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# GULF OF BOTHNIA YEAR 1991

## PHYSICAL TRANSPORT EXPERIMENTS

Swedish Meteorological and Hydrological Institute
Finnish Institute of Marine Research
Canada Centre for Inland Waters

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Title (and Subtitle)

The Gulf of Bothnia Year-1991
Physical transport experiments

Abstract

The Gulf of Bothnia Year 1991 project was a multi-disciplinary programme aiming at a better understanding and knowledge of the ecological system of the northern part of the Baltic Sea, including also the physical processes affecting the system. This report describes the Finnish-Swedish-Canadian physical sub-programme for studies of sea currents and hydrography of the Bothnian Sea. General results of the field experiments are given as well as the marine meteorological, river runoff and ice conditions during the experiment.

Coastal-open sea exchange and deep-sea mixing processes were investigated using moored current meters and thermistor chains, satellite-tracked drifting buoys and satellite images. The measurements from the coastal transect moorings and some surface layer drifter experiments indicate a weak cyclonic circulation within a coastal boundary layer, the extent of which depends on the depth. The width of the boundary layer varies from a few kilometres at deep coasts to a couple of tens of kilometers in shallow coasts. This circulation is superimposed on burst-like events of alongshore currents, strongly varying both in time and direction and highly wind-dependent. The open sea currents were dominated by inertia and wind-driven currents.
Cont. on next page.

Key words

Physical oceanography, river runoff, hydrography, currents, drifters, remote sensing.

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The drifter experiments and wind observations from the Swedish coast in the northern Bothnian Sea indicate an eastward drift. The typical drift velocity of the surface waters were found to be roughly 1.6 % of the wind speed, indicating that the surface waters can mix horizontally within a couple of months. Cluster drifter experiments performed in the surface layer indicate stronger horizontal dispersion characteristics during quite calm summer conditions than in the autumn during strong winds. The lateral dispersion coefficients varied from $10^5$ $cm^2$ $s^{-1}$ to $10^4$ $cm^2$ $s^{-1}$ respectively. In general more complicated spreading characteristics were found in the north-western part of the Bothnian Sea than above the gently sloping south-eastern part of the basin.

The deep sea velocity measurements with current meters and with a drifter experiment showed also northward currents in the central Bothnian Sea and Bothnian Bay. Interestingly enough in the very deep parts of the basin, 5 meters above the sea floor, high speed burst-like events were observed with velocities up to 30 cm/s.

The hydrography of the Gulf of Bothnia was studied using a network of hydrographic stations, dense both in time and space. Some intensive hydrographic open sea stations and coastal sections were visited once a month for investigations of the time evolution of the hydrographic conditions. The temperatures of the Bothnian Sea were during the field year higher than the monthly mean values from the two preceding decades. The winter of 1990/91 was mild and the weather was warm in July, August and September. The salinities showed negative anomalies at all occasions.

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## List of acronyms

| | |
|---|---|
| GB-91 | Gulf of Bothnia Year-1991 |
| SMHI | Swedish Meteorological and Hydrological Institute |
| FIMR | Finnish Institute of Marine Research |
| NFR | Swedish National Science Research Council |
| CCIW | Canada Centre for Inland Waters |
| NWRI | National Water Research Institute (Burlington, Ontario, Canada) |
| IFYGL | International Field Year on the Great Lakes |
| CBO | Conference of Baltic Oceanographers |

## PREFACE

by Ulf Ehlin, Baltic Marine Environment Protection Commission, Helsinki Commission, Finland

In 1972 Finland and Sweden signed an agreement to co-operate on investigating the degree of pollution of the Gulf of Bothnia, demonstrate long-term changes in the environmental conditions as well as to recommend measures to improve the situation. Simultaneously the Committee for the Gulf of Bothnia was established to plan, co-ordinate and evaluate the work. The Committee has, since then, co-ordinated research activities and worked for intensified co-operation between individual programmes.

To increase the understanding and knowledge of the ecological system of the Gulf of Bothnia, a multi-disciplinary field programme covering at least one year was suggested by the Committee. Authorities, research institutions and universities in Finland and Sweden were engaged to take part in the field programme. It includes various elements, such as input of compounds from land and atmosphere, physical transports within and between sea basins, as well as the distribution of pollutants in the sea from different sources. Critical chemical and biological processes regulating the internal turnover of nutrients have been studied. Monitoring of pollutants has been combined with studies of the effects of different environmental toxins. Stock assessment of fish and investigation of the food quality of fish have been emphasized. Ecological modelling is used to synthesize the results from individual research teams.

In spite of many years of marine research in the Gulf by Finland and Sweden, knowledge of physical transports and exchange processes in the Gulf of Bothnia has been rather poor. However, the investigations carried out during the Gulf of Bothnia Year and reported in this publication are an important and necessary contribution to our understanding of how water and material are transported. The results also create new questions and ideas for further studies.

Dr. Raj Murthy from the Canada Center for Inland Waters, with his great experience from similar studies in the Great Lakes, has been an utmost important participant in the Gulf of Bothnia 1991 programme. The support by the institute he represents is also highly appreciated by the Committee of the Gulf of Bothnia. The Gulf of Bothnia Year has in this way become a project of even more international interest than foreseen by the Committee.

## ACKNOWLEDGEMENTS

A scientific undertaking of this magnitude would not have been possible without the support and encouragement of Pentti Mälkki, Director, Finnish Institute of Marine Research, and Rod Allan, Director, Lakes Research Branch, National Water Research Institute, Canada Centre of Inland Waters. We further acknowledge the Swedish Coast Guard, the Finnish Coast Guard and the crew on board R/V Argos and R/V Aranda.

Also thanks to Mrs. Vera Kuylenstiema for skilful word processing of the report.

# CHAPTER 1

## OVERVIEW OF THE GB-91 PHYSICAL TRANSPORT EXPERIMENTS
by Raj Murthy, Canada Centre for Inland Waters, Canada

### 1.1 Introduction

Most direct human impact on the marine environments occurs close to the shore and therefore the nearshore zones are the areas of most immediate interest to the public. Several physical factors combine to make the nearshore zone quite unique in its hydrodynamics, and the related physical transport and dispersion properties of the nearshore flow are quite complex. The practical importance of this recognition is quite obvious for waste disposal, nearshore erosion, recreation, navigation and many other uses of the nearshore waters.

The physical factors that govern the nearshore flow structure during the ice-free conditions are the wind stress, the bathymetry, the stratification of the water column, the Coriolis force due to earth's rotation and the effects of lateral and bottom friction. The physics of the nearshore flow field is even more complicated in the presence of ice.

All these physical factors contribute to generate complex nearshore flow field as compared to the offshore flow field. These properties play a profound role on the biogeochemical processes in this zone. The fate of the river borne nutrients and pollutants released is just one example. Their residence time and their degree of accumulation in the sediments are determined partly by exchange processes and partly by biotic processes active in the nearshore/offshore region. These processes are identified and their importance is recognized in the background document to the current Swedish Project "Large-scale environmental effects and ecological processes in the Baltic Sea" (Anon., 1989). Though high concentrations of these substances are found in the coastal sediments (Figure 1.1) close to the discharge areas mass balance calculations place their main storage in the offshore region (F. Wulff, pers. comm.). In fact, the major part is found in the Baltic proper despite the concentration of the industrial polluters in the Bothnian Sea. Obviously coastal flow fields and the nearshore/offshore exchange processes must govern these transports.

There are several conceptual models and theoretical ideas concerning the dynamics of the coastal waters (Csanady, 1982; Walin, 1972a; Simons, 1980). However, it is difficult to identify the relative effects of different physical processes in any specific situation to arrive at an adequate predictive deterministic model. Recognizing this difficulty, it is therefore not surprising that current coastal oceanographic research places considerable emphasis on carefully designed experiments to collect long time series data on currents, density structure, diffusion characteristics and other supporting hydrological and meteorological data at several coastal sites. Generally there are several interrelated objectives for such coastal oceanographic experimental programs. Some objectives are site-specific in nature others are directed towards the understanding of fundamental coastal dynamical processes. A good example, more appropriate for the Baltic Sea, is the coastal experiments undertaken by the Canada Centre for Inland Waters (CCIW) for well over two decades on the North American Great Lakes, in particular Lake Ontario (Murthy and Blanton, 1975; Bull and Murthy, 1980; Murthy et al.,1976). The initial thrust for the CCIW Coastal Exchange Experiments was provided by the International Field Year on the Great Lakes (IFYGL) carried out on Lake Ontario in 1972/73. Following the success of IFYGL, CCIW has undertaken several coastal exchange experiments in the Great Lakes. These experiments have produced an impressive collection of data sets on the climatology of coastal currents, temperature structure, dispersal characteristics and related hydro-meteorological parameters for several coastal regions of the Great Lakes and have significantly contributed to our understanding of coastal transport processes (Boyce, 1974 and 1977; Blanton, 1974 and 1975; Csanady and Scott, 1974 and 1980; Csanady, 1972a and 1972b; Murthy, 1973 and 1976; Murthy and Dunbar, 1981; Murthy et al., 1986; Lam et al., 1980).

In the Baltic Sea there is a serious gap in our understanding of coastal physical transport processes, although some limited studies have been carried out mainly in the Baltic proper (Walin, 1972b; Mälkki, 1975; Alenius and Mälkki, 1978; Shaffer, 1979; Gidhagen, 1987; Kullenberg, 1978; Schott and Quadfasel, 1979; Jankowski and Catewicz, 1984; Engquist and Omstedt, 1992). Such understanding is vital, dealing with the current and emerging environmental problems in several coastal areas of the Baltic Sea, in particular the Gulf of Bothnia. The Gulf of Bothnia Year-1991 (GB-91) provided a unique opportunity to plan a comprehensive coastal physical transport experiments.

## 1.2 Objectives

(1) To determine the coastal climatology of currents and density structures, coastal boundary layer characteristics, baroclinic coastal jet and coastal upwelling characteristics from carefully designed coastal transects of moored current meter stations, detailed hydrographic surveys, and remote sensing data.

(2) To determine the Lagrangian properties of coastal exchange characteristics, kinematic particle trajectories and horizontal diffusion characteristics of the upper mixed layer from carefully conducted Lagrangian drifter cluster experiments and remote sensing data.

(3) To investigate the deep sea mixing characteristics during ice-covered and ice-free conditions from moored current meters and hydrographic surveys.

(4) To relate these physical transport and dispersion characteristics to the fate and pathways of chemical substances and estimate nearshore/offshore exchange of these substances within the coastal zone.

(5) To establish a data base for developing and validating coastal hydrodynamic transport and dispersion models for effluent discharges within the coastal zone.

These objectives were carefully considered in the design of the physical transport experiments during the Field Year.

## 1.3 Experiments

In the Great Lakes coastal physical transport experiments, the basic design to collect physical data consisted of laying coastal transects perpendicular to the local shoreline and bathymetric contours with a network of stations distributed along the coastal transect extended typically to 20 - 25 km offshore. Along the coastal transect self-recording current meters, meteorological measuring systems and fixed temperature profilers were placed in preselected mooring stations. The very nearshore network of stations was spaced to cover scales of motion that govern the transport and dispersion of waste effluent plumes other related coastal engineering aspects, such as shore erosion, sediment transport, etc. The offshore network of stations was designed to resolve large scale physical transport and mass exchange processes within the coastal boundary layers.

Great Lakes coastal physical transport experiments provided a good framework to design and plan similar experiments during the Gulf of Bothnia Year. Several distinct but inter-related experiments were planned to be carried out more or less concurrently during the intensive mooring cruises of R/V Argos (Sweden) and R/V Aranda (Finland). Figure 1.2 shows the schematic lay-out of the physical coastal transport experiments in the Gulf of Bothnia. A brief description of the several coordinated physical experiments conducted during GB-91 is given below, details of the individual experiments is given in the appropriate chapters.

(a) Eulerian experiments:

Two coastal transects consisting of a network of current meter mooring stations in coastal chain extending to 50 km and placed perpendicular to the local shoreline and bathymetric contours at Högbonden on the Swedish coast and at Rauma on the Finnish coast. These coastal sites have been chosen to provide qualitatively different topographic and hydrographic conditions. The complex topography off Högbonden stands in sharp contrast to the gentle bottom slope off Rauma. In addition to the current meter moorings, 1 - 2 fixed temperature profilers (thermistor chains) were included in the coastal transects. In addition to the two coastal transects, three open sea mooring stations (F9, US5 and SR5) with current meters at three levels 5, 15 and 50 m above the sea floor were also installed. At each level in addition to current measurements, temperature as well as salinity was also measured. The main aim of these open sea observations is to investigate the deep sea velocity characteristics during ice covered and ice-free conditions and to integrate the open sea physical experiments with coastal physical experiments. Therefore stations US5 and SR5 formed the offshore stations for the Högbonden and Rauma coastal transects respectively. The three deep water current meter stations were operational from November, 1990, to November, 1991, and covered both ice covered and ice free periods. The actual design of the coastal transect and the distribution of the instruments in the two coastal transects differed somewhat and is discussed in the individual chapters.

(b) Lagrangian experiments:

Cluster of drifting buoys (minimum of 6 - 8) set at 5 m depth, equipped with Argos transmitters were tracked continuously at least for 5 - 6 days (10 - 12 inertial periods) in both the experimental sites during the scheduled intensive cruises of R/V Argos and R/V Aranda. A second series of Lagrangian drifter experiments at selected current meter mooring stations in the coastal transect were conducted to identify different water masses and mesoscale eddy structure in support of the remote sensing experiments. Individual drifters set at different depths were also tracked for longer duration (10 - 60 days) to track currents and possibly to determine deep water exchange between basins. Individual drifter experiments to track water masses were planned in between periods of Lagrangian cluster experiments. The type and number of the Lagrangian experiments at the two experimental sites varied somewhat and the details are discussed in the chapters dealing with Lagrangian experiments.

(c) Remote sensing:

Images from NOAA weather satellites are analysed to retrieve sea surface temperature and suspended matter. These parameters can be used to identify and track water masses during coastal upwellings and to estimate surface drift velocity of the water masses from sequential image data. Also the sea surface temperature may be used to determine the synoptic spatial variability of water masses. From a general point of view the Lagrangian drifter data and the satellite image data are complementary. The satellite images can provide information about the spatial and temporal variability of the water masses while the drifters are being followed. During the field year 1991 images from the NOAA satellites were achieved, covering the Gulf of Bothnia and the northern part of the Baltic Proper. 64 days were covered with images.

(d) Hydrographic surveys:

Coastal hydrographic surveys were carried out along the main coastal transects in both experimental sites to coincide with the Lagrangian drifter experiments. A dense network of stations (approximately 2 km apart) were used for hydrographic surveys to resolve the horizontal and vertical gradients and scales of motion. To smooth out the effects of the inertial oscillations, a staggered grid of stations was used. On the onshore survey beginning at deep sea current meter stations US5 or SR5, 4 km station spacing was used. For the offshore survey, the stations were staggered with 4 km spacing. Swedish and Finnish hydrographic surveys differed considerably depending on the availability of the ship and the details of the surveys are given in the individual reports.

(e) Hydrological and meteorological observations:

Hydrological and meteorological data are very crucial for the analysis and interpretation of the data and results of the physical transport experiments. With this in mind, all available hydro-meteorological data are compiled and analysed. The data base includes data from synoptic weather stations (ship observations), synoptic water level stations, river runoff data, ice and sea surface temperature charts. A single chapter will summarize all the hydro-meteorological data base for the Gulf of Bothnia during the Field Year.

## 1.4 Operational plans

The general operational plans for the GB-91 physical transport experiments were developed together with Raj Murthy during the summer of 1990 while he was visiting SMHI. A workshop was convened in February, 1991, at Tvärminne, Finland, to discuss and draw up the detailed operational plans. A joint Swedish and Finnish working group of scientists from SMHI and FIMR after detailed discussions during the workshop finalized individual operational plans for the Swedish and Finnish experiments. Table 1.1 gives the schedule of the physical transport experiments carried out during the Gulf of Bothnia Year-1991. The two operational plans were followed in conducting the experiments, while maintaining close coordination whenever possible. The experiments were successful with detailed data in return.

*Table 1.1. Physical transport experiments schedule.*

| | J | F | M | A | M | J | J | A | S | O | N | D | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1990 Planning**<br>Deep sea current meters | | | | | | | | | 1 | | | | **1) 1990-CBO Conf. Norrköping**, GB-91 Oper. plans |
| **1991 Experiments**<br>Coastal current meters<br>Lagrangian drifter<br>Remote sensing<br>Hydrographic surveys | | 2 | | | | | | | | | | 3 | **2) GB-91 Scientific planning meeting**, Tvärminne, Finland<br>**3) GB-91 Data analysis meeting**, Helsinki, Finland |
| **1992 Data analysis**<br>Climatological summary reports | | | | | | 4 | | | | 5 | | | **4) GB-91 Special symposium - IAGLR 1992**<br>Waterloo, Ontario, Canada<br>**5) 1992-CBO Conference**<br>St. Petersburg, Russia |
| **1993 Scientific analysis**<br>Scientific papers and reports | | | 6 | | | | | | 7 | | | | **6) GB-91 Interdisciplinary workshop**, Åbo/Turku, Finland<br>Data and information exchange: Interdisciplinary<br>**7) GB-91 Conference**<br>Umeå, Sweden, Scientific results |
| **1994 Scientific synthesis** | | | | | | | | | 8 | | | | **8) 1994-CBO Conference**<br>Scientific synthesis |

## 1.5 Data summary and analysis

Following the conclusion of the experiments, Swedish/Finnish working group of scientists from SMHI and FIMR, who participated in the Field Year met at Helsinki in December, 1991, to discuss the next phase namely the preparation of data summaries and scientific analysis. Towards an orderly presentation of the GB-91 physical transports data base, the scientific working group established the following plans:

Phase (1) Develop and/or adapt existing computer software, data analysis procedures and techniques, computer graphics and common format for the presentation and documentation of the data base;

Phase (2) Develop and/or adapt statistical and climatological methodologies necessary for the preparation of the summary reports; and

Phase (3) Prepare statistical and climatological summary reports, as a prerequisite before the scientific analysis of the data.

The data analysis is planned to be undertaken in three phases:

Phase 1 is exclusively devoted to the organization, preparation and documentation of the complete data base on a mutually agreed common format and to the preparation of statistical and climatological summary reports of the entire GB-91 physical transports data base. Some of the subreports were presented at IAGLR-92 Waterloo, Ontario, Canada and at CBO-92, St. Petersburg, Russia to expose the Great Lakes and Baltic scientific community to the initial results of the Gulf of Bothnia Year-1991.

Phase 2 activities on detailed scientific analysis of the physical transport processes is actively promoted and encouraged among all the members of the scientific group either through individual or collaborative efforts. The bulk of the scientific analysis is expected to be completed in time for the special workshop organized by the Gulf of Bothnia Year Organizing Committee in October, 1993, at Umeå, Sweden.

The final phase (phase 3) will be devoted to the preparation of the scientific synthesis reports by the joint Swedish/Finnish scientific group to evaluate and summarize the important scientific results within the context of the overall objectives of the Gulf of Bothnia Year-1991. Also in this final phase of the data analysis modelling development and evaluation utilizing the GB-91 physical transport data base will be undertaken. The scientific synthesis reports are expected to be completed in time for presentation at the CBO-1994.

The present report is mainly devoted to the phase 1 activities namely the preparations of statistical and climatological summary reports. This report is published with the hope that the scientific community will exploit the wealth of data for understanding the physical transport processes and for the development and validation of hydrodynamic and transport models.

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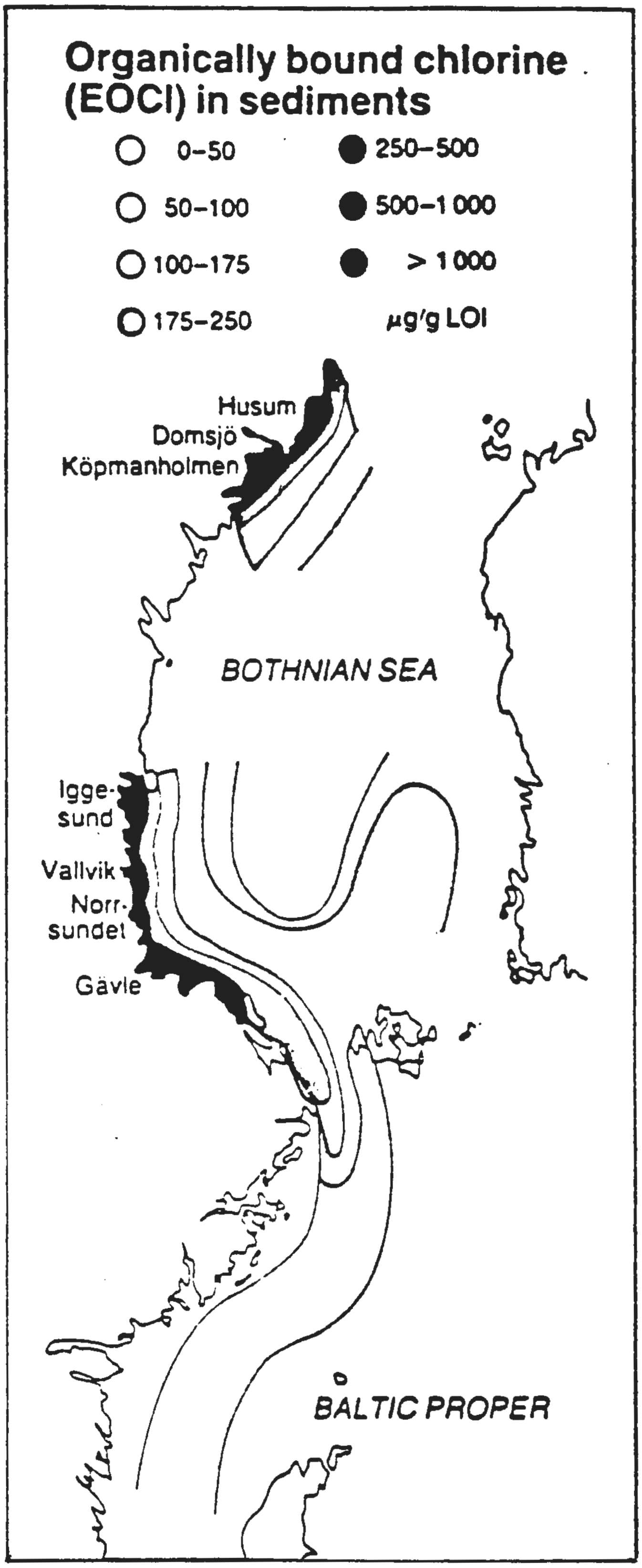



*Figure 1.1. Organically bound chlorine (EOCl) in sediments. (From Håkansson et al., 1988, Swedish Environ. Prot. Agency, Report 3522.)*

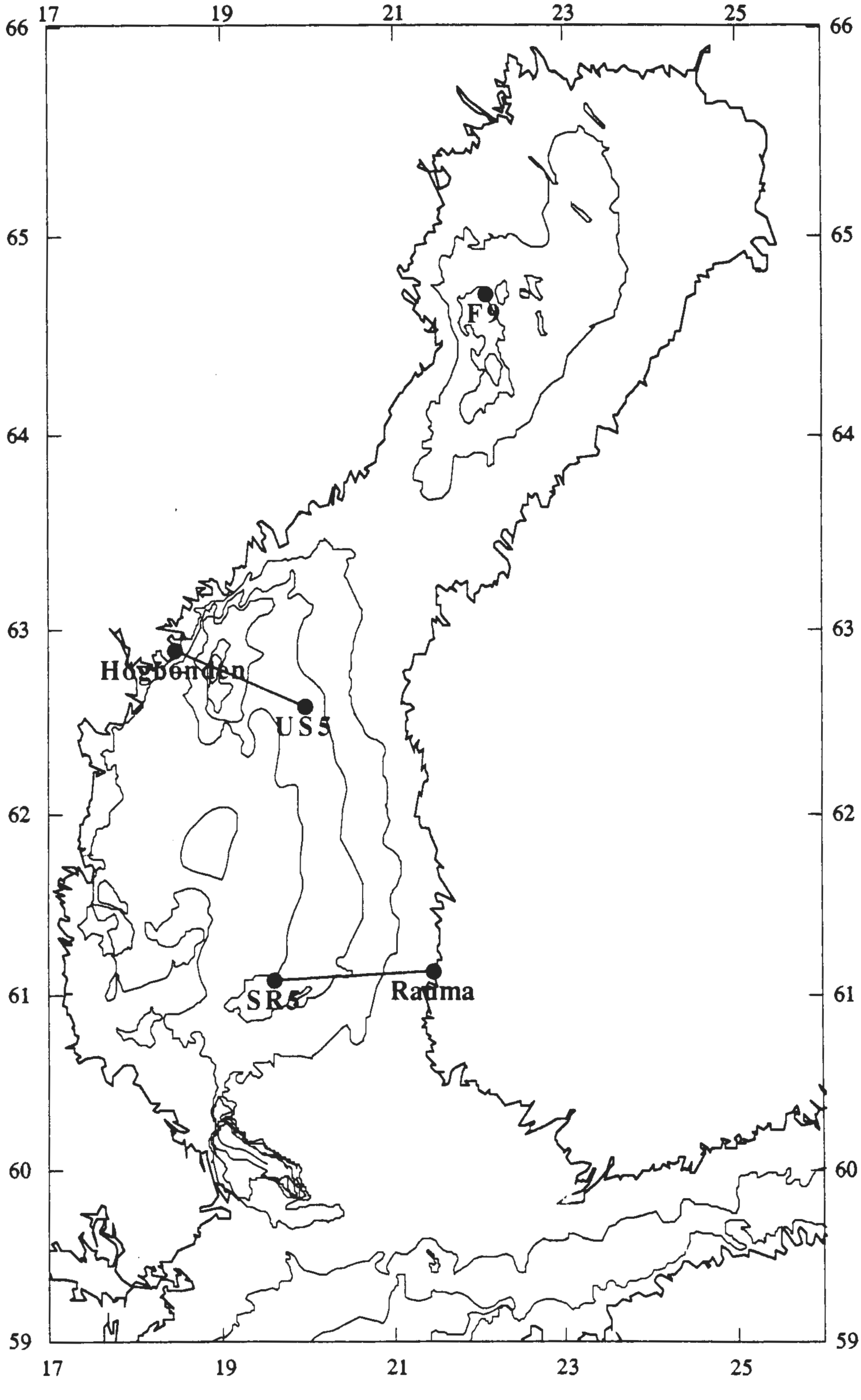



*Figure 1.2. Geographical sites of the GB-91 Physical transport experiments in the Gulft of Bothnia, showing transects of current meter mooring stations ( —— ) and dedicated deep-water investigations at stations SR5, US5 and F9. Depth contour resolution is 50 m.*

# CHAPTER 2

## SWEDISH EULERIAN CURRENT MEASUREMENTS

Eleonor Marmefelt and Anders Omstedt, Swedish Meteorological and Hydrological Institute, Sweden

### 2.1 Introduction

Two Swedish Eulerian experiments have been carried out during the Gulf of Bothnia Year-1991 (GB-91), contributing to the description of the physical transport processes in the Gulf:

(1) coastal transect experiment nearby the island of Högbonden, and
(2) open sea experiment with two stations in the northern part of the Gulf.

The coastal transect experiment focused upon coastal physical processes, such as baroclinic coastal jets and upwelling coastal boundary layers, and it was carried out in close cooperation with the Swedish Lagrangian experiments. The open sea experiment was concentrated on the deep water mixing characteristics during ice-covered as well as ice-free conditions.

### 2.2 The coastal transect experiment

The coastal transect experiment was carried out at Högbonden with four current meter mooring stations, placed perpendicular to the local shore line and to the bathymetric contours, reaching 10 km off the coast (Figure 2.1). The positions of the stations are given in Table 2.1.

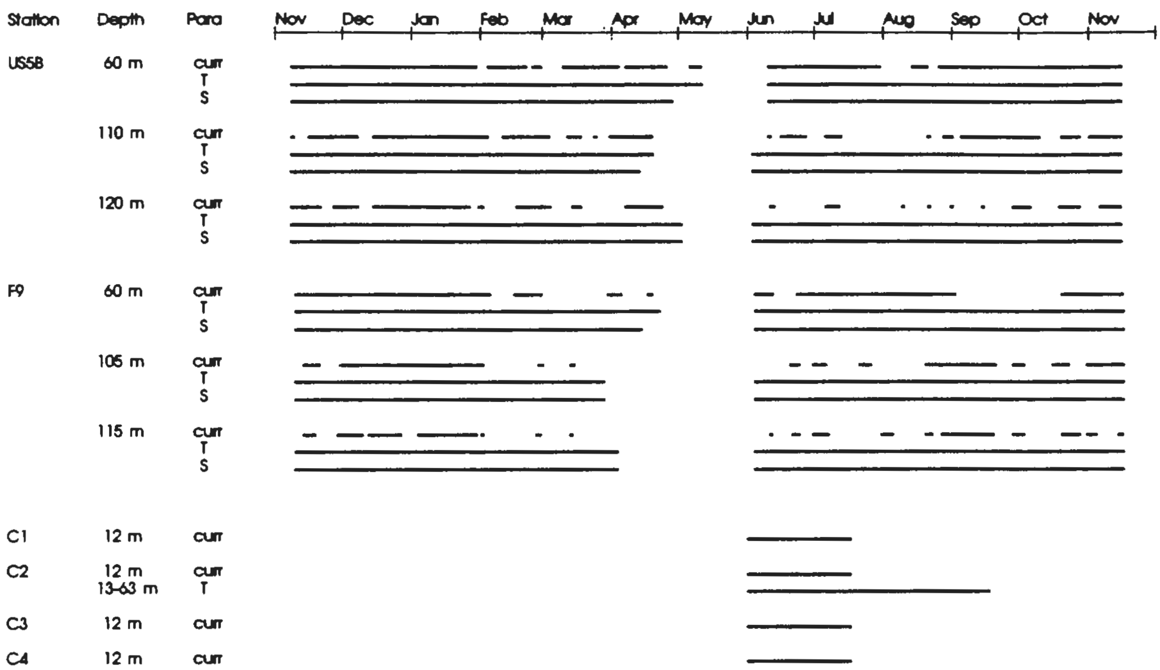
*Table 2.1 Description of the current meter stations of the Swedish Open Sea and Coastal Transect Experiments. The measurements at sites US5B and F9 were performed using Aanderaa current meters, whereas at sites C1, C2, C3 and C4 Sensor Data current meters were used.*

| Station | Latitude | Longitude | Depth (m) | Distance fr. shore (km) | Observation depth, remarks |
|---|---|---|---|---|---|
| US5B | 62° 35.61' | 19° 56.81' | 125 | 64.5 | 60 m from surface; 15 m from the bottom |
| F9 | 64° 42.50' | 22° 05.25' | 120 | 24.2 | 60 m from surface; 15 m from the bottom |
| C1 | 62° 51.16' | 18° 30.58' | 103 | 2.1 | 12 m |
| C2 | 62° 50.57' | 18° 32.20' | 104 | 3.8 | 12 m; thermistor chain between 13 and 63 m |
| C3 | 62° 49.74' | 18° 34.00' | 119 | 5.9 | 12 m |
| C4 | 62° 49.01' | 18° 35.61' | 133 | 8.4 | 12 m |

Each mooring station consisted of one current meter at 12 m depth. The current meters measured currents, temperature and salinity. A thermistor chain was added to the second station off the coast, between 13 and 63 m below surface with the thermistors placed 5 m apart (Figure 2.2).

The coastal transect experiment started on June 1, 1991. The sampling intervals of the current meters and the thermistor chain were 32 min and 30 min respectively. The current meters worked without any failure until their maximum storing capacity were attained, i.e. until July 17, 1991. The thermistors worked until September 17, 1991, when the experiment was brought to an end and the R/V Argos collected the mooring systems. It was then found that the thermistors worked satisfactory during the whole mooring period (Table 2.2).

*Table 2.2. Overview of accepted current, temperature and salinity data from the Swedish Open Sea and Coastal Transect Experiments.*




The current pattern has been illustrated by progressive vector diagrams in Figure 2.3, which shows that the currents were mainly following the coast southwardly. The strongest currents were found at the stations closest to the coast. Thus, the data indicates the presence of a coastal boundary layer. The current data has also been filtered through a low pass filter with 18 to 24 hours cut off, using the statistical program developed by the Canada Centre for Inland Waters. The current climate of the period is illustrated by current roses (Figure 2.4) and time series plots (Figure 2.5). The currents in the coastal zone follow the coast southwardly during weak wind condition. When the winds turn towards north, the currents also change direction towards north. Thus the surface currents in the coastal zone are highly affected by the winds. The wind data were extracted from the nearest weather station Skagsudde. It should be noted that the wind directions are with the wind, i.e. opposite to the direction of what is usually applied in meteorology.

Daily average temperature profiles from the thermistor data at station C2 are illustrated in Figure 2.6.

## 2.3 The open sea experiment

The Swedish open sea experiment was carried out at station F9 in the Bothnian Bay and at station US5B in the northern part of the Bothnian Sea. Three Aanderaa meters were placed at each station, 60 m below the open sea surface and 15 and 5 m above the sea floor. The mooring systems are illustrated in Figure 2.7.

The experiment started on November 7, 1990, at station US5B and on November 9, 1990, at station F9. The Aanderaa meters measured current, temperature and salinity. The two mooring systems were left at their positions until the beginning of June, 1991. As the length of this first mooring period was far beyond the lifetime of the meter battery, the meters were only able to store data as long as their battery worked. The period length for each measured parameter is illustrated in Table 2.2. During the experiment the two mooring systems were served once more in late August, 1991. The experiment was concluded in mid-November, 1991. The observation of temperature and salinity worked without failure as long as the batteries worked satisfactory, but the current observations were less successful. Whether the lack of current observations is due to shortcomings of the meter itself or if the flow velocities are below detection level of the Aanderaa meters is not known. The threshold velocity of the meters is 1.1 cm/s. Table 2.2 illustrates accepted data of each parameter.

Also the data from the open sea experiment has been filtered through the low pass filter. The currents at the open sea stations are illustrated by current roses (Figure 2.8) and by vector time series plots (Figure 2.9). Wind information from the nearest meteorological stations is also shown.

Starting with station F9 in the Bothnian Bay, Figures 2.8 a and 2.9 a shows that northgoing current dominates. At 5 m above sea floor, typical velocities of the filtered currents are below 10 cm/s, but events with velocities above 20 cm/s have been recorded.

At the US5B station in the northern part of the Bothnian Sea, Figures 2.8 b and 2.9 b, the currents are mainly towards northeast. In the deepest layer the currents change mainly between northeast and southwest, with typical velocities of 5 cm/s. Although, during shorter periods, velocities of about 15 cm/s has been observed at 5 m above sea floor.

## 2.4 Statistics and climatology during the coastal transect experiment

The current pattern during the Coastal Transect Experiment of GB-91, illustrated in Figure 2.5, can be divided into three separate events, where the first event is a period of weak, fluctuating winds and southbound currents, that follows the coastal and bathymetric contours. During the second event the wind is stronger and northbound. The currents are highly affected by the wind and are now directed northeastwardly. As the wind is abating, the third event starts and the wind is similar to the first event with its fluctuating direction, although the wind direction is mainly northward during this last event. The currents, however, are once again following the coast southwardly.

The similarity between the first and the third event can be seen in Figure 2.10, especially at stations C3 and C4. At seventy-five per cent of the current observations these stations are below 15 cm/s during these events. The distribution of the current speed at station C1 and C2 is quite similar during the first event, but the currents appears to be stronger during the last event. The second event is characterized by strong currents at the coastal stations (C1 and C2), where 40% of the observations are above 15 cm/s. The currents are even weaker at station C3 and C4 during the second event than during the other events.

During the second event, when the wind increases, the currents turn clockwise. During this turn, the N-S components (the v-components) of the current velocity do not vary as much as the E-W components (the u-components), Figure 2.11, although the average values of u and v are of the same order at each station respectively. Comparing the first and third event stations C1 and C2 are quite similar, where the average u is less than the average v due to the vicinity of the coast, although the standard deviation of u is larger both at C1 and C2. During the first event the u-components of station C3 and C4 are of the same order as at the other stations, but the average v-components are approximately half of C1 and C2. The currents at C3 and C4 do not respond as strong to the wind fluctuations. As could be expected, the average values and the standard deviation during the first and third event are comparable.

So, the currents at the very nearshore stations, C1 and C2, respond quickly to variations of the wind, as they are situated well within the coastal boundary layer. During times of strong winds, the current velocities are large, with relatively moderate fluctuations. The stations C3 and C4 are situated in the outskirts of the coastal boundary layer, where current velocities are lower than at stations C1 and C2.

## 2.5 Conclusions and future analysis

The Swedish Eulerian experiments were carried out quite successfully. None of the current meters were lost and interesting data have been retrieved. The data losses were mainly due to low battery power, as the measuring periods were to long.

The currents in the coastal transect followed the coast, increased in speed towards the coast and were highly influenced by the wind direction. These response characteristics are typical for the dynamics of the coastal boundary and have similarities with, for example, the Great Lakes.

The currents at the open sea stations were more variable in direction and speed. At station F9 and US5B north respectively northeast going currents dominated. The currents were however quite episodic with an upward velocity limit of about 20 cm/s.

Future analysis of the data will concentrate on coastal physical transport processes and deep-water mixing characteristics.

**Acknowledgements**

This work has partly been financed by the Swedish Environmental Protection Agency under contract 5312150-2 and partly by the SMHI.

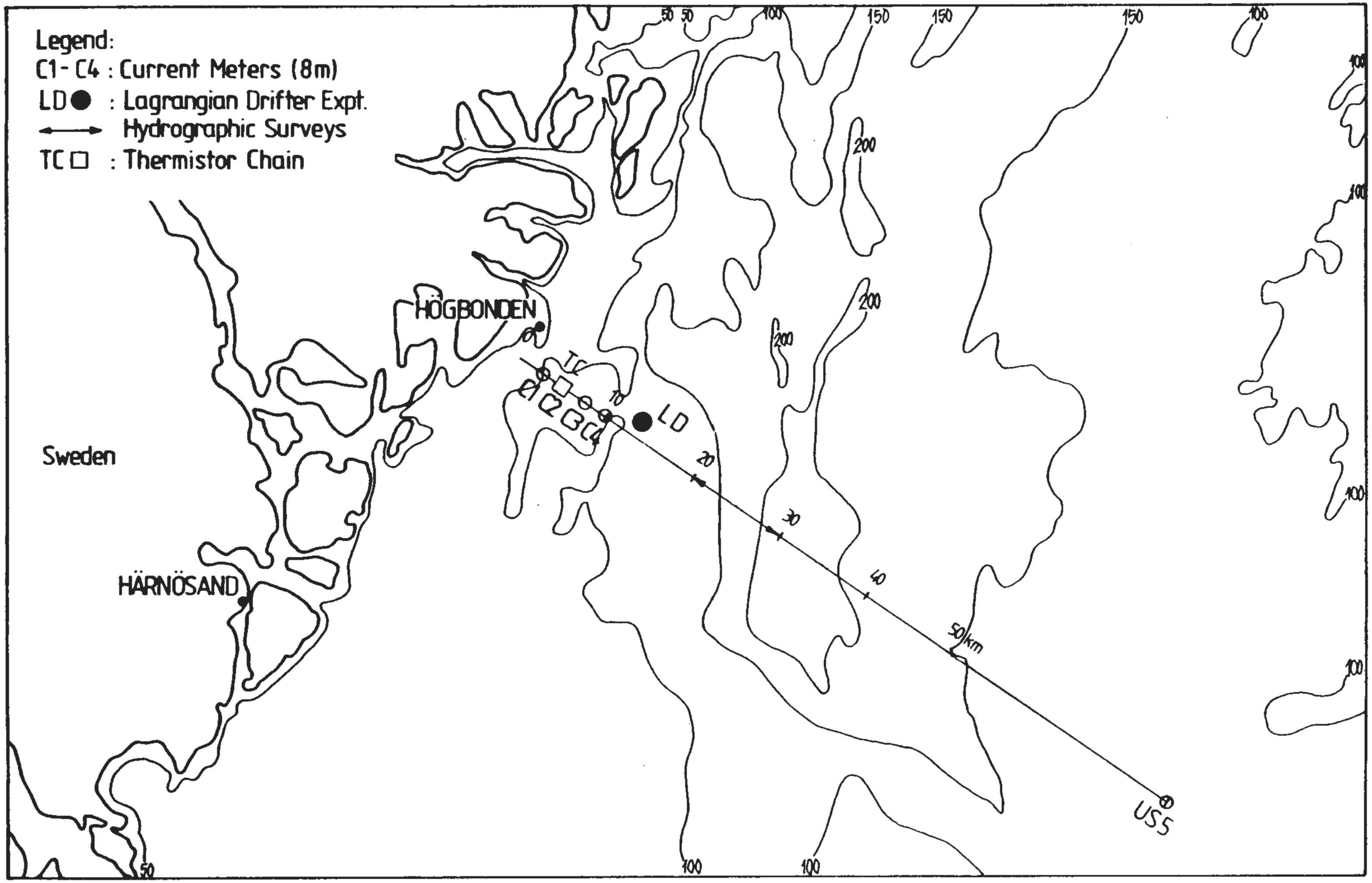



Figure 2.1. *Bathymetric chart of the area where the Swedish Coastal Transect Experiment was carried out.*

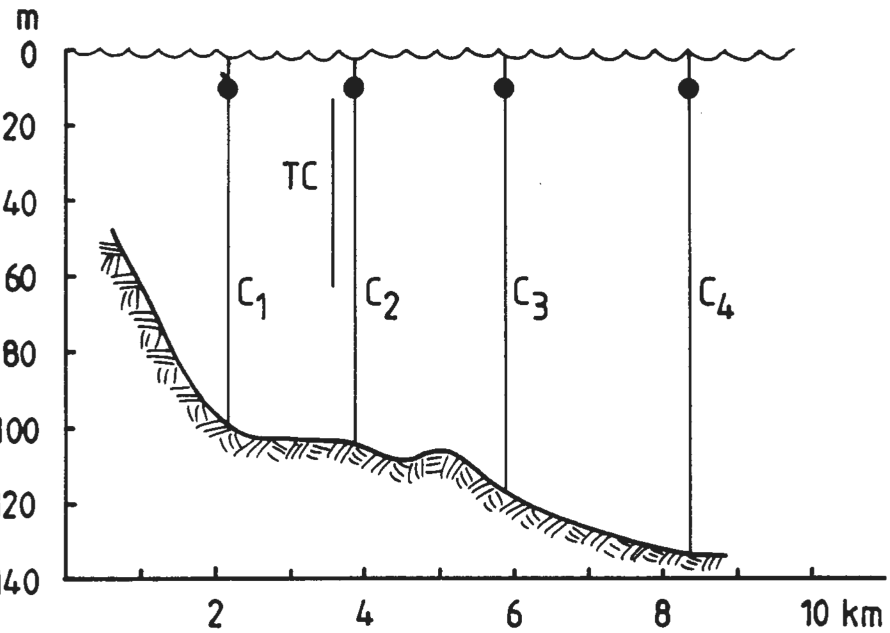



*Figure 2.2. The mooring systems of the Högbonden Transect (C1 to C4) and the thermistor chain (TC).*


*Figure 2.3. Progressive vector diagram of the Swedish coastal transect currents at C1, C2, C3 and C4 named from coast and offshore.*

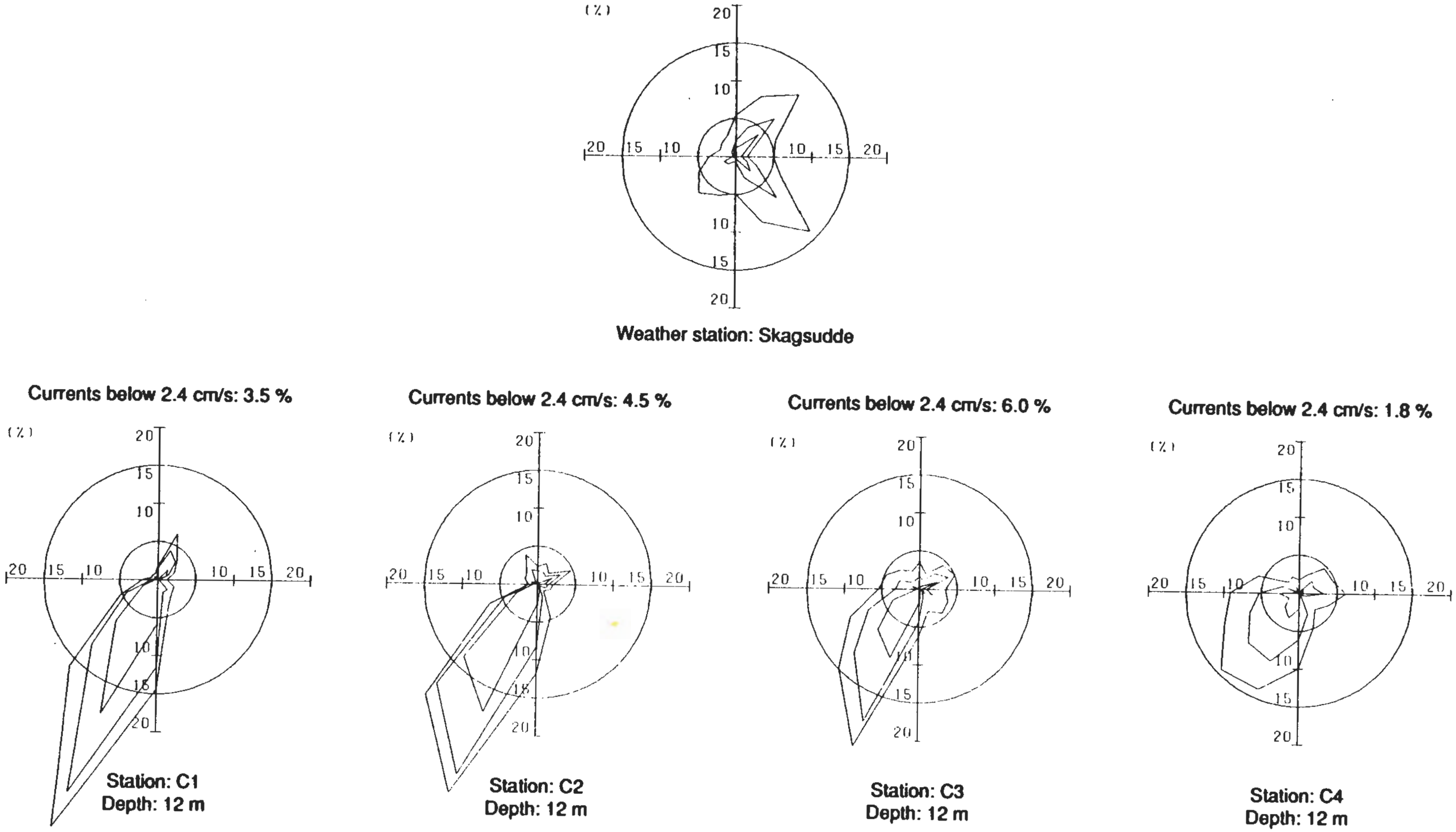



*Figure 2.4.* *Current roses of filtered data from Högbonden Transect, illustrating the distribution of current directions with velocities below 7 cm/s, between 7 and 14 cm/s and above 14 cm/s, respectively. The percentage of currents below 2.4 cm/s is also given for the different current meters, which is the lower limit of the Sensor Data current meters. The wind rose is from the nearest weather station, Skagsudde. It illustrates the distribution of wind stress directions. The direction is with the wind. Here the magnitudes are below 0.07 N/m², between 0.07 and 0.14 N/m² and above 0.14 N/m².*

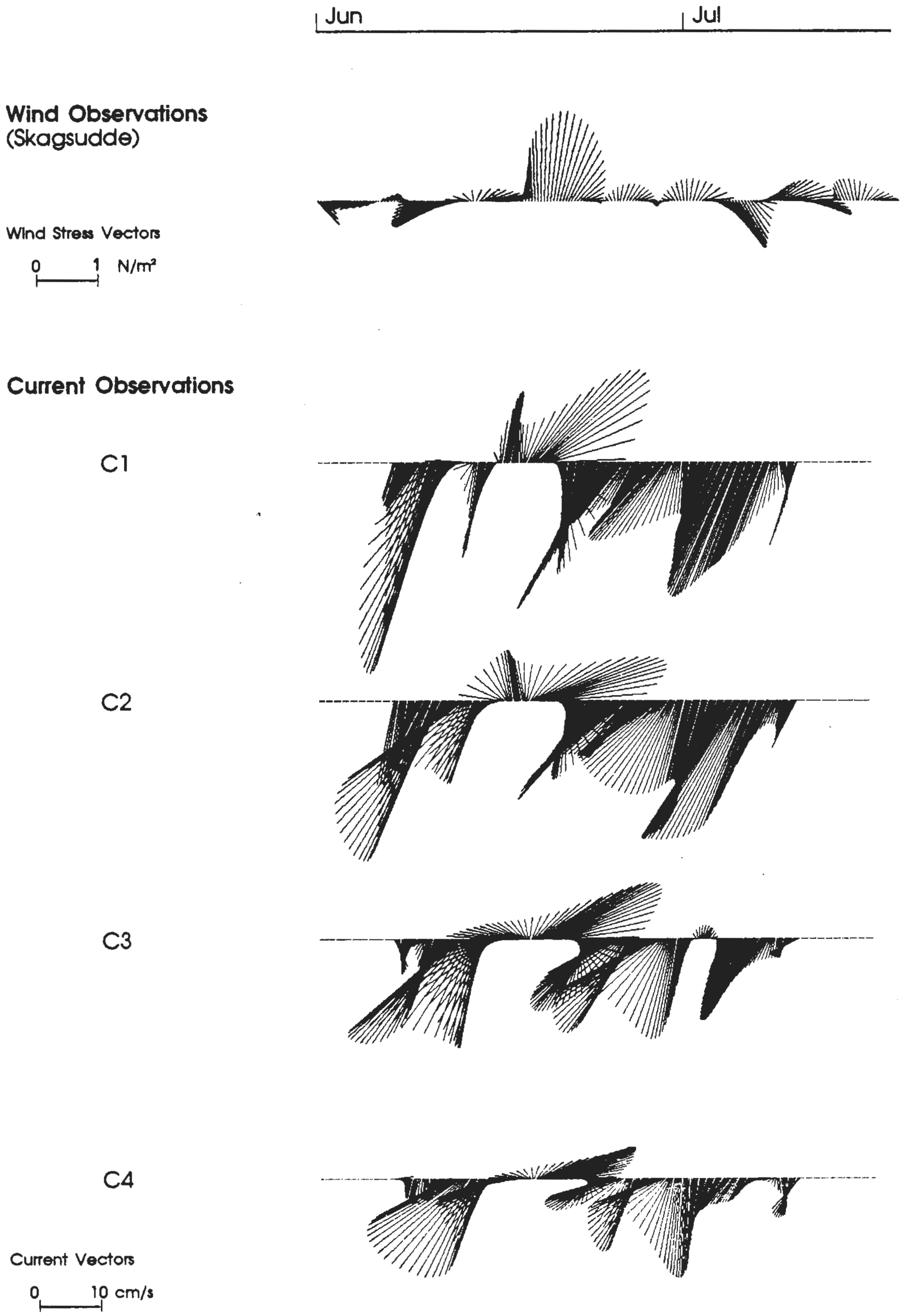



*Figure 2.5. Time series vector plots of wind and current meter data of the Högbonden transect. The data have been filtered with a low-pass filter with 18 to 24 hour cutoff.*

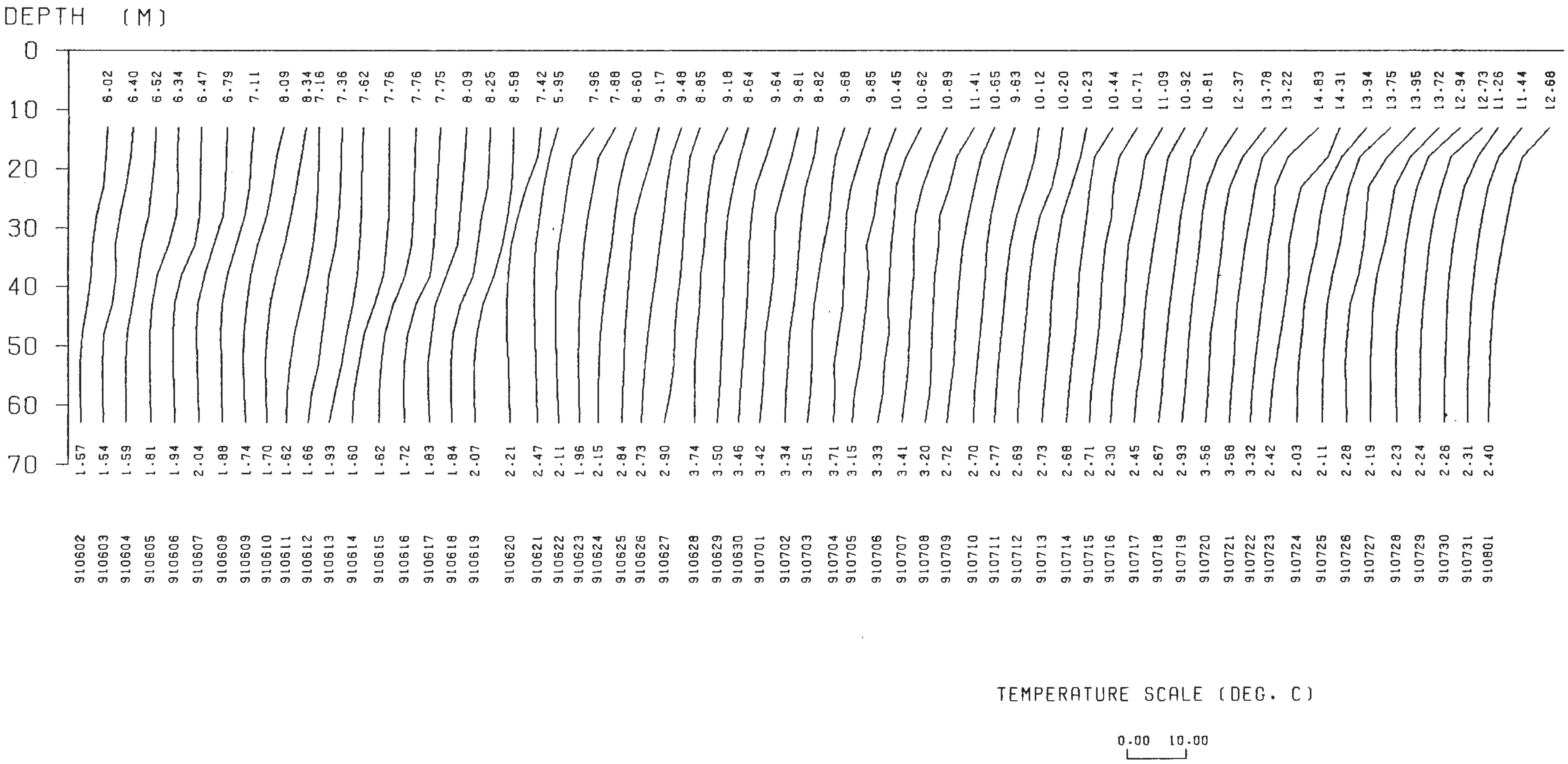



*Figure 2.6.* ***Daily average temperature profiles of the thermistor chain at station C2. The thermistors were placed between 13 and 63 m depth, and 5 m apart.***

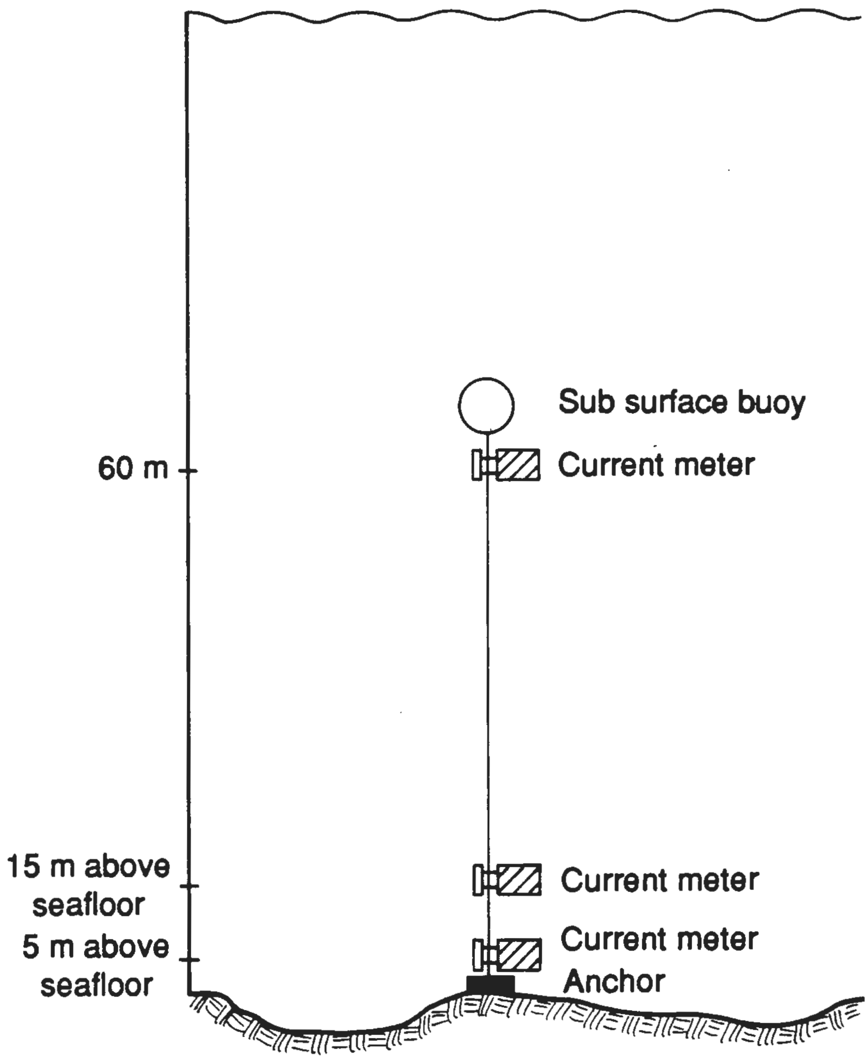



*Figure 2.7. Mooring system of the Swedish open sea experiment.*

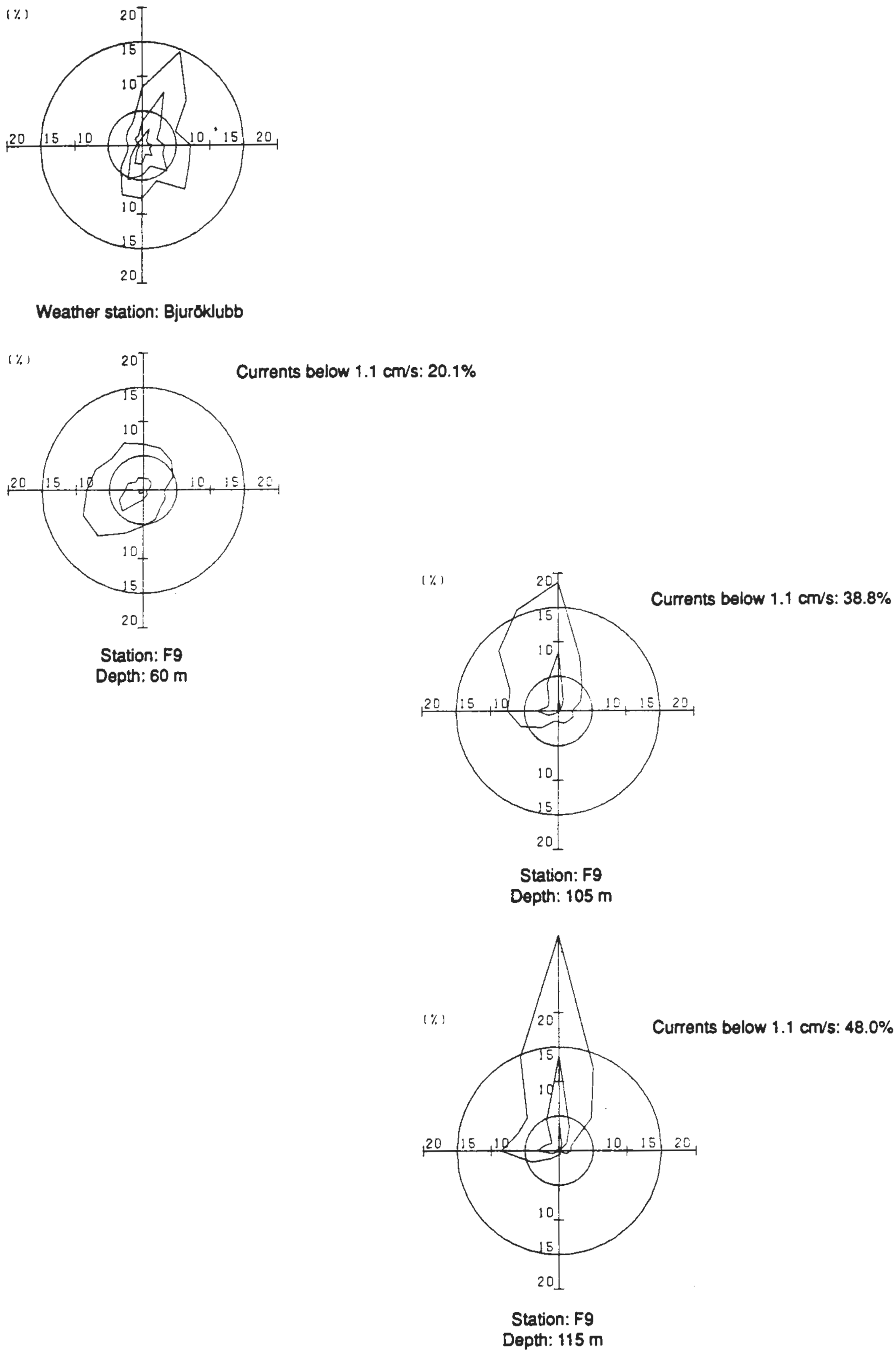
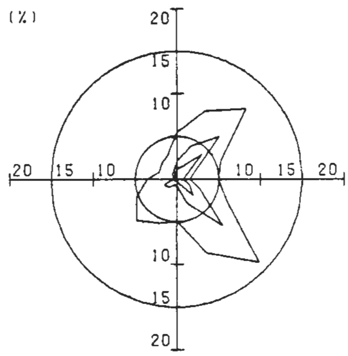
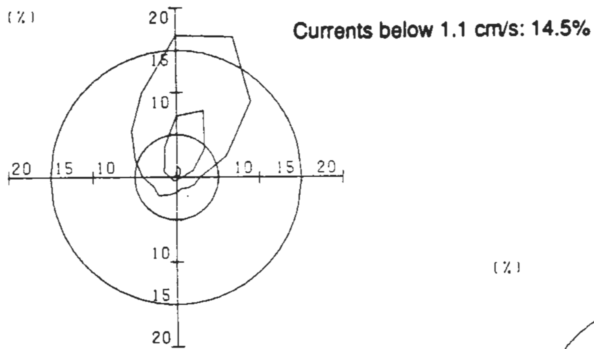


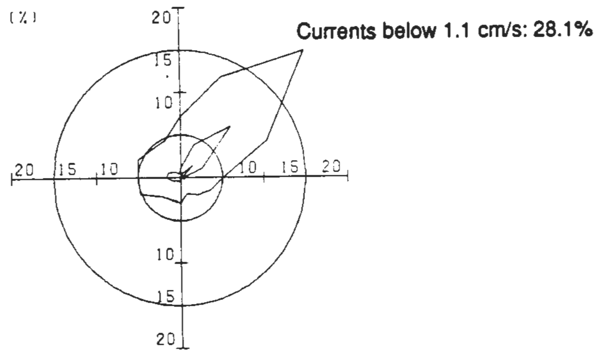

*Figure 2.8a. Current roses from the Swedish Open Sea Experiment in the Bothnian Bay, station F9. Wind data is from the nearest weather station, Bjuröklubb. The data has been treated in the same way as described in Figure 2.4.*



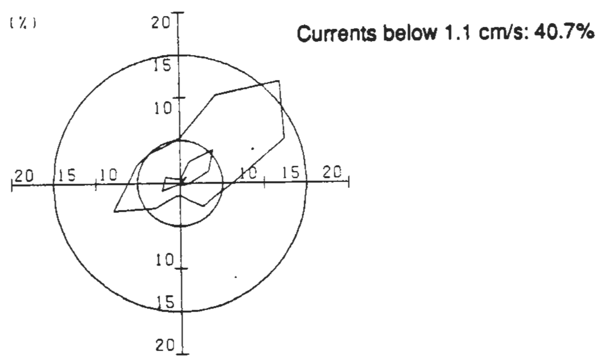

Weather station: Skagsudde




Station: US5B
Depth: 60 m




Station: US5B
Depth: 110 m




Station: US5B
Depth: 120 m

*Figure 2.8b. Current roses from the Swedish Open Sea Experiment in the Bothnian Sea, at station US5B. Wind data is from the nearest weather station, Skagsudde. The data has been treated in the same way as described in Figure 2.4.*

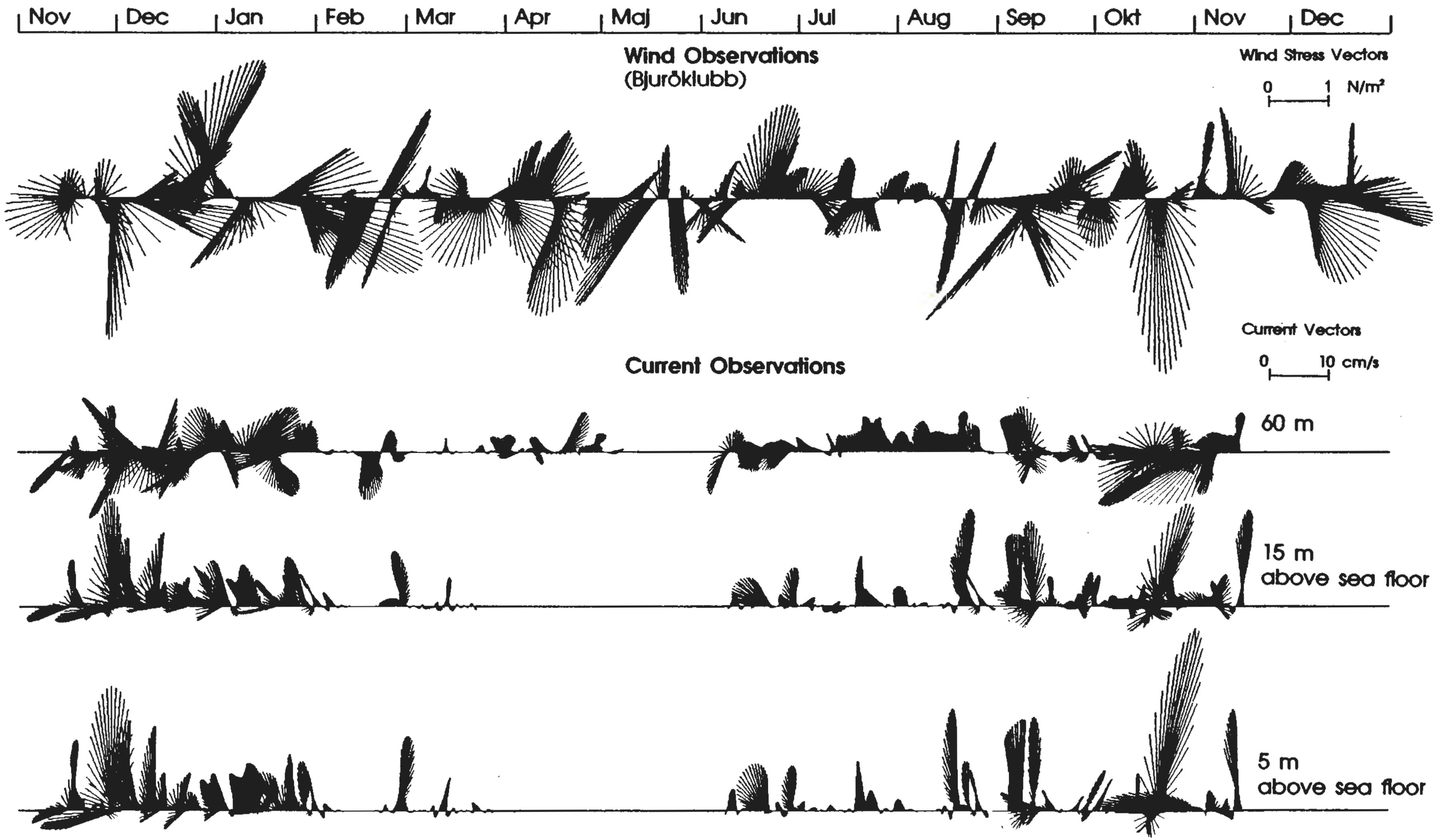



*Figure 2.9a.* *Time series vector plots of wind and current data of the Open Sea station in the Bothnian Bay, F9. The data have been filtered with a low-pass filter with 18 to 24 hour cutoff.*

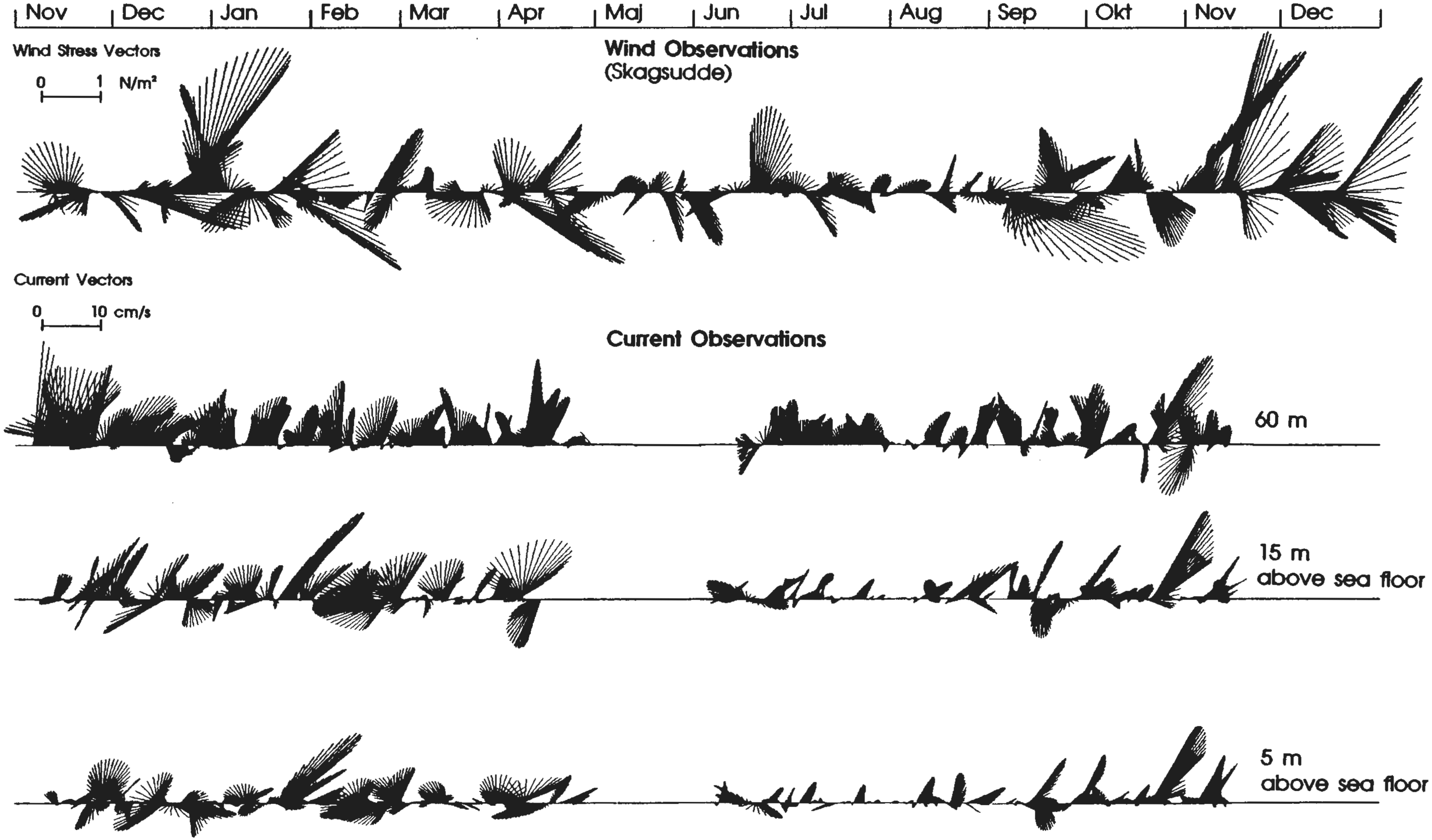



*Figure 2.9b.* *Time series vector plots of wind and current data of the Open Sea station in the Bothnian Sea, US5B. The data have been filtered with a low-pass filter with 18 to 24 hour cutoff.*

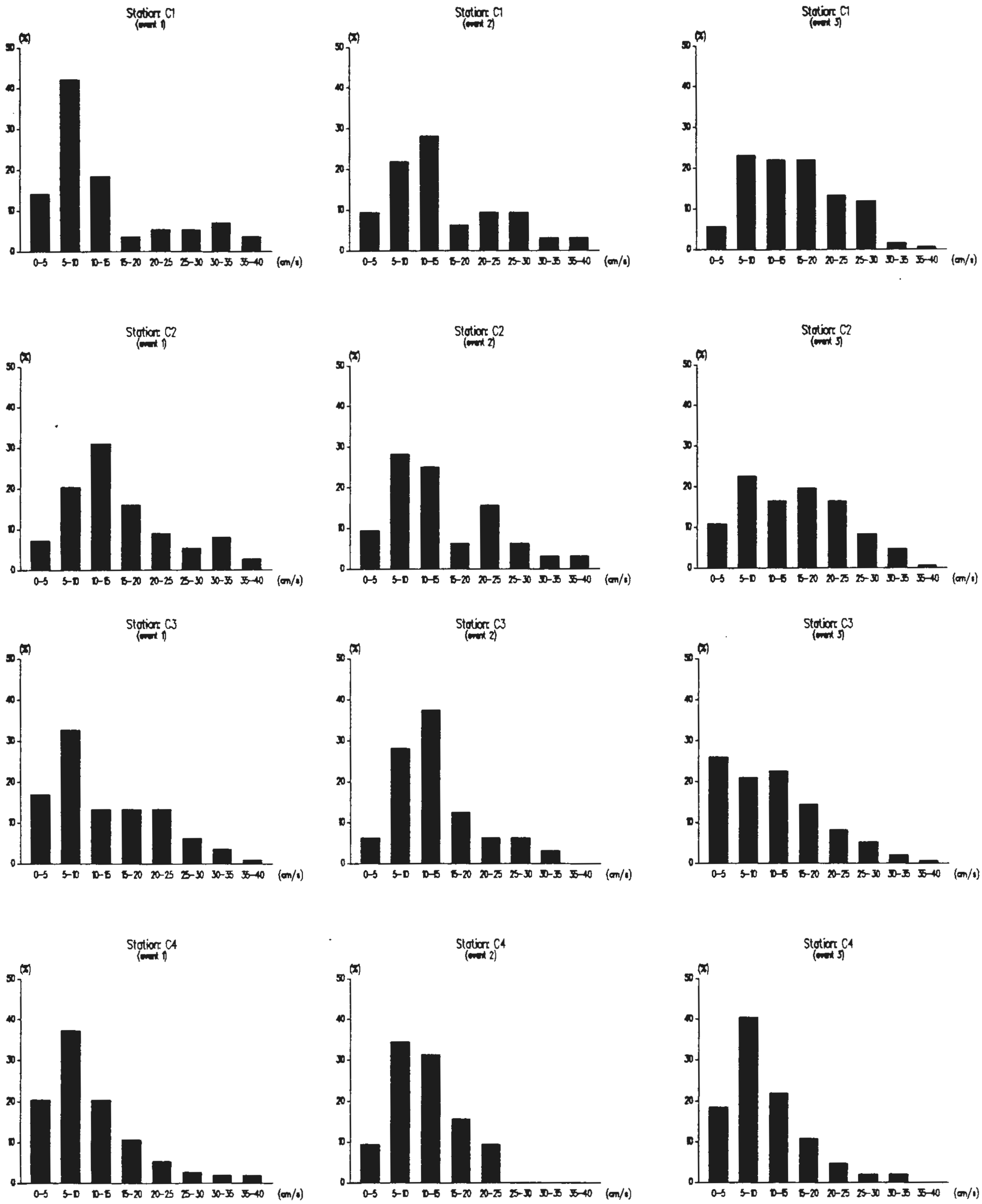



*Figure 2.10. Distribution of current velocity during the Coastal Transect Experiment. The experiment is divided into three separating events, where the first event covers the period from the start of the experiment to June 15, the second event from June 16 to June 19, and the last event covers the period from June 20 until the end of the experiment, July 17.*

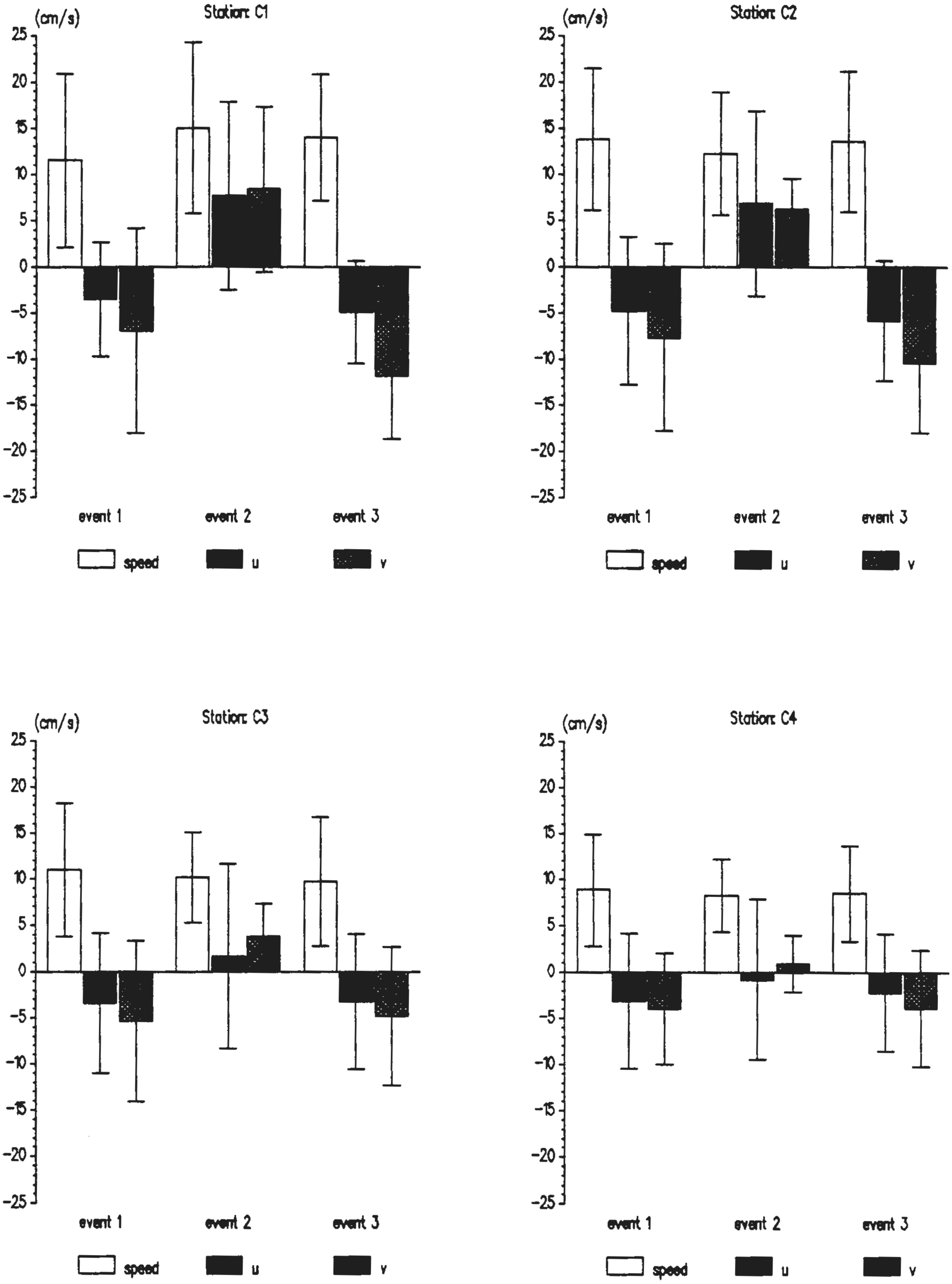



*Figure 2.11. Average values of current speed as well as E-W (u) and N-S (v) velocity components during each event.*

# CHAPTER 3

## FINNISH EULERIAN CURRENT MEASUREMENTS

Pekka Alenius, Finnish Institute of Marine Research, Finland

### 3.1 Introduction

The Finnish experiments were divided into three parts: 1) coastal transect experiment near the city of Rauma, 2) open sea experiment in the central southern Bothnian Sea (station SR5) and 3) a topographic wave experiment along the Finnish coast (Figure 3.1 and Table 3.1 for the locations of the mooring stations). Two of the stations (CM4 and CM6) of the coastal transect experiment were specially chosen to be the same stations which were used as thermistor chain stations in the EROsion and Sedimentation study, EROS, in late 1970's.

The coastal transect experiment was the largest one with seven mooring stations (Figure 3.2). It focused on coastal boundary layers and water exchange between the coastal areas and the open sea. The open sea experiment focused on studies of deep currents and consisted of only one station. The topographic wave experiment was an addendum to the original plan of the experiment. A chain of three mooring stations along the direction of the coastline at 60 m isobath was installed. This part of the experiment focused on studies of the larger scale dynamic process in the Bothnian Sea.

The current meters were Aanderaa RCM4S type equipped with temperature, conductivity, direction and speed sensors. The thermistor chains were Aanderaa TR-2 type instruments with 11 thermistors with 3 meter spacings between each other. Most of the instruments recorded data on 3.5' magnetic tape. The instruments at station SR5 had data storing units. The observation interval was generally 10 minutes for current meters (except during the winter time) and 20 minutes for thermistor chains. The moorings were subsurface moorings with an ODAS-buoy at the surface (Figure 3.3).

### 3.2 The coastal transect experiment

The coastal transect experiment outside Rauma consisted of a chain of seven mooring stations (CM1 - CM7, Table 3.1) along the hydrographic transect EROS 15 - EROS 25. The station chain extended to 50 km offshore perpendicular to the local coast line and bathymetric contours. The bathymetry with gently sloping bottom with no irregularities is quite ideal for this kind of study. Each mooring had a current meter at 8 m depth. Moorings CM5 - CM7 were equipped with an additional current meter at about 60 m depth. Moorings CM4 and CM6 (also known as hydrographic stations EROS 17 and EROS 22) had also thermistor chain installed between 10 m and 40 m depths.

The coastal transect operated from late April to late November, 1991. The magnetic tapes of the current meters were replaced three times during the experiment: in the beginning of June, in the middle of August and in early October. Thus each mooring has four separate time series of data. The spacing between the time series varies from mooring to mooring from hours to several days. Unfortunately, due to technical reasons, the mid-August service of the moorings occurred some days too late; the instruments stopped working before the service and thus some days of data were lost.

*Table 3.1. Finnish current meter sites during the GB-91 experiment.*

| Station name | Latitude (N) | Longitude (E) | Depth (m) | Distance from the coast (about) (km) | Observation depths<br><br>Remarks |
|---|---|---|---|---|---|
| SR5 | 61° 05.0' | 19° 36.0' | 125 | 85 | 60 m from the surface, 5,15 m from the bottom |
| CM1 | 61° 12.8' | 21° 13.2' | 22 | 7 | 8 m |
| CM2 | 61° 13.2' | 21° 09.9' | 25 | 10 | 8 m |
| CM3 | 61° 13.6' | 21° 03.7' | 42 | 15 | 8 m |
| CM4 | 61° 14.0' | 20° 58.5' | 50 | 20 | 8 m, thermistor chain 10 - 40 m |
| CM5 | 61° 14.3' | 20° 52.8' | 60 | 26 | 8 and 60 m |
| CM6 | 61° 15.0' | 20° 43.0' | 80 | 34 | 8 and 60 m, thermistor chain 10 - 40 m |
| CM7 | 61° 16.2' | 20° 24.1' | 120 | 50 | 8 and 60 m |
| PM1 | 61° 36.0' | 20° 53.4' | 60 | 30 | 8 m |
| PM2 | 62° 00.0' | 20° 50.0' | 60 | 23 | 8 m |

The overall functioning of the instruments was good. Only the data set from the 60 m current meter at station CM6 was completely missed due to malfunction of the instrument from mid-August to early October. Some periods of low quality velocity data were observed mainly at station CM5.

Thermal stratification during the coastal transect experiment

Temperature data are available from the ten current meters and two thermistor chains along the coastal transect. The thermistor chain data sets are specially important for the interpretation of the current meter data from 8 m depth. Technically the current meters are difficult to install nearer to the surface than about 8 m in order to gain reliable current measurements. The strong seasonal thermocline in the Bothnian Sea is generally very near to the 8 m depth and therefore the thermal stratification data are needed for interpretation of the current data, because the current meters have sometimes been measuring the surface layer currents, and sometimes they might have been below the thermocline.

The coastal waters of the Bothnian Sea tend to freeze every winter. During the ice-covered period the temperature of the sea is almost homogeneous down to some 60 m depth. The experiment was planned to cover the ice-free seasons as much as possible, thus covering the whole yearly course of the thermal stratification. In the beginning of the experiment the stratification was still typical for the winter or the early spring with constant temperature down to about 60 m depth. The surface layer began to warm at the end of May. The surface layer temperature reached its maximum in late July. The spring cooling period was also mainly covered by observations. At the end of the experiment the sea was completely mixed down to depths below the thermistor chains (see Figures 3.5 and 3.6).

The daily mean profiles of temperature from the moorings CM4 and CM6 show the development of the summer thermocline and its collapse in the autumn. Some interesting events of the thermocline erosion (not seen well in the daily mean profiles) were observed during the experiment, but those cases will be analysed elsewhere.

### Currents during the coastal transect experiment

The observation sites were planned to cover both the coastal boundary layer and the open sea conditions. The coastline is characterized by a number of islands, which makes it slightly difficult even to determine the distance of the stations from the effective coastline. Due to shallowness of the coastal waters on the Finnish side of the Bothnian Sea, the station closest to the coast still remained about 7 km offshore. This might be too long a distance to catch the coastal friction layer inside the coastal jets.

The current roses (Figure 3.7) show the distribution of the observations in different velocity and direction classes. It is clearly seen that the coastal currents are more or less alongshore whereas the open sea currents have more or less evenly direction distribution. The transition from the coastal flow to the open sea currents occurs somewhere about 20 km from the coast. The open sea currents are slower than the coastal currents.

The mean speed of the currents during the whole experiment was less than 10 cm/s, whereas the standard deviation of the speed is about the same order as the speed itself (Table 3.2).

The nature of the currents can be described as episodic (Figure 3.8). The coastal current has very well defined episodes of either northward or southward flows. The current speed to east-west directions is slower than to north-south direction. Thus the currents seem to change the main direction by slowing down, turning and then speeding up again. This kind of phenomenon is not seen in the open sea. The currents follow the winds quite clearly. Storms are clearly seen in the coastal currents. Also during the storms the coastal currents seem to be stronger than open sea currents.

*Table 3.2. Mean value and standard deviation of the current velocity at the coastal transect stations during the whole GB-91 experiment. The unfiltered 10 minute values are used; N is the number of observations. The maximum value is uncorrected and can be erroneous, however, it indicates the range of variability of the current speed.*

| Station/depth | (Max) | Mean | Std | N |
|---|---|---|---|---|
| CM1/8 m | (43.9) | 8.9 | 6.6 | 30833 |
| CM2/8 m | (44.8) | 8.2 | 7.3 | 30802 |
| CM3/8 m | (44.8) | 7.5 | 6.5 | 30807 |
| CM4/8 m | (49.9) | 7.7 | 6.2 | 31025 |
| CM5/8 m | (39.2) | 7.3 | 5.9 | 31026 |
| CM5/56 m | (36.7) | 3.9 | 4.8 | 30791 |
| CM6/8 m | (32.1) | 7.7 | 4.4 | 30992 |
| CM6/60 m | (44.8) | 5.4 | 4.5 | 22762 |
| CM7/8 m | (32.1) | 6.7 | 4.1 | 30836 |
| CM7/60 m | (29.6) | 4.2 | 3.8 | 30459 |
| PM1/8 m | (39.2) | 7.0 | 4.5 | 28889 |
| PM2/8 m | (44.6) | 7.9 | 6.2 | 28936 |
| SR5/60 m | (25.7) | 3.2 | 3.4 | 25857 |
| SR5/103 m | (-) | - | - | - |
| SR5/113 m | (25.7) | 3.3 | 3.6 | 36072 |

## 3.3 The open sea experiment

The open sea station SR5 in the central southern Bothnian Sea was the main station of the chemical and biological projects of the GB-91 experiment. At this station the currents were planned to be measured for one year from late 1990 to late 1991. The mooring was equipped with acoustic release system to facilitate observations during the ice-covered season too. The mooring was operational from November, 1990, to November, 1991.

The Finnish open sea experiment was the unlucky part of the Finnish physical experiments during the GB-91 Year. First the nature itself organized a very mild winter with no ice cover on SR5. The second and more severe difficulty was the operational problems with the instruments; mainly problems with the batteries. This caused long periods of lost data in the midwinter. Due to some technical failures the data sets from mid-August to early October, 1991, were also lost. The instruments had data storing units, and thus once the memory of the unit gets cleared nothing can be done to save the data again.

The currents in the deep layers were quite slow (Table 3.2). The direction of the isobaths is reflected in the current directions. Specially the current rose at 15 m from the bottom shows clearly that the currents follow the bottom topography.

## 3.4 The topographic wave experiment

In order to study the larger scale topographic phenomena two additional mooring stations (PM1 and PM2) were used. They were installed at the 60 m isobath to the north from the coastal transect. These stations together with the station CM5 form a chain of three stations with about 40 km distance between two successive stations.

The current meters were installed at 8 m depth as in the coastal transect. The instruments worked quite well during the whole experiment. The period of lost data in the middle of August is slightly longer at these stations than at the coastal transect. The moorings were deployed about a week earlier in November than the coastal transect stations.

The structure of the currents at these stations was quite similar to that of the station CM5 (Figure 3.7). The data reflects the properties of the transition zone from the coastal currents to the open sea currents. The northern station PM2 showed slightly larger current speeds than the station PM1. The coastline bends slowly towards northwest in the area where the station PM2 was, and thus the mooring stations seem to represent the coastal currents more than station PM1.

## 3.5 Conclusions and future analysis

The Finnish Eulerian experiments were carried out according to the original plans of the GB-91 physical experiment. In spite of some disappointments with one or two moorings the experiment can be considered very successful. All the instruments were retrieved and most of the data seem to be usable in spite of the fact that some problems in the rotors of the current meters occurred in the beginning of the experiment. The current speed seems to have been below the threshold speed of the instrument sometimes, which causes slight difficulties in the time series analysis. Nevertheless, the amount of low quality data was, however, quite small. Minor manual corrections to the clearly erroneous data values have been made by linear interpolation.

The data sets seem to be suitable for extensive time series analysis with spectral methods, for example, the time evolution of energy at different frequency bands should be possible to study on the basis of these data.

The data obtained from this experiment provide sound basis for several kinds of studies of the dynamics of the coastal regions of the Bothnian sea. The thermistor chain data seem to be suitable for analysis of diurnal processes and catastrophic collapses of the thermocline during heavy storms.

The long time series of this experiment and the time series data from earlier experiments give possibilities to analyse the general dynamic features of the area more thoroughly than has so far been possible.

### Acknowledgements

Hannu Grönvall is acknowledged for the cooperation in the final planning of the mooring network. The technical success of the experiment was based on the years of experience of the field group of FIMR under the guidance of Osmo Korhonen. Tapani Stipa did a lot of work in the preliminary data analysis phase.

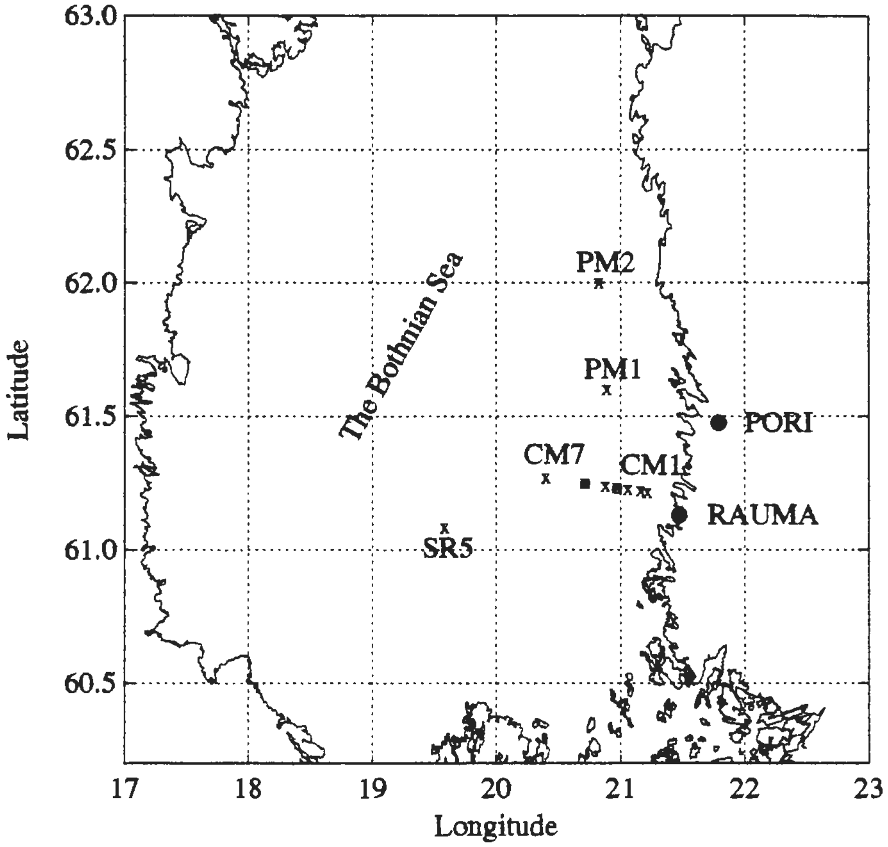



*Figure 3.1. Location of the Finnish mooring stations.*

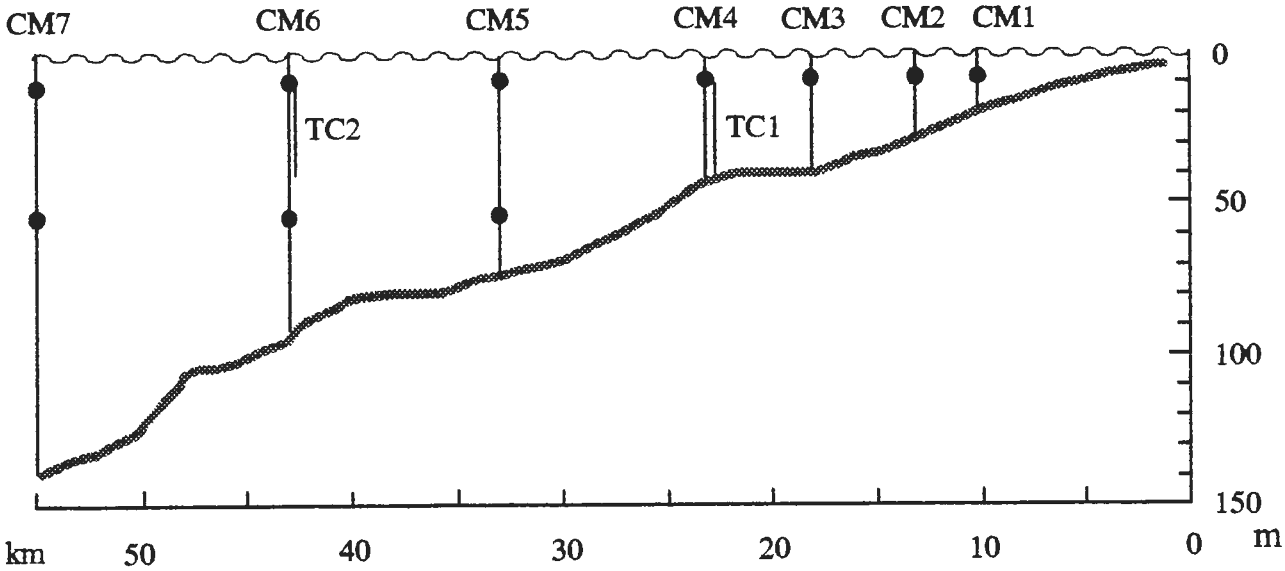



*Figure 3.2. The moorings at the Rauma transect.*

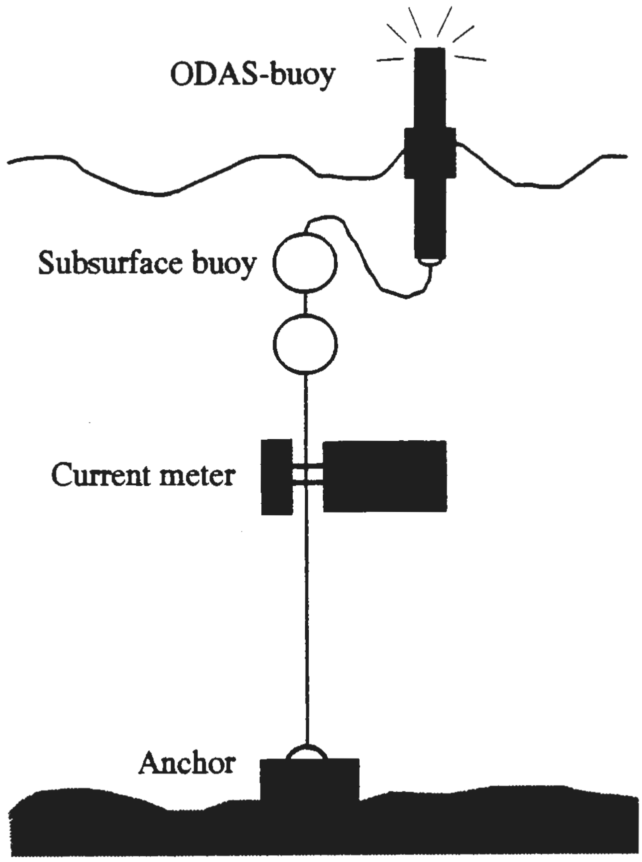



*Figure 3.3. Schematic figure of mooring system.*

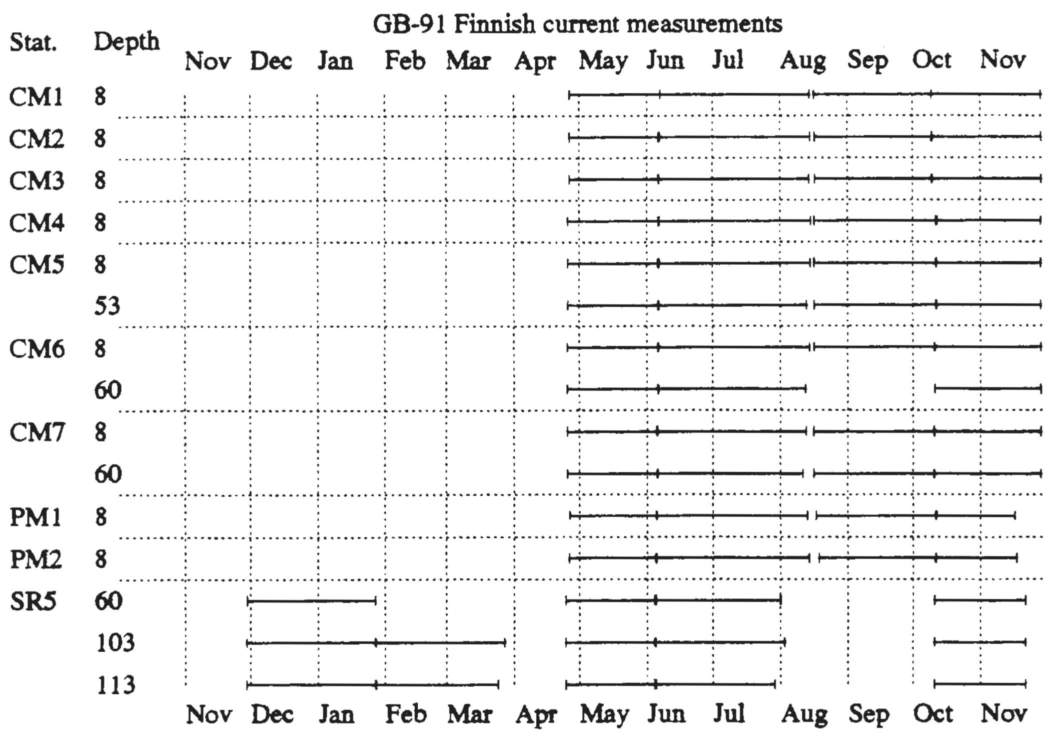



*Figure 3.4. Observation periods with high-quality velocity measurements.*

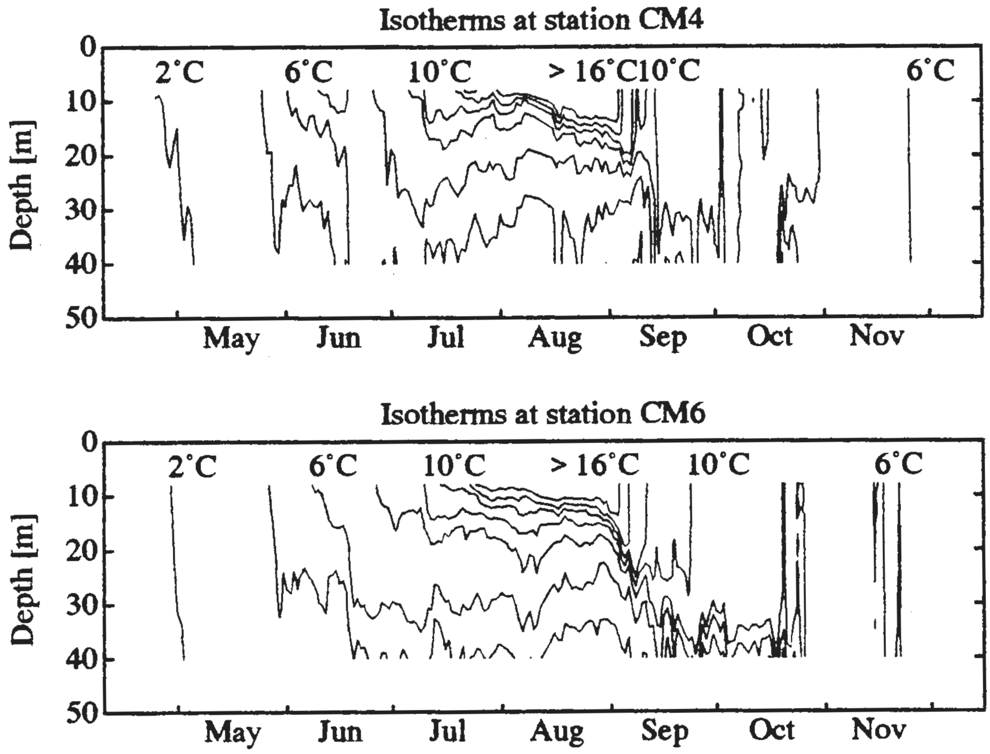



*Figure 3.5. Daily mean isotherm depths at the thermistor chain stations CM4 and CM6.*

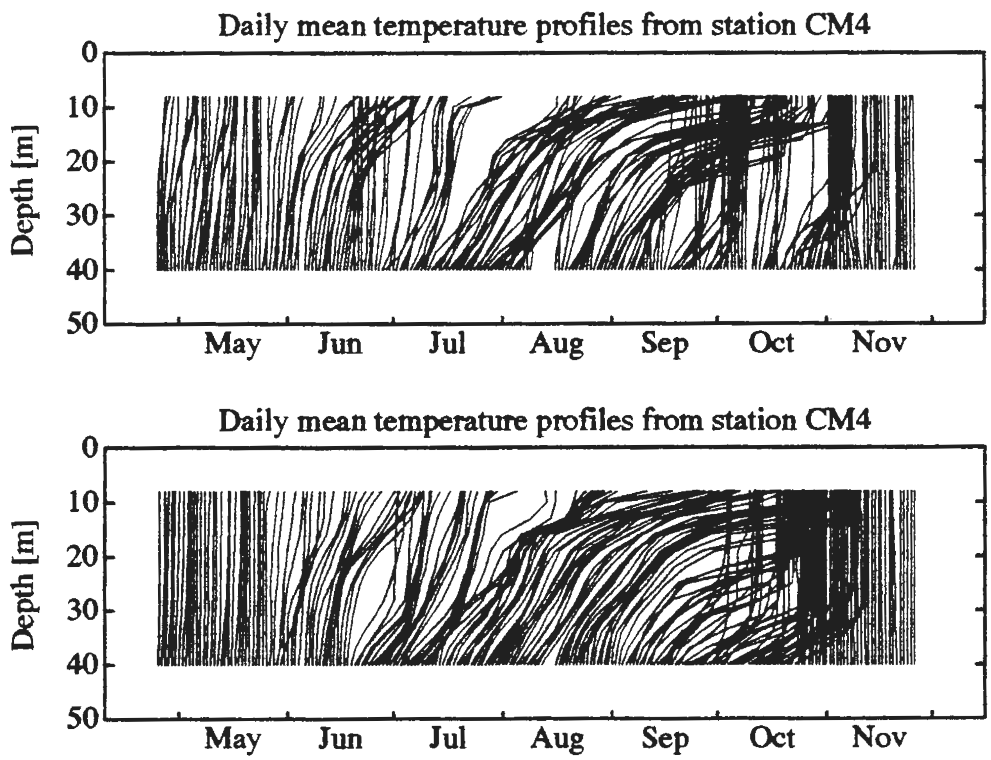



*Figure 3.6. Daily mean temperature profiles at the thermistor chain stations CM4 and CM6.*

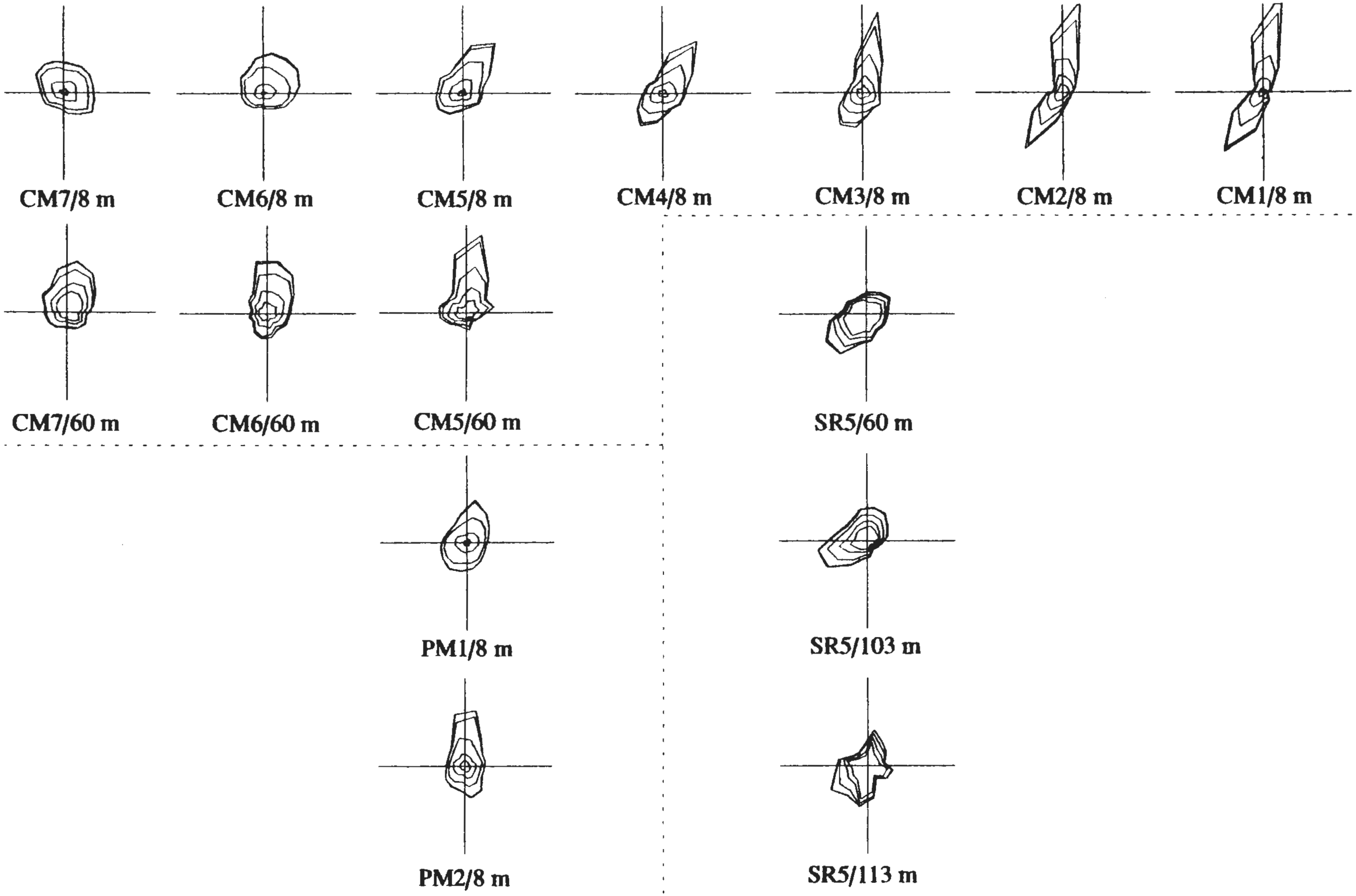



*Figure 3.7.* *Schematic current roses from the Finnish current meters, illustrating the distribution of the current directions in different speed classes.*

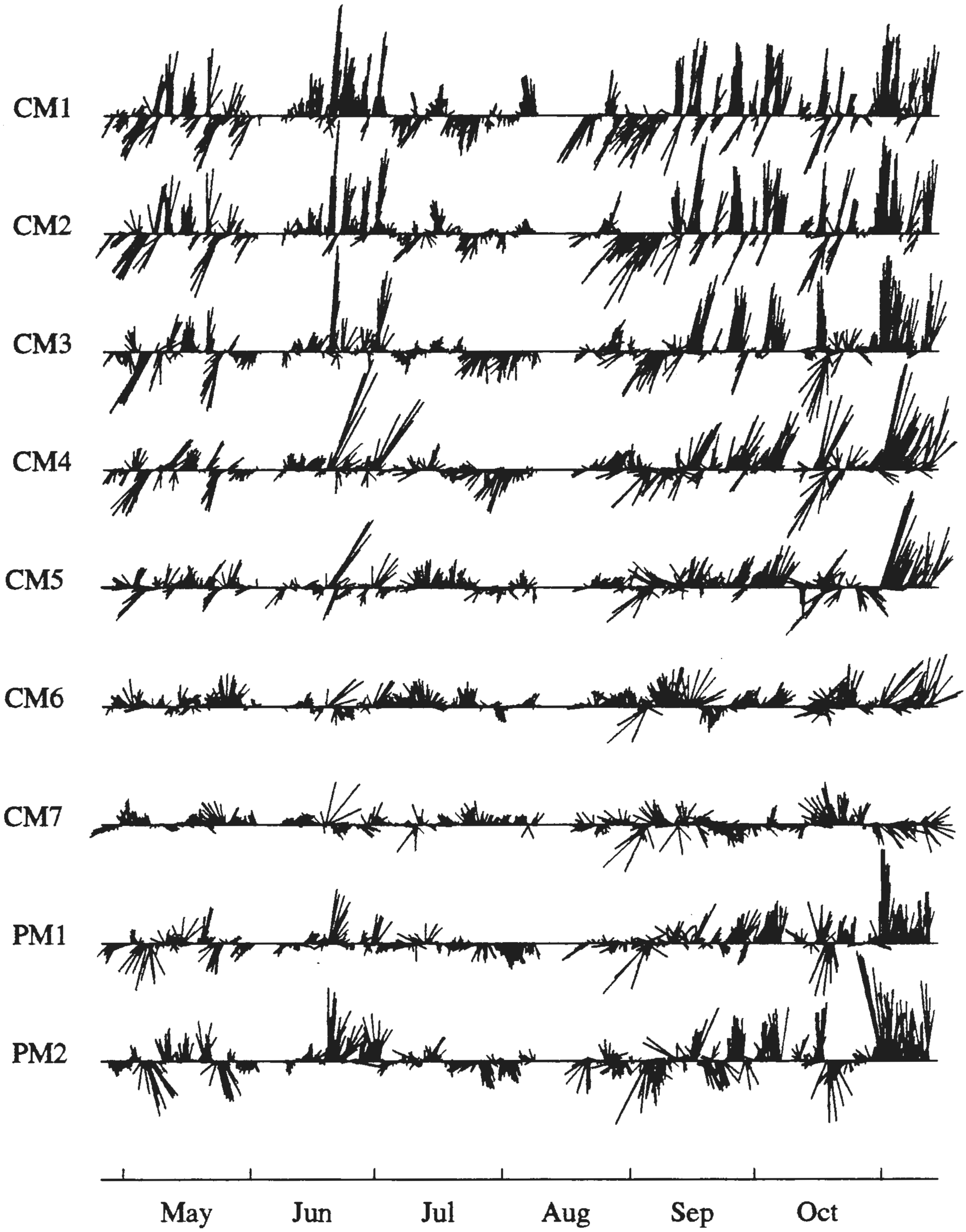



*Figure 3.8. Graham-filtered current vectors plotted with 6 hours intervals at 8 m depth on the coastal transect (stations CM1 - CM7) and stations PM1 and PM2. The figure clearly shows the episodic nature of the currents.*

# CHAPTER 4

## SWEDISH LAGRANGIAN CURRENT EXPERIMENTS

Bertil Håkansson, Swedish Meteorological and Hydrological Institute, and Lars Rahm, Linköping University, Sweden

The need to estimate mass flux and dispersion in a coastal-offshore region characterized by a complicated topography and stratification has increased in recent years. One example is the investigation of the biogeochemical cycles in the Baltic Sea, another is the need to define subgrid diffusion in numerical models. Field studies are needed to describe and quantify these processes. Thus Lagrangian experiments were carried out in the Bothnian Sea during the "Gulf of Bothnia Year-1991" using clusters of Argos drifters deployed in the surface layer. (Two locations have been used, east "Högbonden" and west Raumo (Figure 4.1)). The experiments are interpreted by using Lagrangian dispersion statistics, hydrographical observations, meteorological forcing and remote sensing. The aim is to characterize the nature and the scales of the dispersion processes.

### 4.1 Swedish experiments at Högbonden

The Swedish experiments were located offshore of the island Högbonden, 20 km on the coastal transect. Intensive hydrographic survey data just before or after each deployment of the drifters, remote sensing data of sea surface temperatures and moored current meter including a thermistor chain data are also available for the interpretation of Lagrangian data. The topography of the area is complicated and drastically different from that of Rauma where the Finnish Lagrangian experiments were carried out (cf. Figure 4.1).

The mean density stratification in the Högbonden area is characterized by a shallow thermocline at 10 meters depth during June to October. In November a combined halo- and thermocline coincide at about 40 meters depth (Juhlin, 1987). The corresponding mean Rossby radius of deformation is 2.5 to 3 km in June to October and 5 km in November. During the present investigation the Rossby radius of deformation is typically 3 - 4 km at the Högbonden area (cf. Chapter 7).

### 4.2 Technical description and data quality

The Lagrangian current experiments were carried out using nine Argos drifters, consisting of (Figure 4.2) four Hermes, three Conmar I and two Conmar II buoys of Canadian and Norwegian origin (Table 4.1). The smaller drifters were used for the cluster experiments, while the larger ones with a different geometric configuration and weight were solely used for water mass tracking. The drogues consisted of square sails covering a depth interval of 5 - 7 meters.

The drifter positions were measured by the Argos system. With a doppler technique it locates 400 MHz transmissions from buoys using polar orbiting satellites. Depending upon the height of the antenna over the sea surface generally 10 - 30 fixes per day were obtained. Histograms of daily measured positions are shown in Figure 4.3. Although only data from 2 drifters are presented here, these are representative for all experiments. In the June experiment there is a reduced amount of data during evening times (i.e. 8 to 12 p.m.), whereas in November this time period has increased to also encompass morning hours (i.e. 8 p.m. to 3 a.m.) for the Canadian Hermes drifters (5385). This aging my have several reasons, for example it can depend on battery loosing power, increased sea state or a combination of these factors. The Norwegian Conmar I drifters performed better in November than in June due to some malfunctions, which were repaired by the manufacturer and some minor changes done by SMHI in the time between these experiments.

*Table 4.1. Characteristics of the drifters used during GB-91.*

| Drifter data | Conmar I | Conmar II | Hermes elliptical |
|---|---|---|---|
| Length, m | 1.5 | 2.45 | 0.4 |
| Maximum diameter, m | 0.5 | 0.8 | 0.6 |
| Submerged part, m | 1.0 | 1.5 | 0.15 |
| Weight in air, kg | 20 | 100 | 50 |
| Cross area above sea surface, $m^2$ | 0.085 | 0.274 | 0.085 |
| Cross area of drogue, $m^2$ | 7.2 | 11.0 | 7.2 |
| Drogue depth, m | 7 | 7 | 7 |

While the Norwegian Conmar I drifters gave more fixes per day (probably due to their more favourable antenna position) the frequency of low quality fixes were much higher than the Canadian Hermes drifters. Note that the accuracy distributions presented in Figure 4.4 are based on corrected data, taking into account raw data the amount of low quality positions will increase especially for the Conmar I drifters. However, both types of drifters show a clear decreasing accuracy in time. The amount of high quality accuracy are reduced for the Hermes drifters during June to November, whereas for Conmar I the low quality accuracy increases slightly during the same time period. In summary the performance of the Canadian Hermes drifters were more congruent and reliable than the Norwegian ones.

Wind, waves and vertical shear can give the drogue a slip compared to the true water motion, hence the drifters do only approximately measure the Lagrangian movements (cf. Krauss et al., 1989). To reduce the slip induced by wind the area of the window shade drogue was kept at least 40 times larger than the area of the drifter exposed to air. The drogue was loaded with additional weights at the upper and lower parts to prevent the drogue to loose its proper drag against the current.

## 4.3 Experimental logistics

Six cluster and five single drifter experiments were carried out covering the summer and late autumn season (Table 4.2. a - b). The cluster experiments were deployed in a triangular pattern except the one in September which was deployed along a line. After deployment the positions of the drifters were followed daily to prevent shoring and unwelcome recovery, using the Argos communication programme ELSA and direct telephone access to the computers in Toulouse, France and Washington, D.C., USA, for real-time positioning. In emergency ships of opportunity (pilot vessels, coast guard ships and fishing boats) were used, nevertheless in most cases the Swedish and the Finnish Coast Guard made the recoveries.

*Table 4.2 a. Characteristics of the 6 cluster experiments. All were released in a triangular geometry except experiment in September in which case the drifters was deployed along a line. The Julian days cover the time period of analysed data.*

| Drifters | No. | Date | Mean start position | Julian days |
|---|---|---|---|---|
| 5385-88, 9868-69 | 6 | June 3 | N 62 48.0' E 18 42.0' | 154 - 159 |
| 5385-88, 9868-69 | 6 | June 11 | N 62 42.0' E 18 54.0' | 162 - 169 |
| 5385-88, 9867-69 | 7 | August 12 | N 62 42.0' E 18 54.0' | 224 - 232 |
| 5385-88, 9868-69 | 6 | August 21 | N 62 47.3' E 18 40.4' | 233 - 242 |
| 5385, 5387-88, 9868-69 | 5 | September 1 | N 62 35.0' E 18 50.0' | 244 - 260 |
| 5385-88, 9867-69 | 7 | November 5 | N 62 42.0' E 18 50.0' | 311 - 322 |

*Table 4.2 b. Characteristics of the 5 single drifter experiments. The Julian days cover the time period of analysed data.*

| Drifters | Type | Date | Start position | Julian days |
|---|---|---|---|---|
| 7198 | Conmar II | June 11 | N 63 37.0' E 19 06.2' | 163 - 229 |
| 5386 | Hermes | August 12 | N 62 42.7' E 18 52.2' | 225 - 255 |
| 7199 | Conmar II | August 12 | N 62 37.8' E 19 04.6' | 225 - 247 |
| 5387 | Hermes | November 5 | N 62 43.0' E 18 53.3' | 312 - 333 |
| 9867 | Conmar I | November 5 | N 62 43.0' E 18 54.0' | 312 - 333 |

The first experiment in June was located about 13 km from the coast, whereas the other experiments were initiated at a distance of 26 km to decrease the risk of shoring. In all cluster experiments the number of drifters were 5 to 7. Each experiment lasted 5 to 16 days depending on weather conditions, shoring and the availability of vessels for recovery.

## 4.4 Data analysis

The analysis is made using software developed at CCIW. A manual correction of outliers was performed. It is based on interpolated hourly values of velocity from raw data. The most extreme velocities compared to the estimated internal wave speed (≈ 0.4 m/s) were excluded. It was found that almost all outliers were data obtained within an hour from the previous one.

Two examples of the results, one from cluster experiment in June, 1991, and one single drifter track are presented in Figure 4.5 and 4.6. To get an overview of all measurements 24-hour mean centroid positions from the clusters as well as for the single drifter tracks were calculated. Figure 4.7 shows the centroid positions for all experiments. Mean centroid or water mass velocity vary between 3 to 9 cm/s (Table 4.3).

*Table 4.3. The 24-hour mean positions of the centroids.*

| Hour | Date | x (km) | y (km) | Hour | Date | x (km) | y (km) |
|---|---|---|---|---|---|---|---|
| 26.00 | JUN 3 | 75.81194 | 84.88316 | 5.00 | SEP 1 | 85.77 | 84.14 |
| 50.00 | JUN 4 | 69.76032 | 83.54402 | 29.00 | SEP 2 | 88.35 | 89.44 |
| 74.00 | JUN 5 | 66.60526 | 88.82848 | 53.00 | SEP 3 | 90.28 | 90.01 |
| 98.00 | JUN 6 | 65.09463 | 88.47729 | 77.00 | SEP 4 | 103.02 | 80.95 |
| 122.00 | JUN 7 | 64.78700 | 88.81368 | 101.00 | SEP 5 | 103.72 | 73.00 |
| 146.00 | JUN 8 | 65.27302 | 89.92796 | 125.00 | SEP 6 | 93.97 | 66.12 |
| | | | | | | | |
| 1.00 | JUN 11 | 85.56924 | 85.58324 | 149.00 | SEP 7 | 87.24 | 60.81 |
| 25.00 | JUN 12 | 79.94564 | 86.63223 | 173.00 | SEP 8 | 83.91 | 53.22 |
| 49.00 | JUN 13 | 77.54450 | 85.06007 | 197.00 | SEP 9 | 82.34 | 46.82 |
| 73.00 | JUN 14 | 69.09816 | 81.35839 | 221.00 | SEP 10 | 83.21 | 45.93 |
| 97.00 | JUN 15 | 62.56797 | 73.77248 | 245.00 | SEP 11 | 78.59 | 44.94 |
| 121.00 | JUN 16 | 55.89242 | 63.91159 | 269.00 | SEP 12 | 65.89 | 33.15 |
| 145.00 | JUN 17 | 51.67978 | 53.35136 | 293.00 | SEP 13 | 69.29 | 27.97 |
| 169.00 | JUN 18 | 50.82958 | 46.59577 | 317.00 | SEP 14 | 67.37 | 27.59 |
| | | | | 341.00 | SEP 15 | 71.65 | 27.91 |
| 19.00 | AUG 12 | 92.48425 | 79.95837 | 365.00 | SEP 16 | 73.74 | 26.13 |
| 43.00 | AUG 13 | 84.42794 | 73.65874 | 389.00 | SEP 17 | 79.22 | 17.57 |
| 67.00 | AUG 14 | 81.31644 | 72.15108 | | | | |
| 91.00 | AUG 15 | 78.91026 | 75.51919 | 20.00 | NOV 7 | 97.71935 | 92.72553 |
| 115.00 | AUG 16 | 80.87115 | 79.77476 | 44.00 | NOV 8 | 96.48875 | 93.08250 |
| 139.00 | AUG 17 | 80.50301 | 80.34074 | 68.00 | NOV 9 | 92.09618 | 87.36826 |
| 163.00 | AUG 18 | 79.16720 | 79.99339 | 92.00 | NOV 10 | 90.30782 | 77.56422 |
| 187.00 | AUG 19 | 74.56587 | 80.86292 | 116.00 | NOV 11 | 97.04533 | 85.25599 |
| 211.00 | AUG 20 | 72.08187 | 81.98997 | 140.00 | NOV 12 | 10.57386 | 80.22209 |
| | | | | 164.00 | NOV 13 | 11.75425 | 85.68864 |
| 14.00 | AUG 21 | 77.06812 | 87.57580 | 188.00 | NOV 14 | 12.94964 | 81.86169 |
| 38.00 | AUG 22 | 80.55722 | 89.62970 | 212.00 | NOV 15 | 13.13736 | 72.15375 |
| 62.00 | AUG 23 | 84.44883 | 92.78918 | 236.00 | NOV 16 | 13.25635 | 65.78349 |
| 86.00 | AUG 24 | 94.80206 | 95.66991 | 260.00 | NOV 17 | 13.70906 | 67.39565 |
| 110.00 | AUG 25 | 93.52610 | 91.47171 | 284.00 | NOV 18 | 13.35217 | 66.64080 |
| 134.00 | AUG 26 | 90.95036 | 93.68900 | | | | |
| 158.00 | AUG 27 | 92.92747 | 91.16994 | | | | |
| 182.00 | AUG 28 | 88.88871 | 79.12368 | | | | |
| 206.00 | AUG 29 | 89.90414 | 73.34943 | | | | |
| 230.00 | AUG 30 | 96.80478 | 70.15604 | | | | |

The daily mean single drifter tracks are presented in Figure 4.8. In all cases the drift is eastward with mean velocity and direction varying from 2 to 7 cm/s and 80 to 140°. The data for each case are presented in Table 4.4. The wind information was taken from a coastal station close to Högbonden (Skagsudde). Daily mean winds were used in the comparison with the single drifters. The mean wind varied from SW to NW with a magnitude of 1 to 5 m/s.

*Table 4.4. Mean velocity characteristics from single drifters (cm/s) and wind (m/s). U and V represent E-W and N-S components, respectively. θ is the clockwise angle from north, in the direction of the wind and drift speed.*

| Julian days/variable | $U_{mean}$ | $U_{std}$ | $V_{mean}$ | $V_{std}$ | $\theta$ | $\lvert V \rvert_{mean}$ |
|---|---|---|---|---|---|---|
| 163 - 220 /drifter 7198 | 1.9 | 0.5 | -0.6 | 0.2 | 107 | 2.0 |
| /wind | -1.1 | 2.7 | -0.8 | 3.1 | 54 | 1.4 |
| 225 - 250 /drifter 5386 | 4.4 | 1.8 | -4.3 | 1.4 | 134 | 6.1 |
| /wind | -2.2 | 3.2 | 0.5 | 3.7 | 103 | 2.3 |
| 225 - 245 /drifter 7199 | 4.2 | 1.7 | -3.1 | 1.7 | 126 | 4.4 |
| /wind | -1.6 | 2.7 | -0.3 | 3.1 | 79 | 1.6 |
| 312 - 333 /drifter 5387 | 4.1 | 1.4 | 0.7 | 0.9 | 80 | 4.1 |
| /wind | -4.6 | 3.0 | -1.4 | 5.8 | 73 | 4.8 |
| 312 - 333 /drifter 9867 | 2.9 | 0.8 | 0.4 | 0.5 | 82 | 2.9 |

## 4.5 Conclusions

The drifter tracks all show an eastward drift across the northern part of the Bothnian Sea. The drifter speed is roughly 1.6 % of the mean wind speed and slightly to the right of the wind direction, as could be expected from Ekman theory. Inertia currents were frequently superimposed on this drift. This is in accordance with offshore current measurements by Alenius and Mälkki (1978) at the Pori-Rauma region. They found that surface Ekman drift and inertia motions were the dominant features in the current field. The crossing of the Bothnian Sea occurred on times scales of roughly a week (strong westerly winds) to a couple of months. Hence, a horizontal mixing of the surface layer over a season seems possible. This confirms the Monte Carlo simulations of the surface layer mixing in the Bothnian Sea by Funkquist and Gidhagen (1984). They also used pseudo-Lagrangian particle tracking in their calculations based on climatological wind forcing.

One cluster experiment (and several single drifter experiments) showed the rectifying effect of the coast even at distances far exceeding the local Rossby radius. This also is in accordance with findings of Alenius and Mälkki (1978). However, most cluster experiments did not show this feature.

In future work the drifter experiments will be used for dispersion calculations and statistical description of the surface current characteristics in the Bothnian Sea.

**Acknowledgements**

The participation of Canada Center of Inland Waters has been a prerequisite for the success of the Lagrangian current experiments and analysis. We thank especially Ken Miners at CCIW for preparing the Canadian Hermes drifters and for supplying the Argos data tapes regularly. We are also grateful for the assistance given by the crews on the Finnish and Swedish Coast Guard ships as well as those on the Swedish Fishery Board ship. Further we will thank Robert Axelsson, Gustaf Westring, Robert Hillgren and Henrik Lind at SMHI for devoting time and interest of drifter performance, management and technical assistance.

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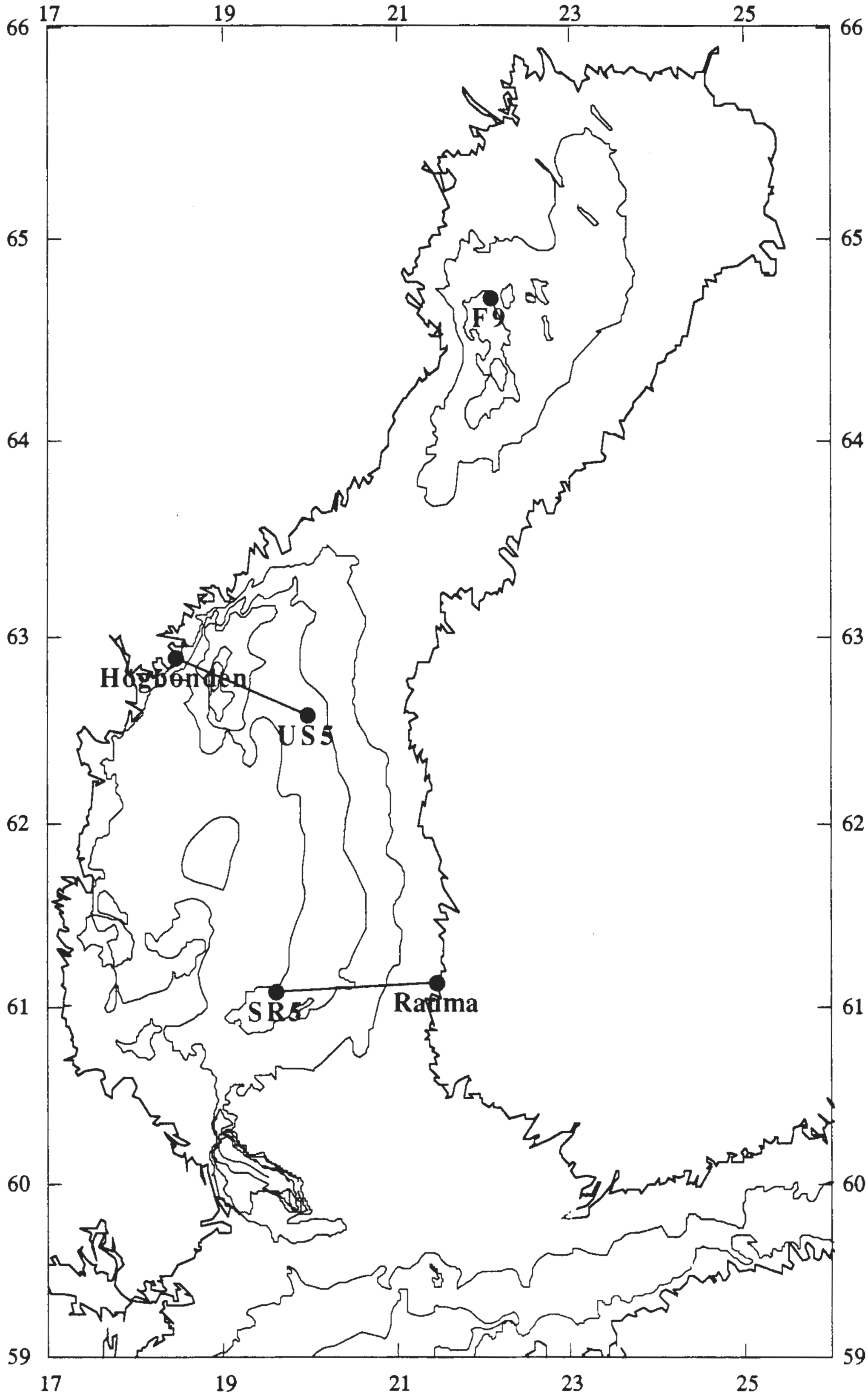


*Figure 4.1. Chart of the Gulf of Bothnia with measurement transects for current meter moorings.*

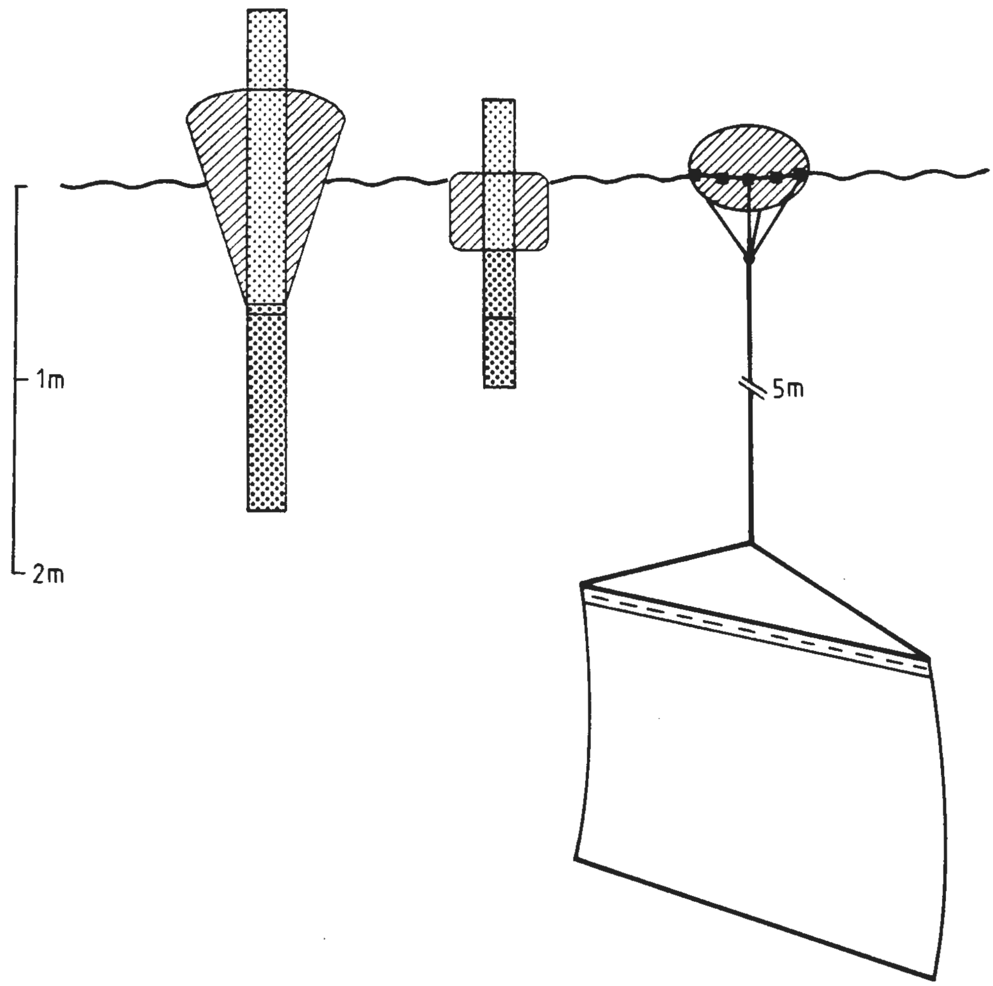


*Figure 4.2. Sketch of the drifters (from left to right: Conmar II, Conmar I and Hermes) used in the Lagrangian current experiments.*

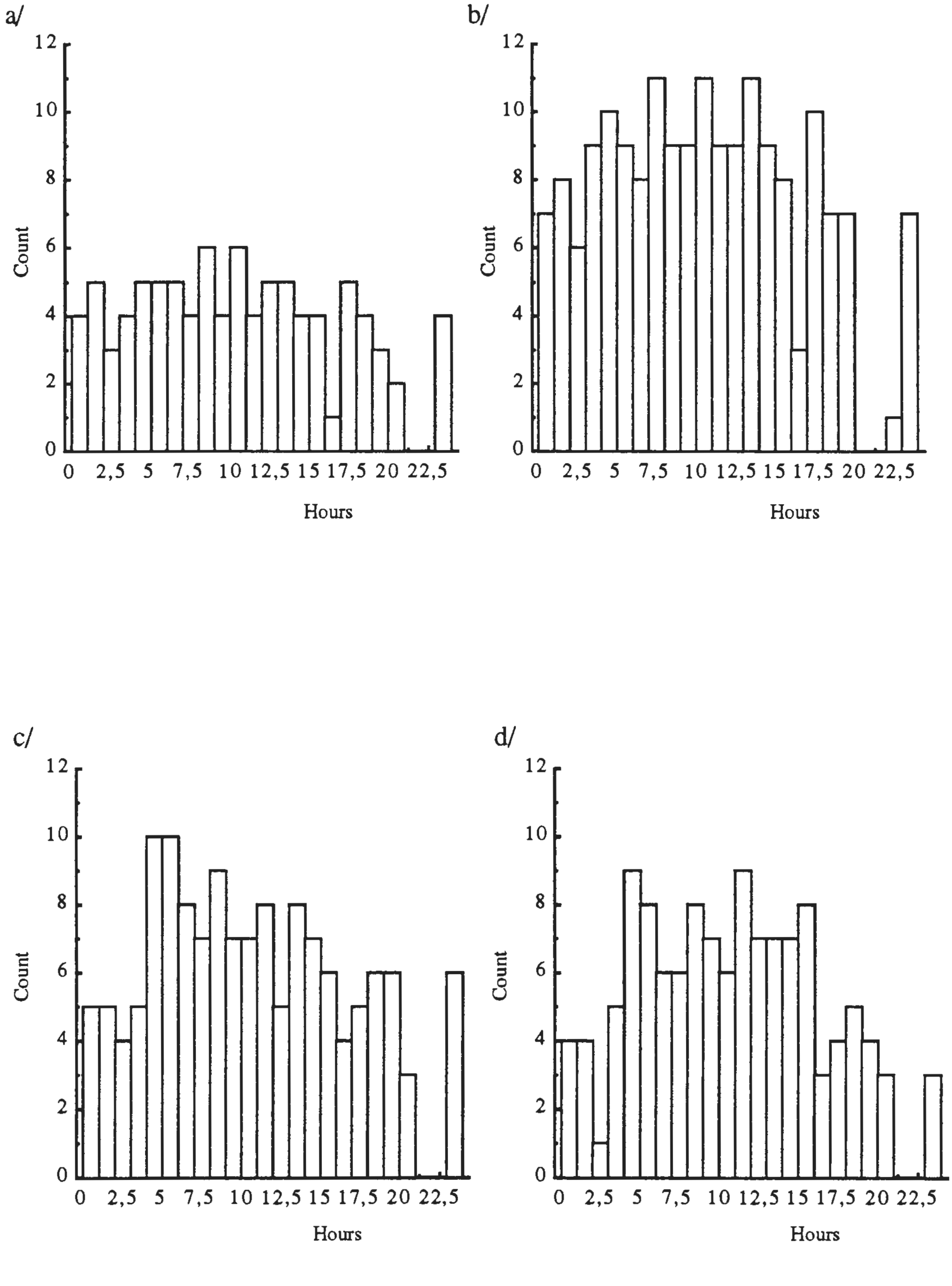


*Figure 4.3. Histogram of the daily distribution of position fixes. The presented data are taken from the performance of a) drifter 9869 and b) drifter 5385 during the second cluster experiment in June, and c) drifter 9869 and d) drifter 5385 during the cluster experiment in November.*

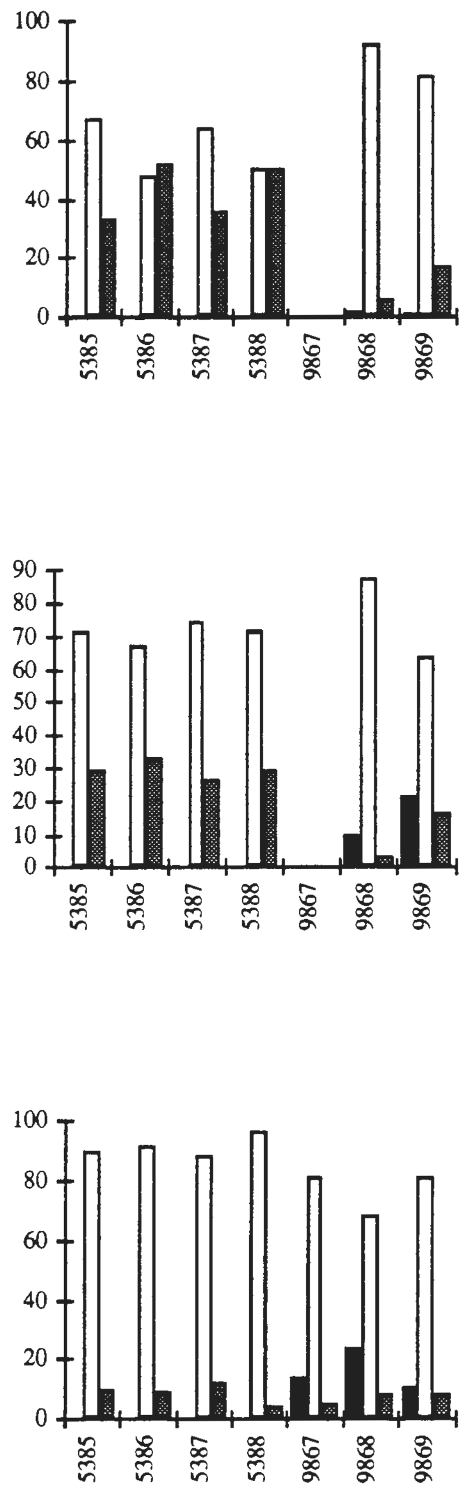


*Figure 4.4. Accuracy of drifters during cluster experiments. Top from second experiment in June, middle from first experiment in August and bottom from November experiment. The general position accuracy of the Argos system is divided into three groups, here presented in grey, white and black columns corresponding to the standard deviation of 150, 350 and 1000 m.*

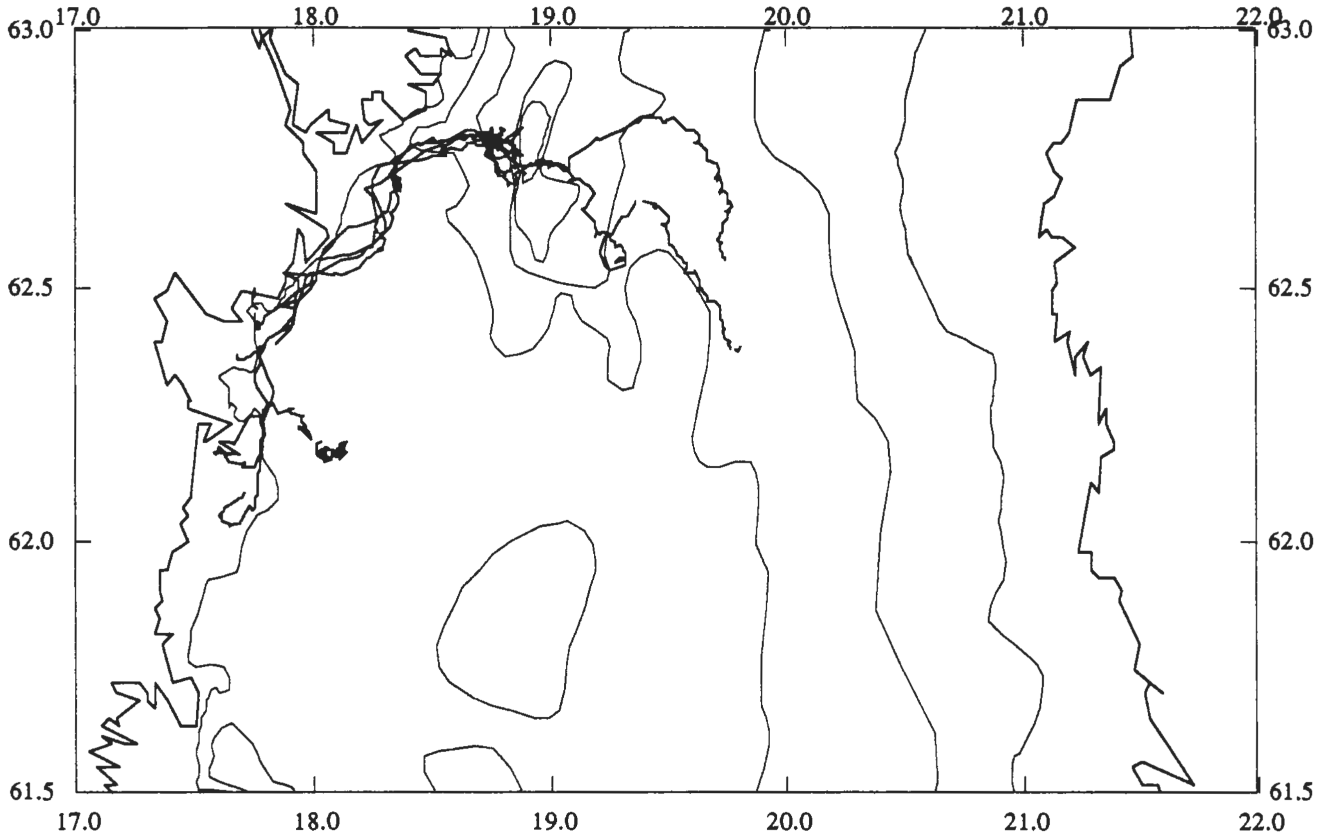


*Figure 4.5. The second cluster experiment in June, 1991. Raw data from 6 drifters are plotted. The time of deployment and recovery was June 11 and June 18, respectively. Four drifters were captured within the coastal current, whereas the other two moved offshore.*

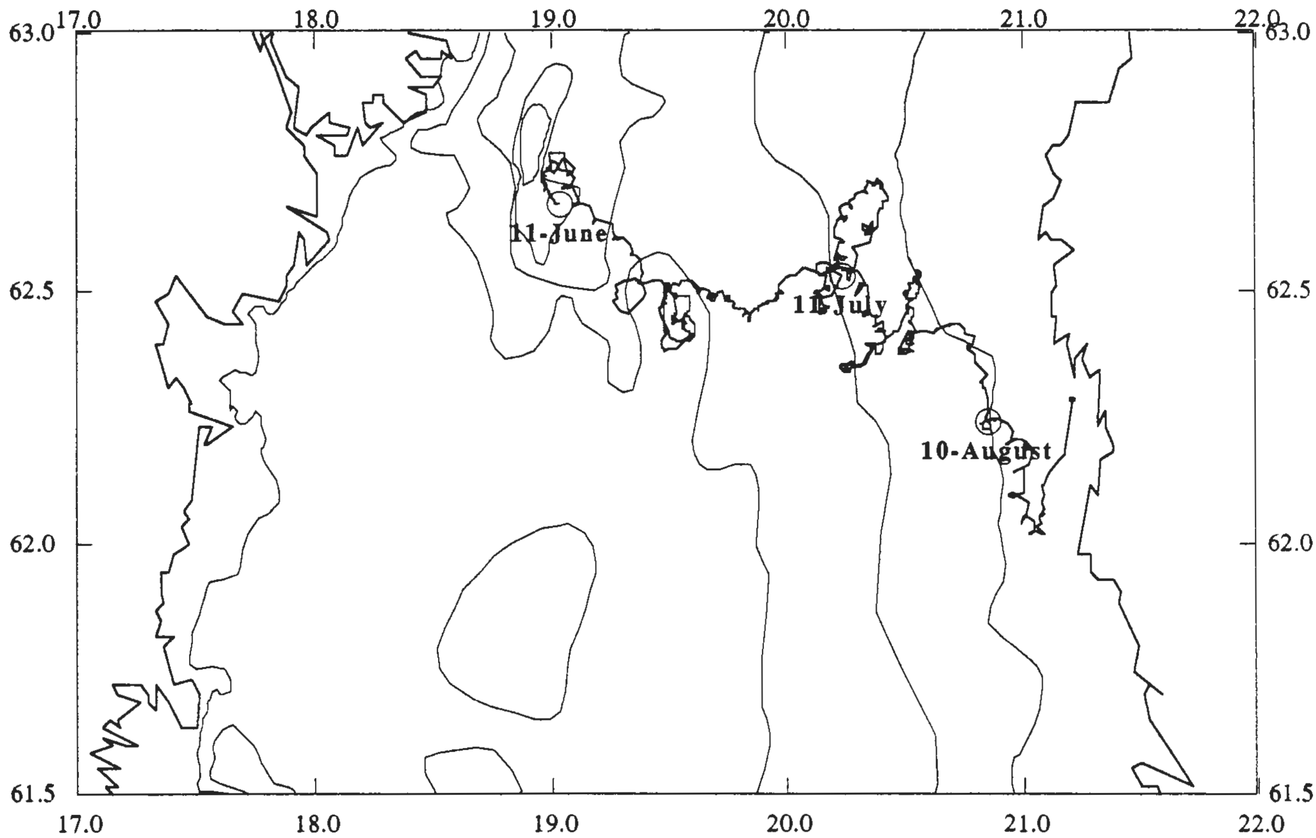


*Figure 4.6. Plot of drift position from drifter 7198 during summer, 1991.*

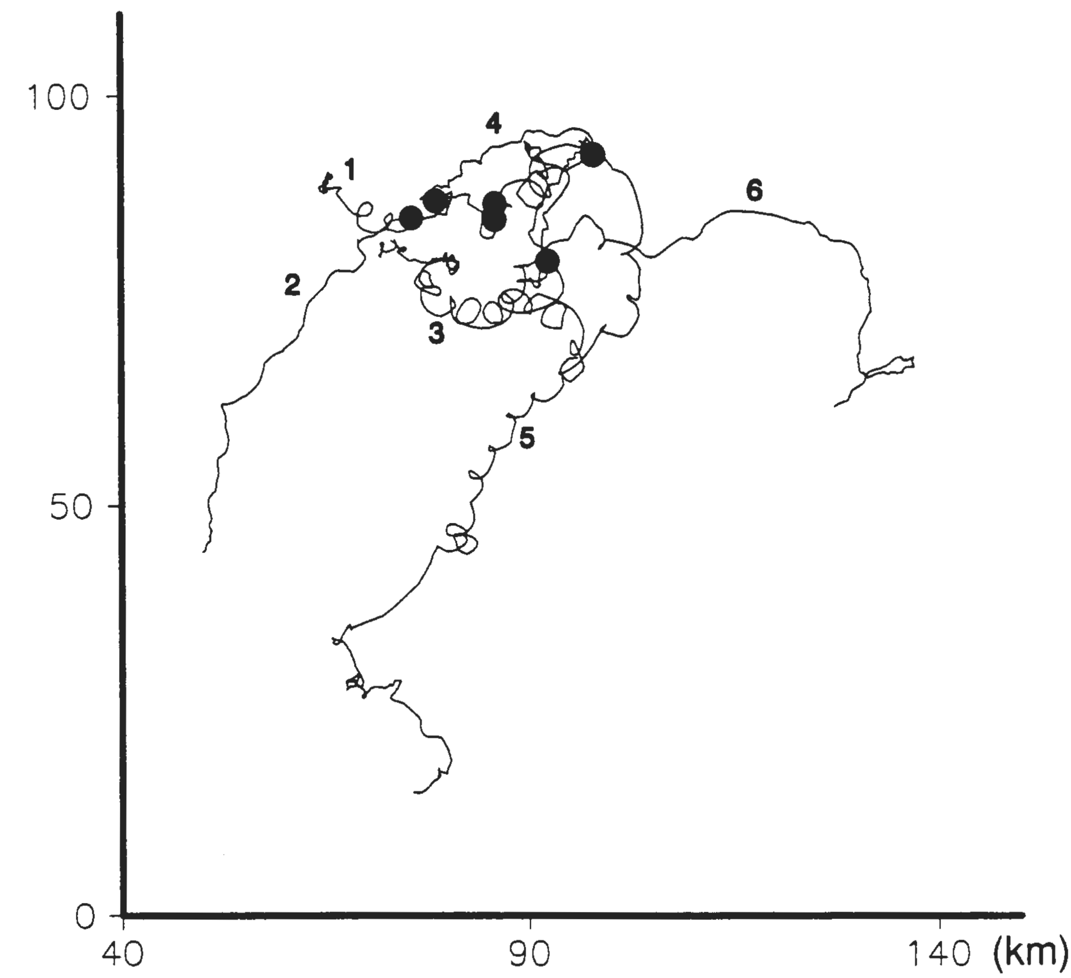


*Figure 4.7. Centroid positions from all 6 cluster experiments.*

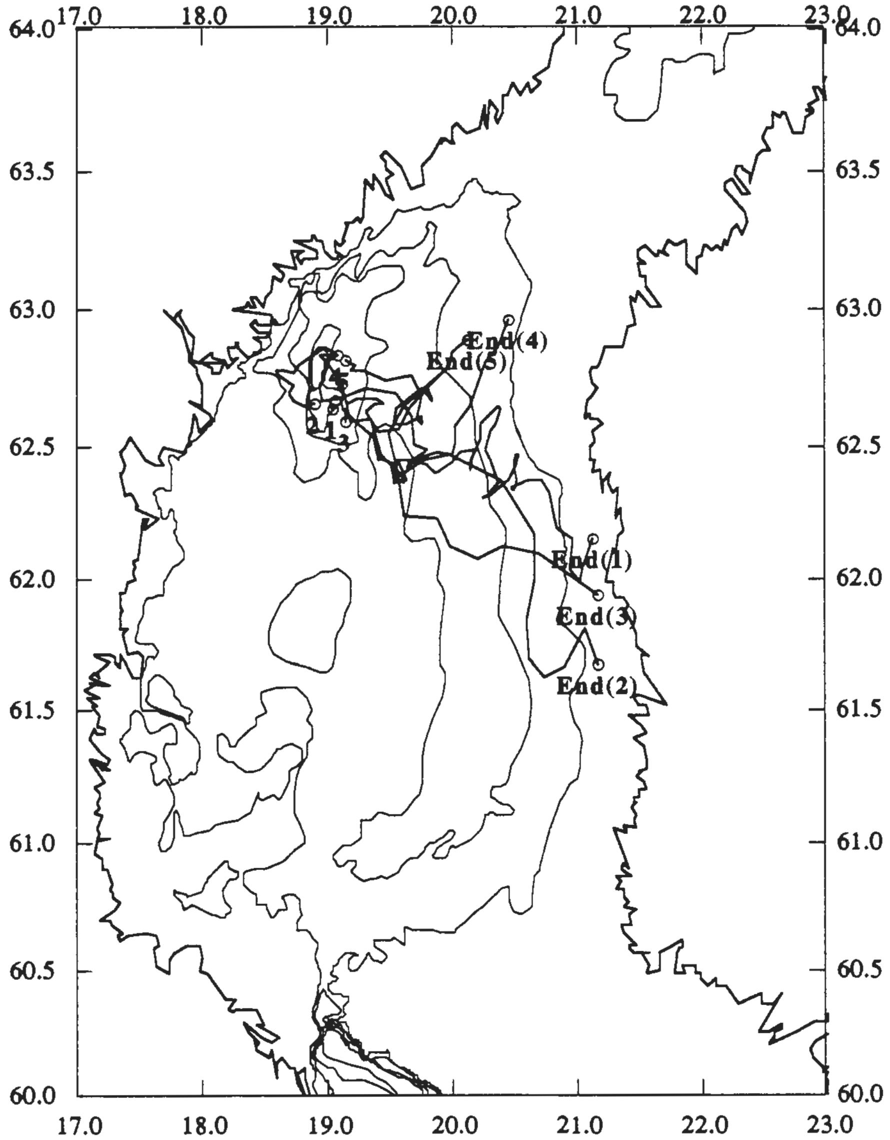


*Figure 4.8. Single drifter tracks derived from daily mean positions in the Bothnian Sea. In all cases a mean eastward drift can be noted.*

# CHAPTER 5

## FINNISH LAGRANGIAN CURRENT EXPERIMENTS

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### 5.1 Introduction

The primary goal of the Finnish drifter experiment was to gain information of the marine drift and dispersion in the eastern Gulf of Bothnia, both during summer conditions of low wind and strong thermal stratification, and during the strong-wind autumnal conditions. Additionally, the drifter data is to be used together with the on-site current meter data, for getting a better spatial and temporal representativeness of the current information in the Gulf of Bothnia.

### 5.2 Experiments

The Finnish Lagrangian drifter experiments were carried out near the eastern coast of the Bothnian Sea, at the latitude of 61° N. The area is mostly open sea, the depth of which decreases gradually from almost 100 m in the offshore, down to 10 m in the coastal area, some 6 km from shore. The coast is a mosaic of small islands in the N-S section. Land elevations on the coast are low. Figure 5.1 shows the GB-91 Rauma coastal transect where Lagrangian drifter experiments were carried out. Two cluster experiments with eight drifters each (four Canadian design produced by Hermes Electronics Inc. and four Norwegian design produced by Christian Michelsen Research) were conducted from June 4 - 18 and November 5 - 16, 1991. The Canadian drifters had a rather flat surface buoy whereas the Norwegian drifters had a somewhat higher surface buoy with an antenna mast. Both types of drifters were equipped with rectangular sail of 2.4 m × 3.0 m. Steel bars were inserted in the top and bottom of the sails. Figure 5.2 shows the schematic sketch of the two drifters used in the experiments. The surface floaters contained batteries and the necessary electronics for transmission to the Argos system, which was used to track the drift of the buoys. No additional sensors were installed on the buoys in question.

Additionally, one deep water mass tracking experiment was performed near the international Baltic Sea monitoring station SR5, in the middle of the Southern Gulf of Bothnia. The depth in the area varies between 60 and 130 m.

The drifters for the cluster experiments were released from *R/V Aranda* yielding a one point deployment area, with a mutual distance of the buoys of no more than 50 m, in the beginning. The drifters were also recovered by Aranda, except of one. It was recovered by the help of the Isokari Pilots. For the cluster experiments, the sail (lower margin) was installed at the depth of 5 m, whereas for the water mass tracking experiment it was at 70 m.

The first cluster experiment was performed during the first half of June, 1991 (Table 5.1 below). All the eight buoys were deployed in the position of 61.155° N, 20.917° E.

*Table 5.1. Dates and sites of deployment and recovery of the buoys and the number of locations determined by the Argos system during the drift period for the cluster experiment 1.*

Deployment of all buoys: 61.155° N, 20.917° E on June 4, 1991, 13 UTC.

Recovery:

| ID | Date and time | Site | Number of locations | Remarks |
|---|---|---|---|---|
| 5380 | 18.6 02:30 | 62.092° N, 20.780° E | 242 | Recovered without sail |
| 5397 | 17.6 19:00 | 61.732° N, 21.257° E | 226 | Found in a net, correct data up to June 16 |
| 6671 | 17.6 14:40 | 61.683° N, 21.213° E | 240 | - |
| 6672 | 17.6 16:20 | 61.695° N, 21.287° E | 247 | - |
| 10855 | 18.6 04:25 | 61.805° N, 20.870° E | 237 | - |
| 10856 | 17.6 15:10 | 61.758° N, 21.217° E | 245 | Found in a net |
| 10857 | 17.6 13:15 | 61.630° N, 21.072° E | 249 | - |
| 10858 | 18.6 05:30 | 61.895° N, 21.157° E | 247 | - |

The buoy with an Argos identification number (ID) of 5397 was found tied in a float of a fishing net, where it had been no longer than one day most apparently, as deduced from the location data. The sail was cut off. ID of 10856 had drifted to a fishing net also, shortly before it was picked up. ID of 5380 was found drifting dented without the sail. Judging from the trajectory, it had lost its sail at quite an early stage of the drift.

The conditions of light wind, up to 5 to 8 m/s from the south or from the northeast, prevailed during the experiment, cf. Figure 5.3.

The second cluster experiment was performed in the beginning of November, when the wind was stronger and there was no temperature-induced surface layer stratification any more. Eight drifters were used, released in a similar way as in the June experiment. Details are given in Table 5.2.

*Table 5.2. Dates and sites of deployment and recovery of the buoys and the number of locations determined during the drift period for the cluster experiment No. 2.*

Deployment of all buoys: 61.170° N, 20.623° E on November 5, 1991, 14 UTC.

Recovery:

| ID | Date and time | Site | Number of locations |
|---|---|---|---|
| 5380 | 16.11 08:25 | 61.973° N, 21.120° E | 160 |
| 5397 | 16.11 08.30 | 61.973° N, 21.120° E | 150 |
| 6671 | 16.11 08:40 | 61.972° N, 21.122° E | 143 |
| 6672 | 16.11 08:25 | 61.973° N, 21.120° E | 159 |
| 10855 | 16.11 10:20 | 61.955° N, 21.116° E | 163 |
| 10856 | 16.11 11:25 | 62.083° N, 21.264° E | 173 |
| 10857 | 16.11 08:00 | 61.979° N, 21.077° E | 181 |
| 10858 | 16.11 07:20 | 61.981° N, 21.191° E | 185 |

In this experiment the buoys drifted quite close to the shore, which might have influenced the very end of the drift.

Typically for the season, the winds were moderate or rather strong with several days of winds above 10 m/s, mainly from directions between south and southwest (Figure 5.3).

After the drifters of the cluster experiment 1 were recovered, one of them (ID of 10853) was trimmed to the 70 m depth and deployed at SR5 (61.083° N, 19.583° E) on June 18, 1991, at 20:30 UTC. The drift given in Figure 5.10 was very occasional, with periods of very low drift velocities interrupted by a few more intense movements. It can not be ruled out that the buoy would have touched the bottom at some stage, since the buoy stayed quite a long time in an area of depths sporadically even below 70 m. On the other hand, there is actually no proof that the slow movement of the drifter would not have been due to small current velocities during that period. Finally, a comparison to be made with the moored current meter data will verify the data.

After August 5, approximately, however, the buoy lost its sail for an unknown reason and started drifting towards the city of Rauma in the beginning, and turned later southwardly in the alongshore direction. Finally, it was picked up on August 14 by the Isokari Pilots, a few miles away from the pilot station (60.72° N, 21.02° E).

## 5.3. Data summary

Basically, the Argos system records the buoy ID number, location coordinates, accuracy class of location, time of each observation and, as an alternative, possible sensor data.

The location accuracy for an Argos buoy depends on the geometry and duration of a satellite pass, on the transmission interval and velocity of motion of the buoy and, on the stability of the transmitter oscillator of the buoy. Generally, the position accuracy of the Argos system is divided into three categories; the standard deviations of coordinates being 150 m in class 3, 350 m in class 2 and 1 km in class 1, defined and given by Argos. Figure 5.4 shows the distribution of various classes for the cluster experiments.

In addition to the other experiments, some location tests were performed in a fixed place on land in order to study the distribution of the location errors. By means of these calibrations it is possible to verify the reliability of the Argos location classes. Mean values of standard deviation in various location classes for all the buoys are presented in Table 5.3. It can be seen that during our test period the differences between the three classes were not as large as generally stated by Argos.

*Table 5.3. Mean values of standard deviation of a fixed test place position determinations for various location classes.*

| | Location class 3 | Location class 2 | Location class 1 |
|---|---|---|---|
| Latitude | 295 m | 293 m | 442 m |
| Longitude | 190 m | 575 m | 562 m |

Figure 5.4 shows the distribution of various location classes for the cluster experiments. The distribution was better for the cluster experiment No. 1 than for No. 2, so that the portion of the best location class was larger and the portion of the poorest class was smaller for the summer experiment than for the autumn experiment. This result can be caused by seasonal variation in the content of wind-induced wave energy. The Canadian buoys showed, however, a better behaviour in both experiments compared to the Norwegian; they had larger percentage of the best category locations and a smaller amount of the worst category. The difference might be caused by different behaviour of the buoys in the field of wind waves, but differences in the oscillator stability of the buoys may also affect the distribution. The latter was studied during the fixed place test period, and the standard deviations of the buoy locations are given in Figure 5.5 as averages, for the Canadian and Norwegian buoys. The Canadian buoys showed a slightly better accuracy.

The drift data were revised in the following way. If the difference between successive locations of a buoy was distinctly larger than would be expected considering the limits of the drift speed and the typical location accuracy, the observations were removed manually from the data. In this sense, some of the Norwegian type buoys showed more erroneous positions and random scattering than the others. In addition, for the study of the overall trajectories a linear interpolation scheme and a filter (of Butterworth type II) were used to damp the noise caused by inaccuracies in successive positions. For spectral studies of the time series of the drift, an interpolation and smoothing technique developed for the Finnish Antarctic Weddell Sea buoy studies was used (Launiainen et al., 1991; Vihma and Launiainen, 1993).

The smoothed trajectories of the various buoys are given in Figure 5.6 for Cluster 1 and in Figure 5.7 for Cluster 2, respectively. Analogously, Figure 5.8 shows the overall trajectory of the centroid (center of population) for Cluster 1 and Figure 5.9 gives the centroid for Cluster 2.

In both experiments, the overall drift was to north - northeast, i.e. the buoys were approaching gradually the Finnish coast in the north-south direction. Generally, this is in accordance with the wind conditions prevailed, especially when taking into account a modification caused by the general circulation pattern in the Gulf of Bothnia. The question will be reported in more detail in a later study.

The mean drift velocity as calculated for the centroid was 0.10 m/s for Cluster 1 and 0.16 m/s for Cluster 2. Additionally, Cluster 1 of a low-wind summer period showed distinctly larger dispersion than the autumnal higher wind speed period of Cluster 2, which shows much more homogeneous drift trajectories. In Cluster 1 (Figure 5.6) one of the buoys (ID of 5380) showed suspicious trajectory; the overall trajectory was ca 1.5 times longer than the others, and after four days from the deployment the trajectory is very different from the others. Additionally, the buoy was found without the drogue sail.

We may summarize that the trajectories of Cluster 1 showed more complicated and oscillatory behaviour, and also inertial oscillation was found from several trajectories of Cluster 1, for example for June 15 - 16, 1991. Inertial period (~ 13.6 h) was also found frequently from analysis of the drift spectra, especially for summertime Cluster 1. Finally, the mean velocities and dispersion characteristics give us a first order estimate of a lateral dispersion coefficient of $10^5$ $cm^2$ $s^{-1}$ for Cluster 1 and of $10^4$ $cm^2$ $s^{-1}$ for Cluster 2. The deep water drifter showed (Figure 5.10) an interesting trajectory including quite a period of practically no motion up to velocities of 0.15 m/s. Later, the deep water data are to be linked with moored current meter data.

## 5.4. Conclusion and future analysis

The drifter experiments were carried out successfully; none of the drifters were lost and the drifters functioned reasonably. Because of the technical properties of the drifters, however, one of the two types used showed more random spikes in the trajectories, to be filtered out. The buoy data of drift velocity and direction revealed interesting differences in drift and dispersion between the two periods studied. Finally, the data allow us first order estimates for the dispersion coefficients in question. On the other hand, the amount of experiments was sparse, and further efforts are necessary.

Further analysis of the data will concentrate on time series and spectral analysis, on studies to compare the drift with the meteorological data and on a closer analysis of dispersion characteristics. Comparisons with current meter data will also be made.

The analysis of the wind-induced drift will be based both on the direct wind observations and on the calculations of the geostrophic wind. The latter is drawn from a high resolution atmospheric pressure grid. This is because the wind data of coastal synoptic weather stations often poorly represent the marine wind conditions. The above was the case especially during the Cluster Experiment 1, when the local wind, observed from the coastal stations, was frequently from land to sea.


## Acknowledgements

The drifter experiments were planned by a steering group, in which Dr. R. Murthy (CCIW), Mr. P. Alenius (FIMR), Mr. H. Grönvall (FIMR), Dr. B. Håkansson (SMHI), Dr. L. Rahm (SMHI) and Dr. A. Omstedt (SMHI) had a central role.

The field group of the Finnish Institute of Marine Research, under the guidance of Mr. O. Korhonen, and the personnel of R/V Aranda are kindly acknowledged for the field work.


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Vihma, T., and Launiainen, J. (1993)
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J. of Geophys. Res., in press.

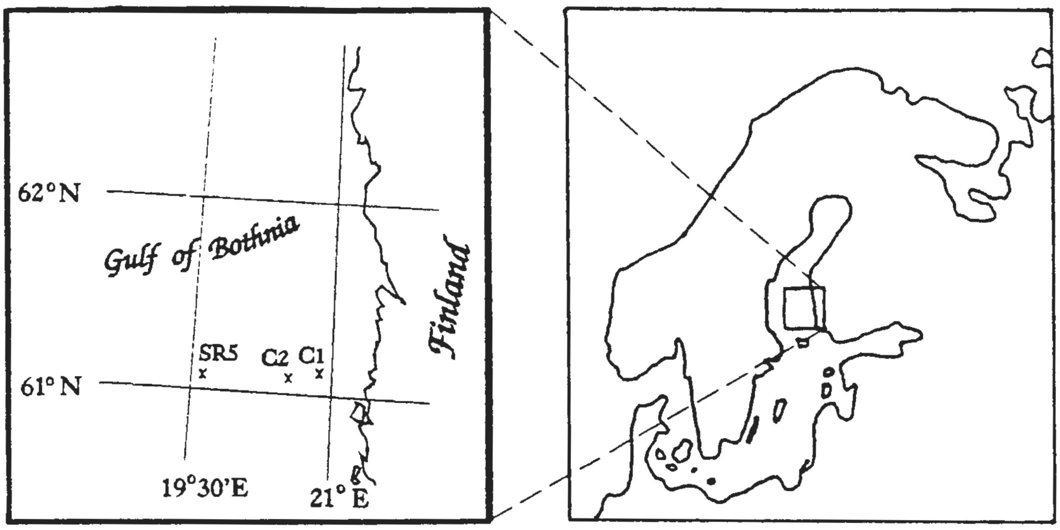



*Figure 5.1.* *Research area in the eastern Gulf of Bothnia. C1 and C2 indicate the deployment sites of cluster experiments and SR5 shows the deployment site of the deep water trajectory experiment.*

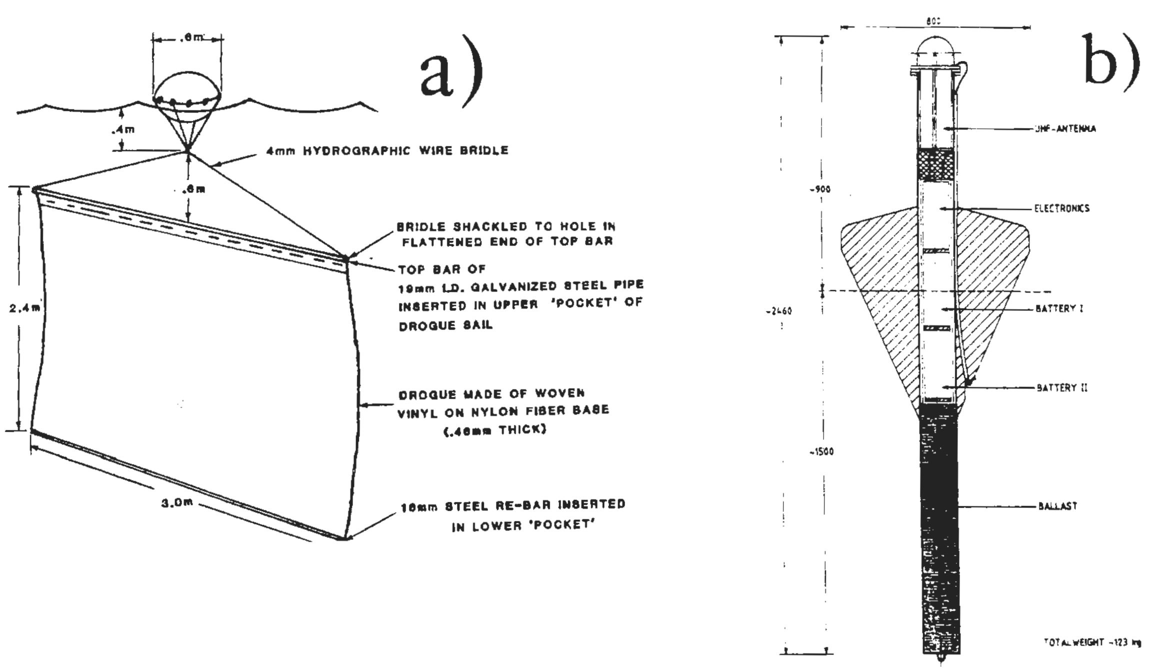
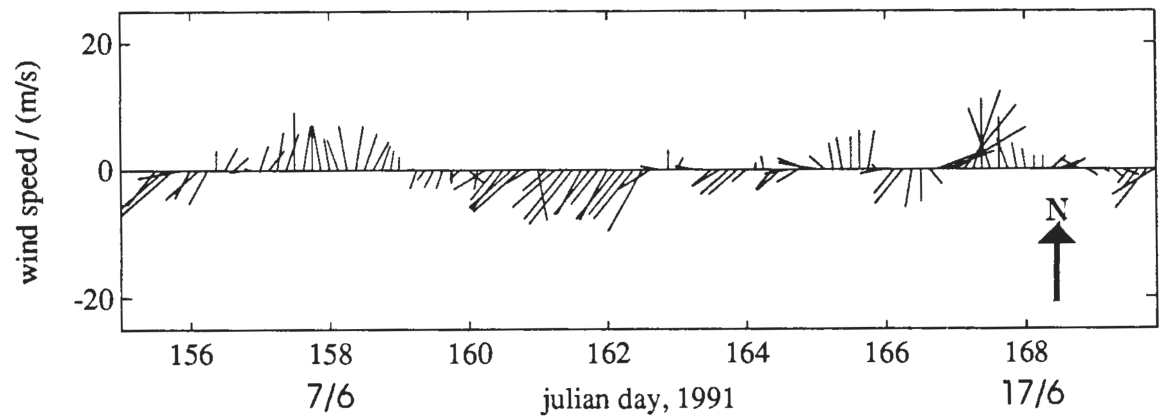



*Figure 5.2.* *Overall sketch of the buoy types used (in different scale). The drogue for the Norwegian buoy in b) is the same as for a).*

a)




b)

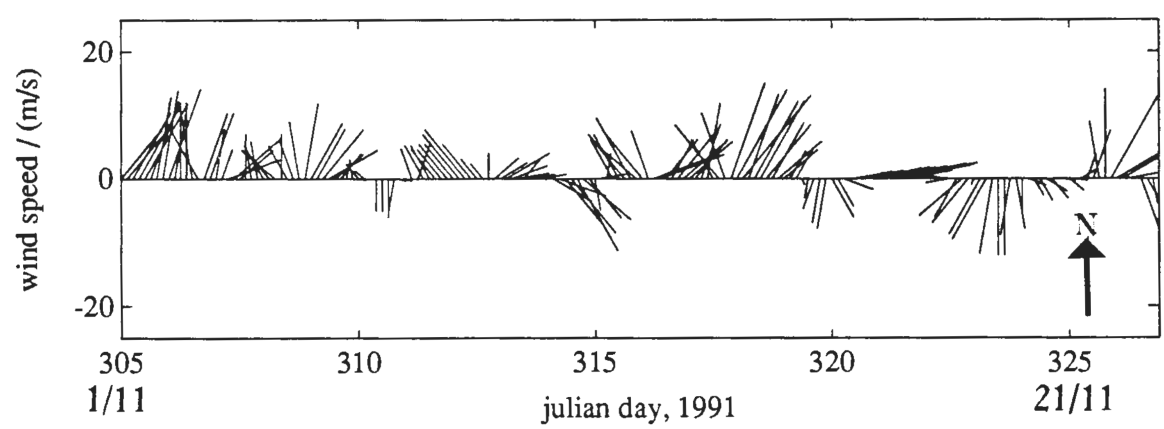
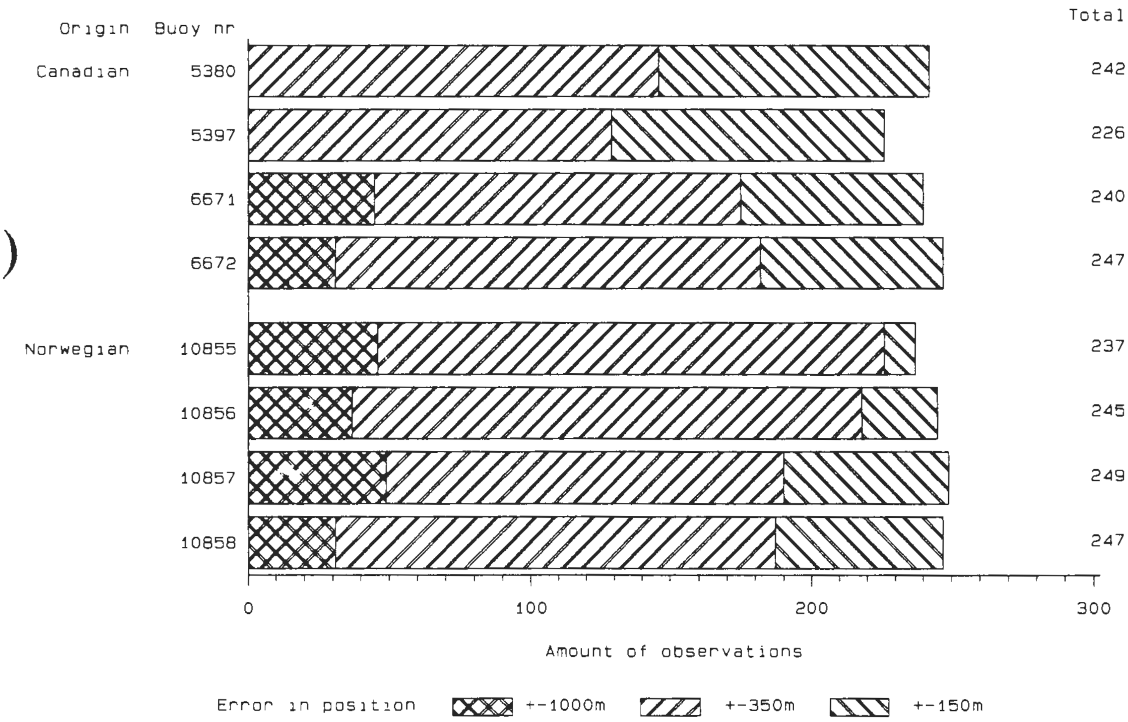



*Figure 5.3. Wind vectors as observed at Valassaaret (63.4° N, 21.2° E) in the Northern Gulf of Bothnia (3 hour intervals) during the cluster experiment 1 in a) and during the cluster experiment 2 in b), respectively.*

a)




b)

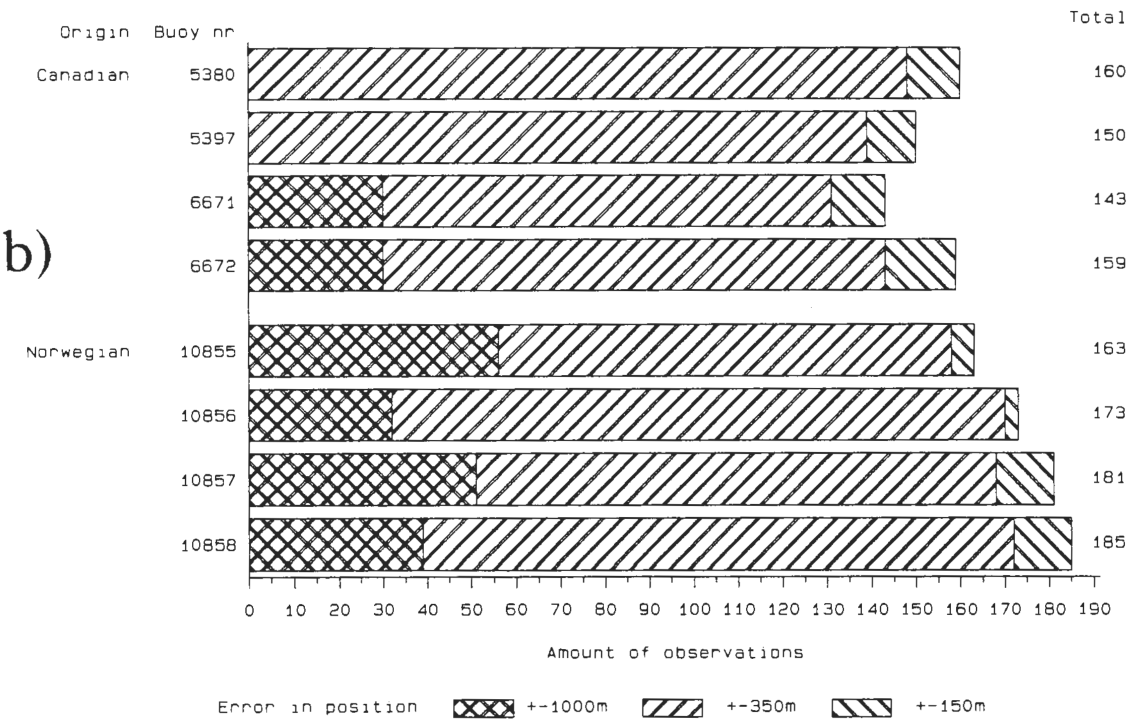



*Figure 5.4. Location accuracy given as the distribution of location classes of the Argos system for the drifters used in the Finnish drifter experiment. a) gives the results for Cluster 1 and b) those for Cluster 2, respectively.*

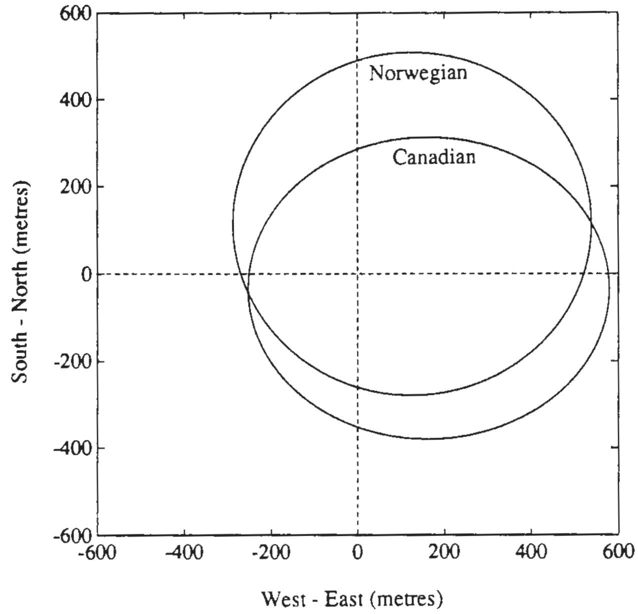



*Figure 5.5.*
*Standard deviations of the location accuracy during a test period in a fixed place. Different Argos-location classes are not separated and values are calculated as overall averages for the Canadian and Norwegian buoys. The figure is centered in the mean coordinates of the locations of the best accuracy class. (This was found to be within 120 m from the location given by the GPS-location system.)*

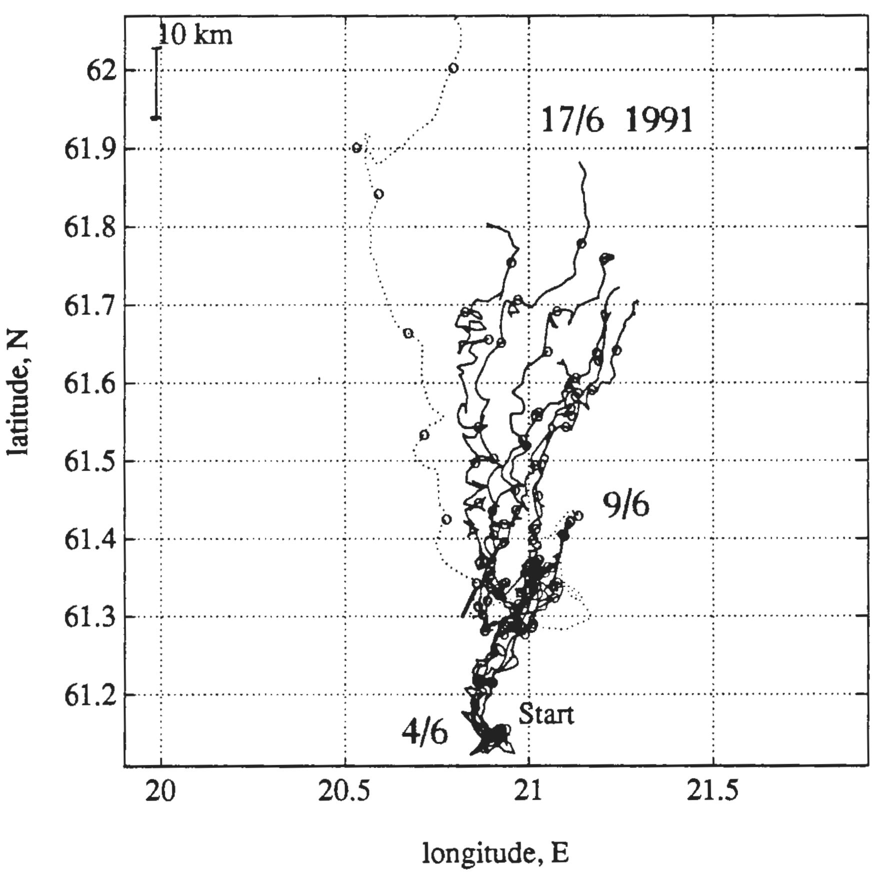



*Figure 5.6.* *Drifter trajectories for the Cluster Experiment 1; positions with daily intervals are given as circles. Dotted line indicates suspectable data. The scale is given in the figure.*

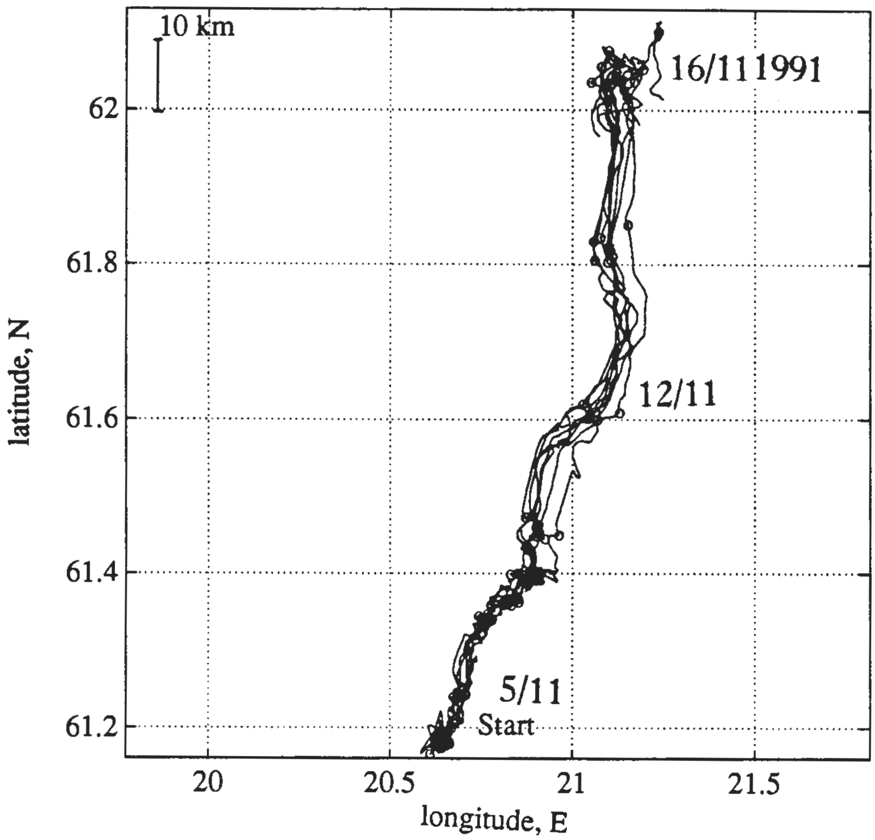



*Figure 5.7. Drifter trajectories for the Cluster Experiment 2; positions with daily intervals are given as circles.*

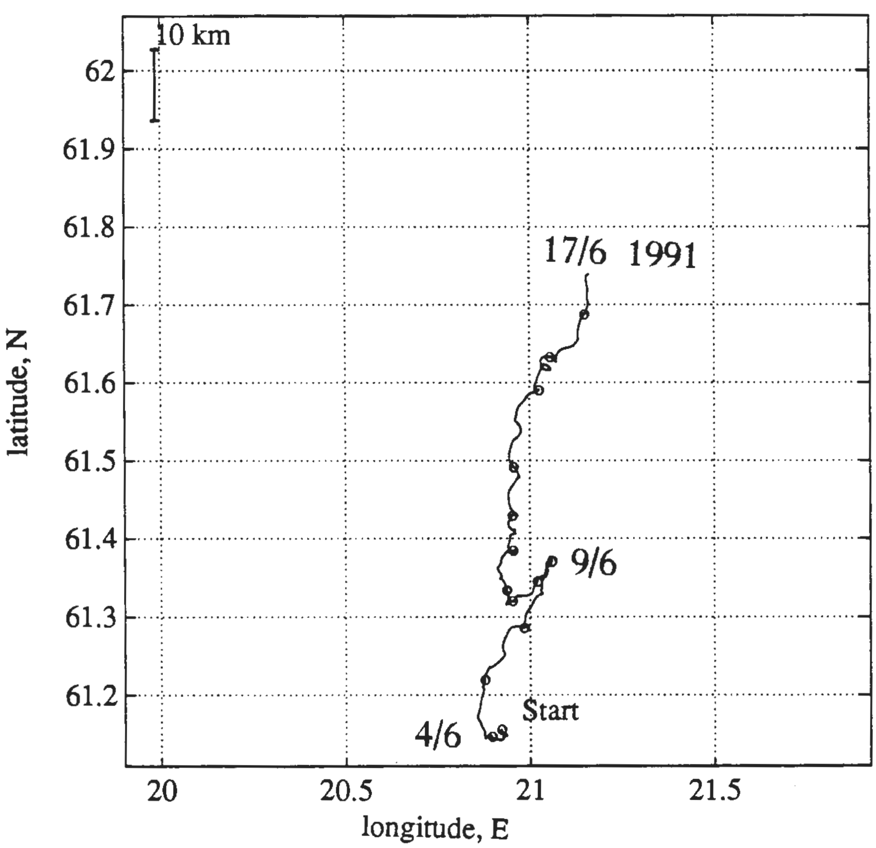



*Figure 5.8. Centroid (center of population) trajectory for the Cluster Experiment 1; daily positions are given as circles.*

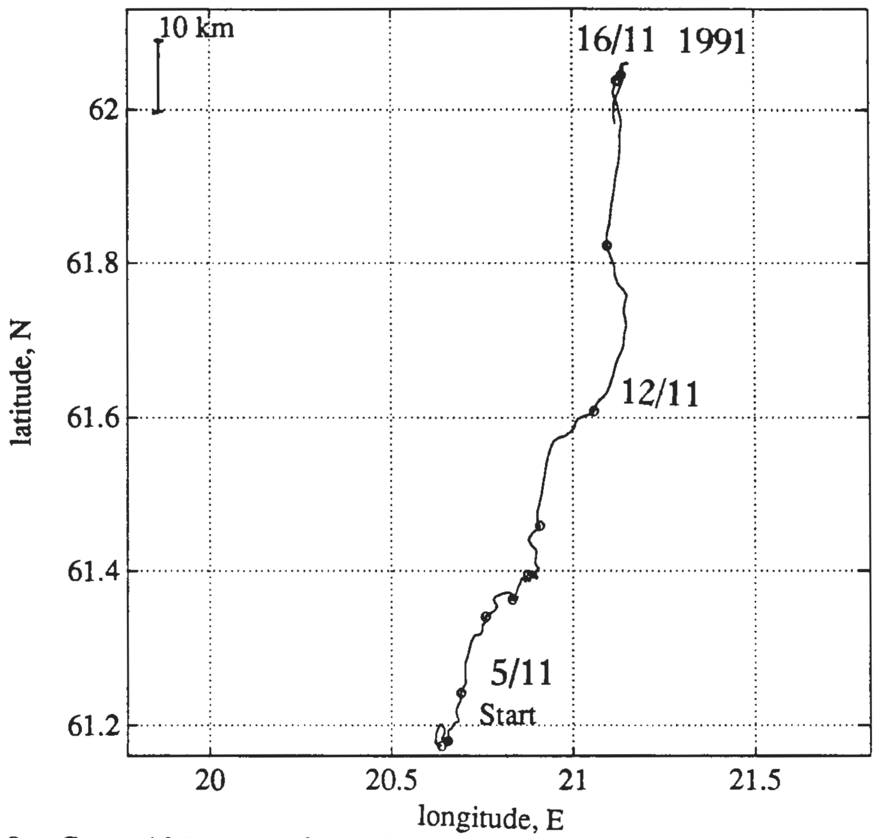



*Figure 5.9. Centroid (center of population) trajectory for the Cluster Experiment 2.*

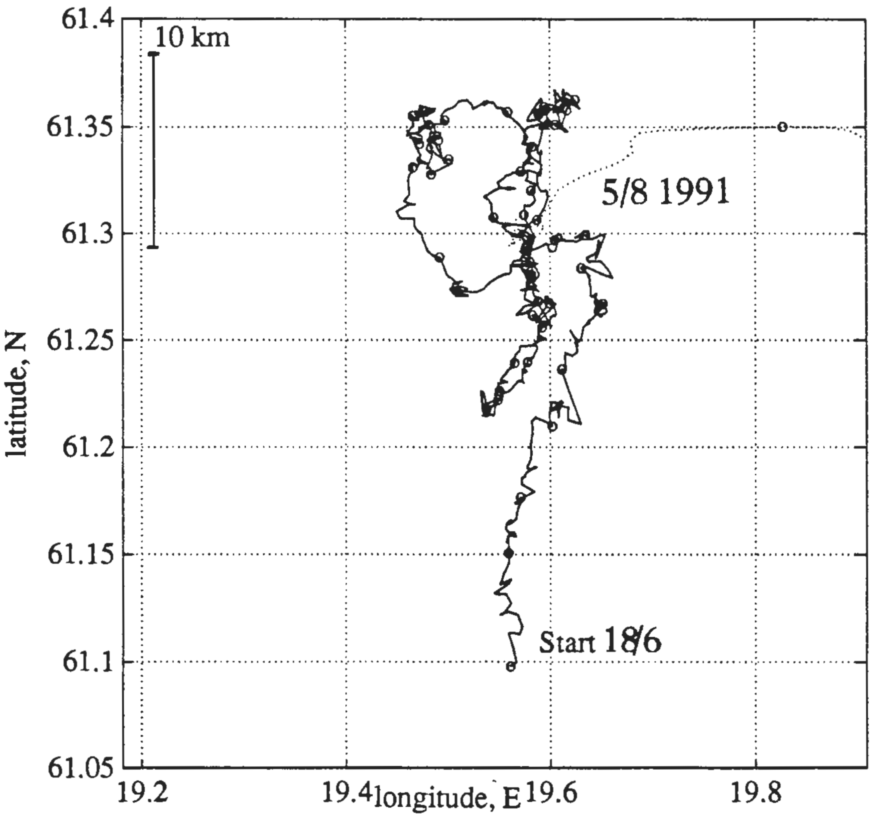



*Figure 5.10. Trajectory of the deep water experiment. Most of the drift at the end of the experiment after August 5 (dotted line) was scaled out of the figure. Positions with daily intervals are given as circles.*

# CHAPTER 6

## REMOTE SENSING EXPERIMENTS

Bertil Håkansson, Swedish Meteorological and Hydrological Institute, Sweden

### 6.1 Introduction

Measuring techniques used for oceanographic variables on an synoptic time scale covering vast areas such as an ocean basin are almost absent today. One existing method which partly has the potential to measure upper ocean variables is remote sensing. Combining remote sensing, ship and/or buoy measurements are most attractive since then synoptic coverage, vertical structures and variations in time can be combined.

In the present project remote sensing data has been gathered during one year. The aim is to investigate and analyse the image data with respect to synoptic scales in sea surface temperature, water mass analysis and sea surface currents from sequential images. A second aim is to provide the physical transport studies as well as other inter-related projects during GB-91 with image data.

### 6.2 Technical description

Remote sensing data from the weather satellites NOAA-AVHRR 11 and 12 have been received during the Gulf of Bothnia Year-1991. The image data set stored consists of subimages covering the Gulf and the northern part of the Baltic Proper in Mercator projection. Although, the images do have data from five different frequency channels (two visual and three thermal wave bands) three were chosen to be stored (one visual and two thermal bands), since this amount were considered to be optimal regarding image processing, analysis and storing capacity. In this way analysis of both surface temperature and some marine optical properties can be quantified.

The geometric resolution is at best 1.1 km (in nadir) and at worst about 5 km in far range (2800 km from nadir) for NOAA-AVHRR data. In order to avoid low resolution data those images, received at SMHI with a satellite height of less than 60 degrees above the horizon, were not stored. The radiometric resolution is 0.12 K in temperature and 0.1 % in spectral albedo. The total radiometric coverage in the images are -3 to 27 °C and 0 to 23.5 %, corresponding to maximum resolution (least significant part of the 10 bit word of image data). More detailed technical information of NOAA-AVHRR can be found in Lauritzen et. al. (1979).

### 6.3 Data coverage and quality

Image information in thermal and optical wavelengths are sensitive to clouds and air moisture. Cloudless atmosphere is a necessity if information is to be obtained from the ocean surface. Hence, useful data for oceanographic purposes are scattered in time although images are received approximately 5 to 11 times daily. The total amount of stored images are shown in Figure 6.1 together with the daily mean cloudiness. The total number of days covered by images are 64 of which 37 has been covered with more than one image. Due to the overall climate conditions the number of days with low cloud-coverage are most frequent during the summer months, which also is the period most frequently covered with images. In most cases there is a correspondence between low cloud-coverage at Skagsudde and the number of stored images, except during January to April when it appears that more images could have been gained. However, it is not obvious that single station data can be compared with horizontally averaged information as are the cloudiness determined from satellite images. Local effects may be different from the large-scale ditto.

## 6.4 Some examples

July is the month with a large amount of cloudless images. It was also a very warm and calm period compared to average conditions. In Figure 6.2 the mean image brightness temperatures from three line sections are presented along with air temperature data from two coastal stations (Skagsudde and Brämön). The air temperature variation is strong between night and day, whereas the temperature variation in the sea surface layer is less pronounced, as expected. In fact, the horizontal sea surface temperature pattern is also indeed stable. A time series of sea surface brightness temperature images covering the Bothnian Sea from July 3 to 8 is shown in Figure 6.3. Along the gently sloping topography in the eastern part of the Bothnian Sea a relatively cold water area is located, reaching from the Åland archipelago up to the northern Quark. Warmer water is found above the shallow area in the western part of the basin and along the coasts. This pattern reflects to some extent the depth distribution (cf. Figure 1.2), with relatively colder water above the central deep parts of the Bothnian Sea and relatively warmer water above shallow areas. Note also the persistent and relatively sharp temperature front along the eastern slope of the Bothnian Sea.

Another case from August 14, 1991, shows the mesoscale variability in the Bothnian Sea (Figure 6.4). Colder water is formed in the western part of the basin probably caused by cold air coming from northwest, creating a temperature difference of about 1 K. At this particular event drifter experiments took place at Högbonden.

## 6.5 Conclusions and future work

The July images are the most frequently occurring ones. During the end of this month fog is present in parts of the images, but despite this they are of good quality. During spring and winter time, 1991, clouds limited the visibility severely and hence there is only a few images from this period. In general we found that clouds were limiting the amount of good quality data during the whole year. The mean image sampling rate was 17 % for the Gulf of Bothnia during 1991. This may be compared to a similar monitoring study of the Skagerrak and Kattegat area during 1989 when the mean coverage was 25 % (Håkansson and Moberg, 1990). Whether this discrepancy depends on the different locations of these areas or just that it is from different years is not clear.

The image data are at the present time used for calculations of temperature frontal-zone statistics and spatial scale analysis of sea surface temperature features in the Bothnian Bay and Sea.

## Acknowledgements

Mats Moberg is most kindly acknowledged for technical assistance and management of the monitoring work. This project was financed by the Swedish Environmental Protection Agency and by the Swedish Meteorological and Hydrological Institute.

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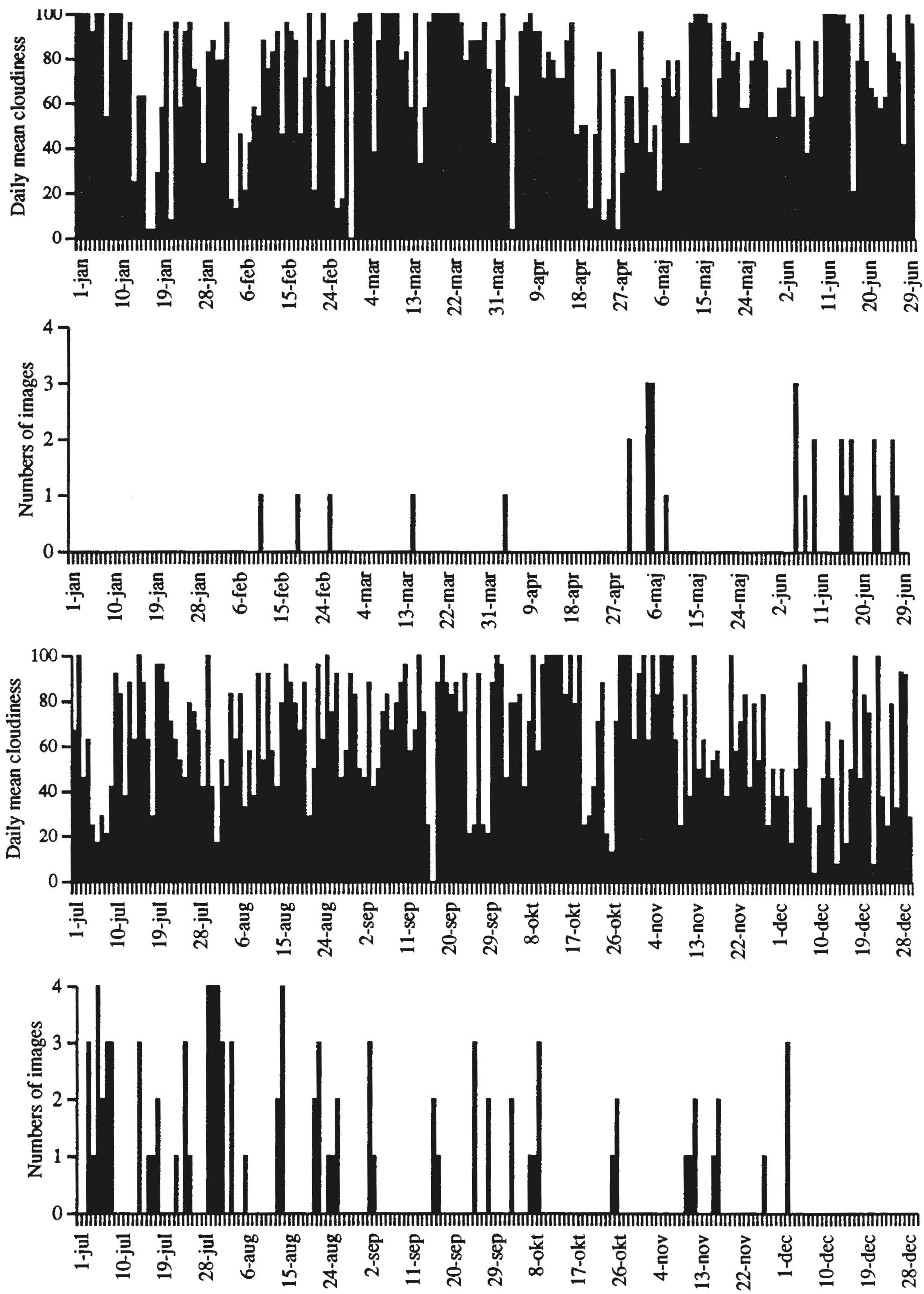


*Figure 6.1. Achieved images and daily mean cloudiness at Skagsudde weather station, 1991.*

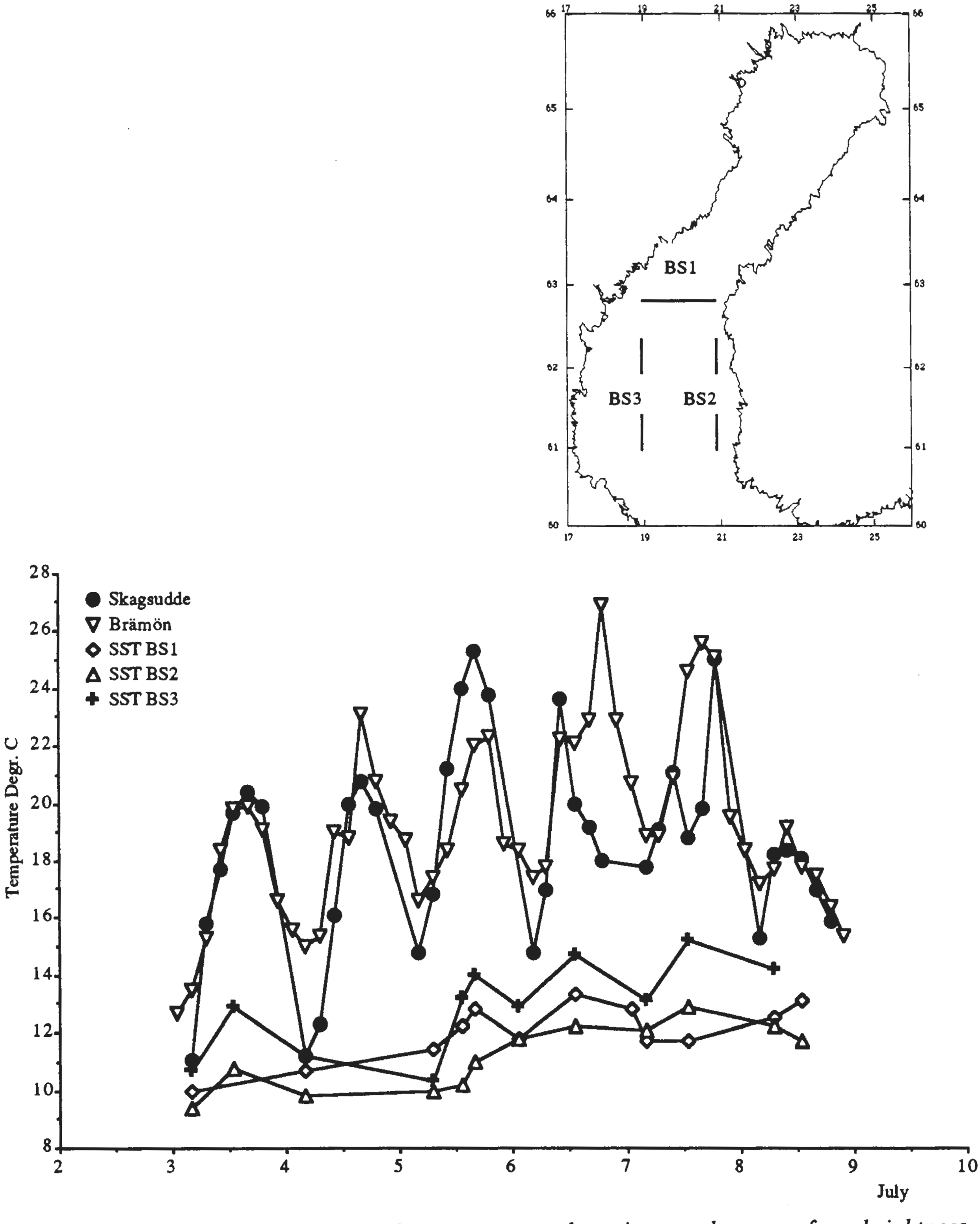


*Figure 6.2. Air temperature from two coastal stations and sea surface brightness temperatures from three line sections in the images, covering the Bothnian Sea.*

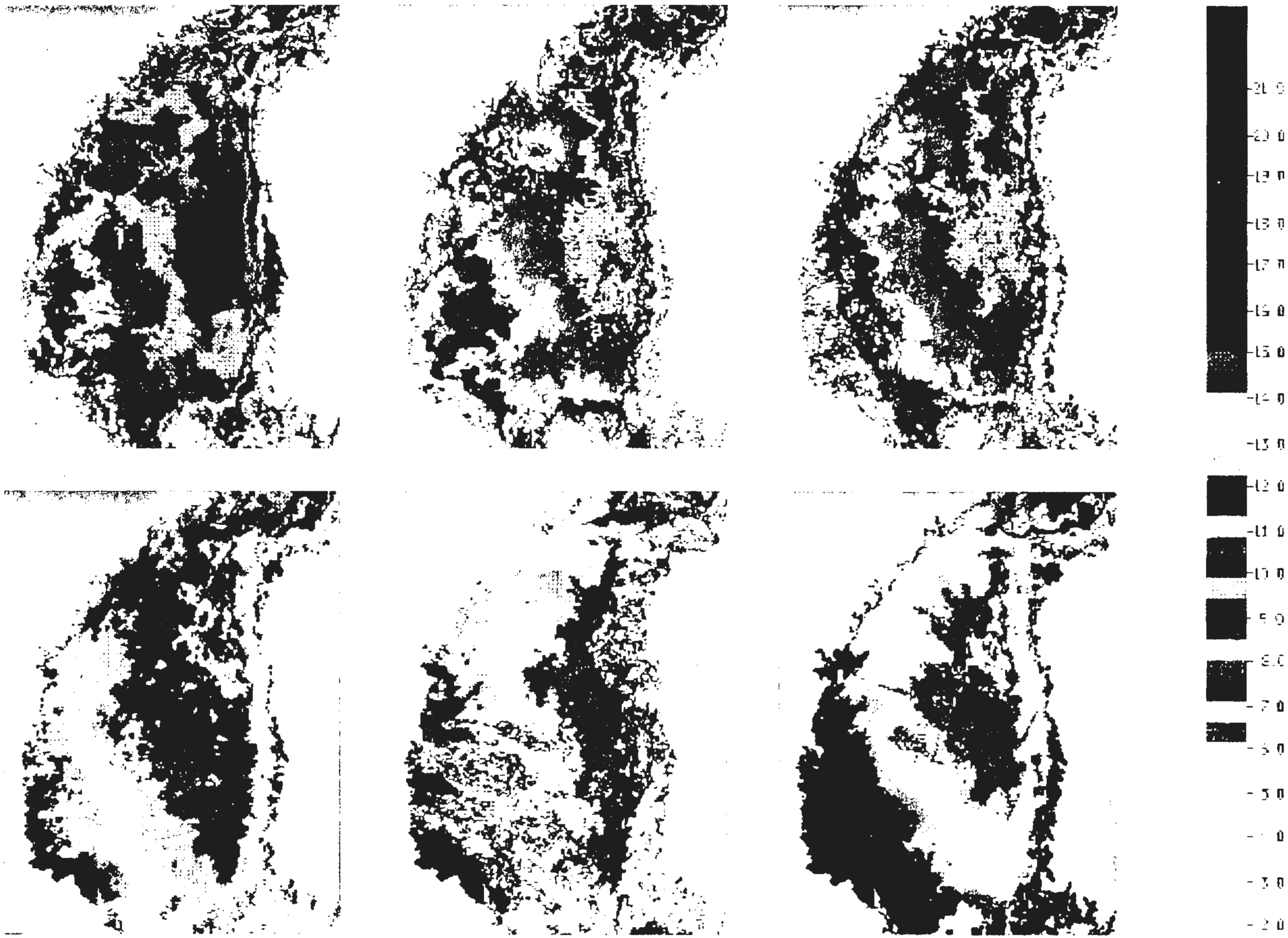

*Figure 6.3.* *Time series of brightness temperature images from July 3 to 8, 1991.*

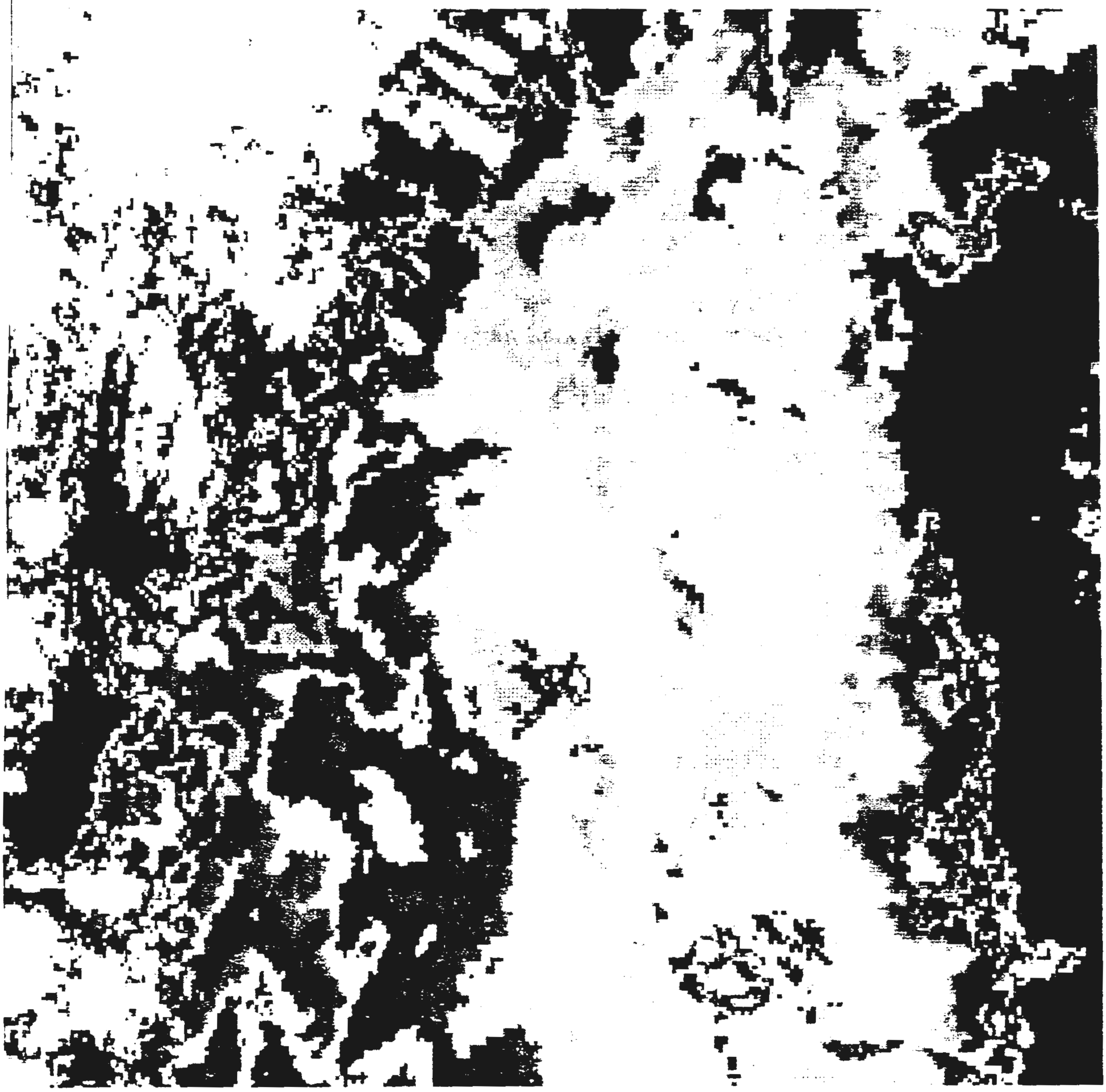

*Figure 6.4. High resolution brightness temperature image from August 14, covering the northern part of the Bothnian Sea.*

# CHAPTER 7

## SWEDISH HYDROGRAPHIC SURVEYS

Björn Sjöberg, Swedish Meteorological and Hydrological Institute, Sweden

### 7.1 The Swedish program

An extensive hydrographical program was performed during the Gulf of Bothnia Year-1991. The program can be divided into three different parts with somewhat different objectives; surveys, intensive open sea stations and intensive coastal stations. The principals in the project were the Swedish Meteorological and Hydrological Institute (SMHI), the National board of Fisheries, the Swedish Coast Guard, the National Administration of Shipping and Navigation and the Umeå Center for Marine Research.

In all, six surveys were realized during the period, from November, 1990, to November, 1991 (Figures 7.1 - 7.6). During four expeditions the hydrography of, essentially, the western part of the Gulf of Bothnia was mapped. The first expedition was carried out in November, 1990, and was followed by surveys in May/June, August and November, 1991. In January and March two surveys were performed covering the Quark and the Bothnian Bay.

The purpose of the surveys were mainly descriptive, i.e. to get a synoptic view of hydrophysical/hydrochemical state of the Gulf (or parts of) at different seasons during a year.

Those hydrographical stations, which were classified as intensive (Figure 7.7), were visited more than 10 times during the year. Those closest to the coast represent a part of an ongoing monitoring program, which is carried out by SMHI in cooperation with the Coast Guard. The open sea intensive stations were visited by the Umeå Marine Research Center in cooperation with the Coast Guard. The main purpose with the open sea stations were to study seasonal biological/ecological variations.

Below, we will limit our discussion to the results obtained from the four surveys covering parts of the Bothnian Sea; the reason being that the main objectives with this data report is to account for the physical experiments, of which all took place in the Bothnian Sea. The results from the intensive stations will only be discussed briefly.

### 7.2 Materials and methods

The surveys were performed with the National Board of Fisheries' research vessel R/V Argos. The vessel is equipped with a MkV CTD (Conductivity, Temperature and Depth sensor) from EG & G Marine Instruments. Due to problems with the pressure sensor on the CTD only a minor part of the CTD-data could be used. The major part of the data presented below therefore consists of water bottle data using reversing thermometers and a laboratory salinograph (MINISAL from AGE-Instruments), for measurements of temperature and salinity, respectively.

## 7.3 The salinity and temperature distribution

Water mass characteristics

The water masses in the Gulf of Bothnia are essentially a freshwater dilution of surface water from the Baltic Proper. The highest salinities, about 7.5 units, were found in the deepest parts in the south of the Bothnian Sea, the lowest, 1 - 2 units, in the surface waters in the northernmost parts of the Bothnian Bay.

The temperature/salinity characteristics are presented in Figure 7.8. The data from the Bothnian Sea and the Bothnian Bay are different from each other, since the salinities in the Bothnian Sea varied between approximately 4.7 and 7.5 units and the salinities in the Bothnian Bay were always below 4.3 units. In the Bothnian Sea the lowest temperatures were associated with intermediate salinities (ca 5.8 units), causing a "boot-like" look to the T-S curve. The reason for this is the existence of a perennial halocline, which counteracts vertical mixing. In the Bothnian Bay, where there is no perennial halocline, the lowest temperatures were associated with the highest salinities, resulting in a nearly linear relationship between salinity and temperature.

The Northern Quark constitutes a transition zone, where presumably a considerable amount of mixing occurs.

Seasonal variability

During winter the temperature stratification is practically nonexistent. A thermocline started to develop in May in the Bothnian Sea, and in June in the Bothnian Bay. The surface water attained maximum temperatures (15 - 17 °C) in the beginning of August (Figures 7.9 and 7.11) when the vertical temperature stratification was maximal. During the second half of August and in the beginning of September the thermocline deepened and became weaker and, finally, at the end of September in the Bothnian Bay and in the beginning of October in the Bothnian Sea, it disappeared.

Also the salinity variations have a distinct seasonal component due to seasonal variations in freshwater runoff and to the varying ice conditions (Figures 7.10 and 7.12). In the Bothnian Sea maximum surface salinities were measured during winter and early spring (November - May), minimum in late summer (July - September). Corresponding variations were also found in the Bothnian Bay.

There exists a weak but significant perennial halocline in the Bothnian Sea, at about 50 - 80 m depth, which has no counterpart in the Bothnian Bay. Below the halocline the salinities are governed by inflowing water from the Baltic Proper. A slight maximum in the deep water salinities during October - November, at least in the southern parts of the Bothnian Sea, could be an indication of an inflow. If this is a recurrent phenomenon has to be established by further analysis of historical data.

## Regional variability

The surface water isohalines, down to about 50 m depth, run in general parallel to the Swedish coast line, with the lowest values closest to the coast (Figures 7.13 -7.18); the main reason being the large amount of freshwater runoff from that side of the Gulf. The Quark is an exception where the isolines bend over and become nearly normal to the coastline.

The inclination of the isohaline surfaces varied considerably. At e.g. the section MS (Figures 7.19 and 7.29 - 31) there existed a well defined, 10 - 20 km wide coastal boundary layer in June with salinities less than 5 units close to the coast. Later, in August, the salinities close to the coast had decreased and the boundary layer was 30 - 40 km wide, and finally, in November, there was no trace of any boundary layer at all.

The strongest horizontal gradients measured, during all four studies, were in the Quark, where the salinity decreased from south to north at an average of about 0.02 units/km. The off-coast gradients in the Bothnian Sea and the Bothnian Bay were generally smaller, usually less than 0.01 units/km.

During the November study an upwelling event occurred in the Bothnian Sea, between Härnösand in the north and Söderhamn in the south. The surface water was driven off-coast and cold, slightly more saline water from approximately 50 m depth had come to the surface (Figures 7.15, 7.28 and 7.31).

## Stability and density characteristics

Since it is essentially the salinity that determines the density, most of what has been said above concerning salinity also holds true for density. Temperature is important in regard to density distribution only during summer, and then only in the surface layer, where the temperature stratification is strongest. However, the seasonal variation in temperature is essential since it shows when vertical advection occurs, both during spring when the water is warmed and during autumn when the water is cooled. In the Bothnian Bay the whole water column is affected by this vertical advection while in the Bothnian Sea the perennial halocline sets a lower limit below which the advection has only minor effects.

Using observed temperature and salinity we have calculated the buoyancy frequency. It is proportional to the vertical derivative of the density and is thus a measure of the stability of the water column. Maximum values are obtained in the lower half of the thermocline during late summer (August - September). In the Bothnian Sea there is always a local maximum associated with the perennial halocline.

We have also calculated the internal Rossby radius of deformation, since this is a natural length scale which is of fundamental importance when studying horizontal advection-mixing processes. As a starting point we have used the long wave and hydrostatic approximations. Considering only free baroclinic waves, assuming a wave like solution (locally) in the horizontal and in time we construct a vertical eigenvalue problem for the pressure variable. Using the calculated buoyancy frequency we can determine the eigenvalues (which can be interpreted as internal phase velocities) by solving the eigenvalue problem numerically, following a Runge-Kutta scheme. To calculate the deformation radius we divide the obtained eigenvalue with the local Coriolis parameter. The results are shown in Figures 38 - 41. Typically the deformation radius varied between 2 and 4 km.

## 7.4 Concluding remarks

The temperature in the Bothnian Sea (Figure 7.42) was found higher than the monthly mean values calculated from the last two decades (1970 - 1979, 1980 - 1989). This is partly explained by the mild winter in 1990/91 and partly by the warm weather during July, August and September (Section 9). The salinities (Figure 7.43), on the other hand, showed negative anomalies on all occasions, i.e. the salinity values were lower than monthly means.

It has become clear during the present project that the Northern Quark is an important transition area between the Bothnian Bay and the Bothnian Sea. An area, where a considerable amount of mixing probably occurs. The mixing is presumably governed by the wind, since the average depth of the Quark (about 20 m) is equal to or less than the Ekman layer for winds larger than 5 m/s.

## Acknowledgements

We do thank all those people who have made this project possible. Especially we would like to thank the crew on board the R/V Argos and the laboratory personnel at the SMHI Oceanographical Laboratory who all worked endless days in a good mood without showing any signs of tiredness.

The Swedish Meteorological and Hydrological Institute and the National Board of Fisheries are also gratefully acknowledged for the financial support given to the project.

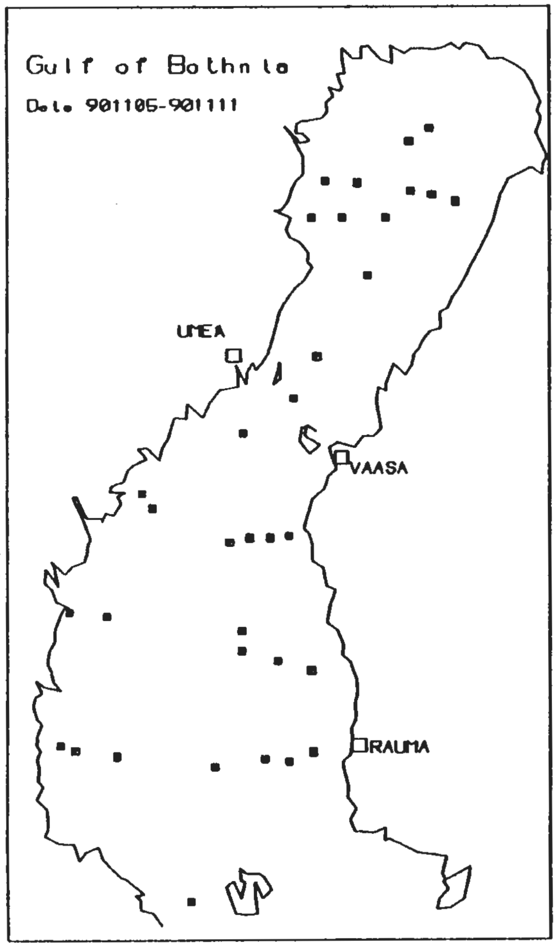


*Figure 7.1.*
*Hydrographical stations visited by the R/V Argos, November 1990.*

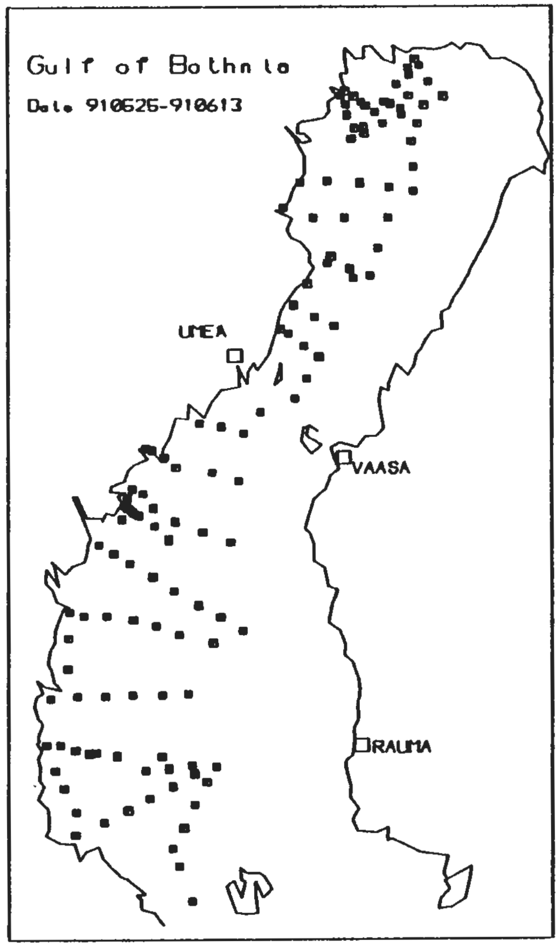


*Figure 7.2.*
*Hydrographical stations visited by the R/V Argos, May - June 1991.*

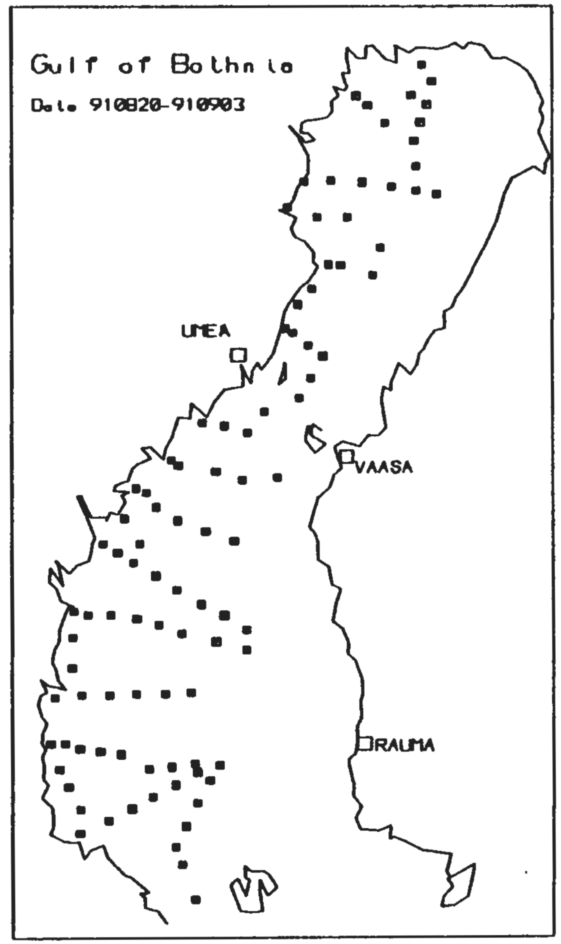


*Figure 7.3.*
*Hydrographical stations visited by the R/V Argos, August - September 1991.*

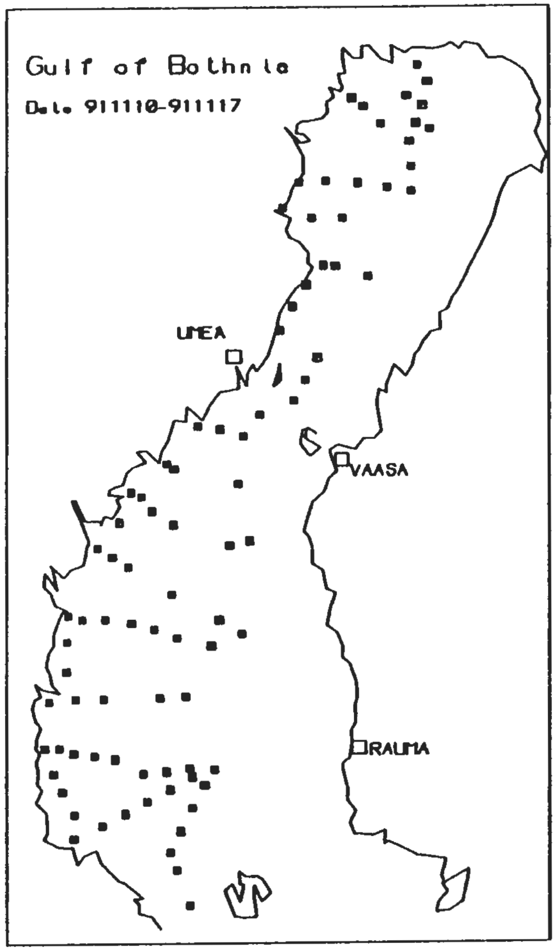


*Figure 7.4.*
*Hydrographical stations visited by the R/V Argos, November 1991.*

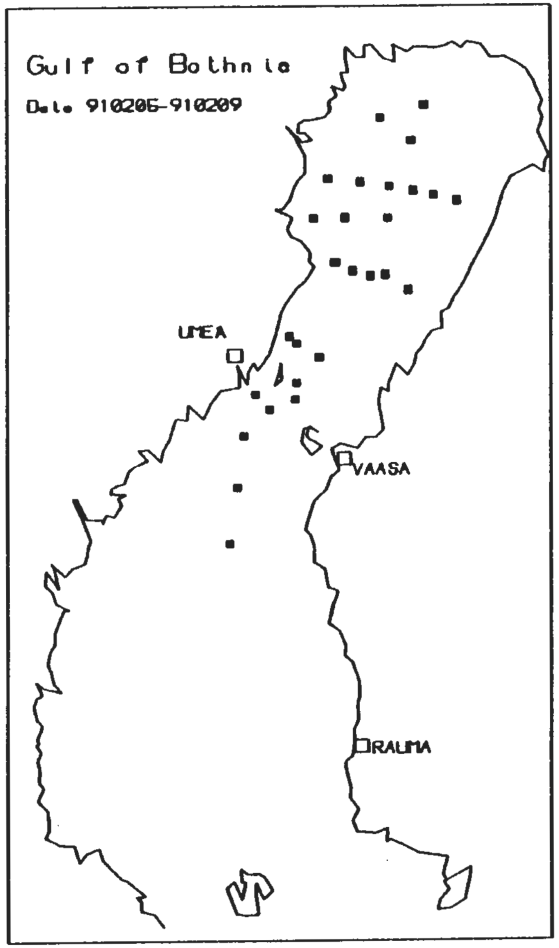


*Figure 7.5.*
*Hydrographical stations visited by the ice-breaker Ymer, February 1991.*

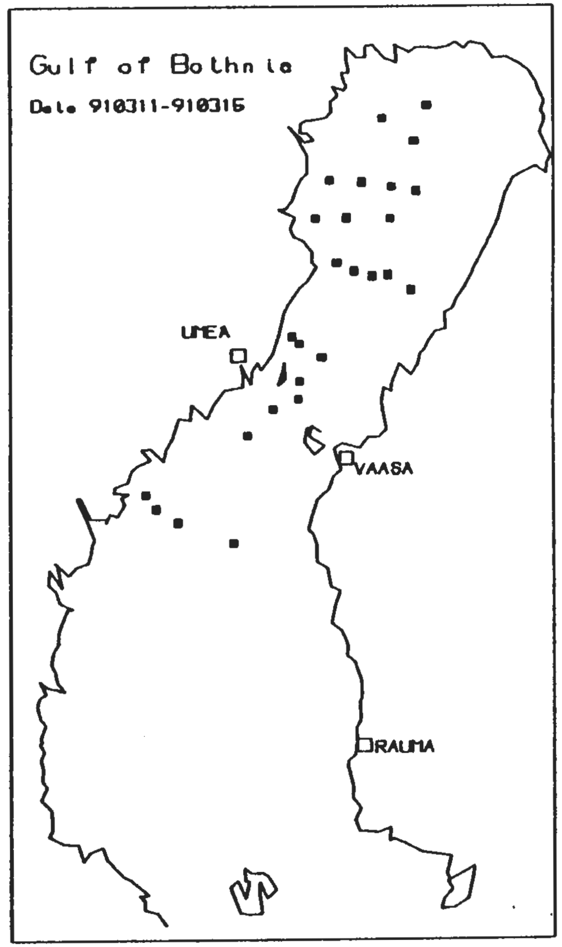


*Figure 7.6.*
*Hydrographical stations visited by the ice-breaker Ymer, March 1991.*

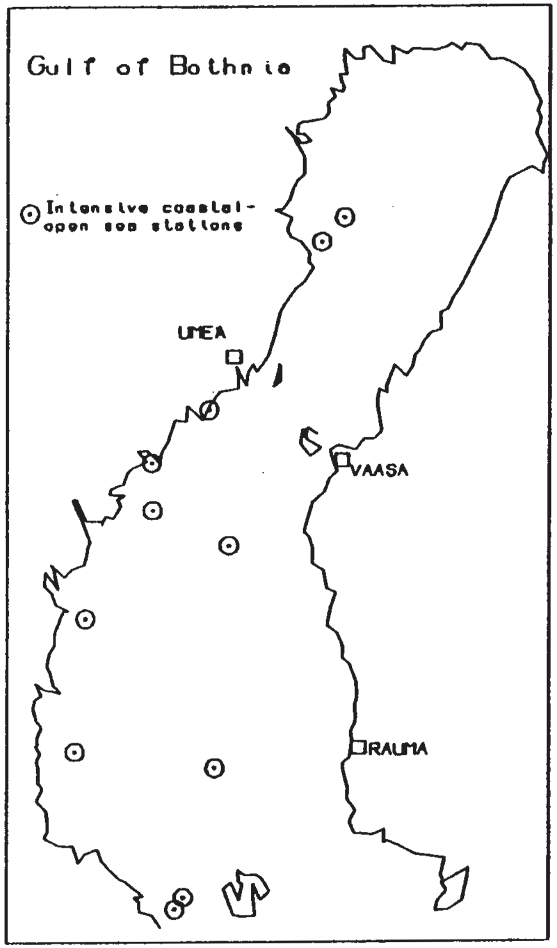


*Figure 7.7.*
*Hydrographical stations which were visited more than 10 times during 1991, i.e. intensive stations.*

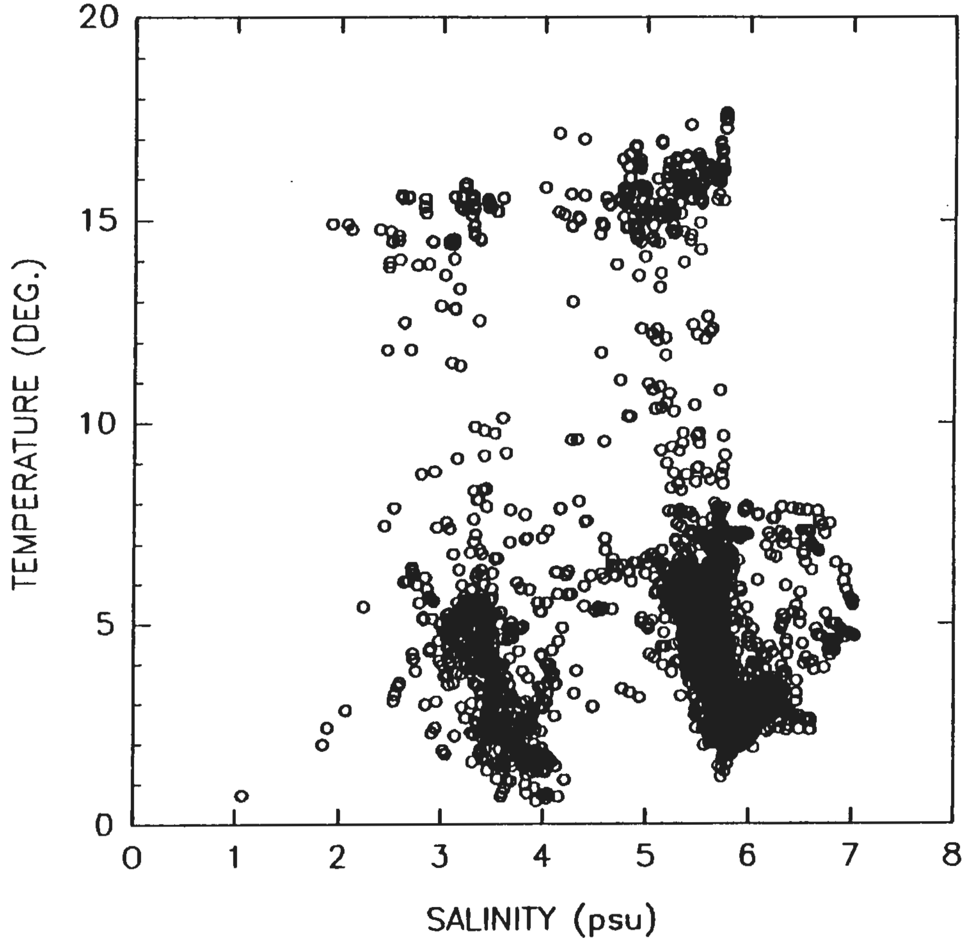


*Figure 7.8.*
*Temperature/salinity diagram showing the results from all four expeditions with the R/V Argos.*

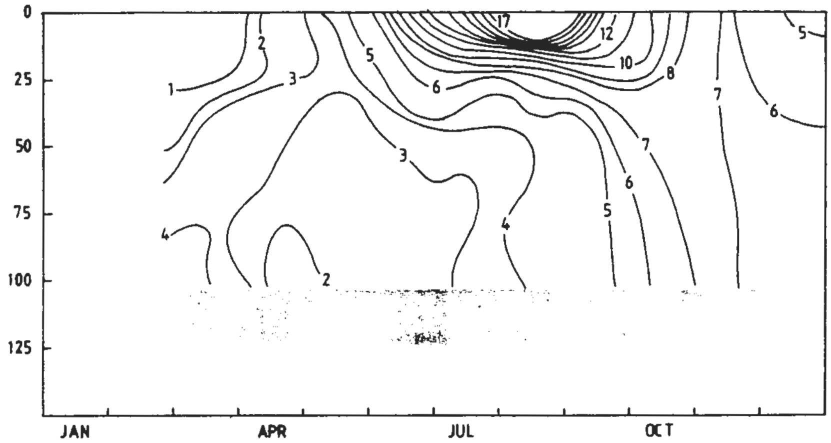


*Figure 7.9. Seasonal temperature variation at Singö in the southern part of the Bothnian Sea.*

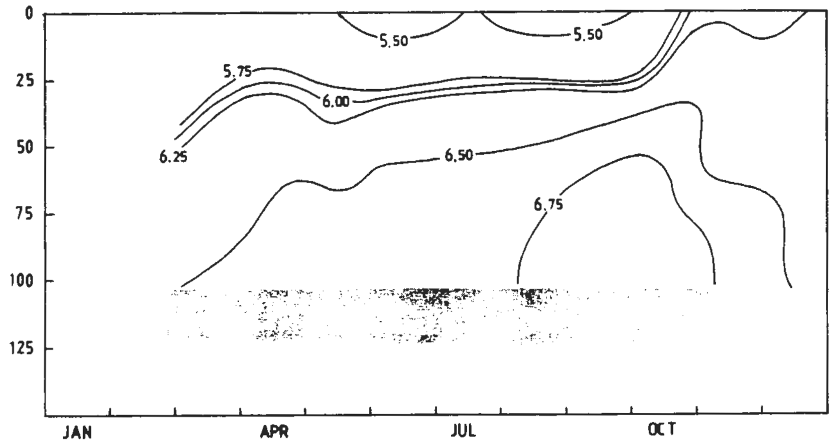


*Figure 7.10. Seasonal salinity variation at Singö in the southern part of the Bothnian Sea.*

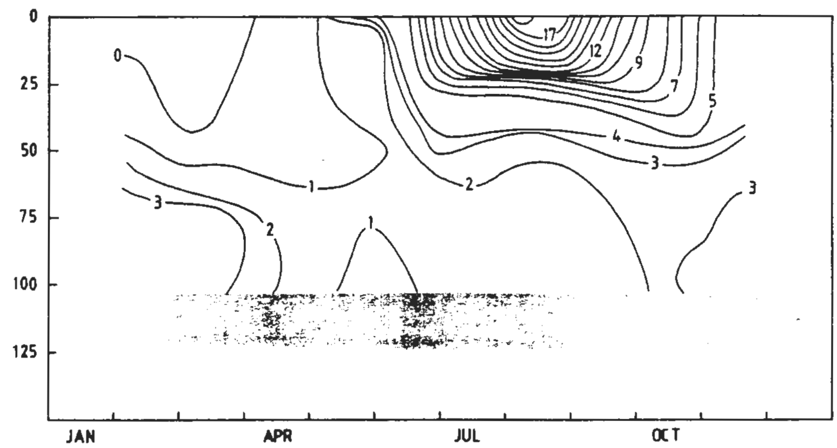


*Figure 7.11. Seasonal temperature variation at F9 in the Bothnian Bay.*

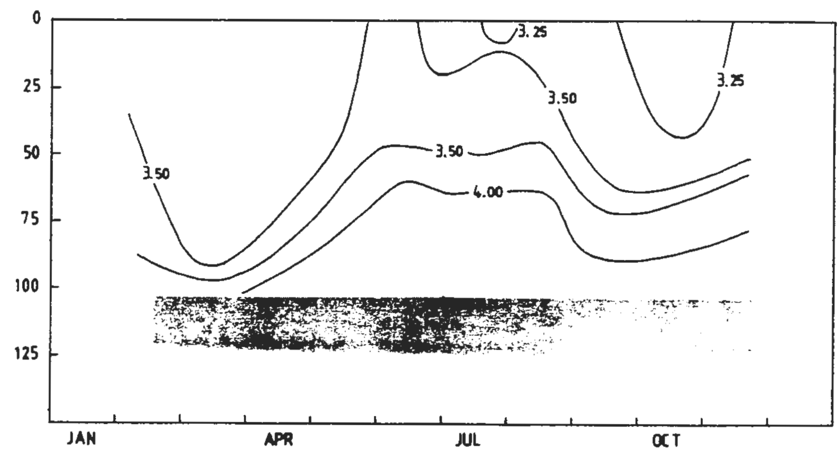


*Figure 7.12. Seasonal salinity variation at F9 in the Bothnian Bay.*

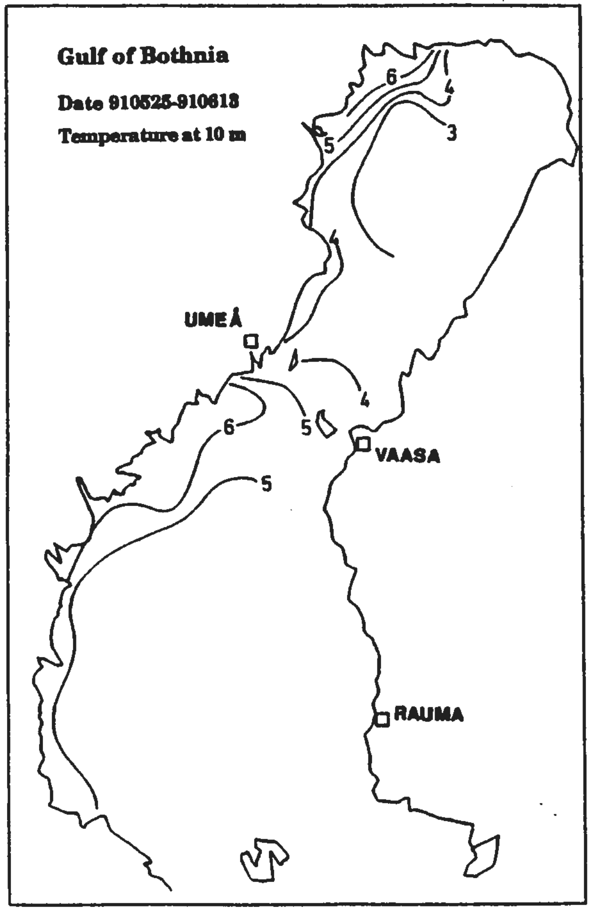


*Figure 7.13.*
*Temperature distribution at 10 m depth, May - June.*

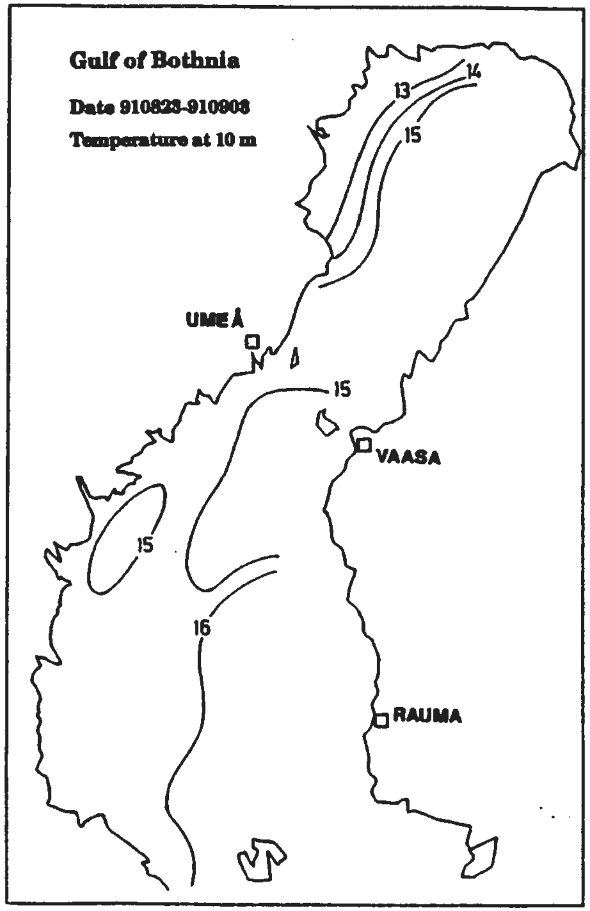


*Figure 7.14.*
*Temperature distribution at 10 m depth, August - September.*

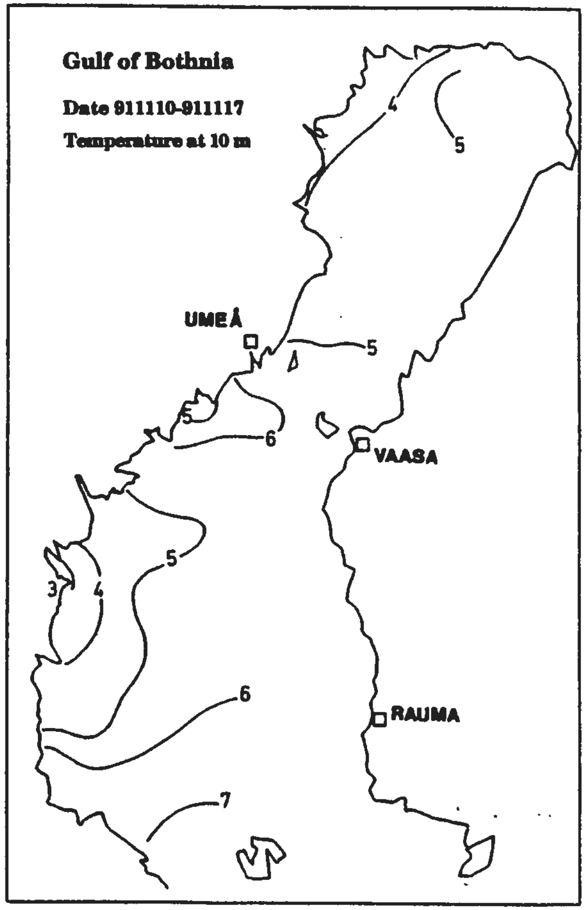


*Figure 7.15.*
*Temperature distribution at 10 m depth, November.*

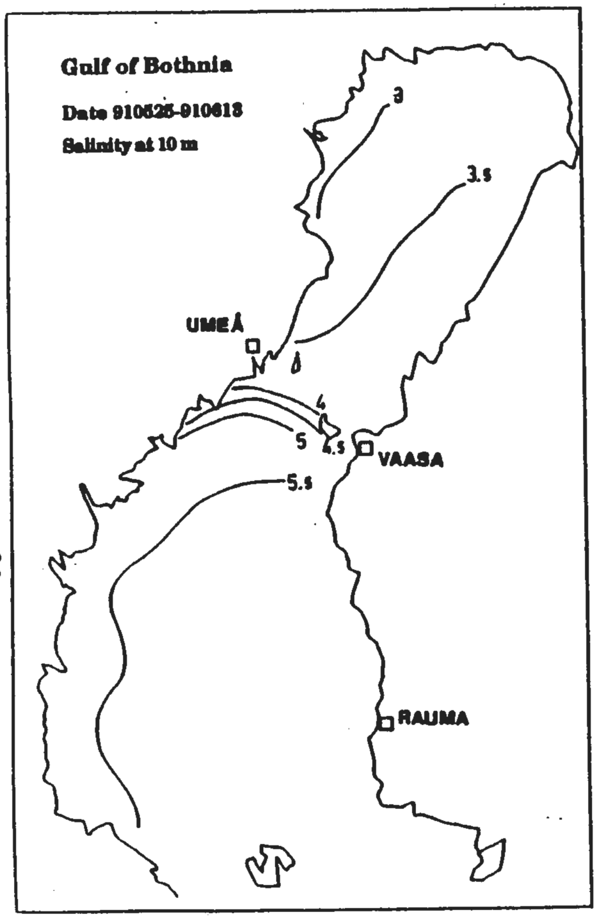


*Figure 7.16.*
*Salinity distribution at 10 m depth, May - June.*

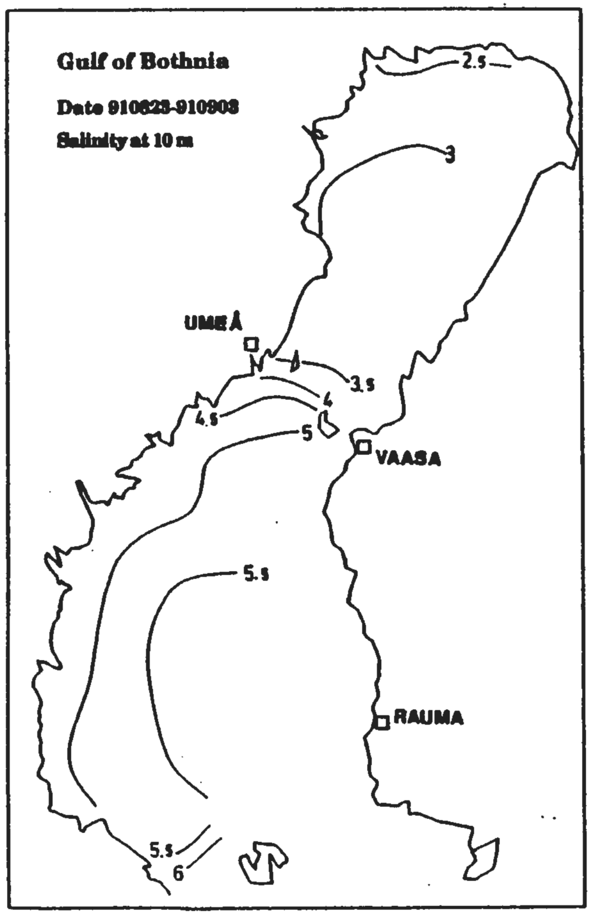


*Figure 7.17.*
*Salinity distribution at 10 m depth, August - September.*

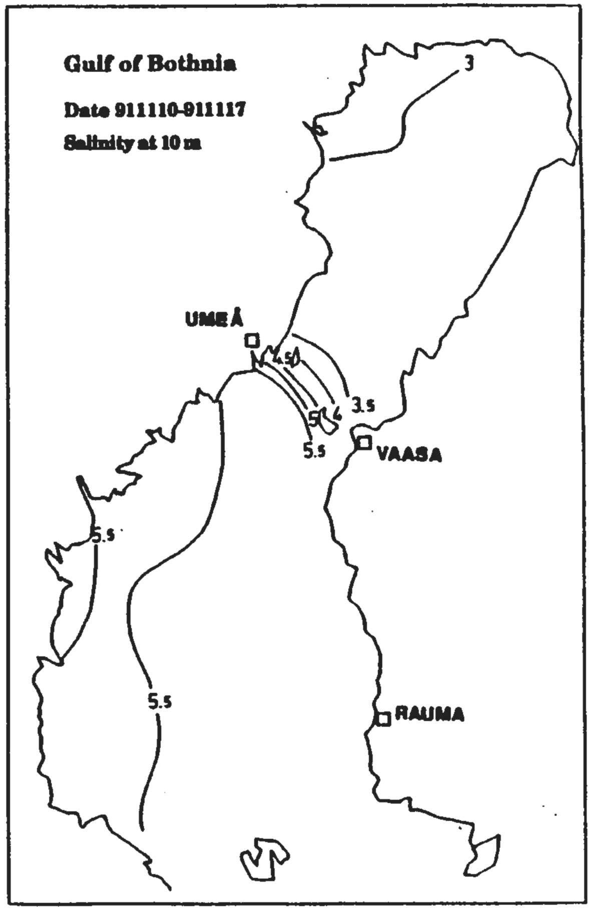


*Figure 7.18.*
*Salinity distribution at 10 m depth, November.*

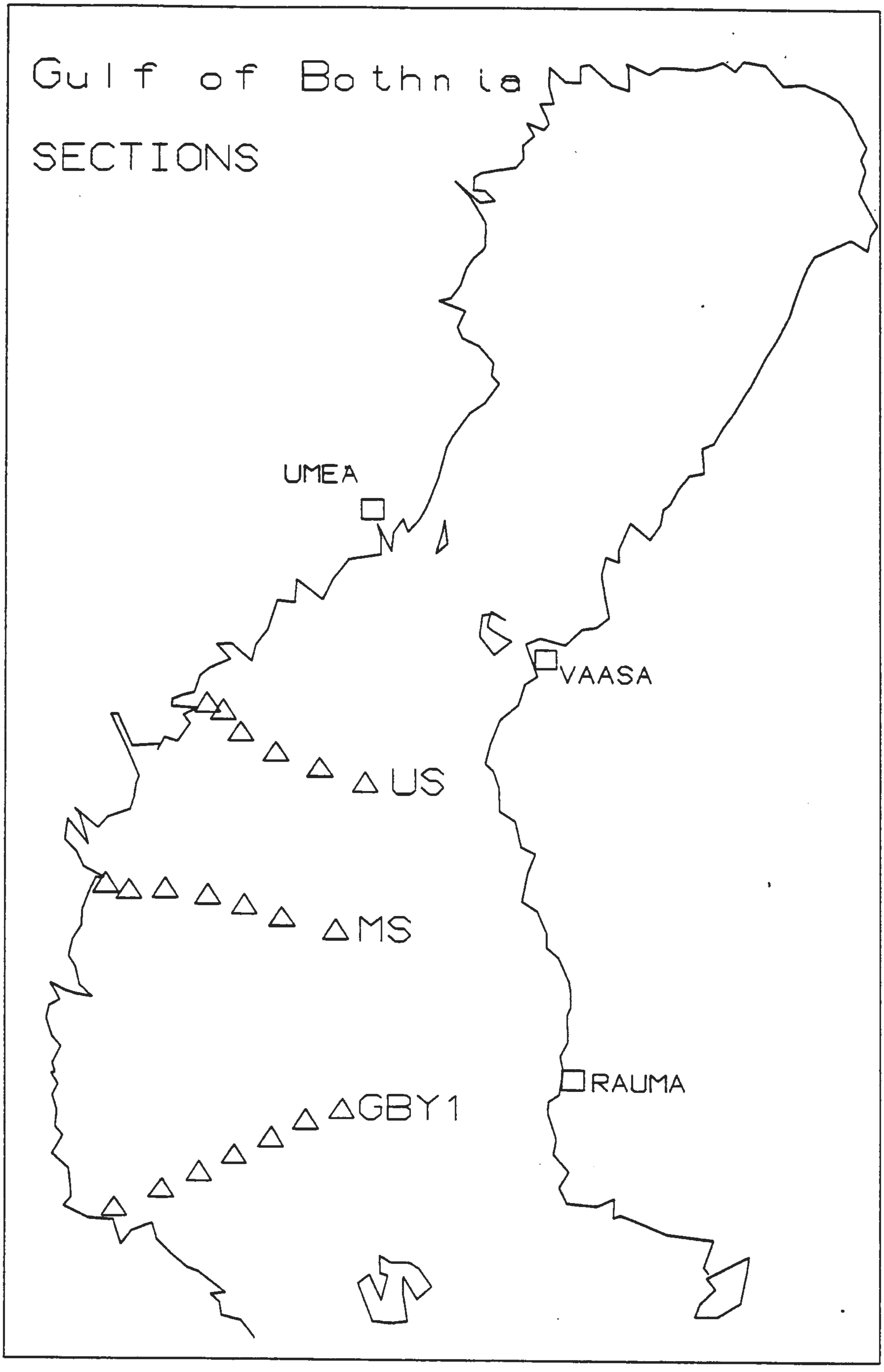


*Figure 7.19. Key map showing the different sections.*

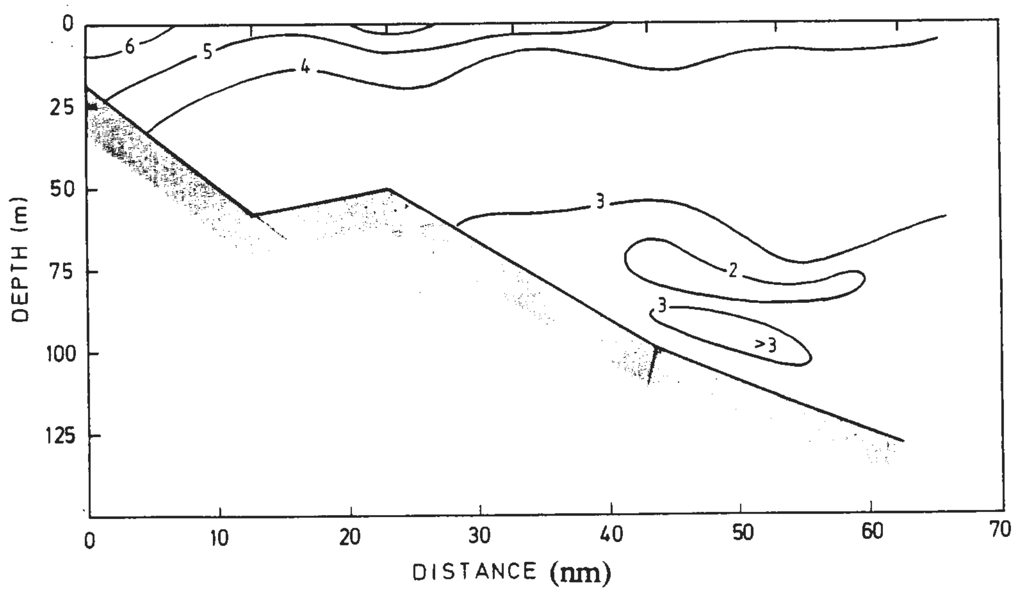


*Figure 7.20. Temperature distribution along the GBY1 section, May - June.*

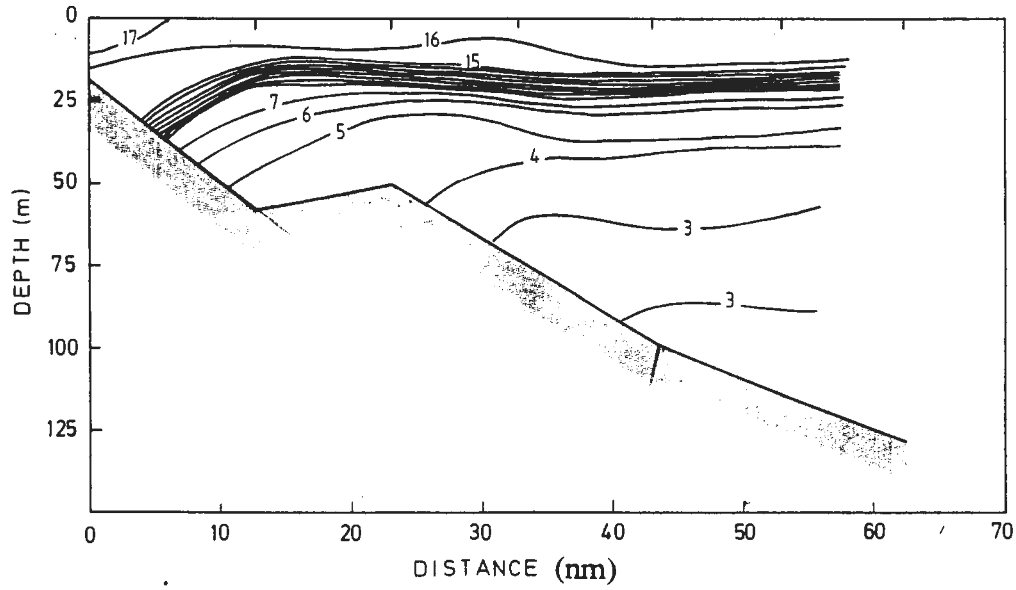


*Figure 7.21. Temperature distribution along the GBY1 section, August.*

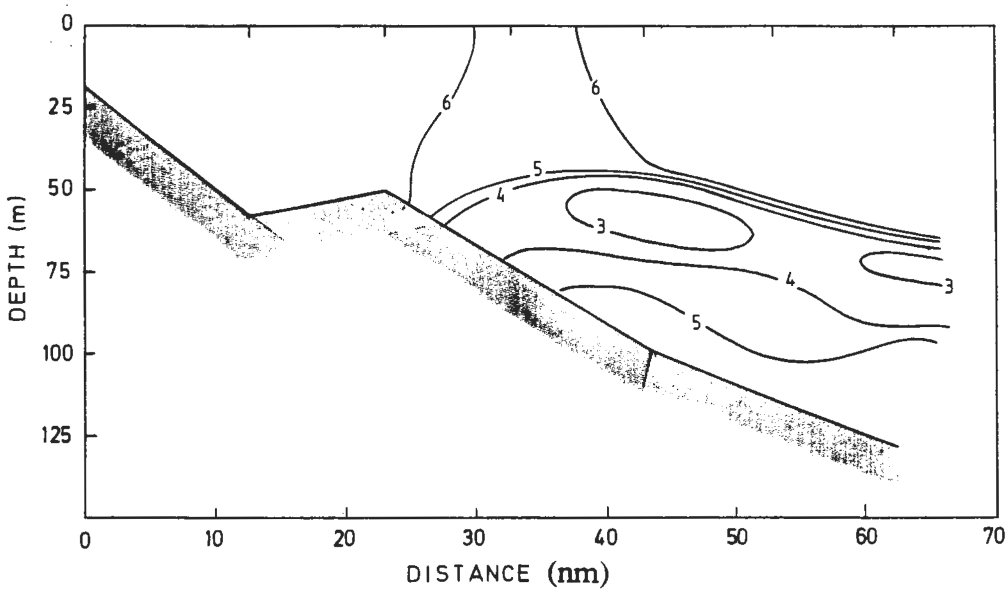


*Figure 7.22. Temperature distribution along the GBY1 section, November.*

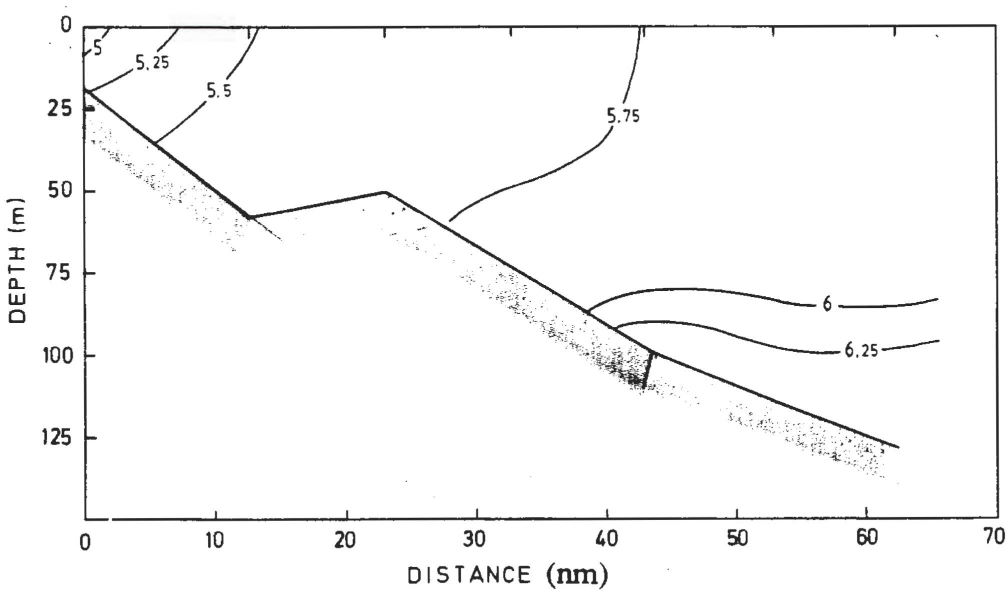


*Figure 7.23. Salinity distribution along the GBY1 section, May - June.*

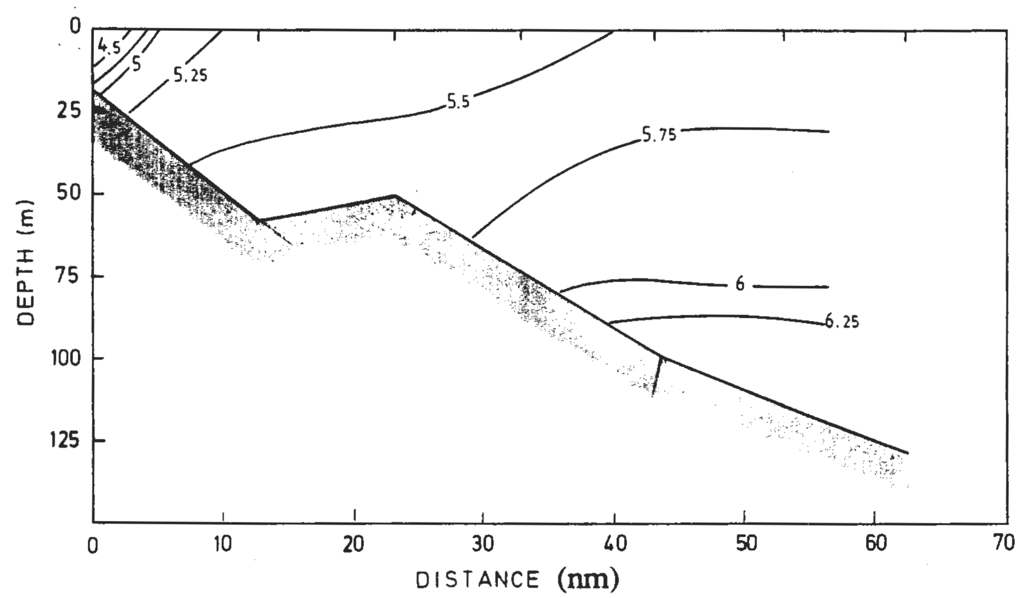


*Figure 7.24. Salinity distribution along the GBY1 section, August.*

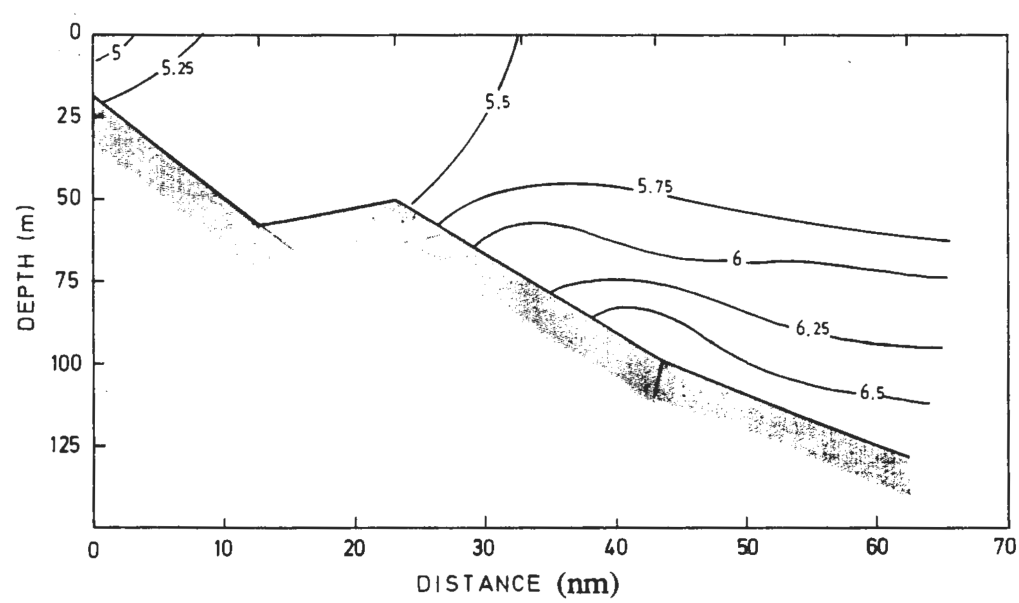


*Figure 7.25. Salinity distribution along the GBY1 section, November.*

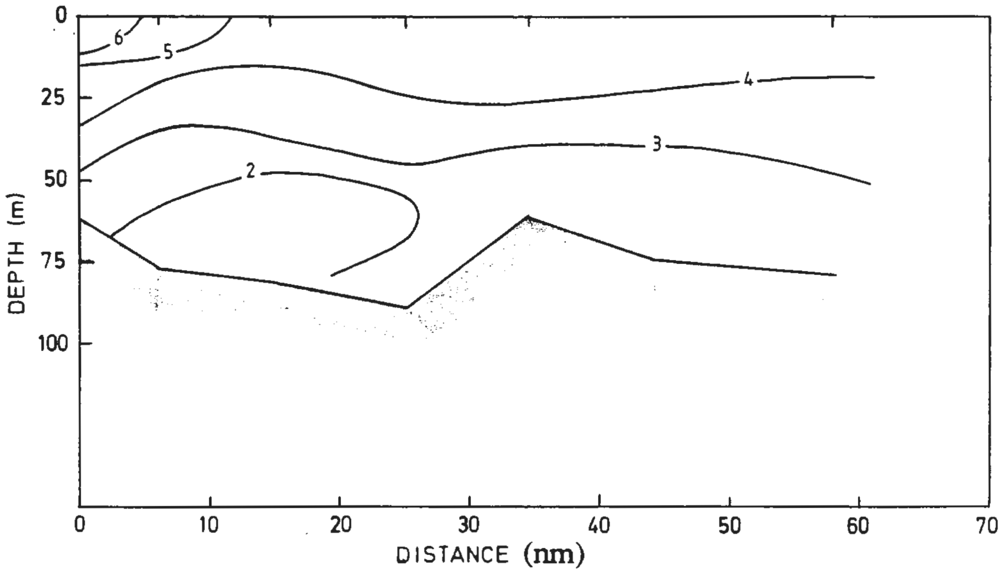


*Figure 7.26. Temperature distribution along the MS section, May - June.*

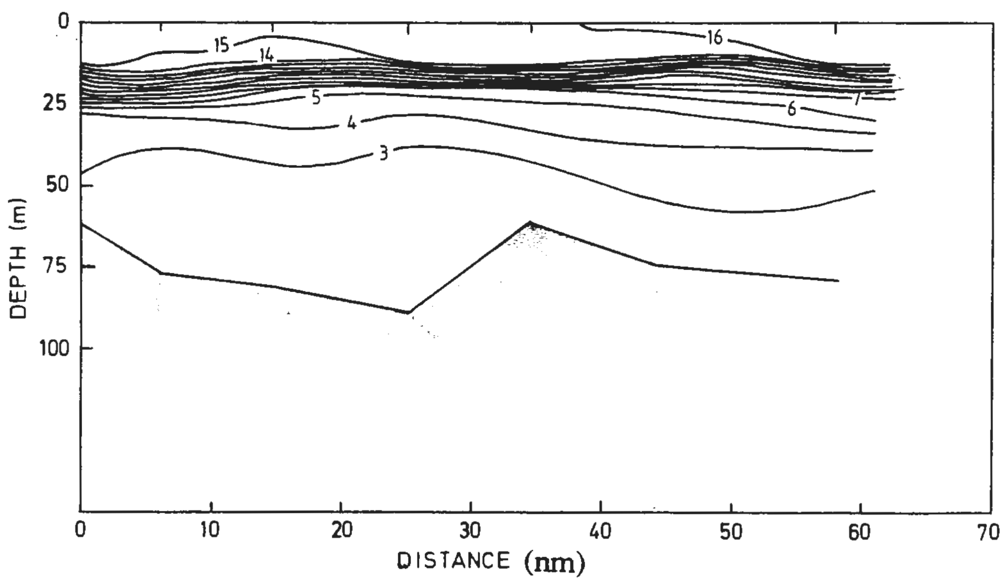


*Figure 7.27. Temperature distribution along the MS section, August.*

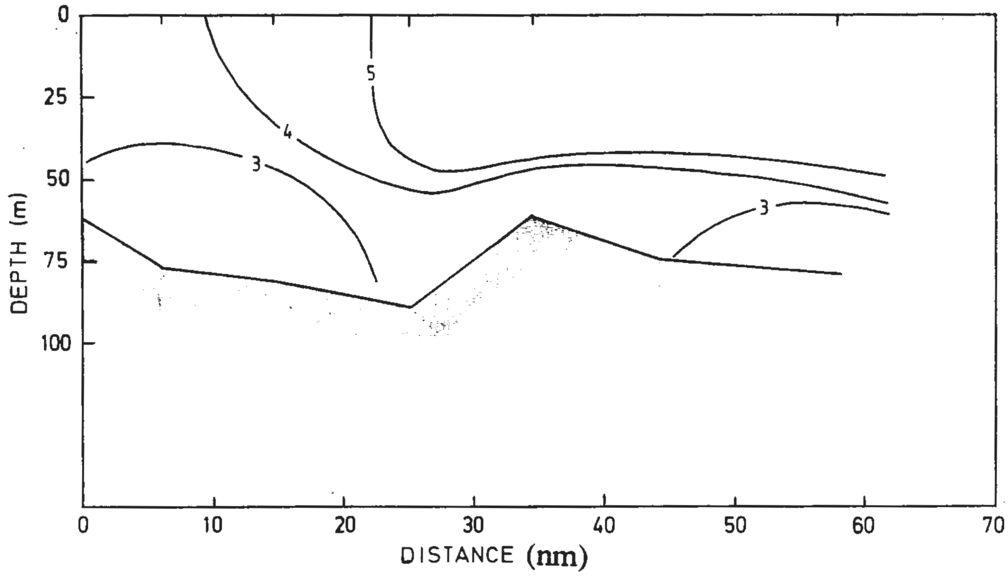


*Figure 7.28. Temperature distribution along the MS section, November.*

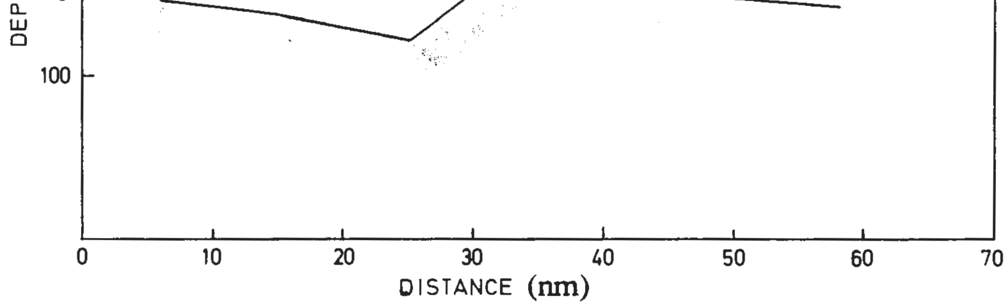


*Figure 7.29. Salinity distribution along the MS section, May - June.*

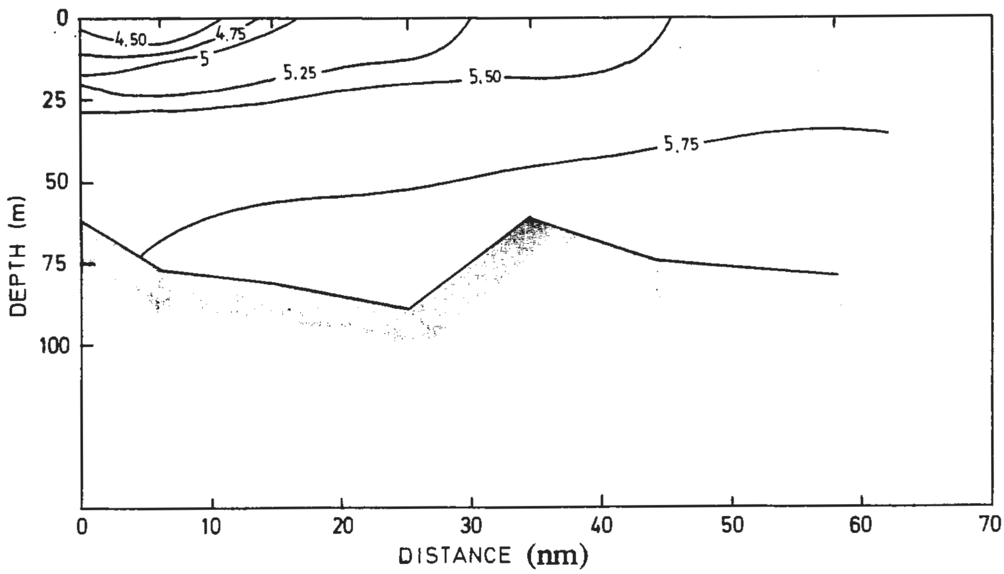


*Figure 7.30. Salinity distribution along the MS section, August.*

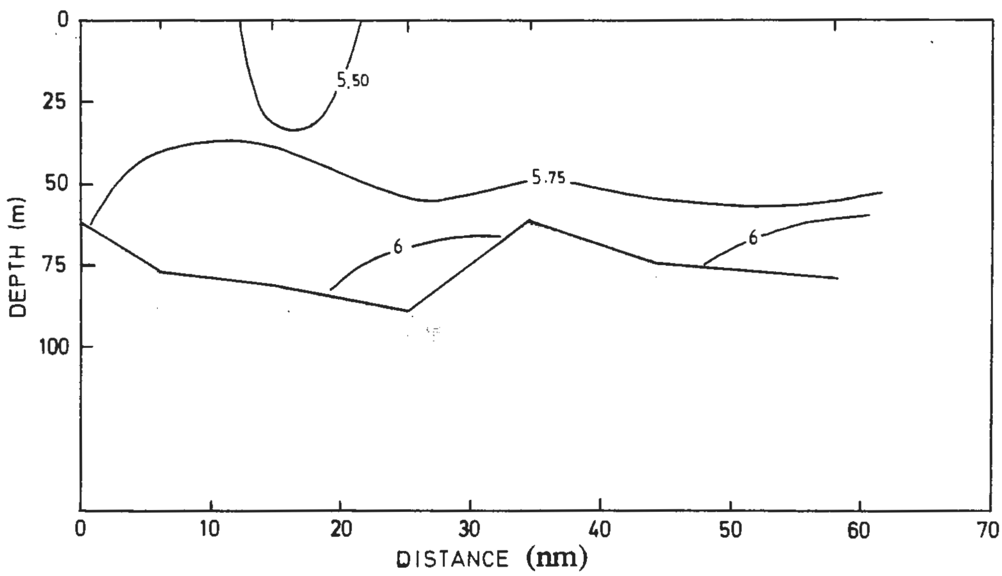


*Figure 7.31. Salinity distribution along the MS section, November.*

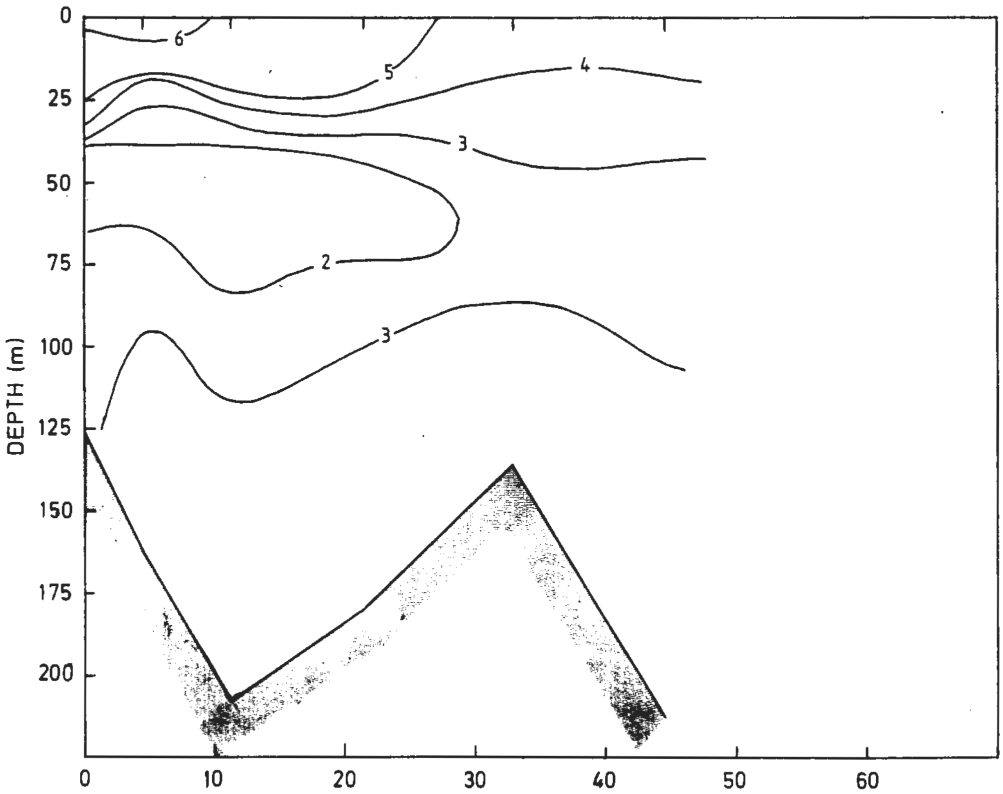


*Figure 7.32. Temperature distribution along the US section, May - June.*

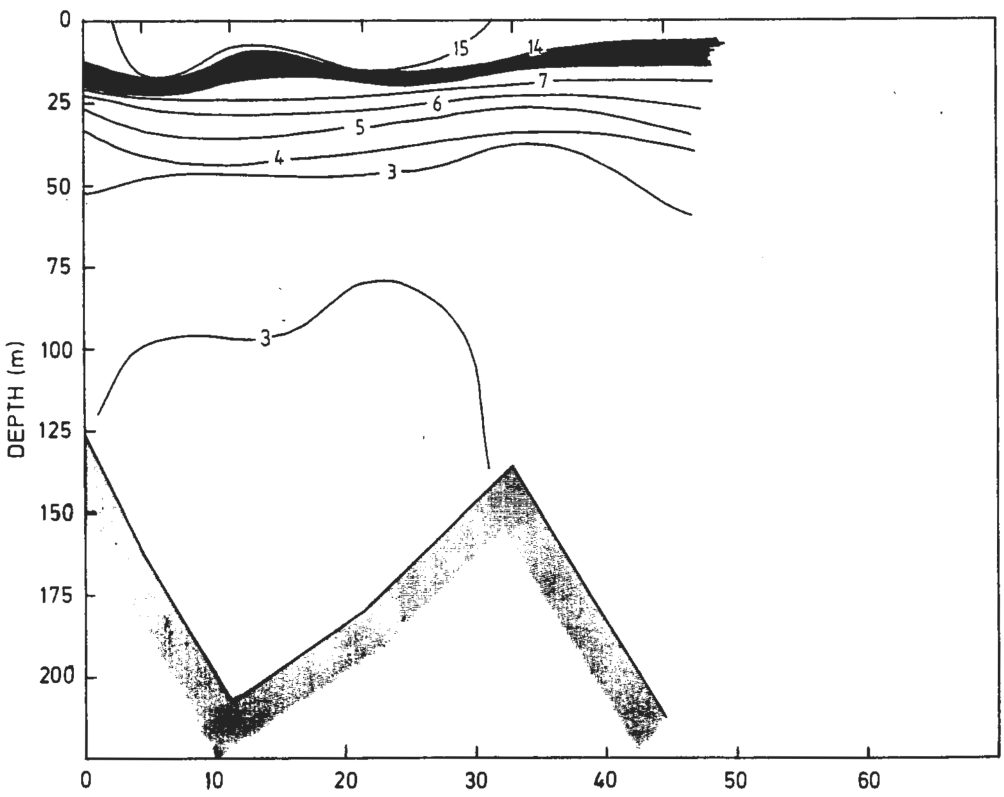


*Figure 7.33. Temperature distribution along the US section, August.*

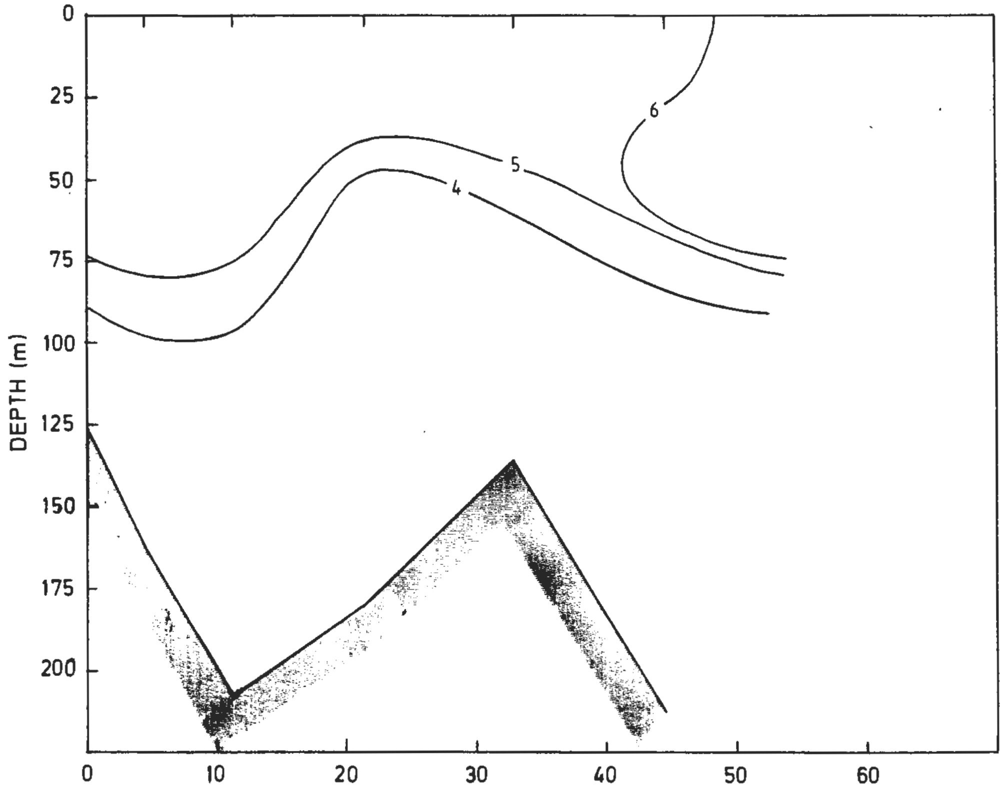


*Figure 7.34. Temperature distribution along the US section, November.*

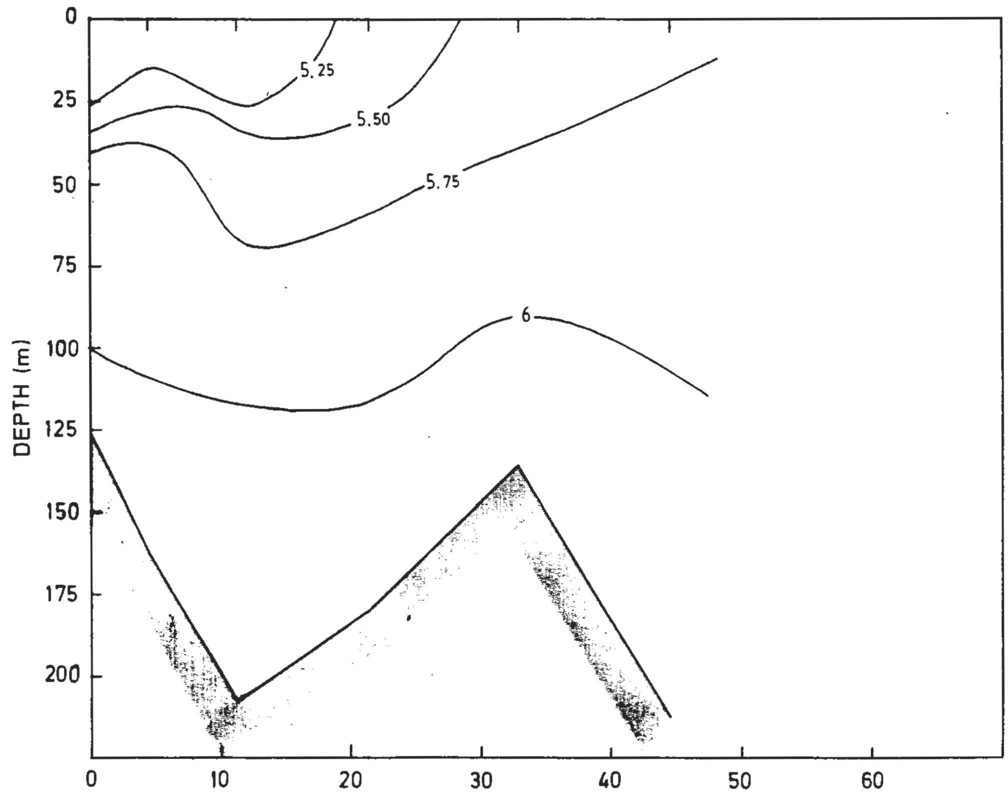


*Figure 7.35. Salinity distribution along the US section, May - June.*

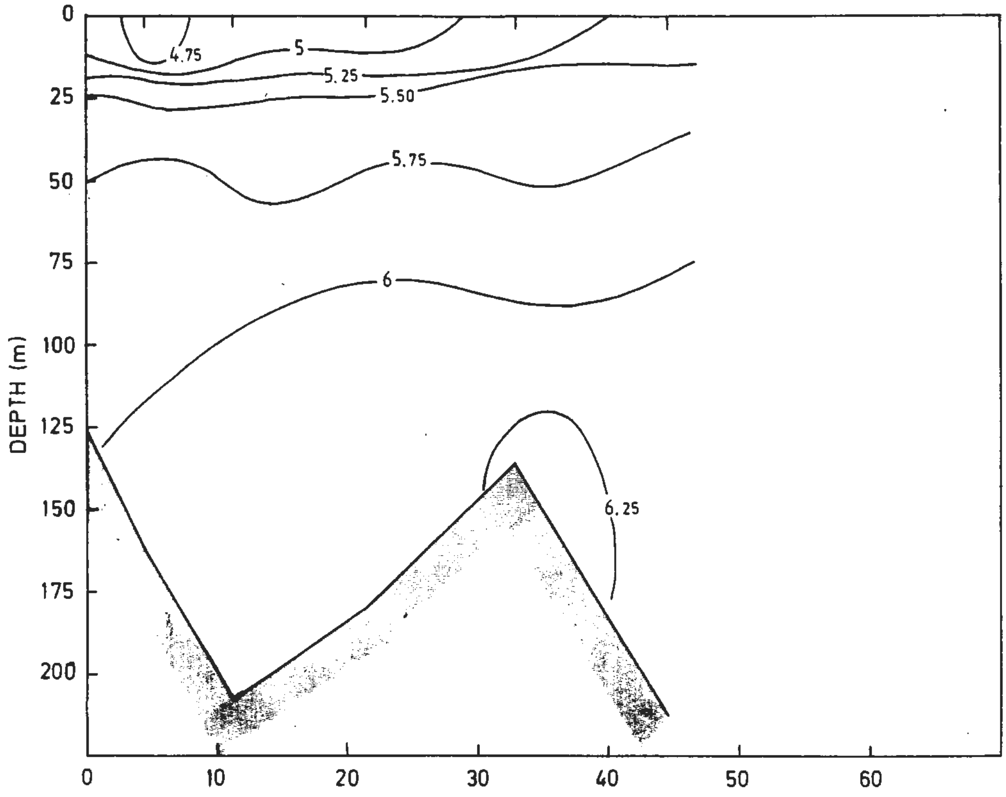


*Figure 7.36. Salinity distribution along the US section, August.*

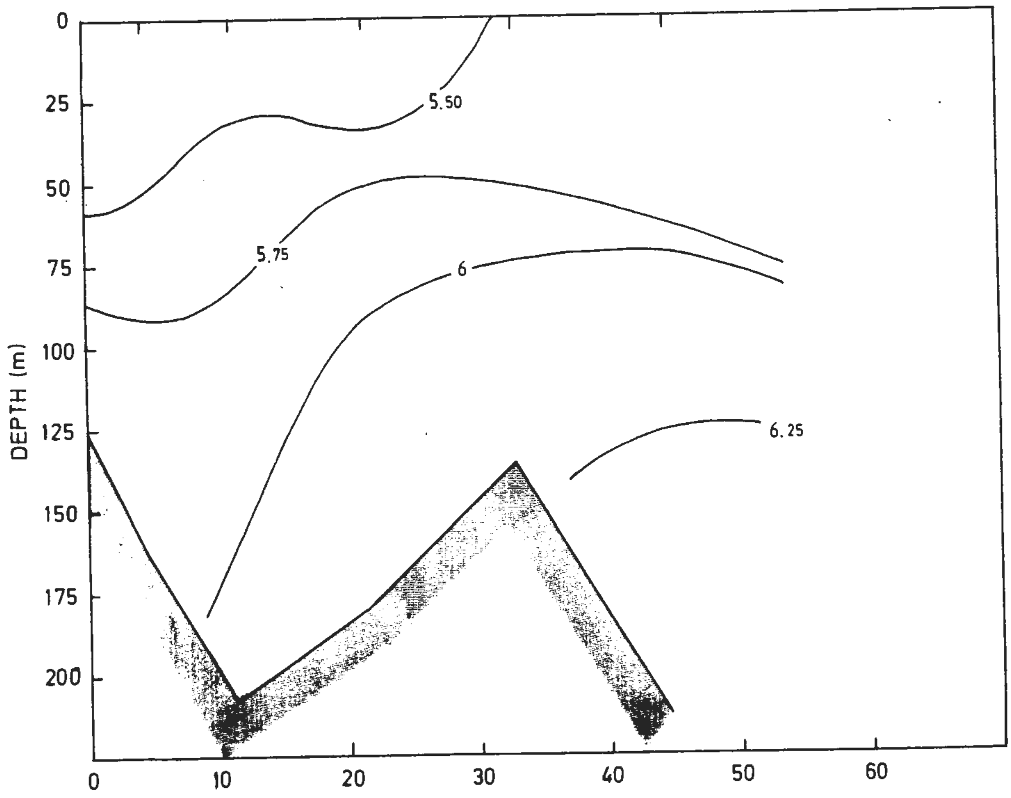


*Figure 7.37. Salinity distribution along the US section, November.*

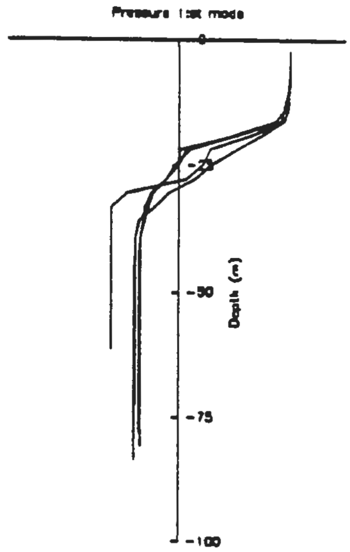


*Figure 7.38. Examples of how the vertical structure of the first mode $P_1$ varies with depth. The scale on the ordinate is arbitrary.*

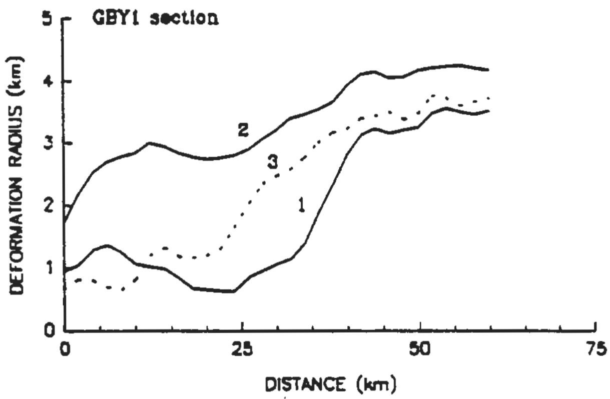


*Figure 7.39.
The deformation radius as a function of distance from the coast at section GBY1. The numbers refer to the expeditions in May (1), August (2) and November (3).*

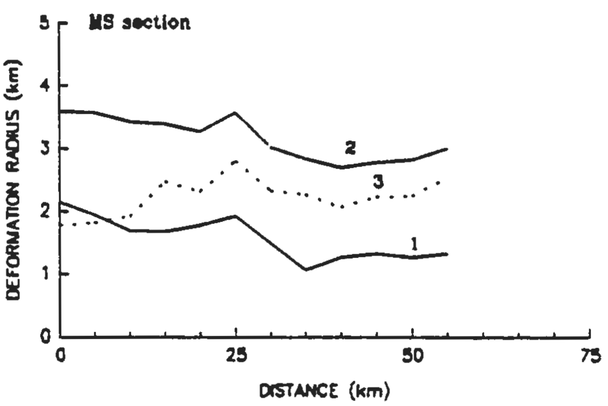


*Figure 7.40.
The deformation radius as a function of distance from the coast at section MS. The numbers refer to the expeditions in May (1), August (2) and November (3).*

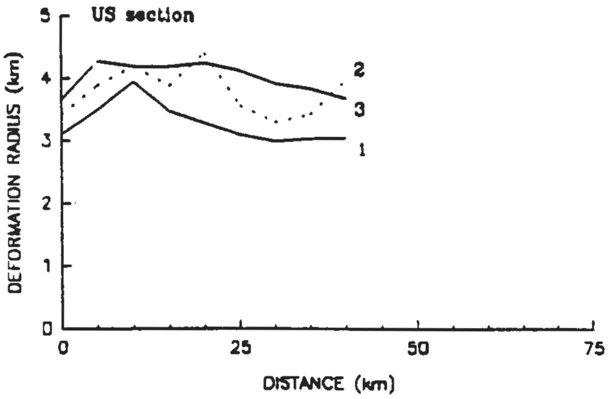


*Figure 7.41.*
*The deformation radius as a function of distance from the coast at section US. The numbers refer to the expeditions in May (1), August (2) and November (3).*

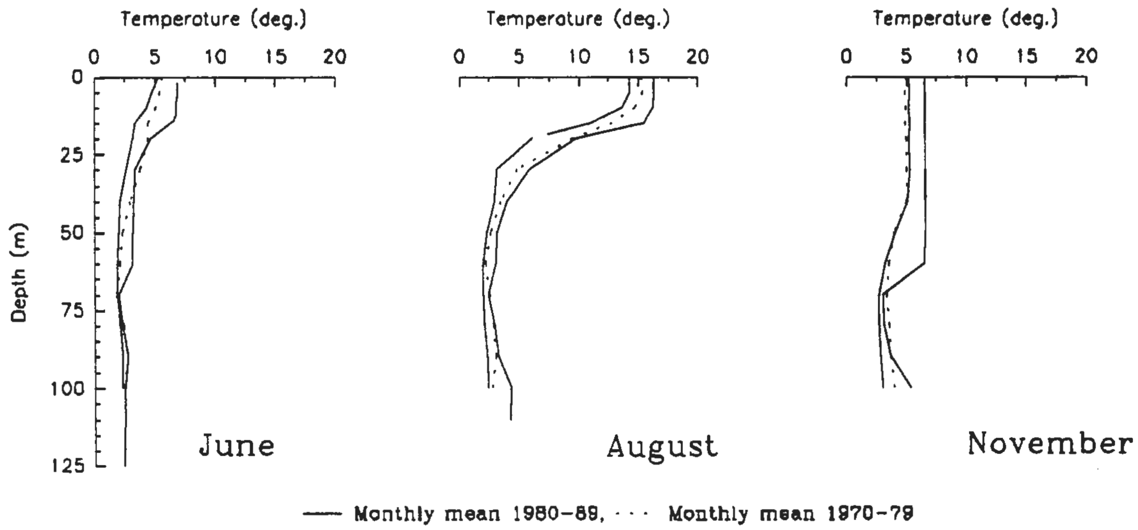


*Figure 7.42. Temperature profiles, measured and mean, in the central part of the Bothnian Sea.*

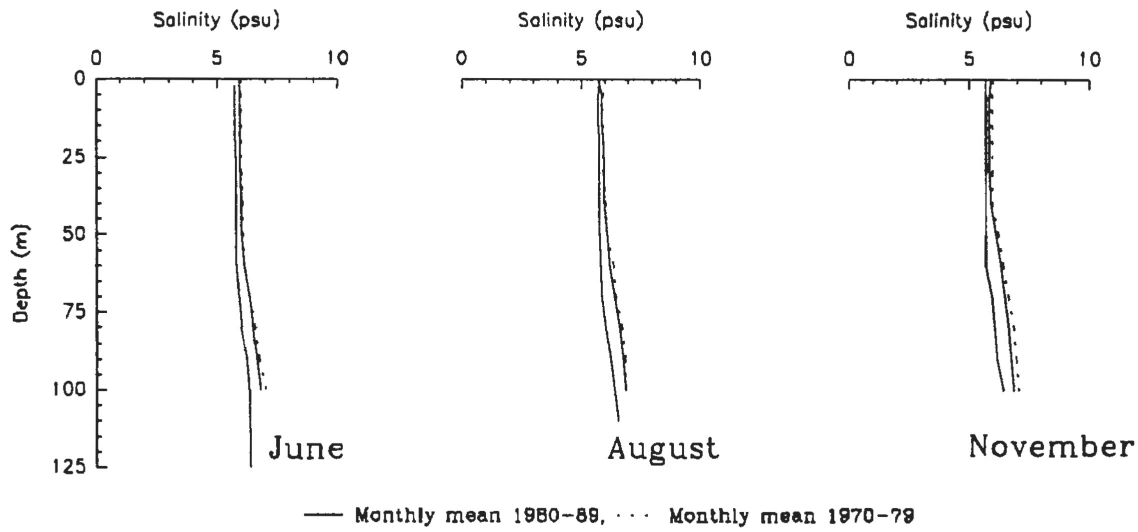


*Figure 7.43. Salinity profiles, measured and mean, in the central part of the Bothnian Sea.*

# CHAPTER 8

## FINNISH HYDROGRAPHIC SURVEYS

Riikka Hietala, Finnish Institute of Marine Research, Finland

### 8.1 The Finnish Program

Hydrographic data were collected to get a picture of the seasonal temperature, salinity and density stratification of the Gulf of Bothnia and to help the analysis and the interpretation of data of other physical experiments. The data can be divided into two parts: data from intensive stations (SR5 and EROS transect) visited nearly every month during the year 1991 and data during Finnish drifter experiments. Besides, in October hydrographic data were collected from the whole Gulf of Bothnia. Finnish CTD-stations during the GB-91 Year are shown in Figure 8.1, and the dates of observations are presented in Table 8.1.

*Table 8.1. The dates of CTD-observations in the Gulf of Bothnia during the GB-91 Year.*

| Station or sea area | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SR5 | 16<br>25 | | 12 | 10<br>11<br>16<br>18<br>23 | 7<br>8<br>14<br>16<br>22 | 3<br>8<br>18 | | 13<br>22 | 13<br>14 | 9<br>21<br>23 | | |
| EROS transect | 24 | | 11 | 19<br>24-25 | 6<br>23 | 6<br>(stag-gered grid)<br>6-7 | | 15 | 13 | 8<br>23-24<br>(partly) | 5-6<br>8<br>10<br>14-15<br>17 | 6 |
| Bothnian Sea (7 transects) | | | | | | 7-12 | | | | 9-13 | | |
| Bay of Bothnia (6 transects) | | | | | | | | | | 13-16 | | |
| Coastal grid (6 transects) | | | | | | | | | | | 4-7<br>7-9<br>10-11<br>(partly)<br>14-16<br>17-18<br>(partly) | |

Used instruments

The surveys were performed with the research vessel Aranda of the Finnish Institute of Marine Research. R/V Aranda is equipped with MkIII and MkV CTD from EG and G Marine Instruments. Due to malfunctions MkV could be used only from March to the middle of June, otherwise MkII was used. The conductivity sensor of MkIII was uncalibrated, and the conductivity values have been corrected afterwards.

## 8.2 Hydrography of the open sea station SR5 and the coastal transect EROS during the year 1991

Hydrographic surveys were carried out along the main coastal transect, so called EROS transect (Table 8.2) outside Rauma and at the open sea intensive station SR5 in the deep southern part of the Bothnian Sea at least once a month except February and July during the GB-91 Year. Eleven EROS stations were approximately 4 km apart from each other and the first one about 15 km from the shore on the transect perpendicular to the local coast line. Additionally, in the same transect there were 7 current meter mooring stations. Also SR5 was a current meter mooring station. The seasonal temperature, salinity and density variations at SR5 are presented in Figure 8.2. Some examples of the temperature and salinity variations in the EROS transect are shown in Figures 8.3 - 8.4.

*Table 8.2. Nomenclature and geographical characteristics of the EROS transect.*

| Name of the station | Latitude | Longitude | Depth |
|---|---|---|---|
| SR 5 | N61° 05.00' | E019° 35.00' | 121.00 |
| EROS 15 | N61° 13.00' | E021° 12.00' | 25.00 |
| EROS 16 | N61° 13.40' | E021° 08.00' | 26.00 |
| EROS 17 | N61° 14.01' | E021° 04.00' | 45.00 |
| EROS 18 | N61° 14.00' | E020° 59.00' | 54.00 |
| EROS 19 | N61° 14.00' | E020° 55.00' | 53.00 |
| EROS 20 | N61° 14.50' | E020° 51,00' | 60.00 |
| EROS 21 | N61° 15.00' | E020° 47.00' | 79.00 |
| EROS 22 | N61° 15.00' | E020° 43.00' | 76.00 |
| EROS 23 | N61° 15.00' | E020° 39.00' | 86.00 |
| EROS 24 | N61° 15.50' | E020° 34.00' | 97.00 |
| EROS 25 | N61° 16.00' | E020° 29.00' | 100.00 |

Owing to the mild weather in January the surface temperature in the Bothnian Sea was rather high in the end of January. It was over 2 °C at the station SR5, about 1 °C higher than on average. In the shallow coastal area the surface temperature was lower. As the whole the winter was mild, ice was formed only very near the coast and in the northern part of the Bothnian Sea. The mixed layer depth was about 70 - 80 m in January. A weak halocline was combined with the weak thermocline. The surface water was coldest in February - March and started to warm slowly in April. In April the coastal transect was almost homogeneous from surface to 60 - 70 meters depth and from the shore to the open sea.

In the end of May the surface temperature was highest near the coast (over 5 °C) and decreased gradually toward the open sea. June was cold and the surface temperature was lower than on average. The temperature structure in the surface layer was complicated.

The mixed layer depth was on average about 10 m.

July and August were warm and thus the surface temperature was almost 17 °C in the open sea and almost 18 °C near the Finnish coast in the middle of August. The mixed layer depth was about 10 m. In the beginning of September the air temperature decreased and the winds were strong. The water cooled and the mixed layer depth increased to about 25 m. In October - November the surface water temperature was on average a little higher than the air temperature. In the end of October the mixed layer depth varied considerably and was on average about 40 m. As usual in the autumn, a weak halocline was combined to the thermocline. The surface temperature was in October slightly higher than the long time average and still highest at the station closest to the coast. In the end of November the mixed layer depth was over 70 m, and the temperature decreased only 1 °C in the thermocline.

Seasonal variations in the surface and bottom salinity at SR5 were quite strong (Figure 8.2 b). The surface salinity was lowest in spring and late autumn. It reached its maximum in June at SR5 and in September at the coastal transect. A weak halocline existed at about 60 - 80 m depth and below it the salinity increased slowly with depth. Often a slight salinity increase was associated with the vertical temperature gradient. In the autumn the halocline coincided with the thermocline.

Different water masses can be found near the bottom in the deep layers during the year, indicating variations in inflow from the Baltic Sea. In spring the temperature of the water near the bottom was about 3 °C and the salinity quite low. In late summer, bottom water with high salinity was found. In September warm and less saline water (about 5 °C) appeared in the deep and was observed also in December.

## 8.3 The June experiment

In June a physical programme was carried out in the Bothnian Sea. After deploying drifting buoys R/V Aranda collected hydrographic data first from the EROS transect (original and staggered grid) and then from seven transects in the whole Bothnian Sea. The surface salinity varied from 5.7 ‰ to 6.2 ‰ and was highest in the middle and east side of the Bothnian Sea except some stations closest to the Finnish coast where the salinity was lower due to river runoff. The temperature and salinity distribution are presented in Figures 8.5 - 8.6. The surface salinity was lowest near the Swedish coast due to larger river runoff and near the Quark due to outflow from the Bothnian Bay. Also in deeper water the salinity distribution was quite similar. The highest salinity (6.8 ‰) was found at the bottom of the middle deep in IS- and MS-transects (Figure 8.1). The warmest surface water (over 7 °C) was found at the stations closest to the Finnish coast. The mixed layer depth was about 10 m at most of the stations, but the temperature often decreased stepwise with depth, beginning near the surface. The coldest water, below 1 °C, was at about 60 -70 m depth and was located on the Finnish side of the southern Bothnian Sea and on the Swedish side of the northern Bothnian Sea. At many stations the salinity started to increase slightly when the temperature started to decrease. Often a weak halocline existed further down or the salinity increased very slowly but uniformly with depth. The density stratification was quite similar to the salinity stratification. The internal Rossby radius of deformation was 1 - 2 km in the drifter experiment area.

## 8.4 The November experiment

In November the second drifter experiment took place and CTD-data were collected in the coastal area where the drifters were moving. The CTD-grid was located near the Finnish coast and its size was 45 × 110 km and it consisted of 6 transects, each with 13 stations (Figure 8.1). One of the transects was the EROS transect. The whole grid was observed three times. Temperature, salinity and density distribution are shown in Figures 8.7 - 8.8.

In the beginning of November temperature differences were small. Water was mixed from the surface to the bottom in the area above 65 m. In deeper areas a weak thermocline existed at about 40 - 50 m depth. As usual in the autumn a weak halocline was combined with the thermocline and below that the salinity increased slowly with depth. The surface temperature was highest near the coast and decreased toward the open sea. The decrease was strongest in the middle of the grid. In the middle of November after a strong storm the mixed layer deepened to about 60 m and the surface water cooled about 0.5 °C except at the shallow stations closest to the coast where temperature decreased about 1 °C. The warmest surface water was now found further away from the coast. Water was mixed from the surface to the bottom in the area with a depth less than 75 m. The thermocline existed only in the western part of some transects where a cold water mass was found between the warmer surface and the bottom water. Because the temperature differences were small, the salinity dominated the density stratification. The internal Rossby radius of deformation was about 4 km at the drifting buoy deployment site.

## 8.5 Conclusions and future analysis

The Finnish hydrographic program was carried out almost according to the original plans. The main coastal transect EROS was not so often visited as initially planned due to e.g. stormy weather. The shallow coastal areas with bottom depths less than 30 m is stratified only in summer. The mean surface temperature is strongly dependent on the mean air temperature. Salinity and temperature variations near the bottom in the southern part of the deep layers indicated variations in inflow of water from the Baltic Proper.

Future analysis will be concentrated on hydrographic structure of the coastal transect and on the combination of hydrographical data with current meter and drifter buoy data.

**Acknowledgements**

Thanks are given to all those people at FIMR who have participated in collecting CTD data on board the Aranda. Also the personnel of R/V Aranda is kindly acknowledged.

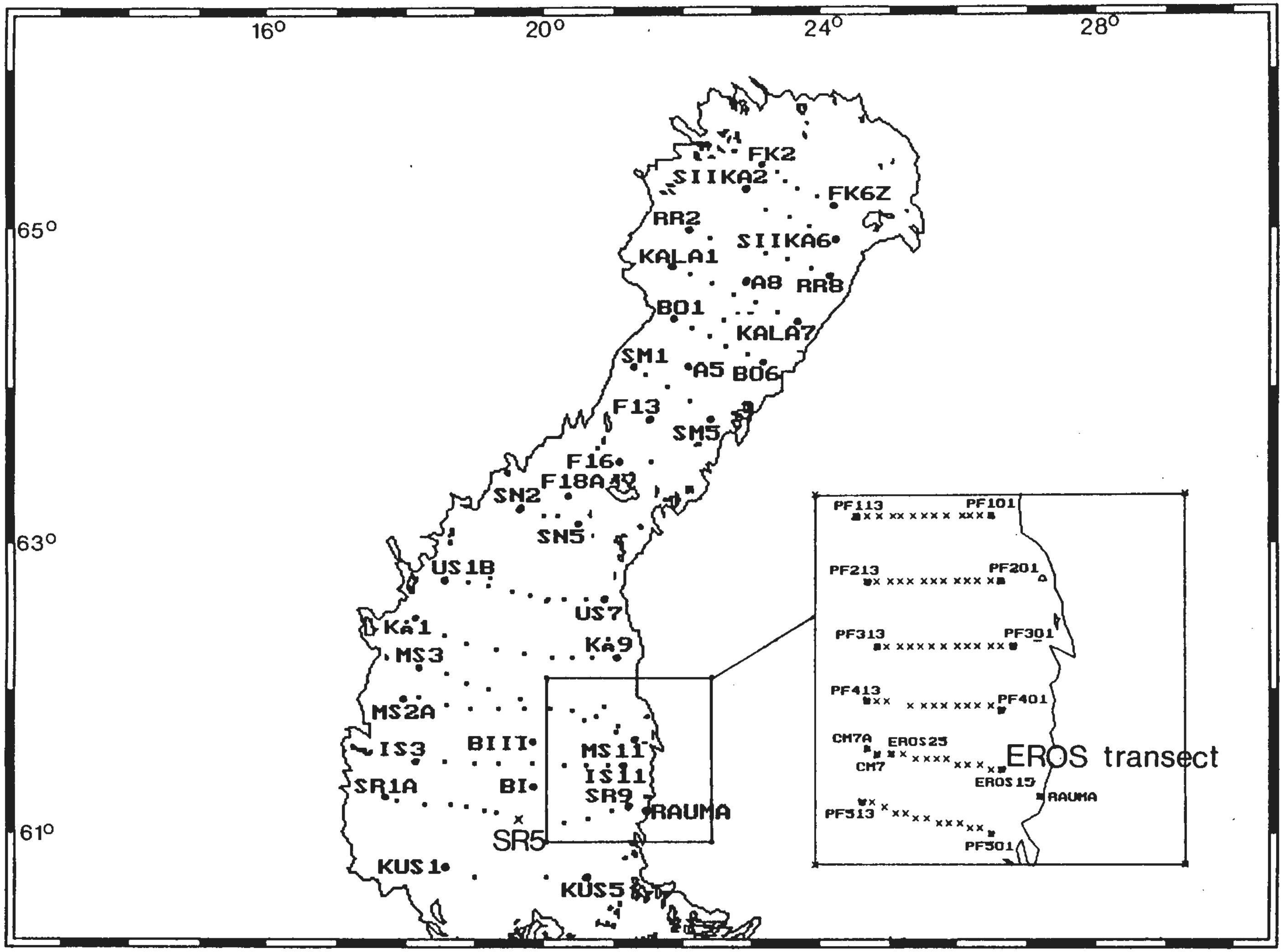


*Figure 8.1.* *Finnish CTD stations during the GB-91 Year. The first and last station name of the transect presented. The coastal grid is shown in the small picture.*

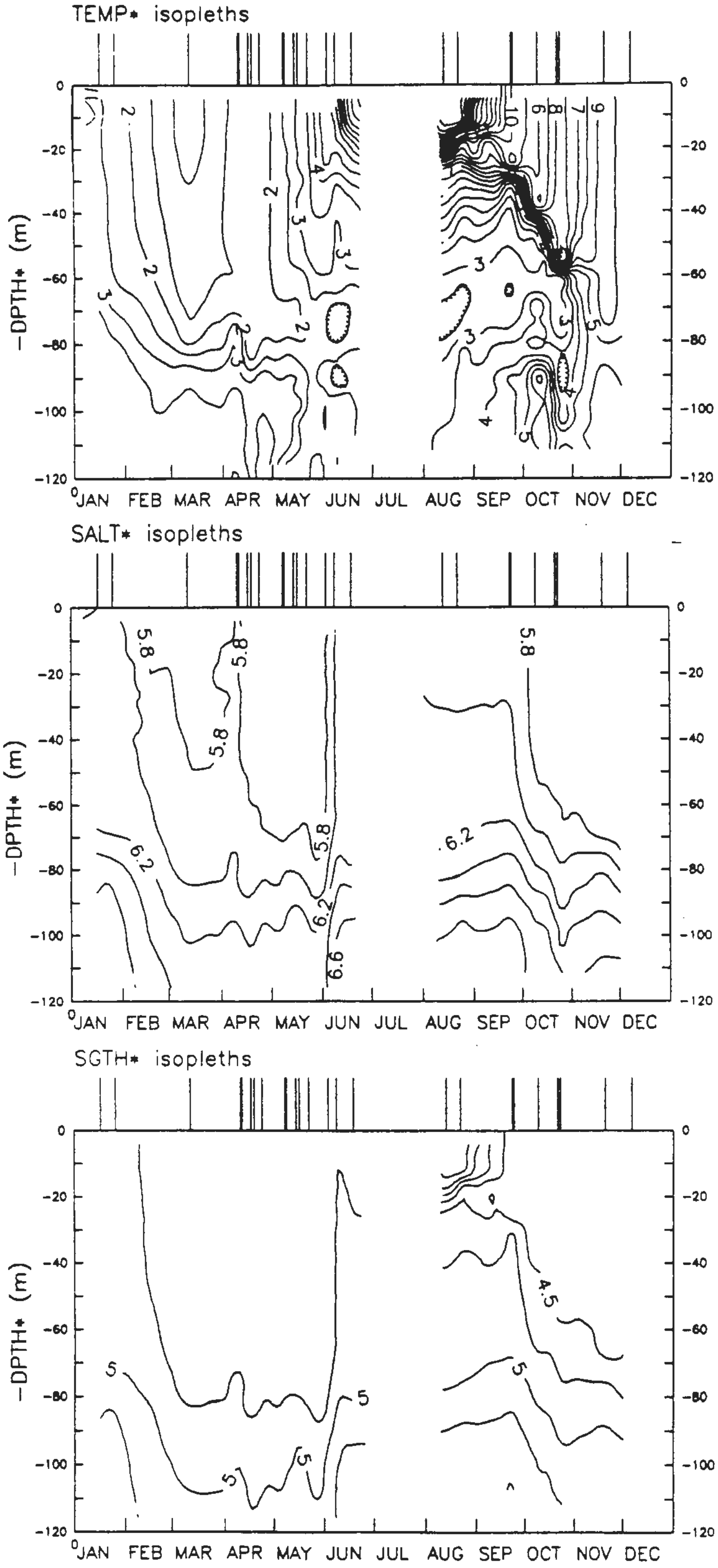


*Figure 8.2.* *Seasonal (upper) temperature, (middle) salinity and (lower) density variation at SR5 in the southern Bothnian Sea. The observation dates are marked with a vertical line on the top of the picture.*

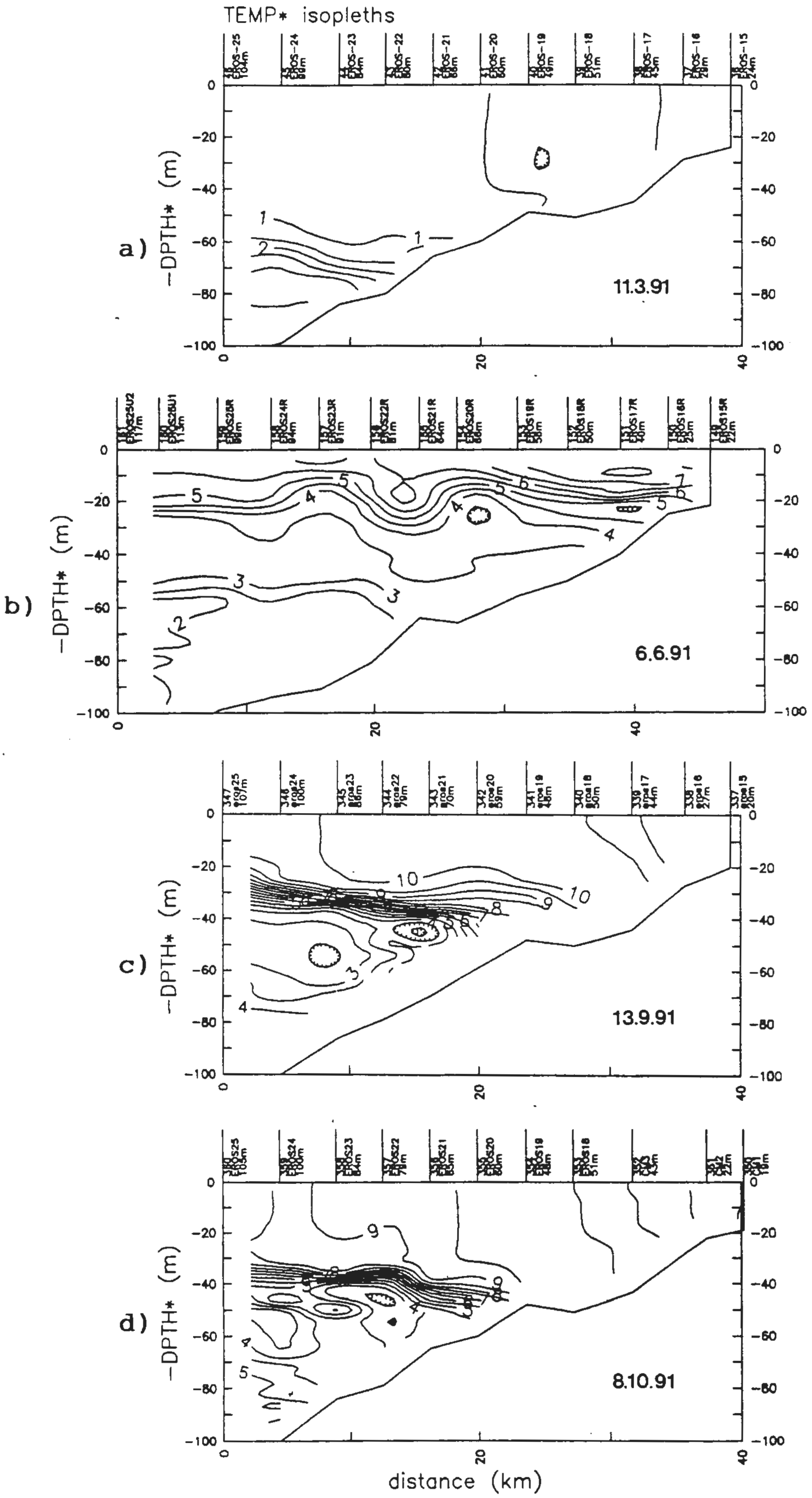


*Figure 8.3. Temperature distribution along the EROS transect outside Rauma. a) 11.3.1991, b) 6.6.1991, c) 13.9.1991 and d) 8.10.1991.*

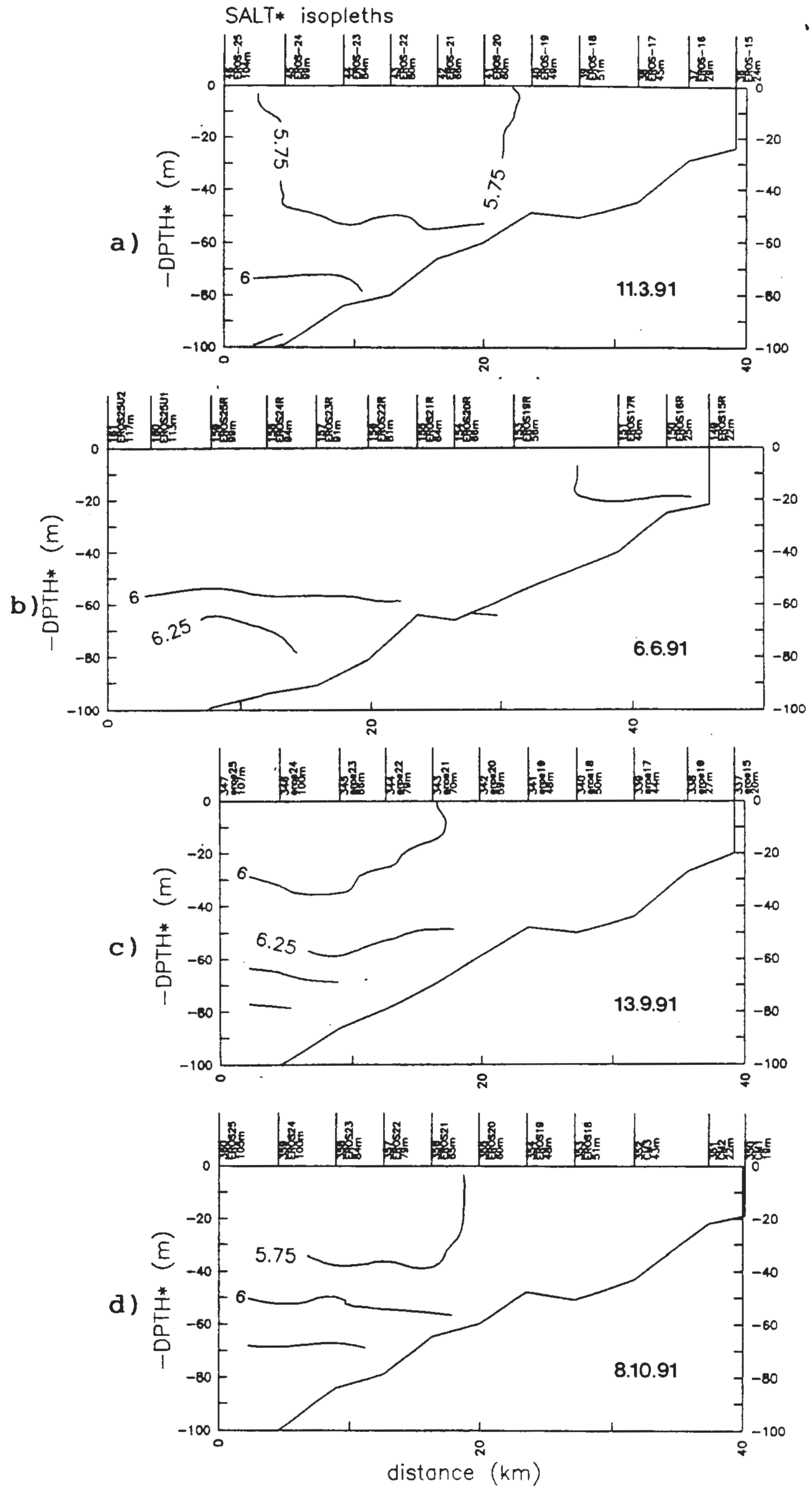


*Figure 8.4. Salinity distribution along the EROS transect outside Rauma. a) 11.3.1991, b) 6.6.1991, c) 13.9.1991 and d) 8.10.1991.*

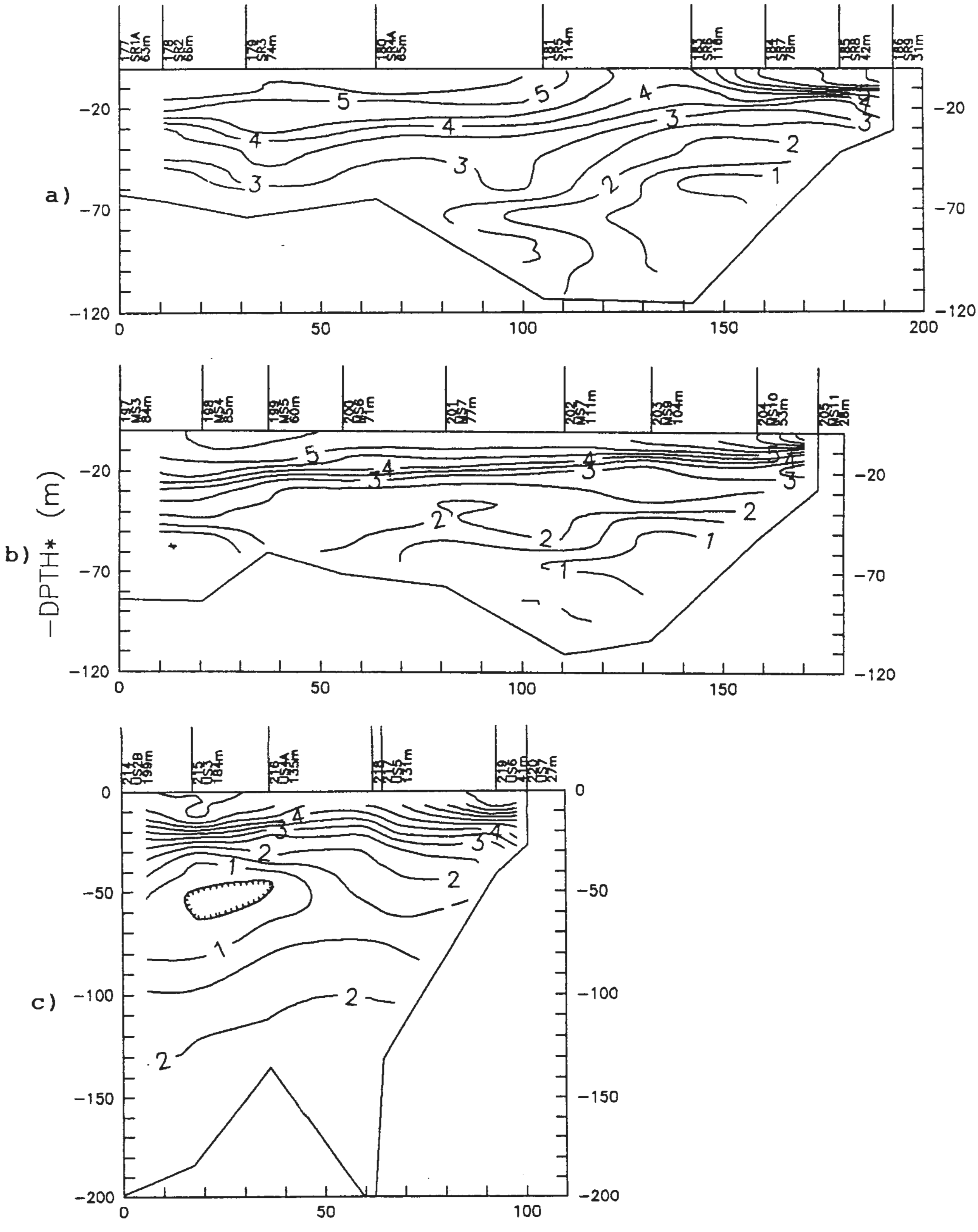


*Figure 8.5. Temperature distribution along a) US section, b) MS section and c) SR section, June, 1991.*

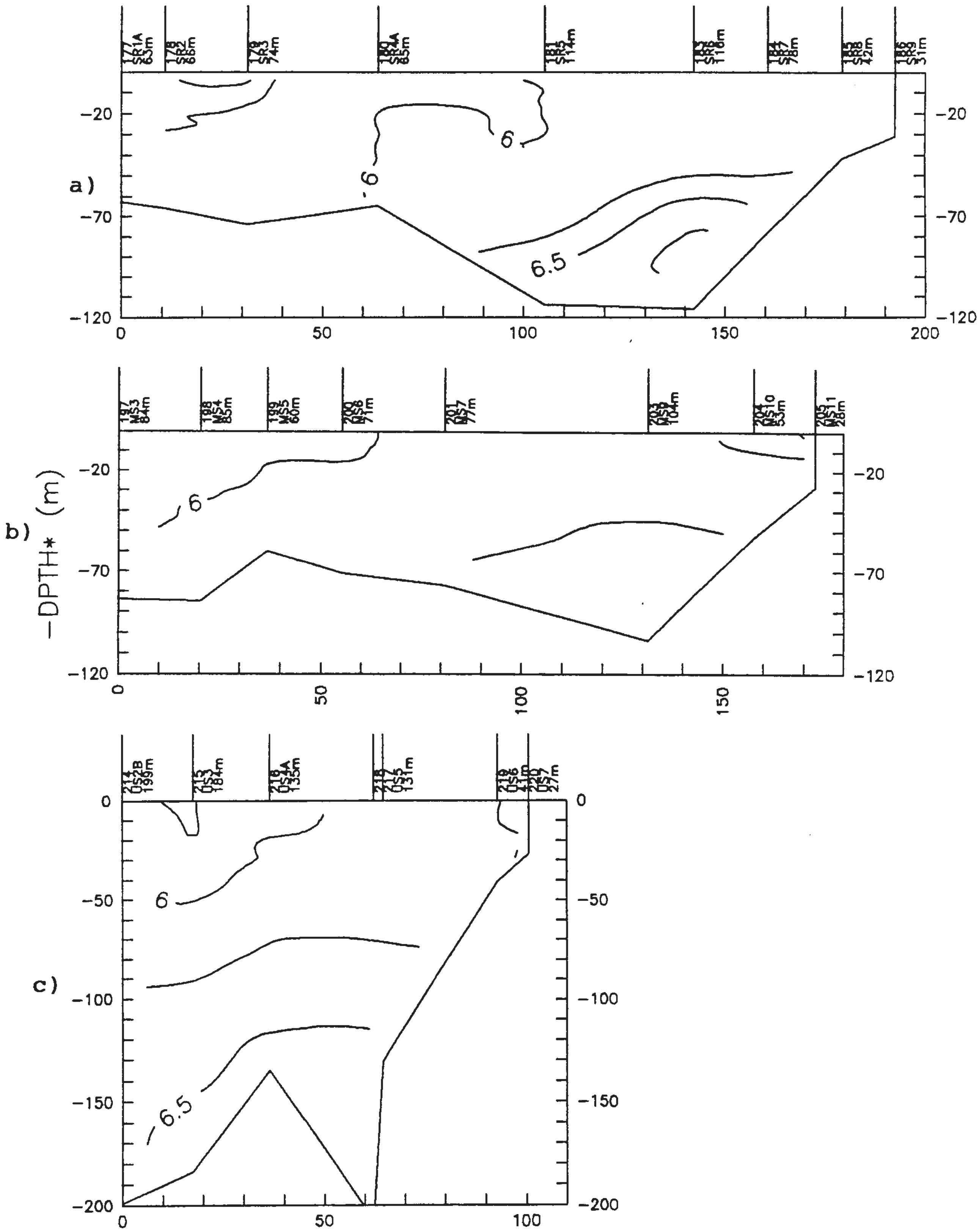

*Figure 8.6. Salinity distribution along a) US section, b) MS section and c) SR section, June, 1991.*

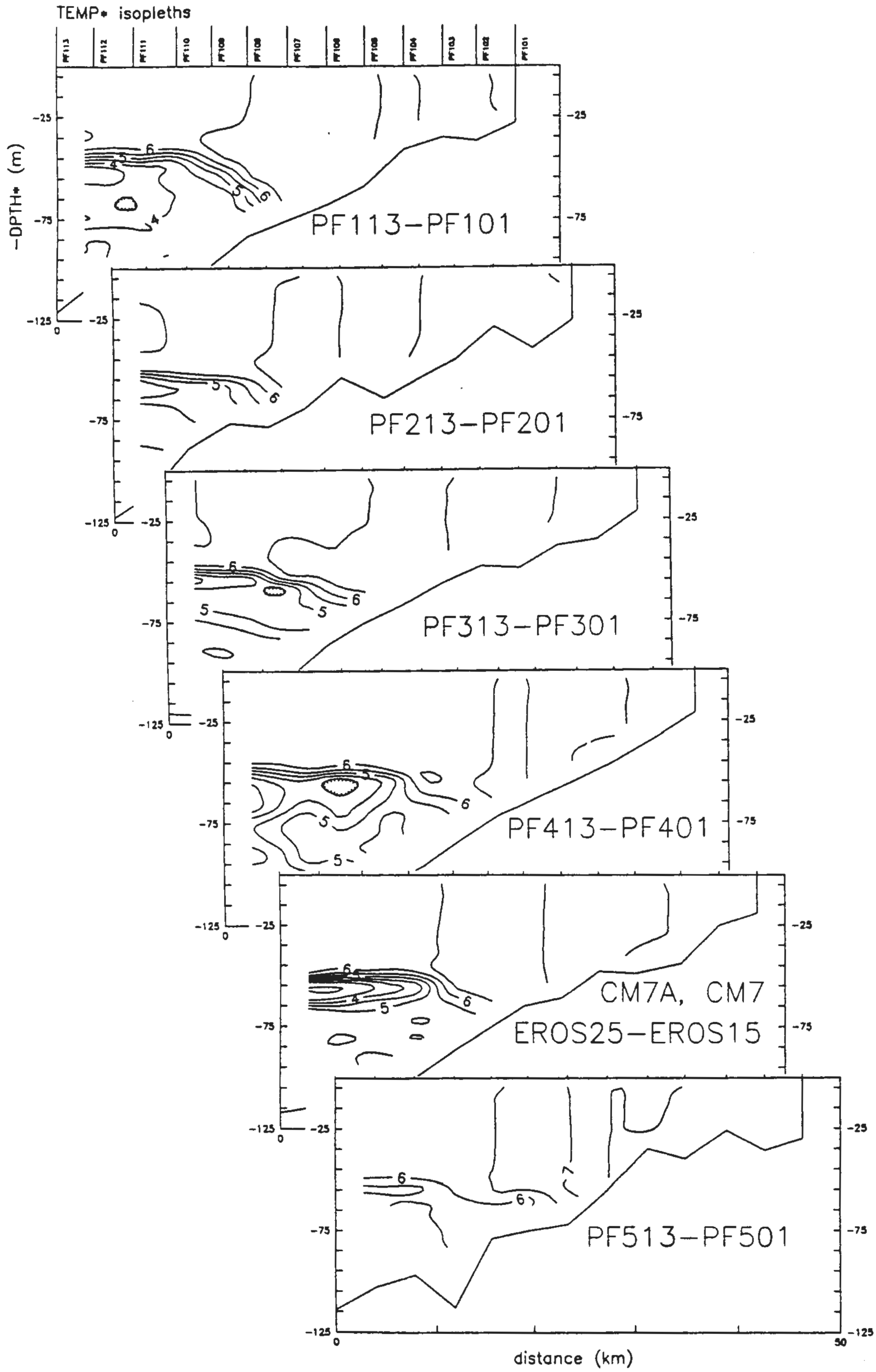


*Figure 8.7. Temperature distribution in the coastal grid near the Finnish coast, November, 1991.*

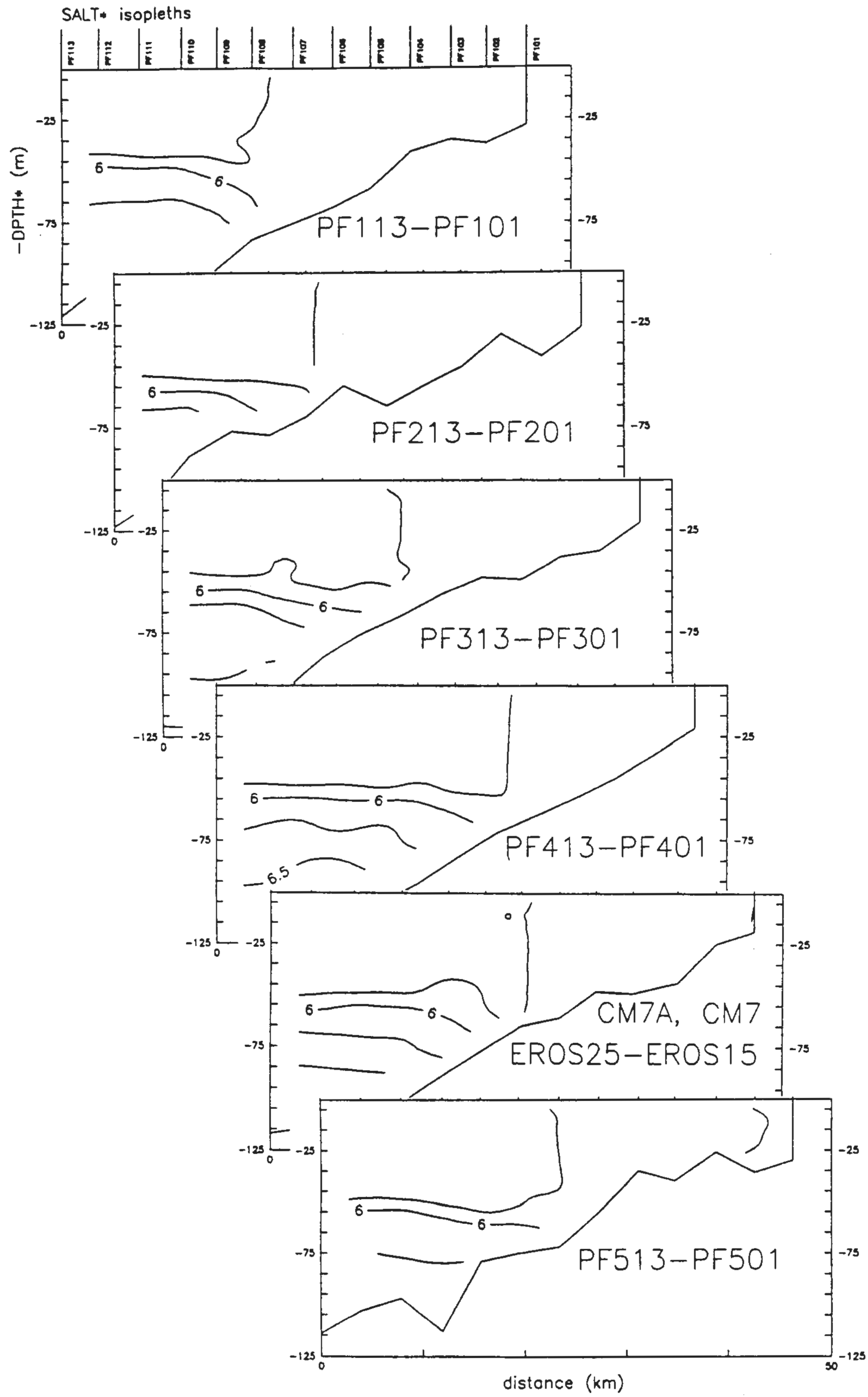


*Figure 8.8. Salinity distribution in the coastal grid near the Finnish coast, November, 1991.*

# CHAPTER 9

## HYDRO-METEOROLOGICAL DATA

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### 9.1 Introduction

This section will shortly outline the hydro-meteorological conditions during the Gulf of Bothnia Year-1991 (GB-91). The field experiment started in November, 1990, and was brought to an end in December, 1991. The material consists of meteorological data from weather stations (Figure 9.1), water-level data (the positions of the water-level stations are illustrated in Figure 9.2), sea surface temperatures and ice charts, and river run off data.

### 9.2 Summary of the weather during the Gulf of Bothnia Year

The winter 1990/1991 was mild and the Bothnian Bay was only totally covered by ice during one and a half month. A rather cold spring was followed by warm weather in July and August. As the autumn was mild as well, the average temperature for the period became 1.5 to 2 degrees above normal. Figure 9.3 illustrates monthly average temperatures during GB-91 compared with 30-year monthly average temperatures for two representative weather stations of the Gulf, Örskär in the southern part of the Bothnian Sea and Bjuröklubb in the Bothnian Bay.

Ice was first formed in the inner bays in mid-November, 1990; a normal date for ice formation to start. During the following month, the weather was cold and the ice formation continued in the archipelagoes in the northern Bothnian Bay. The ice formation ceased in the middle of December and mild, mostly southwesterly winds continued during January. Monthly averages of wind speed and wind direction at Örskär, Bjuröklubb and Valassaaret are illustrated in Figures 9.4 - 9.5. Temporarily, ice was formed at sea, but it broke up after a few days and drifted towards the Finnish coast, where a compressed ice belt was formed.

In the beginning of February, a more general ice formation started, and on February 7, both the Bothnian Bay and the Northern Quark were totally covered with ice. During the calm and cold weather that followed, the ice grew thicker. Ice was also formed off the coasts in the Bothnian Sea.

On February 19, the ice extent reached its maximum (Figure 9.6). Strong southerly winds pressed the ice northwards and the Bothnian Sea became almost ice free. A compressed ice belt remained along the Swedish coast north of Örnsköldsvik. In the Bothnian Bay, minor leads shortly opened up during March. The final breaking up started at the end of March, with a wide lead formed along the Swedish coast. Meanwhile, the ice was heavily compressed against the Finnish coast.

During the mild April, compact ice was situated in the northeastern part of the Bothnian Bay, while the water in the southern parts was open. At the end of April, the ice drifted out from the northern coast and broke up into floes. Thereafter the ice melting was rapid and the Gulf was totally ice free on May 24, earlier than normal.

June was very cold, with sea surface temperatures 1 - 2 degrees below normal. Along the Swedish coast of the Bothnian Sea, the surface temperatures were as much as 3.5 degrees below normal. Due to the warm weather in the beginning of July, the temperature rose rapidly, and was found to be 1 - 2 degrees above normal in the middle of the month, conditions that remained during August. Figure 9.7 illustrates the sea surface temperature during the end of the summer, 1991.

Stormy weather started in the beginning of September. The air temperature decreased to 1 °C below normal and the sea surface temperature to normal. During October the weather was variable. A high pressure caused rather warm weather in the middle of the month. Although, the monthly average temperature was around normal, and the sea surface temperature just above normal. During a short period of cloudiness in the middle of November, new ice was formed in the inner bays of the Bothnian Bay. Mild weather with strong westerly to southwesterly winds followed, keeping open water to most ports in the Bothnian Bay until late December.

## 9.3 Water-level variations during the Gulf of Bothnia Year

The water-level variations are illustrated in Figure 9.8a - b, from which it can be noted that the typical annual cycle with high water-levels during autumn and early winter and low water-levels during spring and summer. The annual variations reflect air pressure variations, with high air pressure systems causing low water levels and low pressure systems causing high water levels. During GB-91 the monthly average of the water-levels were above the 30-year average, except for the period from February to May. The largest water-level variations appeared in September - December and the highest values were reached in November.

## 9.4 River runoff to the Gulf of Bothnia 1991.

This analysis is based upon computed total runoff from the Swedish coast. Data from the Finnish side of the Gulf of Bothnia are not yet available. In figures 9.9 a - c monthly and annual average runoff data are compared with earlier data to give an idea of the runoff to the Gulf of Bothnia during GB-91.

The runoff to the Gulf is originating from at least two different hydrological regimes. The divider in this analysis is set to the same as the border between the Bay of Bothnia and the Bothnian Sea. The discharge to the Bay of Bothnia is dominated by the large northern Finnish and Swedish arctic and mountain rivers as Kemijoki, Torne and Lule rivers. The runoff to the Bothnian Sea is dominated by forest-rivers from both sides of the Gulf.

Monthly averages of the runoff to the Gulf, based upon data from 1961 - 1990, show for both areas a well defined peak in May and early June associated with the snowmelt. With the intention to show the special characteristics of the 1991 runoff compared with earlier years the monthly means for 1961 - 1990, repeated four times, are compared with the last four years 1988-91 (Figures 9.9 a - d).

There is a striking difference between the two basins. The runoff to the Bay of Bothnia 1991 can be considered rather normal, but there is a somewhat lower snowmelt peak (Figure 9.9a). The annual mean 1991 is 1 683 $m^3/s$ compared with 1 714 $m^3/s$ for the period 1961-90 (Figure 9.9d). The runoff to the Bothnian Sea in 1990 and 1991 shows quite unusual patterns compared with the monthly averages (Figure 9.9b). The snow melt peak reach only just over 3 000 $m^3/s$ compared with the average peak of about 4 700 $m^3/s$, and the low flow in summer-time is about 600 $m^3/s$ less then average. Also the runoff in 1990 is unusual and looks similar to 1991, but the differences, compared with the period 1961-90, is not as pronounced as for 1991. Here a meteorological analysis ought to be done to delineate this feature. The influence of the low snowmelt peak in runoff to the Bothnian Sea can also be seen in the total runoff to the Gulf (Figure 9.9 c). However, from a long term perspective and on yearly basis the runoff to the Gulf is normal, 4 037 $m^3/s$ in 1991 compared with the 30 year mean 1961-90 4 150 $m^3/s$ (Figure 9.9d).

The conclusions of this analysis is that the runoff to the Gulf of Bothnia during the GB-91 was normal with respect to the total volume but unusual with respect to the distribution during the year.

An important factor influencing the river runoff is the regulation of river water for hydro-electric power generation in Sweden and Finland. The distribution of power plants in Sweden is shown in Figure 9.10, whereas the degree of regulation of some rivers in Sweden is shown in Table 9.1. Shortly speaking, river water is stored in reservoirs during high runoff in spring and early summer and is later released during autumn and winter (Figure 9.11) for energy production. This antrophogenic phase-shift in runoff may affect physical as well as chemical and biological environments in the Gulf of Bothnia. There are few investigations on this matter. From a physical point of view the runoff represents an important part of the buoyancy flux to the Gulf, driving the estuarine circulation and influencing the vertical stability and hence mixing processes in the water column. A phase-shift of a major part of this buoyancy flux from summer to winter may probably weaken the vertical stability during summer and increase it during winter. It may also change the natural seasonal variation in the estuarine circulation. There is an urgent need to investigate how the total inflow of river water is changed by season before and after the main river water regulations were introduced in Finland and Sweden and what effects these may have on the Baltic.

*Table 9.1. Hydropower production during a normal year in some Swedish rivers expressed in GWh. The degree of regulation (%) gives the relation between the yearly river runoff and the amount of water which can be stored in the reservoir.*

| Rivers | Production (GWh) | Degree of regulation (%) |
|---|---|---|
| Luleälven | 13 600 | 72 |
| Skellefteälven | 4 000 | 62 |
| Umeälven | 7 700 | 27*) |
| Ångermanälven | 11 000 | 43 |
| Indalsälven | 9 600 | 40 |
| Ljungan | 2 300 | 29 |
| Ljusnan | 3 900 | 22 |
| Dalälven | 4 100 | 26 |
| Klarälven | 1 500 | 20 |
| Göta älv | 1 500 | 72 |
| | | *) incl. Vindelälven |

## 9.5 Hydro-meteorological data base

The weather, water-level and river runoff data of the Gulf of Bothnia Year-1991 are stored on PC-diskettes. The Swedish data are available from the SMHI (Eleonor Marmefelt or Anders Omstedt). The Finnish water-level data are available from the FIMR (Riikka Hietala) and the Finnish weather data from the Finnish Meteorological Institute.

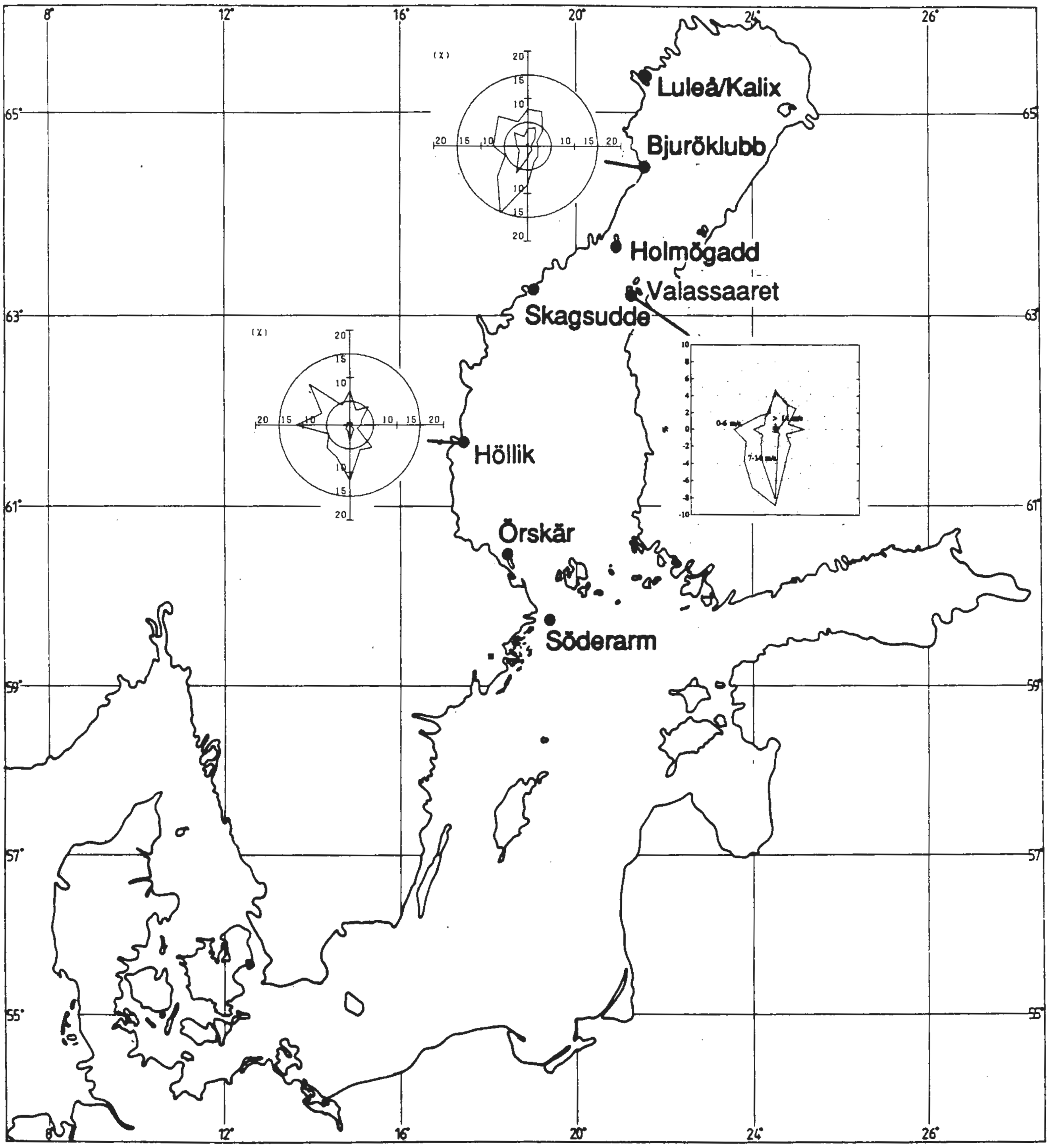


*Figure 9.1. Weather stations in the Gulf of Bothnia. The observed parameters are wind, temperature, relative evaporation and cloudiness. The stations Luleå/Kalix, Bjuröklubb and Holmögadd also observe air pressure. The wind roses from the weather stations Bjuröklubb, Hölik and Valassaaret (22.4. - 22.11.) illustrate the distribution of wind speed directions. The directions are towards the wind. Here the magnitudes are below 7 m/s, between 7 and 14 m/s and above 14 m/s.*

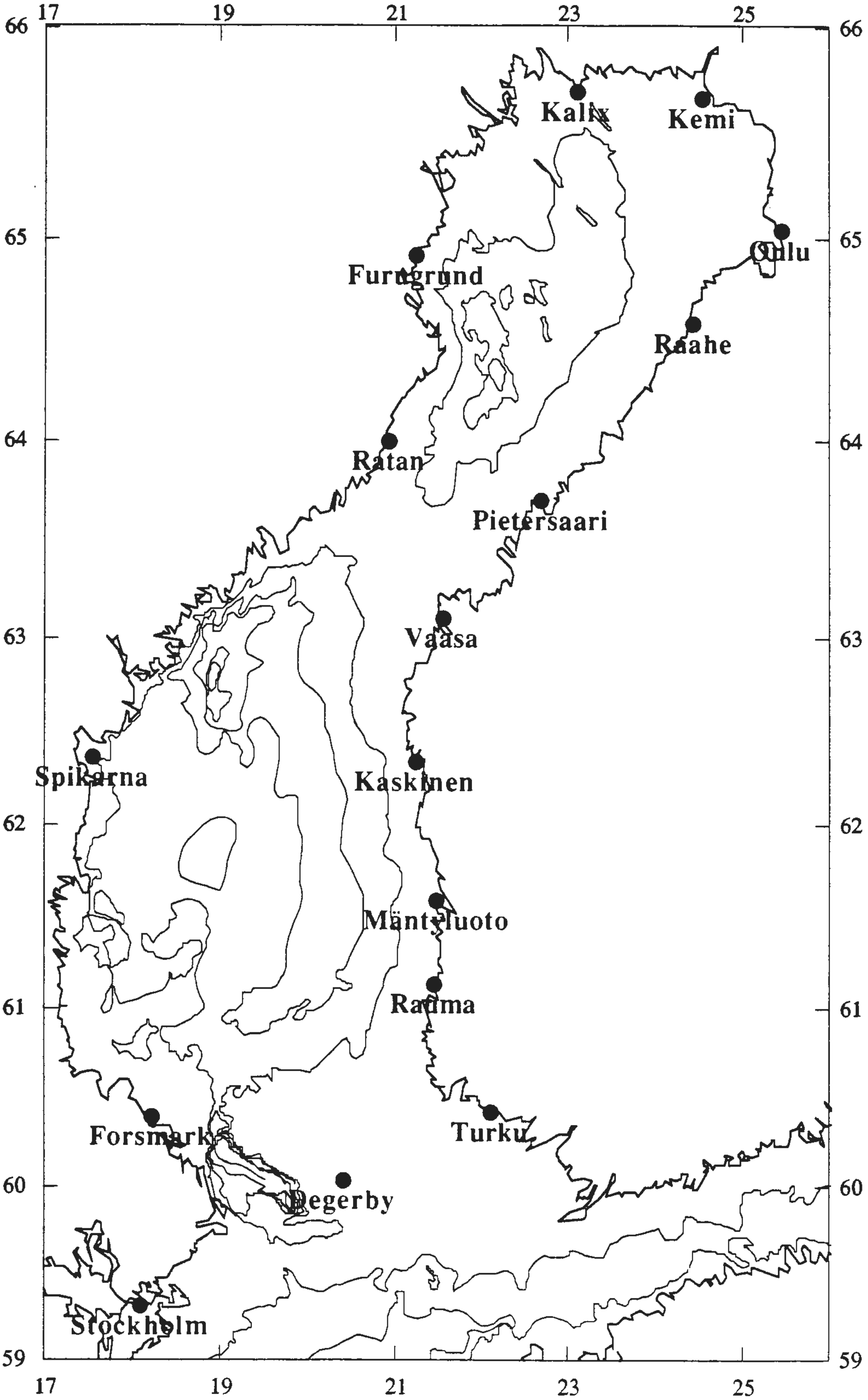


*Figure 9.2. The water-level stations in the area.*

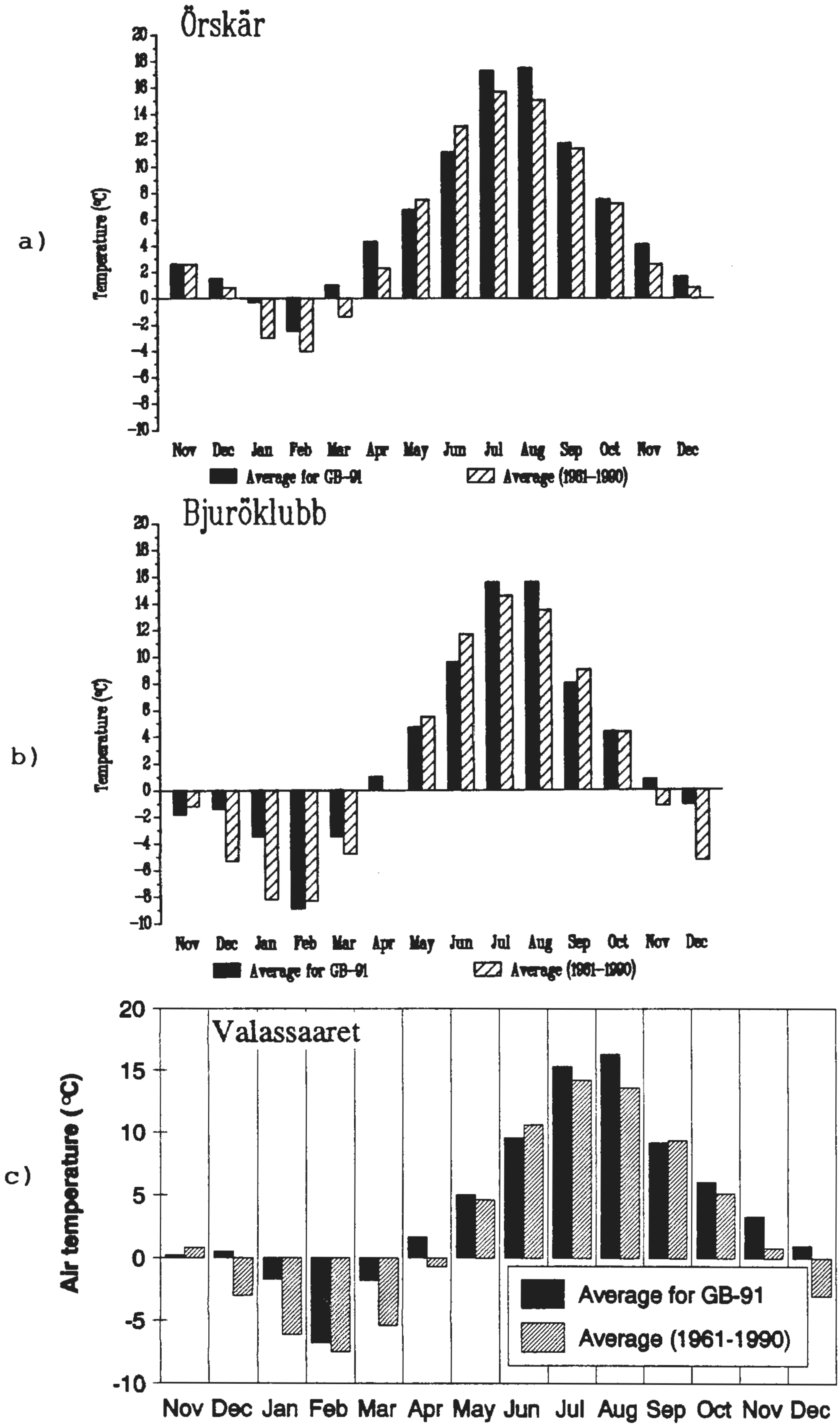


*Figure 9.3. Monthly average temperature from a) the Örskär, b) the Bjuröklubb and c) the Valassaaret stations during the Gulf of Bothnia Year compared to the 30-year period covering the years 1961 to 1990.*

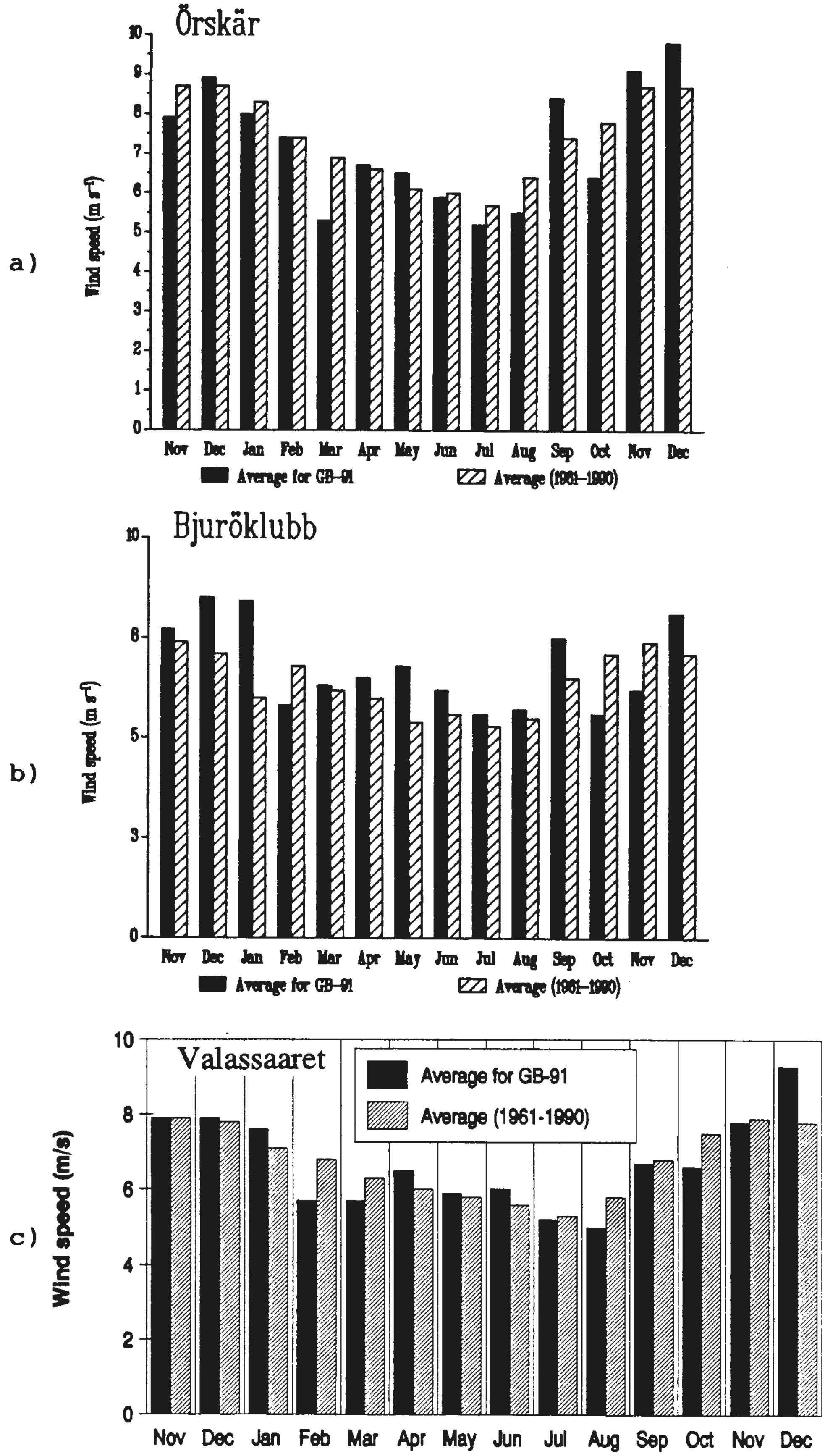


*Figure 9.4. Monthly average wind speed from a) the Örskär, b) the Bjuröklubb and c) the Valassaaret stations during the GB-91 compared to the 30-year period.*

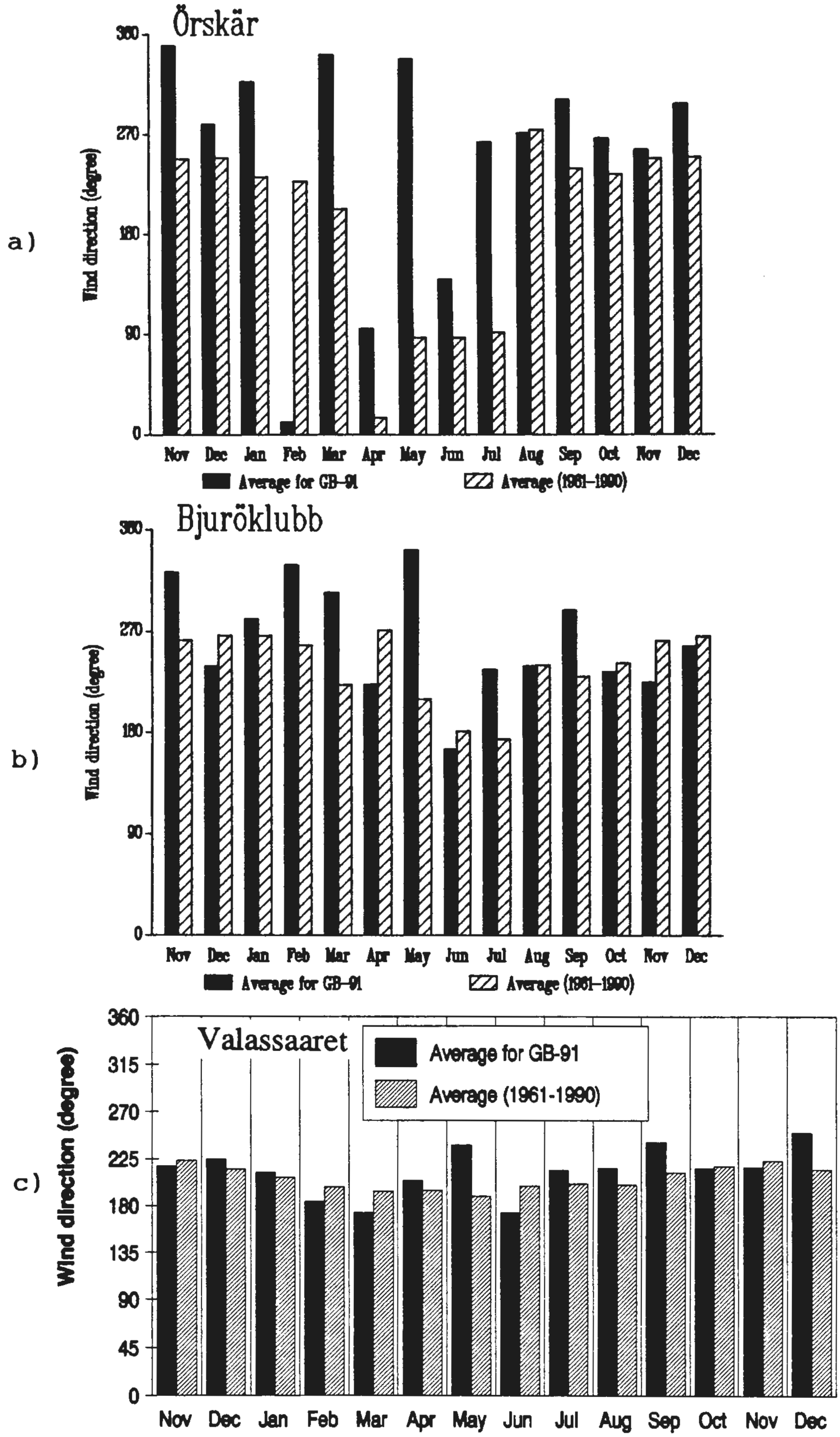


*Figure 9.5. Monthly average wind direction from a) the Örskär, b) the Bjuröklubb and c) the Valassaaret stations during the GB-91 compared to the 30-year period.*

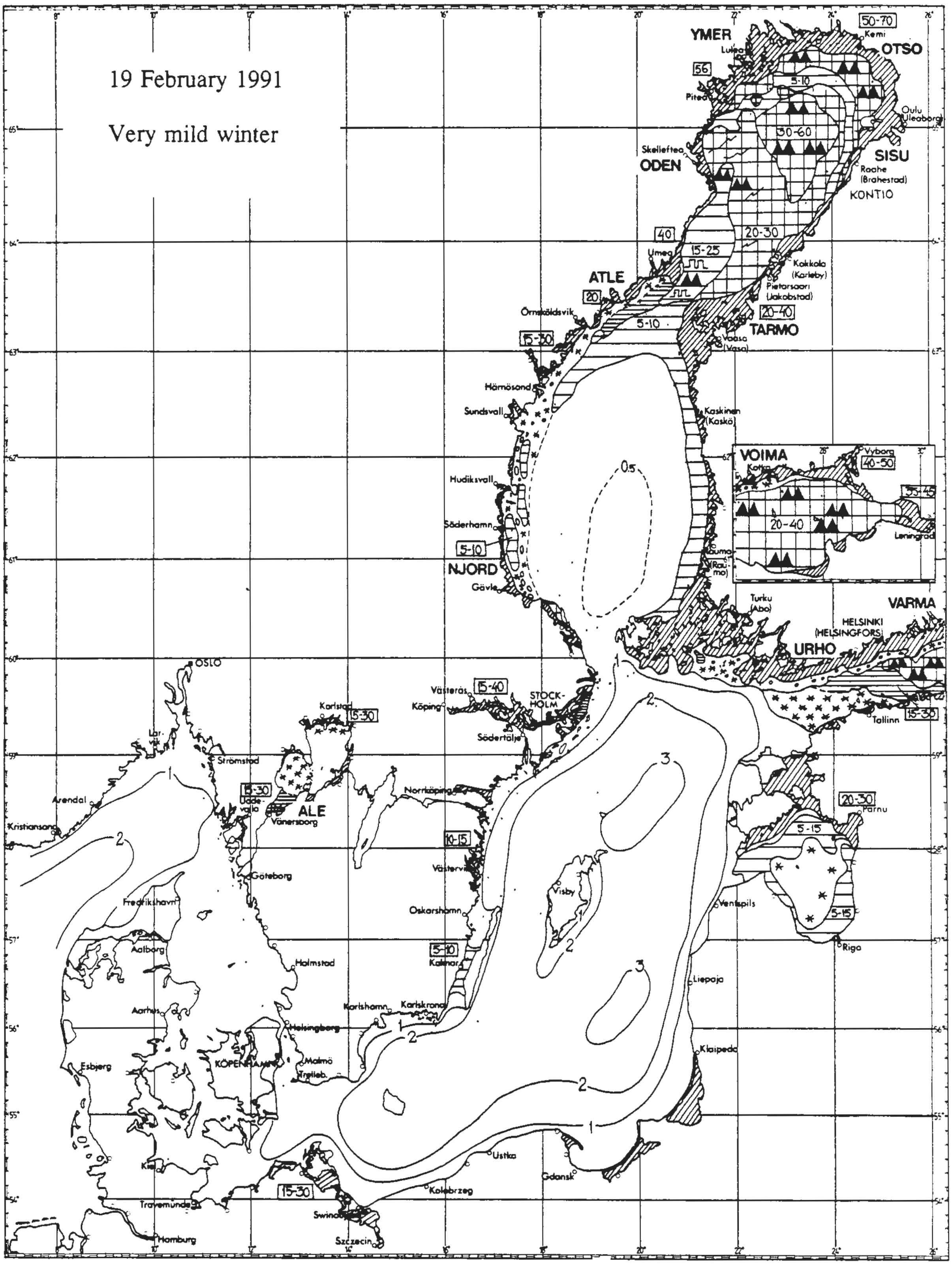


*Figure 9.6. Maximum ice extent during the GB-91 observed on February 19, 1991.*

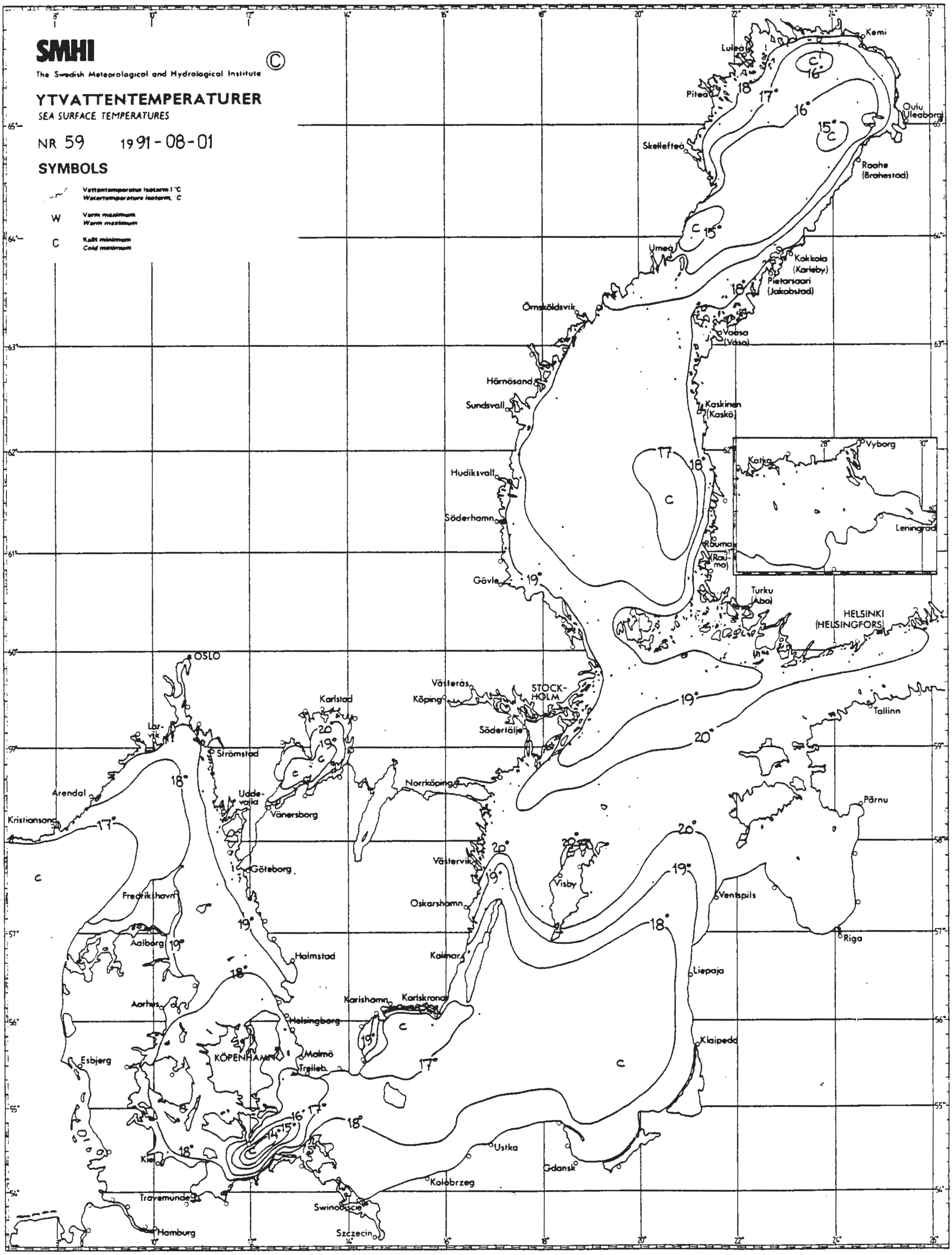


*Figure 9.7. Typical sea surface temperature during the end of the summer of 1991, observed on August 1, 1991.*

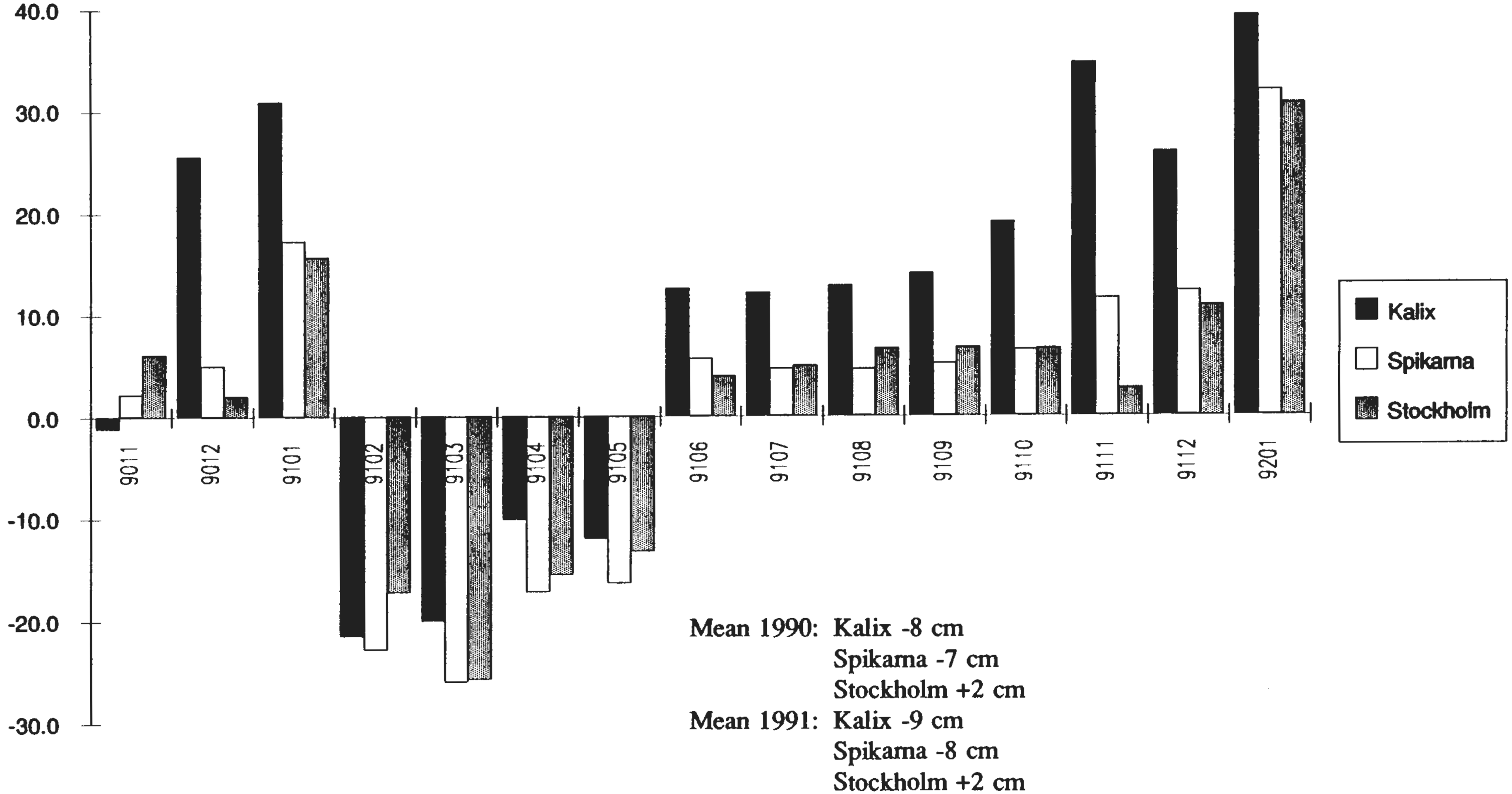


*Figure 9.8a. Monthly deviation in centimetres from average water-level (during the GB-91 from the Swedish water-level stations: Kalix, Spikarna and Stockholm.*

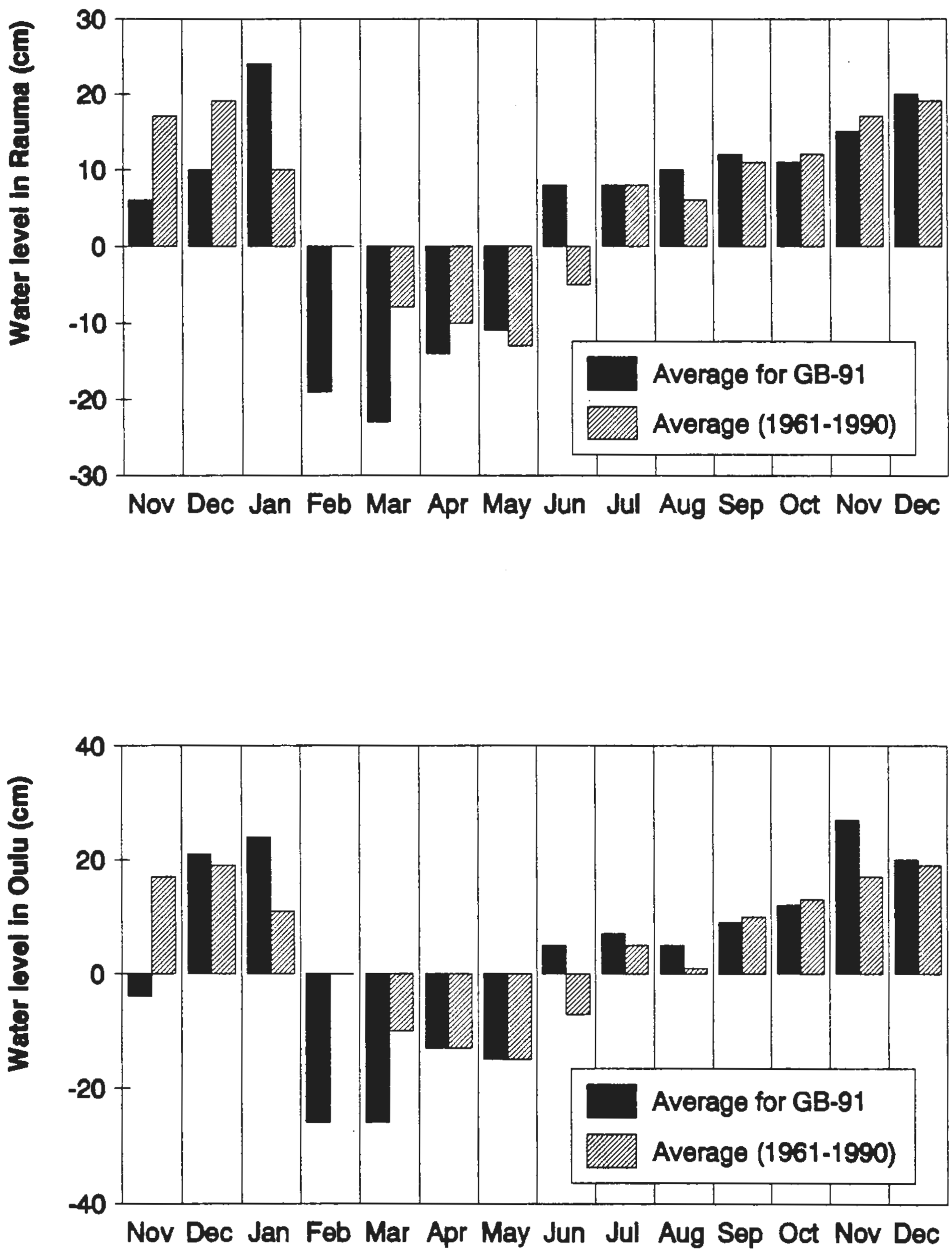


*Figure 9.8b. Monthly deviation from the average water-level during the GB-91 compared to the 30-year period from the Finnish water-level stations Rauma and Oulu.*

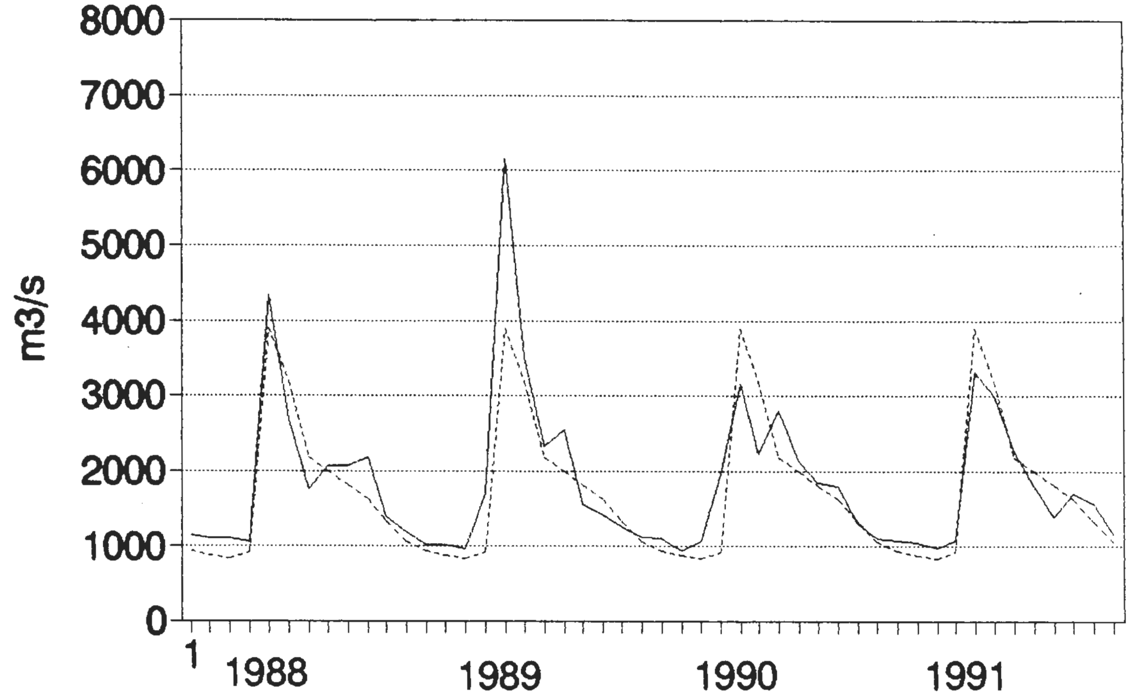


*Figure 9.9a. Monthly runoff from Sweden to the Bay of Bothnia 1988-91 ( —— ) compared with monthly runoff from the period 1961-90 (---).*

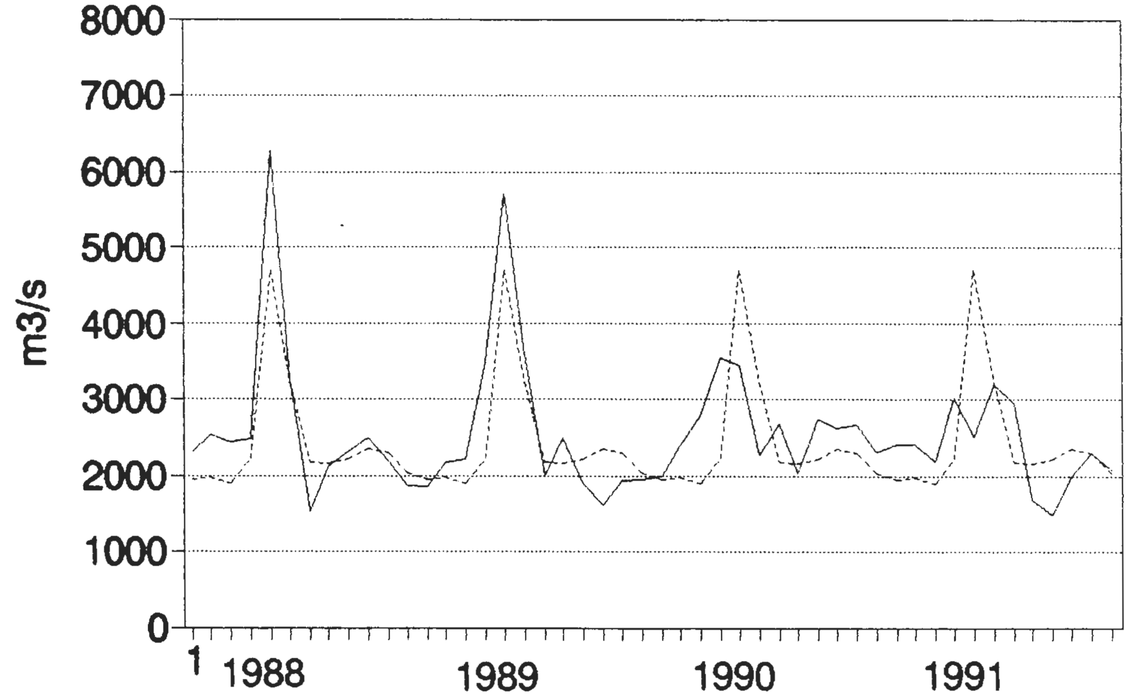


*Figure 9.9b. Monthly runoff from Sweden to the Bothnian Sea 1988-91 ( —— ) compared with monthly runoff from the period 1961-90 (---).*

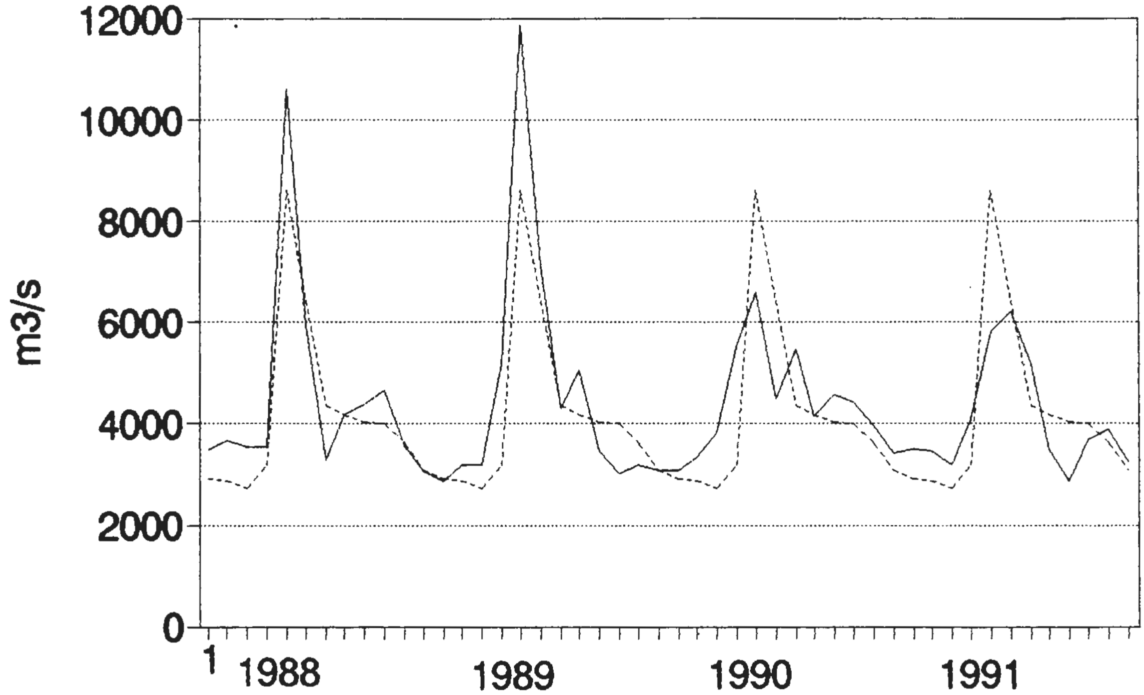


*Figure 9.9c. Monthly runoff from Sweden to the Gulf of Bothnia 1988-91 ( —— ) compared with monthly runoff from the period 1961-90 (---).*

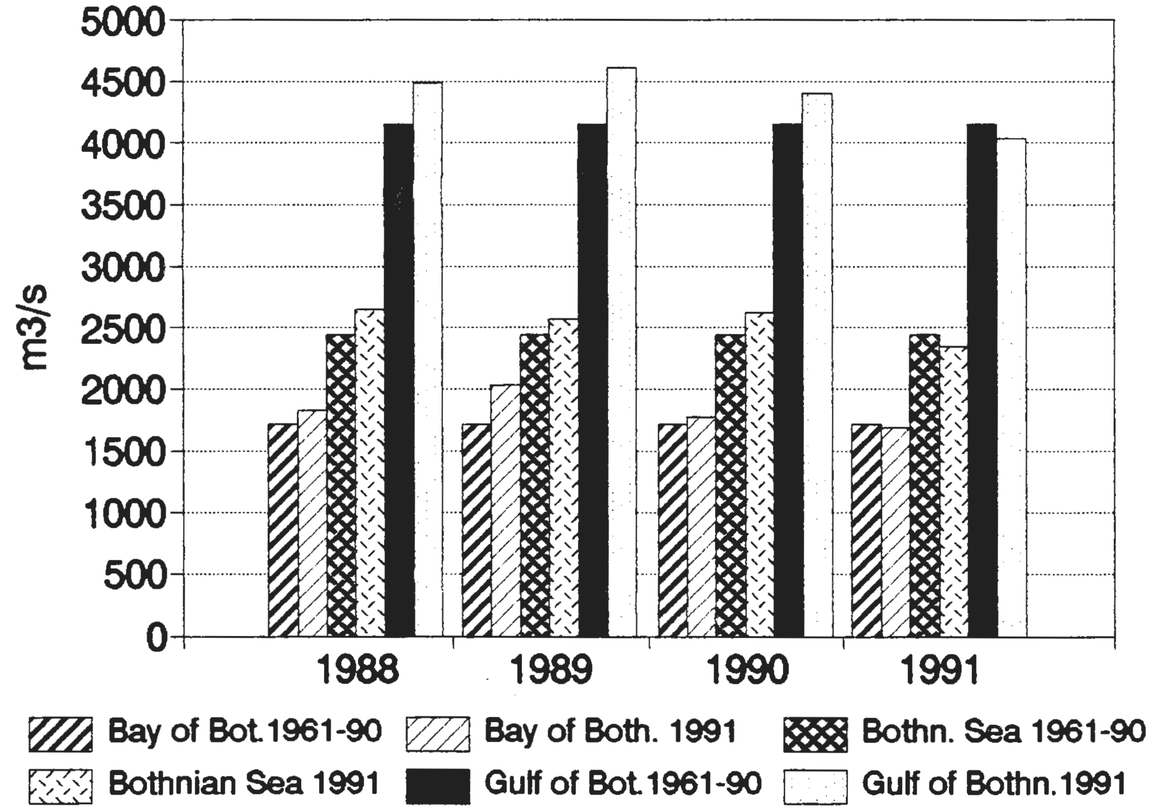


*Figure 9.9d. Annual means of runoff to the Gulf of Bothnia from Sweden.*

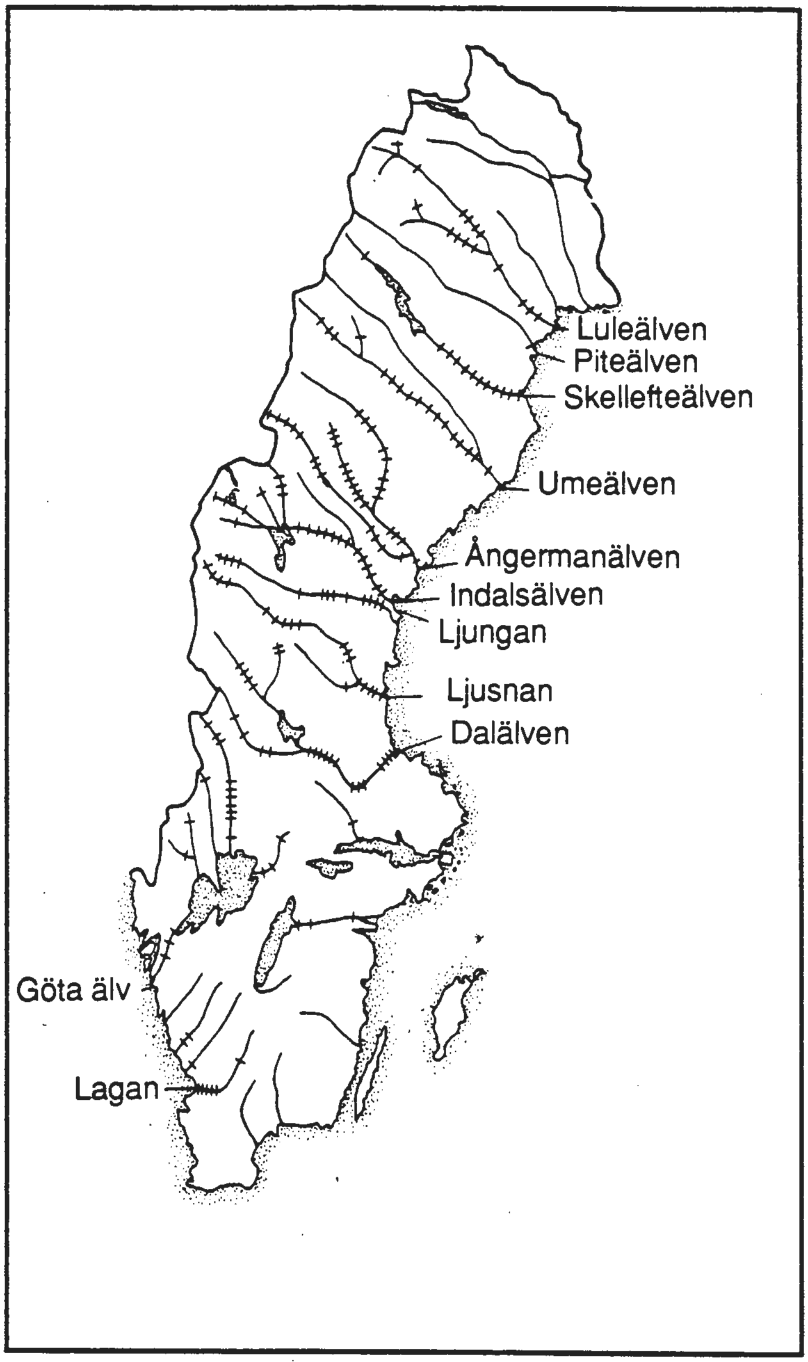


*Figure 9.10. Swedish hydropower plants larger than 10 MW.*

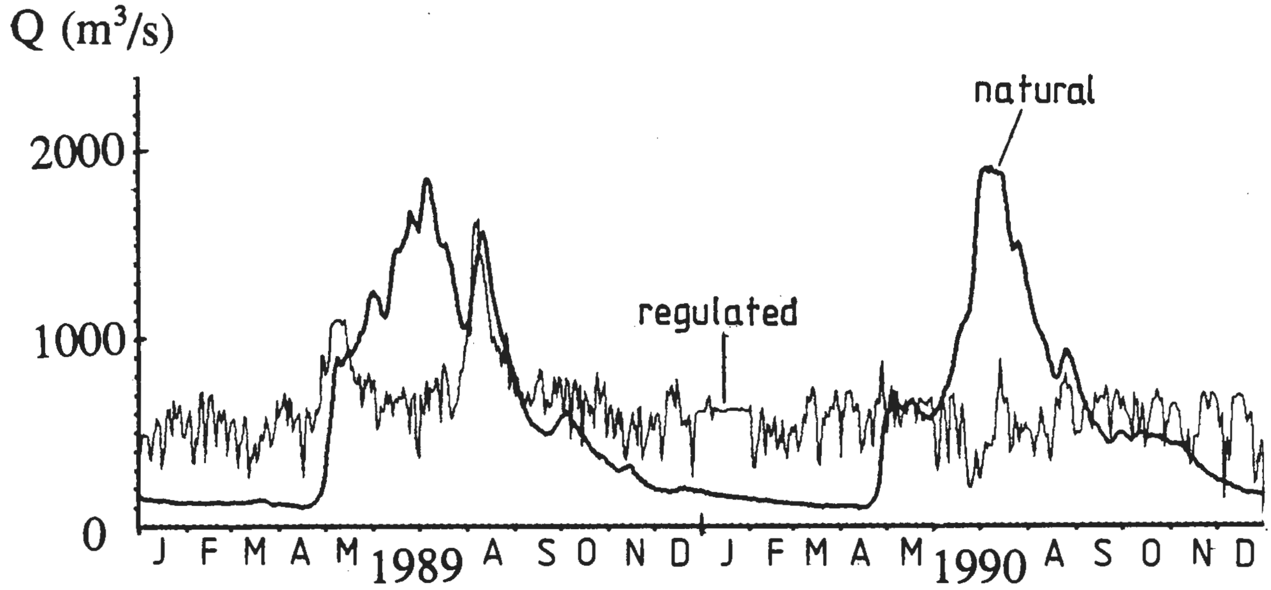


*Figure 9.11. Example of the influence of regulation on the flow in the River Luleälven at Boden (24 488 $km^2$) near the outlet inot the Baltic Sea. Thick curve: Reconstructed natural. Thin curve: Recorded regulated.*

# CHAPTER 10

## SUMMARY

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This report is essentially a statistical and climatological documentation of the data from the GB-91 physical transport experiments and meets objective (1) set out in Page 2 of the report. The next phase will be the detailed scientific analysis of the GB-91 physical transport data base, namely to delineate the dynamical processes including development and verification of hydrodynamic and mass transport models relevant for the coastal areas and the open sea. The scientific synthesis will be addressing objectives (2 - 5).

It is widely accepted by both the oceanographic and limnological scientific community that the physical transport processes mediate the biochemical processes and that the observed variability in biochemical parameters in part is the result of water movements in the marine and aquatic environment. Reviews by Burns and Ross, 1972; Simons et al. (1979), Lam et al. (1983) and Boyce et al. (1987) in the North American Great Lakes system and Åkerblom (1972, 1976), Voipio (1981) as well as Rosemarin (1990) in the Baltic provide a wealth of examples to illustrate this. The GB-91 physical transport experiments were planned and conducted with this broad objective in mind. These experiments were a tremendous success producing a wealth of data characterizing the physical marine environment of the Gulf of Bothnia. This report is published with the hope that the Baltic marine scientific community will exploit the physical data base to investigate the governing physical transport processes and to stimulate and initiate interdisciplinary research, including water quality modelling relevant to address the environmental problems envisaged by the Gulf of Bothnia Planning Committee.

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