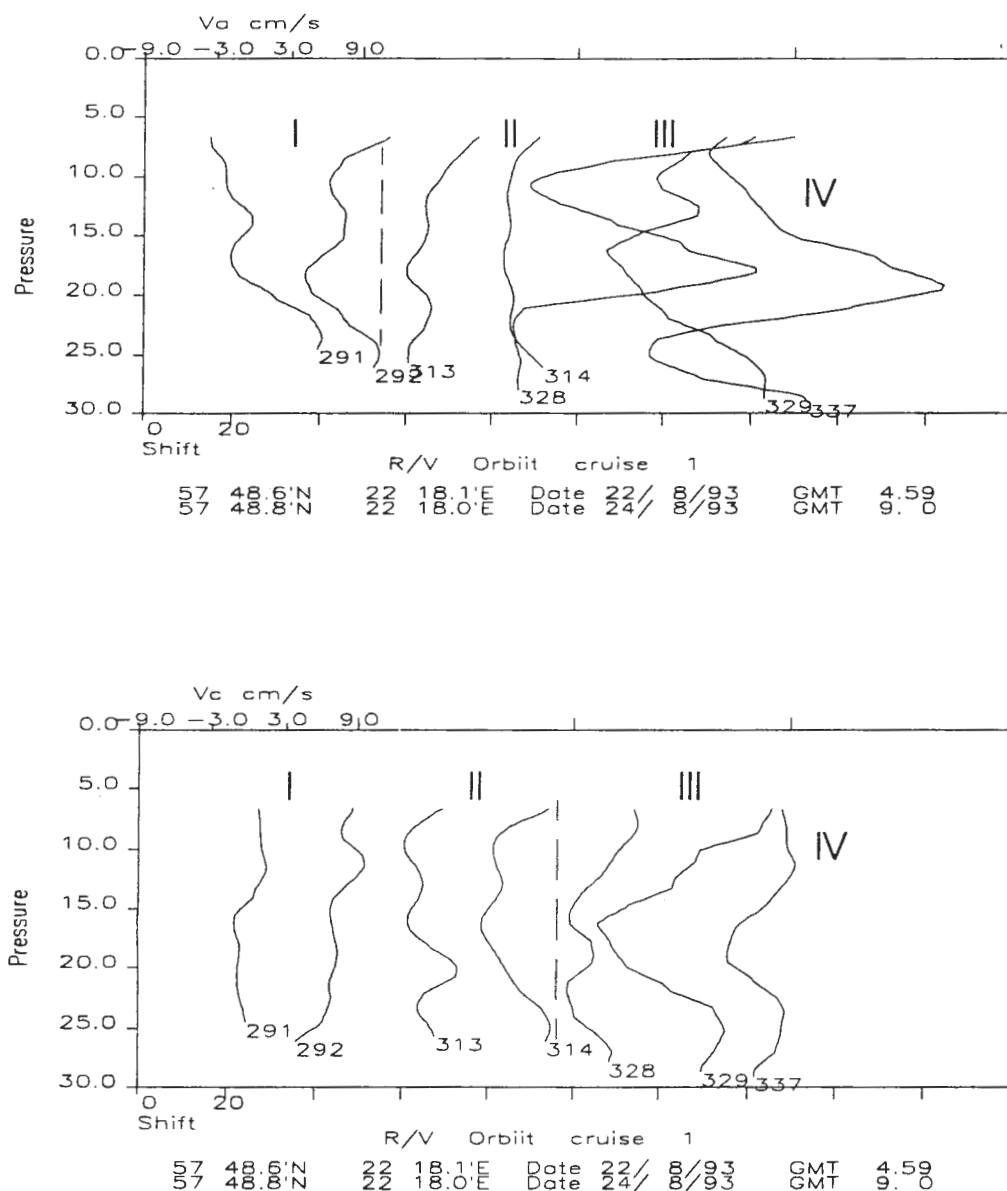


Fig. 2.8. Evolution of along strait and cross strait currents at four different wind cases near the buoy station in the Irbe Strait in August. The velocity scale is given for profiles at station 291, subsequent profiles are shifted gradually by 7 cm/s.

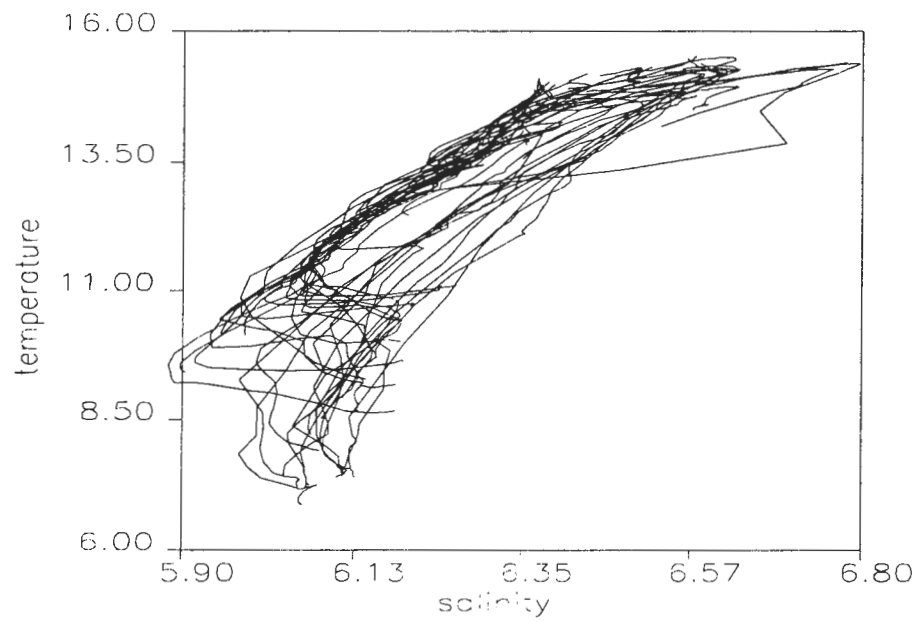
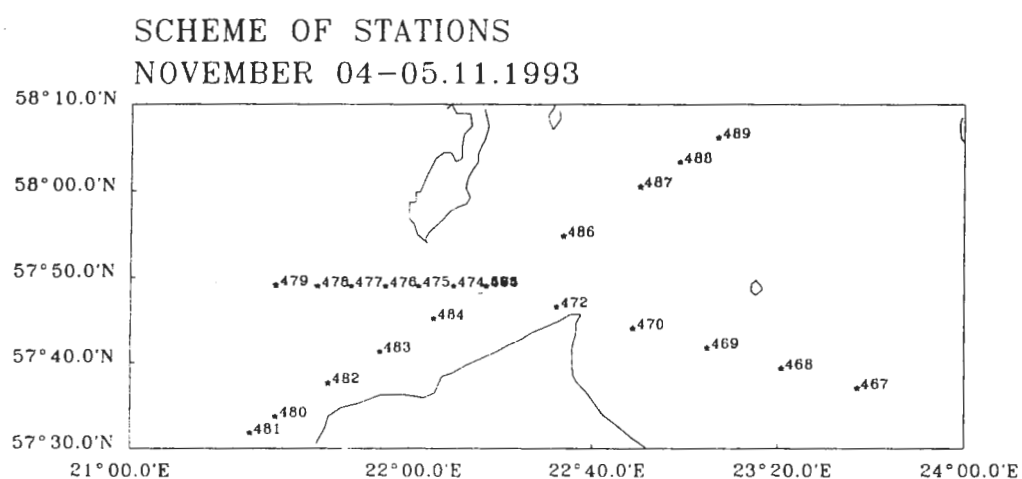


Fig. 2.9. Set of TS curves near buoy station in August (st. 290-340)

a



b

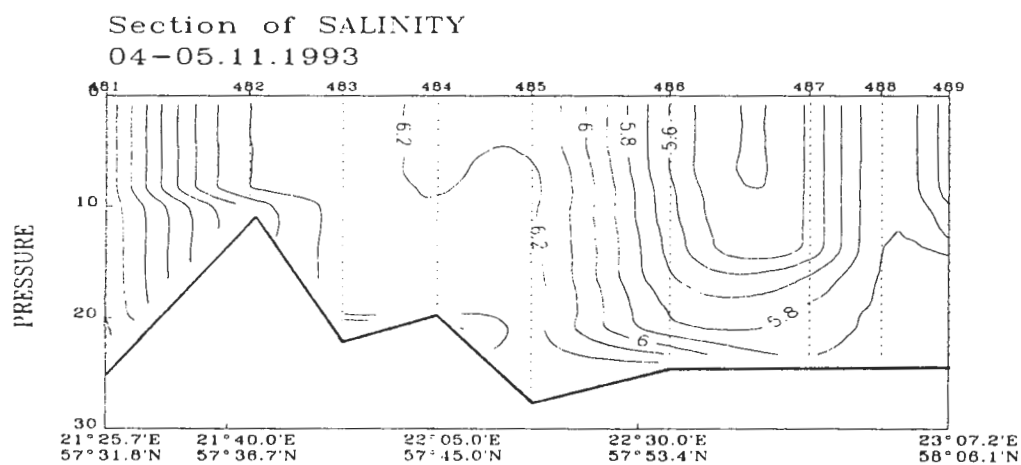


Fig. 2.10. Scheme of stations in November (a). Vertical section of salinity along the transect II (b).

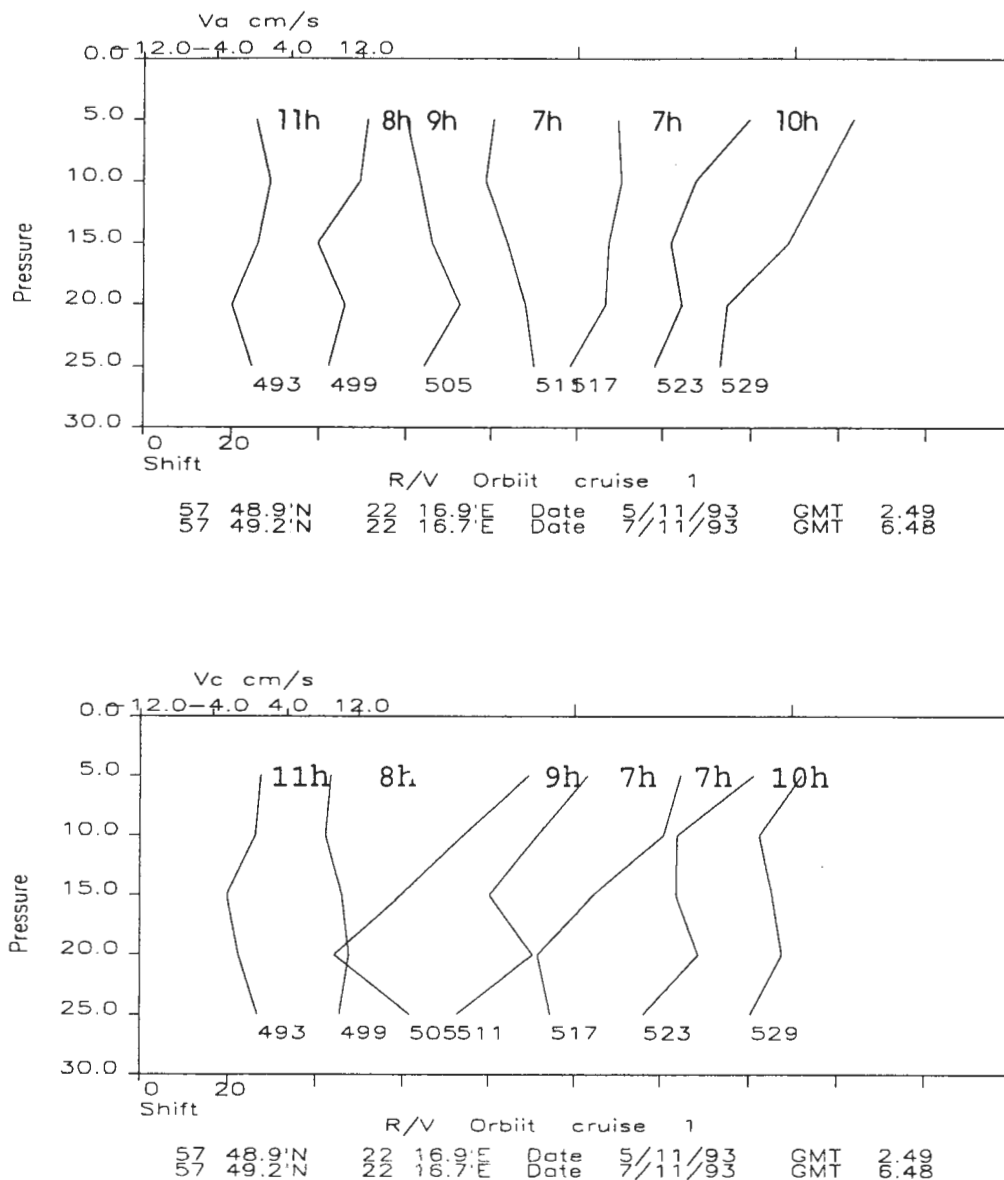


Fig. 2.11. Evolution of along strait and cross strait currents near the buoy station in the Irbe Strait in November. The velocity scale is given for profiles at station 493, successive profiles are shifted gradually by 10 cm/s.

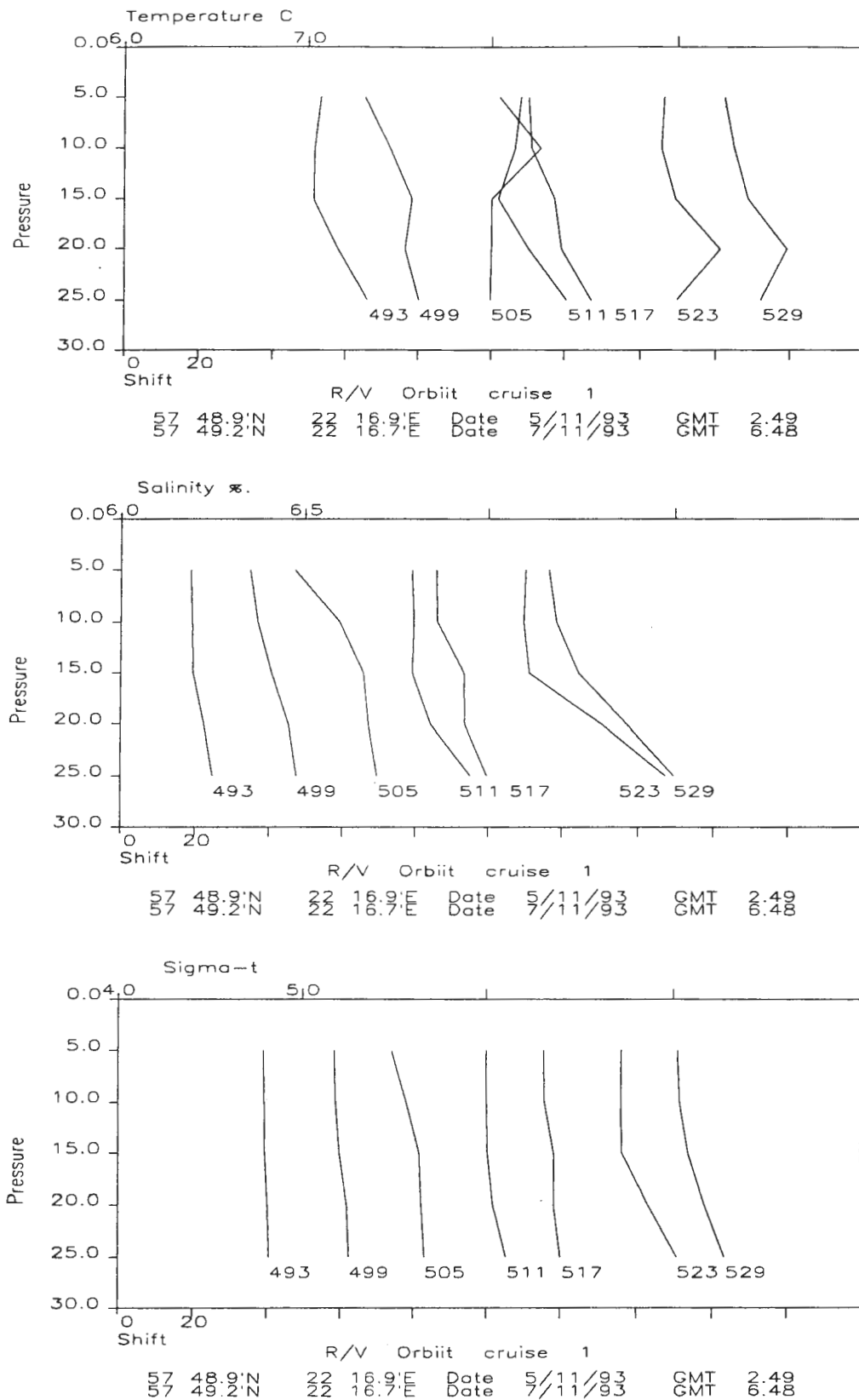


Fig. 2.12. Evolution of salinity, temperature and relative density profiles near the buoy station in the Irbe Strait in November. The scales are given for ptofiles at station 493, successive profiles are shifted gradually by 0.4 °C, 0.2 psu and 0.4 kg/m³ respectively.

3. Description of eulerian current velocity measurements and the role of processes of different time scale of the velocity field in the Irbe Strait

by Urmas Raudsepp (Estonian Marine Institute)

3.1 Measurements

Eulerian current velocity measurements were carried out using SENSORDATA current meters, which record current velocity and direction averaged over 4 minutes with the interval of 4*n minutes. The accuracy of velocity magnitude and direction are 0.1cm/s and 15° respectively. Additionally, temperature data was obtained by a thermistor, mounted on the current meter.

The current velocity measurements were performed twice in 1993. In both cases the buoy station was deployed at the same position (57° 49'N, 22° 17'E, intersection of the main CTD-transects) at 29 meters depth, with two current meters attached to the cable at two depth levels (Fig.3.0). The location of the buoy station was chosen in the middle of the Irbe Strait, where the hydrophysical situation is permanently very complicated. It is the region where different water masses meet, originated the open Baltic Sea and from the Gulf of Riga. Besides strong horizontal gradients, relatively strong vertical stratification has often been observed in the mentioned area.

First period of the measurements of current velocity was from 22 to 24 of August. Two current meters were respectively positioned at 10 and 25 meter depth. As indicated by CTD surveys, made just before the measurements of current velocity, the position of the buoy station was exactly in the main frontal zone. Also, the flow regime is expected to be different due to considerable vertical gradients of temperature and salinity between the locations of upper and lower current meters and due to intrusions of water masses in the form of relatively thin tongues. The shortcomings of this experiment was the shortness of obtained velocity records (nearly 55 hours).

Second series of the Eulerian current measurements were performed from the 4th to 14th of November. Two records of current speed and direction were obtained at 6 and 25 m depth for a ten and half day period. The distribution of temperature and salinity in the area of the location of buoy station was obtained from CTD casts, made just before and after the current recordings. As in August, the strong front was located in the region of current measurements, but the stratification was weaker.

3.2 Preliminary results and discussion of current velocity records

August 1993

First glance to the vector stickplot of raw data¹, depicted with interval of 12 min, suggests different flow regimes in the upper (10 m) and lower (25 m) layers (Fig.3.1;Fig.3.2). Within the first 9 hours, an outflow situation from the Gulf of Riga changed completely to a NW inflow and remained that way for the next 20 hours in the upper layer. For that period, average flow speed was approximately 6 cm/s. Afterwards, the velocity vector made full

1

Relative time is used for the analyses of current velocity measurements and for drawings, which refers to 6.00 GMT on August, 22. The first reasonable values for upper layer and lower layer were got at 24 minutes and one hour later from reference time, respectively.

anticlockwise rotation with an estimated period of 24 hours (Fig. 3.3). The average magnitude of current velocity was 8.3 cm/s and did not change considerably (Std = 2 cm/s) during this revolution.

In the lower layer, the velocity vector rotated clockwise during the first 30 hours of measurements during a prevailing outflow situation. The most regular periodic motion was from 6 to 20 hours (one period) (Fig. 3.3) with an average amplitude of 6 cm/s. There were three short periods in the velocity records of both layers when the flow directions were more or less similar. Lower layer flow followed the upper layer one for the first 6 hours indicating the SW outflow from the Gulf of Riga and during last couple of hours indicating a weak NE inflow. These two events can be occasional. The most remarkable event was that of between 30 and 45 hours, when velocity vectors turned smoothly from the west to the east over the upper half of the Cartesian plane. During 30 to 36 hours the upper layer velocity was stronger, but equalized with lower layer velocity afterwards. The average current velocity magnitudes for the upper and lower layer were 8.5 cm/s and 6.5 cm/s, respectively. This event could be forced by the atmospheric front that passed over the Irbe Strait.

In the above shown analyses, the terms inflow/outflow are used in the sense of the direction of velocity vector to the north-east-south/north-west-south half circle. On the other side, the Irbe strait has approximately the SW-NE direction. So, by looking at the figures of the current velocity vectors, it is clear that the motion of water masses is mainly across the channel. Therefore, the terms inflow/outflow may not have direct meaning of inflow of the Baltic Sea water and outflow of the Gulf of Riga water, but reflect the migration of the water mass along the existing salinity front. Current rose at 10 m confirms this (Fig. 3.4). The main flow direction is between -30° , -75° . (the eastern direction has been chosen as 0° with positive rotation anticlockwise.) Main outflow direction (-125° , -155°) agrees better with channel direction. The distribution of flow directions is different in the lower layer, but still a great deal of flow is perpendicular to channel topography. Preferable flow directions are 90° , 105° , 165° , 195° , 210° , 255° . Besides, this indicates a great deal of outflow in the lower layer.

Comparison of wind (measured in Pärnu with an interval of 3 hours) (Fig. 3.5) and upper layer velocity reveals the nature of the flow as wind driven Ekman transport in general. Depending on the prevailing flow regime the adjustment time for current velocity at 10 m depth may be different.

November 1993

The analyses of raw velocity data² show similar current variability in both layers during the first eight days (Fig. 3.6; Fig.3.7). Major features, which should be pointed out are the periodic changes of the velocity amplitude (24 hours) in the case of nearly constant flow direction (to the NE). The amplitude variance extends to 15 cm/s: 5 - 20 cm/s in the upper layer and 3 - 18 cm/s in the lower layer, which is quite large. The observed discrepancies between these two levels resulted from the effect of minor forces, which after some time the previous flow regime overruns. After the first eight days the flow structure changed completely. In the upper layer the inflow was very quickly replaced by a continuous outflow and remained so until the end of measurements (Fig. 3.8). At the same time a smooth clockwise rotation of velocity vector occurred in the lower layer with an estimated period of one and a half day. Also velocity magnitude was considerably smaller and not in phase with variations in the upper layer any more.

The current roses confirm the anisotropic nature of the current velocity field in the Irbe strait (Fig.3.9). Strong barotropic inflow mostly along channel dominated during the measurement

²

Reliable data from upper and lower current meters start at 12.14 GMT and 12.17 GMT on November, 4, respectively. As data were recorded with an interval of 8 minutes, for further analyses both time series were referred to the same time, which has taken also as zero time for relative time scale.

period. A peak between 203°, 233° resulted from the outflow, prevailing in the upper layer at the end of the measurements.

General the flow scheme can be explained by wind conditions over the area under consideration (Fig. 3.10). Moderate north-western winds (5 m/s) prevailed ten days before the measurements as indicated from the wind record taken at Ruhnu with a half day interval. According to the Ekman theory this wind will initiate mass transport to the south-west, i.e. outflow from the Gulf of Riga. Before and at the beginning of current measurements the wind weakened and turned to the east, which may result in the changing of the current direction to opposite in the Irbe Strait. Two days later the wind speed increased to 10 m/s and started to turn slowly to the south. It directly strengthened the inflow to the Gulf through the mechanism of wind driven Ekman transport. The outflow in the upper layer can be explained by the mutual effect of weakening of the wind speed and increase of the sea level in the Gulf during strong inflow.³

3.3 Different temporal scales of currents

The large variability of current velocity amplitude with diurnal period underlines the hypothesis about the importance of tidal motion in the Irbe Strait. A spectral analysis' tool is used to get statistical evidence about the prevailing periodical components. The measured raw velocity data were pre-processed to make the series statistically stationary. The existing few data gaps are filled by linear interpolation. As the Figures 3.3 and 3.8 of progressive vectors show very strong unidirectional flow, which completely masks periodical oscillations, temporal trend of the current velocity variations is subtracted. The second order polynomial was fitted to the raw data, which gives the best results among the other polynomials. The fitted velocity vectors averaged over four hours are depicted in Figures 3.11 and 3.12 for upper and lower layer, respectively. During the first eight days the flow is barotropic with upper layer velocities greater than in lower layer. Afterwards the flow turns opposite in the upper layer, but continuous inflow persists in the lower layer. Most of the time the flow is directed along the channel. With some concession, these time series can be assumed to represent the wind driven currents and related mass and salinity transport in the certain region of the Irbe Strait.

Remainders of the velocity time series were checked for stationarity by using a method proposed by BENDAT and PIERSOL (1966), and then filtered with second order Butterworth filter with a half power point at a period of 40 minutes. This filter was used forward and backward to remove phase shift and therefore reduces an amplitude by a factor of four at a cutoff frequency. Complex value series of horizontal velocity were formed from the eastern (real part) and the northern (imaginary part) components of velocity vectors,

$$w(t) = u(t) + iv(t)$$

for both levels and then Fourier transformed. The obtained Fourier amplitude spectrum of w is:

3

Let us assume the presence of two external forces, wind stress and sea level difference between the open Baltic and Gulf of Riga, which affect water exchange between these basins through Irbe Strait. If wind stress starts to amass water to the Gulf, in the case of small sea level difference initially, at some moment the difference increases to a value, that is large enough to get over the wind stress. It may result in rapid change of flow direction to the opposite, which is also opposite to directly wind driven Ekman transport.

$$W(\sigma) = \int_{-\infty}^{\infty} w(t) e^{-i\sigma t} dt \equiv \begin{cases} A e^{i\varphi}, & \sigma \geq 0 \\ C e^{-i\theta}, & \sigma \leq 0, \end{cases}$$

representing anticlockwise (A, φ) and clockwise (C, θ) components of the motion. Original power spectral density estimates were averaged over variable frequency bands to increase the degrees of freedom. Spectral density of two frequency bands - diurnal tide (period $T \approx 24$ hours) and local inertial (period $T \approx 14$ hours) - are of the most interest. In the present case, diurnal band covers the period range of 28.36 ± 21.58 hours with central period of 24.81 hours, and local inertial band the range of 14.18 ± 11.15 hours with central period of 13.06 hours. Unfortunately, the local inertial signal and semi-diurnal tidal signal are not distinguishable from present spectral density calculation due to the shortness of current measurement time.

For each value of $|\sigma|$ and corresponding set of $\{A, C, \varphi, \theta\}$, one ellipse exists, which is formed as a component of hodograph trajectory of the velocity vector (MOOERS, 1973). For the diurnal frequency band, the direction of major axis is 30° and temporal phase of the ellipse is -62° in the upper level and 25° and -67° , respectively (Fig. 3.13), in the lower level. The resultant velocity vector rotates clockwise in both cases. These results suggest that diurnal motion has barotropic nature with preferred direction of motion of water particles along the channel. In the inertial frequency band, the directions of major axis of ellipses are -1.5° and -48° for the upper and lower layer, respectively. Also, temporal phases do not coincide being -31° and 131° , respectively. As in previous case, resultant vectors rotate clockwise in both layers.

The orientations of hodograph ellipses at diurnal frequency band suggest the application of spectral analyses to the components of measured velocity vectors on the direction of major axis of ellipse, i.e. $\approx 30^\circ$ (along-channel), and perpendicular to it (cross-channel). This procedure should increase the energy at the along-channel component of diurnal frequency. The results are presented in the Fig. 3.14-3.17 with 90% level of statistical significance. As was expected, the figure of spectral density for along-channel components show peak value at diurnal frequency ($\sigma = 0.0403$ cph) in both depth levels. But, in the spectra of cross-channel component the spectral density has its background value. At the local inertial frequency ($\sigma = 0.0766$ cph), clear peak is present in cross-channel spectra of lower level. It is not surprising because of the orientation of hodograph ellipse, which is nearly perpendicular to the diurnal ellipses. Still, it is not clear, how much energy belongs to the inertial oscillations and how much to the semi-diurnal tide. The results of rotary spectral analyses imply, that larger contribution is from local inertial variability, because of peak values in the spectra of clockwise rotating component. Some peaks at higher frequencies may result from seiches, which period is estimated to 3-5 hours in the Gulf of Riga, approximately.

3.4 Concluding remarks

Time series of current velocity measurements indicate, that vertical structure of the flow field can be quite different depending on a particular stratification. The existence of strong halocline is a good reason for opposite flow above and below it. If vertical gradients of salinity become smaller the entire water column starts react similarly to the external forcing. The slowly varying part of flow field corresponds well to wind driven currents. Due to the shape of the Irbe Strait, flow is strongly unisotropic (prevailing direction is SW-NE). Among the topography and lateral boundaries, the variations of sea level are of first importance, too. The latter parameter controls inflow and outflow events. If amass of water takes place in the Gulf of Riga or persistent outflow occurs, sea

level difference between the Gulf and the Baltic Sea initiate compensating flow, which is opposite to wind driven currents. To be sure about it, the analyses of above mentioned geophysical fields should be carried out on longer time series than used here.

Instantaneous velocity field in the Irbe Strait is composed by a number of different physical processes, which prevail at different times. Strong signal of diurnal period is present and even dominated in velocity records. Statistical evidence for it was tried to get, but duration of complete velocity record was not long enough. The second particular physical process detected from calculation of power spectral density was inertial oscillations. This signal was not as strong as diurnal signal and could not be distinguished from the semi-diurnal one. The oscillatory character of velocity field is strongly contaminated by occasional intrusions of water masses, which pass current meter, in the frontal zone. Lilover (see Chapter 2 in present report) suggest that relatively random character and vertical nonuniformity of current velocity fields are a result of migration of the entire front due to the effect of the changes of wind direction over the Irbe Strait.

References

Bendbendat, J.S. and Piersol, A.G. 1966. Measurements and analysis of random data, Wiley, 390 pp.

Mooers, C.N.K. 1973. A technique for the cross spectrum analysis of pairs of complex-valued time series, with emphasis on properties of polarized components and rotational invariants. *Deep-Sea Research*, **20**, 1129-1141.

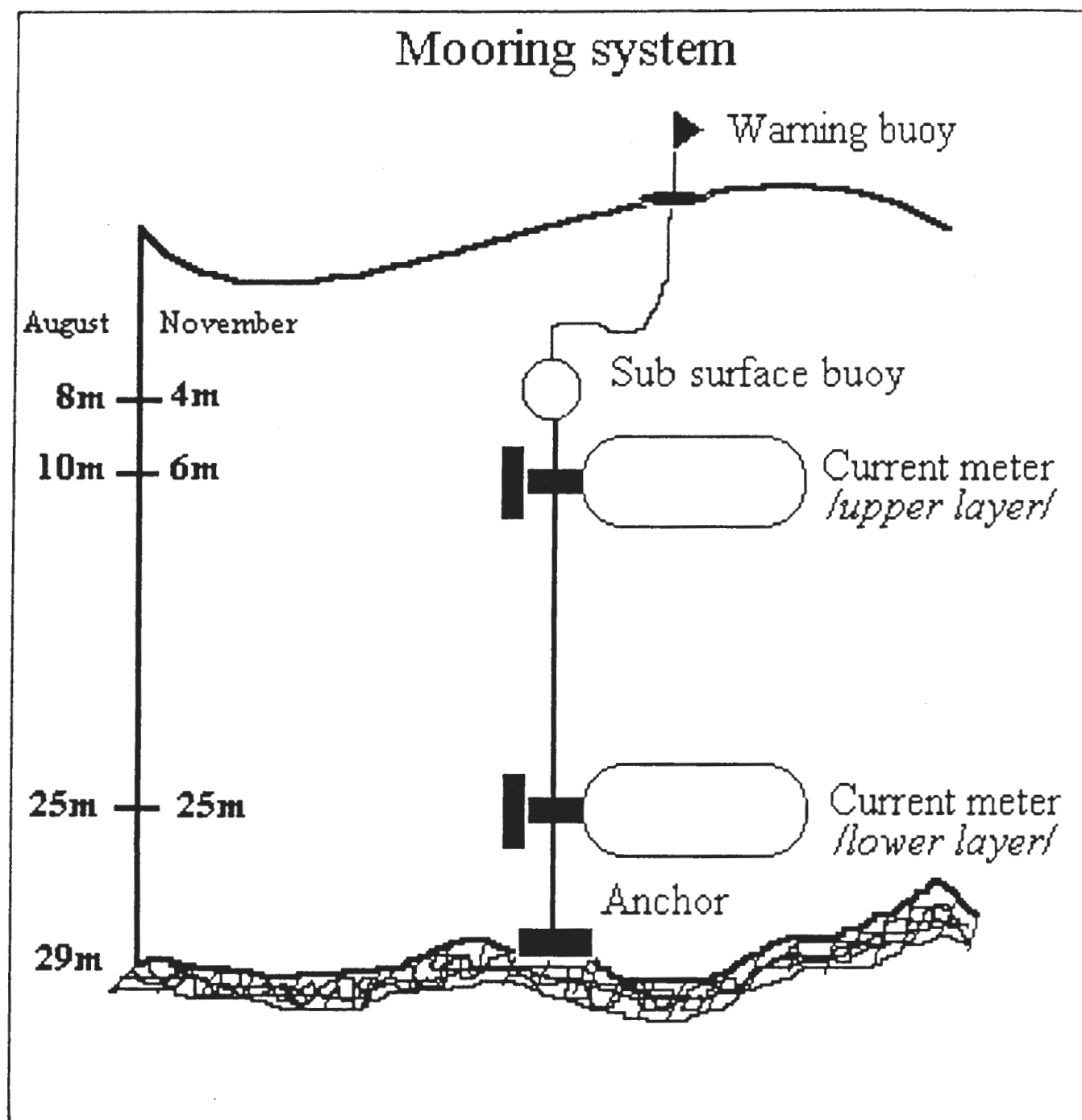


Fig. 3.0. Scheme of mooring station in the Irbe Strait.

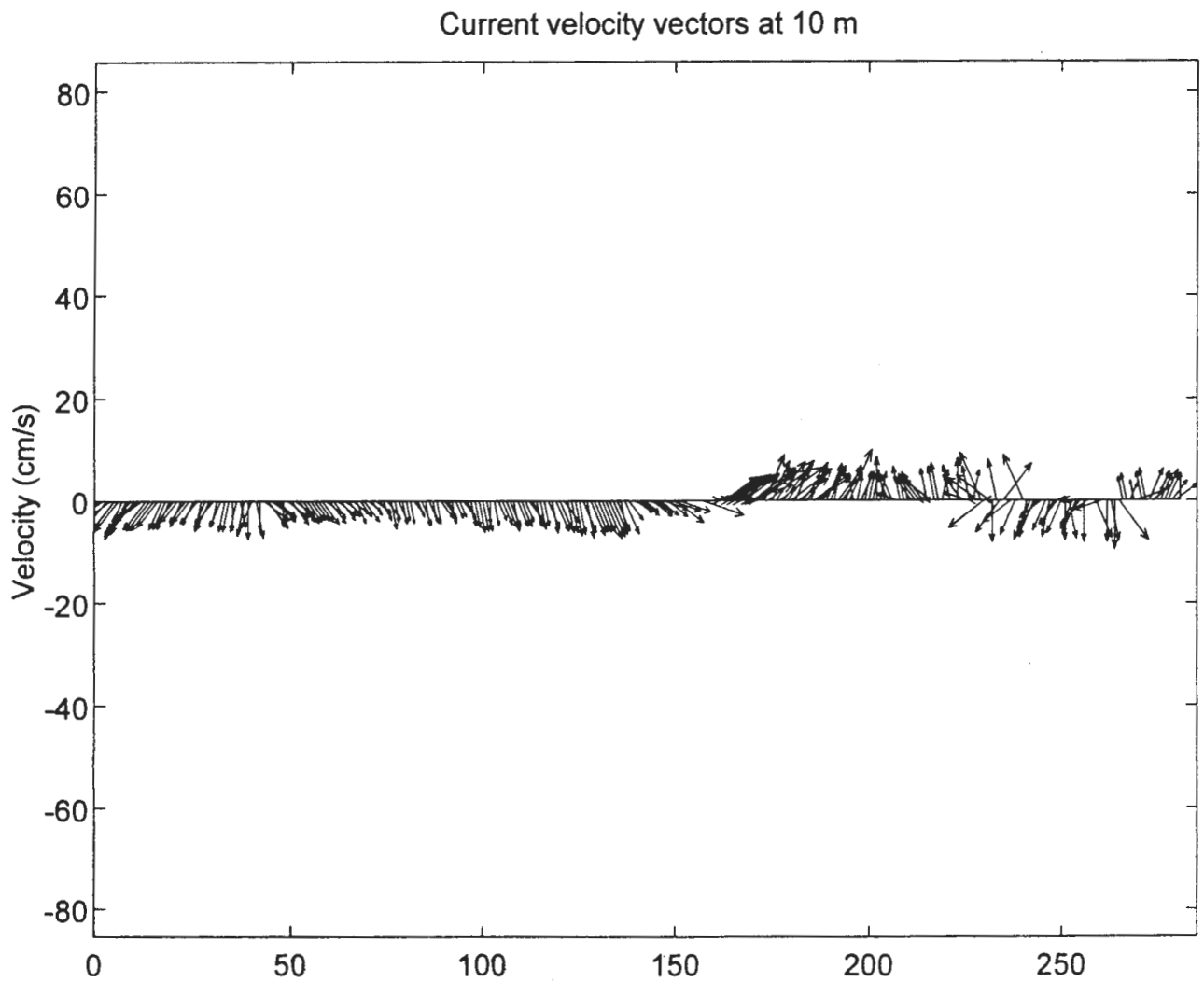


Fig. 3.1. . Raw current velocity vector stickplot at 10 meter depth. Vectors are plotted with an interval of 12 minutes. The y-axis gives the magnitude of velocity vector and numbers on x-axis are serial numbers starting from first reliable data (See text).

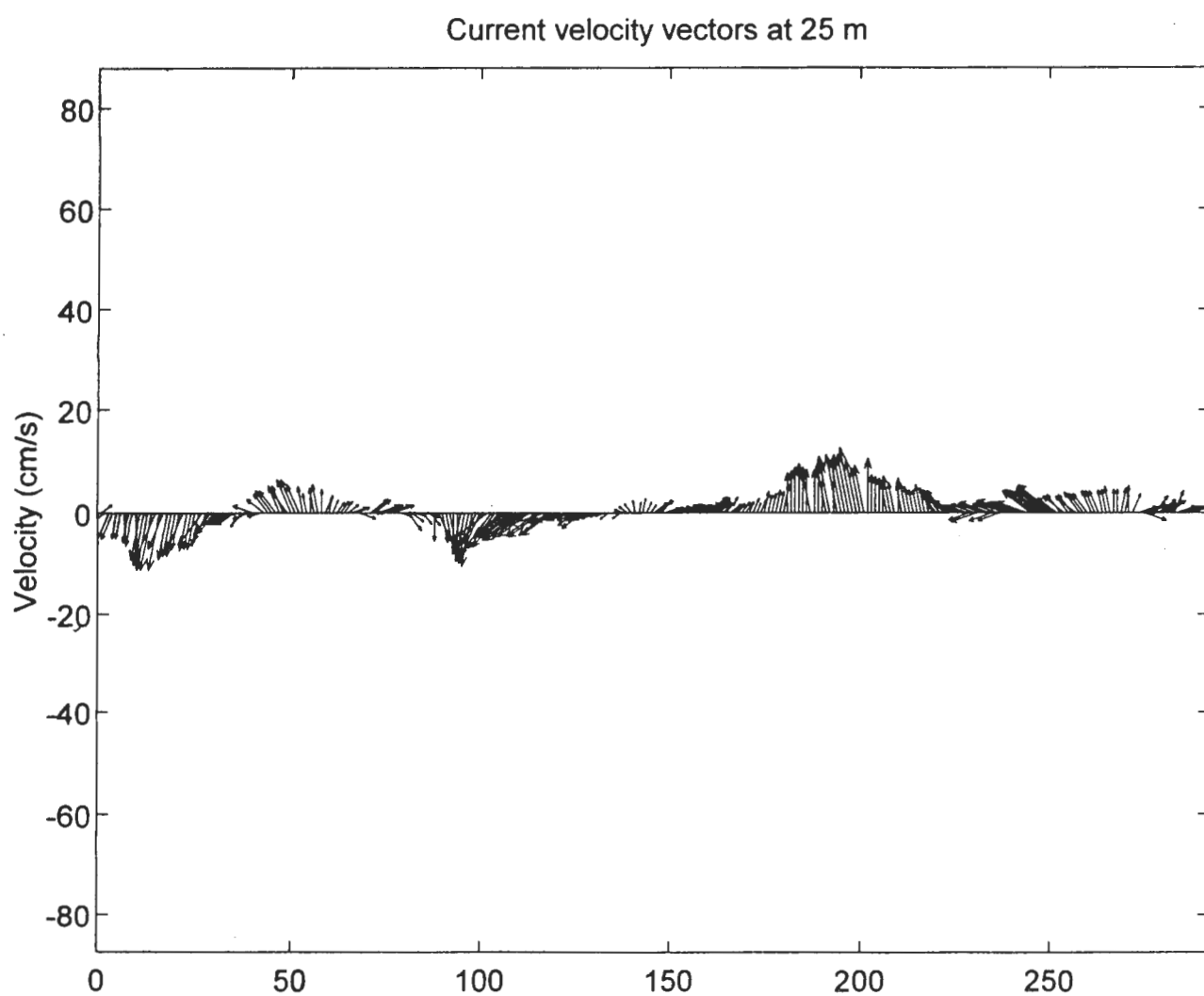


Fig. 3.2. Raw current velocity vector stickplot at 25 meter depth. Vectors are plotted with interval of 12 minutes. The y-axis gives the magnitude of velocity vector and numbers on x-axis are serial numbers starting from first reliable data (See text).

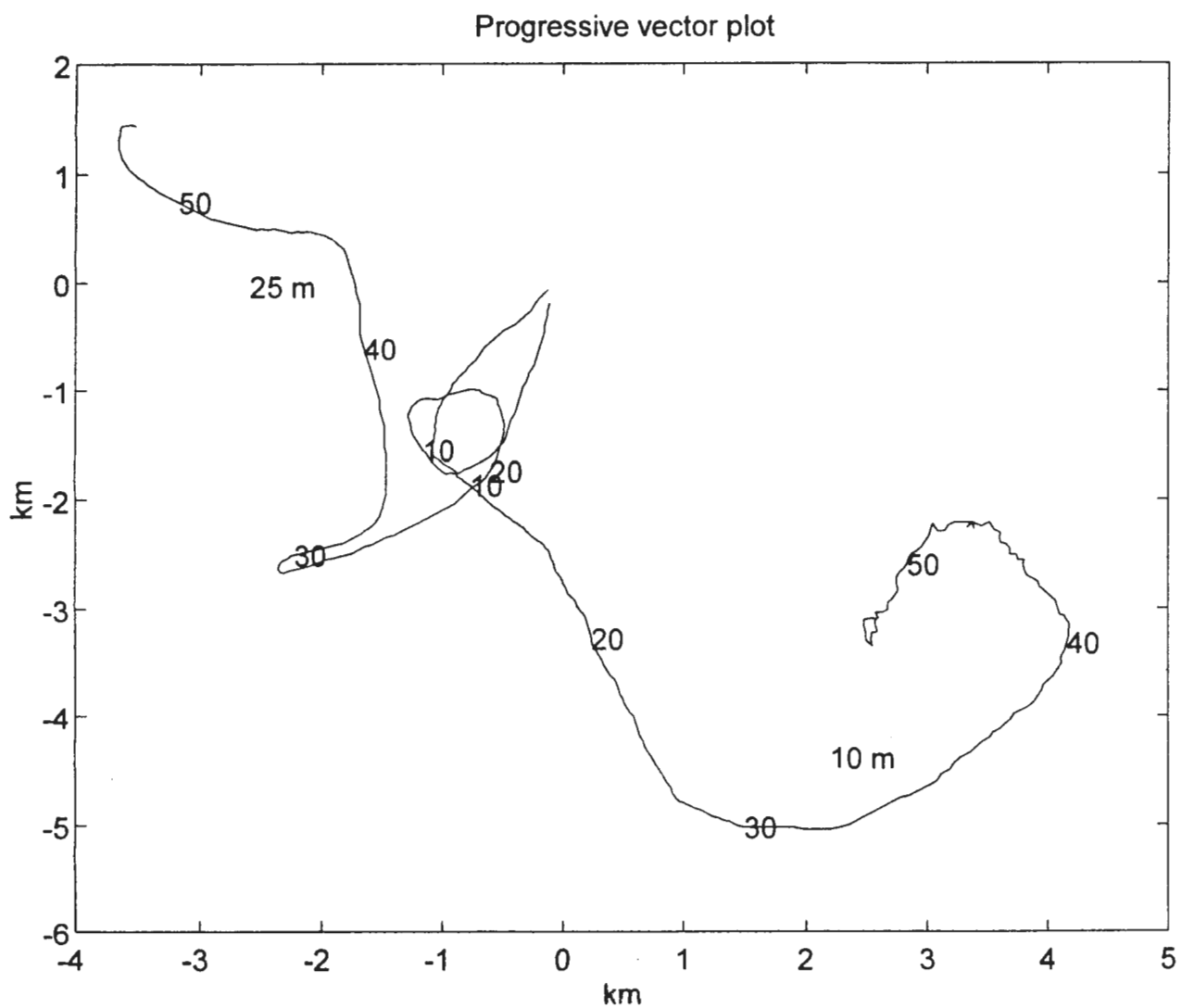


Fig. 3.3. The pseudo-trajectories of water particles. Labels are indicating time in hours from reference time.

Current at 10 m

Current at 25 m

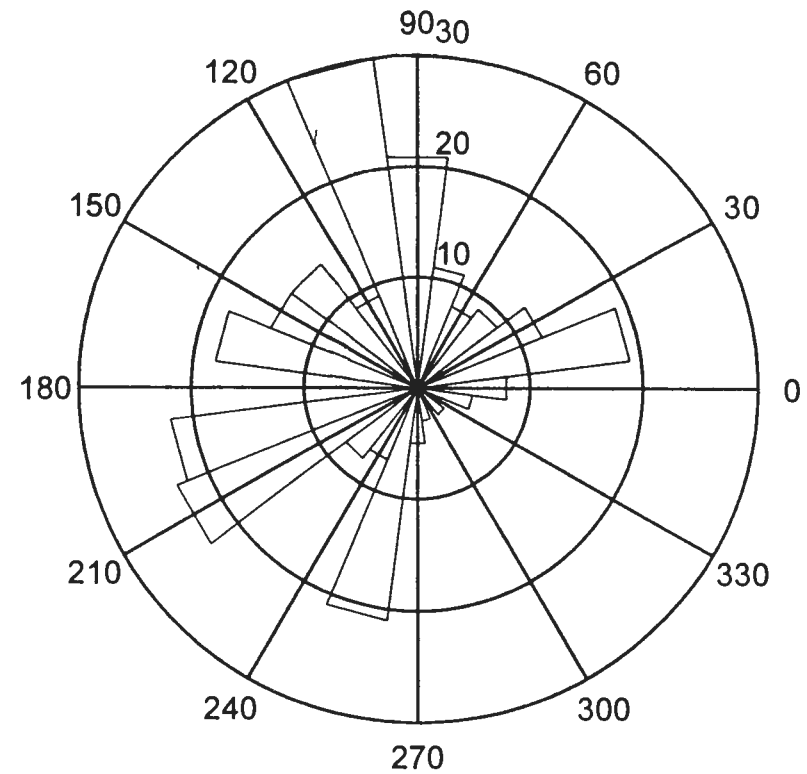
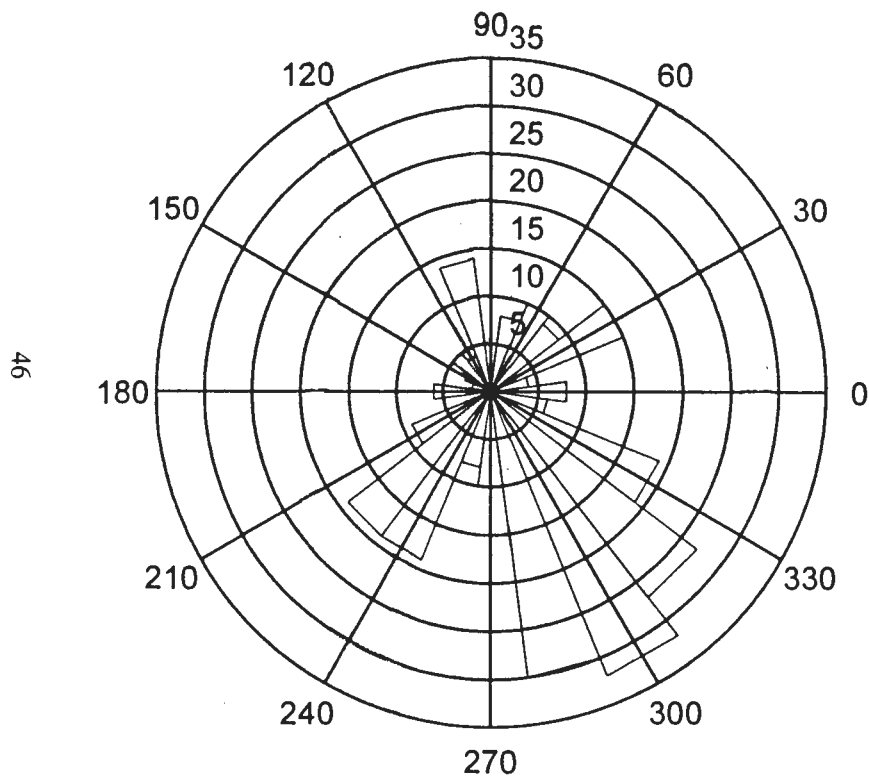


Fig. 3.4. The distribution of current directions. East direction has been chosen as 0° with positive rotation to anticlockwise. Labels at the circles indicate the number of velocity vectors, which direction falls into certain direction bin.

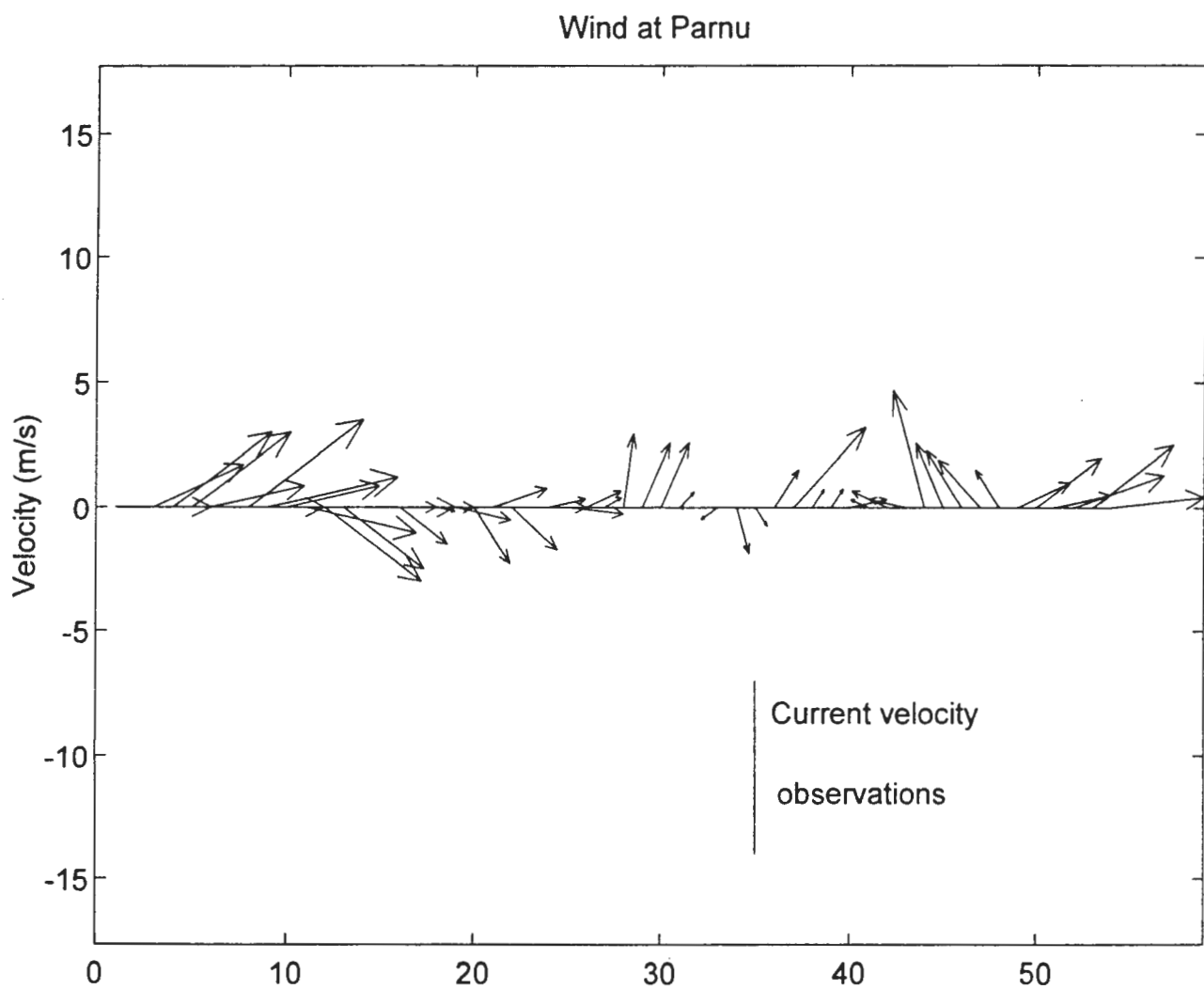


Fig. 3.5. Wind velocity vectors recorded at Pärnu with an interval of 3 hours before (4.5 days) and during the current meter measurements. The y-axis gives the magnitude of velocity vector and numbers on x-axis are serial numbers starting from August, 18.

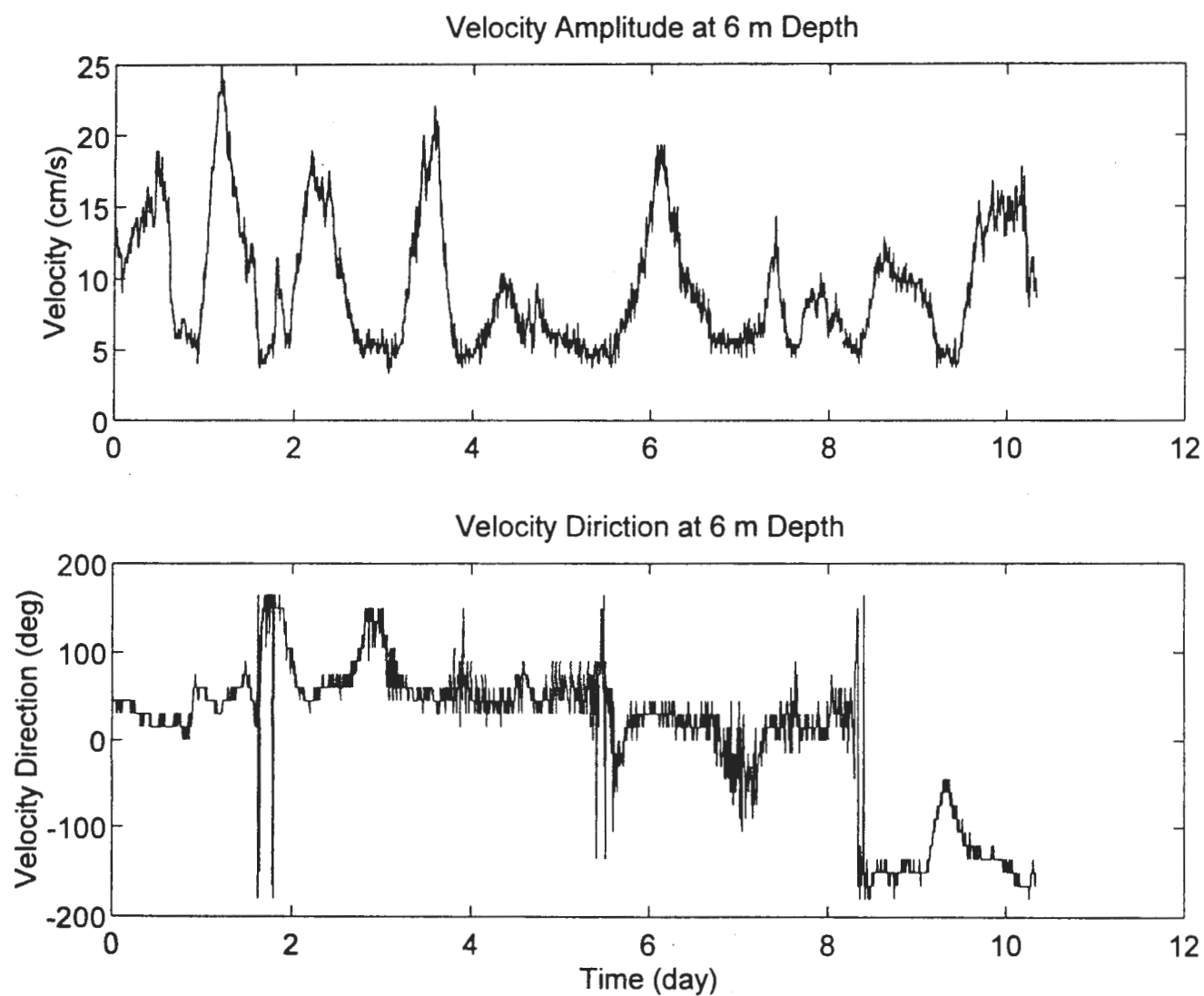


Fig. 3.6. Time series of raw current velocity amplitude and direction at 6 meter depth. Time scale is taken with respect to reference time. (See text.)

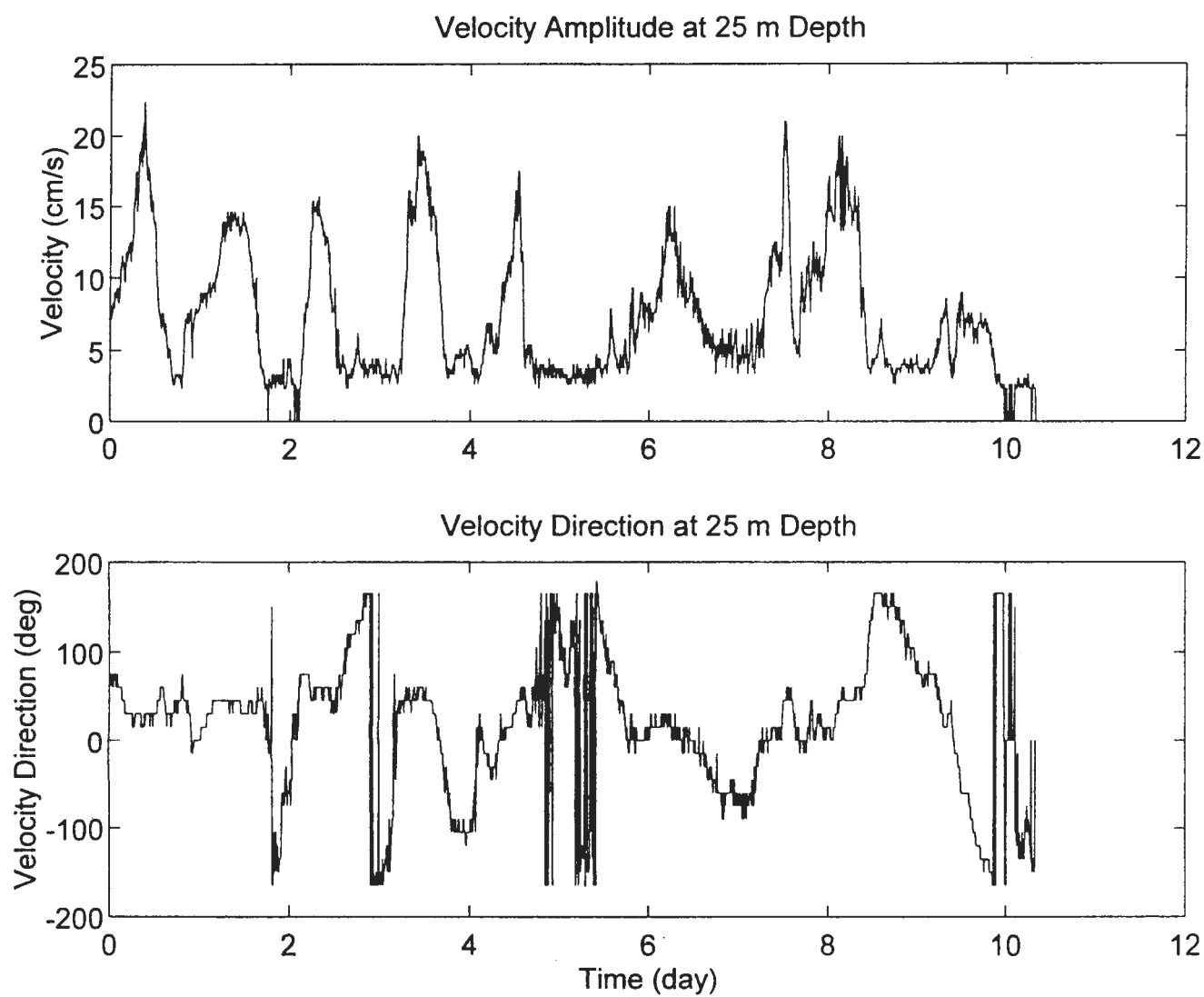


Fig. 3.7. Time series of raw current velocity amplitude and direction at 25 meter depth. Time scale is taken with respect to reference time. (See text.)

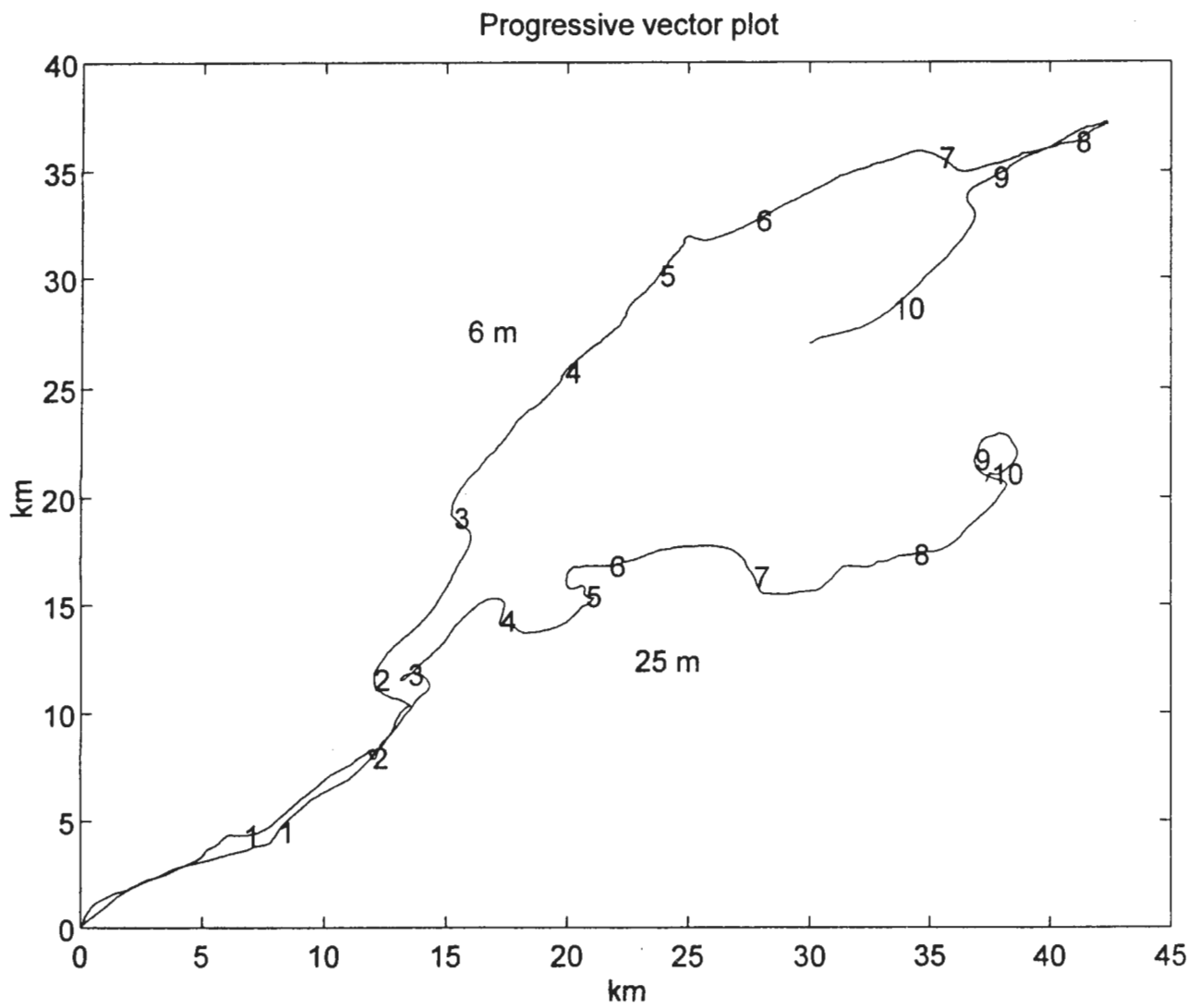


Fig. 3.8. The pseudo-trajectories of water particles. Labels are indicating time in days from reference time.

Current at 6 m

Current at 25 m

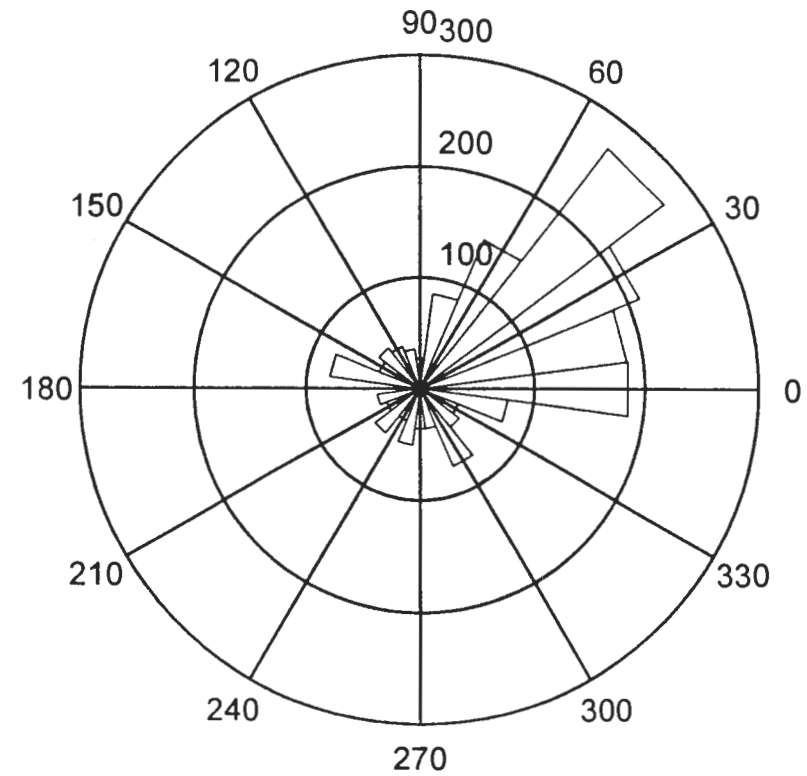
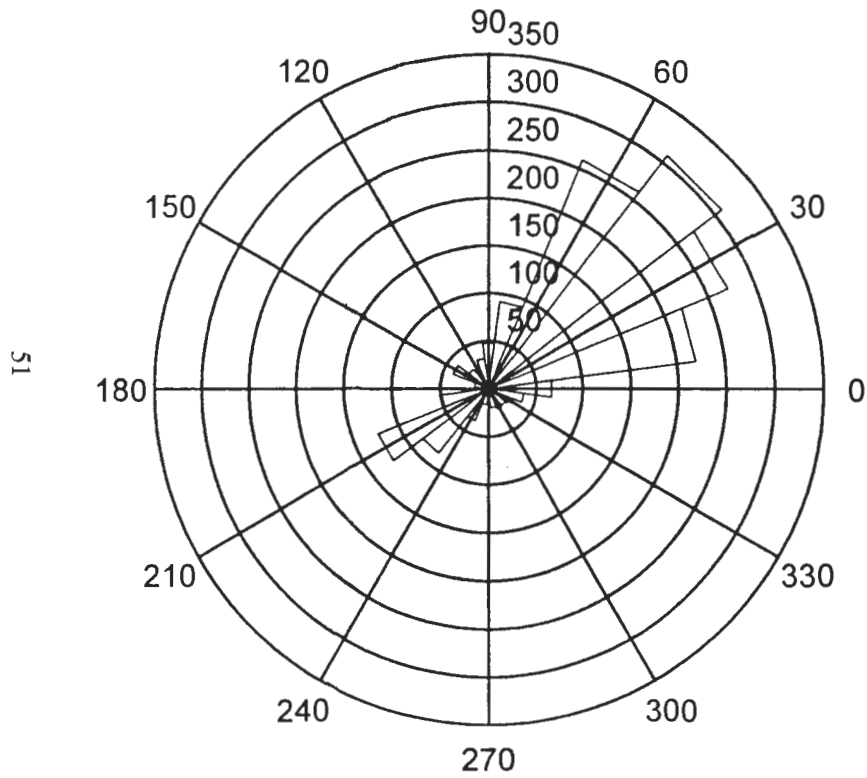


Fig. 3.9. The distribution of current directions. East direction has been chosen as 0° with positive rotation to anticlockwise. Labels at the circles indicate the number of velocity vectors, which direction falls into certain direction bin.

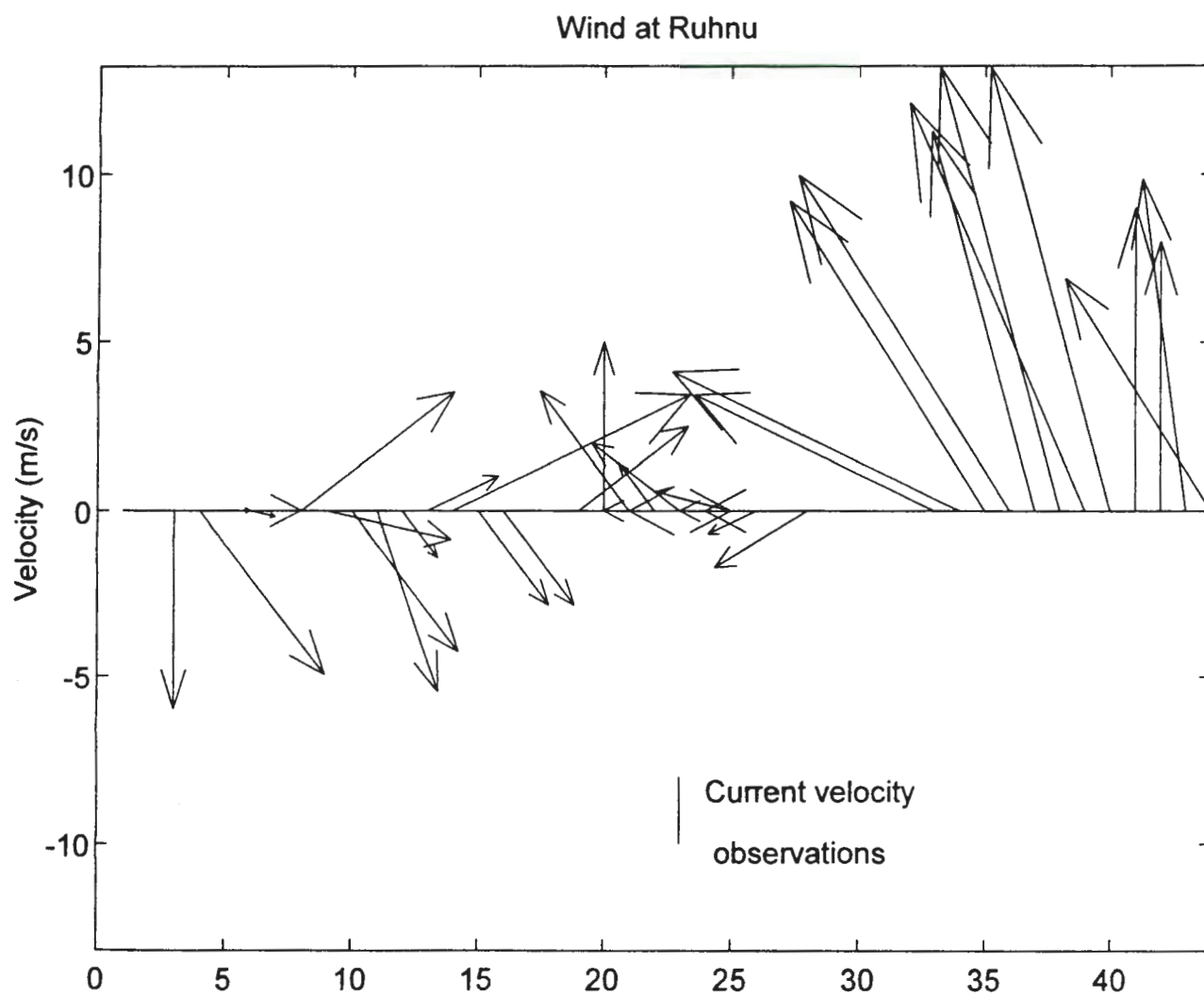


Fig. 3.10. Wind velocity vectors recorded at Ruhnu with an interval of 12 hours before (10 days) and during the current meter measurements. The y-axis gives the magnitude of velocity vector and numbers on x-axis are serial numbers starting from October, 24.

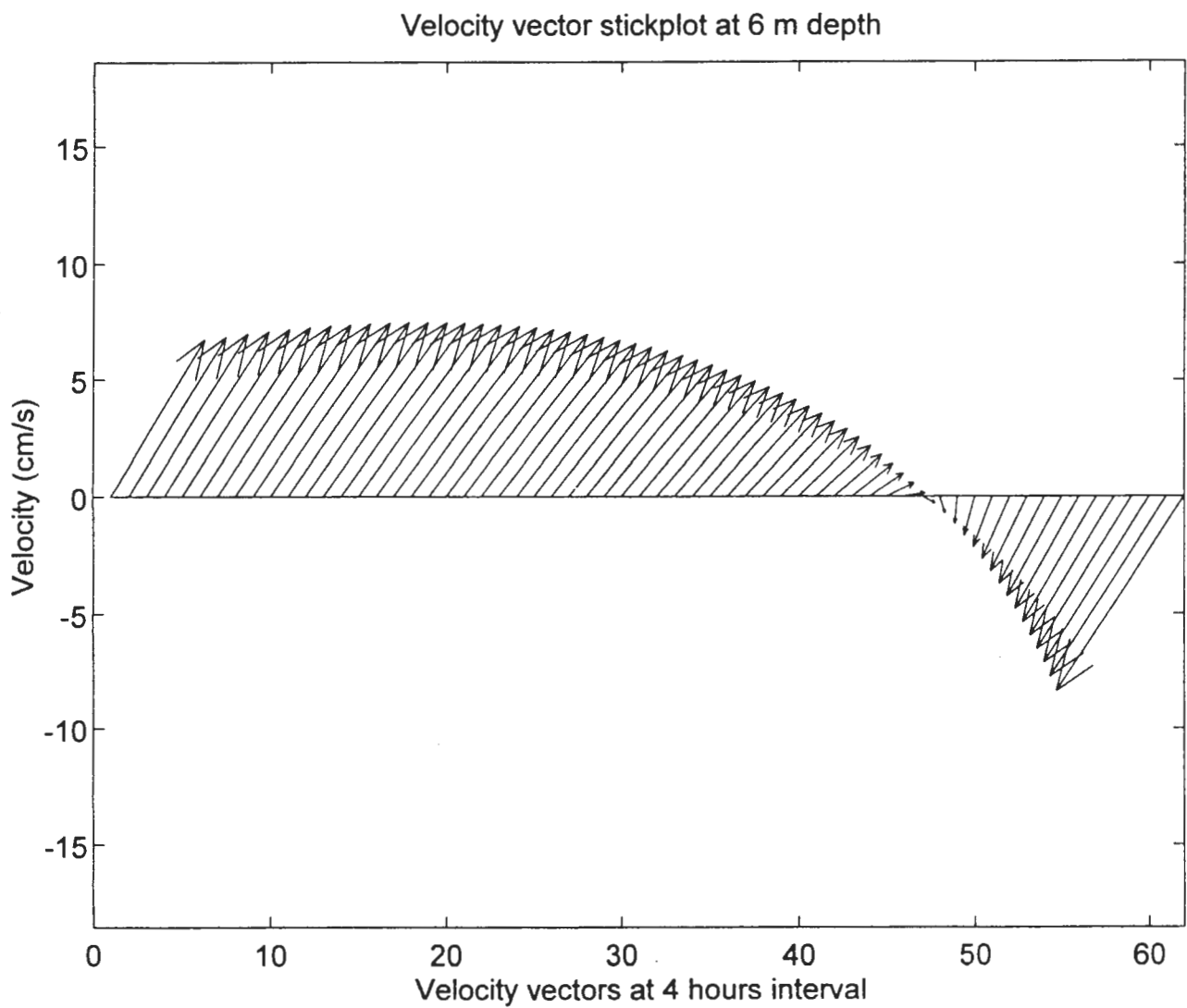


Fig. 3.11. Stickplot of the fitted velocity vectors averaged over four hours at 6 meter depth. The second order polynomial was used. The y-axis gives the magnitude of velocity vector and numbers on x-axis are serial numbers starting two hours later from reference time.

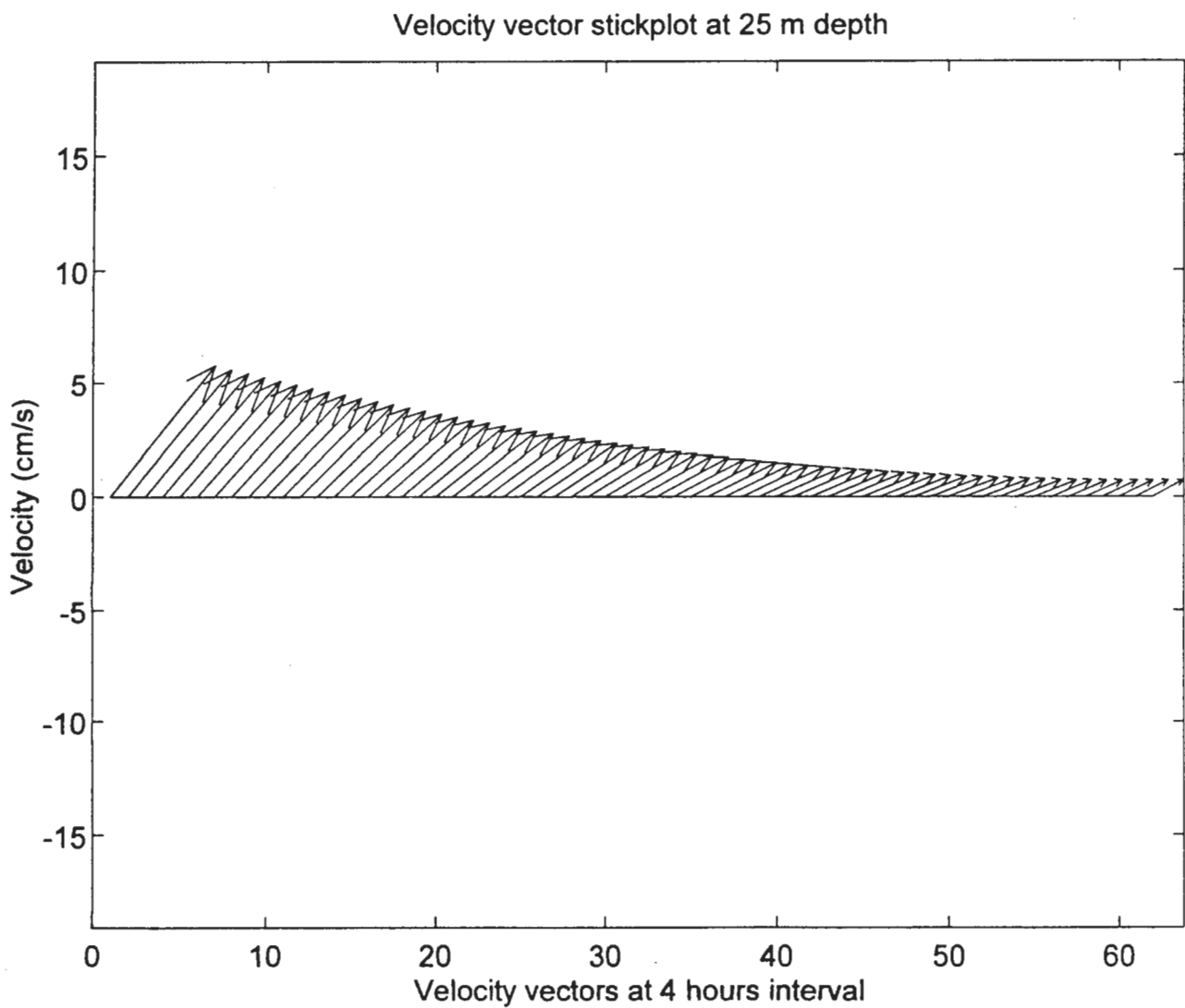


Fig. 3.12. Stickplot of the fitted velocity vectors averaged over four hours at 25 meter depth. The second order polynomial was used. The y-axis gives the magnitude of velocity vector and numbers on x-axis are serial numbers starting two hours later from reference time.

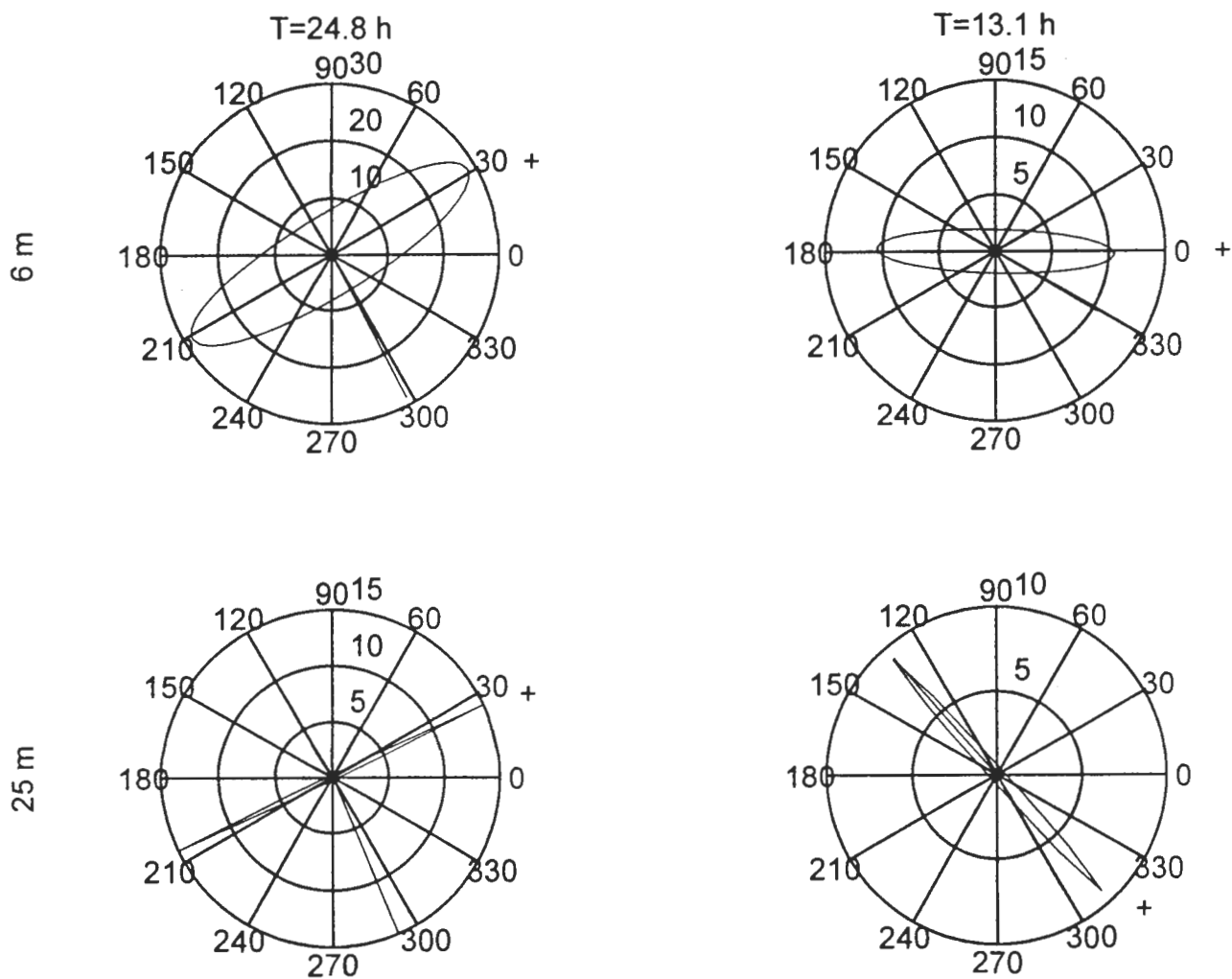


Fig. 3.13. The ellipses formed as hodograph trajectory of velocity vectors at diurnal and local inertial/semidiurnal frequency bands. Sign “+” indicates clockwise rotation of resultant vector. Single lines show temporal phase of each ellipse.

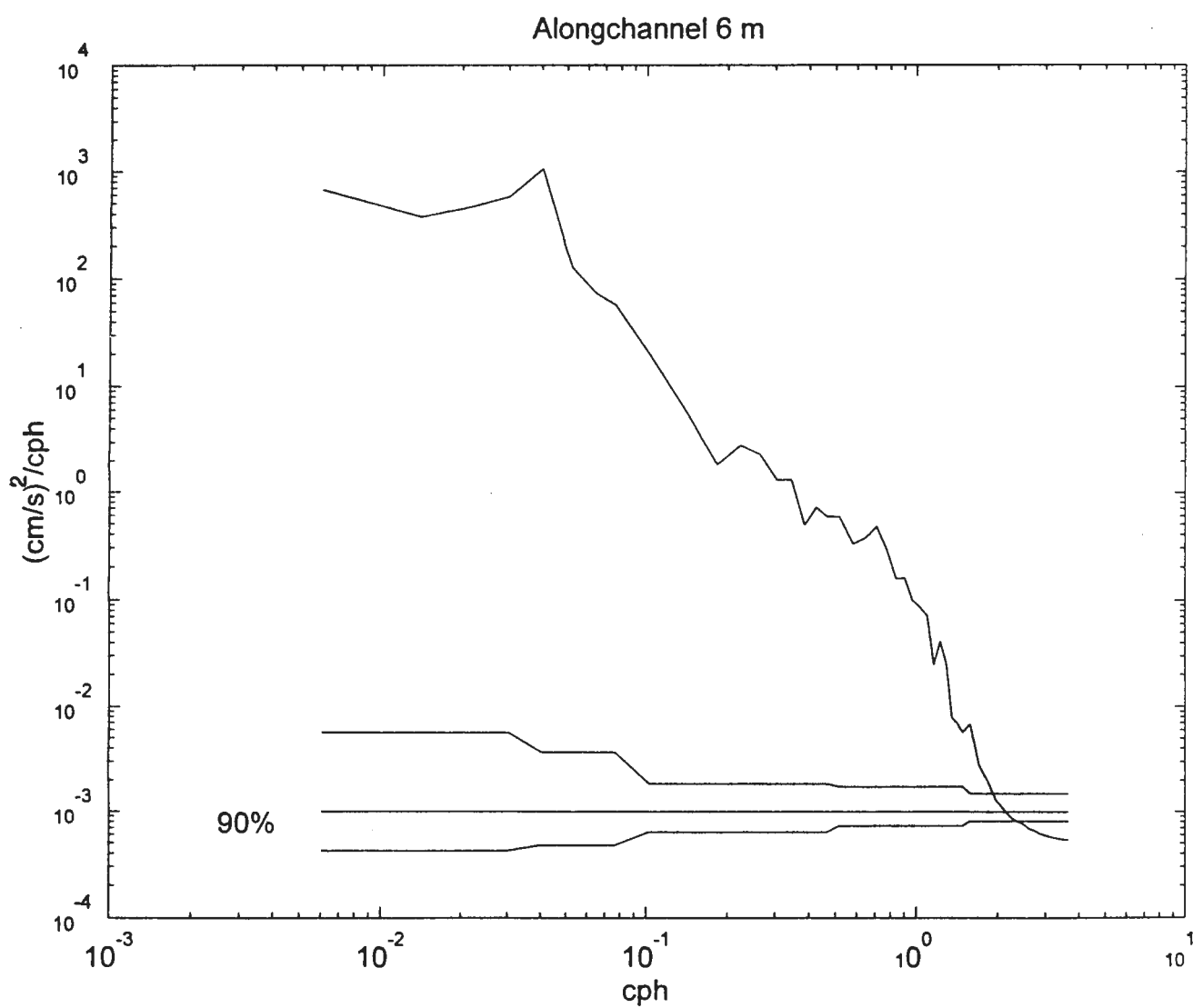


Fig. 3.14. Spectral density of along-channel component of velocity vector at 6 m depth. Significance level of 90% is shown.

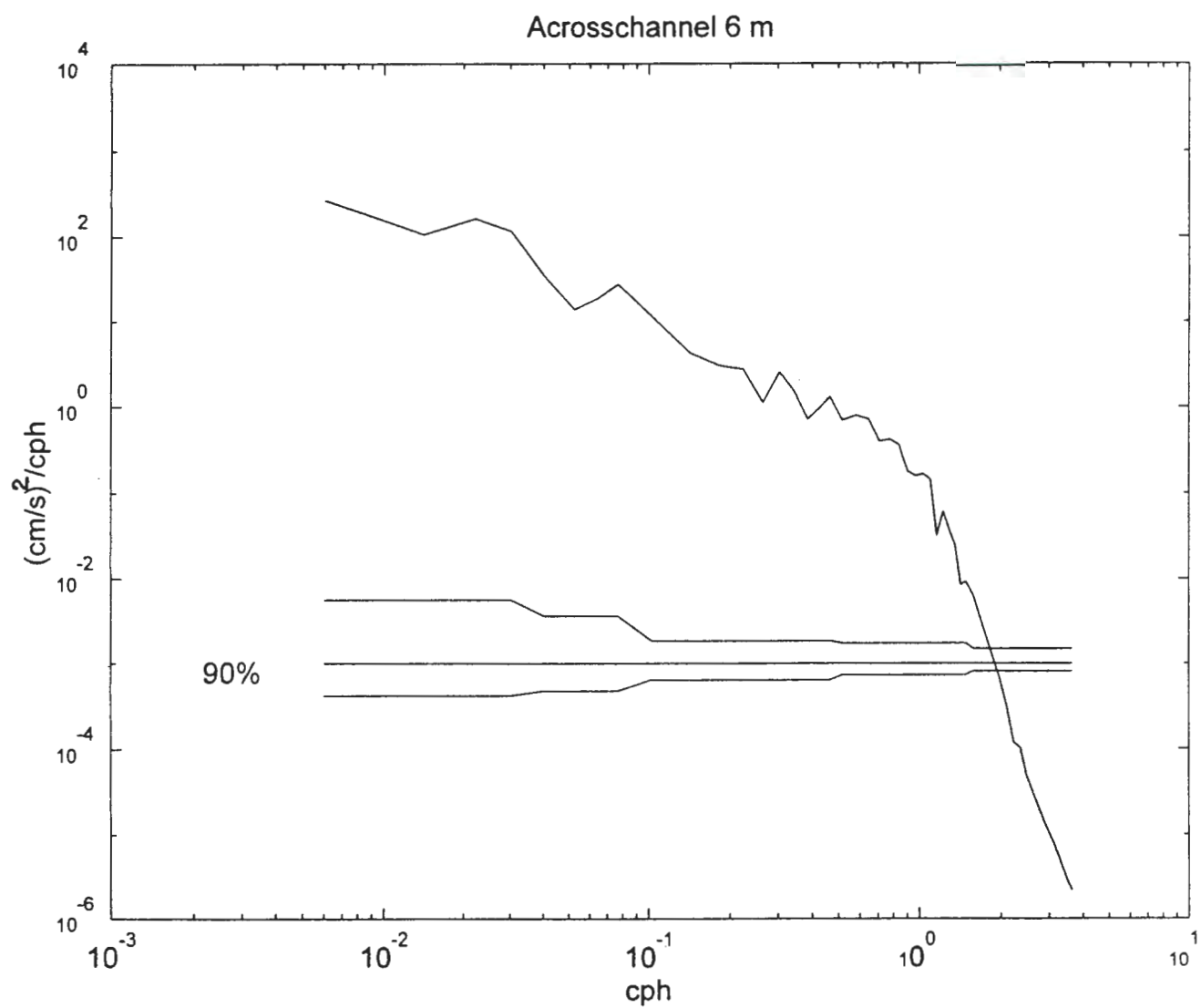


Fig. 3.15. Spectral density of cross-channel component of velocity vector at 6 m depth. Significance level of 90% is shown.

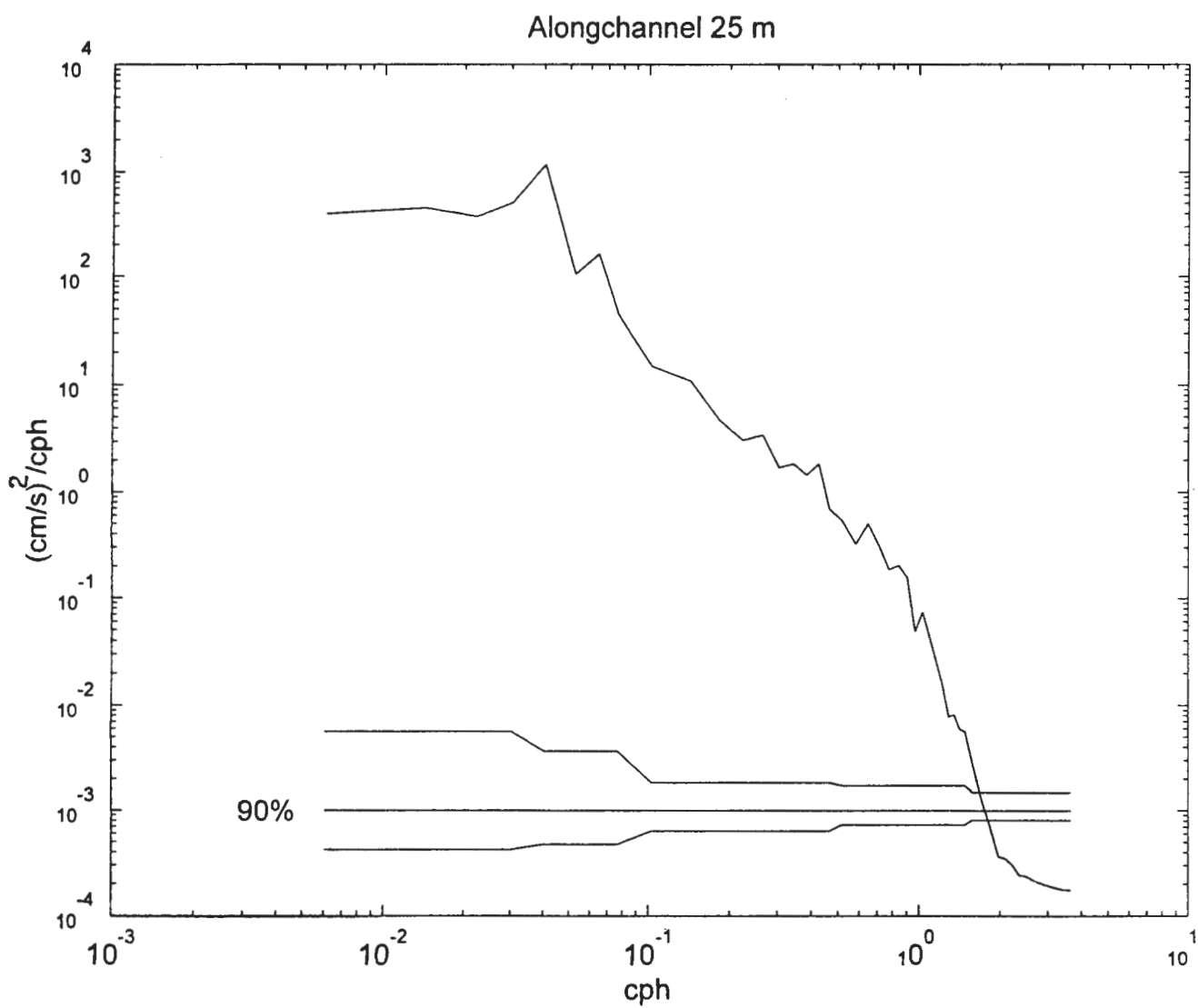


Fig. 3.16. Spectral density of along-channel component of velocity vector at 25 m depth. Significance level of 90% is shown.

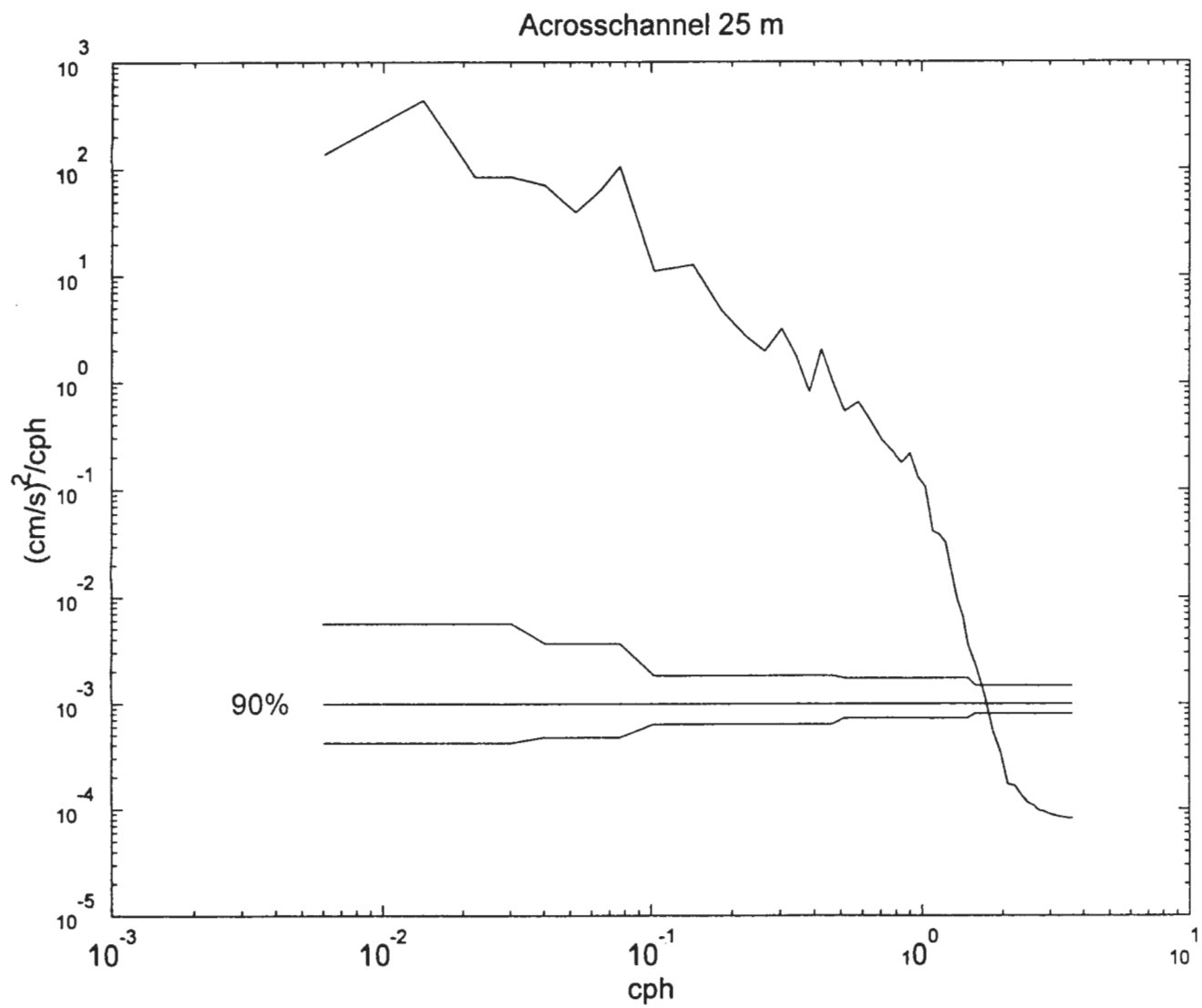


Fig. 3.17. Spectral density of cross-channel component of velocity vector at 25 m depth. Significance level of 90% is shown.

4. Dynamics of nutrients in Gulf of Riga and Irbe Strait

by Kalle Kallaste (Estonian Marine Institute) and Tarmo Kõuts (Estonian Meteorological and Hydrological Institute)

4.1 Introduction

Nutrients have long time been the central subject of discussion, regarding eutrophication problems in the Baltic Sea. The Gulf of Riga is connected to the Baltic Proper through the Irbe Strait, a sound through which occurs the main part of the water exchange. Recently remarkable steps forward were made to understand biochemical cycles in the Baltic Sea (Wulff and Stigebrandt, 1989). There can be two types of sub-ecosystems in the Baltic Sea - the coastal zone and the open sea. If riverborne nutrient inputs into coastal zone water can be estimated quite easily (as runoff and nutrient concentrations measures of the largest rivers take place around all the year), then understanding of the nutrient flux from the coastal zone to the open sea is comparably limited so far. The Baltic Sea is estuary consisting several subbasins, then the Gulf of Riga can be gathered as a coastal zone (max depth 55m) and the Baltic Proper (the eastern Gotland Basin) as the open sea (max depth 255m). The exchange of water and materials through connecting these two basins sound (the Irbe Strait) comes into major interest to evaluate the coastal zone - open sea exchange.

Obtained historical time series of nutrient concentrations in the Baltic Proper and in the Gulf of Riga demonstrate significant differences in the dynamics of nutrients between these two basins. Therefore the transition between the two basins - the Irbe Strait comes into major interest reflecting the variety of processes causing actual exchange of nutrients from one subbasin into another.

4.2 Measurements

Samples for nutrient analysis were collected with Nansen water samplers and stored frozen until analysed at ashore laboratory of Estonian Marine Institute (Pärnu Marinebiology Station). Measurements of nitrates, nitrites, silicates, ortophosphates, total nitrogen and phosphorus were analysed with methods for seawater described by F. Koroleff (1979) and K. Grasshoff (1976). Total nitrogen and phosphorus were oxidized in autoclave in alkaline $K_2S_2O_8$ solution to nitrates and ortophosphates. Nitrites and nitrates analysis were performed on AKEA autoanalyser using a method provided by DATEX. Phosphates and silicates were estimated manually with HITACHI U-1100 spectrophotometer.

4.3 Description of experimental results

Concentrations of nutrients in the Gulf of Riga water showed a normal annual cycle with high values during winter, and early spring and lower during the summer season. Sampling of nutrients in the stations of intensive study (two crossing sections through the Irbe Strait) (see Fig. 4.1) was performed to study in more detail the transition between two different marine ecosystems, which are mainly the phosphorus limited Gulf of Riga and the nitrogen limited Baltic Proper. Such a hypothesis of two types of ecosystems was recently proposed by Yurkovskis et.al., 1993. However, preliminary analysis of our data do not show clearly the expected transition effect on the border of the ecosystems, where much higher primary production (diminished limitation) should principally be present (Tõnis Põder, personal communication).

It should be mentioned that nutrient concentrations in the Gulf of Riga stayed comparably high during the whole summer of 1993. As seasonal thermocline decayed already in October, the last survey carried out in November covered a typical winter situation, when concentrations of PO_4 increased from the typical summer values (around 0.3 to 0.4 $\mu\text{mol/l}$) to the winter values (around 0.5-0.7 $\mu\text{mol/l}$). The summer concentrations of NO_3 covered quite large interval (from 0.07 to 5.5 $\mu\text{mol/l}$), which can be explained by the effect of patchiness, whereas winter concentrations were more homogenous (around 4.0-6.0 $\mu\text{mol/l}$). To outline the characteristic seasonal situations, the following description of nutrient dynamics will be presented.

May

Nitrate concentrations varied between 0.2 and 0.5 (transect I) and 0.16 and 0.7 $\mu\text{molN/l}$ (transect II) and orthophosphates varied between 0.7 and 1.26 (transect I) and 0.45 and 1.1 $\mu\text{mol P/l}$ (transect II) (see Fig. 4.2-4.3).

If no reliable spatial patterns were detected in the distribution of phosphorous concentration, somewhat higher NO_3 concentrations were observed in the northern part of the Irbe Strait and the adjacent area of the Gulf of Riga, with 0.3 - 0.7 and 0.2 - 0.3 $\mu\text{mol/l}$ respectively. Keeping in mind that the Baltic Proper surface layer is depleted in NO_3 compared to the Gulf of Riga, one can expect that data support the idea of inflow along the Latvian coast.

The ratio - NO_3/PO_4 was small at all stations, because of rapidly increasing biomass of phytoplankton (see Fig. 4.4). Characteristic values of the ratio were about 0.25-0.5 on transect I and 0.2-0.85 on transect II.

August

Nitrate concentrations in the upper 10 m layer varied between 0.1 and 1.4 $\mu\text{mol/l}$ and phosphates between 0.2 and 0.4 $\mu\text{mol/l}$ (see Fig. 4.5 - 4.6). Maximum nutrient concentrations were recorded in the bottom layer at the station 263 - above 5.4 $\mu\text{mol/l}$ NO_3 and 1.2 $\mu\text{mol/l}$ PO_4 . No clear correspondence between the nutrient concentration and salinity gradient along the transect could be detected. Increased nutrient content in the surface layer was detected at some stations in the Irbe Strait (e.g. Station 264), most likely due to the upward movement of nutrient rich deep water along the slope. In most cases the nutricline was rather weak, partly due to restricted bottom depth, partly due to relatively high nutrient concentrations in the surface layer, even at the Baltic Proper stations. The nutrient concentrations in the upper layer of Irbe Strait are in agreement with historical data stored at EMI database.

The inorganic N:P ratio in the surface layer ranged from 1 (0.1 station 279) to 3 (station 282), in the bottom layers N:P ratio was slightly higher, around 5.7 (station 283, transect II) (see Fig. 4.7).

November

Concentration of nitrate increased from the open sea towards the Gulf of Riga. If nitrate concentration was below 2 $\mu\text{mol N/l}$ in the bottom layer outside the Irbe Strait (near the Latvian coast), then about 4 $\mu\text{mol N/l}$ on crossing transects through the Irbe Strait and even 6 $\mu\text{mol N/l}$ in the Latvian coastal zone of the Gulf of Riga (see Fig. 4.8). Vertical distribution of nitrates was homogeneous in the Irbe Strait, whereas some increase occurred in the lower parts of the Gulf of Riga.

The concentration of nitrite was higher compared to the August case, being on average about 0.4-0.8 $\mu\text{mol N/l}$.

The concentration of total N ranged between 9 - 28 $\mu\text{mol N/l}$ in the transects, being lower in the open sea and higher in near-bottom layers of the Irbe Strait (see Fig. 4.10).

The concentration of phosphates compared to the concentration of nitrates was more homogeneous, but still some increase towards the Gulf of Riga was observed. Being outside

of the Irbe Strait below $0.3 \mu\text{mol P/l}$ and in the Gulf of Riga about $0.75 \mu\text{mol P/l}$. Comparing the transects II and III, it shows that after the stormy weather (in between sampling these sections), the contents of phosphate concentration in the surface layer increased about 100%. The content of total phosphorus increased from the open sea towards the Gulf of Riga rather continuously from surface to bottom.

The values of total P on the first and second transects were between 0.8 to $1.9 \mu\text{mol P/l}$. On the transect III (after storm) the concentrations of total P was increased 1.5 to $1.9 \mu\text{mol P/l}$. The content of ortophosphates was about 25 - 45 % of the content of total P.

The concentration of silicates on transects was even from surface to bottom and increased from the Baltic Proper towards the Gulf of Riga, being outside the Irbe Strait about $1 \mu\text{mol Si/l}$ and in the Gulf of Riga around $6 \mu\text{mol Si/l}$ (see Fig. 4.9). The highest concentrations were found in the Irbe Strait at the shallow station No.472 ($7.5 \mu\text{mol Si/l}$).

The third transect made after stormy weather showed that the average content of silicates was increased in the water column in the Irbe Strait and in the northern part of the Gulf.

Inorganic N:P ratio in November was increased compared to those values in August (see Fig. 4.11).. Highest N:P ratio was found in the Gulf of Riga water, about 10, and lowest in the Baltic Proper - out from the Irbe Strait.

4.4 Conclusions

In general the concentrations of nutrients in the Gulf of Riga were higher than the values in the Baltic Proper, while concentrations usually increase if going from open areas to the coastal zone. In this study the dynamics of nutrient concentrations, sampled on crossing transects extending from the Gulf of Riga through the Irbe Strait to the Baltic Proper, were analysed in detail. One conclusion is that the nutrient distribution pattern in the transition area is strongly affected by hydrodynamic processes occurring there such as currents, fronts, eddies etc., which therefore cause a resultant nutrient flux towards the Baltic Proper. Data showed good correlation between anomalies of inorganic nutrient concentrations and thermohaline structures in the transition area. Nitrates and ortophosphates showed obvious difference in concentrations between the upper and deep layers, whereas vertical distribution of total phosphorus and nitrogen was quite homogeneous in the Gulf of Riga and in the Irbe Strait.

Yearly observed cycle of N:P ratio (inorganic nitrate divided to inorganic phosphorus) can be outlined as follows (see Fig.4.12):

- in spring strongly below 1 ($0.2-0.4$) in the Baltic Proper and about 1 in the Gulf of Riga
- during summer season about 1, both in the Baltic Proper and in the Gulf of Riga
- in autumn more than 1 in both basins, showing increasing tendency towards the Gulf of Riga.

Acknowledgements

The expedition group of the Estonian Meteorological and Hydrological Institute (leader Ivo Saaremäe, R/V ORBIIT), who performed field activities and laboratory staff of Pärnu Marine Biological Station (head Jüri Tenson, Estonian Marine Institute), who made laboratory analysis, are kindly acknowledged.

References

Stigebrandt A., and Wulff, F. 1989. A model for the dynamics of nutrients and oxygen in the Baltic Proper. *Journal of Marine Research* **45**, 729-759.

Yurkovskis, A., Wulff, F., Rahm, L., Andruzaitis, A., and Rodrigues-Medina, M. 1993. A Nutrient Budget of Gulf of Riga; Baltic Sea *Estuarine, Coastal and Shelf Science*, **37**.

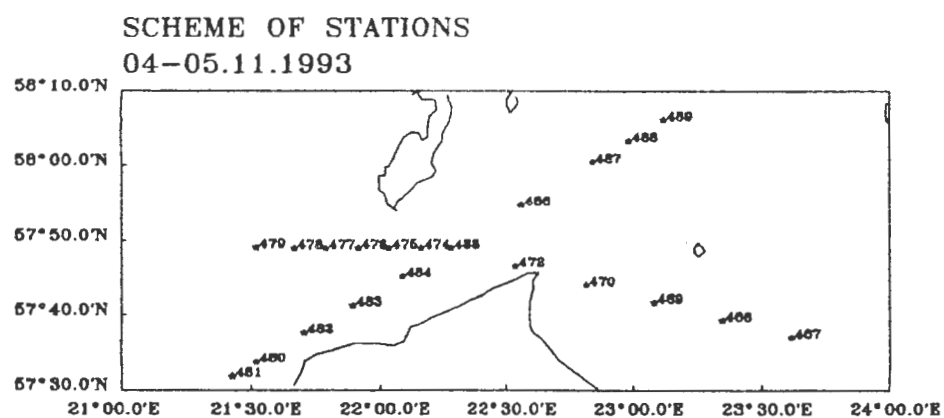
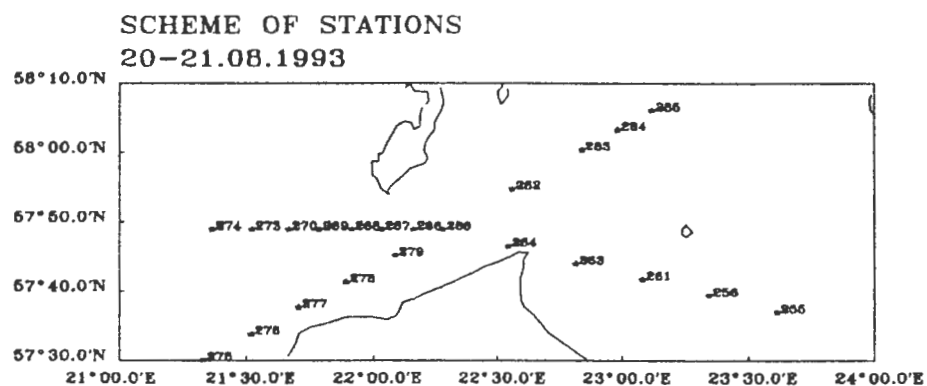
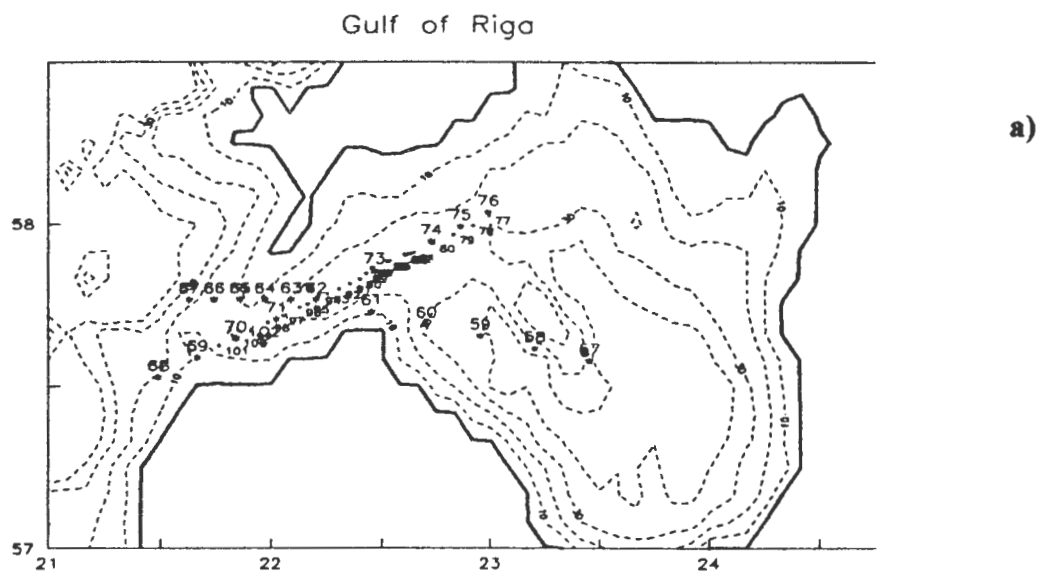


Fig. 4.1 Scheme of nutrient sampling stations during cruises in May (a), August (b) and November (c) 1993

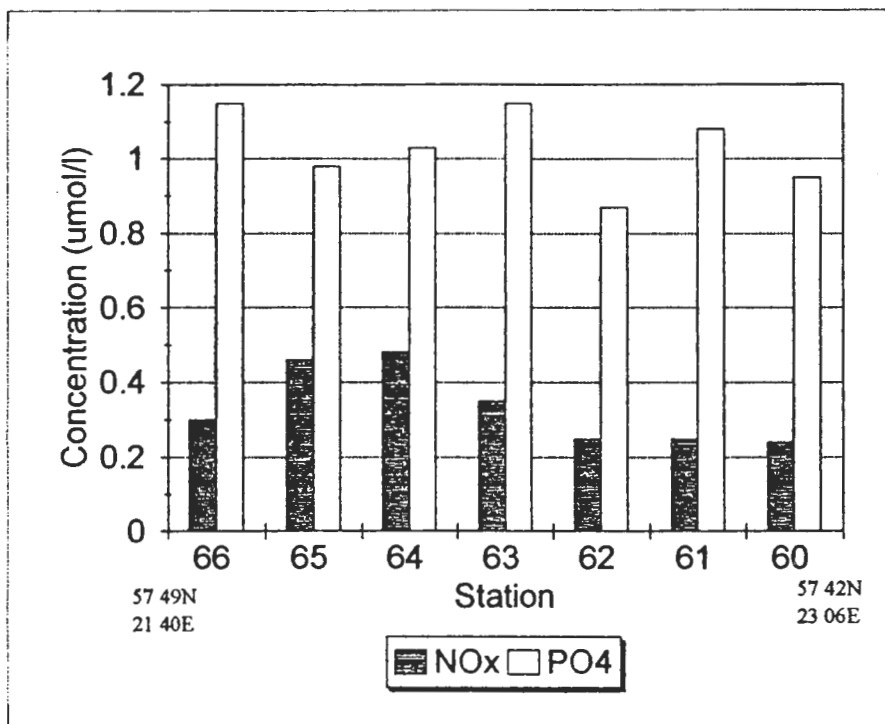


Fig. 4.2 Concentration of nitrates ($\mu\text{mol N/l}$) and phosphates ($\mu\text{mol P/l}$) along transect I in May 1993

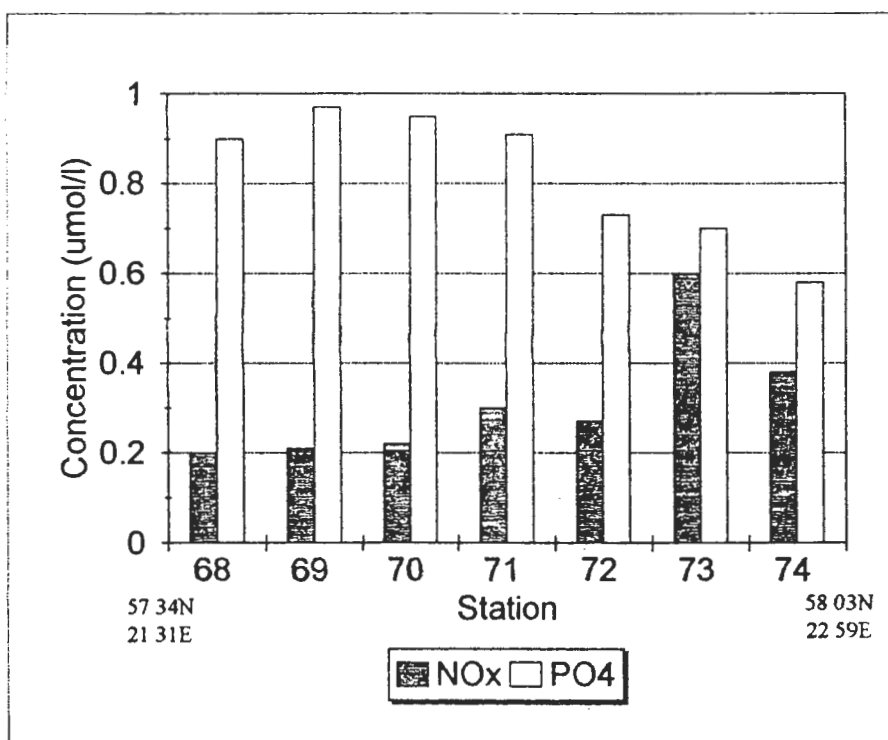


Fig. 4.3 Concentration of nitrates ($\mu\text{mol N/l}$) and phosphates ($\mu\text{mol P/l}$) along transect II in May 1993

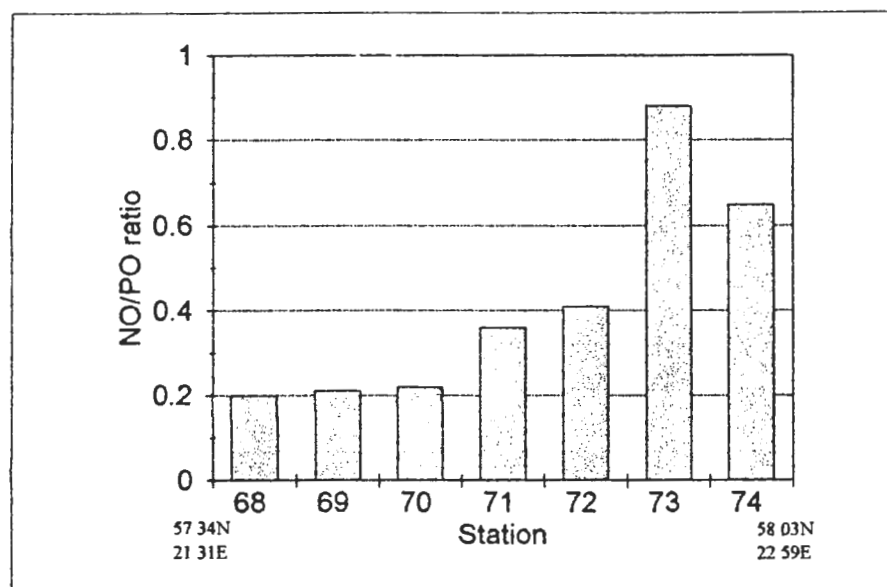
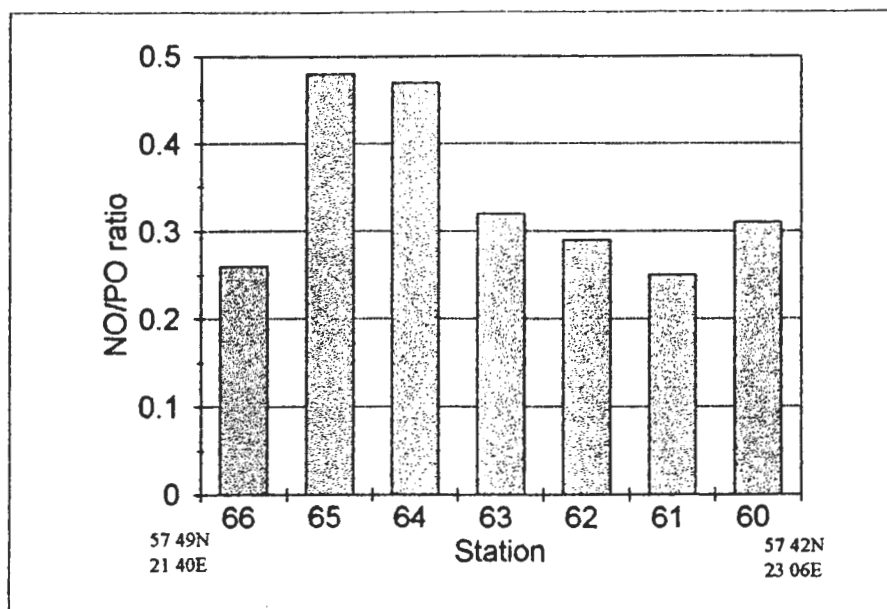


Fig. 4.4 Ratio NO_3/PO_4 along transect I (a) and II (b) in May 1993

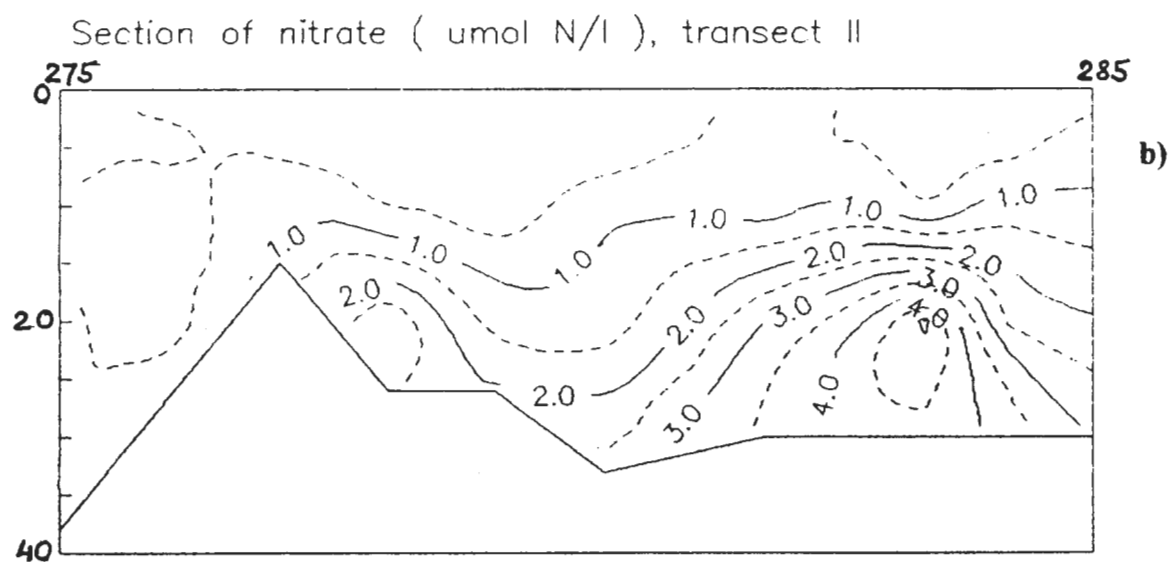
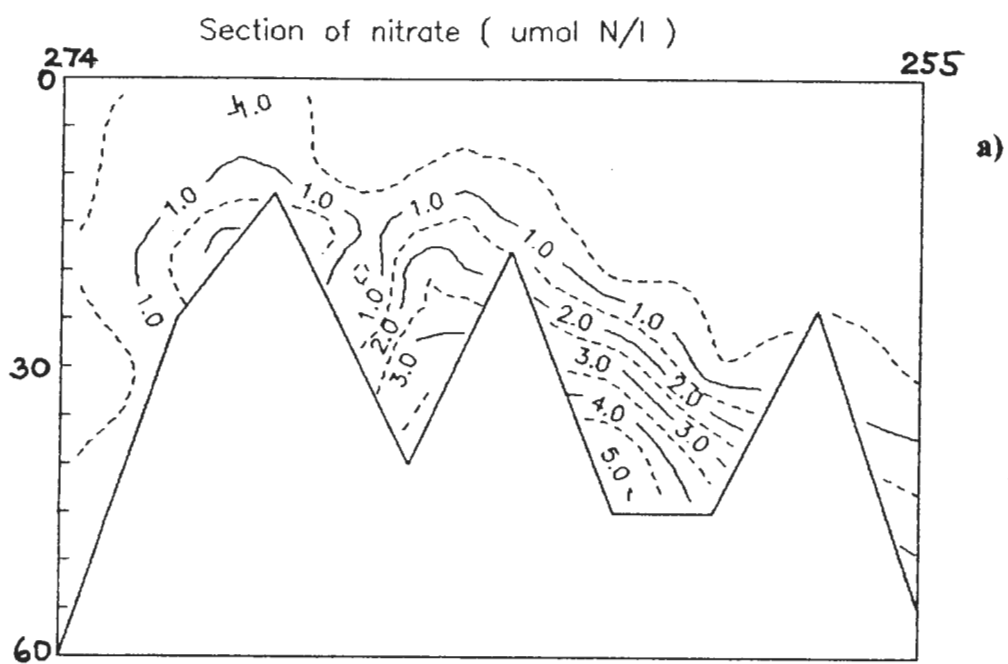


Fig. 4.5 Vertical section of nitrate ($\mu\text{mol N/l}$) field along transect I (a) and II (b) in August 1993.

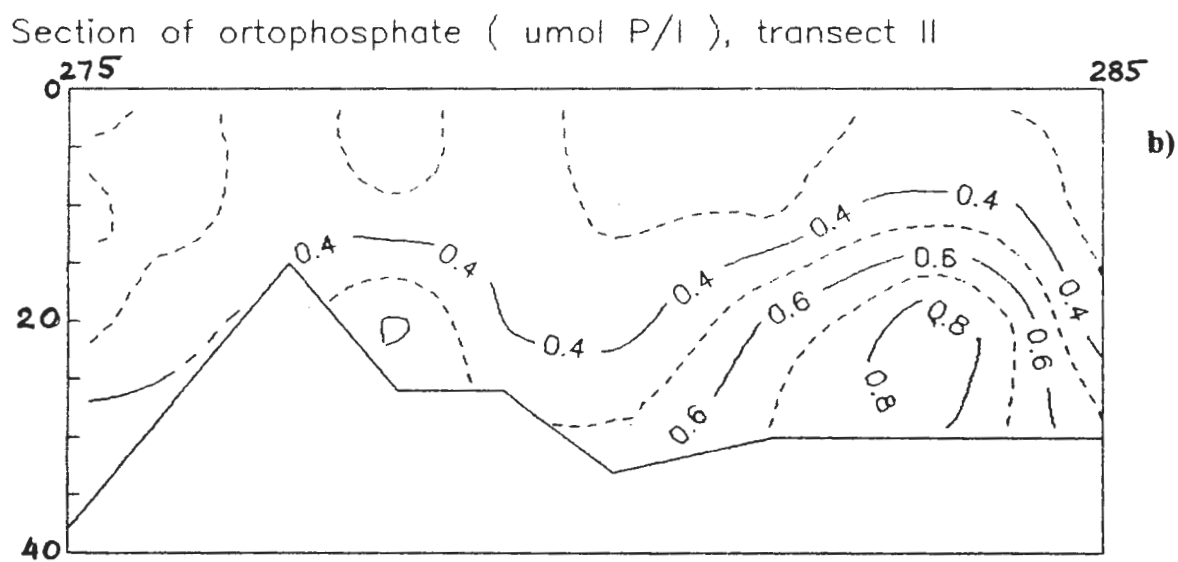
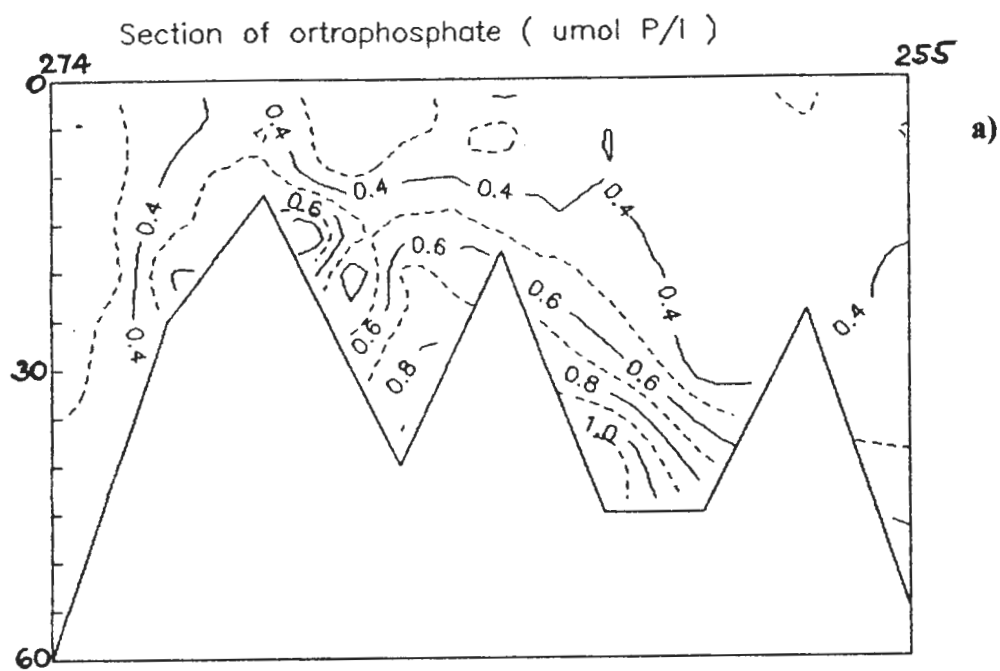


Fig. 4.6 Vertical section of ortrophosphate ($\mu\text{mol P/l}$) field along transect I(a) and II(b) in August 1993.

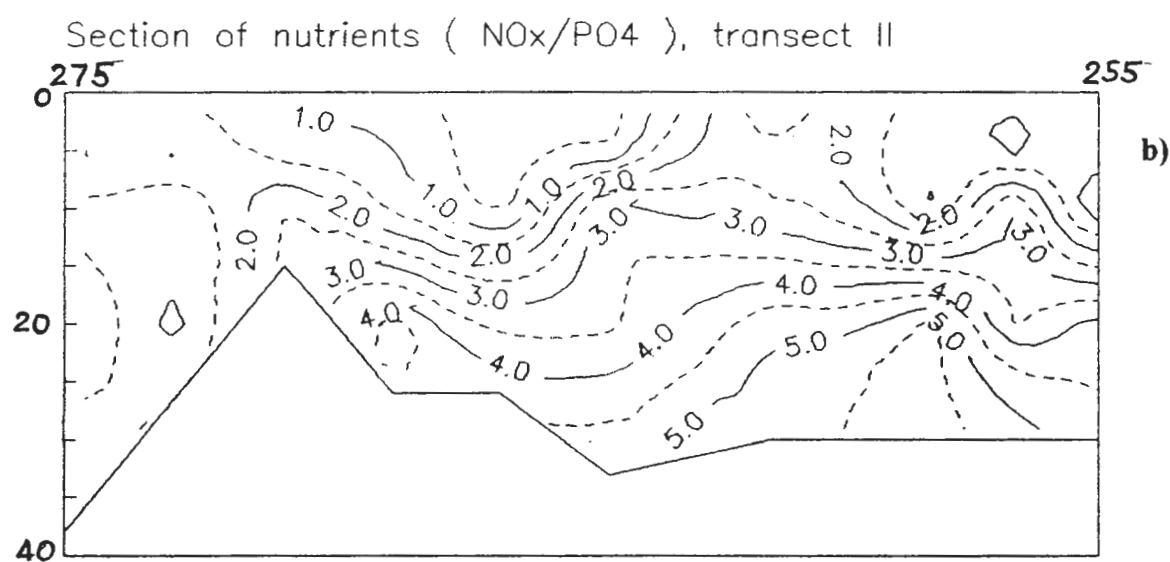
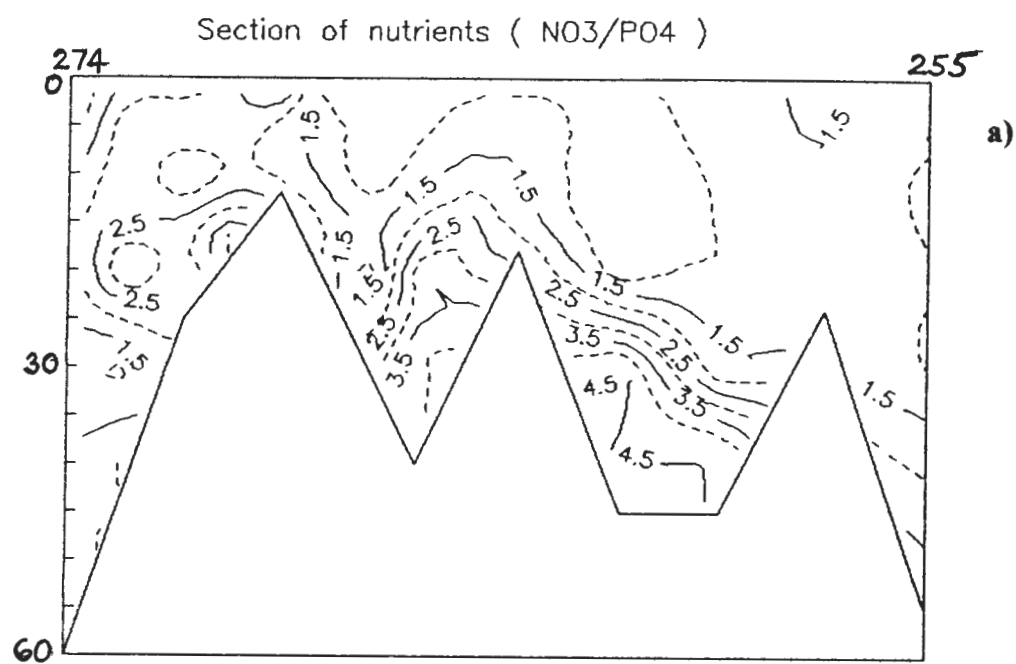


Fig. 4.7 Vertical section of ratio NO_3/PO_4 field along transect I (a) and II (b) in August 1993.

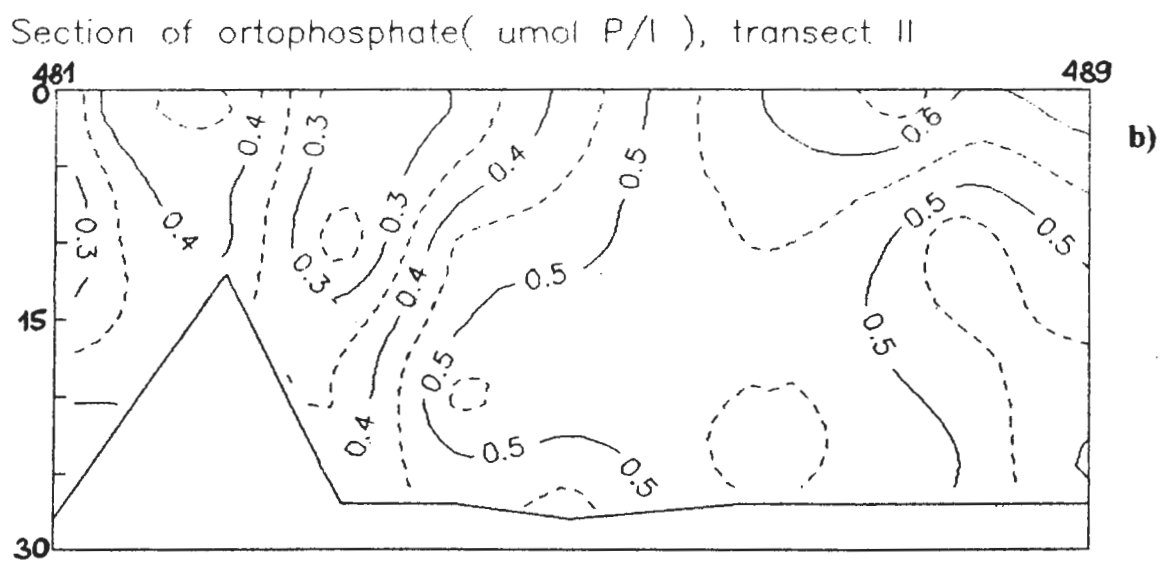
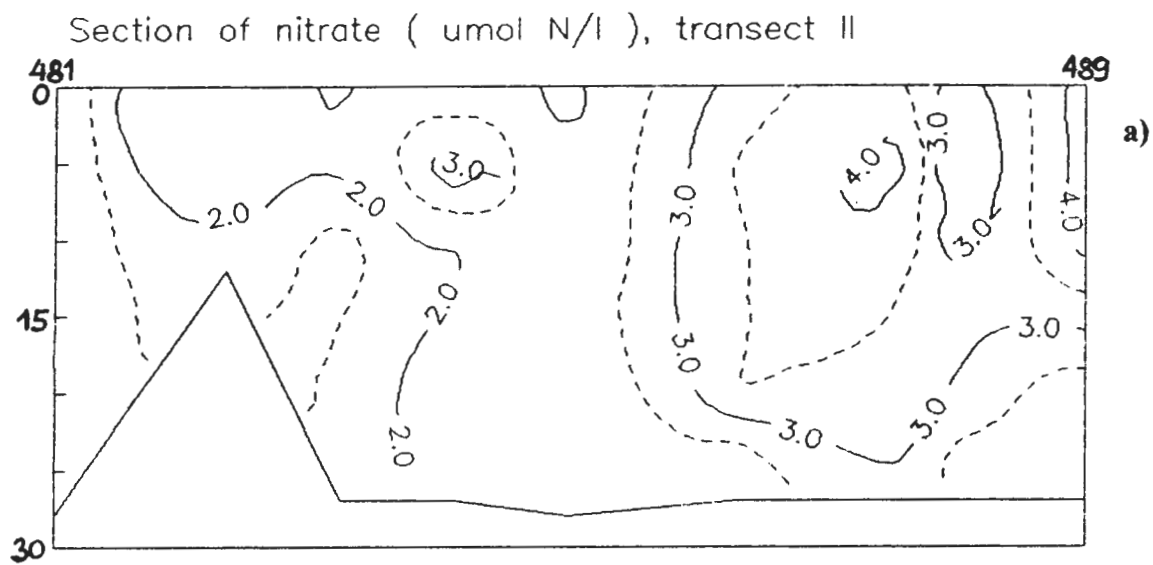


Fig. 4.8 Vertical section of nitrate ($\mu\text{mol N/l}$) (a) and orthophosphate ($\mu\text{mol P/l}$) (b) field along transect II in November 1993.

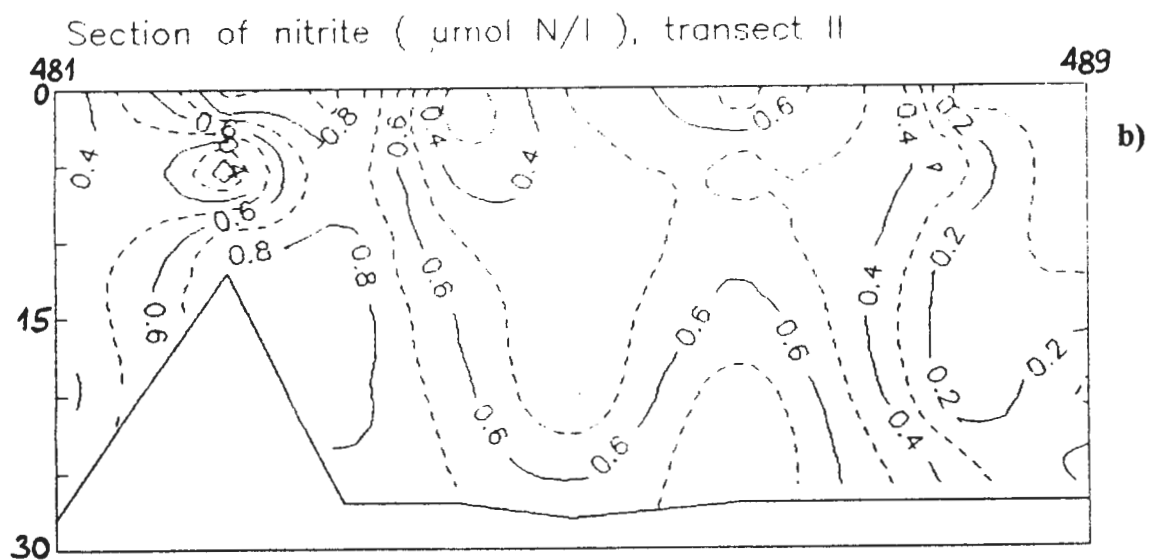
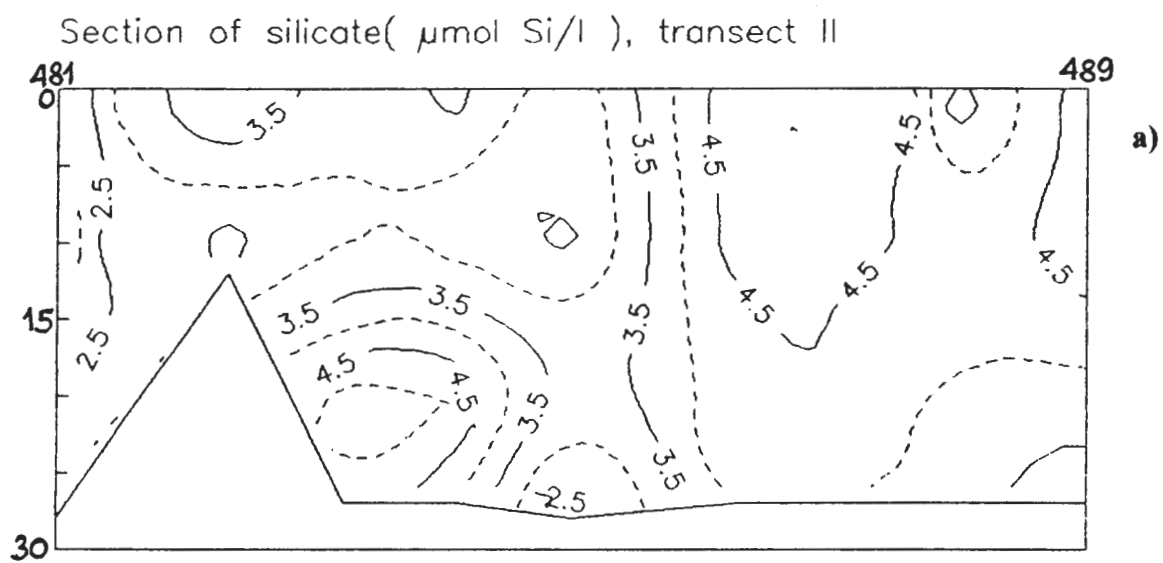
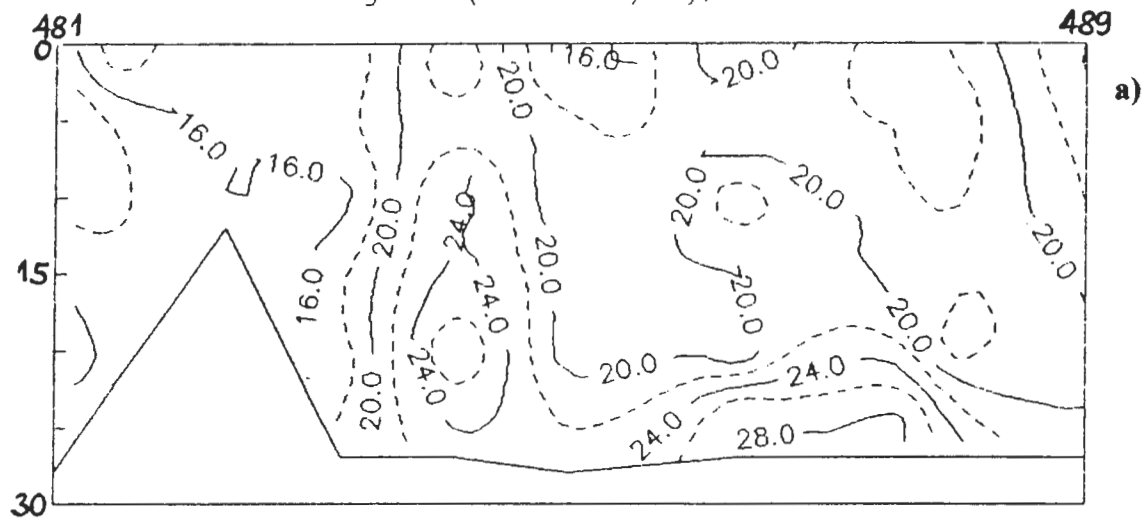


Fig. 4.9 Vertical section of silicate ($\mu\text{mol Si/l}$) (a) and nitrite ($\mu\text{mol N/l}$) (b) field along transect II in November 1993.

Section of total nitrogen ($\mu\text{mol N/l}$), transect II



Section of total phosphorus ($\mu\text{mol P/l}$), transect II

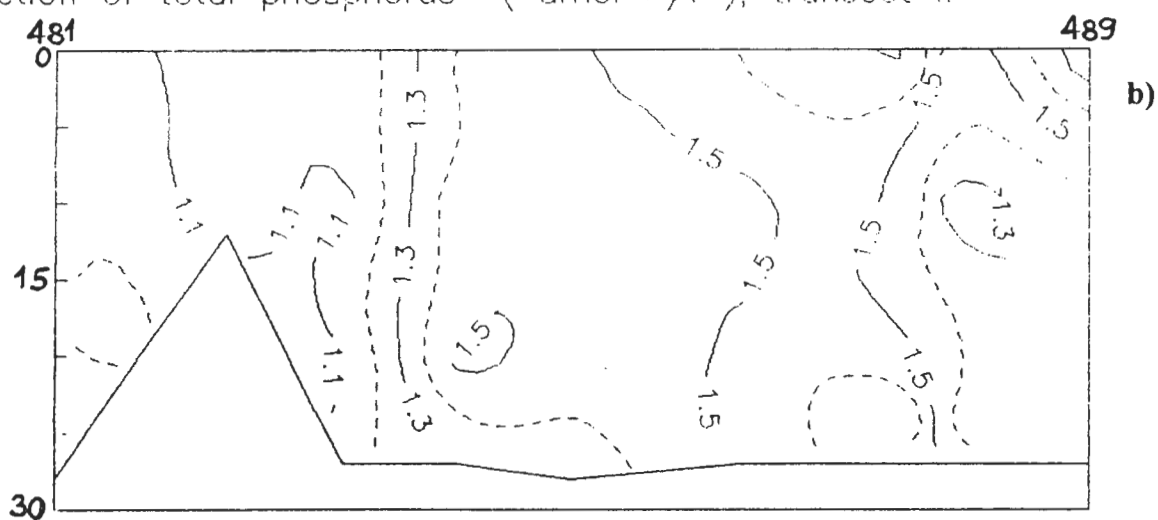


Fig. 4.10 Vertical section of total nitrogen (a) and total phosphorus (b) ($\mu\text{mol/l}$) field along transect II in November 1993.

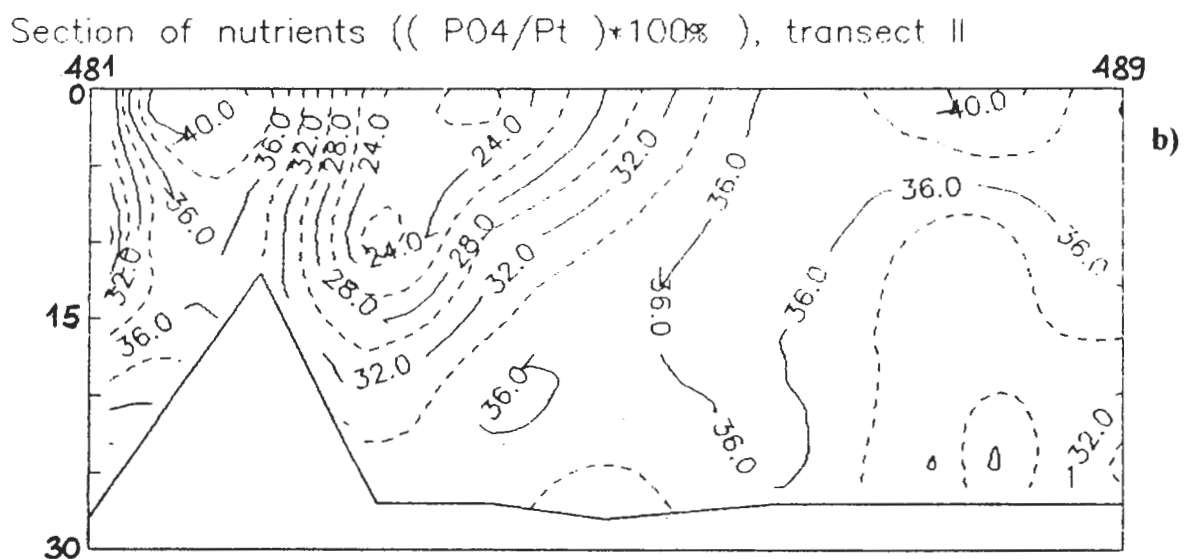
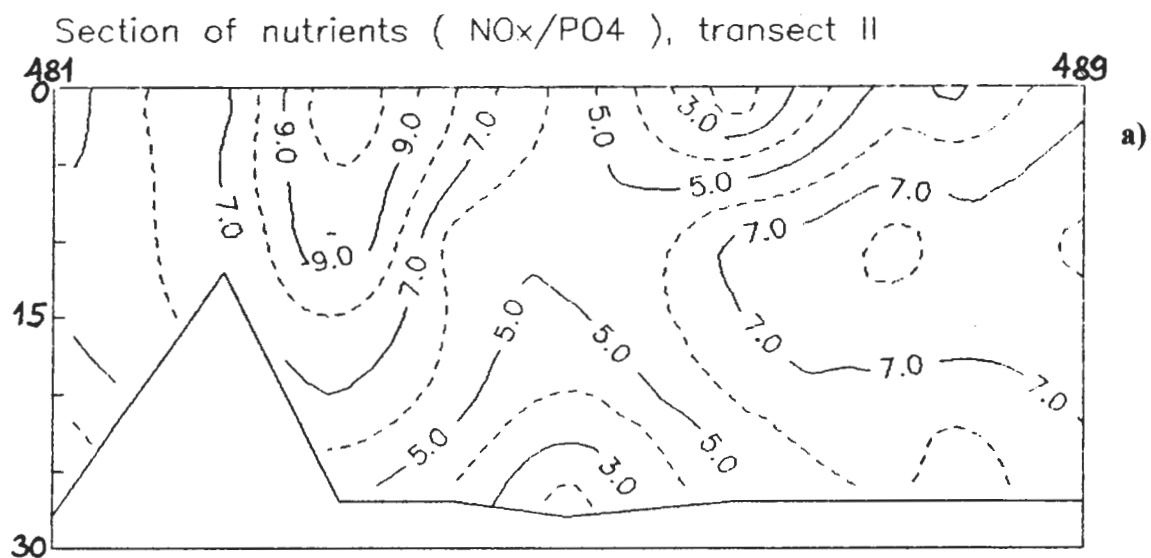


Fig. 4.11 Vertical section of ratio NO_x/PO_4 (a) and ratio $\text{PO}_4/\text{Pt} \times 100\%$ (b) field along transect II in November 1993.

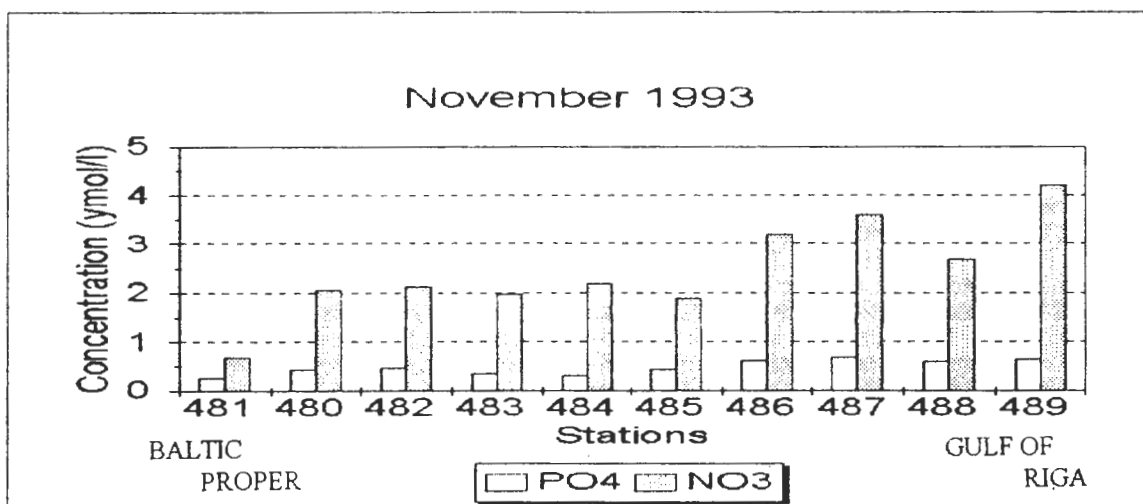
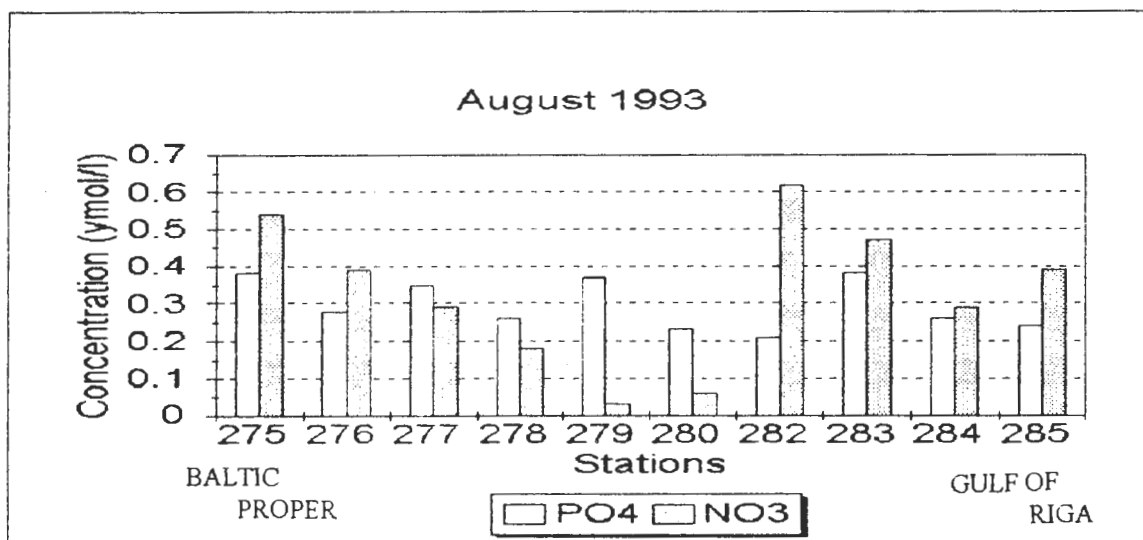
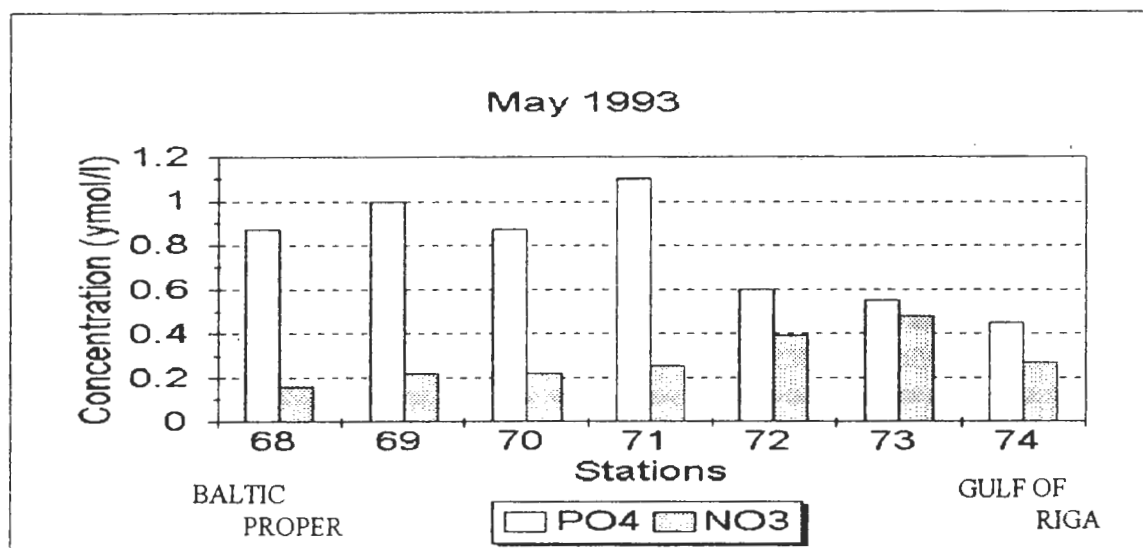


Fig. 4.12 Concentration of nutrients in the surface layer on transect extending from the Gulf of Riga through Irbe Strait to the Baltic Proper

5. The structure of the hydrographic fields in the Irbe Strait in 1993/94

by Urmas Lips (Estonian Marine Institute)

5.1 Introduction

The main aim of the Sub-project Water exchange, nutrients, hydrography and database is to qualify and quantify the water exchange between the Gulf of Riga and the Baltic Sea. About 80-85% of this water exchange takes place in the Irbe Strait - a channel-like sound with sill depths about 25 meters. One of the methods which allows to estimate the water exchange through this sound is the analysis of the data of direct measurements of the currents, salinity and temperature fields. The goal of the present paper is to give a description of the hydrographic fields in the Irbe Strait in relation with the currents and meteorological conditions during four seasons in 1993/94.

5.2 Data

Four seasonal monitoring cruises and three detailed surveys (in May, August and November) are carried out by EMHI and EMI in the Gulf of Riga and Irbe Strait in 1993. An additional survey in the Irbe Strait is provided by SMHI in January 1994. Thus, the monitoring as well as the detailed surveys covered all seasons. Schemes of the monitoring stations and transects in the Irbe Strait are given in Figures 5.1, 5.2.

CTD-measurements are performed using Neil Brown Mark III probe (EMI) and CTD-probe Mark V (SMHI). NB Mark III data quality was checked at EMI by the analysis of water samples using salinometer AUTOSAL. The average difference between CTD and AUTOSAL salinity did not exceed 0.02 psu. Meteorological parameters (wind speed and direction, atmospheric pressure, air temperature) measured during the cruises shall be used for purposes of this study as well. Current measurements are provided using Neil Brown ACM/CTD probe (in May, August and November) and by installing mooring stations with SensorData Current Meters (in August and November). Detailed analysis of the data on currents are prepared by Dr M.-J.Lilover and by U.Raudsepp and are presented in separate chapters of this report. List of available additional meteorological and sea-level data obtained at Estonian coastal stations by EMHI is given in Tab. 5.1.

Table 5.1. *Additional meteorological data obtained at Estonian coastal stations by EMHI.*

Station	Period	Wind, T _a , P _{atm}	Sea level
Pärnu	07-08.1993	every 3 hours	-
Virtsu	01-06.1993	every 3 hours	every 6 hours (not whole period)
Ruhnu	10-11.1993	every 12 hours	-

5.3 General hydrographic description and position of the the Irbe front

The Irbe Strait is a transition area between the Baltic Sea Surface Water (BSSW) and the Gulf of Riga Water (GRW). Salinity of the BSSW is about 7.2 -7.3 psu, salinity of the GRW

is about 5.6 psu. Temperature and density values depend on the season. Usually, as one can see from the large-scale monitoring data (Fig. 5.3), the largest part of the salinity difference between two water masses is described by salinity changes within the narrow region in the Irbe Strait. This jump in salinity (and, of course, in density), which always occurs in this area, is proposed to be called the Irbe Front.

Detailed surveys in the Irbe Strait demonstrated a more complicated vertical and horizontal structure of the Irbe Front and a large extent of its migration. The frontal boundary in the surface layer (Fig. 5.4-5.7) can be situated outside in the Baltic Proper and inside of the Gulf of Riga as well. The most outward location of the surface layer front during the last year was observed in May and the most inward - in August. The front was positioned in the central part of the Irbe Strait in November 1993, in January 1994 and, it seems, it was the case in March 1993, too. The shape of the frontal boundary on the water surface is mapped well by surveys in November and especially in January when a cross-channel CTD-transect was provided. The BSSW is usually transported towards the Gulf in the southern part of the strait and the GRW is transported outward from the Gulf in the northern part of the strait. As a result an S-form boundary appears on the water surface.

Vertical structure of the Irbe Front is usually characterized by a more inward position of the frontal boundary in the deeper layers. Large differences in the shape and location of the frontal boundary near the surface and in the deep layer were observed during May and August 1993 (Fig. 5.8, 5.9). There were two salinity jumps at the 20 m level in both cases. One of them coincided with the surface front, another was far away toward the Gulf in May and toward the Baltic Proper in August.

The vertical sections of salinity presented on Fig. 5.10 and 5.11 show how the Irbe Front looks like in a vertical intersection through the Strait in both cases. In May one can recognize two steps on the frontal boundary - one in the surface layer between stations 45 and 66 and another in the subsurface layer between stations 72 and 73 (within the Gulf already). In August the surface front coincided with the strongest part of the subsurface front in the Irbe Strait. Outside the Strait an intermediate layer with lower salinity is formed beneath the more saline surface layer. However, the situation was stable in the density field (Fig. 5.12) because the BSSW had higher temperature than the GRW below the seasonal thermocline.

General features of the Irbe Front are the following. The front is situated in the central part of the Irbe Strait with possible migration of the surface front in both directions (usually outward into the Baltic Proper) warm seasons when seasonal thermocline is developed. On the water surface the front has an S-form shape. The inclination of the frontal boundary is well-seen during the warm seasons and the front is rather vertical during cold seasons when the water column is almost fully mixed.

5.4 On the causes of the variations in the position and shape of the Irbe front

The observed S-form shape of the Irbe Front is typical for the channel-like contacting areas of two water masses (Tang, 1983; Rodhe, 1992). The average position and the shape of the frontal layer are controlled by external factors: inflow of buoyancy, topography and geometry of the coastline. Because of the positive water balance for the Gulf of Riga the GRRW flows out from the gulf and creates a horizontal density gradient in the transition area. This horizontal density gradient drives a geostrophic current which was well documented by provided measurements of vertical profiles of current velocity (Lilover, present report). For instance, the structure of currents related to the subsurface front in May (see Fig. 2.3-2.5) caused an along-front surface layer outflow from the Gulf water outward in the upper layer.

Here I assumed the occurrence of the S-form frontal boundary which is directed to the West near the Cape Kolka, to the southwest in the strait and to the northwest outside. On the other hand the structure of currents and its variations are much more complicated than those under the geostrophic assumption due to the narrow and shallow (with no uniform topography) sound and existing inertial and diurnal oscillations (see Lilovert; Raudsepp, present report).

Because only one of the external factors controlling the position and shape of the Irbe Front has temporal changes, their variations are fully determined by the inflow of buoyancy. Buoyancy fluxes are determined by the river runoff and atmospheric forcing (heat fluxes and wind forcing). Most important variations and response time of the front to the changes in the river runoff and heat fluxes from/to the atmosphere (including direct radiation) have seasonal time-scale. Water input to the Gulf from the rivers has its maximum in the spring. Thus we could expect the most outward position of the front during spring and early summer. This was the case on the basis of the last year measurements - the surface front was situated outside of the Strait in the Baltic Proper only during the survey in May.

Heat fluxes through the water surface lead to the growth of buoyancy during the warm seasons and to the reducing of buoyancy during the cold seasons. According to that the front was sharper in May and August, and wider in November and January. By existing of developed seasonal thermocline the behaviour of the frontal boundary is different in the upper layer from that in the deeper layer. The surface layer reacts to the direct wind forcing, but currents in the deeper layer have compensating character. Therefore, the inclination of the frontal boundary could be larger and the currents above and below the seasonal thermocline could have opposite directions in May and in August (see about the structure of currents in Lilovert, present report).

The wind forcing affects the shape of the frontal boundary in two manners: 1) wind-induced mixing leads to the decrease of buoyancy and sharpness of the front; 2) along-front component of winds produces a movement of frontal boundary - winds opposing the geostrophic flow above the inclined front tend to flatten its shape (Chanady, 1978). The first of the mentioned effects could be one more reason why the surface front was wider in November and January when wind velocity in average was higher than in May and August. The response-time of the frontal movement to the along-front wind component is expected to be shorter in the warm seasons (see above). This could explain the observed large extent of migration of the surface front during the warm seasons.

Last part of the current paper is dealing with the question if the observed most outward position of the surface front in May and most inward position in August were caused by local wind forcing. Presented graphs of wind direction and velocity (Fig. 5.13, 5.14) show a large variability of local wind field in the area under investigation. The response time of a front in the entrance area to the Gulf of Finland on the basis of measurements on board of R/V Aranda in 1993 was about 5 days (Laanemets, Pavelson, 1994; personal communication).

In May 1993 dominated calm wind conditions with wind speed less than 5 m/s. Only one period before the measurements (9-12 May) wind velocity was 4-8 m/s from NW. On the basis of aboard meteorological observations wind speed was less than 10 m/s from the NE to the NW during the survey. Therefore, significant winds blew from the northern directions in May. Because of the prevailing direction of the frontal geostrophic current in the upper layer from the SE to the NW winds were opposite to the current. The result is seen on the map (Fig 5.4) and section (Fig. 5.10) of salinity - the position of the surface front was outside of the Strait and the frontal boundary was considerably inclined.

In August dominant wind direction was from the SE to the W with speed about 3 - 8 m/s before the measurements period (10-16.08). During the survey winds from the SW direction

prevailed with speed 4-11 m/s. Thus winds were across the front with small along front component in the same direction as the geostrophic current. It seems, that was a reason for the observed most inward position of the surface front. However the response of the front to the different wind conditions needs more detailed measurements.

5.5 Conclusions

Four seasonal surveys of the Irbe Front were carried out in 1993/1994. The mean position of the front was found to be in the central part of the Irbe Strait. The front was sharper during the warm seasons and wider during measurements in November and January. The comparison of data of the hydrographic surveys and current measurements detects the occurrence of along-front current according to the geostrophic assumption. Observed migration of the surface front can be explained partly by the seasonal changes in the river runoff and by the response of the front to the local wind forcing. The latter explanation is preferred, but more detailed measurements, which should be supported by sea level and meteorological observations, are needed for further conclusions.

References

- Csanady, G.T. 1978. Wind effects on surface to bottom fronts. - *J.Geophys.Res.*, Vol. 83, No C9, pp. 4633-4640.
- Rodhe, J. 1992. The water masses of the Skagerrak, dynamics and large-scale mixing. - *Report no 52, Dept. of Oceanography*, University of Gothenburg, 50 p.
- Tang, C.L. 1983. Cross-front mixing and frontal upwelling in a controlled quasi-permanent density front in the Gulf of St. Lawrence. - *J.Phys.Oceanogr.*, Vol. 13, pp. 1468-1481.

SCHEME OF STATIONS

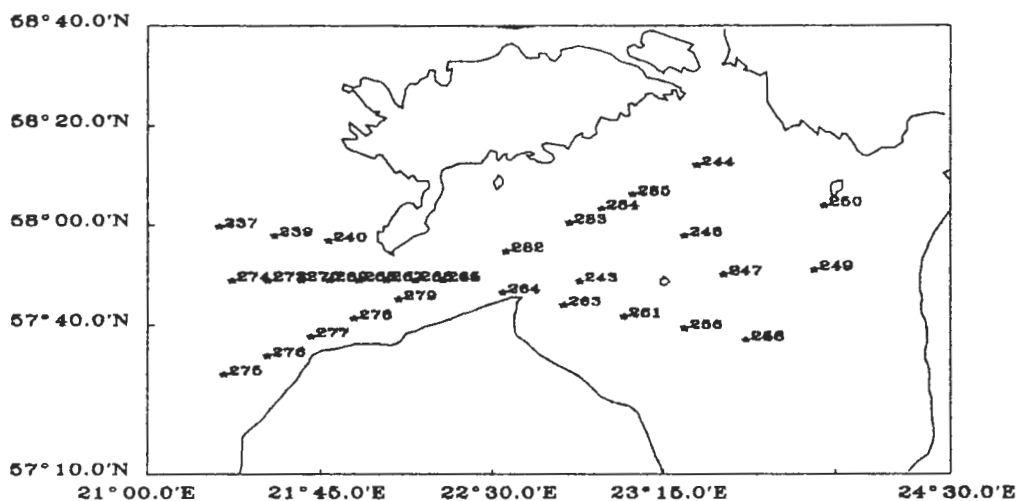


Fig. 5.1. Scheme of monitoring stations and transects in the Gulf of Riga area performed during the cruises of R/V "Orbiit" in May, August and November 1993.

SCHEME OF STATIONS

27-28.01.1994

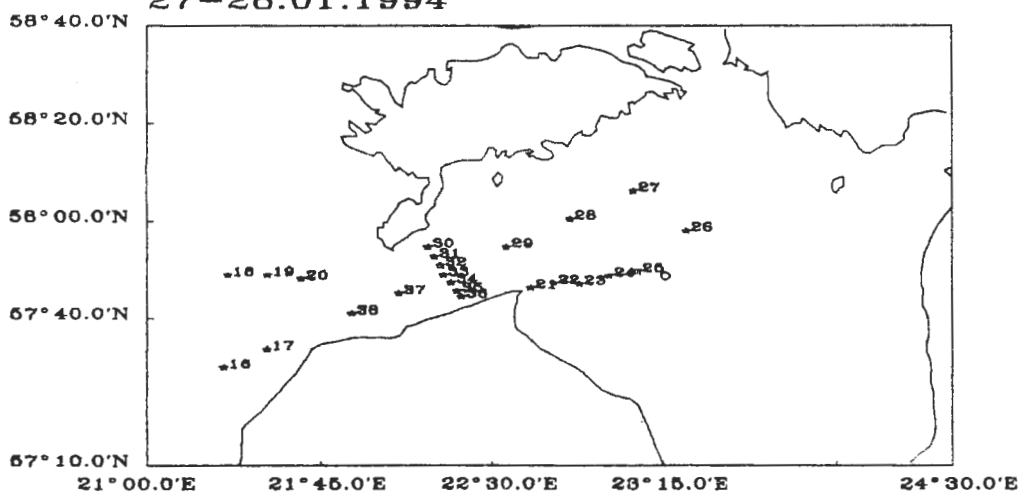


Fig. 5.2. Scheme of transects in the Irbe Strait performed by R/V "Argos" in January 1994.

Section of SALINITY
16-17.03.1993

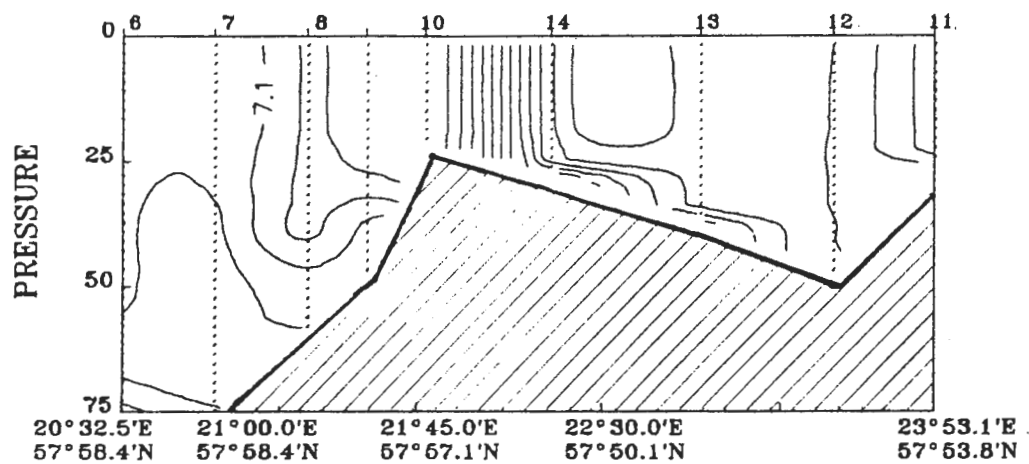


Fig. 5.3. Section of salinity from the Baltic Proper to the eastern part of the Gulf of Riga on the basis of ordinary monitoring data.

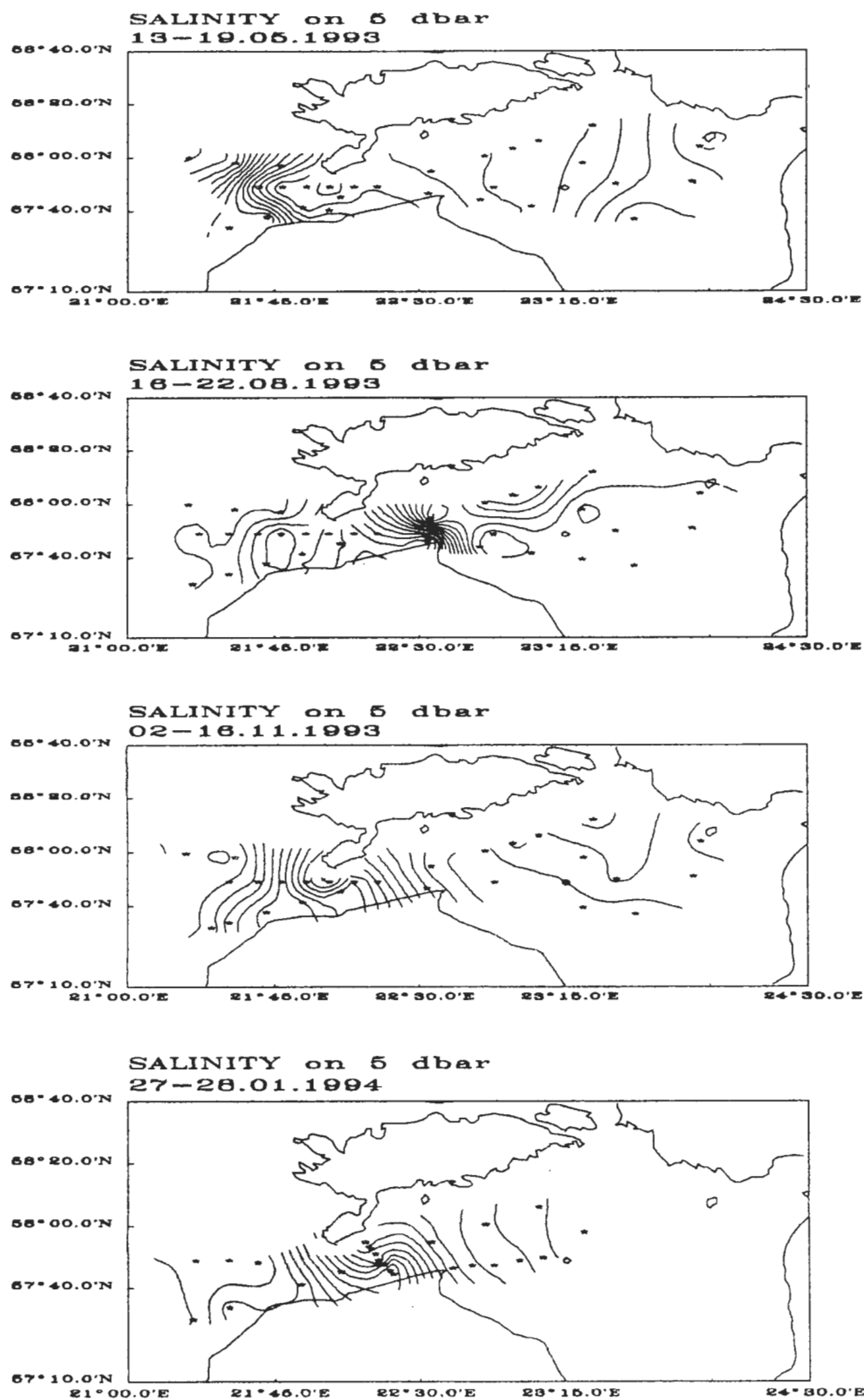


Fig. 5.4-5.7. *Location of the Irbe Front in the surface layer during four seasons.*

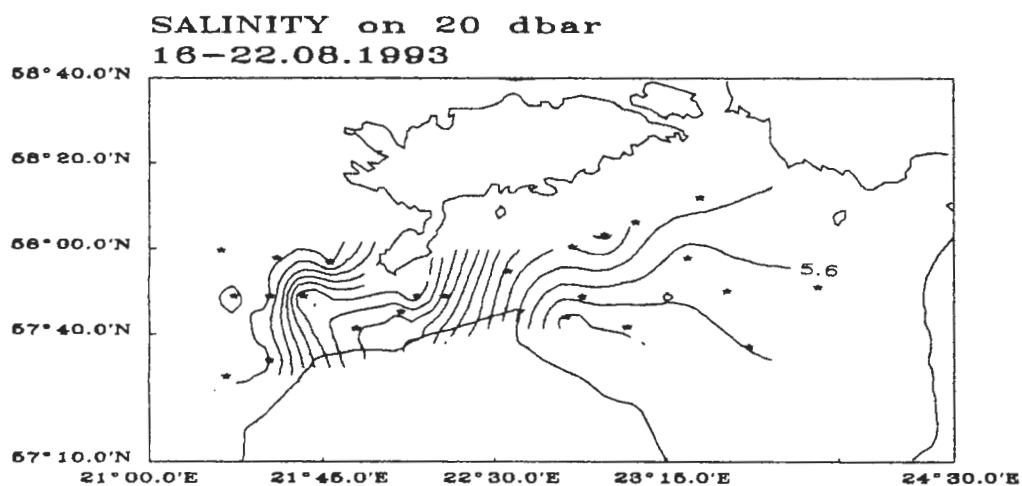
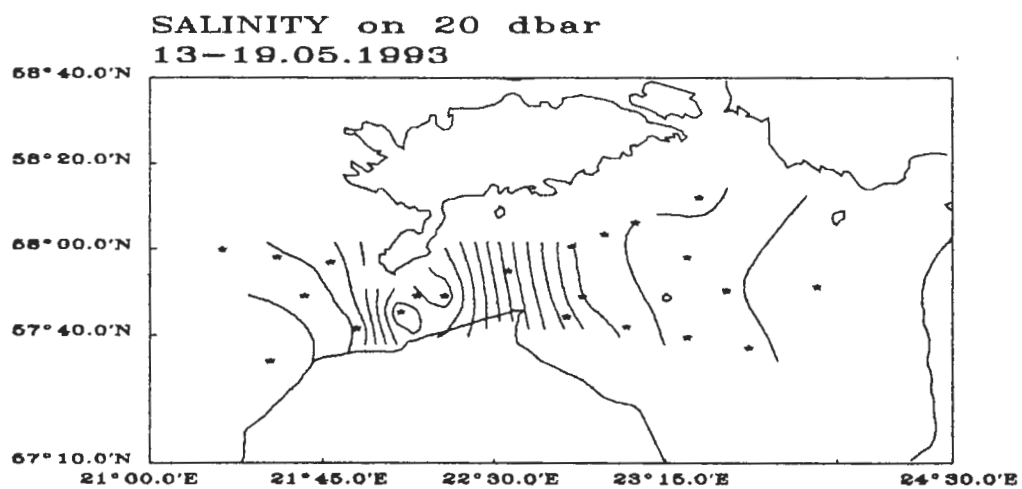


Fig. 5.8-5.9. *Location of the Irbe Front in the deeper layers during the warm seasons 1993.*

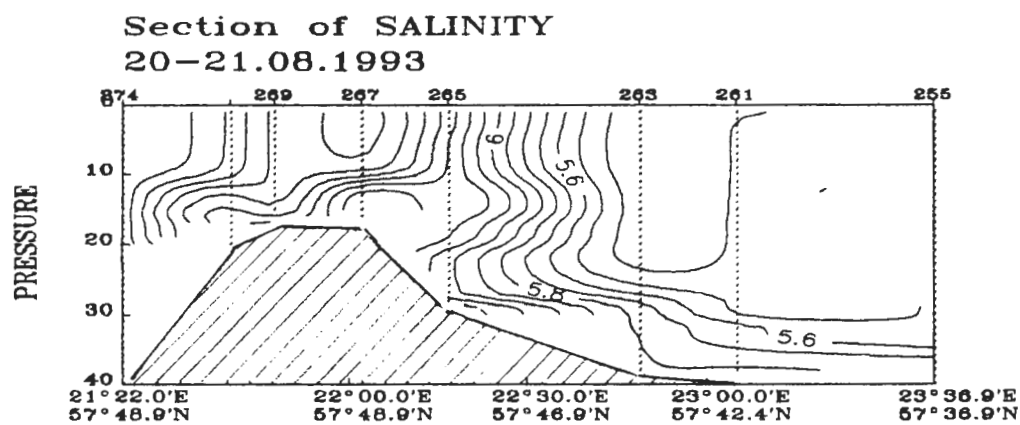
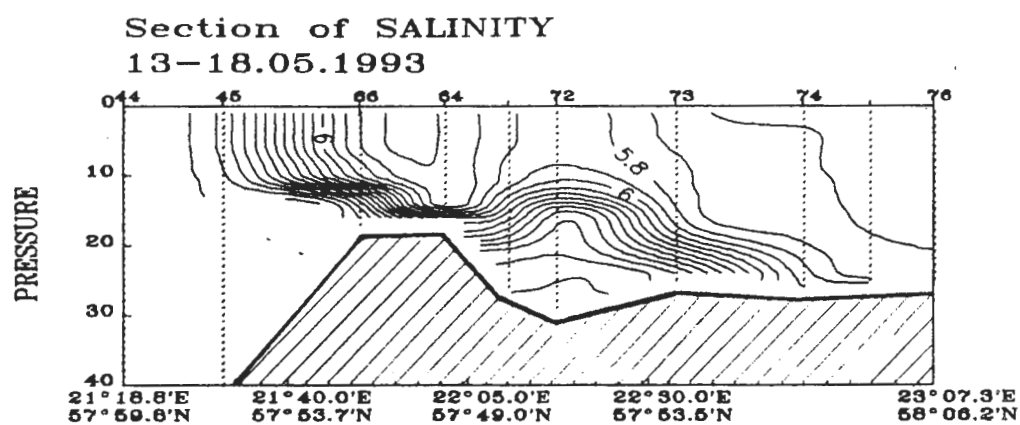


Fig. 5.10-5.11. *Vertical sections of salinity through the Irbe Front.*

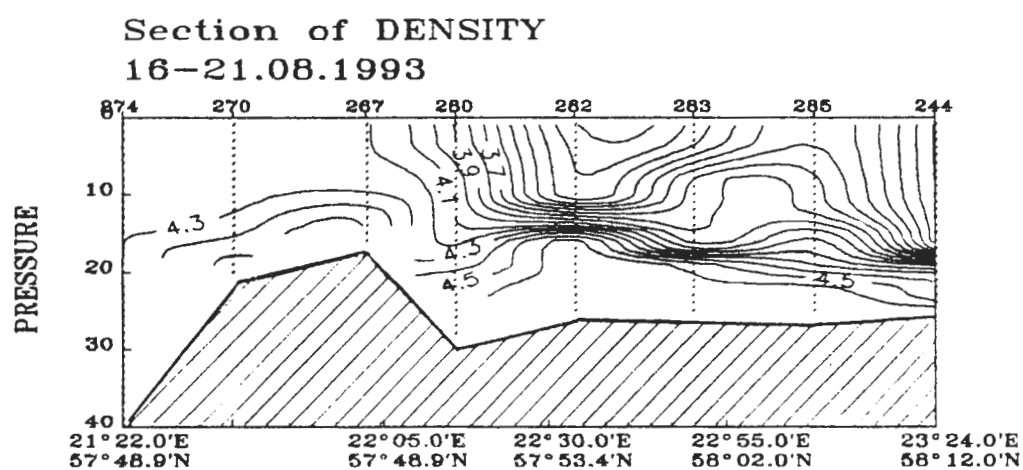


Fig. 5.12. *Vertical section of density through the Irbe Front in August 1993.*

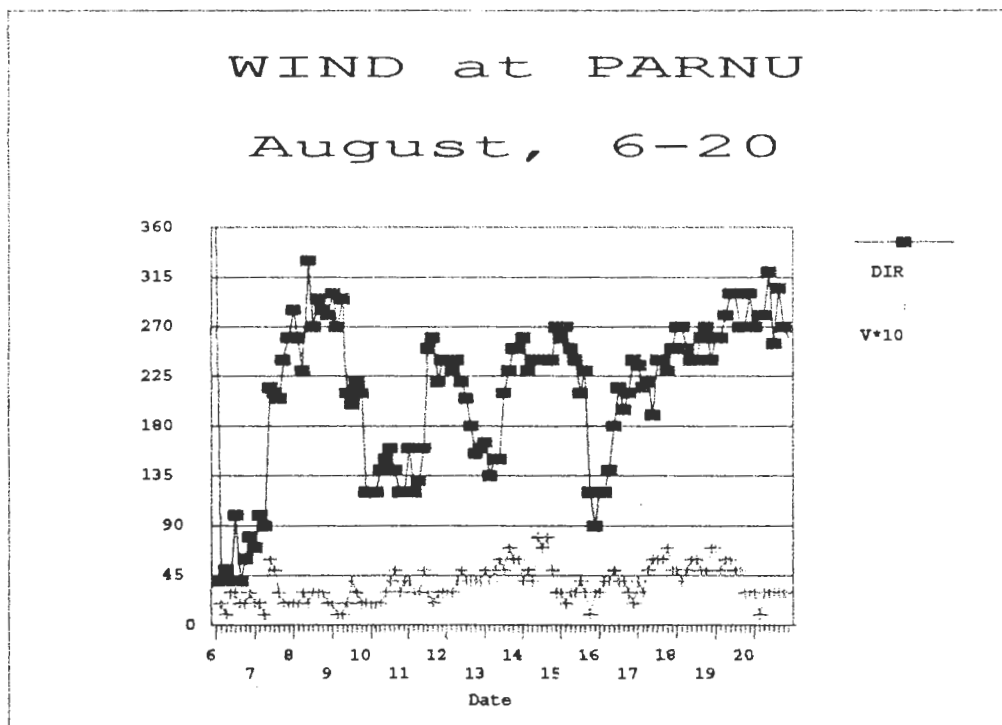
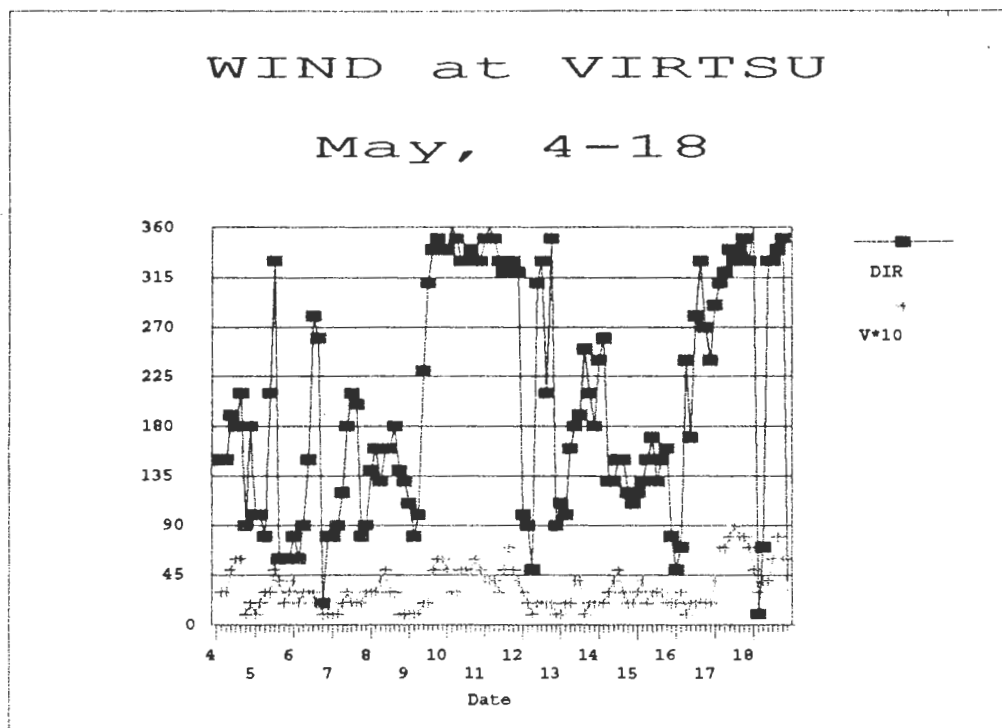


Fig. 5.13-5.14. *Winds before and during surveys in May and August 1993.*

6. Variability of near-bottom current properties in Gulf of Riga

by Tarmo Kõuts (Estonian Meteorological and Hydrological Institute)

6.1 Introduction

Most ecosystem models, built to study the functioning of the marine environment, take into account the resuspension part, which quite frequently is based on some averaged value of about the near-bottom currents. Questions of interest are mostly concerned with variations of bottom shear flow intensity and vertical shift of the current speed in near-bottom layers. The near-bottom shear flow is an important component of driving the turbulence. Turbulent flows cause resuspension of different materials from the upper, floating, layer of the bottom sediments. Knowledge of processes driving the near-bottom resuspension of materials are quite limited so far in the whole Baltic Sea region, specially is relevant experimental evidence lacking.

The same circumstances hold for the Gulf of Riga, where extensive ecosystem modelling is planned for coming years. However, reliable direct measurements of near-bottom current properties in the Gulf is not available.

The water renewal of deep layers in the Gulf of Riga is not available, when seasonal thermocline occurs, take place by horizontal advection of dense bottom currents. Saline water, intruding into the Gulf is originating from the surface layer of the Baltic Proper.

Below will be presented the first outline of the near-bottom current measurements in the Gulf of Riga.

6.2 Measurements

Two series of current measurements in the near-bottom layer of the Gulf of Riga were performed in 1993, both approximately one month of length. The deep current properties were recorded in the Ruhnu Deep (deepest part of the Gulf of Riga, maximum depth about 55m and is situated near the island Ruhnu). Position of the mooring station was same in both cases - 57°35.5N and 23°37.1E (see Fig. 6.1).

Two SENSORDATA current meters were deployed. Technical capabilities of the current meters allowed the recording of the current speed and direction with time resolution 4min, where n is set up before the start of recording and every recorded parameter is averaged over time interval n·4min. Additionally on both current meters the thermistors were mounted, which allowed to record the sea water temperature at the site of the current meter.

The mooring station was of fully undulated type (see Fig. 6.2) and current meters were placed 2m and 4m above the sea floor, where the full depth was about 53m.

Periods of current recording in the Ruhnu Deep were the following:

- 1) July 14. - August 15, 1993.
- 2) September 8.-October 12, 1993.

6.3 Variability of near-bottom current properties

The currents at the site of the mooring station was mostly directed to the south or south-east in the near-bottom layer during both measuring periods (see Fig.-s 6.3 and 6.11). Only during shorter periods, the near-bottom current in Ruhnu Deep turned northwards. From the current roses one can observe that the current direction at 4m above bottom was slightly tilted to left

compared to currents 2 m above bottom during the first period and to right during the second period, however angle resolution of current meters was only 15 degrees. Southward transport of water is clearly shown also on the graph of progressive vector diagrams of the currents during both periods (see Fig.-s 6. 8 and 6.16) as well on the vector stickplots (see Fig.-s 6.6 and 6.13). About two times higher mean current speeds during the second period. Wind conditions over the area showed that in July-August prevailed southern winds and in September-October mostly north eastern winds. Wind speed was quite low during both periods, only at the end of July the wind speed once increased to about 12 m/s (see Fig.6.7). Then in September-October the wind speed ranged below 10 m/s. Preliminary inspection of the vector plots of wind and current shows that there is no correlation between the wind and the current directions.

Below is presented the description of both time series of the near-bottom current.

First current recording, July 14 - August 12.

Current speed varies from values below 2 cm/s (lower sensitivity range of current meter) up to 18 cm/s at 4m above bottom and 15 cm/s at 2m above bottom, ranging mostly however below 8 cm/s. Remarcable increase of current speed took place between 25 and 29 July, from about 4 cm/s to 18 cm/s, which should be quite a rare event for a layer so close to sea floor. If inspecting the air pressure time series in the area (see Fig. 6.9) one can observe that this event is accompanied with passing of a low-pressure (below 990 hPa) system, which lasts about two days and induces firstly the strong northern and then in the next day the strong southern wind (see Fig. 6.7). After such quick fluctuation, the situation in the atmosphere went back into the state like before the event. As passing of the low-pressure usually causes also the change of the sea level, it is evident that sea level difference between the northern and southern parts of the Gulf occurred. The water body immediately responded to the forcing and near-bottom currents which before flowed continuously to the SE, took opposite direction (to the NW) and the current speed was remarkably increased. After the passing of the low-pressure system, the current turned back to the previous direction preserving high current speed for about four days, which was about two times quicker than it took the low-pressure to pass the area. A singular atmospheric fluctuation induced the fluctuation in the near-bottom current system, which in total lasted three times longer than the atmospheric fluctuation itself. After the low-pressure event the current speed went down (below 5 cm/s) and fluctuated on place, changing the direction after every 1-3 days, until the end of measurement period, August 12.

Second current recording, September 8 - October 13.

Near-bottom currents was about two times as intensive in September than during the survey in July-August. Current speed at 4m above bottom several times reached values 20-25 cm/s. Similarly to the first period current variability pattern can be observed from the progressive vector diagram of currents, both 2m and 4m above bottom (see Fig. 6.16). Although such strong low-pressure as in July was not observed in September, the passing of less intensive low-pressures induced similar fluctuations of near-bottom current. Scheme is generally similar to that, recorded in July-August, when the passing of the low-pressure induced the change of continuous current direction from the SE to opposite (the NW). After the low-pressure passed, the current turned back to the SE and restored its previous high speed. Characteristic time interval of occurrence of low-pressure passages was observed to be 9-10 days, which is typical synoptic time scale of atmospheric processes on the latitudes of the Baltic Sea.

6.4 Water renewal processes in the near bottom layer

Sea water temperature in near bottom layer of the Gulf of Riga at the site of mooring station was measured simultaneously with current properties. The obtained two time series covering both observed periods are presented in Fig.-s 6.10 and 6.18. During the first measurement period (July-August) the temperature variations of about 1.5 to 2.0°C were observed in deep layers. Southward currents carried a water mass with characteristic temperature of about 3.5-4.0°C, then after turning to the NW it carried colder water with temperature 2-2.5°C. That indicates that north from the mooring station warmer and south colder deep water was placed permanently. As the lower temperature shows more stagnant conditions, one can conclude that the mooring station was situated at location where a renewing of the stagnant near-bottom water occurs. Data from the second survey show the increase of deep water temperature by about 1°C, which is the result of continuous advective supply of warmer water and relevant mixing. Similar results to the case observed in July, when northward current tends to be colder one, comes out from data measured in September-October. Some rapid temperature variations take place at the end of second measurement period, which shows that the border between near bottom cold (about 3°C) and warmer (about 4-4.5°C) deep water was situated nearby the site of the mooring station. This distribution also can be observed from the deep layer temperature map (see Chapter 1 of the current report). The correlation between variability of current properties and sea water temperature changes was evident, but some delay was observed before temperature regime in near-bottom layer responded to current variation and this response time was estimated to about 12-16 hours, the corresponding length scale in temperature is estimated to about 6 - 7 km.

6.5 Conclusions

Measured time series of deep current properties showed that during both periods active displacement of water masses in near-bottom layer took place quasipermanently. Estimated current direction was in both cases mostly southward, however under conditions of atmospheric forcing it changed to the opposite and was restored again after passing of air pressure fluctuations. Speed of deep current was mostly beneath 8 cm/s in July-August and 15 cm/s in September-October, being thus about two times higher during the second period. Peak values of the near-bottom current velocity, which occurred under certain atmospheric forcing were much higher - up 18-20 cm/s in July and 20-25 cm/s in September-October.

This report is the first presentation of these data and it seems that additional analysis is needed on the described dataset, but as there are planned some additional similar measurements in the near future, then these will be analysed together furthermore. It should be valuable to include some sea level data into the dataset and to perform spectral analysis of current records.

Acknowledgements

Dr. Dag Broman (Stockholm University) who managed the current meters; Mr. Mart Saarso (NOREIA Ltd.) who performed professional field operations and Mr. Urmas Raudsepp for drawing part of graphs are kindly acknowledged.

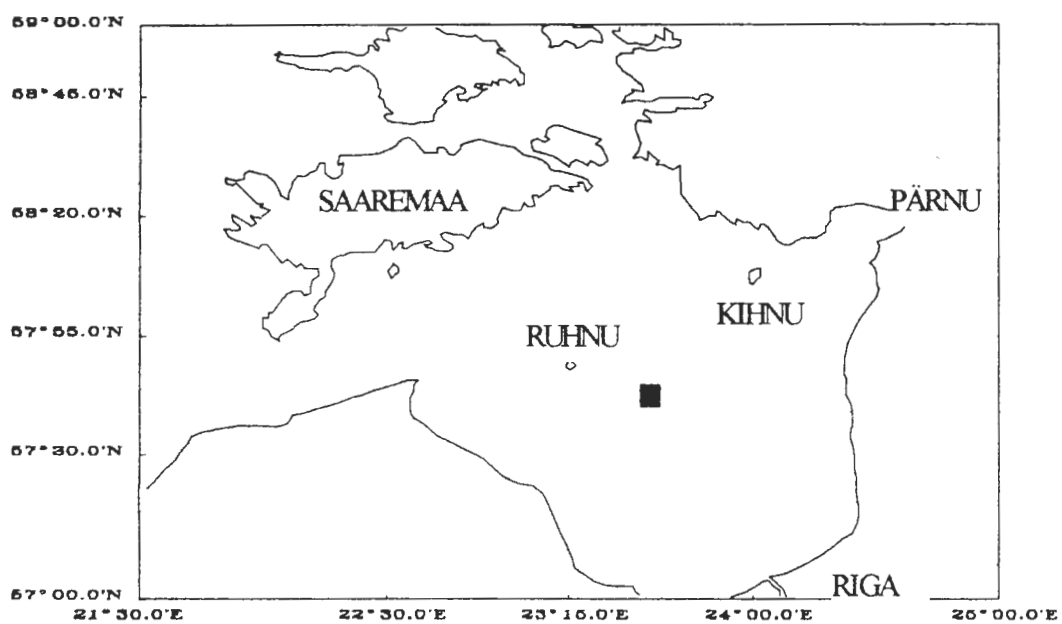


Fig. 6.1 Map of the Gulf of Riga, showing the location of mooring station, where near-bottom current measurements were performed in July-August and in September-October, 1993 (black rectangle).

Mooring system

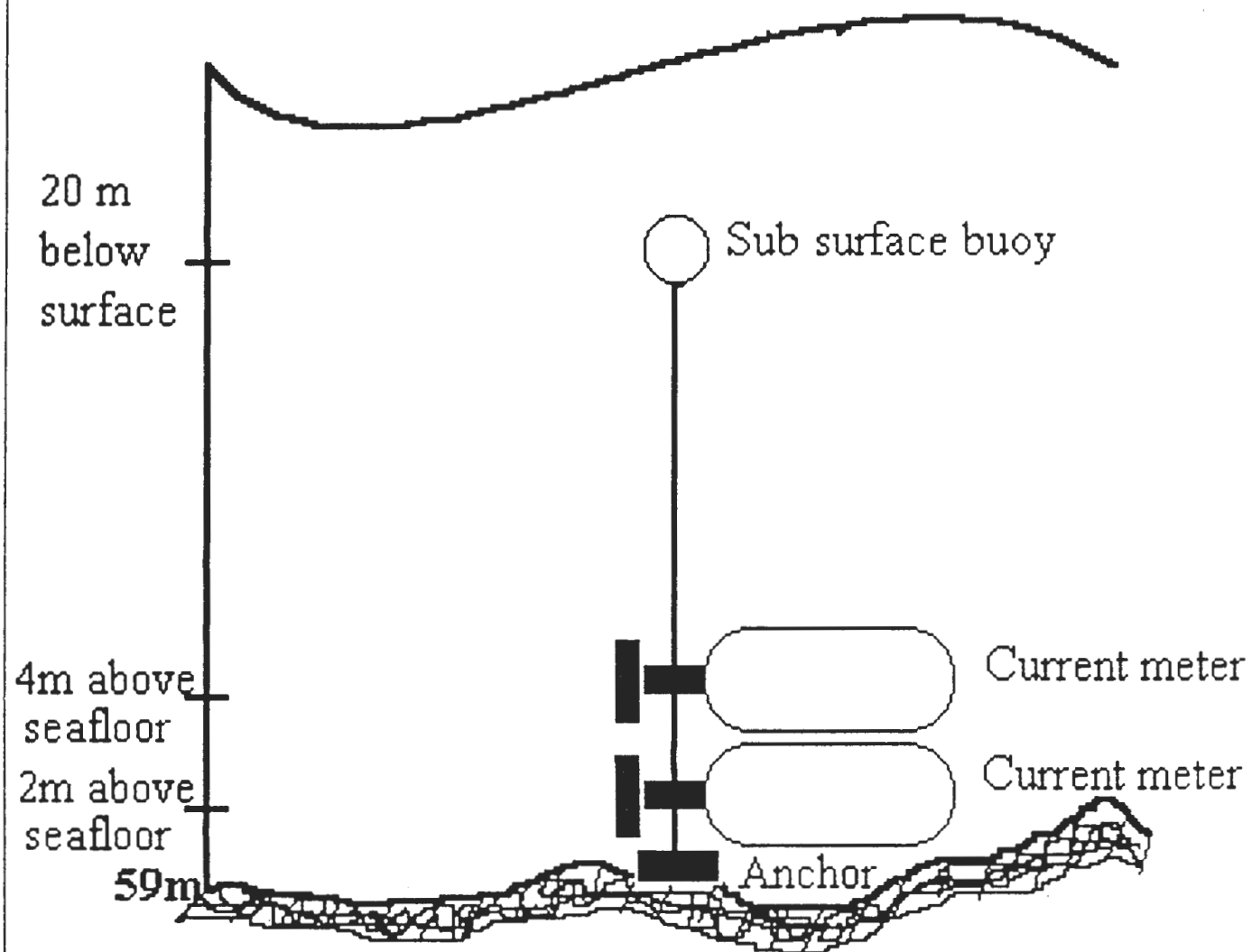


Fig. 6.2 Scheme of mooring station used for current measurements in the Ruhnu Deep

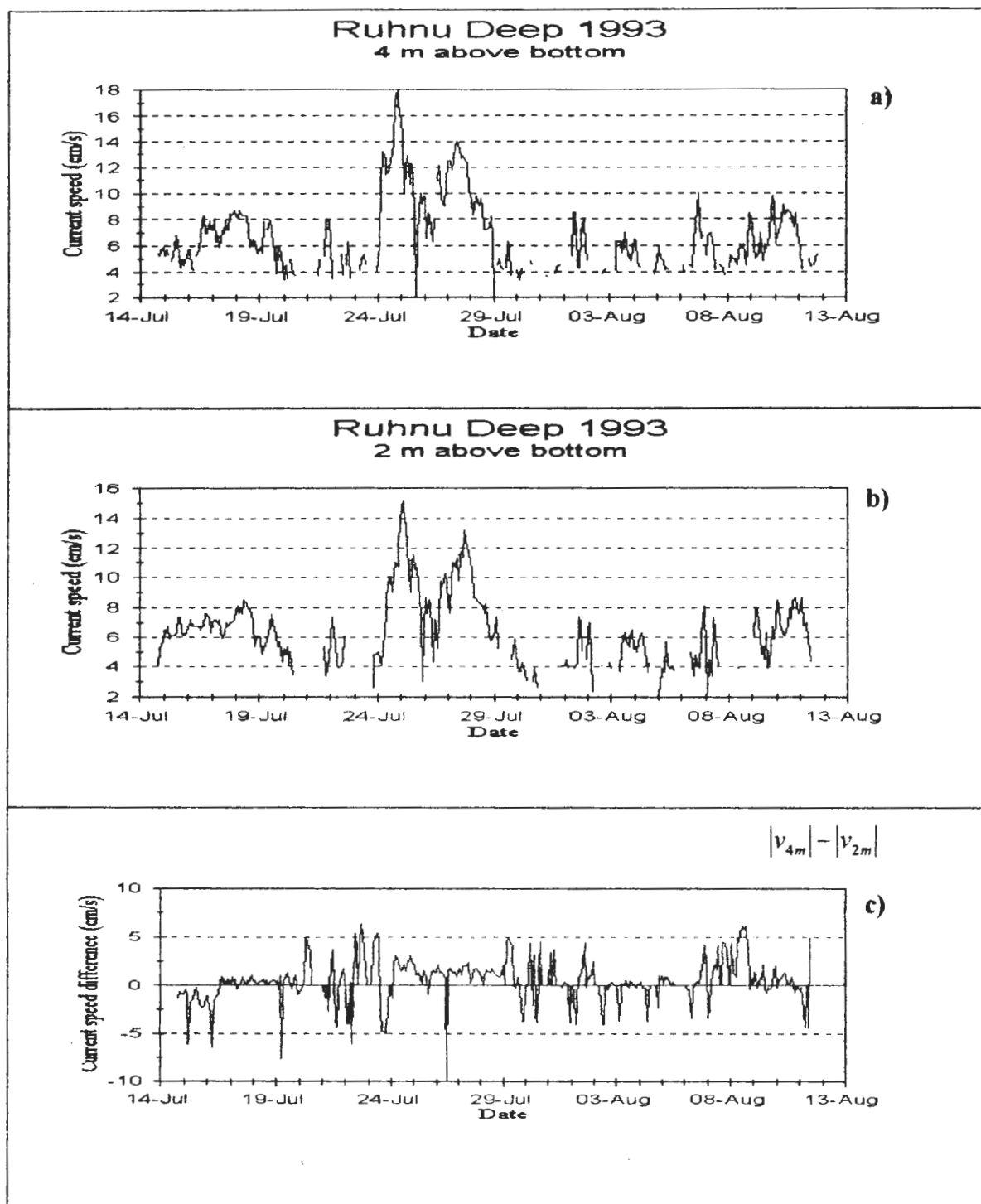


Fig. 6.3 Near-bottom current speed in Ruhnu Deep at mooring station ($57^{\circ}35.5'N$, $23^{\circ}37.1'E$) 4m (a) and 2m (b) above bottom during first measurement period in July-August, 1993. Difference of current speed between 4m and 2m above sea floor is presented on third plot (c).

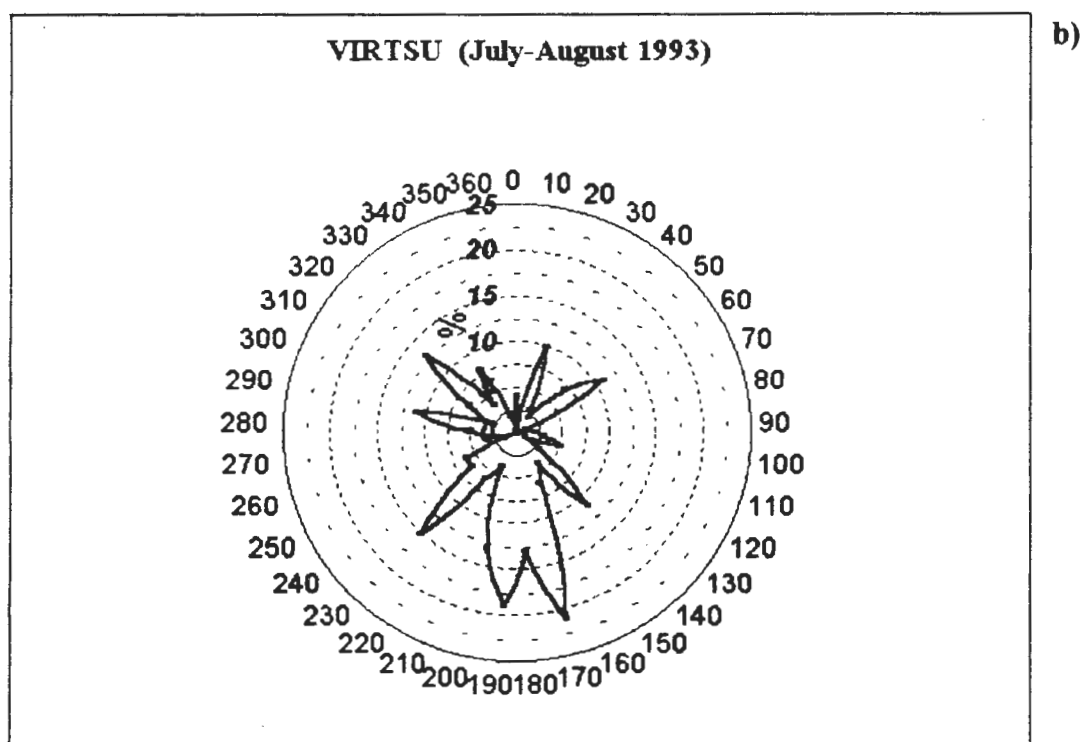
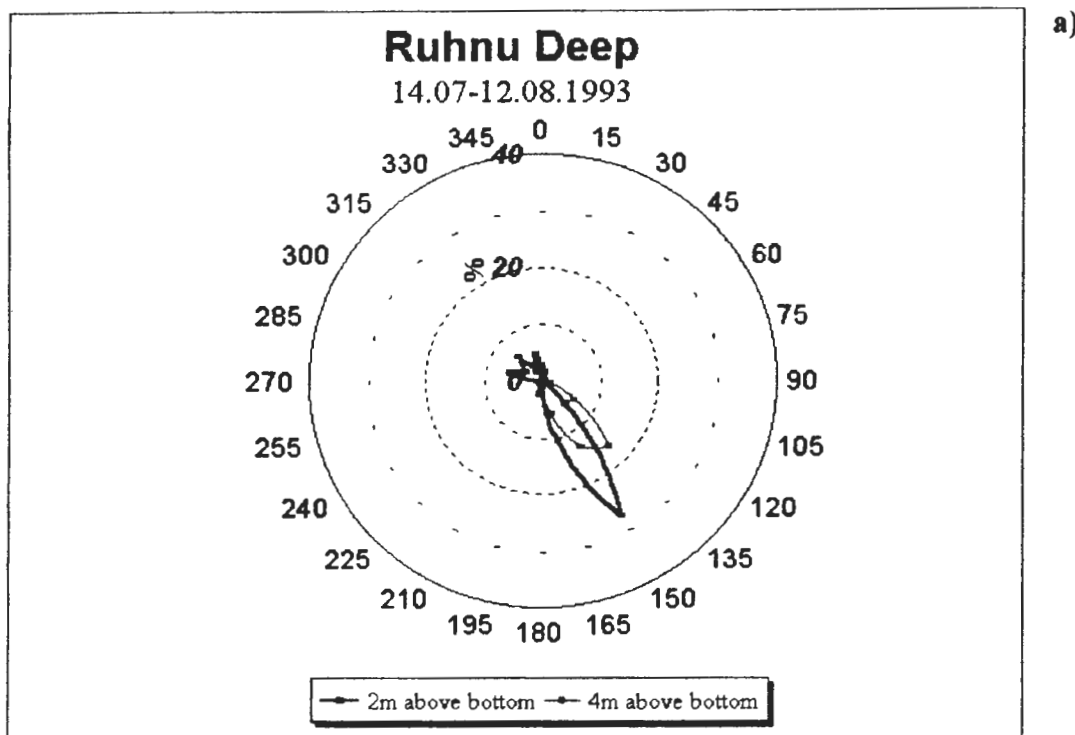


Fig. 6.4 Current roses from the near-bottom layer of the Ruhnu Deep (a) and wind rose at nearby meteorological station Virtsu (b) during measurent period in July-August, 1993

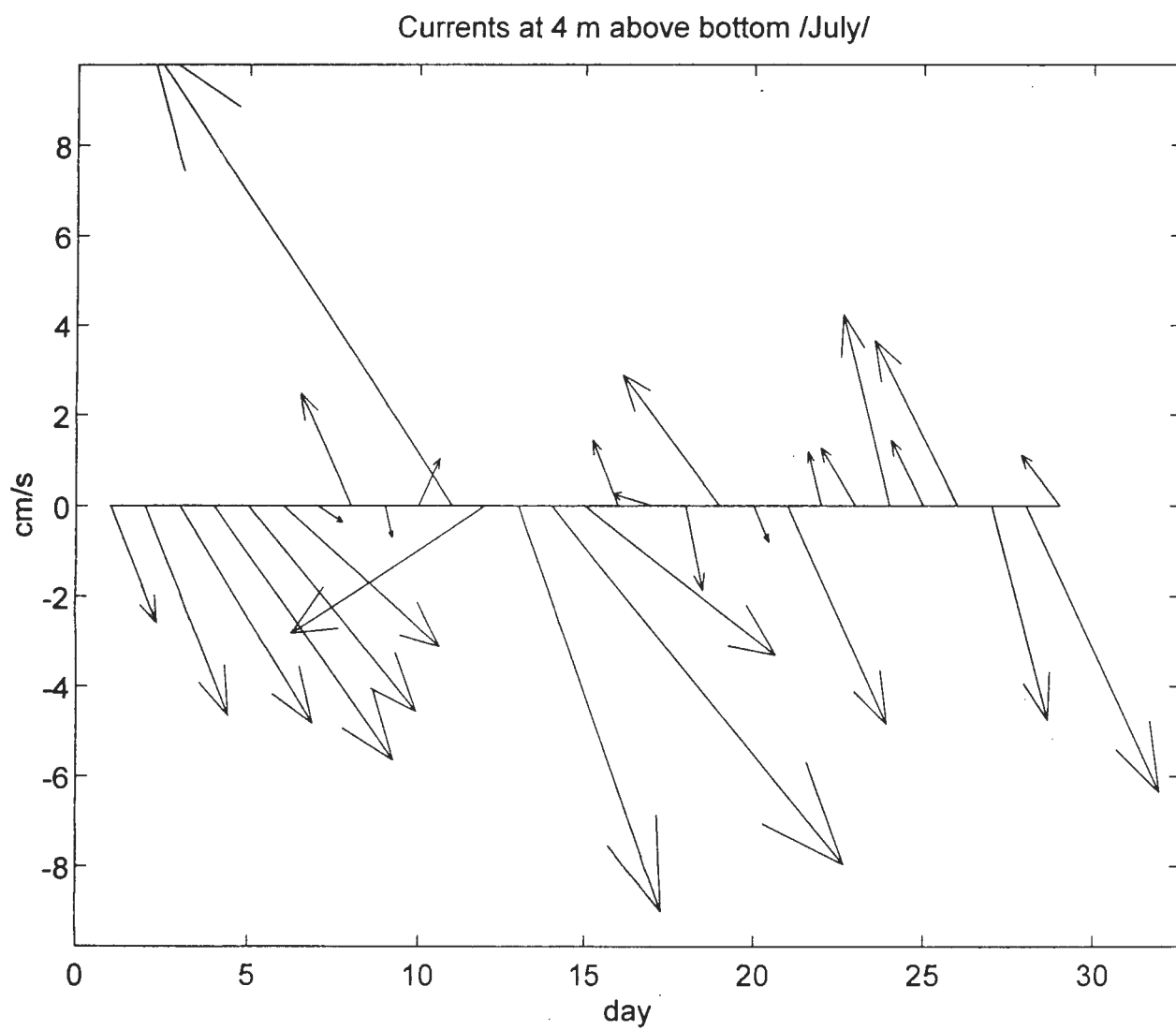


Fig. 6.5 Vector plot of daily average current speed and direction at depth 4m above bottom in July-August, 1993. Day "0" is July 14, 1993 and Northern direction is upward on the plot.

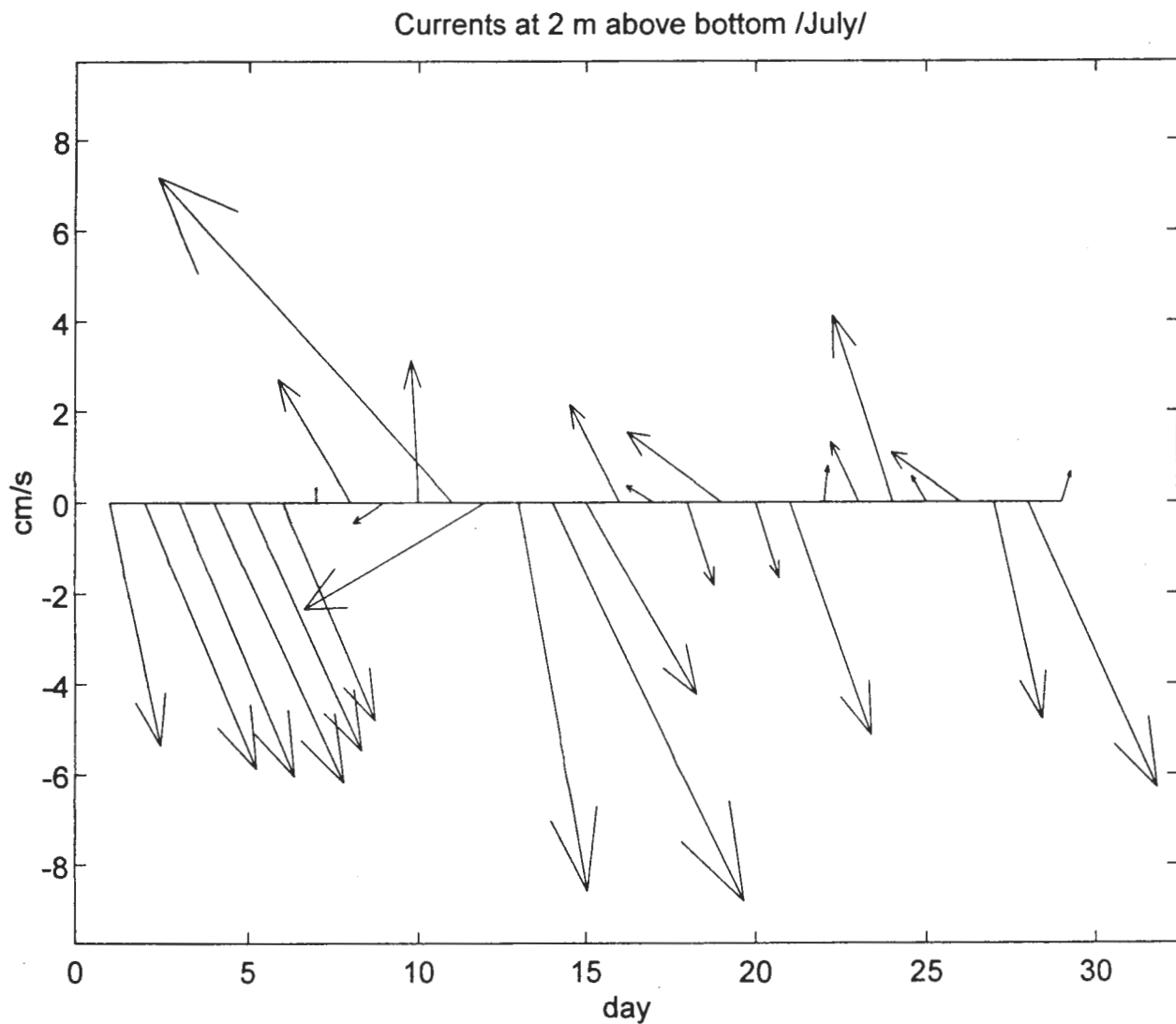


Fig. 6.6 Vector plot of daily average current speed and direction at depth 2m above bottom in July-August, 1993. Day "0" is July 14, 1993 and Northern direction is upward on the plot.

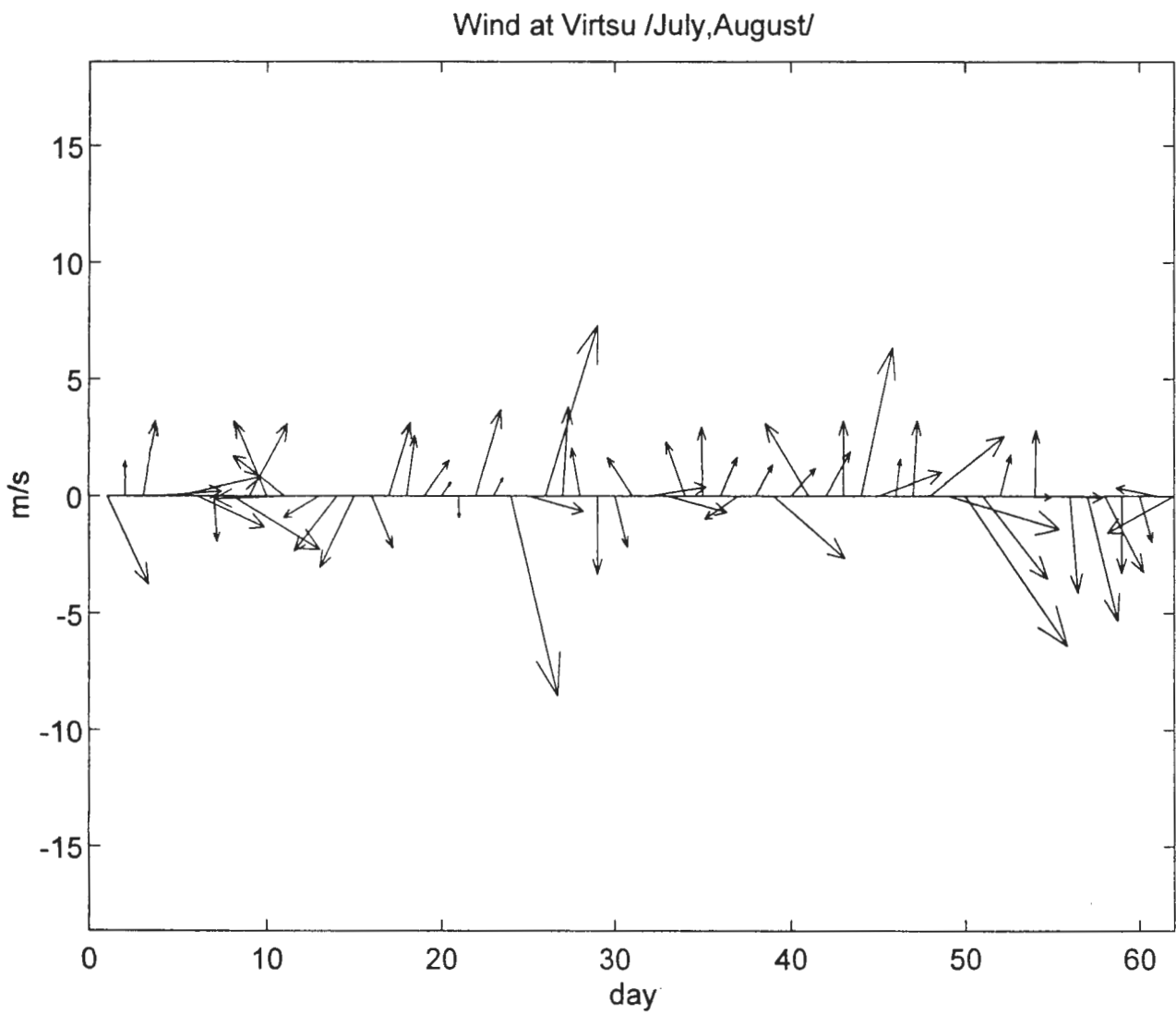


Fig. 6.7 Vector plot of daily average wind speed and direction at meteorological station Virtsu in July-August, 1993. Day "0" is July 1, 1993 and Northern direction is upward on the plot.

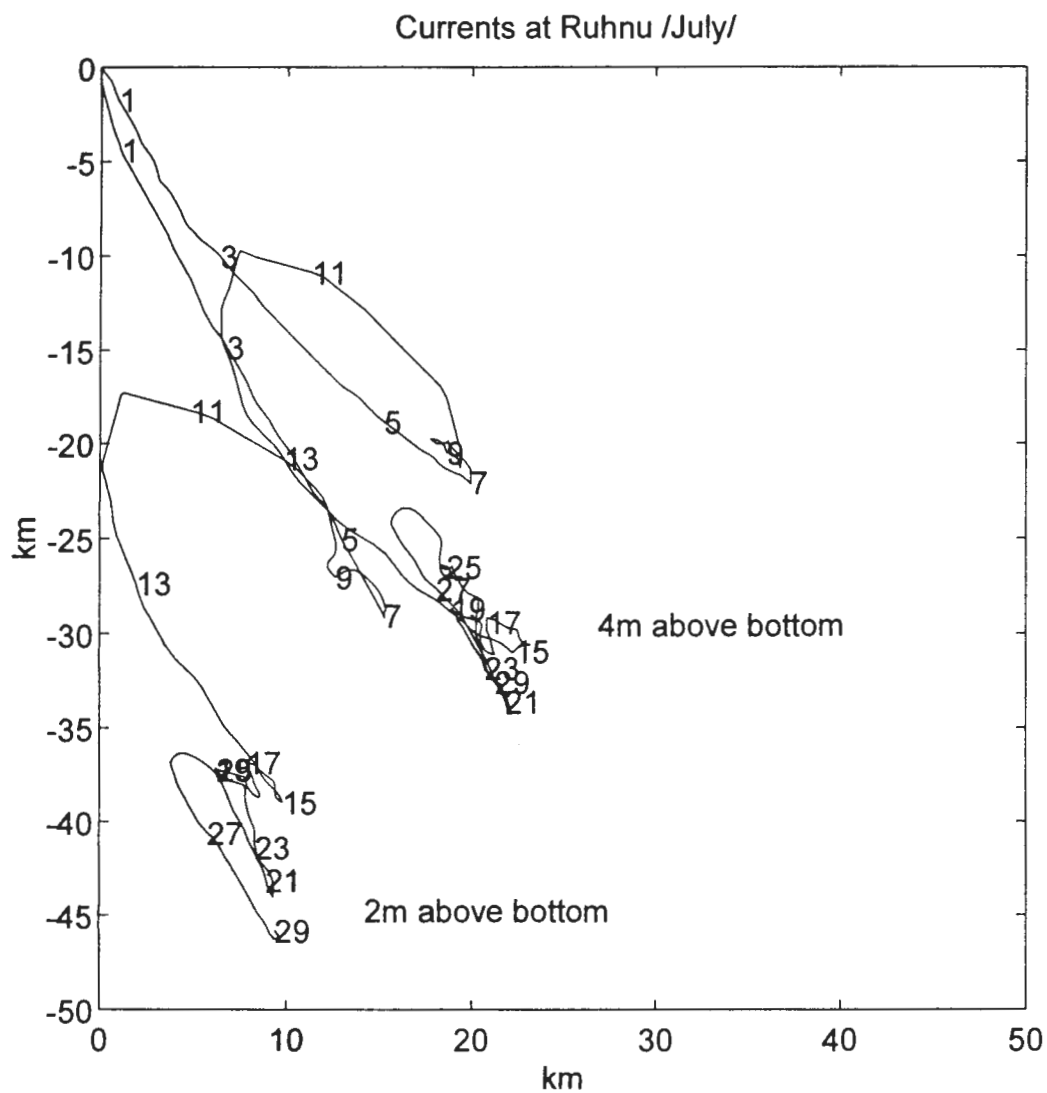


Fig. 6.8 Progressive vector diagram of observed currents in near-bottom layer of the Ruhnu Deep 2 and 4m above bottom in July-August, 1993. Day "0" is July 14, 1993 and Northern direction is upward on the plot.

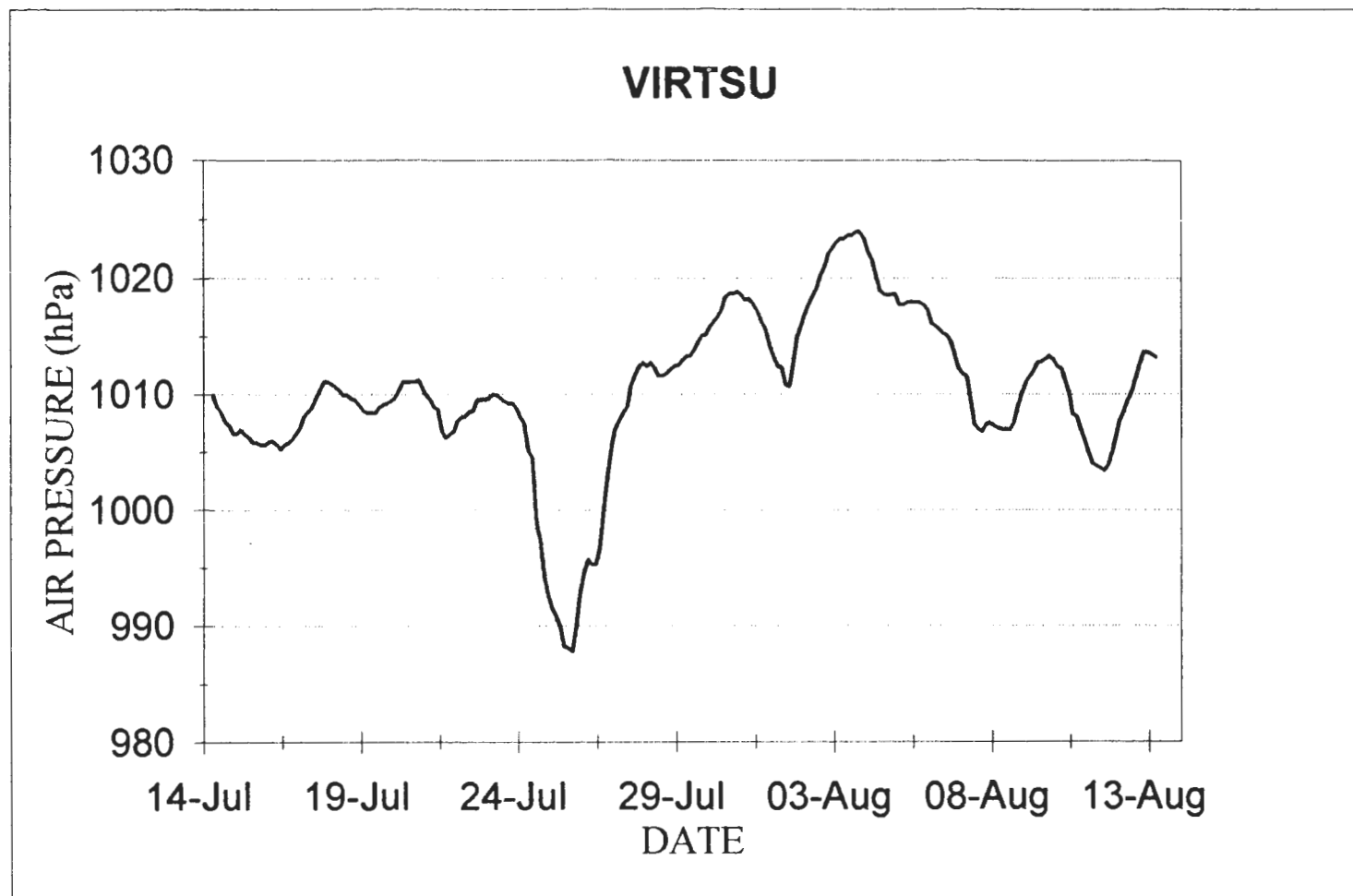


Fig. 6.9 Time serie of air pressure variations in region of the Gulf of Riga observed at meteorological station Virtsu in July-August, 1993.

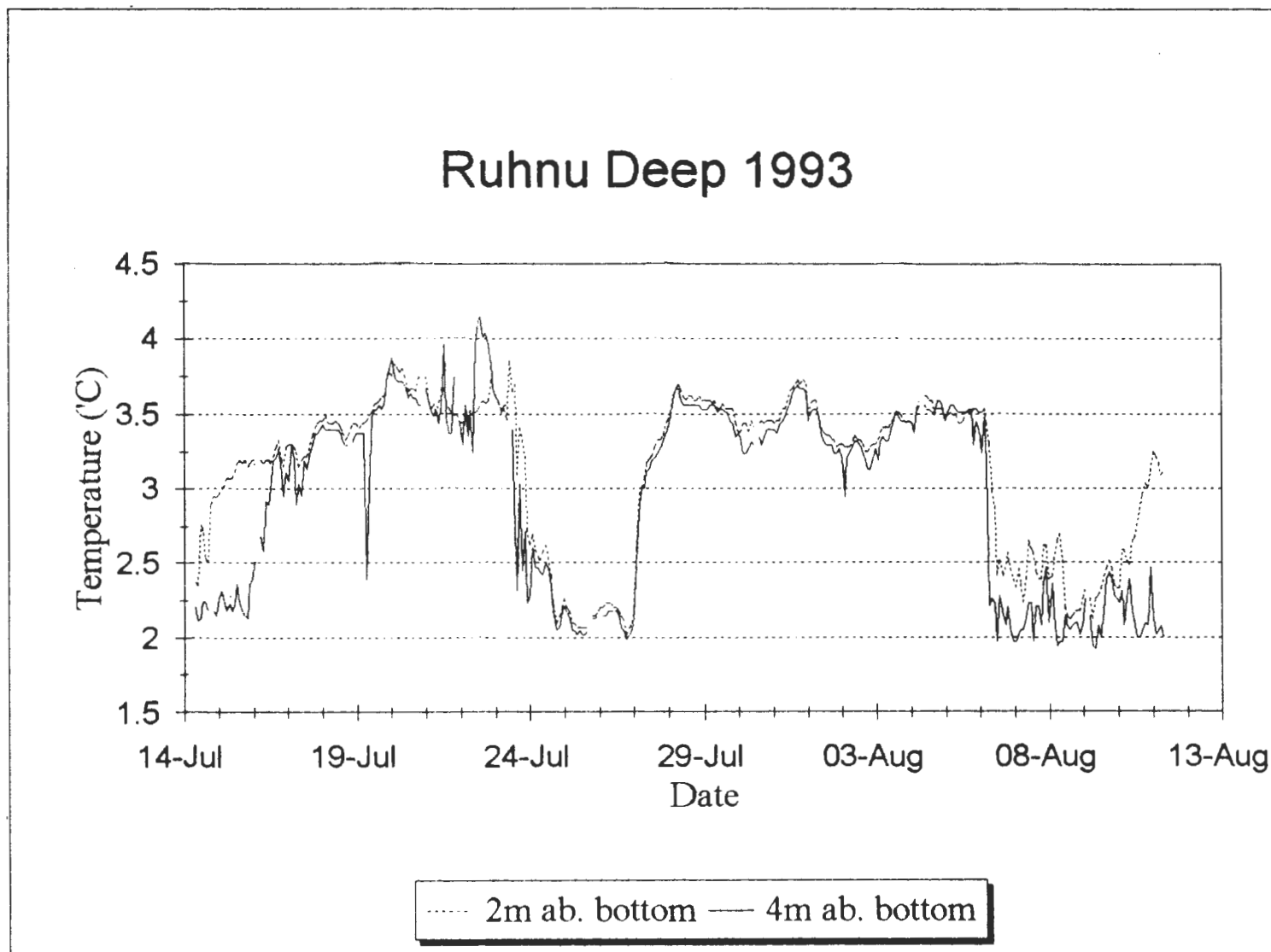


Fig. 6.10 Time serie of sea water temperature in near-bottom layer of the Ruhnu Deep (at the site of mooring station) in July-August, 1993.

Ruhnu Deep 1993 (2m.a.b)

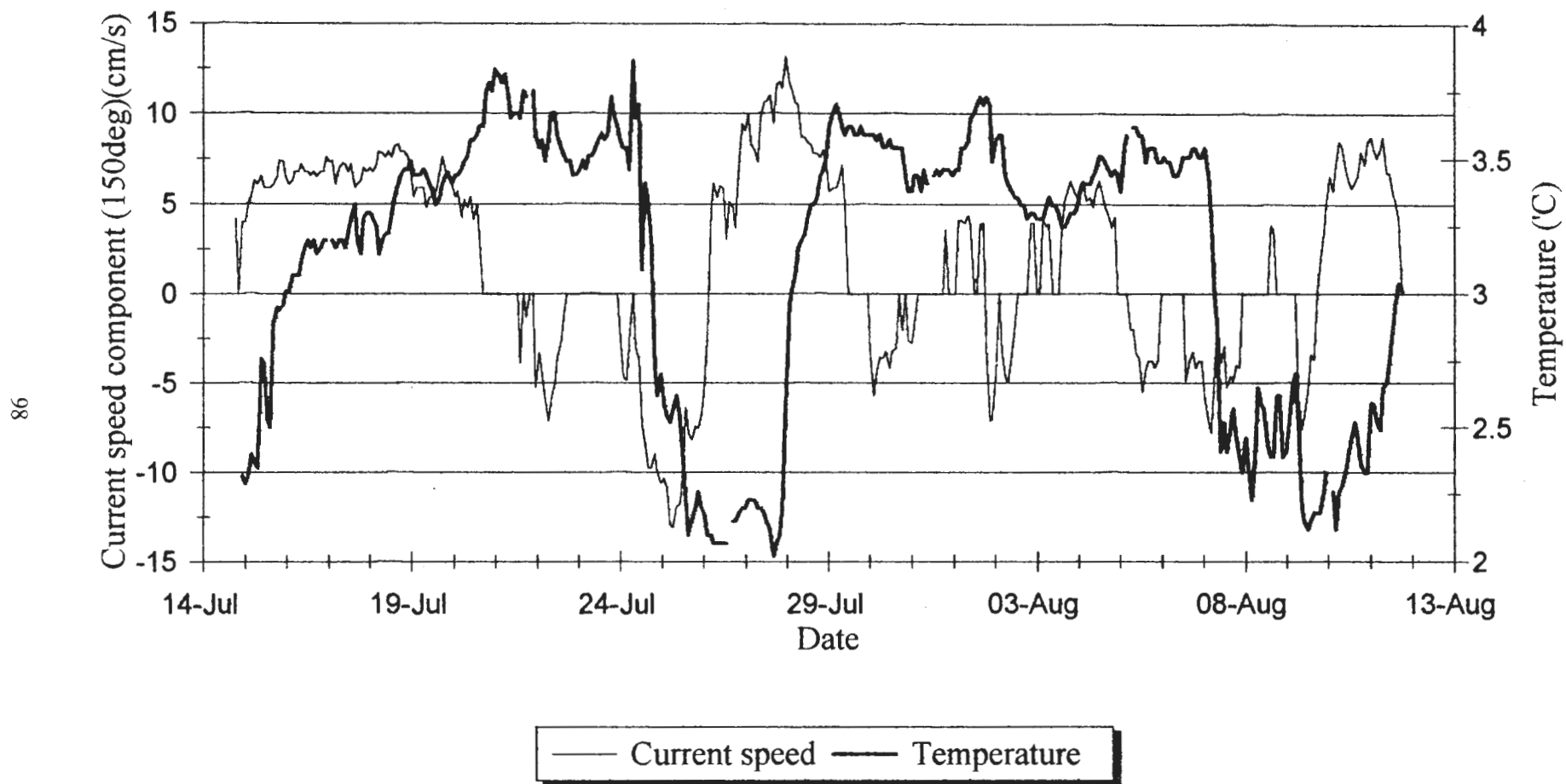


Fig. 6.10a Current velocity component projection on main direction, 150deg (thin line) together with sea water temperature (thick line) 2m above bottom in Ruhnu Deep.

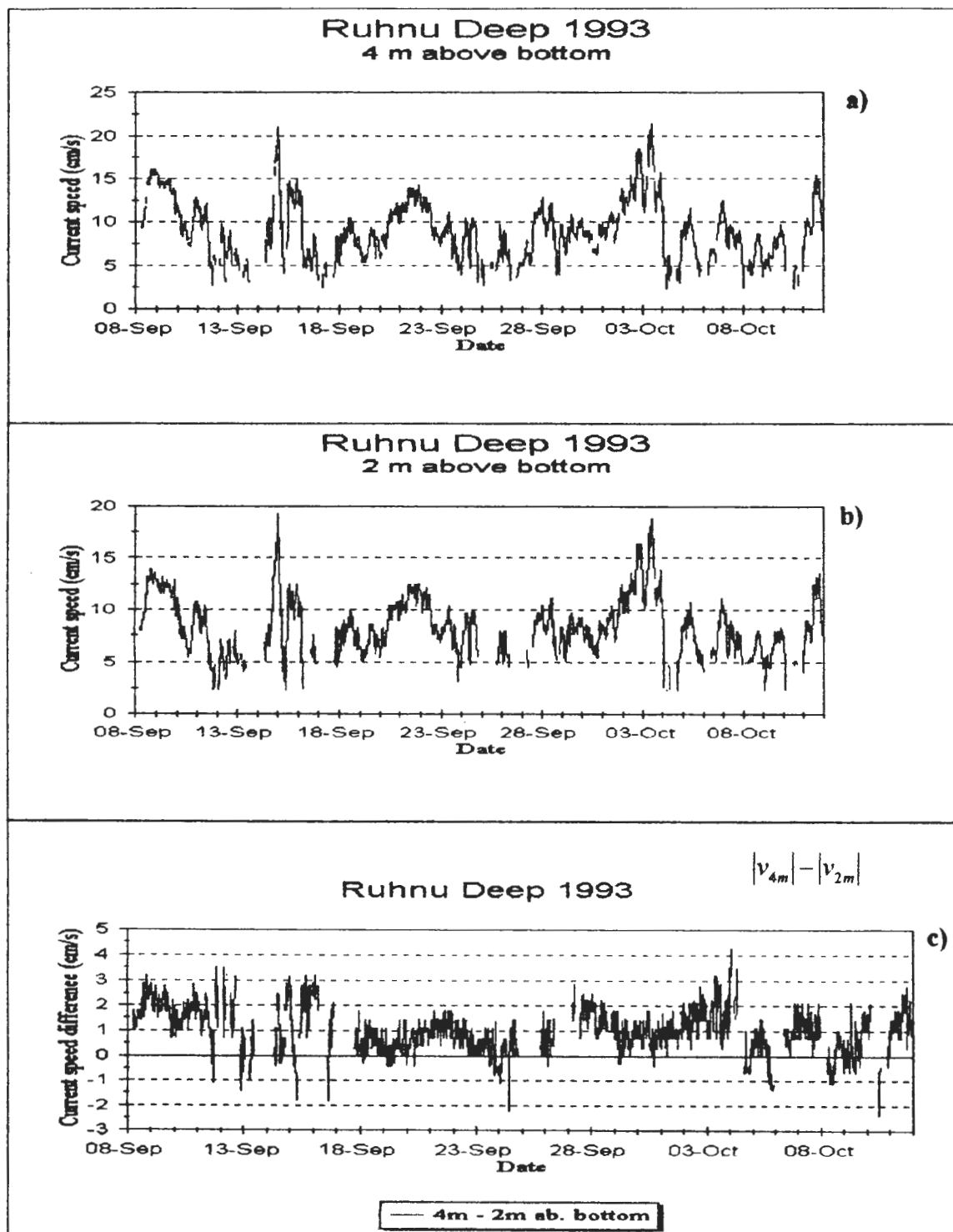


Fig. 6.11 Near-bottom current speed in Ruhnu Deep at mooring station ($57^{\circ}35.5'N$, $23^{\circ}37.1'E$) 4m (a) and 2m (b) above bottom during second measurement period in September-October, 1993. Difference of current speed between 4m and 2m above sea floor is presented on third plot (c).

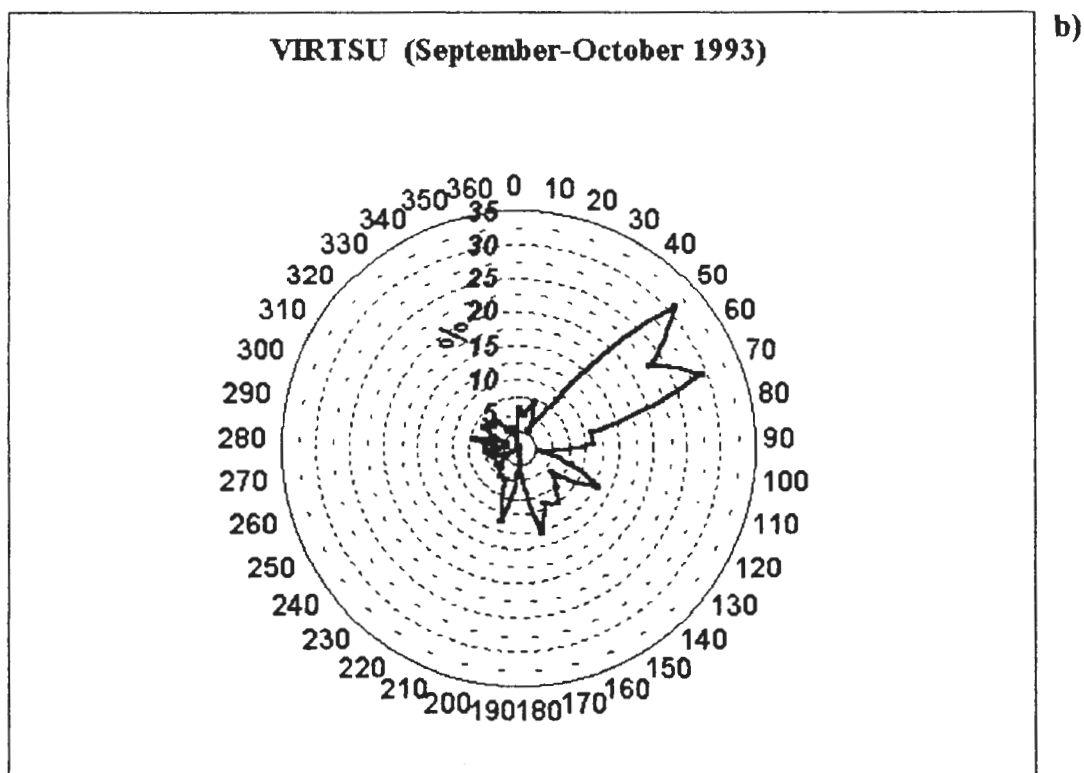
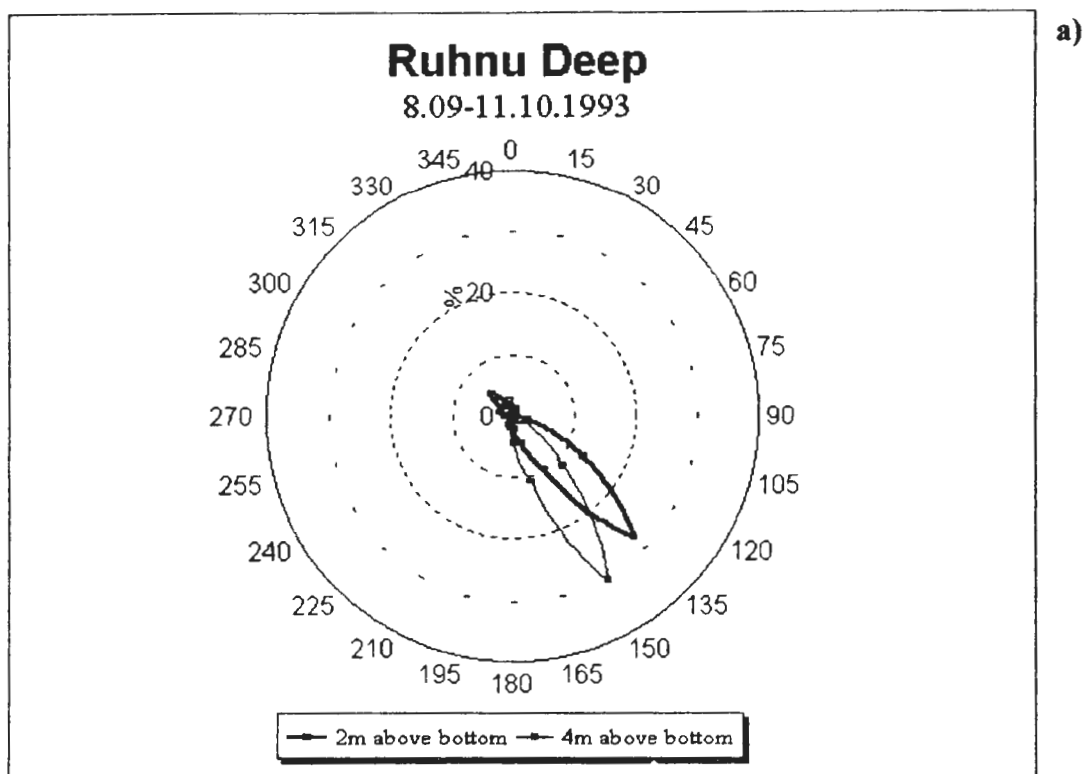


Fig. 6.12 Current roses from the near-bottom layer of the Ruhnu Deep (a) and wind rose at nearby meteorological station Virtsu (b) during measurement period in September-October, 1993

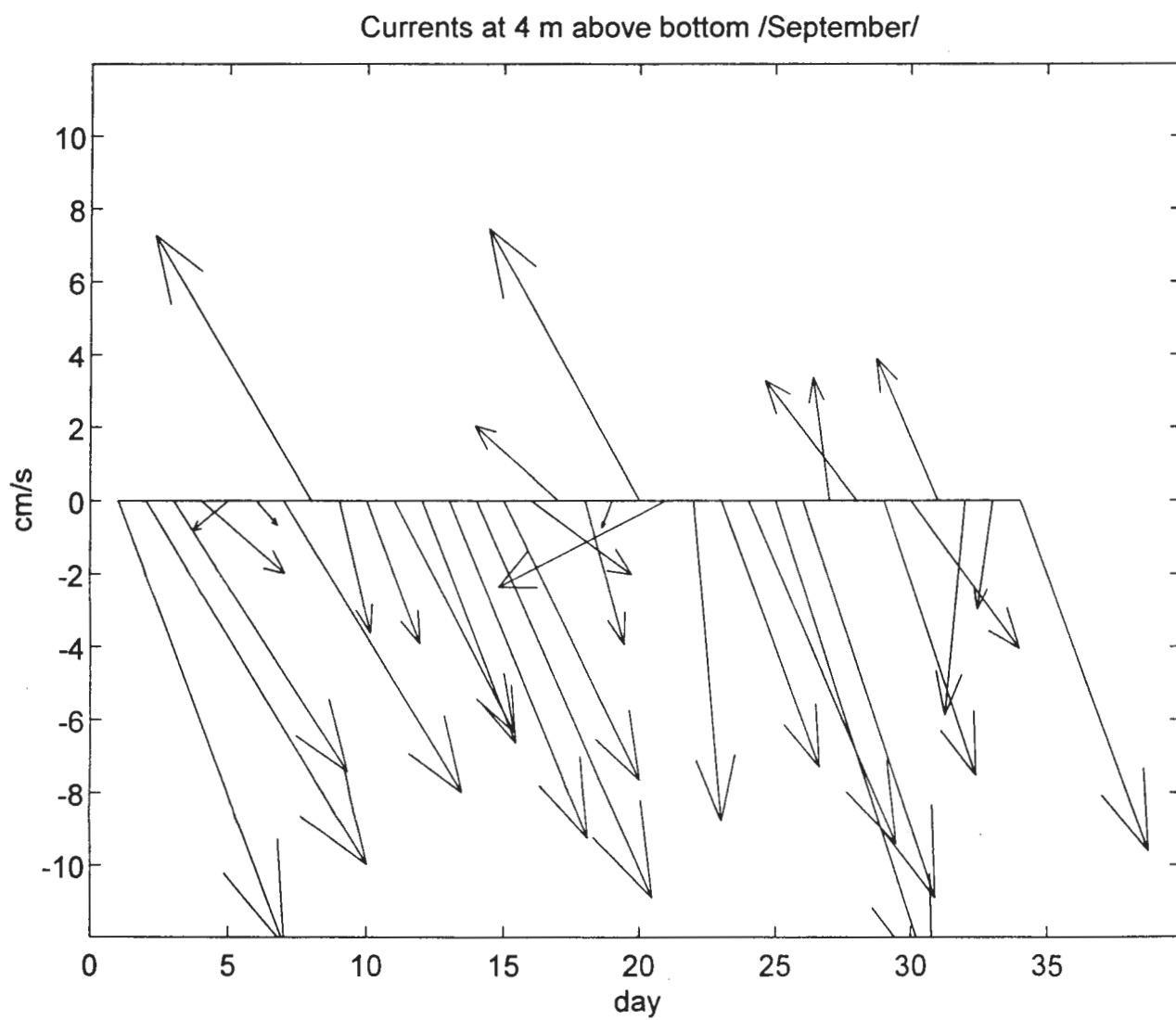


Fig. 6.13 Vector plot of daily average current speed and direction at depth 4m above bottom in September-October, 1993. Day "0" is September 8, 1993 and Northern direction is upward on the plot.

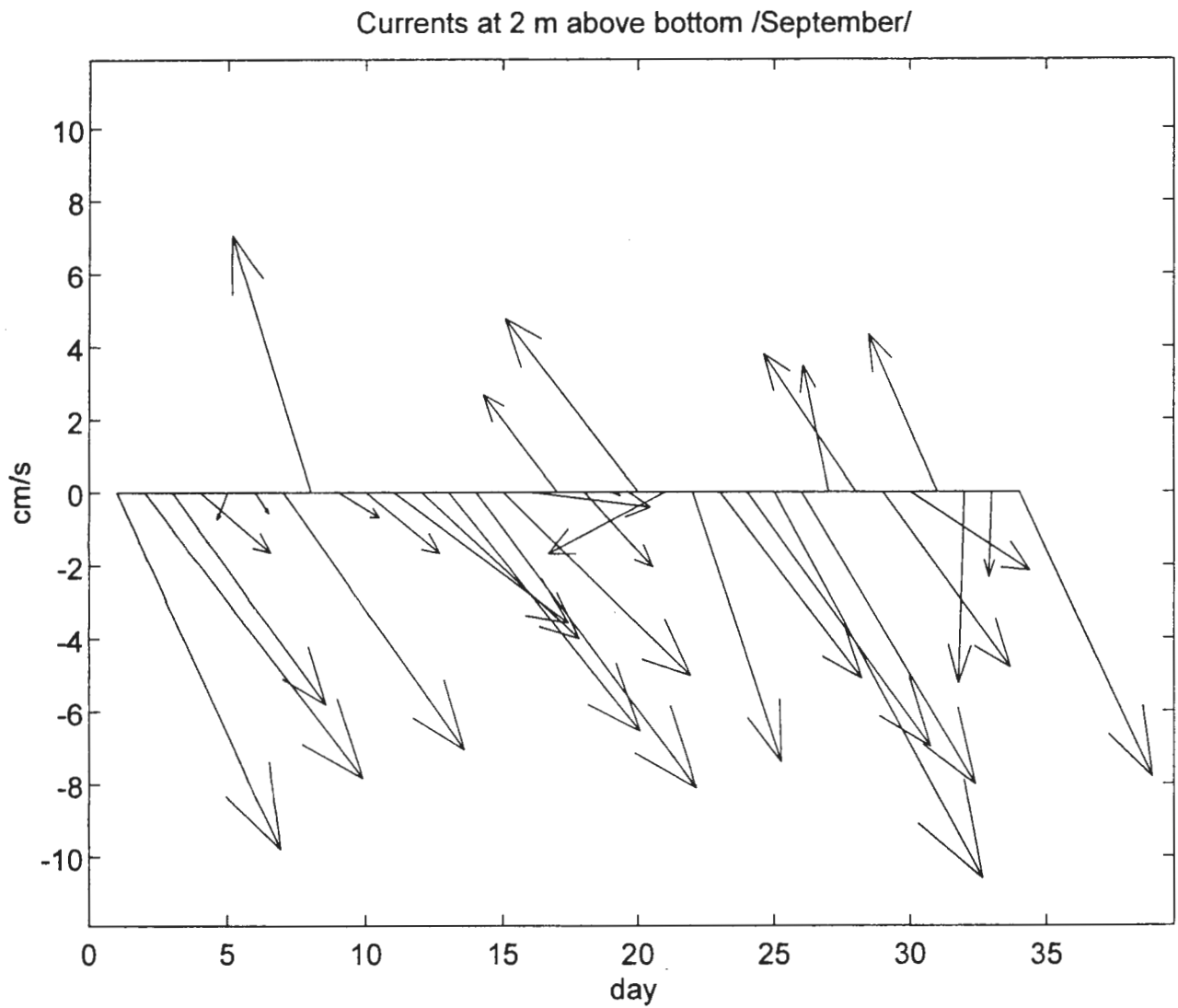


Fig. 6.14 Vector plot of daily average current speed and direction at depth 2m above bottom in September-October, 1993. Day "0" is September 8, 1993 and Northern direction is upward on the plot.

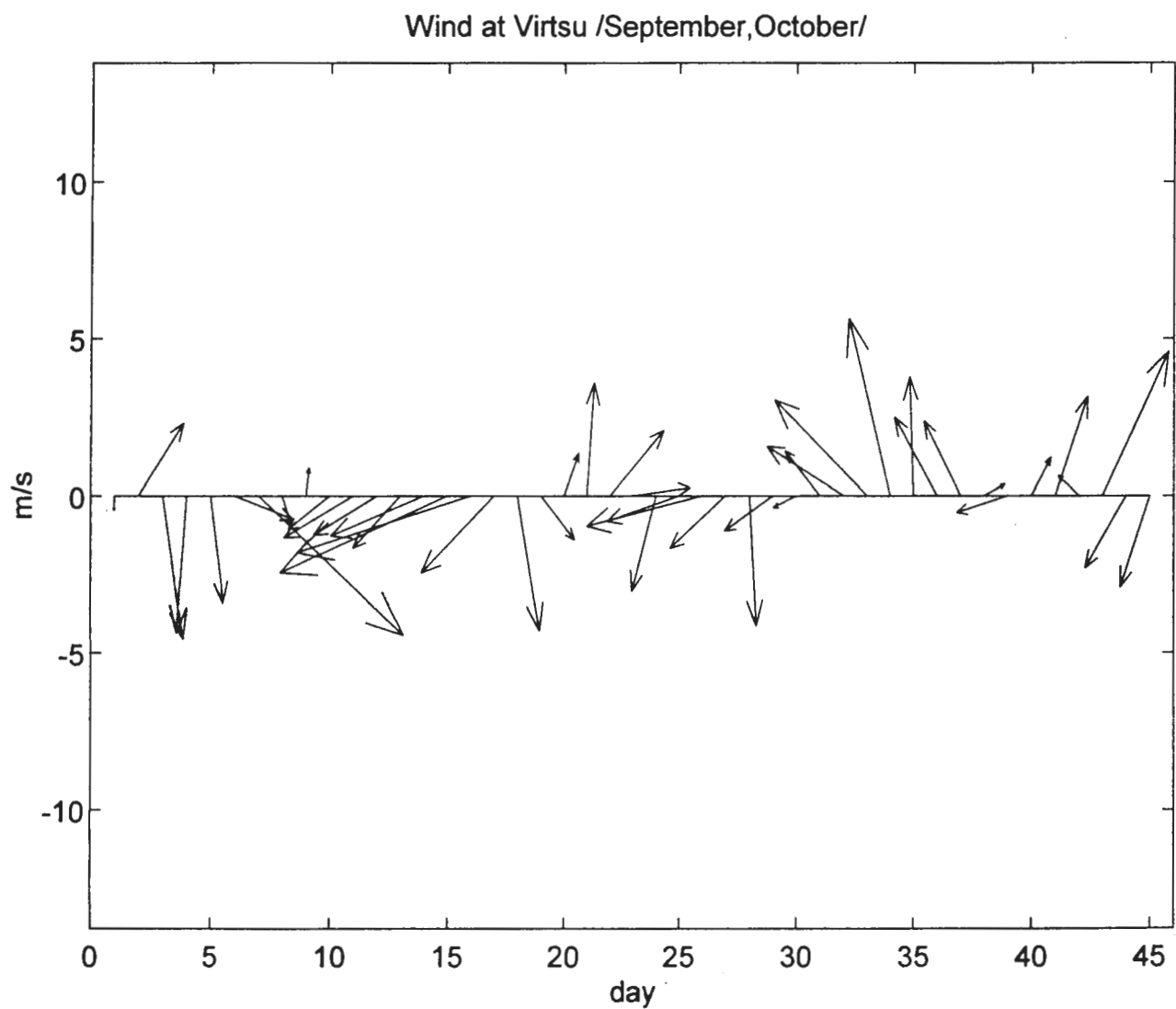


Fig. 6.15 Vector plot of daily average wind speed and direction at meteorological station Virtsu in September-October, 1993. Day "0" is September 1, 1993 and Northern direction is upward on the plot.

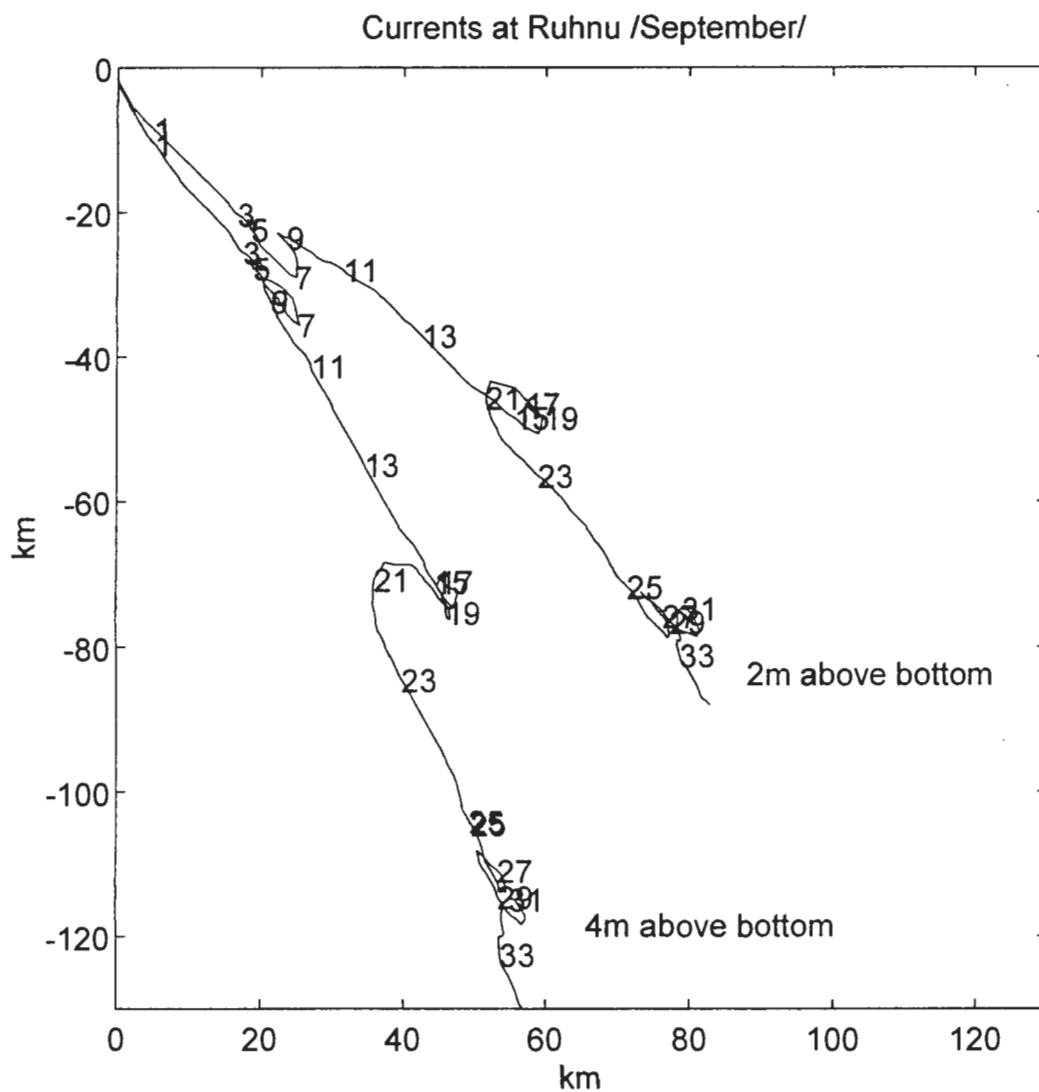


Fig. 6.16 Progressive vector diagram of observed currents in near-bottom layer of the Ruhnu Deep 2 and 4m above bottom in September-October, 1993. Day "0" is September 8, 1993 and Northern direction is upward on the plot.

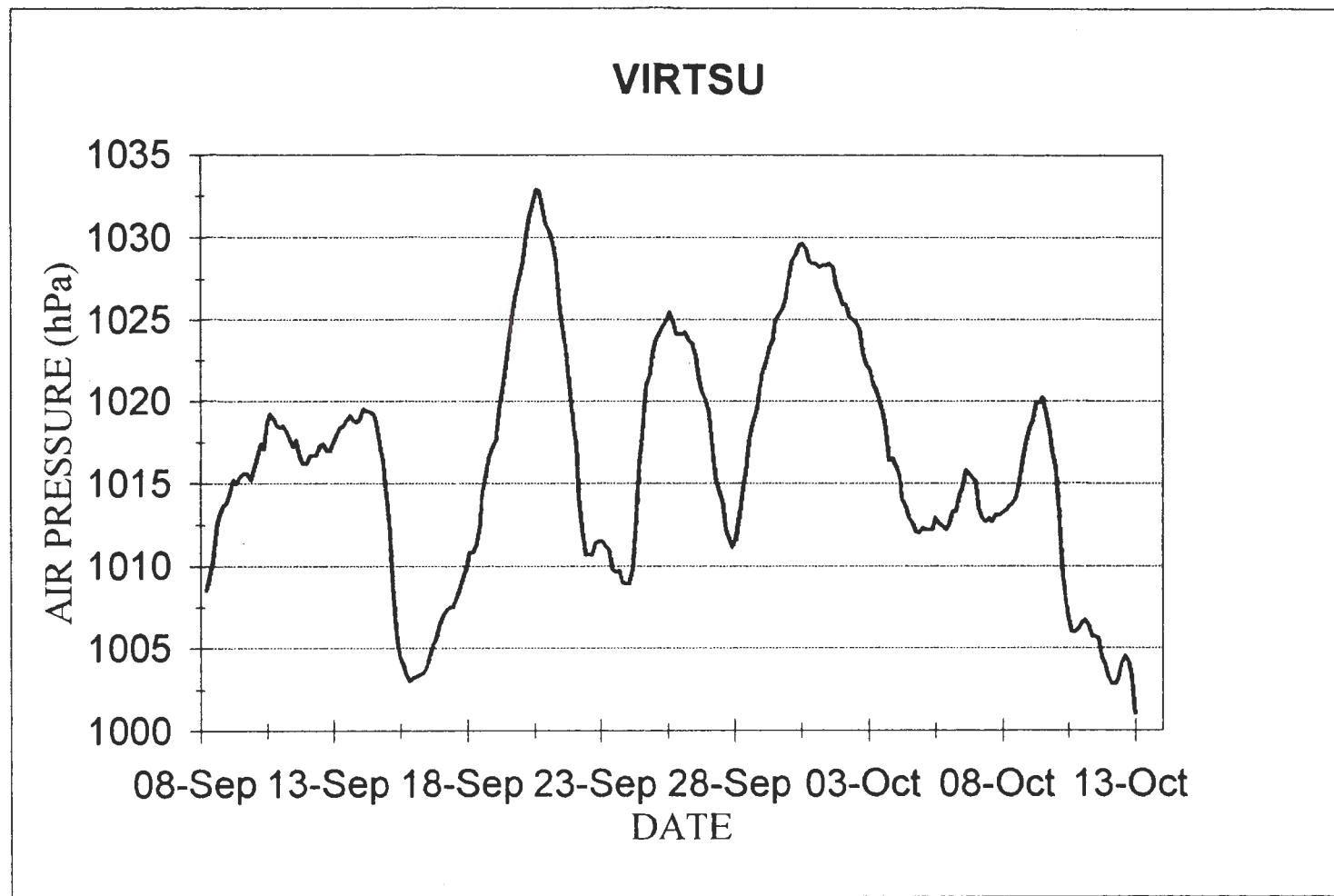


Fig. 6.17 Time serie of air pressure variations in region of the Gulf of Riga observed at meteorological station Virtsu in September-October, 1993.

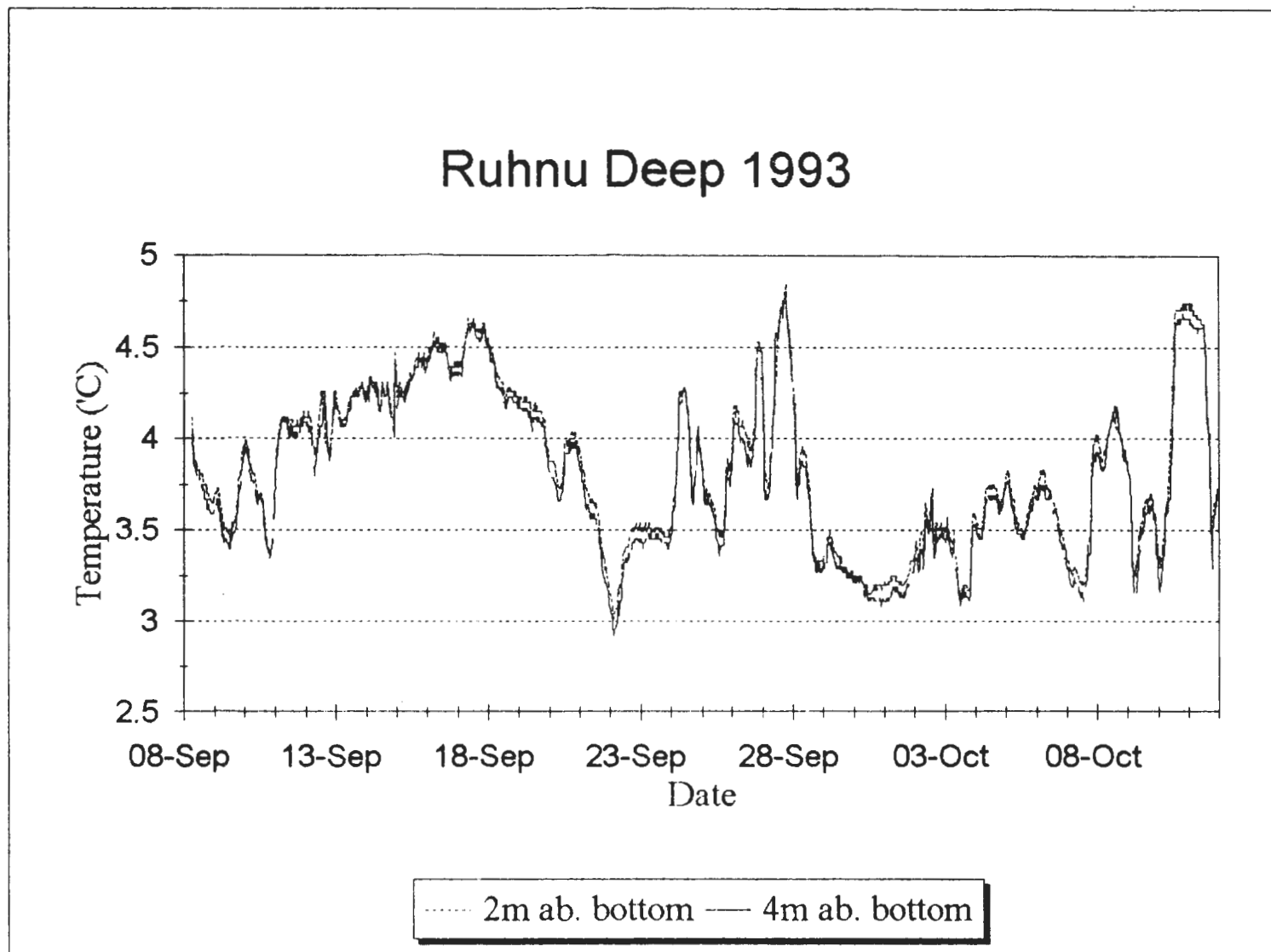


Fig. 6.18 Time serie of sea water temperature in near-bottom layer of the Ruhnu Deep (at the site of mooring station) in September-October, 1993.

7. Sea level variations in the Gulf of Riga in 1993

by Tarmo Kõuts and Svetlana Evreejeva (Estonian Meteorological and Hydrological Institute)

7.1 Introduction

Measurements of sea level in the Gulf of Riga were carried out several coastal stations around of the Gulf. In present overview we take care of data from six measurement sites, which more or less evenly covers whole area of the Gulf. Three stations (Sõrve, Virtsu, Pärnu) are situated on Estonian coast and three (Kolka, Daugavgriva, Skulte) on Latvian coast (see map on Fig.7.1). However station Sõrve was closed in middle of 1993, so sea-level data from there are available only as far as the end of June. Data owners are Estonian Meteorological and Hydrological Institute (EMHI) and Latvian Hydrometeorological Service (LHA), respectively. At sea-level stations Pärnu, Daugavgriva and Skulte are installed mareographs, therefore sea level there is registered continuously and in databases at EMHI and LHA the hourly sea-levels are available for last stations. At rest of the stations an observer checks the sea-level using a bench stick, four times per day (00,06,12,18 UTC). Last method, however, is quite unprecise as sea surface waves influence remarkably on bench stick readings and makes estimation of actual sea-level quite uncertain. One can expect measurement errors as much as 5-10 cm for bench stick readings (Finnish Sea-Level Service, personal communication) and less or equal to 1 cm for mareograph measurements.

All sea-levels presented in current paper are measured in a Baltic System, in reference to "Kronstadt Bench Mark", to which is taken equal the zero sea-level at all coastal stations under discussion.

7.2 Sea level variations

Sea level vary both in time and in space. Five basic factors influence the sea surface topography and sea level variability at a certain location:

- currents
- sea water salinity and temperature (density)
- air pressure field
- wind pattern over area
- fresh water supply

It can be pointed out that the influence of shoreline configuration on the sea level variability pattern (Lazarenko, 1961), which is sea level rise or lowering in case of storm surges, comparably local. Regarding the sea level fluctuations as reflections of ongoing hydrodynamic processes covering the whole water basin (mean sea level, periodical fluctuations of sea level etc.), the local effects are expected to filter out.

Sea level variations in the Gulf of Riga have a complicated nature. From one hand water level changes are caused by water volume changes in the basin and from other by tilt of sea surface under certain meteorological conditions (prevailing winds, low pressure passing etc.). The last type of sea level change does not reflect volume changes in water basin. Fluctuations of water volume are dependent from variability of water balance components, most important of which are river runoff and water exchange with the Baltic Proper. In the Gulf of Riga most commonly the mixture of two types of sea level can be observed (Pastors A.A. and E.P. Iljina, 1976).

Most important periodic fluctuations in the Baltic Sea are year and half year periods (Ekman, 1993). Periodic fluctuations of sea level were recently analysed in Moonsund region and

partly based on level data from Virtsu coastal station. Most intensive spectral peak was observed on period 70 days and less intensive at periods 5.33, 4.27 and 2.9 days. From high frequency oscillations most intensive peaks were observed at periods 23.934 and 12.426 hours (Kõuts T. and U. Raudsepp, 1994). However some more efforts should be put into data processing to eliminate the noisy data from time series before getting final results.

7.3 Long term mean annual cycle of sea level in the Gulf of Riga

To get the long term mean annual cycle of sea-level in the Gulf of Riga, the time series at least 15 years long were used for calculations at every station.

As long term average the low sea-levels are observed in late spring - early summer in all stations around the Gulf. Monthly mean sea-level is minimal in May and varies from -18 cm at Sõrve and Virtsu stations, up to -15, -10 cm at rest of the stations (see bar graphs on Fig. 7.5-7.6). In June-July the sea-level starts to raise again and reach its annual maximum in September-December, when monthly mean sea-level reach 20 cm and even more. It should be pointed out again, that sea-level regime near mouths of big rivers is different from other places and about 5 cm monthly higher mean levels are usually observed there, as a long term mean.

7.4 Sea level variations in 1993

Data

Plots of sea-level time series obtained from Estonian and Latvian coastal stations under observation are presented on Fig.-s 7.2-7.3, which show continuous data at stations Pärnu and Daugavgrīva, when in rest of stations shorter or longer holes of absent data are present. Part of data are absent because of ice conditions, which were hard in some locations in 1993 (Virtsu, Skulte), which disturbed the measurements made with old equipment. Break of sea-level measurements at Sõrve station from July, took place also because of technical reasons.

Mean sea-level in 1993

The mean sea-levels in the Gulf of Riga were calculated on basis of raw data in order to calculate the monthly means and then from the monthly means yearly mean level. Monthly mean sea-levels are presented on graphs (see Fig. 7.4-7.6), when yearly mean and relevant extreme values are presented in Tab. 7.1.

Table 7.1. *Extrem and mean sea-levels at coastal stations around the Gulf of Riga observed in 1993.**

Coastal station	Extremal and mean sea-levels in 1993		
	Min	Max	Mean
Pärnu	-90	+172	+0.5
Virtsu	-125	+111	-
Sõrve	-	-	-
Kolka	-40	+88	+5
Skulte	-75	+120	+2
Daugavgrīva	-73	+146	+7
Ristna	-60	+116	-8

* Data are originating from EMHI and LHA, zero level is Kronstadt Benchmark.

On plots of monthly mean sea-levels one can observe the normal cycle of sea-level on first half of the year, when mean sea-level decreases after maximum in January (about +30 to +50cm) until its minimum in May (about -25 to -35cm). Near the river mouths (Pärnu and Daugavgriva) about 10cm higher extremal values can be observed, than in rest of stations. From June remarkable raise of sea-level observes on graphs at all stations, and monthly mean sea-level reached its yearly maximum already in July-August, which is about two months earlier than long-term mean. After the early maximum, the monthly mean sea-level started decrease again, which is quite unexpected, compared to the long-term mean cycle (see Fig. 7.5-7.6). Furthermore, monthly mean sea-level reached another minimum during year, in November which was even (about 10cm) lower than the minimum observed in May. Afterward sea-level increased again and reached 0 cm, by the end of year.

Correlation between sea-level variations at different stations

Correlation of sea level change in different stations of the Gulf of Riga is high, calculated correlation over measured sea level time series of several years was more than 0.9 in most cases. The last is caused by the smallness of water basin - the Gulf of Riga, so that remarkable uncorrelated fluctuations can not take place there. Correlation coefficients of sea-level variations are presented in Tab.7.2, where station Ristna represents the sea-level of the Baltic Proper. It should be pointed out the slightly lower correlation of the sea-level variations at Kolka station, if comparing these with others.

If inspecting the time series of sea-level in the Gulf of Riga and outside - the Baltic Proper, one observes for year 1993 that the level inside the Gulf is higher than outside during most of time (see Fig. 7.7).

Table 7.2. *Correlation coefficients of sea-level variability observed at different parts of the Gulf of Riga and the Baltic Proper.*

	Pärnu	Virtsu	Sõrve	Daugavgriva	Kolka	Skulte
Pärnu	1					
Virtsu	0.9683	1				
Sõrve	0.9661	0.98	1			
Daugavgriva	0.9685	0.9601	0.9727	1		
Kolka	0.8188	0.8401	0.9297	0.8362	1	
Skulte	0.9615	0.9424	0.9564	0.98495	0.7957	1
Ristna	0.9668	0.9579	0.9708	0.95256	0.8712	0.9504

7.5 Conclusions

Sea level in the Gulf of Riga is highly variable depending mostly from atmospheric forcing, but also from variability of river runoff. Although clearly can be recognized seasonal cycle among others, amplitude of which is about 35-40 cm as monthly mean sea levels. The latter is caused mainly by the air pressure variations over the region. The seasonal cycle of sea level height fits well with variation of the Baltic Proper levels. One can point out the sensitivity of sea level fluctuations to local wind conditions over the Gulf and frequency of events during last months of the year, when water is pushed into Pärnu Bay by SW winds. The water level raises then up to 1.5 m above zero in Pärnu Port (historical maximum even 2.5m above zero).

In 1993 sea-level variations followed historical mean cycle on first half of the year, when its maximum was observed in January. During summer season sea-level raised very fast and reached high level already in August. Second maximum was followed then by rapid

decrease of sea-level, which is quite unusual compared to the long-term mean seasonal cycle.

Acknowledgements

Dr. Evgeny Zakharchenko (LHA) who provided sea-level data from Latvian stations is therefore kindly acknowledged.

References

Ekman, M. 1993 Postglacial rebound and sea level phenomena, with special reference to Fennoscandia and Baltic Sea. *Geodesy and Geophysics*, Helsinki, 9-70.

Kõuts, T., and Raudsepp, U. 1994. Sea level in Moonsund 1976-92. (EMHI Report), Tallinn, 1-35.

Lazarenko, N.N. 1961. Variability of sea level in the Baltic Sea. In: *Trudy gosudarstvennogo okeanografitseskogo instituta*. (in Russian) Leningrad, 39-127.

Pastors, A.A., and Iljina, E.P. 1976. Surges in the Gulf of Riga. In: *Dynamic structures and circulation of water in the Gulf of Riga*. (in Russian) Riga, 9-37.

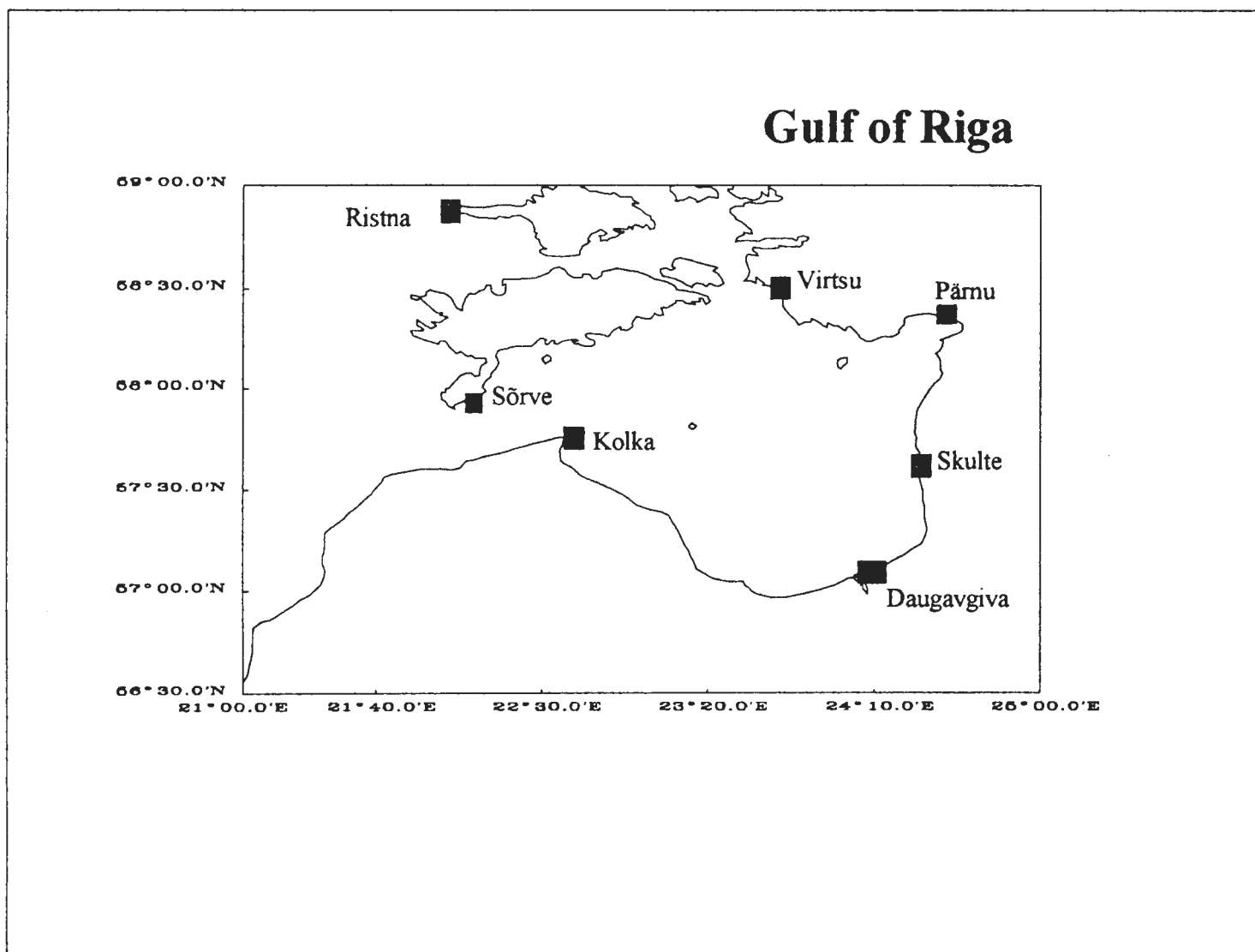


Fig. 7.1 Map of the Gulf of Riga region showing the locations of coastal stations, where measurements of sea level took place in 1993.

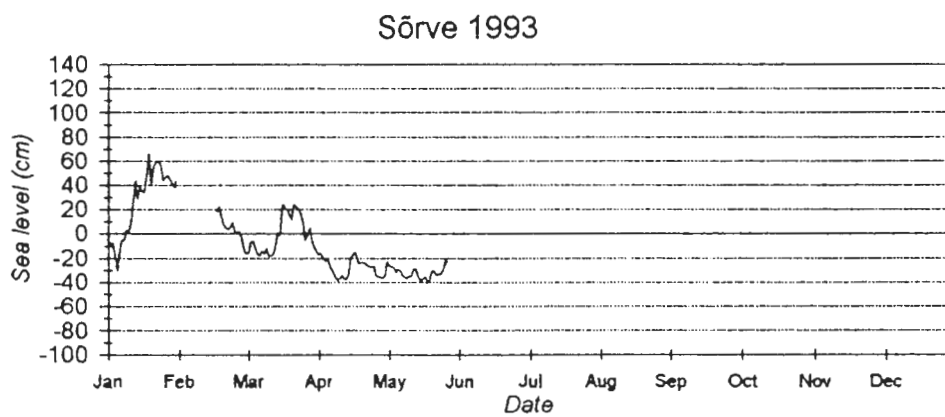
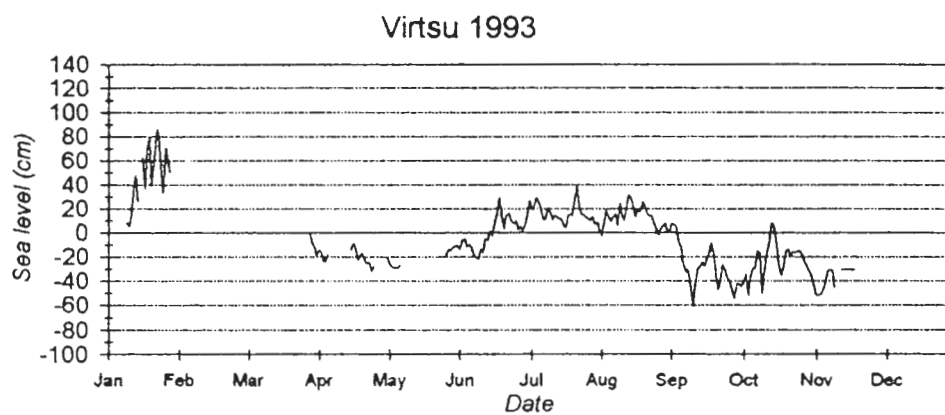
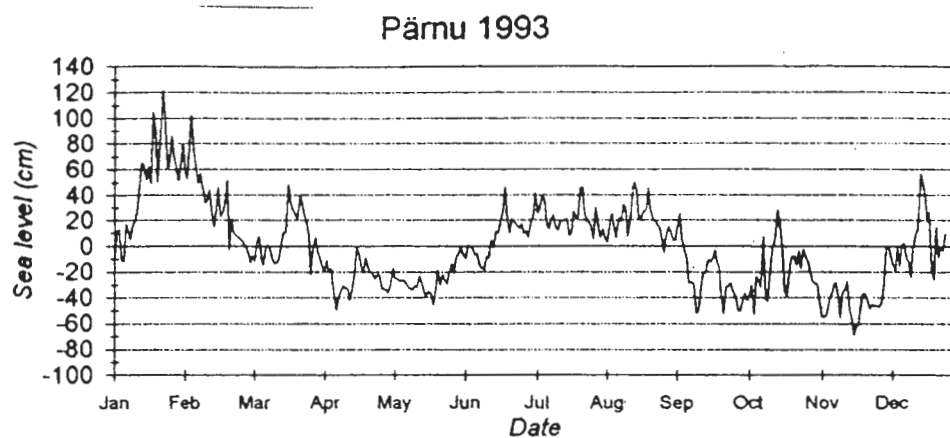


Fig. 7.2 Time series of measured sea-levels at coastal stations Pärnu, Virtsu and Sõrve.

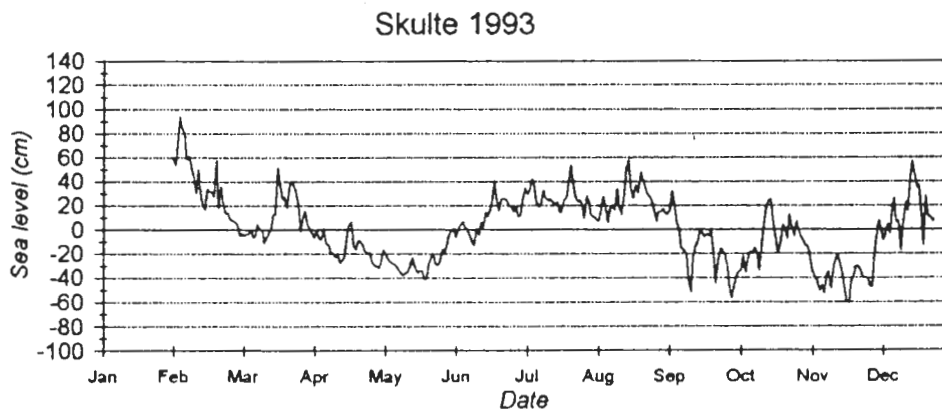
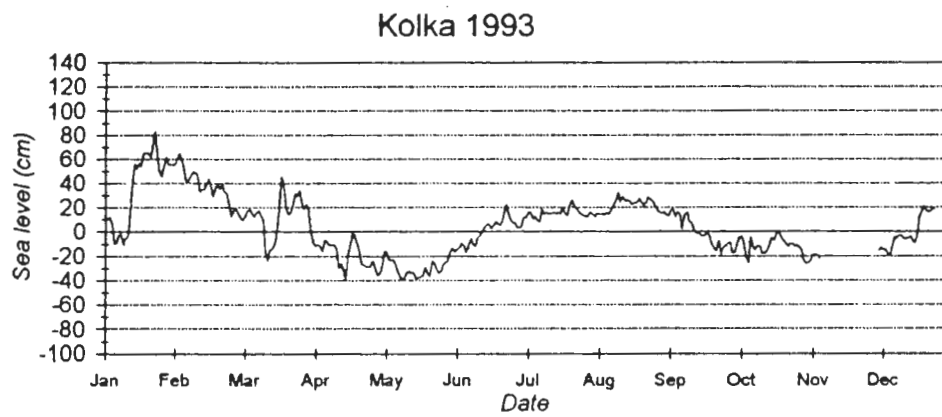
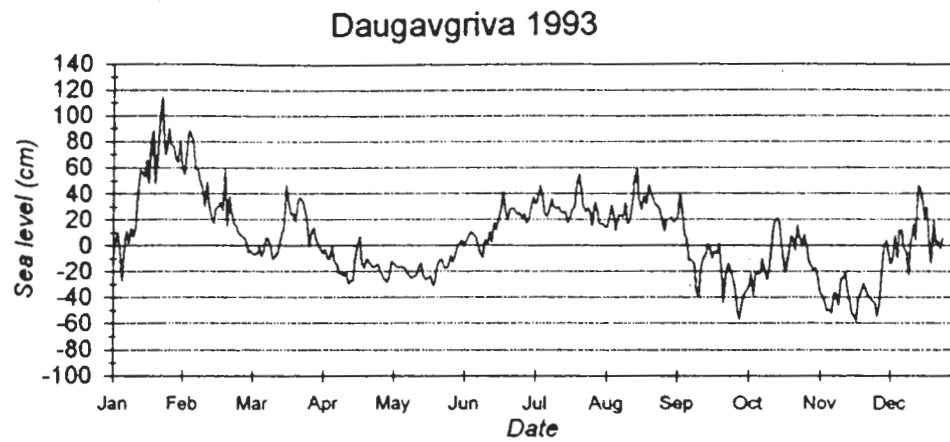


Fig. 7.3 Time series of measured sea-levels at coastal stations Daugavgriva, Kolka and Skulte.

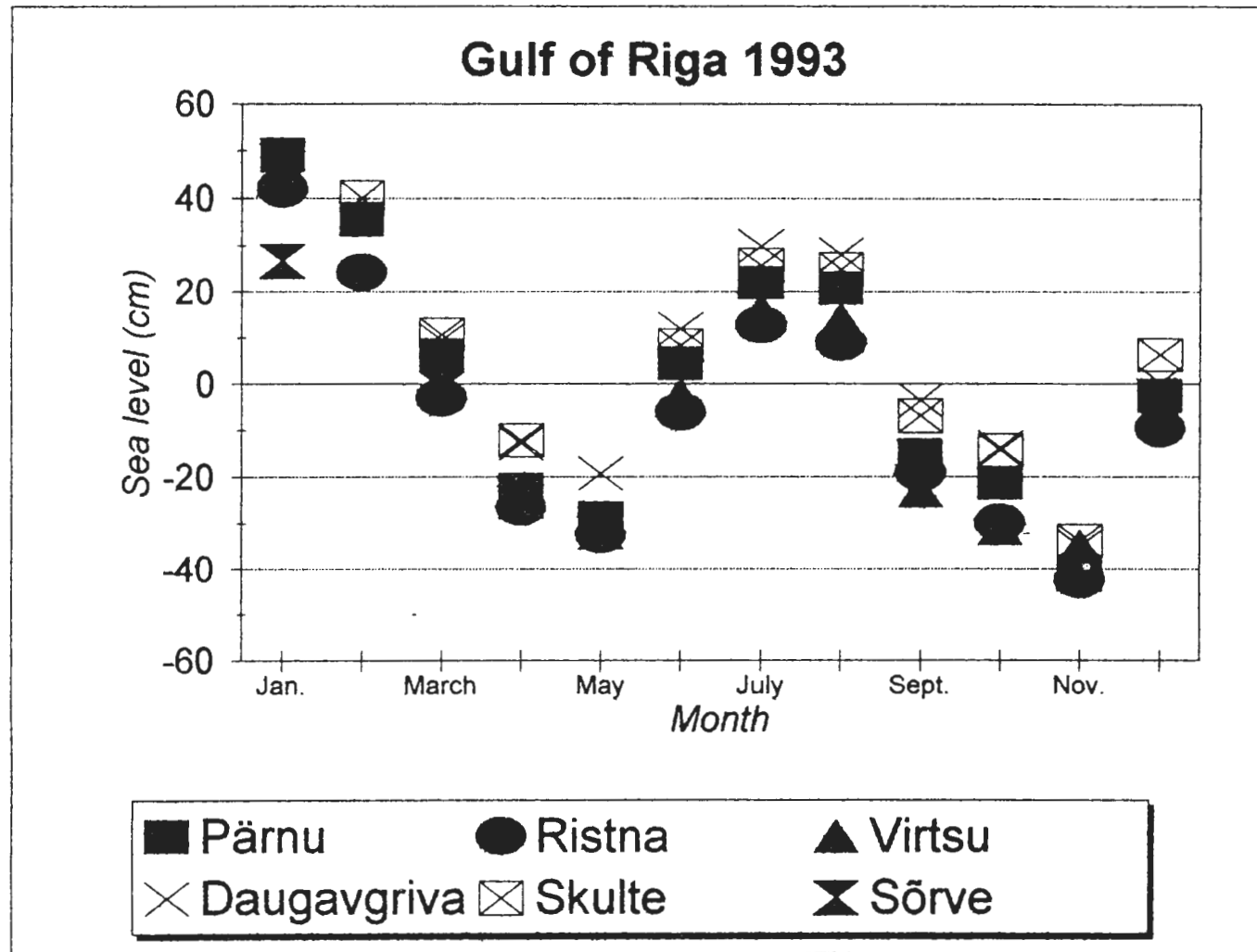


Fig. 7.4 Monthly mean sea-levels in 1993 at different stations in the Gulf of Riga and the Baltic Proper.

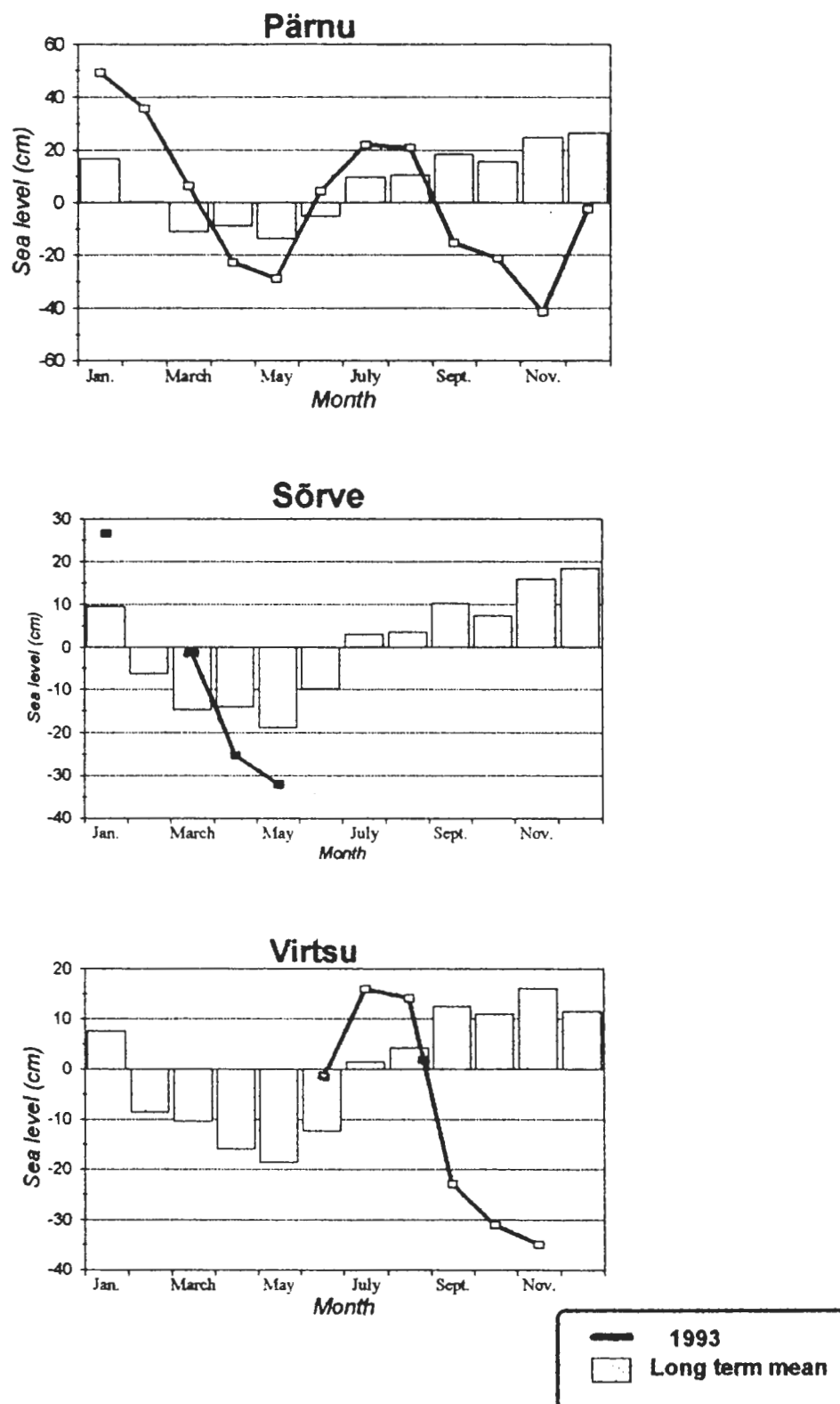


Fig. 7.5 Annual long-term mean cycle of sea-level (bar graph) and monthly mean levels (line) in 1993 at stations Pärnu, Sõrve and Virtsu.

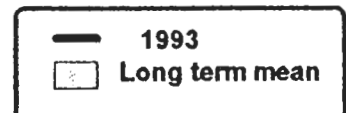
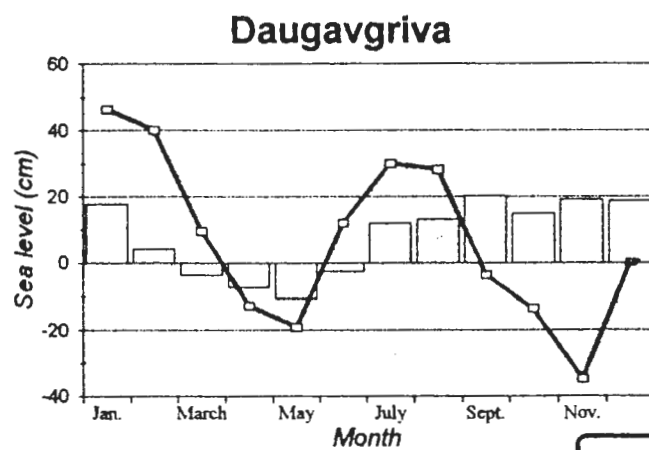
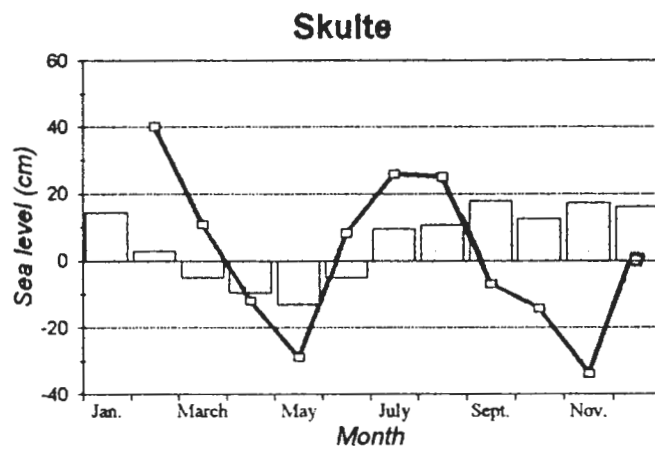
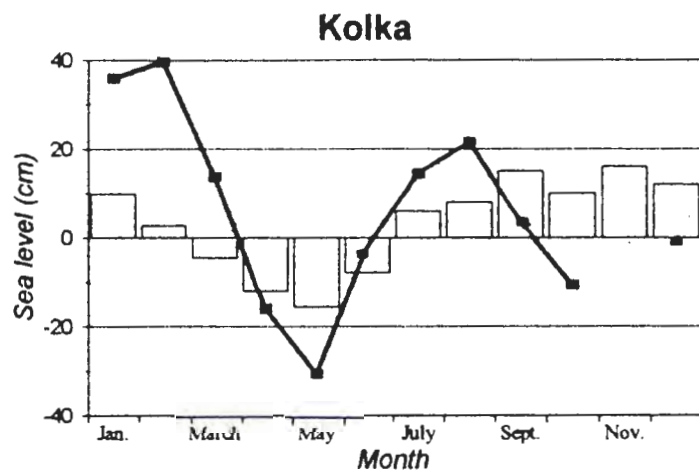


Fig. 7.6 Annual long-term mean cycle of sea-level (bar graph) and monthly mean levels (line) in 1993 at stations Kolka, Skulte and Daugavgriva.

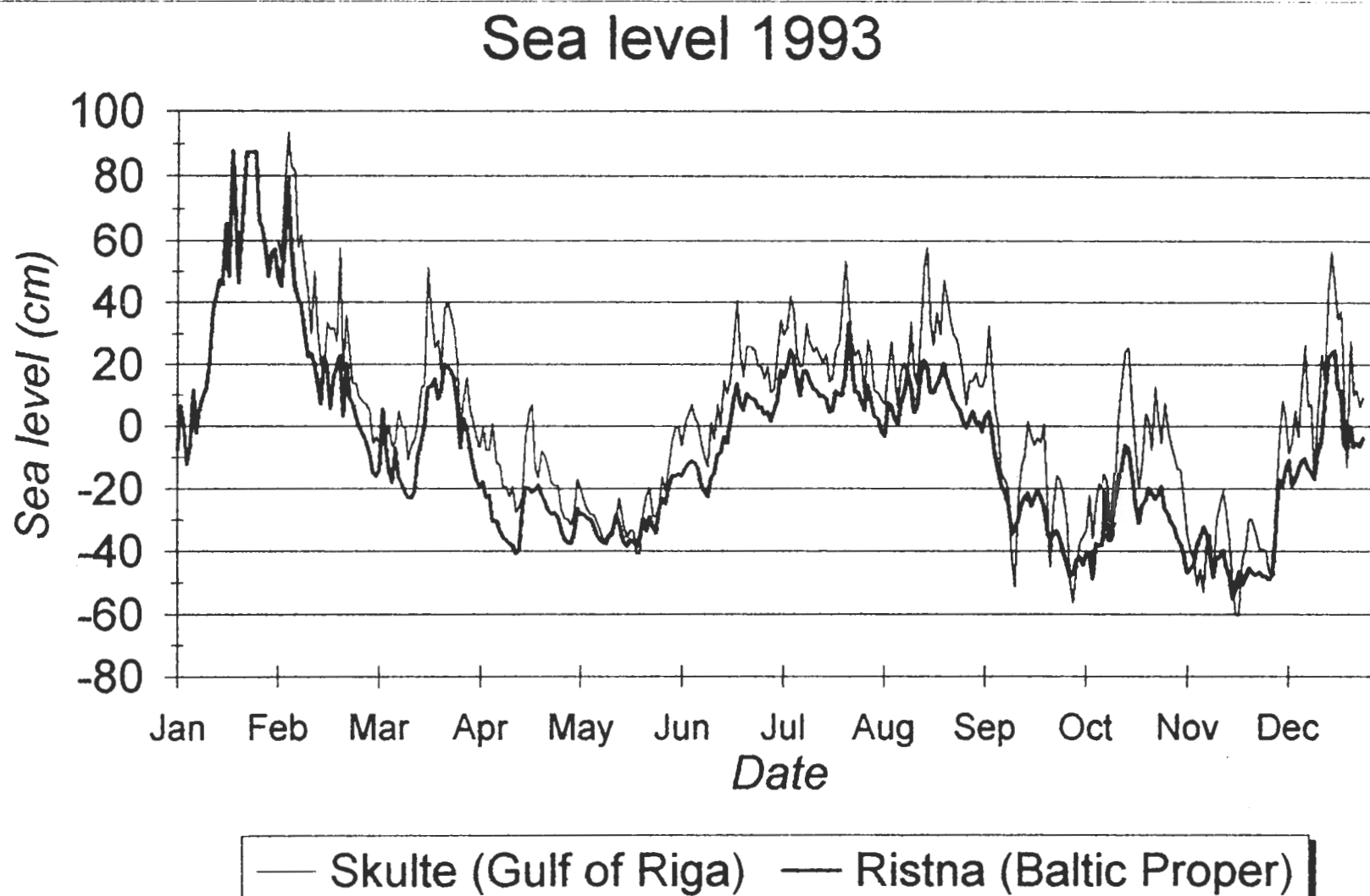


Fig. 7.7 Plot of daily mean sea-levels in the Gulf of Riga (station Skulte, thin line) and the Baltic Proper (station Ristna, thick line) in 1993..

8. Peculiarities of the hydrographic conditions in the southern part of the Gulf of Riga in April - November 1994

by Evgeny Zaharchenko and Dagnia Fedorovich (Latvian Hydrometeorological Agency)

Abstract

The hydrometeorological and hydrographic conditions in the southern part of the Gulf of Riga in April - November, 1994 are analysed using measurement data. Temperature and salinity anomalies in the investigated area are estimated on the basis of the monthly mean values.

8.1 Introduction

Several additional observations within the national monitoring programme were carried out in the southern gulf during the period April - November, 1994. Each week R/V Geofizikis visited the cross-section of station 165 - station 119 (Fig. 1). Water temperature, salinity and oxygen profiles were recorded using a KATRAN sounder. Simultaneously, a standard bathymetric method was used to control the sound data. The first station 165 is situated at a distance of 2.5 km from the Daugava river estuary at a depth of 10 m. The last station 119 is 26.8 km away from the mouth and has a depth of 47 m. To analyse water temperature, salinity and oxygen variations, two stations, station 101a and station 119 were selected, taking into account the morphometrical and physical peculiarities of the area.

The hydrographic regime of the southern part of the Gulf of Riga is very complicated and its variations include nonperiodical and periodical (seasonal) components. The complexity of the area is determined by interaction processes with the atmosphere and the adjoining gulf. On the other hand, the southern gulf is a basin of high freshwater input. About 86% of the total freshwater input is loaded by river Daugava. As a result a strong vertical water structure is observed in this area. A few frontal zones determine the horizontal and vertical distribution of substances. The southern gulf is a dynamically active area and the large scale hydrographic processes influence other regions of the gulf.

8.2 Hydrometeorological conditions

Air Temperature

In 1994, large anomalies in the surface temperature values were observed. During the winter the anomalies shifted such that November and January was warmer (+4.4 °C) whereas February was colder (-4.1 °C), than normal. March and April were characterized by positive anomalies of 1.3 °C to 3.3 °C, respectively. Also large positive temperature anomalies were observed in the second and third week of July and in the first week of August when the anomalies varied between 3.6 and 4.0 °C, moreover an absolute maximum of 25.8 °C was recorded in July. In September and October, the temperature anomalies insignificantly varied between positive and negative values. The temporal distribution of surface temperature and its anomalies are shown in Fig. 2.

Precipitation

The temporal distribution of precipitation and its anomalies are shown in Fig 3. Judging from the Figure, one can see that the most abundant months were January, March and April. A maximum precipitation value of 45.3 mm or 346 % of normal, was observed in the first week of April. The most droughty month was July when the precipitation was only 15.4 mm or 17 % of normal.

Riverine runoff

Corresponding with the precipitation anomalies in January to November 1994, large anomalies were observed in the riverine runoff into the gulf. Judging from Fig. 4, April was the most water-abundant when the monthly water discharge value of the largest Latvian river Daugava was of 3 382 m³/s or 167 % of normal, whereas a larger anomaly of 220 % was observed in June. The months of August to October were of poor abundance when the Daugava river runoff was about 50 % of normal or about 190 m³/s.

8.3 Hydrographic conditions

Water temperature

Just in the very beginning of the observations in the Gulf of Riga in April 1994, a thermocline started to develop at station 101a, but at first the vertical gradient was weak and temperature smoothly decreased from 5 °C in the surface layer to 1 °C in the bottom (Fig. 5). In June, the vertical temperature stratification became strong, and maximum stratification was observed late in July and in August. Late in July, the surface water maximum was 22 °C or about 4 °C higher than normal and repeated an absolute maximum of 1955. From the middle of August, high temperature values gradually decreased. During September, the thermocline had deepened and became weaker and early in October it disappeared and vertical homogeneous temperatures were observed. At station 119, a thermocline started to develop in the beginning of May and a strong temperature gradient was observed in June to September. A maximum temperature of 22 °C (Fig. 6) was observed on the surface in the beginning of August and exceeded an absolute maximum of 21.5 °C observed in 1975. The thermocline started to deepen, but until the middle of October a strong vertical gradient of temperature remained. Unlike station 101a, only in the end of October the thermocline became somewhat weaker and in November complete homogeneous profiles were observed. Also attention should be drawn to a significant temperature rise from 2 °C to 4 °C in the bottom layer in the end of August.

Salinity

The influence of the freshwater input is well expressed in the upper layer of station 101a. Minimum salinity values of 2.0 psu were measured in April (Fig 7) when the riverine runoff was at a maximum. A seasonal halocline existed during April to October and later it became weaker. In the bottom layer, the salinity values were identical to 5.5 psu in April to September and since the middle of October, due to intensified wind mixing and a decrease in river runoff.

At station 119, a seasonal component in the salinity distribution existed too but the influence of fresh water input here was less expressed than at station 101a. Judging from Fig. 8, one can see that a minimum salinity value of 4.7 psu was recorded in the surface layer in April. In the deep water, salinities of about of 5.8 psu have no significant changes during April to August. In the end of August, the salinity values increased to 6.1 psu, that is 0.2 psu higher than normal and was preserved till the end of October. The last

phenomenon may be attributed to a salt water input to the gulf. Also it should be noted that at station 119 salinity values higher than 6 psu have not been recorded since 1988.

Dissolved oxygen

For the whole period April to November, the oxygen conditions in the upper layer of the investigated area may be characterized as normal. The oxygen content values slowly decreased from about 10 mg/l in April to 5.2 mg/l in September (Fig 9 and Fig. 10). Since October, the oxygen content increased to 7.5 to 8.0 mg/l. The oxygen conditions in the bottom layer were low with an oxygen decrease to 3.2 mg/l at station 101a in August and September and to 2.8 mg/l at station 119 in September and October. Such low oxygen contents have not been observed since 1985. A strong vertical gradient in the oxygen prevailed the whole autumn, but disappeared in November due to cooling and increased wind mixing.

8.4 Concluding remarks

The main peculiarity of temperature in the southern part of the Gulf of Riga in 1994 was the extremely high values observed in July and August. This phenomenon may be partly explained by a relatively mild winter and very warm July and August.

The temporal salinity distribution shows that in the end of August a salt water intrusion into the area of station 119 took place, and for the first time over the last 6 years the salinity has become higher than 6.0 psu, which is close to normal. Low oxygen concentrations were recorded in the southern gulf in August to October. Oxygen content lower than 4.0 mg/l was observed for the first time since 1985.

Acknowledgements

We would like to thank the Steering Committee of the Gulf of Riga Project who have made this additional cruises of R/V Geofizikis possible. The Swedish Meteorological and Hydrological Institute and Finnish Institute of Marine Research are highly acknowledge too for the financial and technical support.

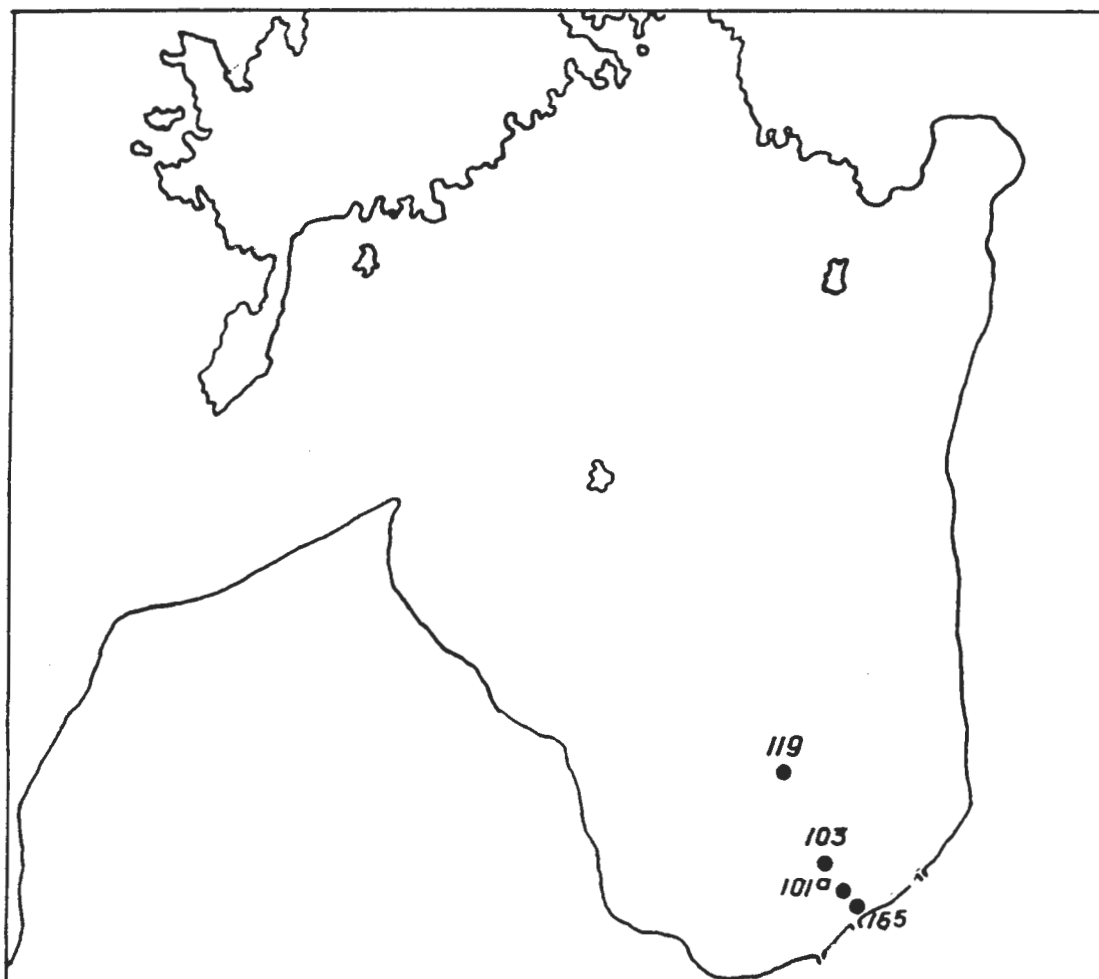
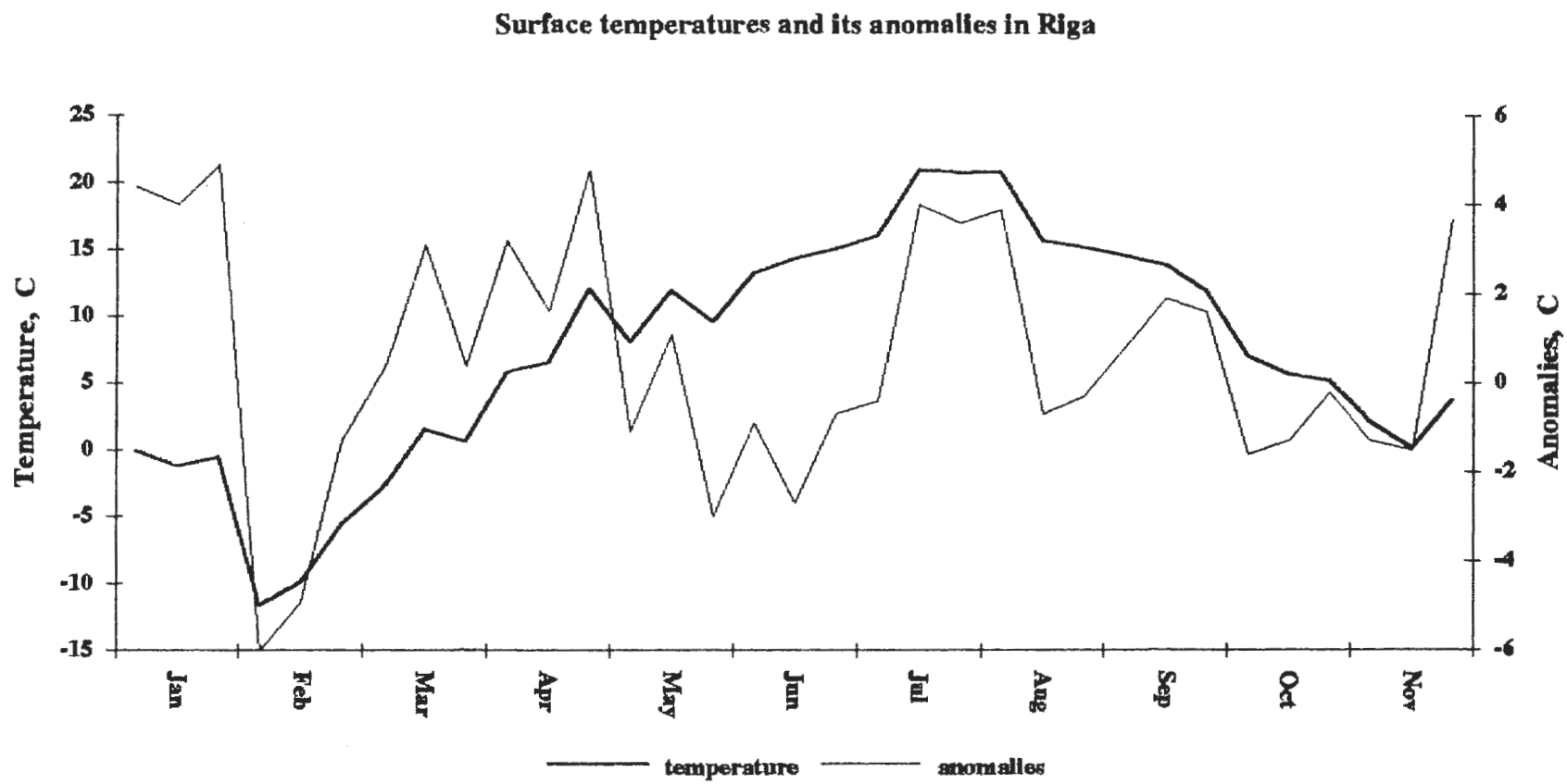


Fig.1
Hydrographical stations visited by the R/V Geofizikis, April-November 1994.

**Fig. 2**

Precipitation and its anomalies in % of normal in Riga

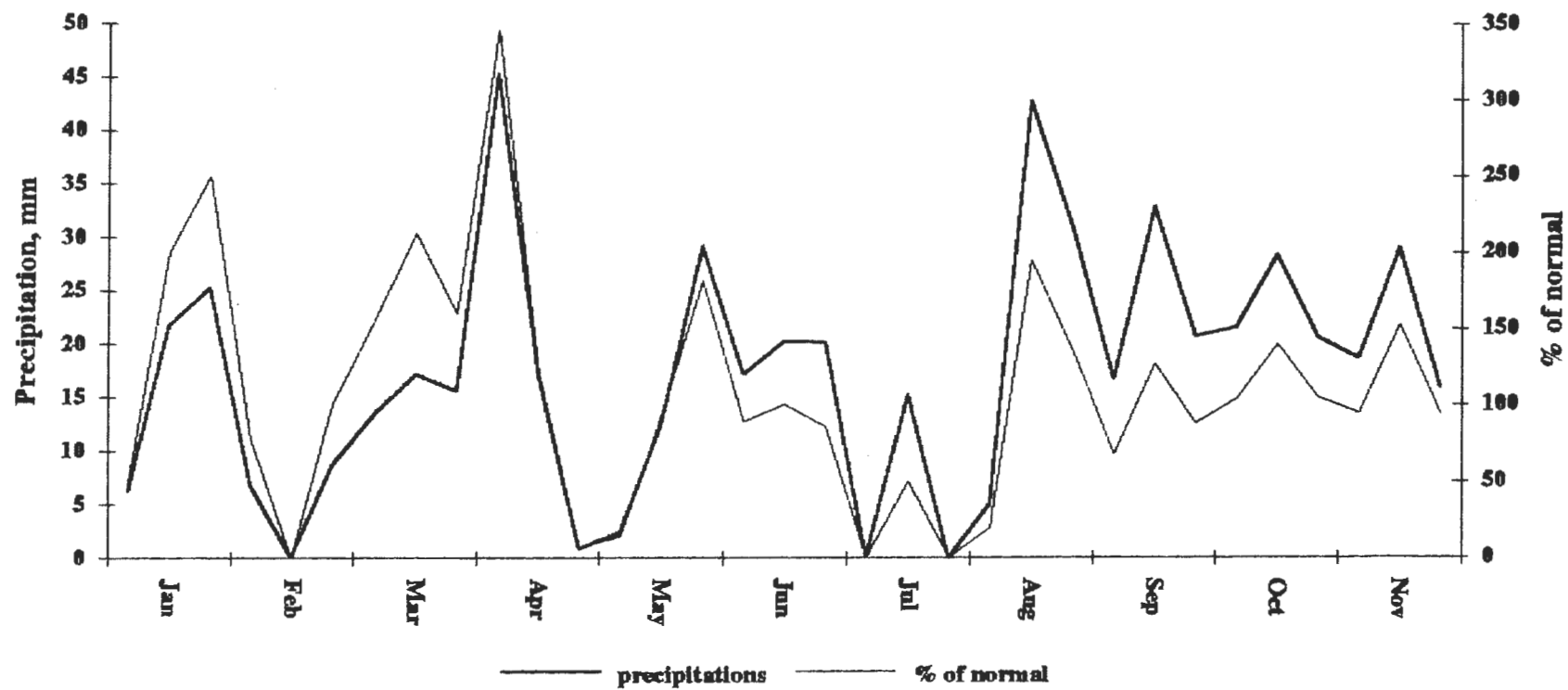


Fig. 3

Daugava river water discgarge and its anomalies in % of normal

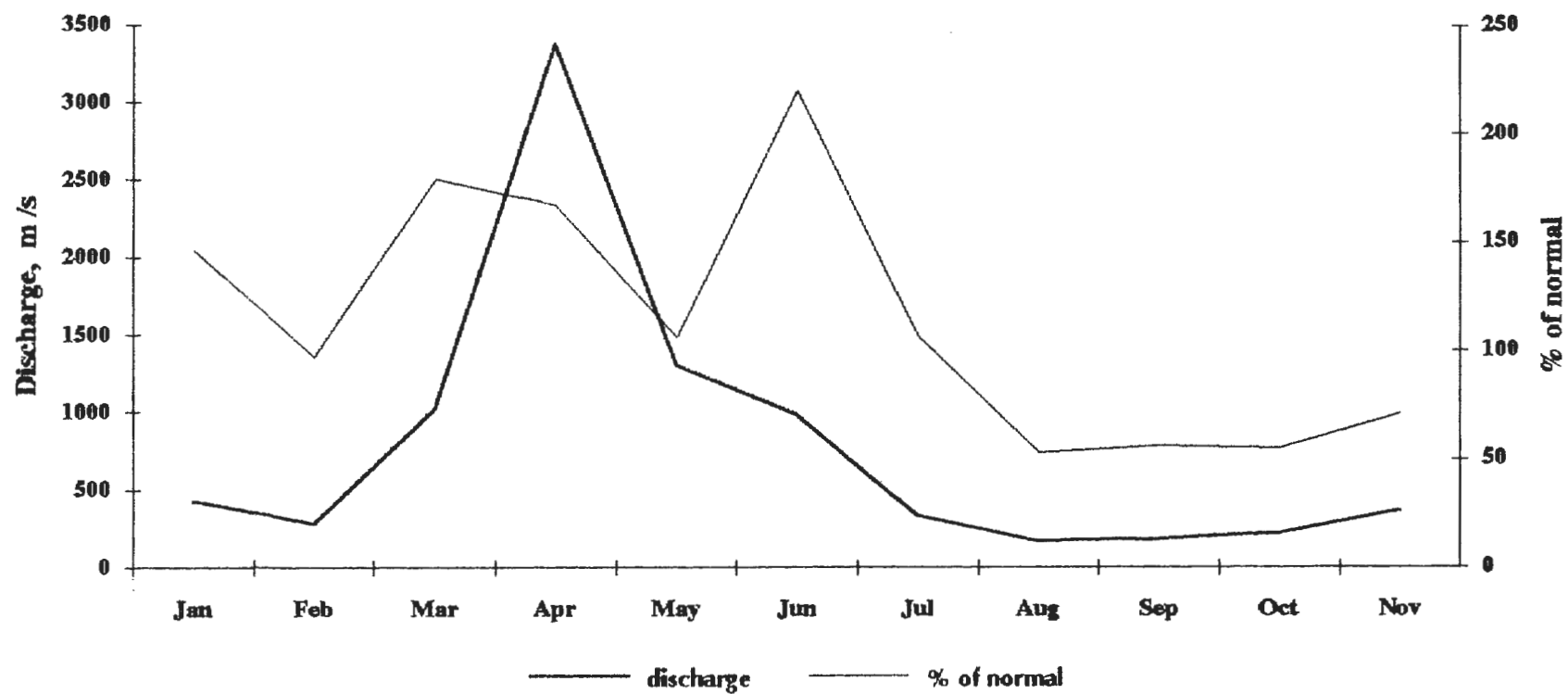
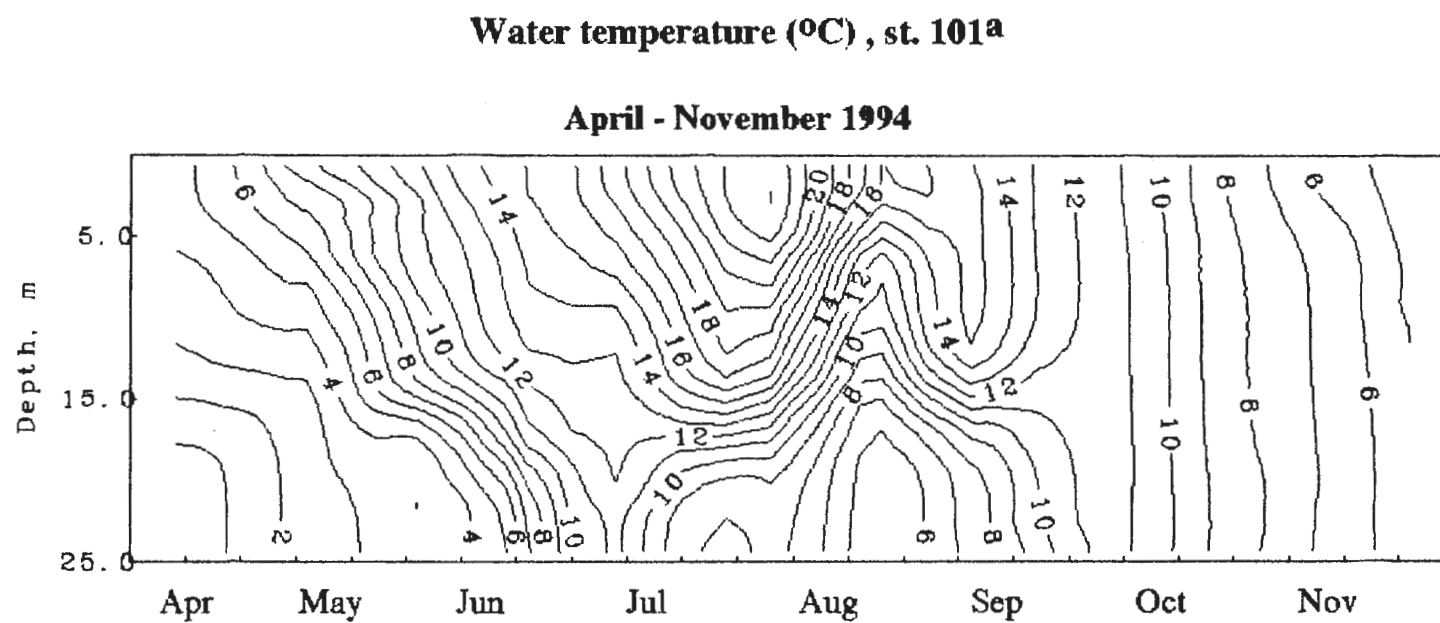
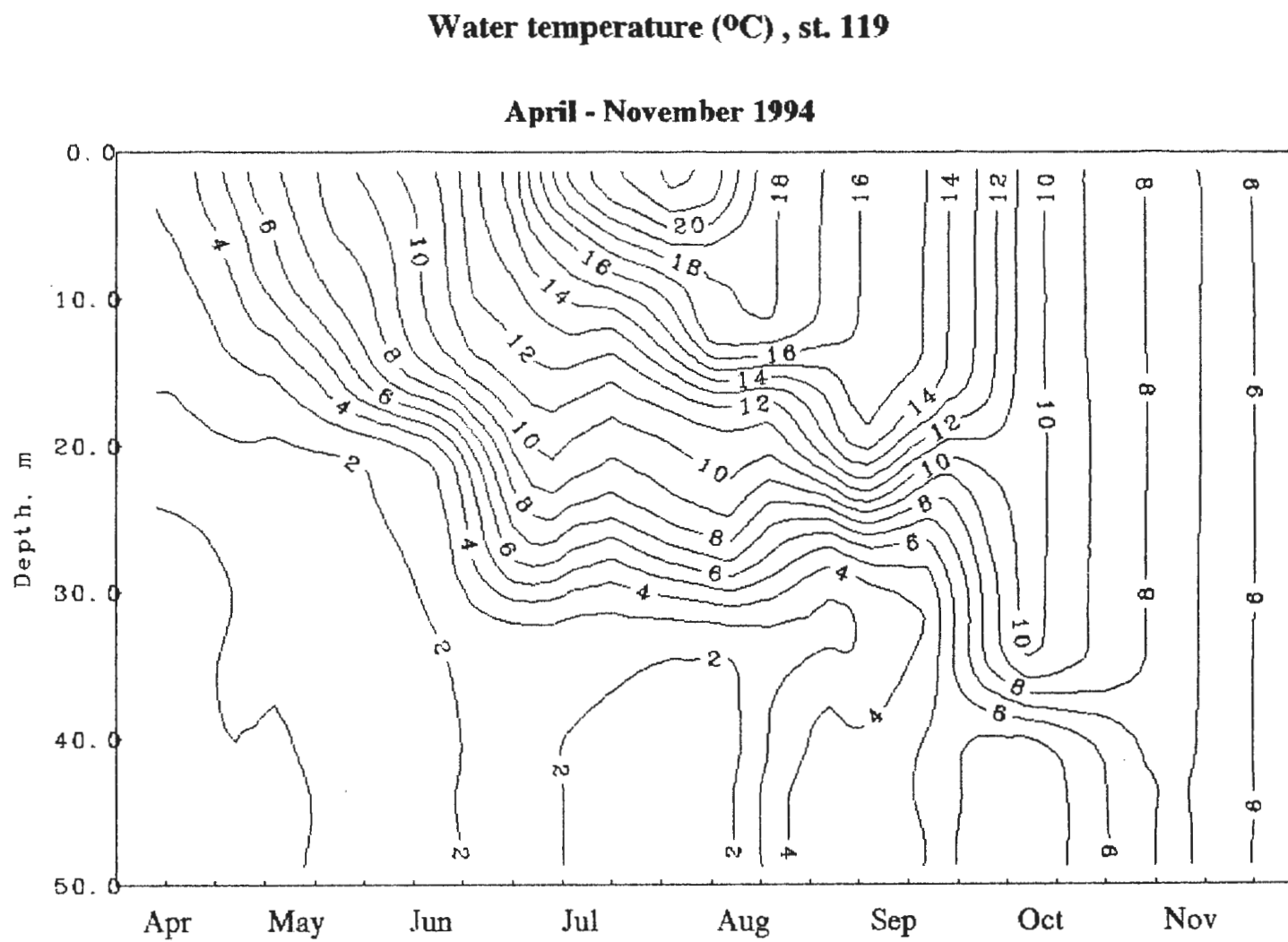
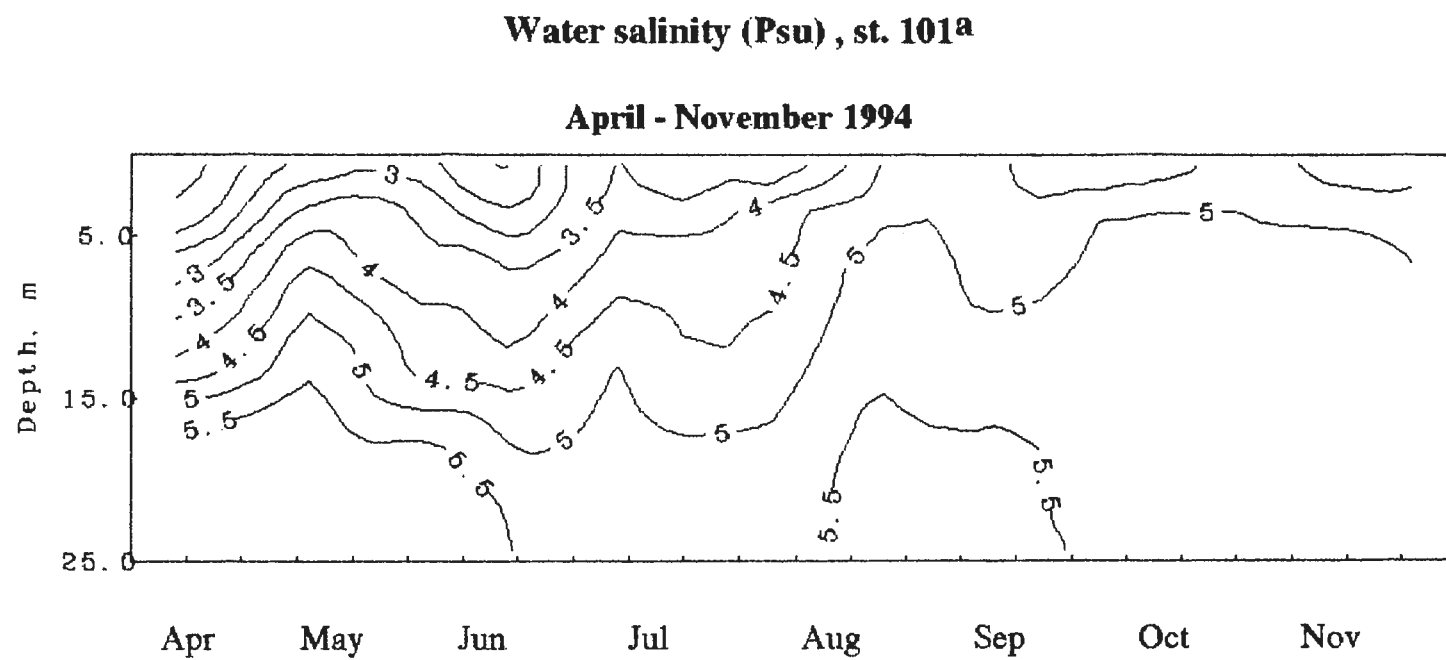
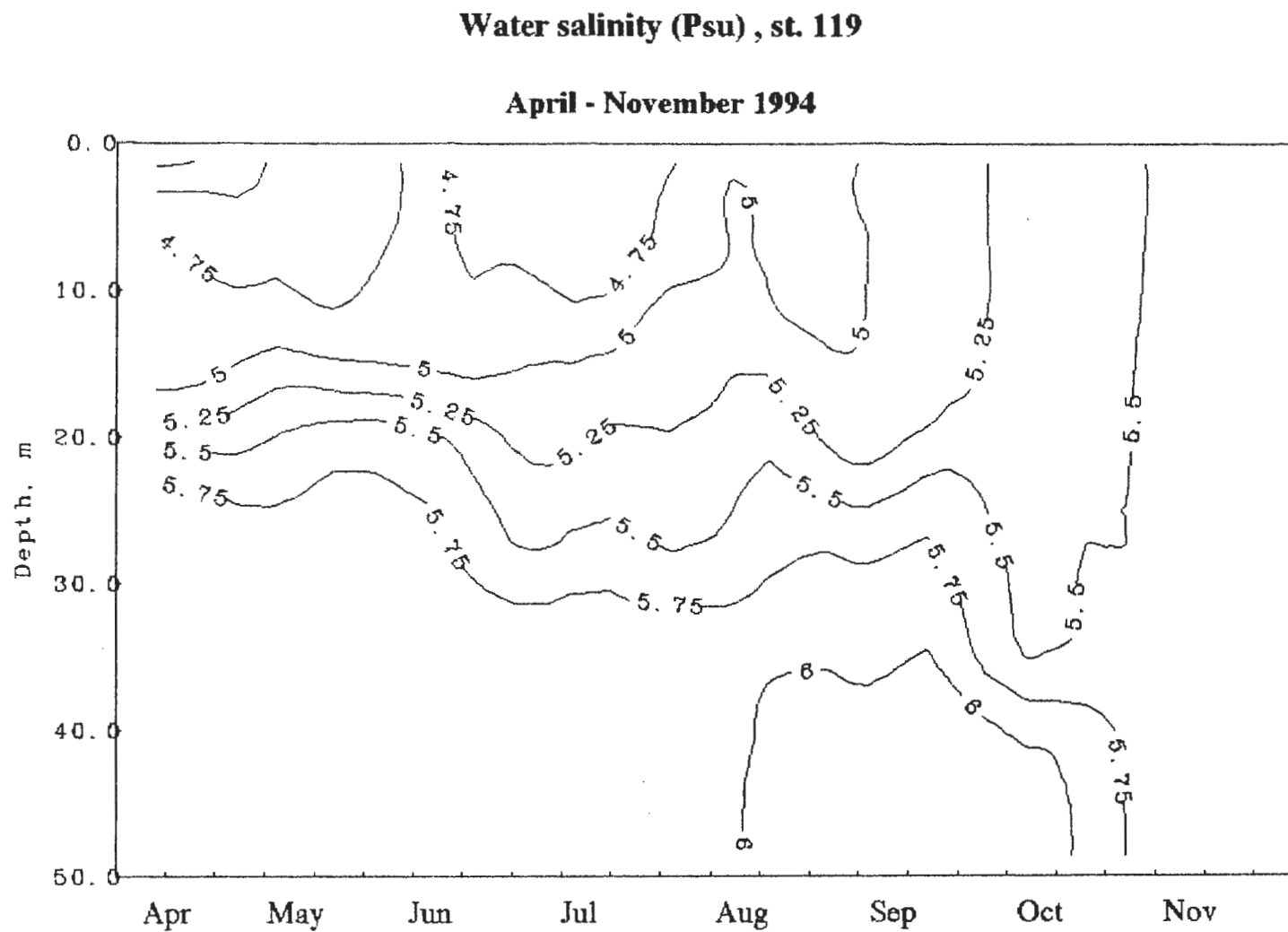


Fig. 4

**Fig. 5**

**Fig. 6**

**Fig. 7**

**Fig. 8**

Oxygen (ml/l), st. 101a

April - November 1994

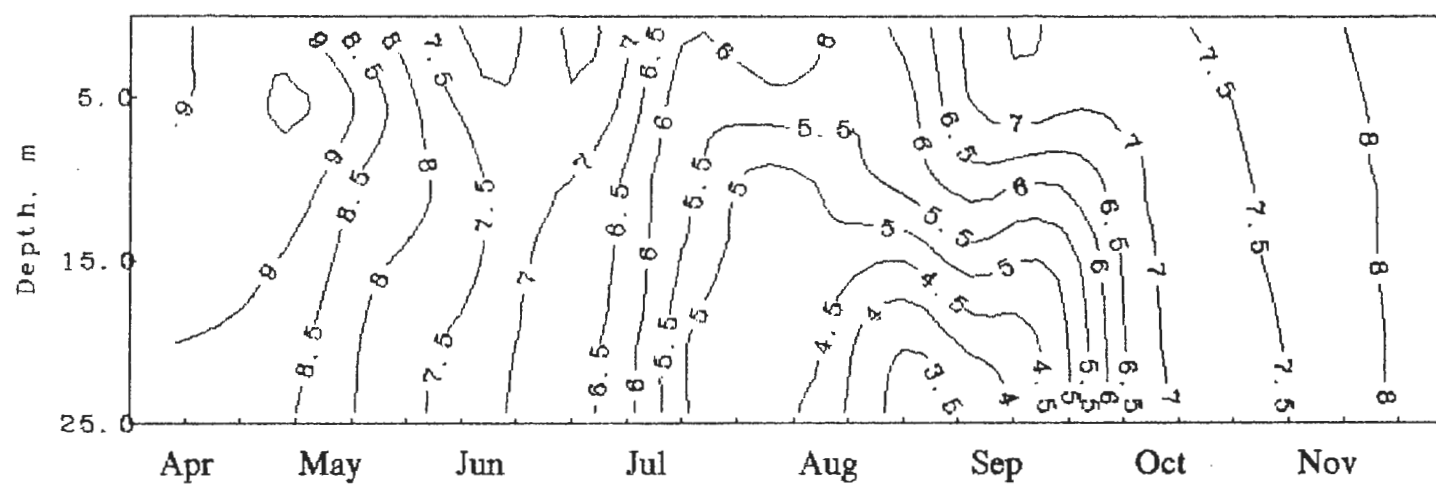


Fig. 9

Oxygen (ml/l), st. 119

April - November 1994

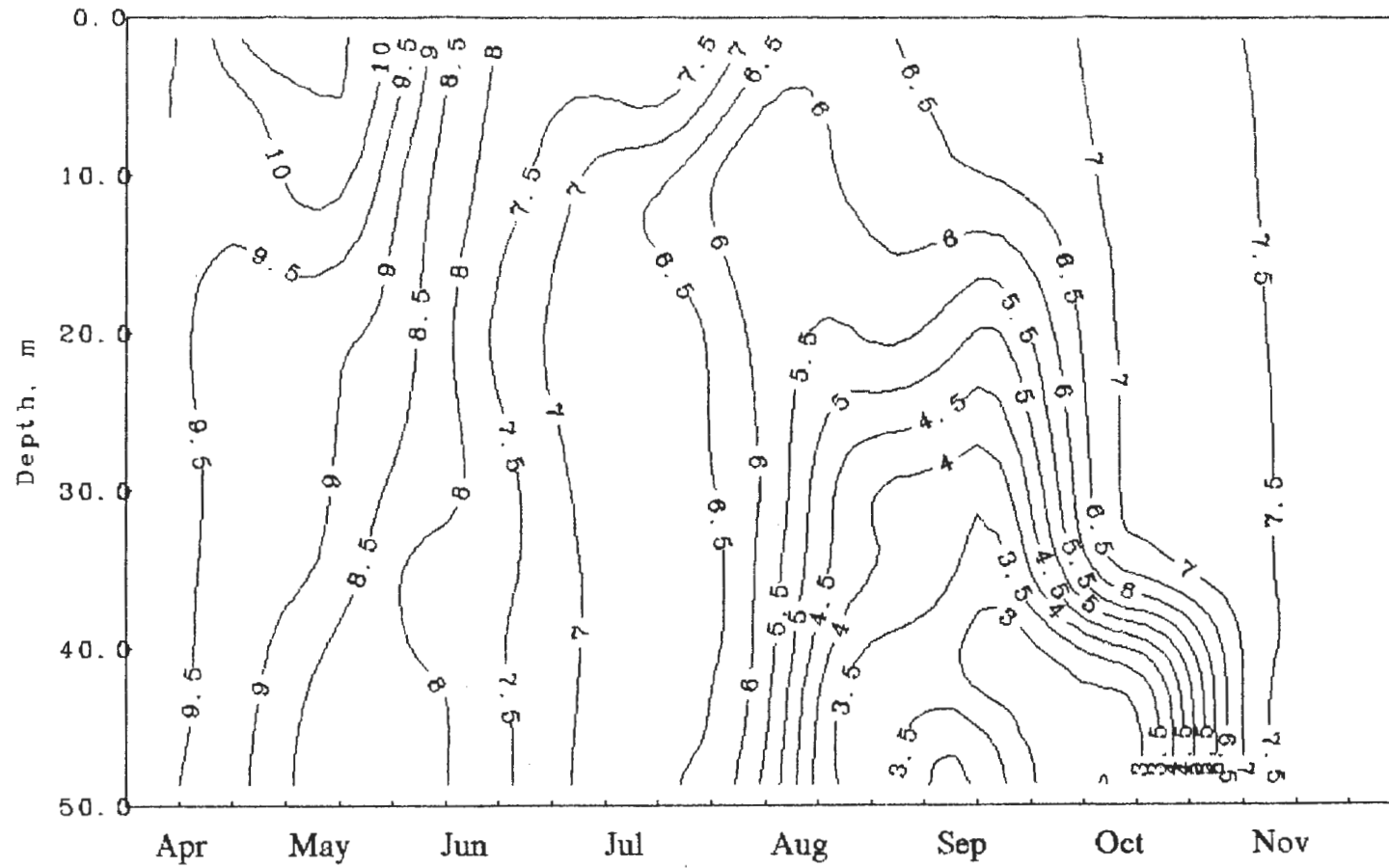


Fig. 10

9. Upwelling processes in the Gulf of Riga

by Evgeny Zaharchenko and Dagnia Fedorovich (Latvian Hydrometeorological Agency)

9.1 Introduction

Early studies of upwelling processes (Zaharchenko and Kostukov 1987) showed its importance in mixing and redistribution of all substances within the gulf, including spatial redistribution of the water temperature and salinity. Also a temporal scale of 1-15 days and a spatial of 10-100 km were determined for upwellings in the Gulf of Riga. A more active upwelling was distinguished along the western coast. The main goal of this contribution is to continue investigations on the upwelling processes in the Gulf of Riga.

9.2 Materials and methods

Taking into account the temporal-spatial scale of upwelling and historical data the following measurements were used in the analysis made in 1994:

- measurements of temperature and salinity from aboard the R/V Geofizikis, once per month along the 12-15 m isobath from the Cape of Kolka to Ainazi;
- measurements of temperature and salinity in the transect Roja, once per month;
- measurements of temperature at the coastal station Kolka, 4 times per day and at the coastal station Roja 2 times per day;
- measurement of salinity at the coastal station Kolka, once per day;
- satellite images;

The automated station was operated from June 17 to September 28. Temperature, salinity and current were recorded at an interval of 3 hours. Unfortunately, because of the sensor disrepair most of the current data were rejected. A scheme of the stations is shown in Fig. 1, and a list of the stations is given in Table 1.

Table 1 List of stations has been visited in the Gulf of Riga in April - November 1994.

Name of the station	Latitude	Longitude	Depth
162	N57° 19.1'	E024° 21.6'	13
163	N57° 10.3'	E024° 14.7'	13
164	N57° 06.2'	E024° 05.8'	16
101a	N57° 06.0'	E023° 59.0'	21
165	N57° 06.3'	E024° 00.7'	14
170	N57° 03.2'	E023° 29.2'	14
168	N56° 58.9'	E023° 42.5'	14
167	N57° 01.4'	E023° 55.3'	14
166	N57° 02.7'	E023° 58.1'	13
135	N57° 23.7'	E023° 58.1'	44
142	N57° 34.1'	E022° 59.6'	41
110	N57° 49.2'	E023° 03.7'	36
110a	N57° 49.2'	E022° 58.6'	40
111	N57° 49.1'	E022° 52.8'	39
112	N57° 49.1'	E022° 49.6'	31
119	N57° 17.5'	E023° 50.8'	44
103	N57° 10.3'	E023° 55.9'	38

9.3 Results and discussion

Peculiarities of hydrography of the Gulf of Riga in 1994

Large anomalies in the hydrographic parameters were observed in the Gulf of Riga in 1994. For the first time over the last 5 years the gulf was covered with ice completely. From the first of February to the middle of April, the ice covered the gulf and only in the middle of April the water temperature became higher than 0 °C. Due to a cold spring and early summer, warming of the water masses in the gulf was slow before July. The water temperature increase from May to June was only of the order of 2 °C. Judging from Fig. 2, one can see that in June the surface water temperature was 11 °C or about 2 °C lower than normal. In July, the warming was rapidly increasing, and surface water temperatures of 23 °C were recorded. This value is 0.5 °C higher than previous maximum recordings. In August, high temperature values continued, and the vertical temperature stratification was at its maximum. The temperature vertical structure was characterized by the absence of an upper quasi-homogeneous layer. Only in September, with the beginning of the water cooling, a thermocline started to develop. Later it deepened and became weaker, and in the beginning of November it disappeared. Thus, the most suitable period of observing the upwelling processes in the Gulf of Riga was July to August when a strong vertical temperature stratification dominated.

Also the salinity variations in the upper layer have a seasonal component due to the seasonal variations in the freshwater runoff and vertical convection processes (Fig. 3). Maximum surface salinities were measured during the autumn and early spring and minimum ones in summer. In the bottom layer, the salinity variations had a seasonal component forced by vertical convection processes mainly, and late in November vertical homogeneity was observed in the salt distribution. It should be noted that in May, June and August salt water intrusions through the Irben Strait were recorded, and a distinct increase was observed in the bottom layer. Also judging from Fig. 3 one can see that in August the halocline was clearly expressed. Taking into account the vertical salinity stratification, August is the most preferable period to observe an upwelling process.

Upwelling process in 1994

The upwelling processes in the Gulf of Riga is often caused by strong gradients in surface air pressure fields above the Baltic Sea area, the resulting wind transport can produce coastal divergencies. These upwelling events can reach the surface of the gulf if the upper quasi-homogeneous layer is less than 10 m. In other cases upwelling can be recorded in the sub-surface layer only (Zaharchenko and Kostukov, 1987). Also it was determined that the upwelling in the Gulf of Riga has a significant spatial nonhomogeneity, and a highly active upwelling was observed at the western coast. A typical case when upwelling reaches the surface of the gulf is shown in Fig. 4. The satellite image shows us a large spot of cold bottom water near the western coastline of the gulf, and a frontal zone between isotherms of 2.8 to 7.1°C is traced too. A deep water lifting at the western coast was stipulated by the current structure in this area. Judging from Fig. 5 one can see that in August 1994 the main maximum of the current distribution was oriented along the coast but the second one of 195 degree was oriented in the perpendicular direction to the coast. Just the last stipulate that cold and salt deep water was transported to the western coast.

As it was mentioned above, August 1994 was a period most preferable to observe upwelling processes in the Gulf of Riga. In August 5 to 11, a monitoring cruise was carried out in the gulf. The temperature and salinity distribution in the transect Roja show us that an upwelling process occurred during the observation period. Judging from Fig. 6, one can see that the isotherms from station 142 to station 173 had significantly risen, and at station 173 the vertical temperature gradient was the highest. Hence, the surface

temperature decrease, from 23 °C at station 142 to 20 °C, at the coast may be attributed to an upwelling process. Also the isohaline 5.5 psu (Fig. 6) shows a significant rise towards the coast.

The high spatial resolution of the observations made in August allow us to determine a peculiarity in the upwelling process. Fig. 7 shows that in August the highest vertical gradient of temperature was observed at the western coast and the most cold bottom water with a temperature of 5 °C was observed between station 172 and station 173. Simultaneously, at the southern and eastern coast the temperatures near the bottom were significantly higher and varied between 13 and 18 °C. The salinity vertical distribution was of the same character. Judging from Fig. 8, one can see that at the western coast the vertical gradient of salinity was quit strong and maximum salinity was observed near the cape of Kolka. At the southern coast, the influence of concentrated freshwater inflow was traced, determining the vertical salinity gradient and low salinity values of 3.5-4.5 psu. At the eastern coast, no vertical gradient of salinity was observed.

9.4 Summary

The paper presents the main results from investigations of the upwelling processes near the coastal zone of the Gulf of Riga in 1994. This year, large anomalies in the hydrography of the Gulf of Riga were recorded. The vertical structure of the water was very complicated. The last was attributed to an interaction process between the surface and the atmosphere and to the water exchange between the gulf and Baltic Proper. In 1994 the upwelling in the gulf was observed to take place in the subsurface layer along the western coast of the gulf. Most likely this event is a result of a coastally trapped south-eastward moving deepwater intrusion.

Reference

Zaharchenko E., and Kostukov J. 1987. Forecasting of upwelling processes in the western part of the Gulf of Riga , *Meteorology and Hydrology*, 6, 88-95 (in Russian).

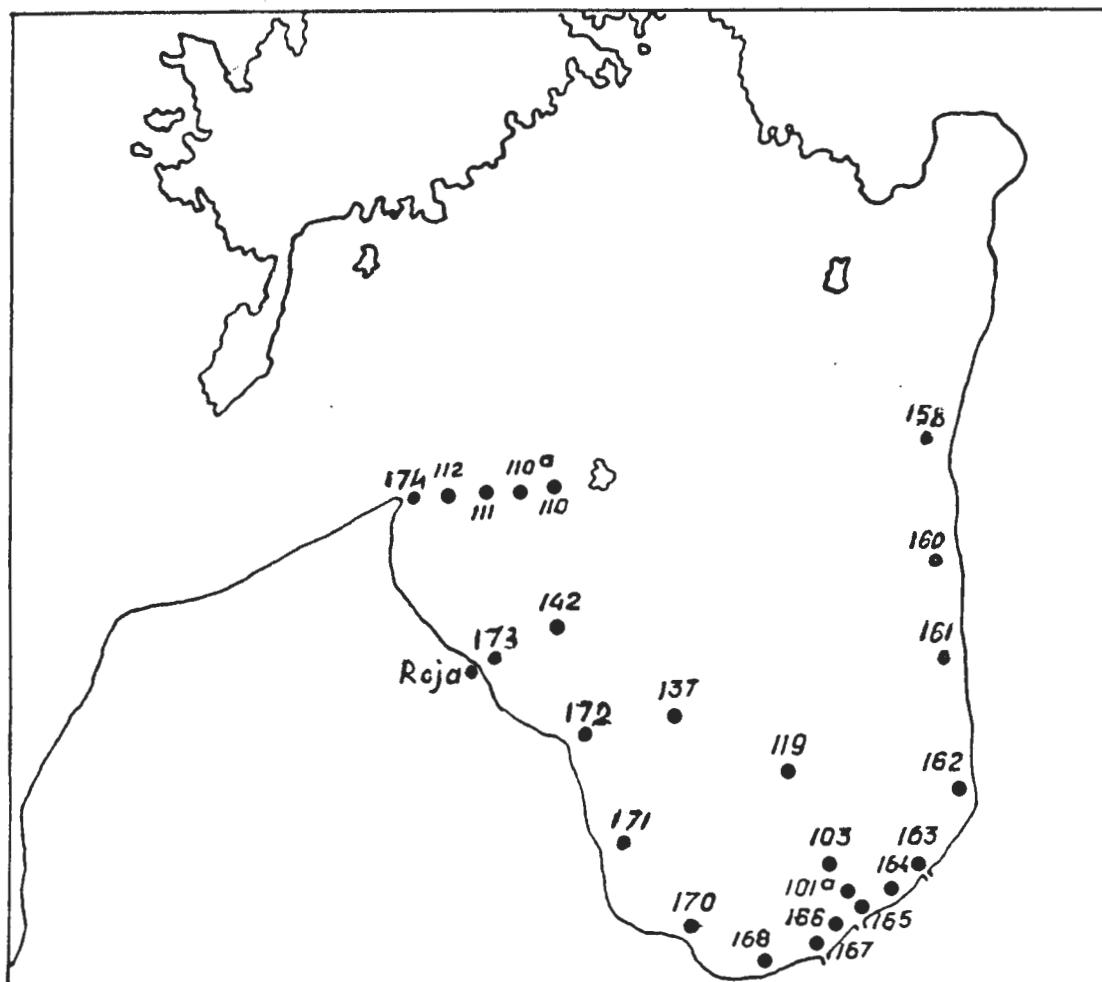
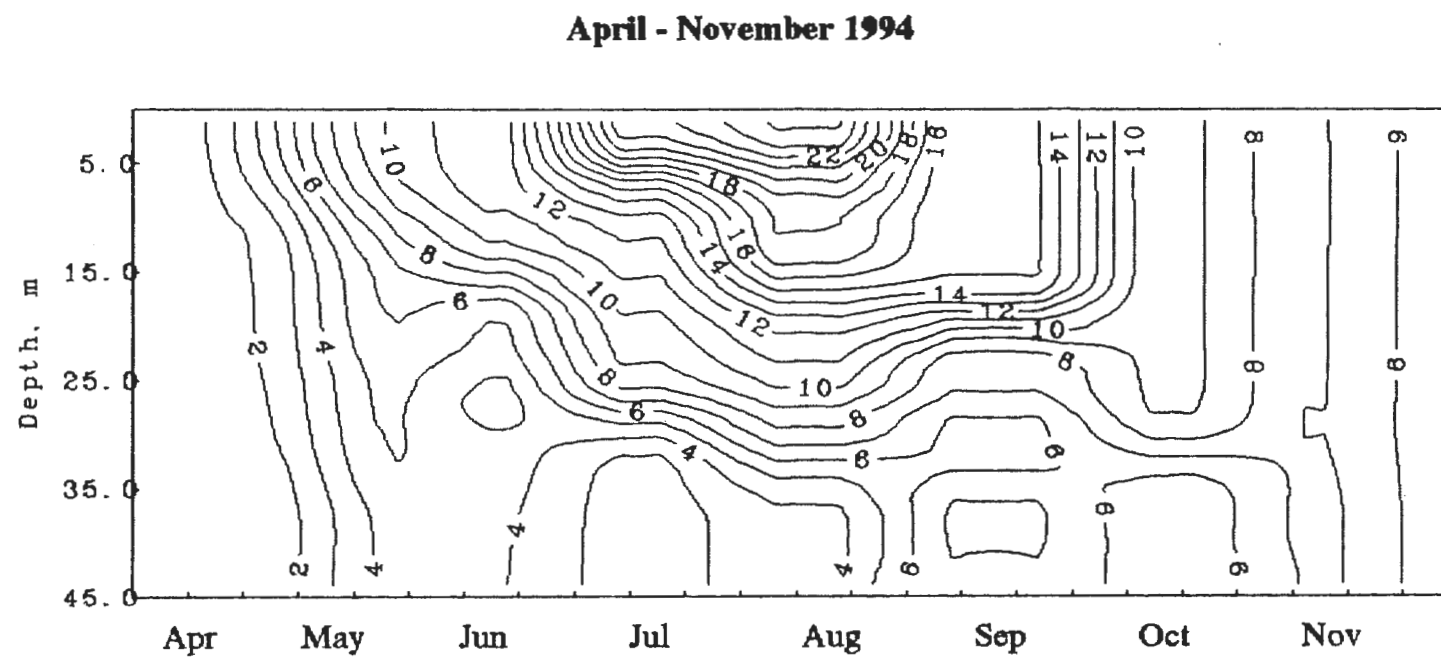


Figure 1. Scheme of stations has been visited in June - September, 1994.

**Fig. 2**

Temperature distribution (degree) at st. 142

April - November 1994

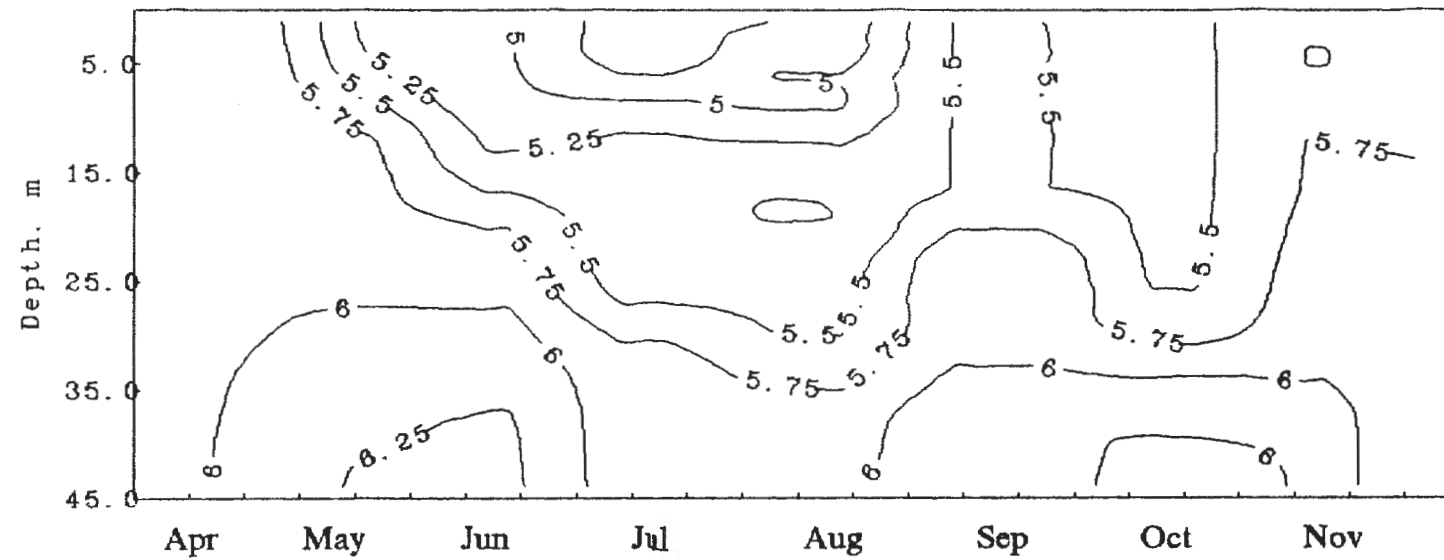


Fig. 3

Water salinity distribution (Psu) at st. 142

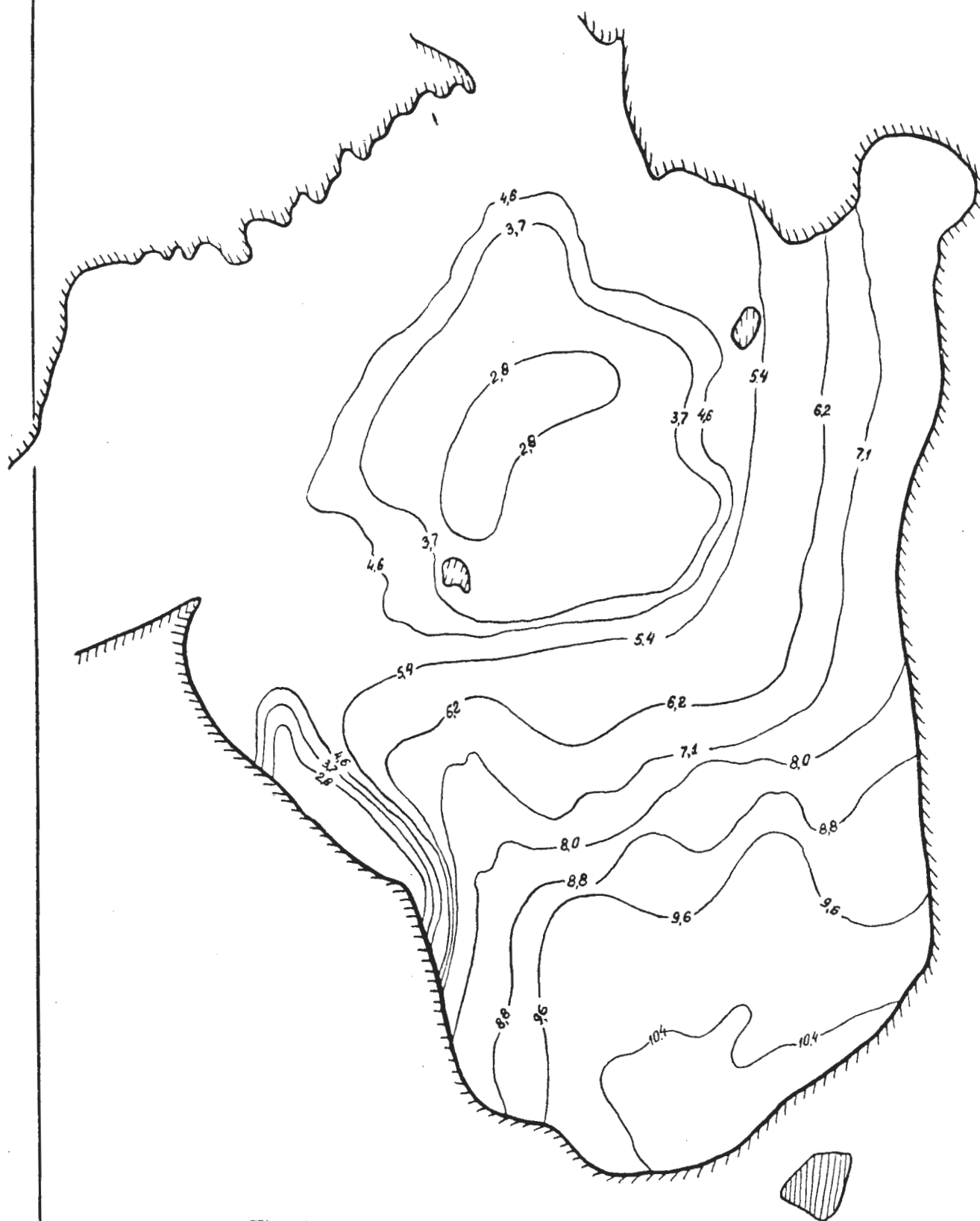


Fig 4

Radiation temperature (degree)
(NOAA-6, 1986-05-16)

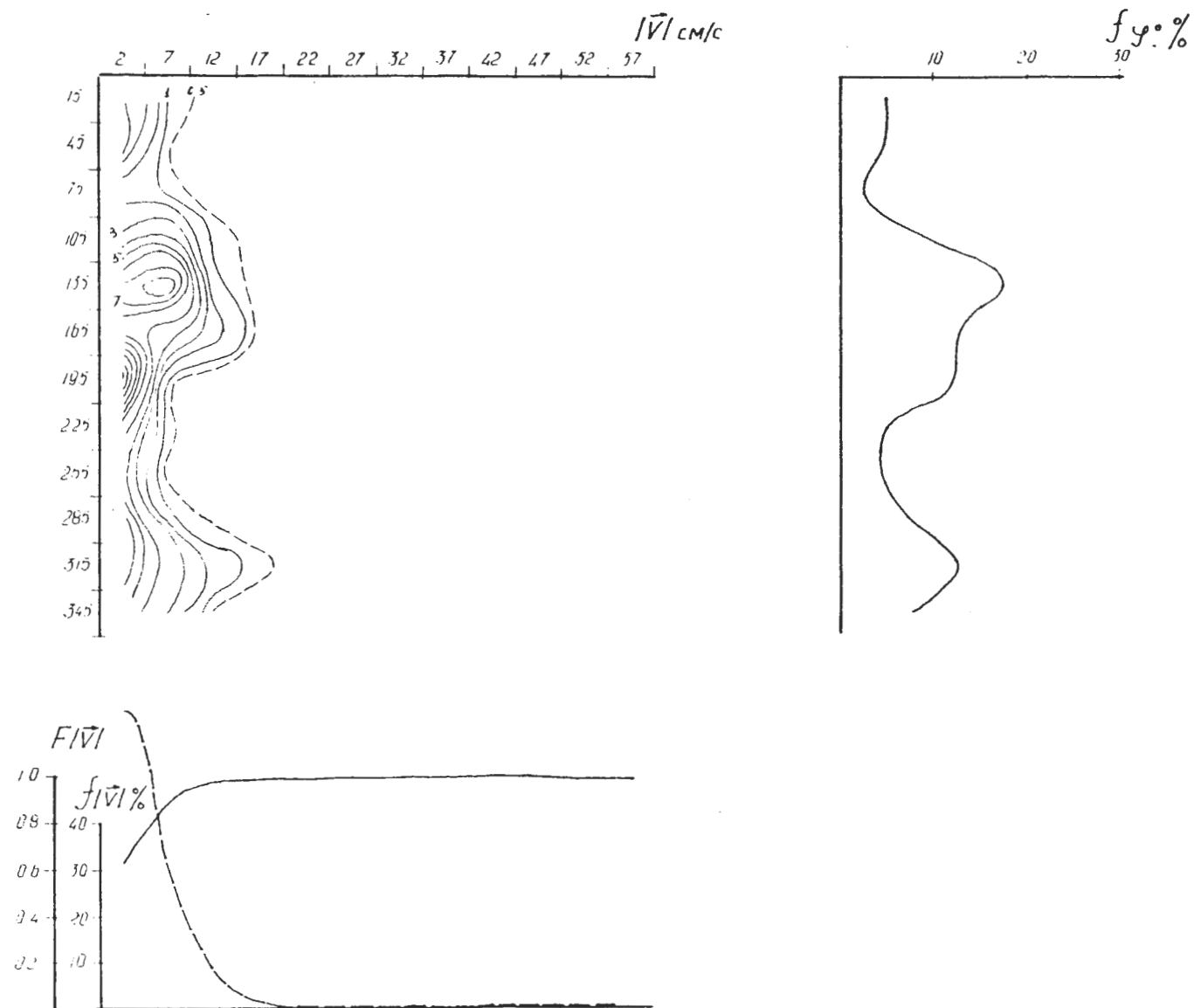


Fig.5

Two dimensional density in the current distribution
st. 173, August 1994

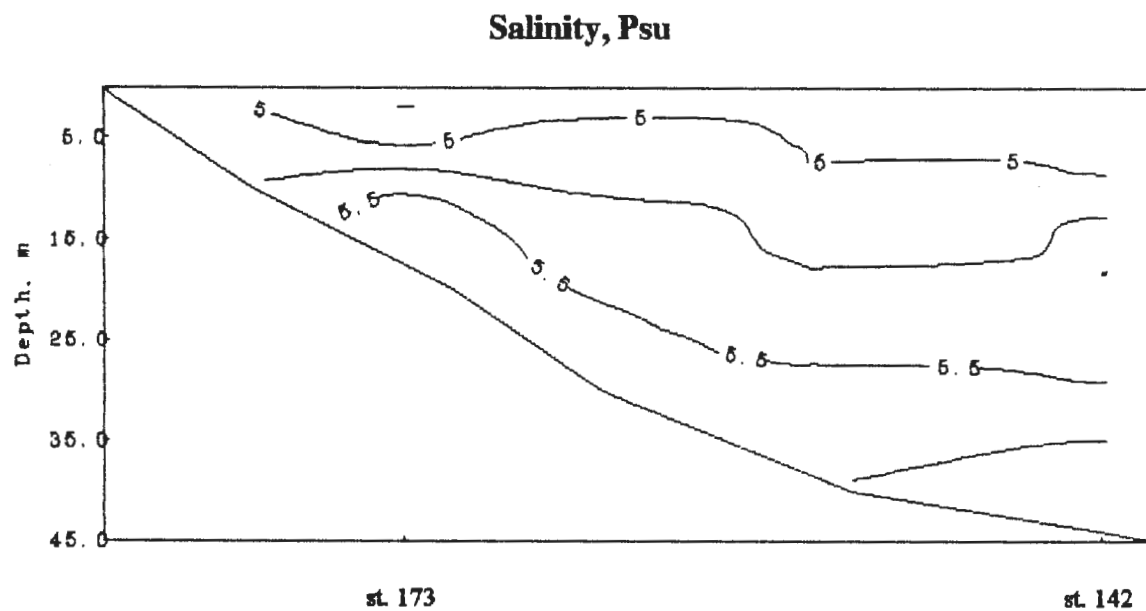
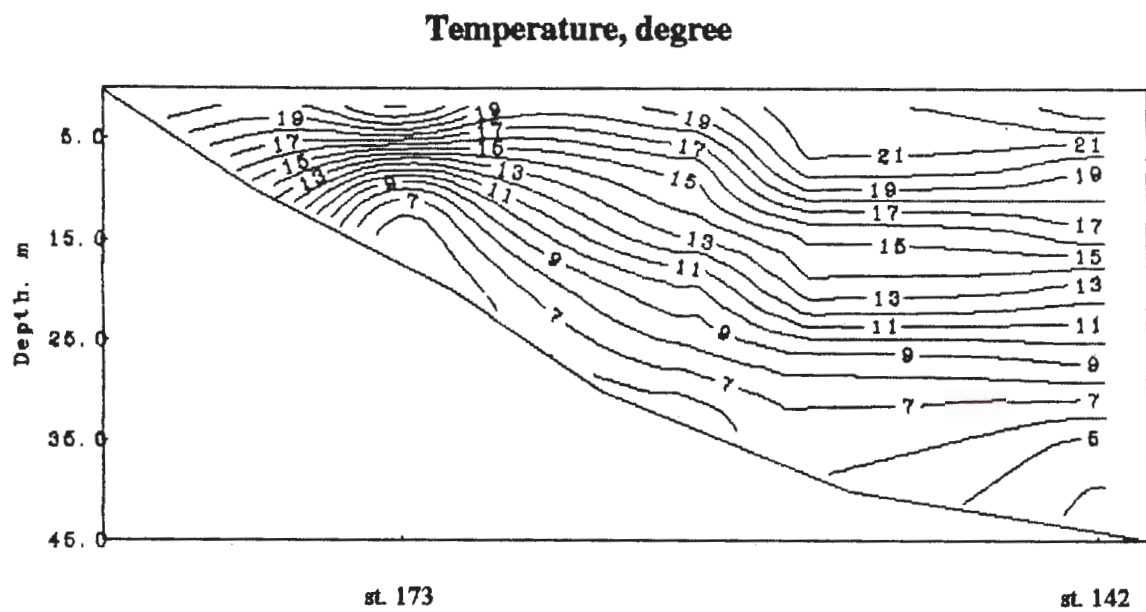


Fig. 6

**Temperature and salinity distribution along cross-section Roja,
August 1994**

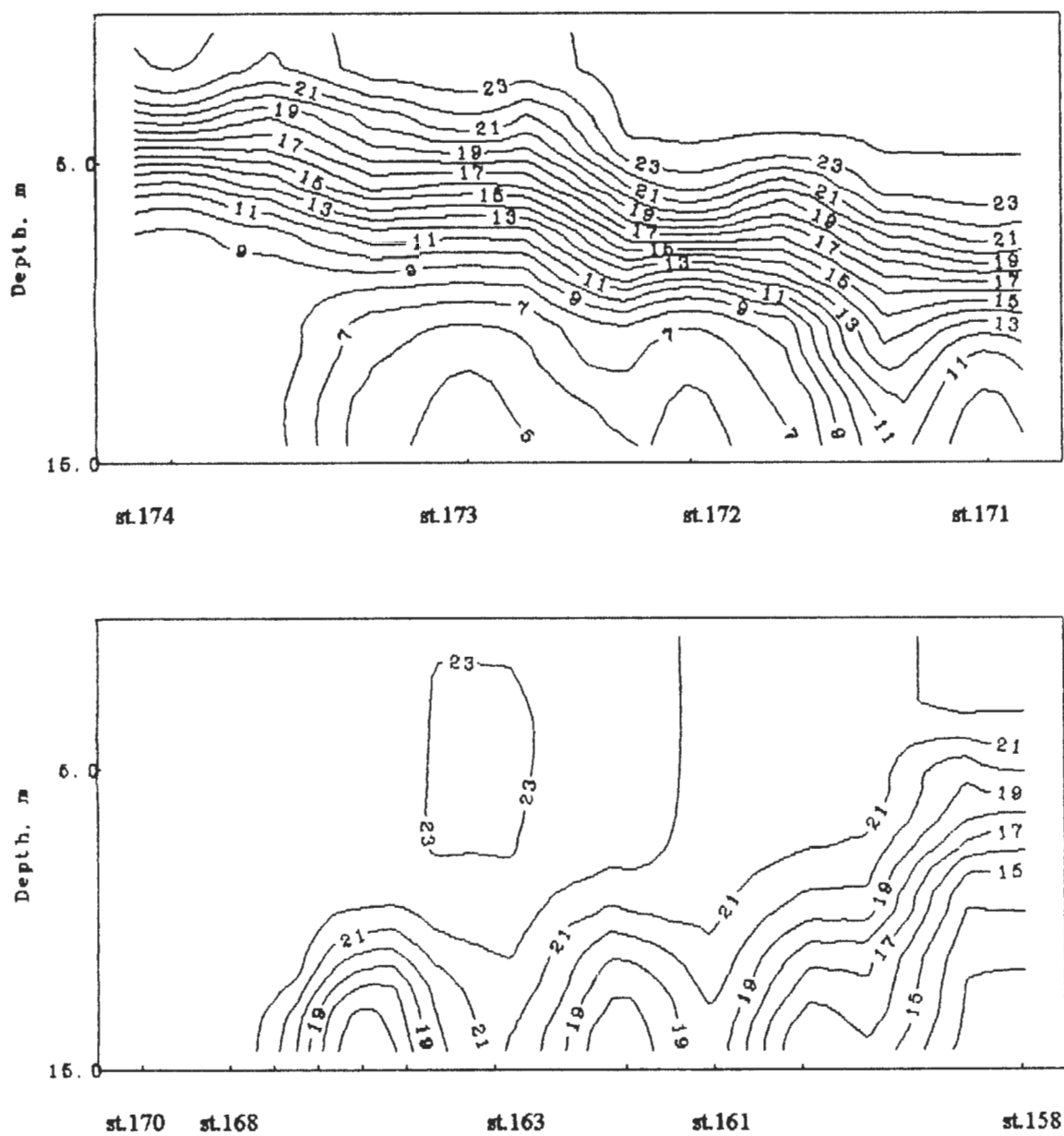


Fig. 7

**Temperature (degree) distribution along the coast,
August 1994**

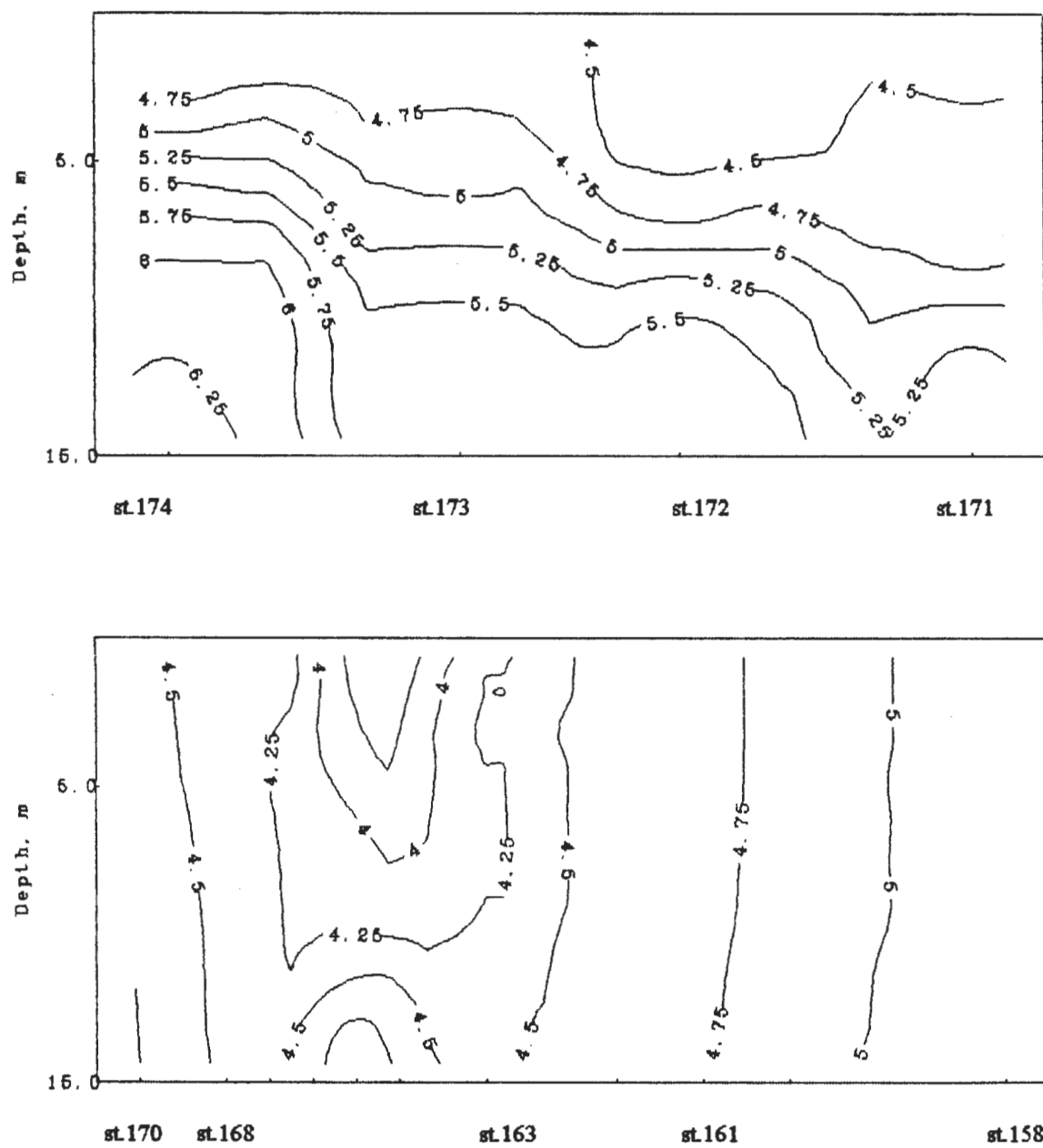


Fig.8

**Salinity (Psu) distribution along the coast,
August 1994**

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Haven runt Sverige 1991. Rapport från SMHI, Oceanografiska Laboratoriet, inklusive PMK - utsjöprogrammet. (The conditions of the seas around Sweden. Report from the activities in 1991, including PMK - The National Swedish Programme for Monitoring of Environmental Quality Open Sea Programme.)
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