BALTEX

Baltic Sea Experiment

World Climate Research Programme / Global Energy and Water Cycle Experiment
WCRP GEWEX

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BALTEX

Initial Implementation Plan

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Table of Contents

FOREWORD

The hydrological cycle and the exchange of energy between the atmosphere and the surface of the Earth controls and regulates the climate in a fundamental manner. This takes place directly as transport of latent heat over large distances and indirectly in the way clouds and snow on the ground effect the radiation balance. To address these central issues, The World Climate Research Programme has launched GEWEX, the Global Energy and Water Cycle Experiment, with the overall objective to study the energy and water cycle in the global atmosphere.

Due to the large geographical variability of the water cycle it is considered a sound strategy within GEWEX to undertake specific regional experiments in different climate regions. Such a strategy has the advantage of focusing attention on specific problems in these areas, and may therefore draw on the interest and knowledge which already exist there.

The Baltic Sea and its huge drainage basin may be considered an optimal example of such a region and this document constitutes an attempt to formulate an Initial Implementation Plan for BALTEX, the Baltic Sea Experiment. It has been developed by the BALTEX Scientific Steering Group consisting of scientists from ten countries: Belarus, Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden, all of which border the Baltic Sea or have major river basins within its domain, or both.

A BALTEX Scientific Plan was developed in 1993 and has served as a background document in this work. Several aspects of the BALTEX programme are unique in comparison with other GEWEX regional programmes and it is the only one with a marine component. A particular important part of the research will be to develop methods for the determination of precipitation and evaporation over a large water body.

The plan focuses on five areas: 1) collection of *in situ* as well as remote sensing data, 2) reanalysis of existing data sets, 3) data-assimilation with emphasis on coupled systems, 4) numerical experiments and model development and 5) process studies and associated field experiments. The science programme is being organized in seven separate research networks, actively supported by an advanced infrastructure of data services, satellite data processing, numerical modelling and data assimilation.

Lennart Bengtsson
Chairman
BALTEX
Scientific Steering Group

EXECUTIVE SUMMARY

I. Scientific Goals and Main Objectives of BALTEX

BALTEX will explore, model and quantify the various processes determining the space and time variability of the energy and water cycle of the Baltic Sea and its catchment area. BALTEX will undertake specific assessments of the total flux divergence of heat, water and momentum for this region and determine its coupling to the large-scale atmospheric circulation and to the water exchange through the Danish Straits. The scientific objectives will be addressed by a combined observational and modelling approach where the Baltic Sea, the land surfaces of its catchment area and the atmosphere will be considered as one system.

The main emphasis of BALTEX is on the physical and dynamic processes of the coupled meteorological, hydrological and oceanographic system where the development of better coupled regional models for the European region is a key objective. However, it is anticipated that these models will constitute essential building blocks in studies of a biological and ecological nature for the area.

The BALTEX region covers an area of 2.1 x 10^6 km^2. It ranges from a mild and humid mid-latitude to a subarctic climate. Frequent and complex synoptic-scale cyclonic activity and subsynoptic-scale depressions are characteristic, sometimes leading to excessive surface fluxes and heavy precipitation over much of the region. Snow accumulation and melting, and highly variable rainfall patterns determine the runoff conditions in the BALTEX region. The Baltic Sea itself is a unique brackish sea with complex hydrography and variable sea-ice conditions. Its annual net water discharge through the Danish Straits is comparable to that of major river systems such as the Mississippi River.

The complex interactions of atmospheric, land surface, hydrological and oceanographic processes within the system are poorly understood. This is particularly the case for small-scale processes, which are generally not adequately resolved or represented in present models. The objectives of BALTEX include the improvement of the parameterizations of these and other relevant processes in meso- and regional-scale climate and weather forecast models. Parameterizations and other methods to be developed in BALTEX will be based on general physical principles in order to make models and research tools applicable to other water catchments on the globe, for example the other GEWEX regions.

BALTEX will be beneficial for short range weather prediction, medium and long term climate prediction, climate monitoring and impact studies, observational techniques and networks design, water resources assessment and management, as well as environmental aspects. In order to address the serious environmental problems such as the severe pollution in many parts of the BALTEX region and the contamination of important fresh water resources, ecological models are required as decision support tools. For the improvement of these models a detailed, physically based description of the water and energy fluxes in the area is a prerequisite. Consequently, a programme like BALTEX, which incorporates comprehensive and coupled modelling for the atmosphere, the ocean and the land surface will provide a solid framework for environmental investigations and enable more realistic environmental predictions and scenario calculations to be developed.

II. BALTEX Programme Elements

The implementation plan for BALTEX is divided into five basic programme elements. They constitute the key elements of the overall BALTEX scientific strategy and are summarized as follows:

1. Collection of *in situ* and remote sensing data

High-quality observations are fundamental in order to estimate energy and water cycles. Existing observational networks, most of them part of operational services will provide the bulk of the meteorological, hydrological and oceanographic data needed for initialization and validation of models and for diagnostic studies. The BALTEX region has a dense network of, in particular, meteorological and hydrological stations and, hence, is potentially a very suitable region for studies of energy and water cycles. The plan recognizes a series of actions required to improve the systematic exchange of data, such as high resolution observations of precipitation. Special efforts will be devoted to improving the usage of satellite and weather radar information and to establishing a comprehensive network of weather radar stations for the BALTEX region.

2. Re-analysis of existing data sets

Re-analysis projects will be carried out for specific intensive data periods using different coupled models. These projects will create consistent data sets for diagnostic budget studies which will support the quantitative determination of the energy and water cycle of the BALTEX region.

3. Data assimilation

Data assimilation techniques will be applied to obtain a synthesis of observed and model derived data. Advanced systems based on high resolution models are presently being developed by some of the meteorological services in the area. Data assimilation systems need to be developed especially for oceanographic and hydrological purposes, a challenging task for BALTEX.

4. Numerical experiments and coupled modelling

This element will be an important aspect of BALTEX research. Different models covering a wide range of scales and complexity will address specific scientific issues related to the BALTEX objectives.

5. Process studies including field experiments

Process-related experiments, both field and numerical, will provide results validating the different models. The central aims of the process studies will be to arrive at improved model parameterization schemes, and to verify algorithms applied to remote sensing data.

III. BALTEX Research Networks

Several research projects have been defined which form the backbone of the BALTEX programme elements. These projects cover the areas of data assimilation, modelling, field

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experiments and diagnostic studies. The BALTEX projects will cooperate and interact, providing mutually beneficial feedback. They will be linked together in the frame of seven research networks.

Three of the research networks are combined with data studies and modelling.

1. Full-scale studies of the energy and water cycle

The projects within this network will undertake comprehensive diagnostic calculation of the water and energy balance for the whole region. The development of high resolution coupled data-assimilation schemes and the evaluation of different models with respect to resolution and physical parameterization will be included here.

2. High-resolution process studies with the emphasis on hydrological modelling

The main thrust of the projects in this network will be the development and improvement of hydrological models. Existing physically-based and conceptual models are to be combined and further developed with the perspective of their coupling to high resolution atmospheric models. It is essential to establish hydrological data assimilation techniques for integrating remote sensing data with distributed hydrological models. Procedures for up- and downscaling of parameters and process equations will be worked out. Finally, a soil-vegetation-atmosphere transport model will be established and a coupling between high-resolution hydrological and atmospheric models will be developed and tested.

3. Coupled modelling of the Baltic Sea

This research activity includes basically oceanographic modelling, including ice models, and data assimilation. At present BALTEX is the only regional GEWEX study which includes a major marine research component. This network includes the assimilation of historical data in order to estimate transports through the Danish Straits. More precise knowledge on the net in- and outflow between the Baltic Sea and the World Ocean is regarded as a key to constraining and, hence, to improving the accuracy of precipitation-minus-evaporation estimates at the surface of the Baltic Sea.

The other research networks are essentially field experiments. They are referred to as networks because they will be composed of numerous contributions from various research groups contributing to different measurement aspects with different techniques and approaches.

4. Cloud / Precipitation / Air - Sea Interaction Field Experiment

The major objectives here are the investigation of the development of clouds and precipitation over the open sea, the validation of methods estimating evaporation at sea, and the intercomparison of different methods of measuring precipitation, such as ship-borne rain gauges, radar, and satellite remote sensing methods.

5. Cloud / Precipitation / Air - Land Surface Field Experiment

The major objectives of this experiment are to investigate the influence of topography and land types on cloud and precipitation development, to validate methods estimating evapotranspiration, to investigate the interactions between the atmosphere and the land surface, to develop and validate data assimilation techniques for the integration of remote sensing data and distributed hydrological data, and to evaluate the spatial variability of hydrological variables and processes and their importance for coupled atmospheric-hydrological models.

6. Atmosphere - Ice - Ocean Field Experiment

The major objectives include the investigation of the air-ice, air-sea, sea-ice interaction processes, the investigation of the ocean boundary layer beneath the ice, the investigation of the atmospheric boundary layer at the sea-ice margin, and the validation of ice models.

7. Baltic Sea Vertical Advection/Mixing Field Experiment

The major objectives include investigating the physical processes maintaining the stratification in the Baltic Sea, the vertical mixing processes which transport saline water upwards and fresh water downwards, and the diapycnal mixing below the seasonal pycnocline, as well as the understanding of the distribution of saline water entering the Baltic Sea through the Danish Straits.

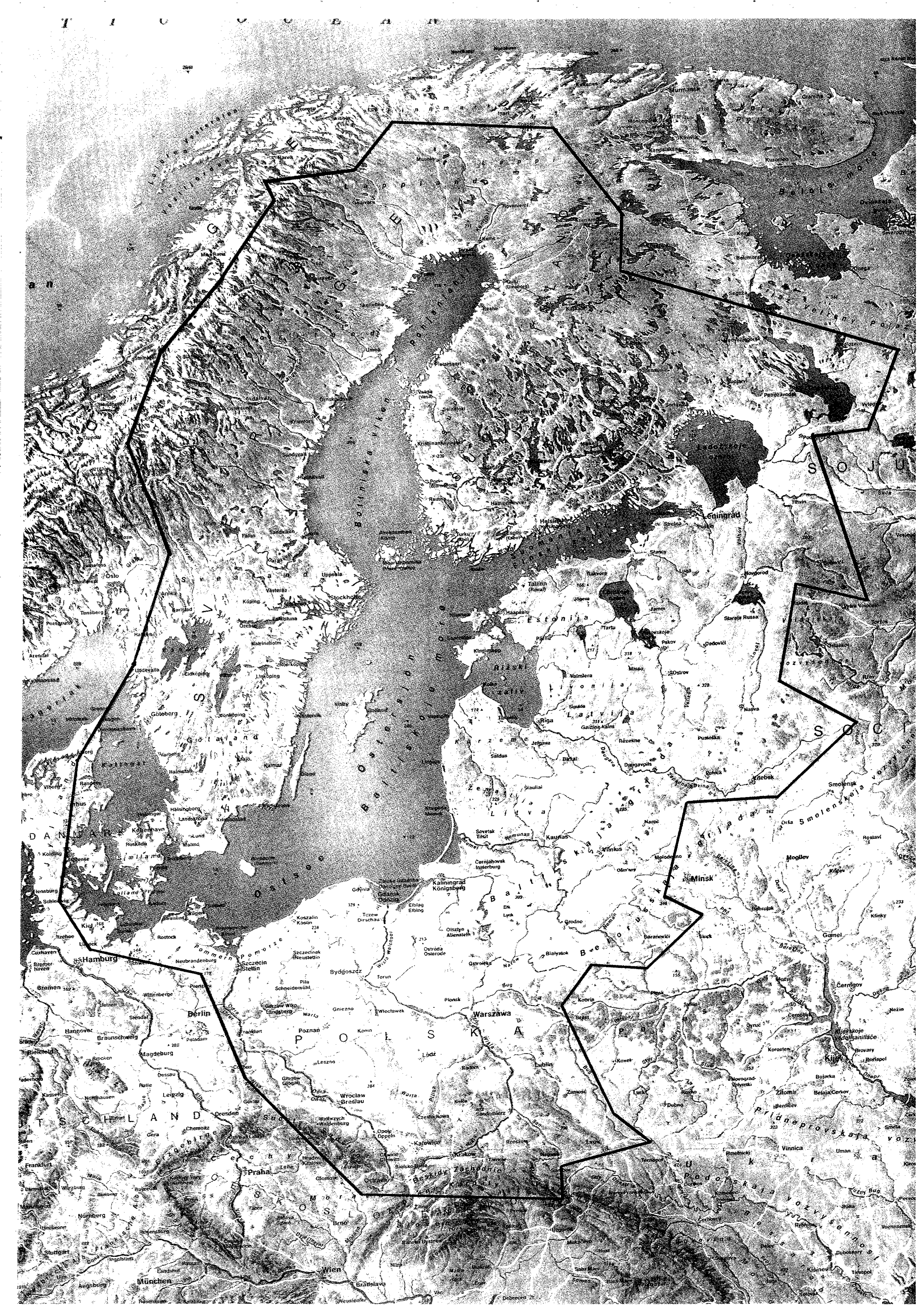
Because of the complexity of these field experiments the present initial version of the implementation plan merely outlines the basic design of these experiments. Detailed plans will be provided at a later date. The time schedule foresees implementation in 1997 though this may be subject to some delay. The major field experiments will nevertheless be preceded by pilot studies. A pilot study for the cloud/precipitation/air-sea interaction experiment is already planned for summer 1995 and will be carried out in the surrounding of a small island east of Gotland. The observational period of the BALTEX Pilot Study for Intensive Data Collection and Analysis of Precipitation (PIDCAP) is scheduled for August to October 1995. The objectives of PIDCAP include 1) the collection, analysis and intercomparison of measured and estimated precipitation from different data sources in order to identify and establish reliable standards for model validation, and 2) the validation of the output of different regional models against such precipitation data sets.

IV. International Co-operation

International co-operation is a prerequisite for the success of BALTEX. To date, operational and research organizations and institutions from 10 nations are participating and co-operating in this interdisciplinary research programme. Representatives of these nations constitute the main organizational bodies of BALTEX such as the Science Steering Group and the different working groups. As the practical requirements for meteorological, hydrological and oceanographic data vary, it has been decided to establish three BALTEX Data Centers which will be implemented at different national agencies. DWD in Offenbach, Germany, SMHI in Norrköping, Sweden, and FIMR in Helsinki, Finland have started to act as the BALTEX Data Centers for meteorology, hydrology and oceanography, respectively. Each center will generally act as a metacenter, where all essential information concerning the data (e.g. originator, formats, availability, accuracy) will be collected and distributed.

V. Time Table

BALTEX is planned to extend over a ten-year period. The build-up phase will last through 1996 and foresees the preparation of field experiments, the realization of pilot studies, the establishment and testing of models, and the preparation of research data sets. The major research phase of BALTEX is scheduled for 1997 lasting until at least 2001, and will include the main field experiments and model studies.



Murmansk
Leningrad
Minsk
Warszawa
Berlin
Hamburg
Praha
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München
Stockholm
Oslo
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Tallinn (Reval)
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POLSKA
DANMARK
D E U T S C H L A N D
S O J U
Estonija
Latvija
Litva
Rižskij zaliv
Ladožskoje ozero
Beloje more

1 BALTEX - THE BALTIC SEA EXPERIMENT

1.1 Introduction

Our ability to understand and predict weather, climate, and global climate change, depends critically on our capability to observe and model the processes governing the hydrological cycle and the energy cycle of the climate system. Water vapour is the dominating greenhouse gas in the atmosphere, and water, in the form of clouds, plays a major role in controlling the climate on Earth. Snow and ice on the ground change the surface albedo, and the availability of water in the ground affects the way in which heat and moisture enter the atmosphere. The supply of freshwater to the oceans is of major importance for the vertical circulation in the ocean and the associated vertical exchange of heat and salinity.

Because of the very high temporal and spatial variability, there is insufficient information about details of the hydrological cycle. The lack of empirical data leads to specific problems of how to incorporate and describe the hydrological processes in large-scale weather and climate models.

To address these issues and to reduce the uncertainties in our understanding of the hydrological and energy cycles, a special programme, GEWEX, the Global Energy and Water Cycle Experiment has been established within the World Climate Research Programme, WCRP.

The aim of GEWEX is to determine from observations the distribution of water and energy fluxes on a global scale and to compute estimates of these fluxes from predicted atmospheric properties. The Scientific Plan for GEWEX (WMO 1990) defines the following four scientific objectives:

- to determine the hydrological cycle and energy fluxes by means of global measurements of observable atmospheric and surface properties,
- to model the global hydrological cycle and its impacts in the atmosphere, the ocean, and on the land surface,
- to develop the ability to predict the variations of global and regional hydrological processes and water resources, and their response to environmental change,
- to foster the development of observation techniques, data management and assimilation systems suitable for operational application to long-range weather forecasts, hydrology and climate predictions.

The goals of GEWEX can be best met by studying the hydrological processes in different climate regions of the world. The Baltic Sea and its drainage is such a region, covering an area of 2.1×10^6 km^2, about 17 % of the European continent (Figure 1.1). The Baltic Sea itself, connected to the ocean via very narrow straits, occupies more than 0.4×10^6 km^2.

Figure 1.1, left page: The BALTEX region

This area has a very interesting meteorology and hydrology representing a dynamically-, highly-active region with considerable variance from synoptic to interannual time scales. The land area consists partly of a mixture of boreal forests and lakes in the north with an increasing amount of arable land towards the south. The total river discharge into the Baltic Sea is well known and amounts to some 470 km^3/year. The net discharge into the World Ocean is only approximately known and an accurate value of this net flow needs to be determined.

1.2 The BALTEX Scientific Objectives

A scientific plan for an experiment to study the hydrological and energy exchange processes for the Baltic Sea and its drainage region, BALTEX, the Baltic Sea Experiment, has been developed (Raschke 1994). The principle scientific objectives of BALTEX are summarized as follows:

- to explore and model the various mechanisms determining the space and time variability of energy and water budgets of the BALTEX region and this region's interactions with surrounding regions,

- to relate these mechanisms to the large-scale circulation systems in the atmosphere and oceans over the globe,

- to develop transportable methodologies in order to contribute to basic needs of climate, climate impact, and environmental research.

The BALTEX region includes the entire water drainage basin of the Baltic Sea. BALTEX will primarily be a "cage experiment" with the objective to assess the total flux divergence of heat, water and momentum. The basic programme elements will be:

- Collection of *in situ* and remote sensing data
- Re-analysis of existing data sets
- Data assimilation
- Numerical experiments and coupled modelling
- Process studies including field experiments.

An important outcome of this research is the development of comprehensive, coupled regional models capable of realistically modelling the water and energy cycles of the BALTEX region. These models will include processes in the atmosphere, in the Baltic Sea and at the associated land areas, which will include river runoff as well as the feedback effects between these domains (Figure 1.2). The regional models will be coupled to a large-scale hemispheric or global model providing the time-varying, horizontal boundary conditions for the regional model. The river runoff into the Baltic Sea, as well as the net water exchange with the World Ocean through the Danish Straits will have to be very accurately measured in order to obtain an independent estimate of the fresh water balance over the Baltic Sea itself. For the Baltic Sea it is, at present, not known whether precipitation minus evaporation, even on an annual basis, is negative or positive.

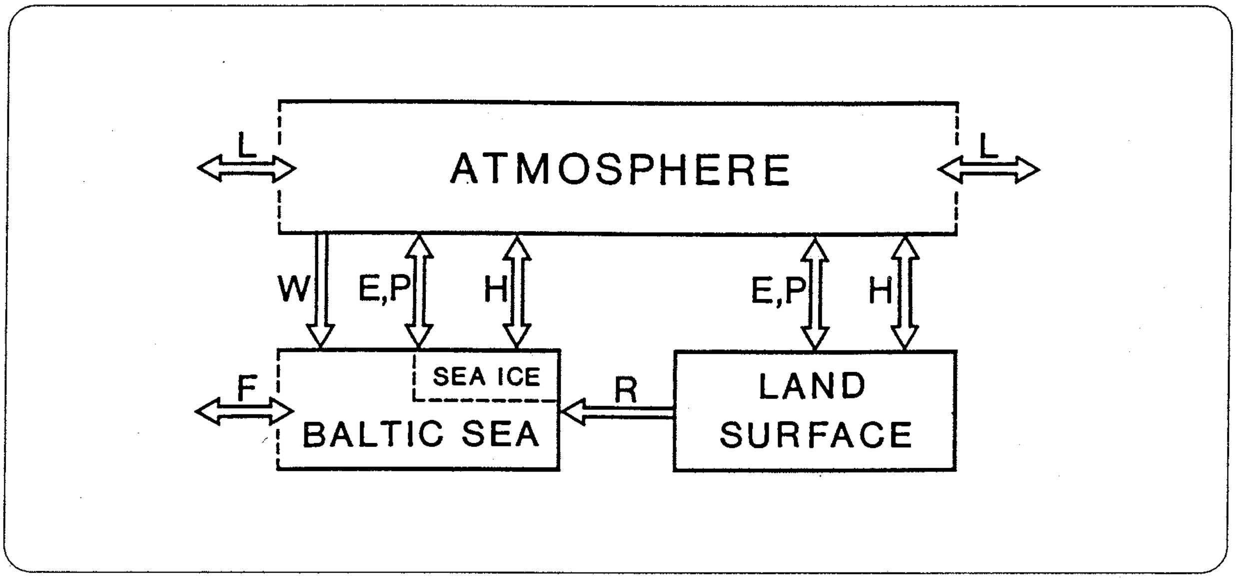


Figure 1.2 Principal coupling mechanisms between atmosphere, land surface and Baltic Sea. Arrows denote direction of influence.

E, P Evaporation and Precipitation over land and sea
F Inflow and outflow through the Danish Straits
H Heat and energy flux at the air-sea and air-land interfaces, including radiation
L Lateral exchange with the atmosphere outside the BALTEX region
R River runoff
W Wind stress at the sea surface

1.3 Contents of the BALTEX Initial Implementation Plan

The BALTEX initial implementation plan describes the scientific and technical programme needed to meet the objectives of BALTEX. Section 2 summarizes the deliverables of BALTEX, in particular the impact that the execution of the programme will have on climate and climate change research, and the consequences which the programme will have for the development of more reliable weather prediction systems. The consequences which the programme will have for environmental modelling in the Baltic Sea, by providing a comprehensive dynamical physical modelling framework, are stressed.

Section 3 outlines a modelling and observational strategy for BALTEX. The work will be concerned with modelling and observational studies for a series of different scales, addressing process-related investigations and field experiments, regional modelling and data-assimilation, numerical experimentation and the re-analysis of existing data sets.

Sections 4 and 5 analyze the observational requirements for BALTEX. In several aspects the land surface region has good atmospheric data coverage, with, for example, some 40 radiosonde stations within the area. Problems, on the other hand, are related to the coverage of radar data around the Baltic Sea, where additional stations will be needed in the eastern and the southeastern part of the area. Oceanographic data, as well as atmospheric data from the

Baltic Sea are sparse, and all efforts should be made to enhance the observation system and provide a prompt exchange of these data. Comprehensive records of hydrological data exist in the BALTEX region, but unfortunately there is no routine, systematic exchange of this regional data.

The importance of data assimilation systems for regional area coupled models, along the same lines as those which are available for atmospheric models, is highlighted in section 6. Advanced systems based on high resolution models are presently being developed by some of the meteorological services in the area.

Modelling research, as outlined in section 7, will be a major aspect of BALTEX, ranging from the use of comprehensive models to models addressing specific scientific issues. Of particular importance for BALTEX will be the development of a very high resolution (10 - 20 km) coupled atmosphere/ocean/land surface forecasting system.

The initial implementation plan identifies a number of process-related experiments, the objectives of which are to provide results validating the different models, leading to improved model parameterization schemes, and to verify algorithms applied to satellite data. These experiments for BALTEX are presented in section 8. However, it should be stressed that the plan at this stage is only to provide a preliminary discussion, and it is foreseen that a detailed expert planning must be undertaken before an implementation of the field experiments can be considered.

Section 9 summarizes BALTEX research projects in the areas of data assimilation, modelling activities and process studies as outlined in sections 6, 7 and 8, and defines research networks as an overall scientific coordination of BALTEX research.

Section 10 contains a proposed data policy and a data management plan. It is suggested that BALTEX will foster the highest possible free exchange of observations, model codes and results of model experiments and calculations. This will be conditional on a strict scientific use of the data and a feedback of scientific information to the original source of the information. Specific data centers will be established, working in close co-operation with the BALTEX scientific community.

Sections 11 and 12, finally, present the interface to other relevant international research programmes and the BALTEX organizational structure, respectively.

1.4 Time Plan for BALTEX, 1994 - onwards

BALTEX is a programme which is planned to exist for a period of approximately ten years. It will include a build-up phase through 1996 and an observational phase including field experiments starting in 1997. The final years will be concerned with scientific evaluation of the experiments.

(i) Build-up Phase 1994 - 1996

This phase will concentrate on the development of model data assimilation systems and the commencement of the numerical experimentation programme. The necessary data archives will have to be established as well as the data management infrastructure. Of particular importance will be the preparation of assimilated data sets for two selected periods, the winter of 1986/87 and for the period from September 1992 until September 1993. One reason for this choice is the occurrence of salt water inflow event into the Baltic Sea during winter 1992/93. On the other hand comparison of the winters 1986/87 and 1992/93 is of major interest because of the considerable difference in the extent of sea ice coverage.

The BALTEX Pilot Study for Intensive Data Collection and Analysis of Precipitation (PIDCAP) will start with its first observation period during August to October 1995 (section 8). A special data assimilation project for the BALTEX region is planned at DWD for January 1996 onwards.

(ii) Observational Phase 1997 - 2001

During this phase of BALTEX the central field experiments and studies will be conducted. They will be supported by high resolution non-hydrostatic meso-scale models as well as comprehensive limited area models designed to address the major scientific objectives of BALTEX. This phase will also see the development and preparation of transportable tools for application in other characteristic areas, for example the other GEWEX regions (see section 11.1).

2 WHAT WILL BALTEX ACHIEVE ?

An improved understanding of the hydrological and energy cycle for the BALTEX region will not only be of considerable benefit for the region itself but also for weather, climate, water resources and oceanographic modelling in general and will create a sound scientific basis for environmental investigations. The BALTEX programme will provide an enhanced scientific knowledge in these areas, leading to more accurate numerical models for the prediction of climate and weather. Of particular interest will be the development of coupled atmosphere/ocean/land surface models at high resolution, drawing on the joint competence of meteorological, hydrological and oceanographic scientists. The scientific outcome of BALTEX will be transferable to other regions, thus benefitting the prediction of climate and weather in other parts of the globe as well as providing support for many other research programmes within WCRP and IGBP.

2.1 Prediction of Weather-related Events

A central output from the BALTEX programme are the improved atmospheric models developed through couplings with hydrological and oceanographic models. Such models will improve the accuracy of operational weather predictions in the BALTEX region. This will be of vital importance for various sectors of the society, which regularly make use of weather predictions.

The Baltic Sea plays a central role in trade and shipping. Shipping requires more reliable forecasts particularly in respect to adverse weather conditions, the state of the sea and the sea ice situation (Figure 2.1). Icing on ships is a serious problem particularly in stormy conditions at low temperatures.

Severe storm surges do occur particularly at the inner parts of bays. This is especially serious in rapidly moving systems when the water level can change critically in a few hours. Many cases causing casualties have been reported, also in recent years.

Floods caused by extreme rainfall and melting snow occur often in the BALTEX region and cause major damage (Figure 2.2). The accuracy of the present forecasting systems is, in general, limited by weather forecasting accuracy.

The Baltic Sea is also playing an increasingly important role for leisure activities, presently mainly in the coastal regions, but will gradually increase over larger regions as sailing with more advanced boats becomes more common. Accidents due to the sudden development of meso-scale weather systems causing loss of life and property are not unusual.

In some Baltic countries the agricultural sector is today on a routine basis making use of weather predictions as input to agricultural management models for planning irrigation, fertilization and other cultivational practises.

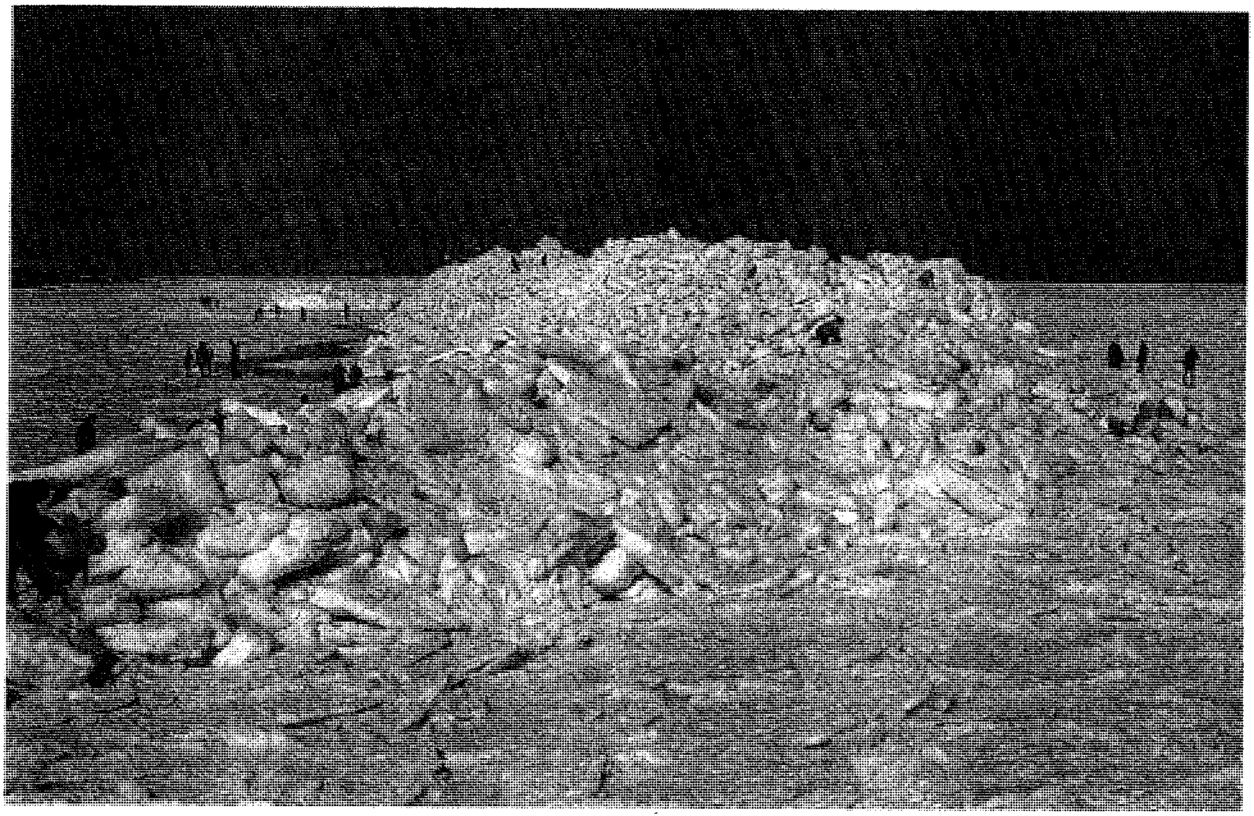


Figure 2.1 In February 1986 nearly all of the Baltic Sea, including the southern and western parts, was ice-covered. During a period with strong easterly wind the sea ice was pressed against the coast in northern Germany leading to the formation of huge ice brash barriers in some areas. The photo was taken near Hohwacht, Schleswig-Holstein, showing a view along one of these barriers. The coastline is about 200 m to the left, the overall length of this particular barrier amounted to nearly 1 km.
(Photo by Hans-Jörg Isemer)

2.2 Climate Monitoring and Impact

The BALTEX programme will provide increased understanding of energy and water fluxes over a large and climatologically important high latitude region of the Northern Hemisphere. In particular the interaction with a huge inland sea and surrounding land areas will be explored, including intense meso-scale features. The present knowledge gap may be illustrated by the fact that there is no solid scientific basis for assessing whether the net precipitation (precipitation minus evaporation) over the Baltic Sea is positive or negative.

Figure 2.2 Flooding in river Ångermanälven in northern Sweden in August 1993 caused by heavy rainfall when the reservoirs of the hydropower system were full. (Photo by Jörgen Hildebrandt, Pressens Bild AB, Sweden)

3 OBSERVATIONAL AND MODELLING STRATEGY

3.1 Key Elements of the Overall Scientific Strategy

The BALTEX research strategy will focus on the following themes which are in accordance with the BALTEX scientific objectives summarized in section 1.2:

- to explore and model the various mechanisms determining the space and time variability of the BALTEX region energy and water budgets and this region's interactions with surrounding regions,
- to relate these mechanisms to the large-scale circulation systems of the atmosphere and oceans over globally,
- to develop transportable methodologies in order to contribute to the basic needs of climate, climate impact, and environmental research.

Process studies are essential in order to fill in the gaps of present knowledge on the processes governing energy and water exchange. The understanding of, for example, precipitation and evaporation over land and sea, energy fluxes at horizontal inhomogeneities such as different land types, coasts or sea ice margins, and the formation of vertical stratification due to river runoff and inflows to the Baltic Sea needs to be improved. Well designed process-oriented field experiments will address these questions.

Observations are fundamental for all estimates of energy and water cycles and, compared to other regions, the BALTEX region is well covered by data. The bulk of the observations will be obtained from existing networks of meteorological, hydrological and oceanographical services. These standard observational data will be collected and archived, quasi-permanently, for the BALTEX period.

Non-standard observational data sets will be added to the standard data. Extended monitoring data of oceanographic parameters will be collected during the BALTEX period. Historical data sets of importance will be identified and used for climatological background studies. One important component of the data collection is the availability of remote sensing information in the area, particularly from radars and satellites.

Another component is data from previous and ongoing large scale projects in the BALTEX region. Three different data centres will be responsible for the archiving and supply of strategic meteorological, hydrological and oceanographical data, respectively.

The complexity of the processes studied and the differences in temporal and spatial distribution of data makes it difficult to study energy and water cycles by utilization of observed data only. Instead, data assimilation techniques will be applied to obtain a synthesis of observed and model-derived data.

Modelling, and particularly coupled modelling, is the means by which the knowledge about physical processes will be synthesized and hypothesis tested. This work will be based on process studies and data collection activities. Optimal use will be made of previous modelling experience from countries in the area. The examination of model outputs by independent groups is strongly encouraged. Observational studies and numerical experiments will improve the understanding of the energy and water cycles.

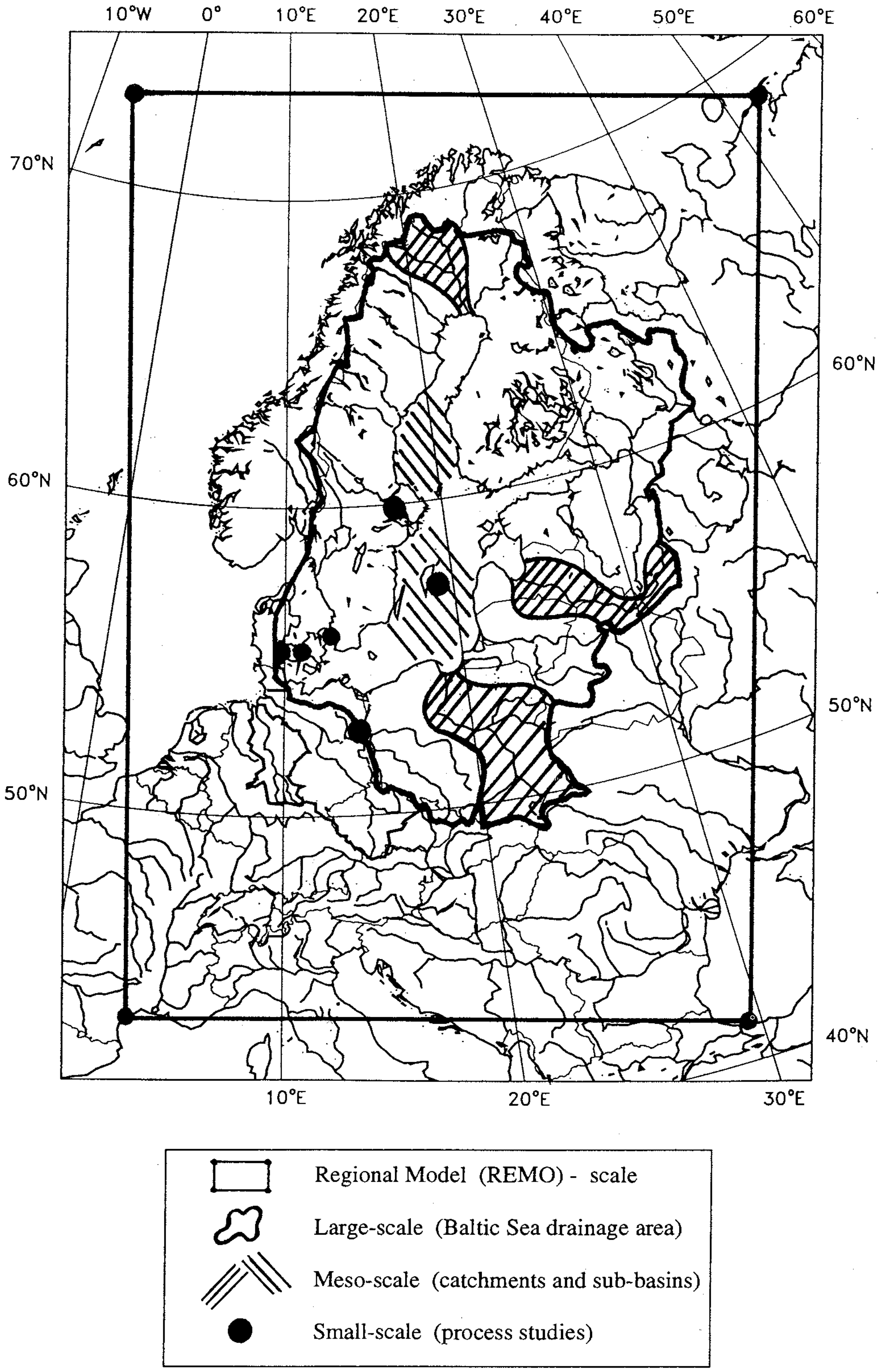


Figure 3 Sketch of principle research scales and areas of BALTEX, as referred to in the text. Note that the marked meso- and small-scale areas represent a minimum requirement for BALTEX. Other river catchments or key areas will also be investigated as part of the BALTEX programme.

Re-analysis of available data for a standard period and the use of coupled models for generating gridded data will create consistent data sets for diagnostic budget studies of the water and energy cycles. These data sets will be validated thoroughly using independent measurements from, for example, satellite sensors and field experiments.

Finally, the BALTEX programme will explore the potential synergetic effects by the integration of state of the art of interdisciplinary approaches in meteorological, hydrological and oceanographical sciences.

3.2 Research Scales and Areas

The three principle horizontal research scales within BALTEX are:

- The BALTEX region, i.e. the Baltic Sea and its entire drainage area. In the following this region will also be referred to as the "large scale". For computational reasons the associated regional atmospheric model is extended over a larger area, which will be denoted as the REMO scale.
- The medium size catchments and sea basins, which will be referred to as the "meso-scale".
- Small research areas for process studies and model development either on the land surface or in parts of the Baltic Sea. Such areas are identified as the "small scale" in the following.

The extent and locations of different scales and research areas are shown in Figure 3. Note, that reference to e.g. specific river catchments in Figure 3 is exemplary and does not exclude investigations of other meso-scale or small-scale areas.

3.3 Atmosphere - Land Surface Coupling

The strategy for developing, validating and applying the atmosphere - land surface coupling is outlined in Table 3.1.

The aim of the small-scale process studies is to improve understanding of the processes governing the exchange of water and energy between the atmosphere and the land surface. This will also include a study of the importance of the horizontal inhomogeneities of land types (lakes, crop types, snow/ice, coastline etc). At the meso-scale the programme will focus on modelling studies, whereas the research results obtained at the small scale will be incorporated, adapted as required and validated. On the basis of the results from the catchment studies, hydrological models will be established for the entire BALTEX region and coupled to atmospheric models. The aim of the modelling at the regional scale, which corresponds to the atmospheric model area, is to ensure that adequate boundary conditions are available to the BALTEX region, within the atmospheric model. It is envisaged that little emphasis will be required for the corresponding hydrological modelling of areas outside the BALTEX region.

Table 3.1 Scales and science strategy for atmosphere - land surface coupling

Scale	Size (km)	Spatial resolution in modelling (km)	Data base	Research focus
Large scale	Atmosphere: 10^3 - 10^4 Hydrology: 10^3	Atmosphere: 10 - 30 Hydrology: 1 - 5	Standard observational network	• Coupled atmospherie - land surface models • Prediction of regional climate impacts
Meso-scale	10^1 - 10^3	Atmosphere: 2 - 10 Hydrology: 0 .1 - 0. 5	All available data for at least the following study areas: • Torneälven catchment • Daugava catchment • Vistula catchment	• Data assimilation of remote sensing data • Scaling of model process descriptions and parameters • Validation of coupled models
Small scale	≤ 10	Atmosphere: 2 - 5 Hydrology: 0.01 - 0.05	Small hydrological research catchments with special field measurement programmes, at e.g.: • NOPEX • Lindenberg	• Process submodels • Atmosphere - land surface interaction • Process studies

Table 3.2 Scales and science strategy for atmosphere-ocean coupling

Scale	Size (km)	Spatial resolution in modelling (km)	Data base	Research focus
Large scale	10^3 - 10^4	Atmosphere: 10 - 30 Ocean: 5 - 30	Standard atmospheric and hydrographic data, runoff data and data from process studies, data from monitoring activities	• Data assimilation • Coupled atmosphere - ocean models • Ocean modelling including sea ice
Meso-scale	10^1 - 10^3	Atmosphere: 10 - 30 Ocean: 1 - 10	Data from process studies and runoff data	• Data assimilation • Process submodels
Small scale	≤10	Atmosphere: 2 - 10 Ocean: 0.1 - 1	Data from process studies and inflow data	• Inflow dynamics and - mixing • Model nesting • Process submodels

3.4 Atmosphere - Ocean Coupling

The strategy for developing, validating and applying the atmosphere-ocean coupling is outlined in Table 3.2.

The small-scale studies aim to improve the understanding of the inflows to the Baltic Sea and the mixing of the inflowing water in the entrance area. This water intrudes as a dense bottom current into the Baltic Sea. At meso-scale the programme will focus on fronts, eddy structure and the ice-ocean boundary. The large-scale studies will develop coupled atmosphere/ocean models, which includes a sea ice model. These models will be used for energy and water cycle studies for the whole region and used for the simulation and understanding of the regional climate.

4 *IN SITU* MEASUREMENTS

This section includes parameters which are directly measured in the field. Remote sensing data are the subject of section 5.

Different types of *in situ* data sets are relevant for BALTEX. Firstly, data used for initialization of atmospheric, hydrological and oceanographic models are to a large extent provided by existing routinely operating networks. Atmospheric models particularly, require these data from extended parts of Europe and nearby ocean areas. A part of these standard observational data is available in real-time mode while others are transmitted only in delayed mode. Secondly, data sets for validation of models are mainly required from the Baltic Sea catchment area or parts of it. Most of these data will also be provided by existing networks. A third purpose are diagnostic studies. Fourthly, BALTEX field experiments and observational periods will provide enhanced data sets with specific resolution in time and space. They are needed especially for process studies, model development and numerical experiments.

4.1 Meteorological Data

4.1.1 INVENTORY

The catchment area of the Baltic Sea is a densely observed region of the globe. Part of the standard meteorological surface and upper-air observations which are taken at the operational stations, is routinely disseminated through the global telecommunication system (GTS).

Meteorological surface-land observations are provided by both synoptic and climate stations. The first category (Figure 4.1) includes observations of common atmospheric parameters such as air temperature, windspeed and direction, humidity, cloud cover, weather condition, precipitation and air pressure. In general, synoptic stations transmit data on a three-hourly basis, mostly in real-time mode. Climate stations provide a reduced set of parameters at a lower frequency. These data are, to a greater degree, only available in delayed mode. However, the climate station network is much denser compared to the synoptic surface station network.

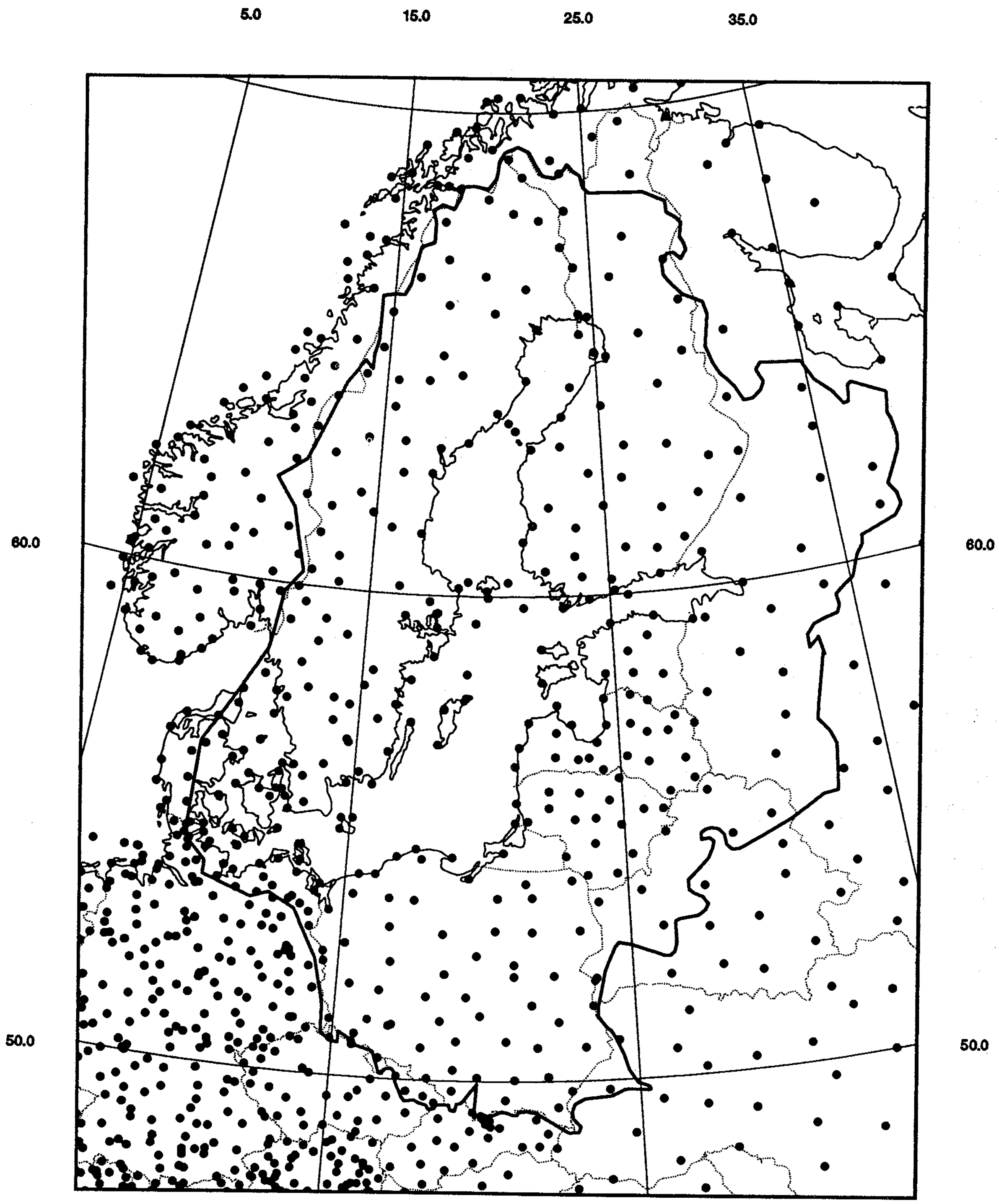


Figure 4.1 Locations of meteorological surface stations in, and adjacent to, the BALTEX region. Only part of the land stations disseminate meteorological observations in real-time in order to initialize operational weather forecast models. The map gives a typical example showing those stations which made available meteorological reports via GTS to the routine forecast service of DWD in a four-days period in February 1995 (by courtesy of DWD, Offenbach, Germany).

Additionally, there exists a network of precipitation stations most of which measure daily precipitation. In general, the number of these stations is much larger compared to the number of synoptic stations, in some countries by a factor of up to 20.

In addition to the manned stations, an increasing number of automated stations is transmitting meteorological data. Meteorological reports from voluntary observing ships (VOS) and anchored automated stations in the Baltic Sea are routinely available. The VOS reports can be used to estimate evaporation and the heat budget at the surface of the Baltic Sea. Historical records of VOS observations from the Baltic Sea, which are especially prepared for scientific research (e.g. COADS), are now available for periods longer than a century.

Different networks with a much lower density of non-standard meteorological stations exist, measuring e.g. the surface radiation budget and the soil water content, or observing different characteristics of vegetation.

Upper-air *in situ* data are mostly available from the aerological station network. The station density of this network is much less than that of the surface observations, however, it is one of the most dense upper-air station networks when compared to other regions in the world. More than 40 aerological stations are routinely operating in the BALTEX region (Figure 4.2). Since nearly all radiosonde observations are disseminated through GTS they are available in real time. Further meteorological data, especially concerning upper troposphere winds and temperatures are obtained from commercial aircrafts which transmit automated reports (AIREPS) in real time mode. AIREPS are now being used to initialize forecast models on a routine basis.

Approximately 100 years of standard meteorological surface data are available from this network providing unique test material for climate models. Precipitation data have been collected for more than 150 years at some stations. Radiosonde data have been available since about World War II, however, homogeneity problems exist due to different sonde types, which create problems for climate investigations.

4.1.2 REQUIREMENTS

The spatial coverage of the BALTEX region, especially of the standard upper-air *in situ* data, is substantial; nevertheless, a further increase in the spatial coverage would be most beneficial. A minimum requirement is that the density of existing networks will not be reduced during the BALTEX research period. Any change of observational methods should be carefully documented and all efforts should be undertaken to guarantee homogeneity (with respect to measurement or analysis technique).

With regard to other networks, improvements will be necessary for BALTEX. Firstly, the availability of precipitation, radiation, and evapotranspiration data from existing networks should be enhanced.

These data are primarily needed for model validation and verification. In addition to the existing station network operated by the national services, a number of stations at universities are operating in connection with different research programmes. They measure e.g. the surface-radiation balance and turbulent fluxes to a high standard. It is necessary to identify these stations and platforms and to include the relevant data into the BALTEX data set.

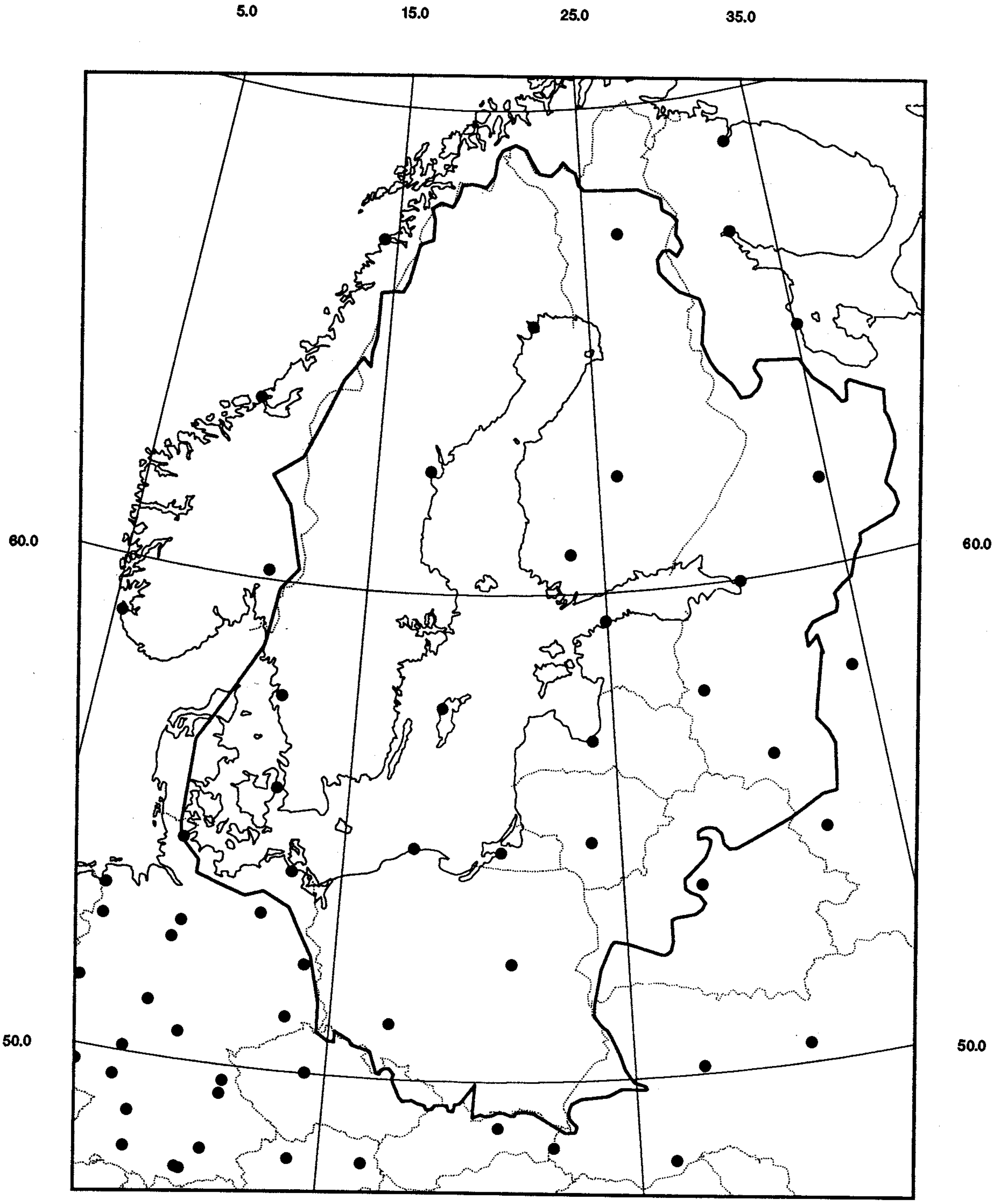


Figure 4.2 Locations of upper-air radiosonde stations in, and adjacent to, the BALTEX region. The map gives a typical example showing those stations which made available upper-air meteorological reports via GTS to the routine forecast service of DWD in a four-days period in February 1995 (by courtesy of DWD, Offenbach, Germany).

Secondly, there is a major gap in the *in situ* meteorological observations from the Baltic Sea. The installation of automatic measurement devices, especially for precipitation and vertical fluxes, on regularly operating ferry boats (Figure 4.3), other voluntary observing ships, or automatically operating buoys, is planned.

Thirdly, with respect to the important problem of subgrid-scale parameterization of energy and water fluxes, BALTEX will carry out special field experiments and, thus, make an increased number of meteorological *in situ* observations available with high spatial and temporal resolution. This includes land-based observations as well as air-borne measurements from aircraft of e.g. vertical boundary layer fluxes over heterogeneous terrain and over the Baltic Sea.

4.2 Oceanographic Data

4.2.1 INVENTORY

Our knowledge about the oceanographic conditions in the Baltic Sea relies to a large extent on measurements from research vessels which have monitored this sea for many years (e.g. the Baltic Monitoring Programme of HELCOM, see Figure 4.4). These data are archived at national centers and at HELCOM. From extensive measurements of water temperature, salinity and chemical parameters such as oxygen, we have a reasonable understanding of the thermohaline circulation of the Baltic Sea. However, few attempts have been made to use this large amount of data for modelling purposes, or to relate the measured density field to circulation, or to calculate monthly mean properties.

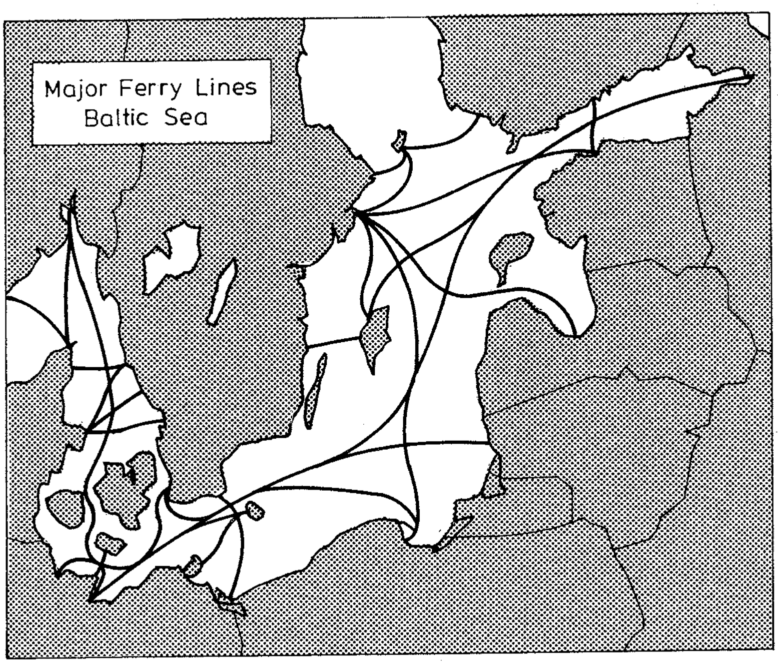


Figure 4.3 Major ferry lines in the central, southern and western Baltic Sea.

Accurate measurements of the net outflow through the Danish Straits is a central requirement in order to determine the overall fresh water budget of the Baltic Sea. Denmark started continuous current, temperature and salinity measurements in the Great Belt in 1987 and in the Øresund in 1992 (Figure 4.5). Using these data the net transports through the straits can be estimated with a high temporal resolution. At present these data are stored at the Danish Hydraulic Institute (DHI) and are made available for scientific research upon request.

Real-time delivery of oceanographic data and data products from the Baltic Sea consists of basic parameters, such as water level, sea surface temperature, and ice conditions from moored telemetering stations or automatically collected and transmitted data. For the time being, real-time recording and telemetry on the eastern coastline of the Baltic Sea are not complete. Sea surface temperature (SST) is recorded in real-time at some coastal stations, usually close to or at the lighthouses, on ferries and on some voluntary observing ships. Data collection and storage are mostly nationally organized. The network is quite sparse, but it is important when considering e.g. the calibration of satellite infrared information. SST maps are available twice-weekly, all year around. Research vessels operating in the Baltic Sea transmit on their routes, BATHY and TESAC data through GTS to coastal stations. Unfortunately, the number of these messages has declined during recent years. Nevertheless, national data centers obtain part of these data on an operational basis.

The Finnish Institute of Marine Research (FIMR) operates real-time collection of temperature and salinity on three ferries running regularly between Helsinki and Travemünde, Helsinki and St. Petersburg and between Vaasa and Umeå.

National ice services (for example at DMI, FIMR, SMHI, BSH) collect data on ice conditions and produce daily both coded ice information and faximile maps on ice conditions for customers around the Baltic Sea. These activities cover the entire ice season.

There are a number of long historical records (about 100 years), in existence concerning temperature and salinity in the Baltic Sea. The world's longest continued series of sea level observations is from Stockholm which began in 1774 (Ekman 1988). Information on ice coverage in the Baltic Sea extends back to the year 1721, port statistics for some harbours even further. Similarly, data on ice in rivers and lakes have been collected systematically for more than 100 years.

4.2.2 REQUIREMENTS

One of the key requirements for BALTEX is the continued measurement of currents, temperature and salinity in the Danish Straits, including the Little Belt. All efforts should be undertaken to keep the existing measurement facilities and data management structures operational. Additionally, continuous hydrographical point measurements with high vertical resolution are necessary both at the sills (3 to 4 stations) and in the Arkona Basin (1 station) to permanently monitor the water transports in the western Baltic Sea. A monitoring programme for the Baltic Sea circulation and for the ice thickness evolution should be established for the major BALTEX research period. Monthly values of fresh water inflow from all river systems in the Baltic Sea area are necessary as model input. The latter data set together with the net inflow through the straits will provide an overall constraint for the difference between evaporation and precipitation and hence for the whole water cycle of the Baltic Sea. Monitoring activities will have to be extended especially in the western part of the Baltic Sea. The number of hydrographic sections to be performed during special enhanced obser-

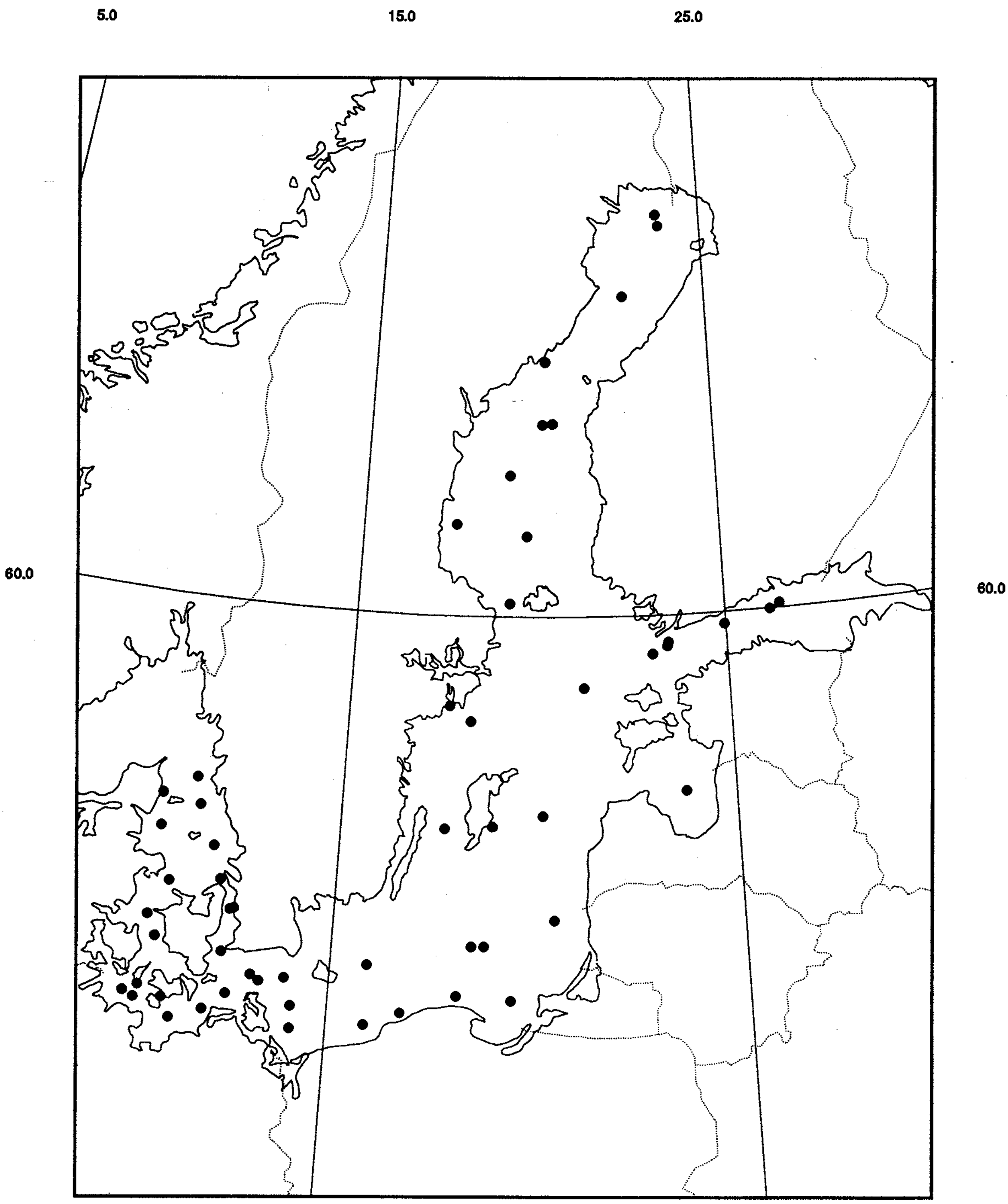


Figure 4.4 Sampling stations of the Baltic Monitoring Programme (BMP) of HELCOM in the Baltic Sea (see HELCOM, 1988, for detailed information). National shallow water stations for sampling macrozoobenthos are also included in the map because a complete hydrographic series should be taken at these stations. Note that additional national monitoring stations in the Baltic Sea exist, part of which are less regularly occupied. Station positions were obtained by courtesy of the HELCOM Secretariat, Helsinki, Finland.

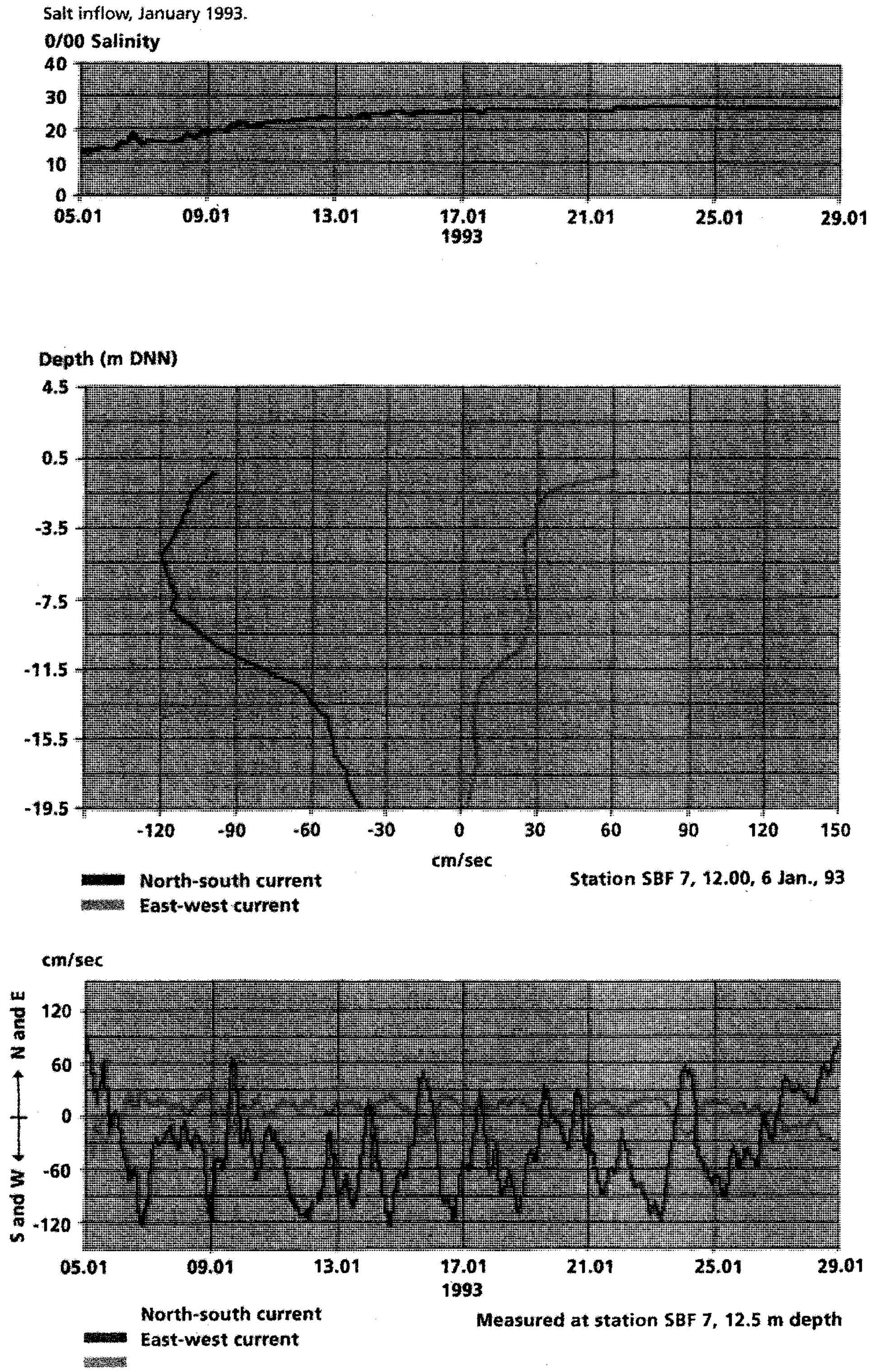


Figure 4.5 The salt water inflow event to the Baltic Sea in January 1993 as measured in the Great Belt near the small island of Sprogø. Top: Increase of surface salinity. Middle: Vertical profile of horizontal current components on January 6, 12 MET. Bottom: Timeseries of the north and east component of the current. Note the high variability of the current on the daily time scale which is superimposed on the strong mean southward flow into the Baltic Sea (by courtesy of Storebælt AS Copenhagen, Denmark).

vational field study periods needs to be increased. Further requirements of oceanographic *in situ* data include sea level data from all existing coastal and island stations (around the Baltic Sea and additionally from stations in the Skagerrak and the North Sea), SST, and information on ice coverage and thickness. During the special observation periods, ice maps from the routine services will be needed on a daily basis.

4.3 Hydrological Data

4.3.1 INVENTORY

The bulk of hydrological *in situ* data includes observations of river runoff, lake storage, snow, ground water, soil moisture and evapotranspiration. River runoff data in particular are obtained from station networks operated by national hydrological services. These services are organized differently in the countries surrounding the Baltic Sea. Hydrometeorological services exist in the Baltic states, Sweden, Russia, Belarus and Poland while hydrological and meteorological services are separated in the other countries. On a national level, various services store different components of the hydrological data sets. This is also the case for river runoff data, which have to be obtained from a number of different sources. The number of runoff stations is of order of one thousand, though only few of these, have real-time data transmission.

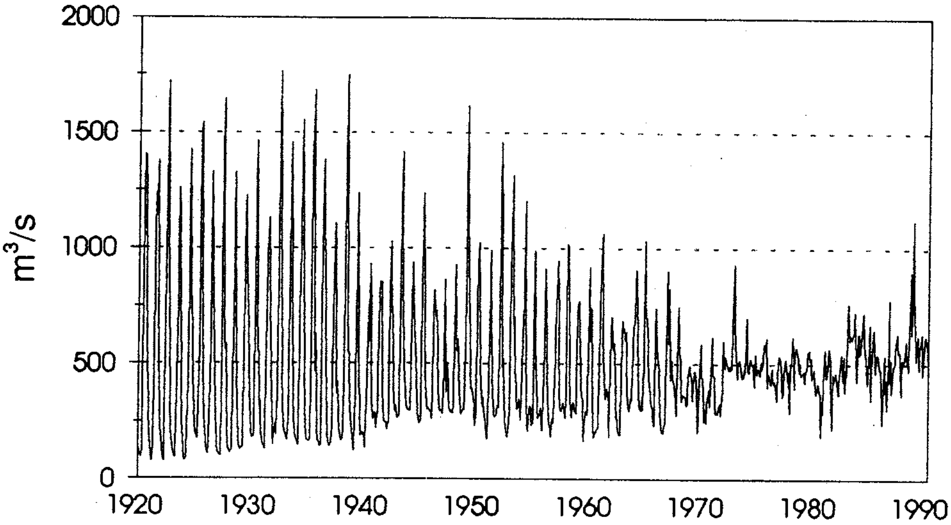
Hydrological data, other than runoff data, are available to a varying degree, depending on the procedures of the different national hydrological, meteorological and hydrometeorological services. Special national networks, however, with a low density of agro-meteorological stations report water content in different soil layers. Meteorological synoptic-station reports include soil temperatures at different levels, these are partly available in real-time transmission. Evapotranspiration and potential evaporation data are, in general, not available through routinely operating networks. Snow observations are made as depth readings at a number of meteorological stations in some of the countries and are often available in real time. In some areas (for example in Finland) extensive snow-course programmes are carried out and long records of the snow water equivalent exist, although observations are not available in real time. Observations of ground water levels are also available in the area but have to be obtained from different organizations.

4.3.2 REQUIREMENTS

A homogeneous data set of daily runoff data is required at least for enhanced observational and modelling periods. For some test catchments a more or less complete station coverage is required while for others data from a few key stations may be sufficient. Detailed hydrological modelling efforts are planned e.g. for the catchment areas of the Vistula, Daugava and Torneälv Rivers. A BALTEX-related German project is focussed on the Weser and Elbe Rivers.

Daily values of air temperature and precipitation, and monthly values of potential evaporation are needed as input to hydrological models. Also, physio-geographic information on e.g. topography, soil type and vegetation coverage is a prerequisite. The presently available resolution of these data sets might not be sufficient for the modelling of small sub-basins, in particular.

Some historical data sets from the BALTEX region are available which are suitable for studies related to interannual and inderdecadal variability. River runoff records of the region are of the longest and most reliable in the world. Monthly values exist which span more than a century at some stations. Daily runoff values for some major rivers are available as far back as the year 1848.



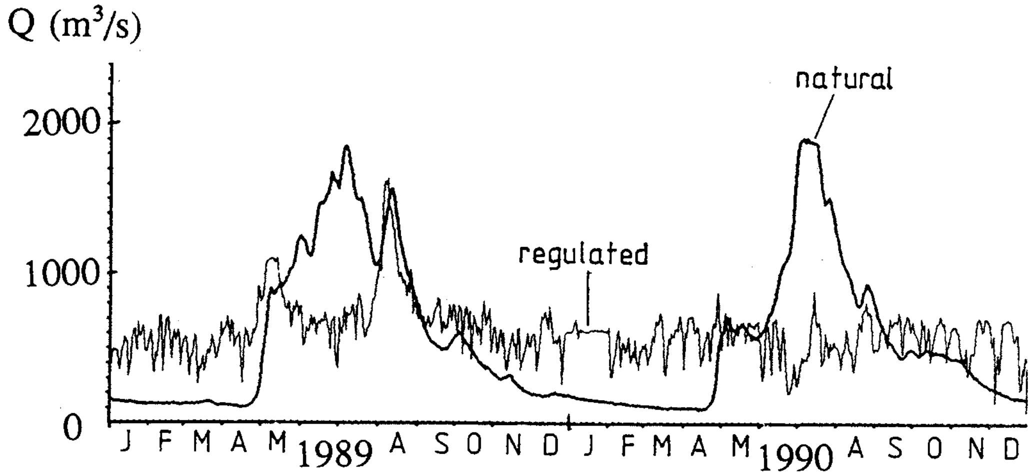


Figure 4.6 Effect of hydropower development in the river Luleälven in northern Sweden. Top: Monthly runoff record for the period 1921 - 1990. Bottom: Comparison of the daily values of the regulated river flow versus the reconstructed natural flow for the years 1989 and 1990 (from Bergström and Carlsson 1993).

A data base of the total river runoff into the Baltic Sea, based on monthly runoff data from some 200 stations, has been established at SMHI (Bergström and Carlsson 1993). At present this data base covers the years 1950 - 1990 but will be updated to cover the whole BALTEX research period.

A number of rivers are strongly regulated for hydropower production (particularly in Sweden); this leads to a significant deviation of the regulated river runoff when compared to the natural cycle (Figure 4.6). Detailed information on the regulating procedures is required from the companies concerned, as are the area discharge relationships for some of the major lakes.

Almost all of the data are station data. At present the establishment of gridded hydrological data sets is a research requirement in hydrology and is not routinely practised. In some of the BALTEX countries, gridded data on runoff, snow, soil moisture and ground water are available from special research projects or institutes upon request. It will be most valuable to transfer these techniques to all countries in the BALTEX region in order to obtain homogeneous hydrological information with sufficient area coverage, in real time.

5 REMOTE SENSING DATA FROM SATELLITES AND RADAR

5.1 General Remarks

The remote sensing data from operational and experimental satellites and from weather radar have proven essential in providing information for areal surveys of a large variety of atmospheric and ground properties, and processes. The BALTEX research will make intensive use of such valuable information, since this area, in particular, is overflown by many satellites several times per day. These observations may also be used within BALTEX to interpolate between point measurements of various quantities.

Information about the radiation budget components at the ground and at the top of the atmosphere is of particular relevance to this project as are details on cloud fields and their radiative and microphysical properties, the sea surface level and temperature, the vegetation cover and land use, rainfall intensities and frequencies, the tropospheric humidity, wind fields, sea ice and also snow. Figures 5.1 to 5.3 show some examples of analyses of the cloud frequency, vegetation index and the sea surface temperature.

Most European meteorological services maintain receiving stations for the data from operational Low Earth Orbit polar (LEO) and Geostationary Earth Orbit (GEO) satellites, but increasingly the European organization EUMETSAT will take over the responsibility for the distribution of various products from these satellite measurements. Table 5.1 lists operational satellites, data of which are presently available, and also future satellite projects of relevance. An overview on present and future operational and experimental earth observing satellites and their instrumentation is provided in ESA (1994).

There will be only very limited experimental data available from a few wind profilers. Lidar measurements and cloud radar should also be considered experimental at one or two stations which are measuring cloud boundaries and aerosol layers.

Table 5.1 Operational satellite projects supporting BALTEX.
(More details are listed in ESA, 1994: CEOS-Dossier, Satellite Missions. European Space Agency, Paris, Sept. 1994.)

Satellite (Agency)	**Orbit (Status)**	**Primary application areas (major instruments)**
Present Meteosat System (EUMETSAT)	geostationary (in service)	Meteorology, climatology (images)
Meteosat Second Generation (EUMETSAT)	geostationary (approved for year 2000)	Meteorology, climatology (images with higher resolution, GOMOS, GERB)
NOAA-series (NOAA)	polar at 820 km (in service)	Meteorology, climatology, SST, ice, snow (AVHRR/2, MSU, HIRS/2, SSU, etc.)
Meteor 3 No 7 (Russia)	polar at 1200 km (in service)	Surface, oceanography, Atmospheric dynamics (ScaRaB, imaging radiometer)
DMSP-system (USA)	polar at 833 km (in service)	Meteorology, climatology (SSM/I etc .)
SPOT-series (CNES)	polar at 830 km (in service)	Cartography, vegetation (HRV, DORIS)
LANDSAT-series (NASA)	near-polar at 700 km (in service)	Land surfaces (MSS, TM)
METOP (EUMETSAT)	polar at 800 km (approved for year 2000)	Meteorology, climatology, SST, ice, snow Land and ocean surfaces (ASCAT, AVHRR, HIRS, ScaRaB, MIMR, IASI + 5 others)
Resource series (Russia)	near-polar at 240 km (in service)	Cartography, land surfaces, oceanography

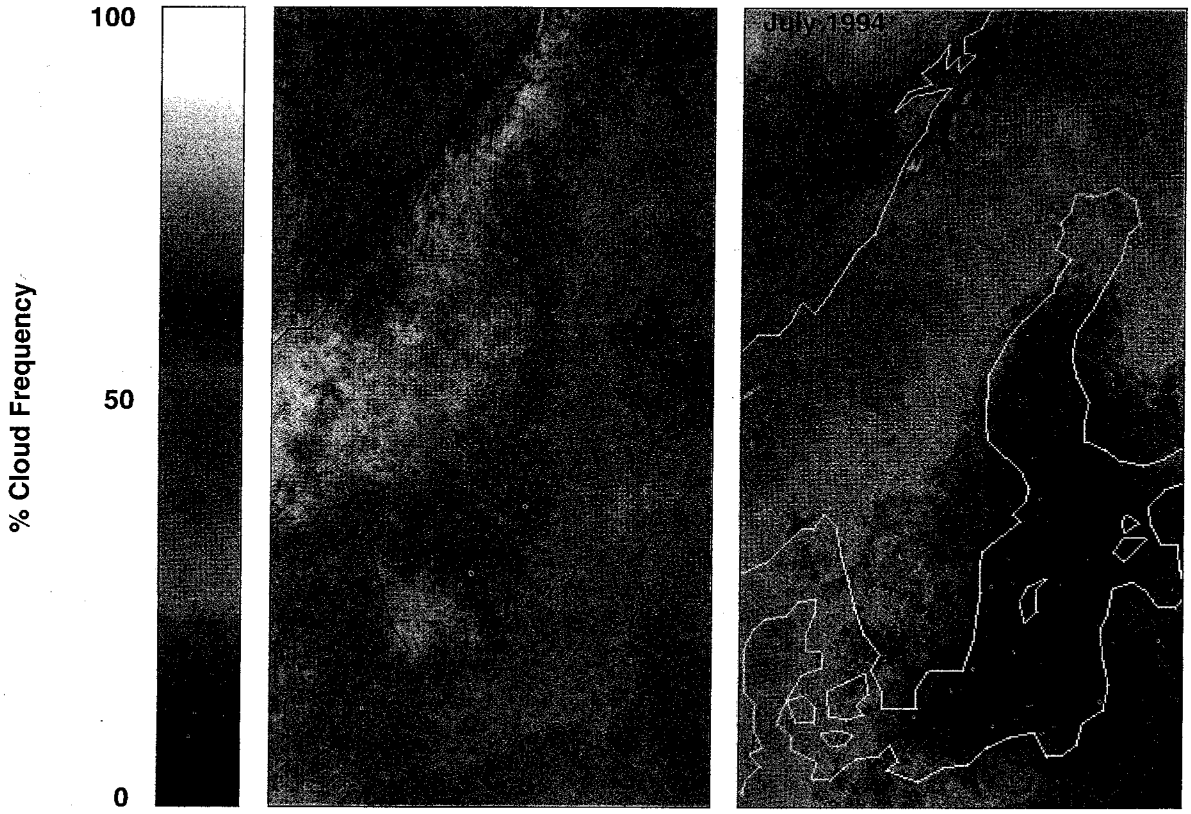


Figure 5.1 Satellite-derived cloud frequencies (%) for the months of July 1993 and July 1994. All available NOAA-AVHRR satellite overpaths in the area are used and averaged into monthly images. While unusually high cyclonic activity caused a high degree of cloudiness in July 1993, the summer of 1994 was dominated by high pressure, with a low amount of clouds. Note that the Baltic proper was essentially cloudfree during July 1994 (by courtesy of K.-G. Karlsson, SMHI, Sweden).

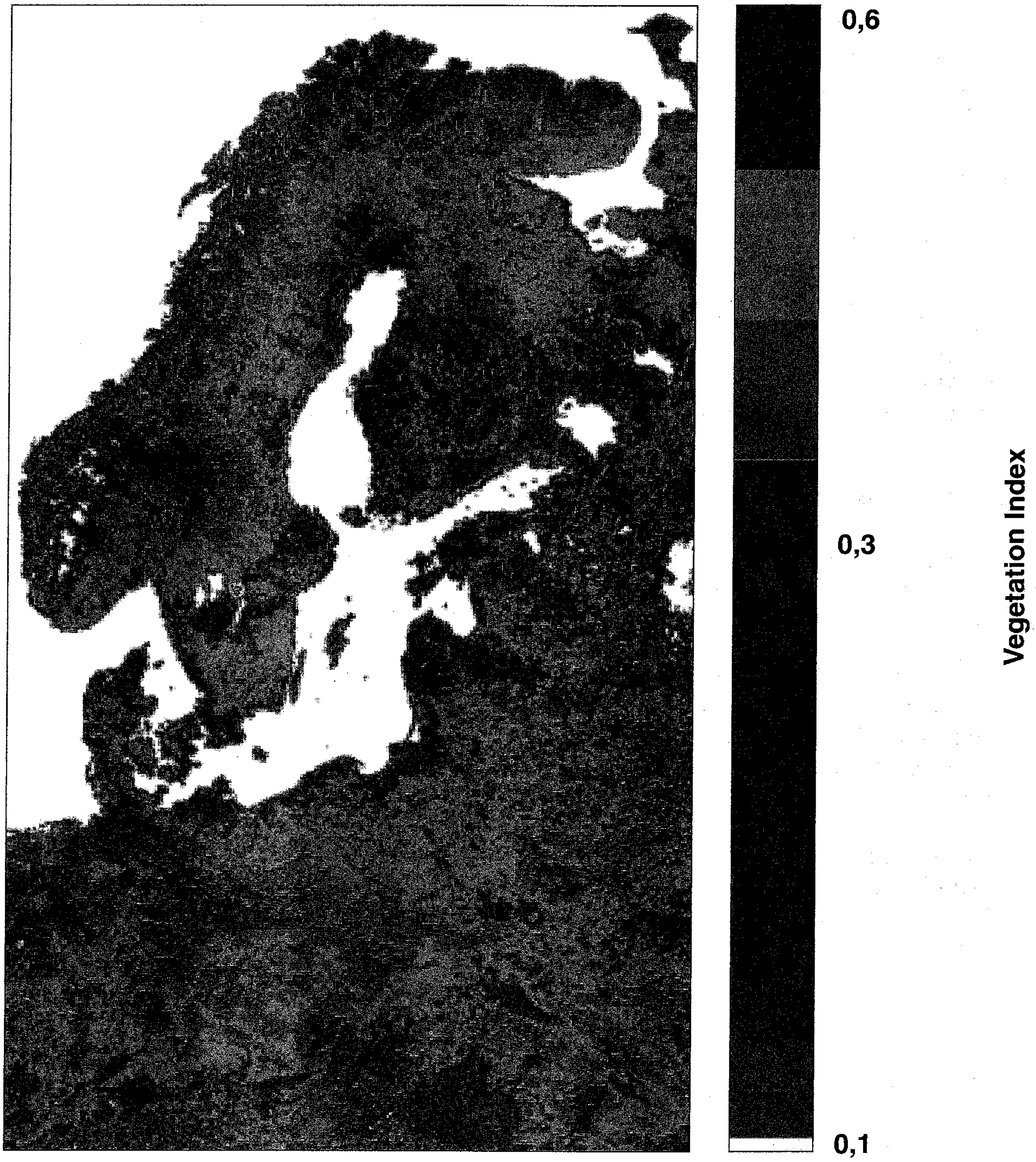


Figure 5.2 Normalized Difference Vegetation Index (NDVI) in the BALTEX area computed from AVHRR channels 1 and 2. NDVI is sometimes called greenness and is closely related to the net biomass productivity. The image is composed of several paths from the period 3rd - 6th July, 1994. No atmospheric correction has been applied (by courtesy of M. Eckardt, FU Berlin, Germany).

5.2 Operational Satellites

5.2.1 GEOSTATIONARY SATELLITES

The geostationary Meteosat system, now operated by EUMETSAT, provides coverage of almost the entire BALTEX region. The most north-eastern positions of the images, however, are "seen" under very slanted angles with low spatial resolution. At present Meteosat provides images in the 0.5 µm (visible), 6.3 µm and 11 µm spectral ranges with spatial resolutions in this region of about 3 to 4 (visible) and 6 to 8 km (infrared), but with temporal resolutions of 30 minutes. These data are received by many stations. An additional calibration is made within the framework of the ISCCP (International Satellite Cloud Climatology Project), but availability of respective coefficients may be subject to a few months delay.

The future Meteosat system (MSG - Meteosat Second Generation) will provide much higher spatial resolutions and more spectral channels in the solar and thermal infrared spectral ranges. MSG may also carry a well-calibrated earth radiation budget instrument. However, the first satellite of this new series will not be launched before the year 2000.

5.2.2 POLAR ORBITING SATELLITES

There are already several American, Chinese, Japanese and Russian satellites in near-polar orbits. Due to the overlap of adjacent orbits at higher latitudes, the BALTEX region is covered several times per day. However, these data are not always easily accessible for research.

The NOAA Polar Orbiting Operational Environmental Satellite (POES) series with the "conventional" NOAA-satellites, as well as the U.S. military Defense Meteorological Satellite Programme (DMSP) satellite series, will constitute within many spectral ranges the major system of observations. Multispectral imaging data with resolutions of about 1 km are available 4 to 6 times each day over the BALTEX region, and more often over its most northern portions. There are several data acquisition stations in the BALTEX region operating routinely and in a research mode, respectively. An example for the application of these data is the operational cloud classification scheme which has been developed at SMHI. It is based on NOAA-AVHRR data using multi-spectral methods (Karlsson 1989). Mean cloudiness conditions for months and entire years have been derived using this technique for the BALTEX region (see Figure 5.1).

Infrared temperature and humidity sounders are supplemented by microwave units to reduce the effects of clouds. In other spectral regions these multi-spectral data provide additional information on cloud water, precipitation, sea ice and atmospheric water vapor.

Towards the end of this century the American satellites will be supplemented by the first European Meteorological Operational satellite METOP. Furthermore, observational data of land surfaces and, in part, of clouds will also be available from the earth-resources satellite systems LANDSAT and SPOT.

Table 5.2: Experimental satellite projects of relevance for BALTEX.
(More details may be found in ESA, 1994; CEOS-Dossier, Satellite Missions. European Space Agency, Paris, Sept. 1994.)

Satellite (Agency)	Orbit (Status)	Primary application areas (major instruments)
JERS-1 (NASDA)	polar at 680 km (in service)	Land surfaces (OPS, SAR)
ERS-1 (ESA)	near-polar at 785 km (in service)	Earth resources, oceanography, ice and snow, meteorology, land surfaces (AMI, ATSR, Altimeter)
ERS-2 (ESA)	near-polar at 785 km (to be launched ~ 1995)	as ERS-1 (AMI, AATSR, Altimeter, GOME, PRARE)
RADARSAT (Canadian Space Agency)	near-polar at 800 km (~ 1995)	Ice, snow, land surfaces (SAR)
ADEOS (NASDA)	near-polar at 796 km (~ 1996)	Physical oceanography, atmospheric water and energy (e.g. OCTS, POLDER)
ENVISAT-1 (ESA)	near-polar at ~ 800 km (approved for 1998)	Oceans and land, ice and snow, atmospheric processes

5.3 Experimental Satellites

A summary of experimental satellites of relevance for BALTEX-related research is given in Table 5.2.

The European satellite ERS-1 and its successor ERS-2 carry a Synthetic Aperture Radar (SAR). The imagery can give information on sea ice coverage, thick-, thin-, ridged- and fast ice during cold weather conditions. Recently, several studies have shown the operational usefulness of ERS-1 SAR for sea ice mapping in different regions, including regions like the Baltic Sea (Håkansson et al. 1995). SAR data imagery can improve the accuracy of the digital sea ice charts, which basically is the information used for updating sea ice and weather forecasting models. The ERS-1 and ERS-2 satellites have a narrow swath width.

The Candadian RADARSAT, scheduled for launch in 1995, has several different swath widths, one of which is about five times larger than the ERS SAR sensor, covering most parts of the Baltic Sea within one orbit. RADARSAT will be an excellent source for ice drift information. However, data availability of RADARSAT will need to be investigated.

Recent research activities are dedicated to use sea levels retrieved from altimeters in data assimilation studies of ocean circulation models. Several satellite-borne altimeter missions have contributed to the development of techniques and analysis schemes, leading to an accuracy of close to 10 centimeter in sea surface heights. The American-French TOPEX/POSEIDON mission (Fu et al. 1991) is collecting data for a three to five years period and covers the same area every ten days.

Altimeter data for the Baltic Sea can also be obtained from the ERS-1 and ERS-2 missions. The altimeter instrument can measure sea surface topography, wind speed and significant wave height. In addition, information on the atmospheric water vapour content, which is necessary to correct estimates of sea level, can be obtained from a microwave radiometer onboard the satellite.

The ERS satellites carry a specially designed instrument for high-precision sea surface temperature measurements, the Along-Track Scanning Radiometer (ATSR). It is multispectal imaging radiometer, but with a ellipsoidal scanning procedure. Therefore, the same spot on earth is viewed from two angles, thus facilitating the correction for atmospheric influence in the measurements. Accuracies of tenths of a degree Celsius have been demonstrated.

The SSM/I instrument has been flown in polar orbit science 1987 and the instrument is scheduled for at least 10 - 15 more years of use on future DMSP satellites. Estimates of water vapour and liquid water in the atmosphere, and precipitation intensity may be deduced from this instrument, however, with different degree of accuracy over land and ocean areas. SSM/I data include the potential of deriving wind speed and latent heat flux at the sea surface. The establishment and application of all these methods to the Baltic Sea and the BALTEX region, respectively, is among the challenging research tasks for BALTEX.

Sounding information from the TIROS Operational Vertical Sounder (TOVS) instruments on the NOAA-satellites have been available for many years. A new version of the instrument, ATOVS, will be launched with NOAA-K in late 1995. It will contain an improved microwave sounding capability via the Advanced Microwave Sounding Unit (AMSU). Soundings in cloudy areas will then be improved which together with new data-assimilation approaches may augment the use of the TOVS instrument. Furthermore, some of the AMSU channels may be used in the same way as the microwave instrument SSM/I for monitoring of precipitation and liquid cloud water.

The European Space Agency in co-operation with EUMETSAT plans to launch the new satellite ENVISAT in 1997. In addition to some instruments which are compatible to those of METOP and which are presently on operational meteorological satellites, the new satellite will also carry a radiation budget instrument (ScaRaB, Scanner for Radiation Budget).

A new multispectral imaging radiometer (POLDER), also measuring the polarization of reflected radiation, will be launched in 1996 onboard the Japanese satellite ADEOS. Data from this new instrument will help to better identify high thin cloud and aerosol layers, and also ground vegetation.

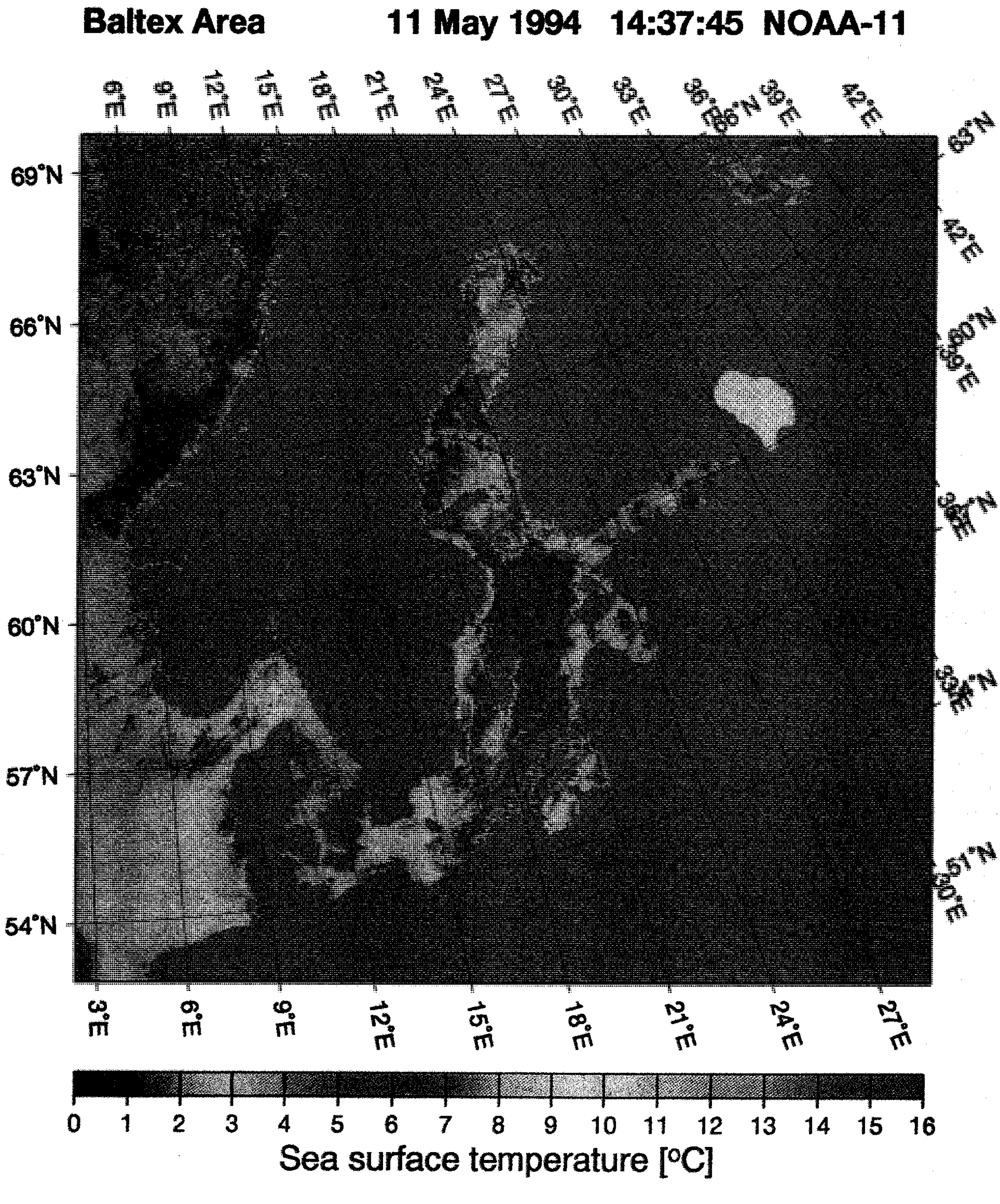


Figure 5.3 Sea surface temperature of the Baltic Sea on 11th May, 1994, derived from AVHRR data using the NOAA-NESDIS algorithm. The high values in the Gulf of Finland are questionable due to unrealistic corrections for atmospheric humidity in that area (by courtesy of GKSS, Geesthacht, Germany).

The availability of data from these European experimental satellites is not yet certain in all cases. While some of the data from ERS-1 can be obtained via ESA's network, e.g. the data center in Frascati, Italy, others, like those of the ATSR, are still not yet in the public domain.

Currently, ESA and the EU are planning to build up a more effective organized data service through the Committee on Earth Observation Satellites (CEOS), which will be located at the Joint Research Center in Ispra, Italy.

5.4 Radar Measurements

Weather radar data are very important for the BALTEX observation system. Radar observations are extremely useful to identify and locate the precipitation areas. The temporal and areal resolutions of radar data are superior to the conventional rain gauge network. Radar scans may be as frequent as every 15 minutes, and the horizontal resolution is 2 km for most of the radar stations. At present, radar data are mostly used to monitor the actual precipitation situation and as a qualitative guidance in operational weather forecastings.

The weather radar stations of the meteorological services in Denmark, Sweden, Finland, Norway, Poland and Germany form, at present, a quite dense network of modern digital radars. Most of them are C-band radars, operating at wavelengths near 5 cm where the attenuation of radar signals, caused by atmospheric gases and precipitation, is optimal for the detection of hydrometeors. Radar systems from different manufacturers (e.g. Gematronics and Ericsson) are operational in the BALTEX region. Many radars have a Doppler capability, thus allowing measurements of the radial wind components in the presence of precipitation. The weather radar stations in Finland, Norway and Sweden are now organized and linked together in NORDRAD - the Nordic Weather Radar Network. A fairly complete and updated review of weather radars in Europe is given in 'Weather Radar Networking, COST Project 73, Final report' (see also Collier and Chapius 1990).

The present coverage of the BALTEX region by radar (see Figure 5.4) is still incomplete. At present, at least 22 radar stations are in operation covering large areas of Scandinavia as well as parts of the Baltic Sea, northern Germany and Poland. Two additional stations in Sweden and one in Poland (the range of which are marked by dashed lines in Figure 5.4) will be operational within the next two years. A single station has a limited spatial coverage, the horizontal radius of which is approximately 120 km. Local obstacles near the station may lead to deformations of the ideal circular form of the radar range (see Figure 5.4).

Most beneficial for BALTEX, and therefore it should obtain first priority, will be the extension of the radar coverage over the whole Baltic Sea, where only a few ground-based precipitation measurements are available. Such a complete coverage of the Baltic Sea may require about six additional radar stations: Two additional stations near to the coastline of Poland, one radar in each of the three Baltic countries Estonia, Lithuania and Latvia, respectively, and an additional radar station in Finland to close a small gap up in the northern part of the Baltic Sea.

The relationship between radar reflectivity and precipitation intensity is strongly non-linear and depends on several factors related to water phase and droplet/crystal distributions and concentrations. As a consequence, precipitation amounts may be subject to considerable uncertainties when estimated on the basis of radar data only (e.g. Sauvageot 1994).

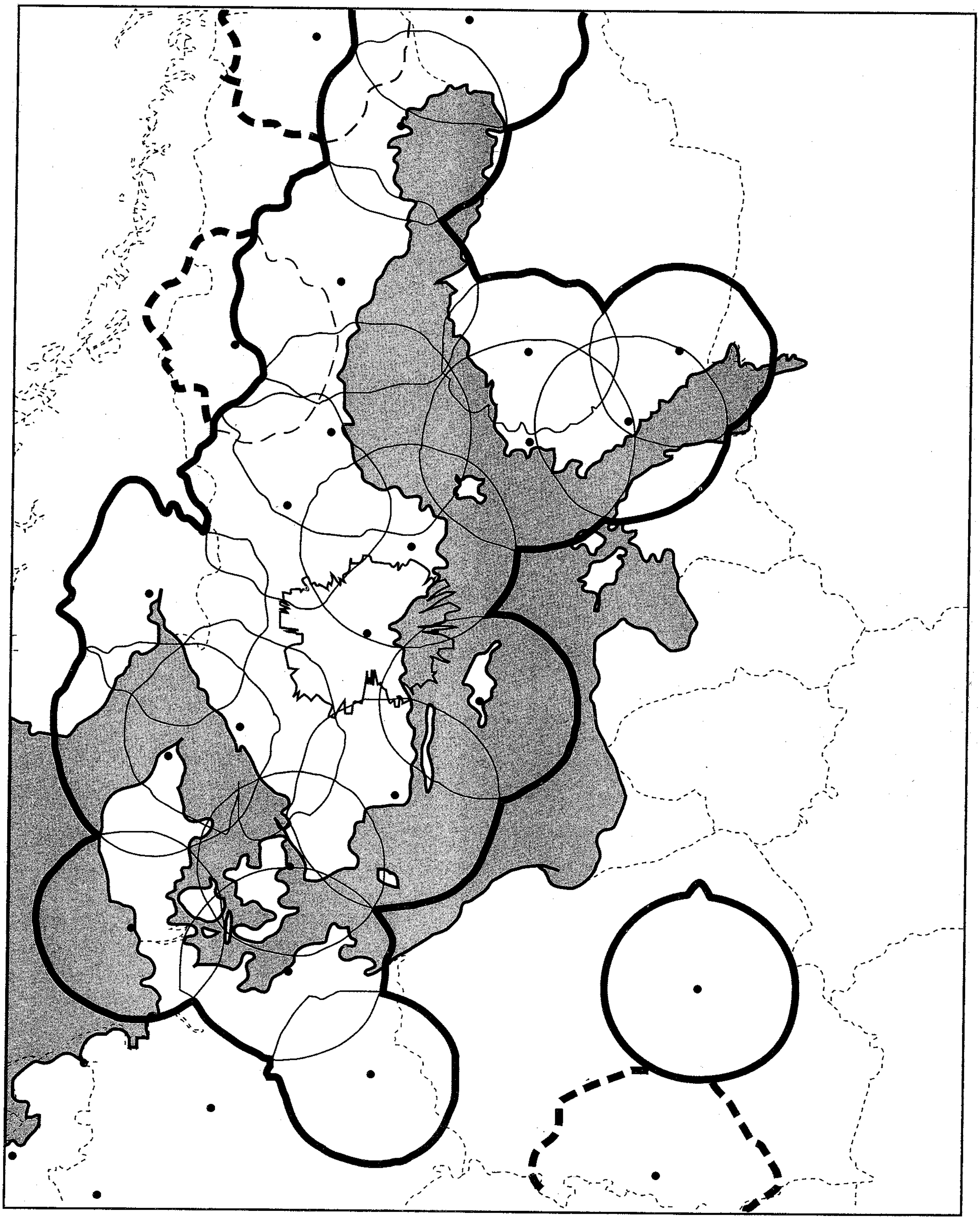


Figure 5.4 Locations of radar stations in, and adjacent to, the BALTEX area. An estimate for the radar-covered area is given by connecting the outer boundaries of individual station radii around each station. Area coverage of planned stations in Sweden and Poland is given by dashed lines (by courtesy of J. Svensson, SMHI, Norrköping, Sweden).

The development of methods to correct radar data will be linked to the development of objective analysis methods using e.g. preliminary first guess fields from weather prediction models. A combined meso-scale precipitation analysis scheme based on radar data, synoptic observations, direct rain measurements, and model-produced precipitation forecast fields will be used in BALTEX. Such a scheme is presently being developed and tested at SMHI based on the HIRLAM weather forecast model (see sections 6.1 and 7.2). The BALTEX Pilot Study for Intensive Data Collection and Analysis of Precipitation (PIDCAP, see section 8) will serve to compare radar data with precipitation estimates from different other sources and to improve meso-scale precipitation analysis schemes.

A BALTEX project has been started to directly measure precipitation on several ferry boats in the Baltic Sea. These data, although sampled from moving platforms, will be used to validate the precipitation amount which is derived from the radar network and from the meso-scale precipitation analysis scheme.

BALTEX will implement a strategy for exchanging radar data. For BALTEX research purposes it will be sufficient to store the radar data in archives and make them available for the BALTEX research community in delayed mode.

6 DATA FROM DATA ASSIMILATION ACTIVITIES

The complexity and the spatial scales of the processes which determine the energy and water cycles of the BALTEX region make it difficult to study these cycles using observed data only. Since the atmospheric processes involved are included in operational weather forecasting systems, it seems natural to utilize these systems within BALTEX. These operational systems normally consist of an analysis scheme, a forecast model and an initialization procedure. Routinely observed data are generally available every 6 hours so they may be introduced into the system at this frequency in a so-called data assimilation cycle to obtain a synthesis between observations and the model state (Figure 6). An advantage of using this method is that a number of quantities derived from the model become consistently available. Among the results from data assimilation systems are the fluxes of water, heat and momentum as well as higher order moments of atmospheric variables. Global forecasting systems have been used successfully to infer e.g. the diabatic heat and moisture forcing of the atmosphere from assimilated data.

The study of the energy and water cycles during BALTEX will require data assimilation on spatial scales that are not yet available operationally. However, as data assimilation techniques are most relevant in assessing data in BALTEX an important component in the overall project is the development of high resolution data assimilation systems.

Another important use of data assimilation is that it makes it possible to check the different data sources against each other and thus provides an excellent tool for monitoring the observational network. Further, it may be used in the context of sensitivity analysis to help guide the implementation of new observing stations.

To improve simulation of the energy and water cycles in the Baltic Sea region it will be necessary to introduce coupled atmosphere/ocean/land surface models, which will include data assimilation.

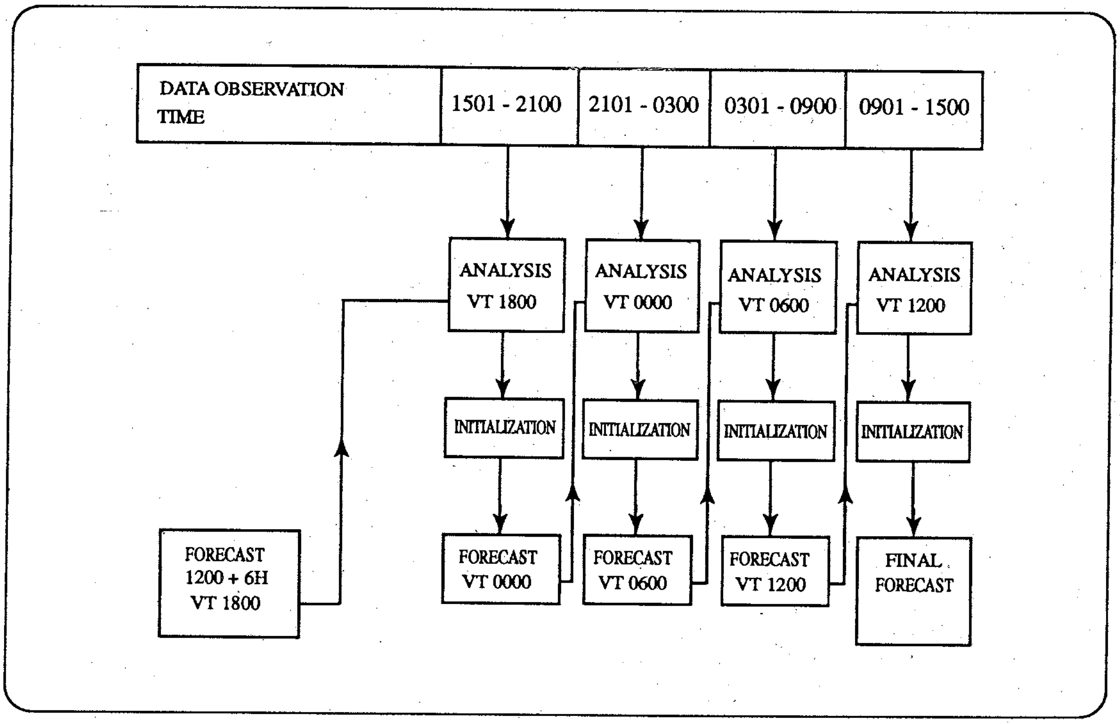


Figure 6 An example of an atmospheric data assimilation system. Observations are collected at intervals of 6 hours around the main synoptic hours, 1800, 0000, 0600 and 1200 h UTC. VT 1800 = valid time 1800 h UTC. Every analysis step uses a 6 hour first guess from the preceding forecast. Initialization is carried out after every analysis step in order to remove unwanted noise.

6.1 Operational Meteorological Data Assimilation

Operational data assimilation for weather forecasting purposes is carried out by several weather services participating in BALTEX. Data assimilation with different configurations of the HIRLAM forecasting system are used at the weather services in Denmark, Finland and Sweden. DWD uses data assimilation together with the Europa Modell.

The HIRLAM-2 forecasting system is operated routinely at DMI, FMI and SMHI. The HIRLAM forecasting model is based on the primitive equations applied in hybrid vertical coordinates and horizontally in the Arakawa C-grid. Horizontal boundary conditions are generally taken from ECMWF forecasts. The HIRLAM data assimilation is based on a limited-area version of the ECMWF Optimum Interpolation (OI) analysis scheme and on an implicit non-linear normal mode initialization. The data assimilation is carried out in 6 hour cycles. The OI analysis scheme includes a multivariate analysis of surface pressure and model level winds and temperatures and a univariate analysis of model level humidities. Input data to the OI analysis are upper-air radiosonde and PILOT wind data, aircraft data and surface observations. The OI analysis scheme also allows for utilization of satellite wind and sounding data, but this option is not utilized at present (October 1994).

The Danish Meteorological Institute uses the HIRLAM system in three different versions: (1) Operationally in 45 km horizontal resolution and 31 levels, (2) operationally in 23 km resolution and 31 levels, (3) experimentally in four different horizontal resolutions and with 40 vertical levels. Lateral boundary conditions for the 23 km version are taken from the 45 km version runs. Similarly, lateral boundary conditions for the 4 km version are taken from the 23 km version runs.

The Finnish Meteorological Institute applies the HIRLAM system in two different versions: (1) Operationally in 55 km horizontal resolution and 31 levels, (2) experimentally in 27 km resolution and with 31 vertical levels. In addition to the HIRLAM OI analysis schemes, FMI uses a separate analysis of sea ice coverage and SST.

The Swedish Meteorological and Hydrological Institute applies the HIRLAM system in two different versions: (1) Operationally in 55 km horizontal resolution and 16 levels, (2) experimentally in 22 km resolution and with 24 vertical levels. The Sundqvist condensation and precipitation scheme with explicit treatment of cloud water is uses operationally. In addition to the HIRLAM OI analysis schemes, SMHI applies a separate analysis of snow depths, sea ice coverage and SST. A coupled ice-ocean model is utilized operationally for coupling to HIRLAM during the assimilation of sea ice information in the Baltic Sea.

The Europa model (EM) and the Deutschland model (DM) are 3-dimensional primitive equation models having hybrid vertical coordinates. EM uses Eulerian horizontal advection while DM uses semi-Lagrangian horizontal advection. Vertical advection is implicit and treated together with vertical diffusion. The EM is run operationally with 20 vertical levels on a 55 km horizontal grid in rotated latitude/longitude geometry. The horizontal resolution of the DM is approximately 14 km, and the number of vertical levels is 20. Both models include comprehensive physical parameterization, in particular with regard to the micro-physics of the condensation and precipitation processes and the soil processes including the effect of vegetation cover. Both model versions run with 6 hourly forward intermittent data assimilations based on a limited area version of the ECMWF OI analysis scheme and a normal mode initialization. Also snow cover, sea ice coverage and SST are analyzed. Lateral boundary conditions for the EM are taken from DWD global model forecast runs and lateral boundary conditions for the DM are taken from the EM forecast runs. The DWD EM data assimilation will provide operational atmospheric analysis on a 55 km grid resolution for BALTEX.

All these data assimilation applications are of interest for the BALTEX research. DWD will supply operational data assimilation data sets from the Europa model to the research community during BALTEX (see also section 7.2).

6.2 Data Assimilation in Hydrological Modelling

There is a long tradition for applying data assimilation techniques in hydrological modelling in connection with real-time flood forecasting. Different data assimilation methodologies have been applied to the conceptual hydrological models in Scandinavia (Bergström 1976, Jönch-Clausen and Refsgaard 1984). Attempts have been made to use spatial satellite data of snow coverage through data assimilation together with semi-distributed hydrological models (Thomsen and Andersen 1984, Brandt and Bergström 1994).

However, no attempt has been made to date to use data assimilation together with distributed, physically based models in the BALTEX countries. Limited experience exists with regard to combining spatial snow coverage data with fully distributed models, and with regard to root zone variables even less experience exists. A first attempt to utilize satellite data together with a distributed model in order to improve the spatial description of soil moisture conditions has been reported from the HAPEX-MOBILHY experiment by Ottlé and Vidal-Madjar (1994).

It is, generally, simplified hydrological models that are integrated into atmospheric models. In order to study and simulate the complete energy and water cycles, coupling of atmospheric models with more realistic hydrological models is needed. It is crucial to obtain an accurate description of the spatial distribution of hydrological variables such as snow coverage, surface temperature, soil moisture, evapotranspiration and vegetation in order to provide reliable calculations of the latent and sensible heat exchanges between the atmosphere and the land surface. Such variables can be estimated from distributed hydrological models and can also be inferred from satellite data. Since observations of soil characteristics such as soil water content are seldomly available, data assimilation techniques have to be developed to control the time evolution of these hydrological parameters in the atmospheric models.

The data assimilation techniques to be developed in order to integrate satellite data into distributed hydrological models should explicitly take the involved uncertainties into account. Hence, the hydrological model should provide estimates of the hydrological variables together with e.g. standard deviations. Simultaneously, the same hydrological variables should be estimated from remote sensing data together with assessments of uncertainties of the estimates. On this basis, data assimilation techniques can be used to obtain estimates on the spatially distributed hydrological variables, which are more reliable than both the model and the remote sensing estimates.

6.3 Data Assimilation in Oceanographic Modelling

The development of assimilation schemes for 3-dimensional ocean circulation models which allow the inclusion of observations of sea level, currents and hydrographic information is an important step towards data assimilation of coupled systems. The principal objective of oceanographic data assimilation in BALTEX is the determination of those fields which are not easily observable. These fields include, in particular, the interior circulation and water mass distribution and the transports through the Danish Straits. Apart from ad-hoc methods of data insertion, most recent developments for assimilation techniques have concentrated on optimal estimation procedures such as Kalman filtering or a variational approach using adjoint models.

Due to the very high computing demands, most activities have been focussed on the assimilation of wind and sea-level data with barotropic or coarse-resolution ocean models. Data assimilation techniques are used in the context of storm surge modelling. In Denmark water level data are assimilated into an semi-operational forecast system for the North Sea, the Danish Straits and the Baltic Sea.

Recently, an adjoint for a 3-dimensional circulation model for the western Baltic-Kattegat region has been developed at IfM Kiel and successfully used to improve the simulation of circulation and salinity distribution, using only sea level observations. It is expected that extension to the full Baltic Sea model will become feasible within the BALTEX period.

Considering the exchange of sea water between the Baltic Sea, Skagerrak, Kattegat, the North Sea and the Atlantic Ocean, the need for data assimilation in coupled atmospheric and oceanic model is obvious. Recent oceanographic model runs have shown that the results can be considerably improved by assimilating sea level data from tide gauges and hydrographic data. Data assimilation methods for salinity and temperature profile data in three-dimensional ocean models are most important. This would require a dense network of stations (distance approximately 10 km) allowing for an objective mapping of the horizontal density distribution, most especially in the Arkona and Bornholm basins, where variations in time and space are large and the hydrographic response in these sub-basins forces the dynamic response in the rest of the Baltic Sea. Such a network may be achieved during special extensive observation periods.

With regard to the air-sea, air-ice and ice-sea interactions, the time scales of the sea surface temperature, surface waves and ice condition changes in the Baltic Sea are so short that introduction of a two-way coupling is needed. A satisfactory solution to this coupled atmosphere ocean data assimilation problem would require a full coupling of atmospheric models to 2-dimensional sea ice or surface waves models which will then need the coupling to three-dimensional baroclinic ocean models. Data assimilation with such complex integrated model systems is not feasible for the time being (1994), and simplified data assimilation systems have to be applied during the first phase of the BALTEX project.

6.4 Data Assimilation Products

The output of data assimilation systems is consistent for many quantities including calculated fluxes and higher order moments of variables. Some of these quantities may be very difficult to check against observed data. Nevertheless, the output data resulting from data assimilation with coupled atmosphere/ocean/land surface models need to be validated thoroughly. Independent, well-controlled observational data sets should be utilized for this validation. Examples of such independent data sets for validation are satellite- and radar-derived precipitation and cloudiness fields, outgoing longwave radiation as determined from satellite data, mast measurements of boundary layer profiles, hydrological observations of runoff and soil water, observations of fresh water content in the Baltic Sea (salinity profile data) and measurements of in- and outflows through the Baltic Sea entrance. Another way of validating the atmospheric data assimilation fields is to use the time history of these assimilation fields to derive diabatic heating rates through a budget calculation (see e.g. Fortelius 1994). These derived heating rates can then be compared with the heating rates as determined by the model parameterization schemes.

6.5 BALTEX Data Assimilation Projects

6.5.1 MESO-SCALE RE-ANALYSIS

Two periods, with interesting atmospheric and oceanographic phenomena, December 1986 through to February 1987 and September 1992 through to September 1993, have been identified as intensive data periods for BALTEX (see section 1.4). Meso-scale meteorological analysis fields over the entire BALTEX region, produced by a modern data assimilation system, are being produced for these periods. These data will for example be used for the forcing of oceanographic models. Proper lower boundary conditions, such as sea ice and sea surface temperatures, will be used during the production of these data assimilations.

6.5.2 OCEANOGRAPHIC DATA ASSIMILATION

A method should be developed which allows the assimilation of sea level, currents and hydrographic observations into general circulation models for the Baltic Sea. The assimilation will allow estimation of the full state vector of variables for initializing models, e.g. for hindcasts during the intense observational periods. It will also be of use in long-term integrations for systematic model validation including the optimization of mixing parameters, and the estimation of surface fluxes. Technically, the development of an adjoint circulation model is the most likely and promising route, although practical considerations may require modifications or even the choice of simpler algorithms.

6.5.3 HYDROLOGICAL DATA ASSIMILATION

A procedure for assimilating remote sensing data in distributed, physically based hydrological models will be developed and validated. It is envisaged that satellite information on soil moisture, vegetation (leaf area index), and possibly evapotranspiration may be combined with model simulations and hence reduce the overall uncertainties in these variables. This assimilation procedure will enable utiliziation of all available information of relevance to atmosphere/land surface coupling. The data assimilation technique will be tested on both the small- and meso-scales before being transferred to the entire BALTEX region.

6.5.4 ASSIMILATION OF HISTORICAL DATA IN ORDER TO ESTIMATE TRANSPORTS THROUGH THE DANISH STRAITS

One of the key problems in BALTEX is the determination of the water transport through the Danish Straits. It will therefore be of considerable interest to obtain long time series of this transport. Measurements of sea level have been carried out for almost 100 years at a number of stations in the Baltic Sea as well as in the Danish Straits. These data should be used, together with atmospheric forcing, as input to a storm surge modelling system in order to derive consistent currents. After the development of data assimilation techniques for 3-dimensional models the calculations should be repeated with this new system in order to get more precise estimates of both transport of matter and water in and out of the Baltic Sea through the Danish Straits.

7 BALTEX MODELLING RESEARCH

7.1 Scientific Issues

The modelling efforts within BALTEX are directed towards the development and verification of models which describe all relevant components of the energy and water cycles in the BALTEX region. The models must be suitable to describe the physical state of the system atmosphere/Baltic Sea/land surface, including its variability on time scales from weeks to decades, on spatial scales ranging from 10 - 20 km to entire basin size. They must also allow the study of the response of the system to natural or anthropogenic changes of the global climate, and they will form the basis for environmental models in the region.

Specifically, the models must be capable of addressing the following scientific issues:

- ***Water budget of the BALTEX region***

This requires an accurate modelling of 1) the vertical energy and water fluxes at the surface of the earth (land and water), 2) the radiation balance at the top of the atmosphere, 3) the horizontal energy and water fluxes through the lateral atmospheric boundaries of the regions, 4) river runoff and 5) the transport of water and salt through the Danish Straits. It also requires an understanding of the dynamics of inflow into the Baltic Sea, and of the thermohaline circulation and mixing processes which determine the long-term distribution of water masses in the Baltic Sea.

- ***Interaction of meso-scale with synoptic-scale processes***

Boundary layer forcing on the atmosphere from inhomogeneous land and water surfaces generates meso-scale secondary circulation systems, land and sea breezes, as well as significant modifications of synoptic-scale circulations. These meso-scale phenomena particularly influence the geographical distribution of precipitation.

- ***Land surface variability***

The land surface shows great variability as a result of different vegetation and land use. Therefore, the energy and water balance is also highly variable. The understanding of this sub-grid variability and its representation in atmospheric and hydrological models is an area of great importance. The contribution of lakes to the water and energy balance is also very important but not yet fully understood. Of particular interest is the evaporation from a mosaic of land and lakes, and the energy balance related to ice formation and break-up on lakes.

- ***Snow in the hydrological cycle***

Snow is a significant component of the hydrological cycle in the BALTEX region. There is a need for a better understanding of the energy balance and for better models of snow accumulation and melting. The areal distribution of processes related to snow is of particular interest.

- ***The role of sea ice in the Baltic Sea***

The mean annual maximum extent of the ice cover in the Baltic Sea is about 50 percent. The ice cover brings a rather rigid film to the air-sea interface considering dynamic effects, an insulating film in thermal effects, and a buffer for the precipitation falling to the sea. Also the ice transports negative heat and fresh water over large distances.

7.2 Atmospheric Models

The fundamental problem with the hydrological and energy cycle is the extremely fine structure of precipitation and evaporation patterns, particularly over land areas. It has been demonstrated in high resolution observational studies in the past (e.g. Bergeron 1970), that even for reasonably stable synoptic systems, such as warmfront precipitation at high lati-