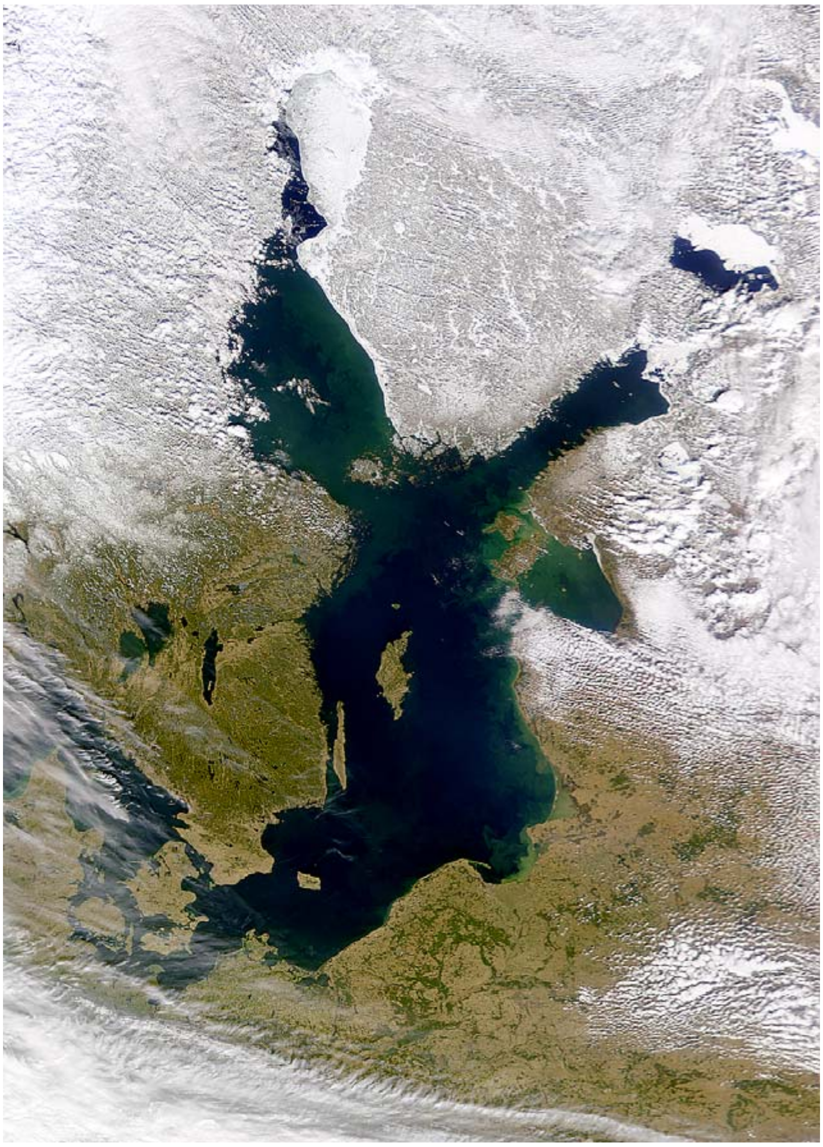
BALTEX PHASE I
(1993-2002)

STATE OF THE ART REPORT



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Chapter 1:

Why BALTEX ?

An Introduction to BALTEX

by

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1.1. Background

Increasing the knowledge on all branches of the energy- and water cycles within the climate system from global to local scales and on their interactions with other components of the climate system has always been a challenge for scientists since it is of vital importance for the understanding of most ecological and economic processes on Earth. As this challenge still exists and will even gain increasing attention due to the steady growth of the world's population and its demands for more natural resources, it approached central importance in the world-wide climate research. The success of regional water management programs depends heavily an accurate knowledge of available resources at present and in the near future.

Despite the many enormous earlier efforts to observe and model individual branches of the hydrological cycle, like the precipitation for the weather and climate forecast, there were very few successful attempts and also possibilities until about 20 to 30 years ago to investigate with observations and models complete water cycles over larger continental-scale regions. Therefore, at that time the "Global Energy and Water Cycle Experiment (GEWEX; see www.gewex.org)" has been formulated within the frame of the World Climate Research Programme (WCRP) with the major task to "observe and model hydrological cycles over all parts of the globe for the purposes of climate and weather research". A summary of the scientific state-of-the-art at that time and the motivation which finally led to the definition and installation of GEWEX is given in the paper by Chahine (1992).

The objectives defined for GEWEX require contributions from a variety of different disciplines of the natural sciences, ranging from the understanding of the dynamics of global general circulation of the atmosphere and oceans to local micro-cloud physics and also to soil, vegetation and ice science. They include also basic problems of direct and remote measurements of atmospheric and terrestrial variables, of data treating and indeed of numerical modeling. The interaction between the vegetation and the water cycle moved now directly into the field of view of atmospheric physicists. Interdisciplinary work had to be established between atmospheric scientists, hydrologists and soil experts, oceanographers and polar researchers on the one side and between modelers and experimentalists on the other.

Soon it became evident that many of the forth-coming questions could only be answered with appropriate efficiency over continental regions with quite well established ground-based observing systems, where also operational meteorological and hydrological agencies existed, which are interested in improvements of their own products. Such regions should be large enough to be fairly well resolved by the at that time state-of-the-art climate models and they should cover catchment areas of major river systems. These allow an accurate and convenient control of the total (net) water budget by measurements of the water runoff in each contributing river at various places and in particular at the last mouth where water reaches an ocean or major lake. Therefore, scientists in the US selected for such studies the basin of the Mississippi/Missouri river systems for the GEWEX Continental-scale Intercontinental Project (GCIP, Ref.), which covers almost about 60% of the area of the United States (with some smaller contributions from Canadian territory) and is their major food chamber.

Within the period 1990 to 1993 some scientists from Germany, Sweden, Finland and Denmark established on the basis of an earlier German proposal the Baltic Sea Experiment (BALTEX; Raschke et al. 2001) as a cooperative effort between meteorological, hydrological and oceanographic agencies and research institutions. This group could soon after later be joint by scientists from other countries located in the catchment area of the Baltic Sea: Poland, Lithuania, Latvia, Estonia, Belarus and Russia. Research groups from the Netherlands and from Austria participated in BALTEX since about 1999.

Support was first sought in several commissions of the German Research Organization (DFG) and of the Federal Ministry of Research and Technology (BMFT). The BMFT later provided considerable financial support for basic research and in particular to integrate the Baltic States, Russia, Belarus and Poland with their high potential of scientific expertise and of long hydro-meteorological data series into the project. This support was joined by various funds from Danish, Swedish and Finnish authorities and for very specific projects also by the European Union. Other bilateral projects helped to upgrade observational systems in these countries.

Canadian scientists concentrated their efforts on the Mackenzie River Basin (MAGS, Mackenzie GEWEX Study; Stewart et al., 1998) and Japanese scientists took the leadership in an multinational team to study the water cycles over eastern Asia and their interactions with the Asian Monsoon systems (GAME: GEWEX Asian Monsoon Experiment; e.g.: Yasunari et al.,). Additionally many already ongoing research activities in the Amazon Basin where summarized within the project LBA (Large-Scale Biosphere-Atmosphere Experiment in Amazonia; e.g.: Nobre et al., 1991).

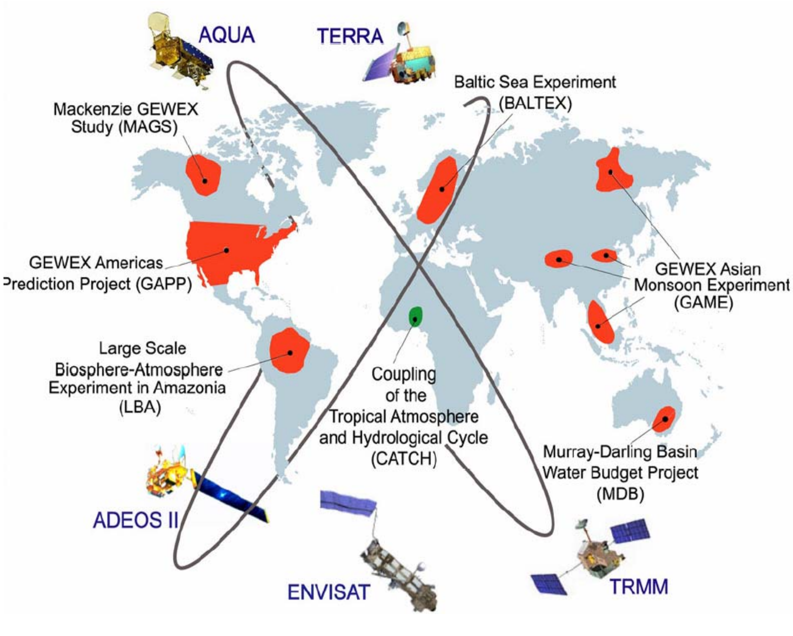

Figure 1.1: The GEWEX observational strategy includes now in addition to already existing worldwide networks several basin wide experiments and new environmental satellites (from WCRP Poster, 2003, on GEWEX).

These earlier Continental-Scale Experiments (CSEs) are still continuing – now with indeed advanced goals and also partly under different names. They have been complemented by other experiments in Africa and Australia. The map in Fig. 1.1 shows the present location of all CSEs in the year 2003.

About 15 years passed since GEWEX had been defined. It stimulated a large variety of extremely qualified and important research activities and in particular its supporting arguments helped to improve ground-based and satellite-based observing systems and the related extraction of climatologically important information from this new and vast amount of data. These efforts, often performed in close cooperation with other research programs, paid back to the world-wide community by much improved understanding of many processes which finally lead to better forecasts of weather at shorter and longer scales, as well as of climate change projections. While the first decade of GEWEX activities can be considered as an exploratory phase, now work in the second phase can concentrate more on applicational aspects.

1.2. Two major open questions

At the time, when GEWEX – and later its continental-scale experiments (CSEs) – were defined there were several basic questions open in our understanding of energy and water transfer in the climate system. They are still not yet completely solved, thus they are still causing considerable uncertainty in weather and climate forecasts at different spatial and temporal scales. Even now (year 2004) many aspects are still unsolved and their solution is subject of major research efforts with the WCRP and IGBP frames.

These open questions were related to the ***measurement and modeling*** of **all components** of the **radiation budget** of the atmosphere at both of its boundaries and also within the atmosphere with particular emphasis of the effect of clouds and of aerosols on it, where also the complex interactions between aerosols and clouds need to be considered;

the **hydrological cycle** at different space and time domains and its interactions with various “external” forcings, such as the atmospheric dynamics or the properties of the earth’s surface; in particular the questions related to soil wetness in all seasons and to the evapotranspiration were completely open. Of particular interest is still the spatial and temporal variability of precipitation. Almost no precipitation measurements are available over the oceans, but also networks over many continental areas required and urgent updating. Models to compute the run-off in larger catchment areas as driven by springs and major precipitation events had to be developed.

In fact both questions are related to each in various ways.

Various modeling and measurement tools had to be developed. The formulation of GEWEX sped up the development of advanced satellite systems, such as the TRMM (Tropical Rainfall Monitoring Mission) to provide global information on precipitating systems in the atmosphere. Further, also basic progress was needed in the handling and distribution of data from different sources. As a consequence the GEWEX management established up to now 19 supporting projects, amongst them are the urgently needed projects GPCP (Global Precipitation Climatology Project), GEWEX Cloud Systems Study (GCSS: to investigate the many processes participating in the life cycle of all cloud systems – see Randall et al., 2003) and Coordinated Enhanced Observing Period (CEOP: to coordinate and stimulate data collection for improved modeling and prediction – see Grassl 2002).

1.3. Scientific Objectives and Structure of BALTEX

The entire water catchment of the Baltic Sea (Fig. 1.2) was chosen, since its only exit to the world oceans, the Danish Straits, is narrow enough to be covered efficiently by models and measurements of the water exchange (annually about 450 km^3) through these gates. This area covers a region of about 2.1 million km^2, where its continental surfaces (about 4/5 of this area) are inhabited by about 80 million people. This area is intensively used by various economical branches of the countries within this area, where the Baltic Sea itself becomes an important water street for the trade between Western Europe and Russia.

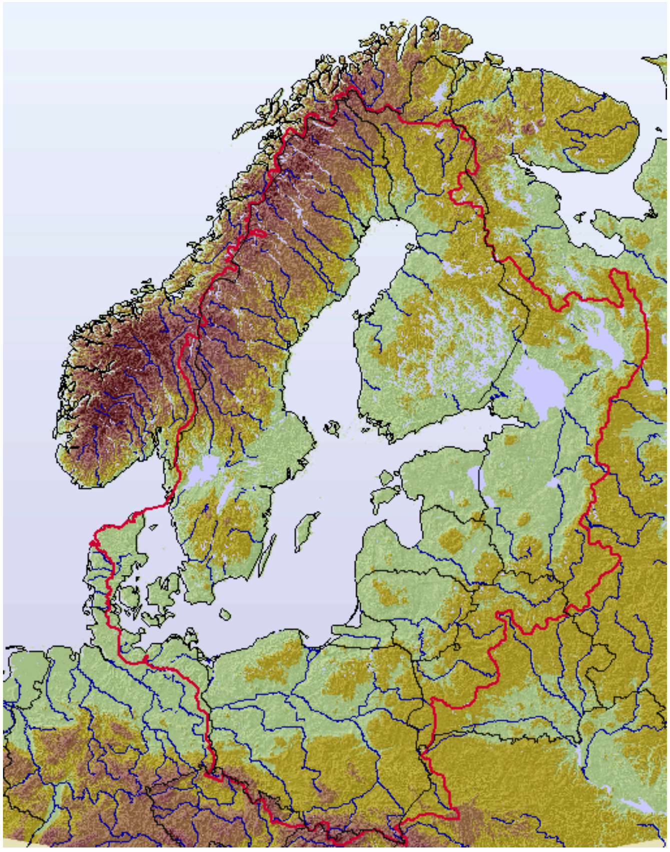

Figure 1.2: The water catchment of the Baltic Sea (red boundary) with its major rivers (dark blue), lakes (lighter blue) and orography (brownish to violet for elevations > 200m above sea level). Borders between the various countries are marked in black (produced using tools at http://www.grida.no/baltic).

At several workshops and two planning meetings, which were held in Norrköping from 26 to 30 October, 1992, (see also Fig. 1.3) and at the University of Uppsala (9 to 11 August, 1993), the scientific objectives and the major elements of the BALTEX structure had been defined. They were summarized in a "Scientific Plan for the Baltic Sea Experiment" (Raschke, 1994) and in the "BALTEX - Initial Implementation Plan" (BALTEX, 1995), and concentrated on basic physical processes

- 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 atmospheres and oceans;

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

These definitions reflect the needs in the ninetieths to understand firstly major physical processes of the hydrological cycle and to find ways to model them with high accuracy.

Figure 1.3: The major decision on BALTEX Hydrology 1992 has been made at the workshop in Norrköping, Sweden, where this small lake symbolically represents the Baltic Sea and also the many hundreds of lakes within the BALTEX catchment area. From left to right: Fortelius, Nilsson, Krauss, Dahlin, Raschke, Bengtsson, Müller, Johansson, Bergström, Håkansson, Laursen. Photo courtesy: B. Carlsson, SMHI.

BALTEX contained 5 major elements: Collection of in situ and remote sensing data; Re-analysis of existing data sets; Data assimilation; Numerical experiments and coupled modeling; Process studies including field experiments.

In the recent years, BALTEX, as also most of the other CSEs of GEWEX, has enlarged its objectives towards more application-oriented research. The earliest stage concentrated indeed on basic research in coupling (or nesting) numerical models of different spatial scales with related numerical studies and in establishing - or upgrading - existing networks for ground-based climatological measurements, in almost all countries within the catchment of the Baltic Sea.

The permanent BALTEX organizational structure consisted during this “First Phase”, which ended about in 2002, of a Science Steering Group and of centers for meteorological data (German Weather Service in Offenbach), Hydrological data (SMHI in Norrköping), and for oceanographic data (FMI, Helsinnki). This group met for the first time on 16-17 May, 1994, at the GKSS Research Center (Fig. 1.4) in Geesthacht, which also became host of the International BALTEX Secretariat. Temporary ad-hoc working groups were formed to define and perform specific research activities. These were also the focus for joint modeling and also experimental activities. Many additional efforts went into the integration and upgrading successfully the already existing radar networks over Scandinavia, Germany and Poland.

An overall report on major achievements during this first phase is given in a review paper (Raschke et al., 2001).

In early 2004, the science plan for BALTEX Phase II covering the years 2003 to 2012 has been published. Future BALTEX research will continue to meet the major objectives of Phase I, in particular reducing uncertainties of estimates of water and energy cycle components in the Baltic Sea basin. The plan however enforces the application of BALTEX Phase I achievements to other research areas such as climate variability and climate change studies including scenarios of potential future climate, and environmental investigations related to nutrients and pollutants. Activities will more closely be discussed with and are expected to be applied by larger user communities, also beyond WCRP's science community, including water resource managers and intergovernmental bodies for the Baltic Sea and its catchments.

Figure 1.4: Members and Guests of the First Meeting of the BALTEX Science Steering Group at the GKSS Research Center in Geesthacht (16 to 17 May 1994). From top to bottom and left to right: First row: Isemer, Willebrand, Skouratovich, Alenius, Woetmann-Nielsen; second row: Launianen, Zaharchenko, N. Gustavsson, Ruprecht; third row: Krauss, Vent-Schmidt, Kaaring, Holopainen; fourth row: Dera, Omstedt, Vuglinsky; bottom row: Kaczmarek, Raschke, Mrs. Smelstoriute, Bengtsson.

1.4. Acknowledgments

Thanks are due to many scientists, science managers, to several national and European funding agencies and to the respective meteorological, hydrological and oceanographic services in all "BALTEX-Countries" for their active role in the formation of this large project. We all acknowledged also the important fact that the political developments at that time allowed very open co-operations.

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Chapter 2:

A short note on the role of the atmospheric circulation as part of the hydrological cycle

by

Daniela Jacob

2.1. Motivation

The investigation of long term water and energy budgets for the Baltic Sea drainage basin can be based on measurements, modelling efforts or a combination of both, but it must take into account all contributing compartments of the regional climate system. This means our knowledge regarding the Baltic Sea, the land surface and its hydrology as well as the atmosphere needs to be integrated.

Even after about 10 years of BALTEX only relatively few studies of the hydrological and energy budgets over the Baltic Sea region exist, of which some are evaluation of model results (Heise, 1996 and Karstens et al., 1996) or analyses of global re-analyses data (Roads et al. 2002; Ruprecht and Kahl, 2003). It could be shown that the long term mean precipitation exceeds evaporation at the surface of the Baltic Sea (eg. Omstedt et al., 1997; Omstedt and Rutgersson, 2000; Omstedt et al., 2000; Lindau, 2002). However a detailed analyses of long term trends and variability in the closed water and energy budgets for the Baltic Sea and its drainage basin is still missing.

The focus of this short note is on the role of the atmosphere as part of the hydrological cycle. It is well known that the climate of Northern Europe is strongly dominated by synoptic variability on many time scales. So far hardly any predictability has been demonstrated to exist beyond a few weeks. Only a small correlation (not particularly robust) with ENSO, suggesting lower surface temperatures in Northern Europe in case of an El Nino and vice versa for La Nina seems to exist. For the longer periods, as far as we presently know winter circulation is dominated by the NAO. However the cause of NAO is not really understood and may just to be an artefact in the interpretation of the chaotic variability of the westerlies.

The atmospheric circulation is dominated by transient cyclones and the climate variations from year to year dependent on changes and variations in the storm tracks. Possible ongoing changes in cyclone track and intensity are investigated for today's climate conditions as well as for future climates in several studies. For example, Sickmöller et al. analyzed winter cyclone tracks using ECMWF re-analyzed data for the time 1979 to 1997. For future climate conditions Bengtsson et al. found that there are no indications for more intense storms, but that significant changes occur in the location of the storm tracks, using an IPCC-SRES A1B scenario simulation from the ECHAM5 coupled climate model.

2.2. Major achievements during the BALTEX Phase I and related programmes

Modeling the hydrological cycle under today's climate

A comprehensive dataset of the hydrological components of the water cycle of the Baltic Sea drainage basin can be simulated by global and regional climate models. State-of-the-art global climate models still have a relative coarse horizontal resolution of either T42 or T106 corresponding to 250 km or 100 km respectively, while regional climate models usually run at 0.5° or 0.16° (50 km or about 18km).

The capability of regional models to simulate the climate in the BALTEX region could be shown in several studies (Heise, 1996; Karstens et al., 1996, Hagedorn et al., 2000; Jacob, 2001, Jacob et al., 2001). These models focus with a high horizontal resolution on the region of interest. At the lateral boundaries they are nested either into global re-analyses or global climate models, which underline the importance of the large scale atmospheric flow for regional climate.

In this study the focus lies on a 15 years time period, covering 1979 to 1993, whereas Roads et al., 2002 focus on 1988 to 1999 and Ruprecht and Kahl (2003) covered the entire re-analyses period from 1948 to 2000. Several other climatological estimates for basin mean quantities are also available form the literature, but outside the focus of this paper.

Analyzing the long-term water budgets from re-analysis data, which are seen as *the best representation of reality,* shows very large differences and points to the fact that the hydrological budgets are not closed at all.

Table 2.1: Long-term water budgets from re-analysis data

	Precipitation	Evaporation	Runoff
ERA15 over land (km^3/year):	1148	845	358
NCEP over land (km^3/year):	1191	1015	677

The observed long term mean runoff into the Baltic Sea is estimated at about 480 km^3 per year. A more detailed study with high resolution regional models improves this situation.

As an example two different versions of the MPI-M regional climate model REMO driven by ERA15 re-analysis data at the lateral boundaries deliver the following:

REMO5.0 on 0.5° versus 0.16° horizontal resolution results in a yearly run-off of 479 km^3 versus 484 km^3/year. In addition, two different REMO versions with a better representation of the coastline and a few changes in physical parameterisations (REMO5.0 versus REMO5.1 both on 0.5° resolution) simulate 479 versus 497 km^3/year runoff. A slight enhancement of the hydrological cycle over land can be seen in the 0.16° simulation, which are of the same order of magnitude as changes due to a better representation of the coastline and the physical processes. As a result the water budget over the Baltic Sea is mainly influenced by the large scale flow.

Modeling the hydrological cycle under future climate

Climate change scenarios either using the Rossby Centre modelling system and different driving models or with the REMO and ECHAM 4 driving fields, show an intensification of the hydrological cycle within the drainage basin. A few examples are given in Fig.2.1.

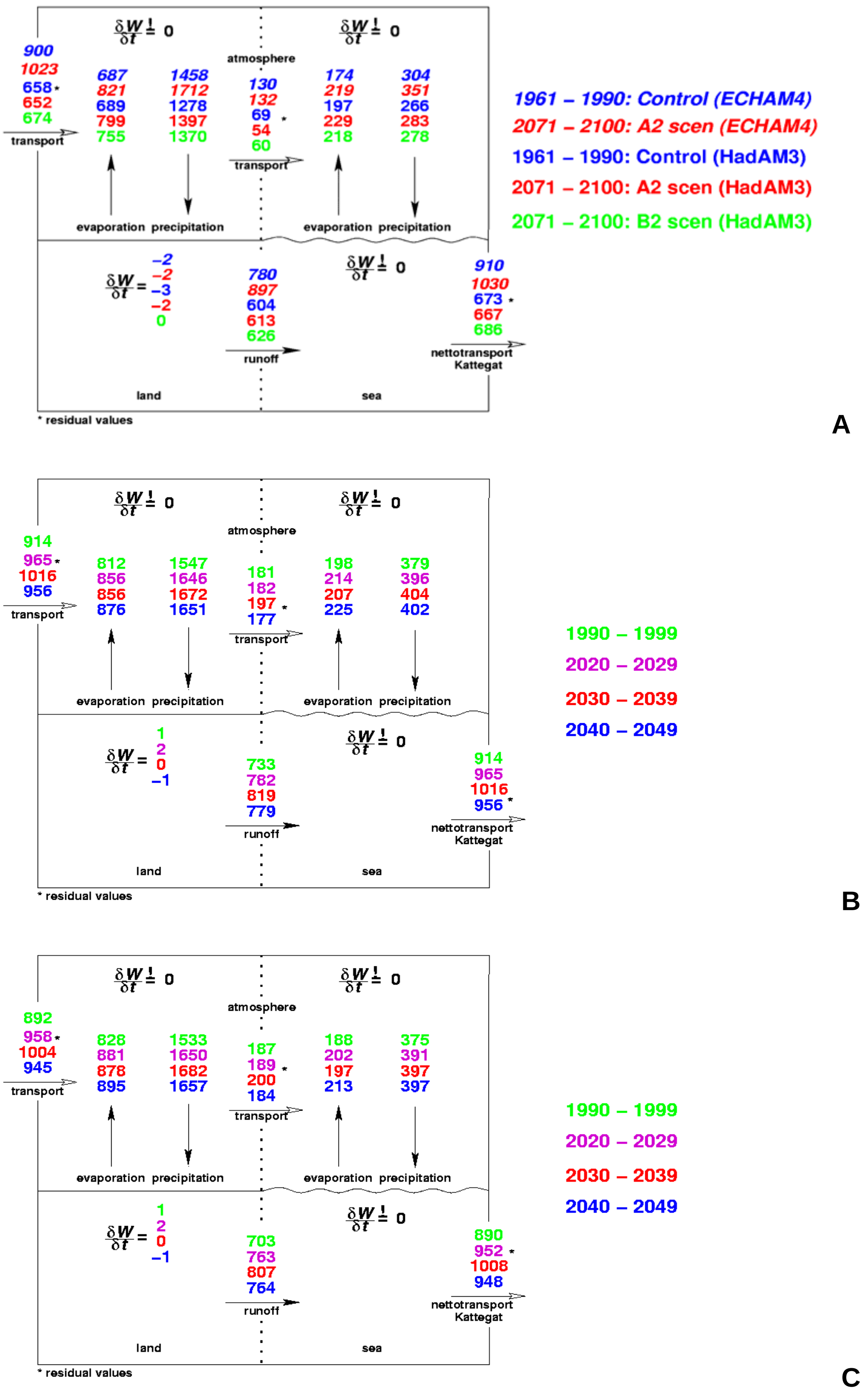


Figure 2.1: Climate change scenarios. A. ROSSBY Centre results in km³/year; B. REMO simulations on 0.5° in km³/year, B2 scenario; C. REMO simulations on 0.16° in km³/year, B2 scenario.

Not only the long term budget for the entire drainage basin is of interest, but also the horizontal distribution of for example changes in precipitation. The results of one possible B2 scenario calculated with REMO5.0 on 0.16° horizontal resolution are given in the following figure.

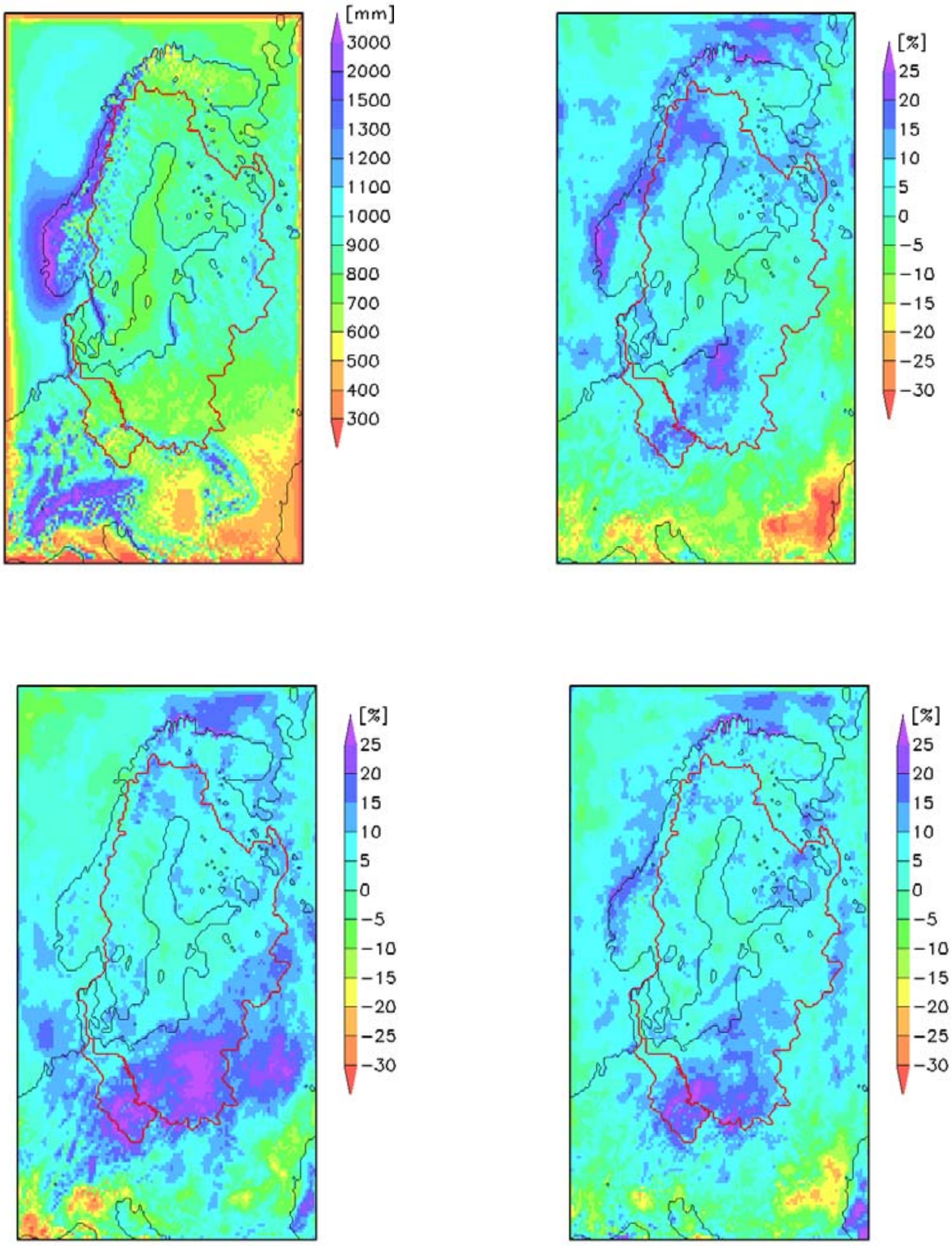


Figure 2.2: Ten year mean precipitation in mm/year for the control run (1990 to 1999, upper panel left), and changes in percent for the following decades: upper panel right: 2020 to 2029; lower panel left: 2030 to 2039; lower panel right: 2040 to 2049.

2.3. Uncertainty measures

The variety of climate change results calls for a definition of uncertainty measures, which is a difficult task. One methodology is to validate the models under today's climate against as many observations as possible and to carry out ensemble climate change simulations. The last has not been done yet, but will be a task within BALTEX Phase II.

The comparison against measurements can not be done for all hydrological quantities and time scales, but for example the precipitation over land is relatively well observed. Over water almost no long term observations exist, only for certain periods measurements have been made. Here comprehensive model calculations are very useful. In addition, the quantification of the uncertainty in the observations is also difficult.

As an example the annual cycle of precipitation over land for the period of 1979 to 1993 and the time series of average precipitation for the same period are shown in Figure 2.3. REMO results on 0.5° resolution are compared against two different precipitation climatologies. It is clearly visible that the differences in the observed climatologies are very large, especially in winter. This is caused by the under-catch of solid precipitation during the winter months, which is very difficult to correct.

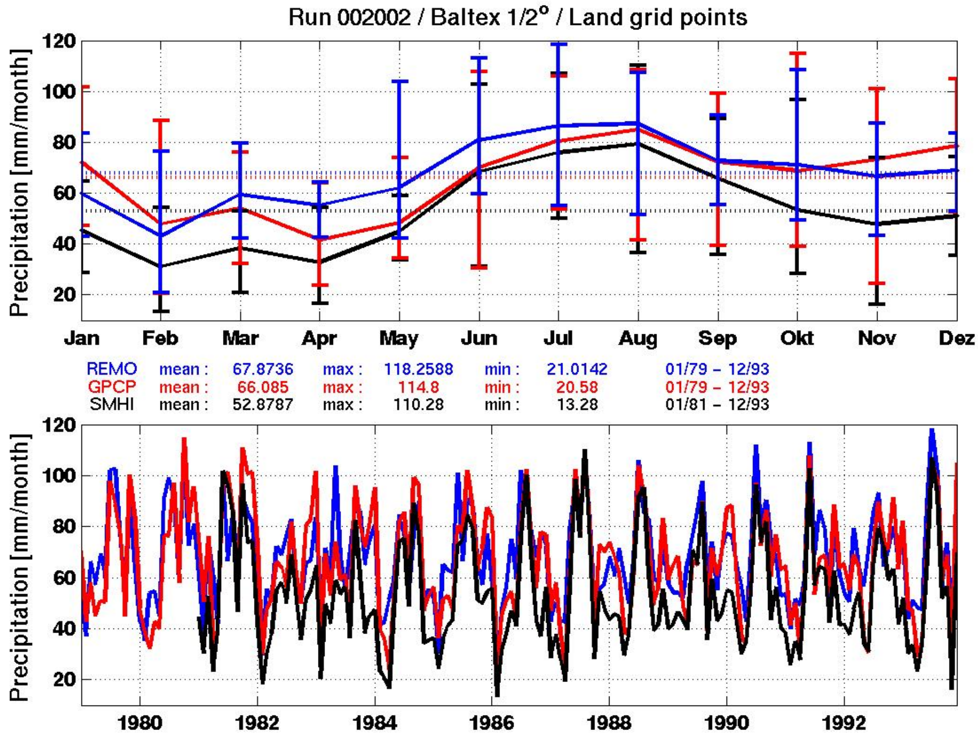
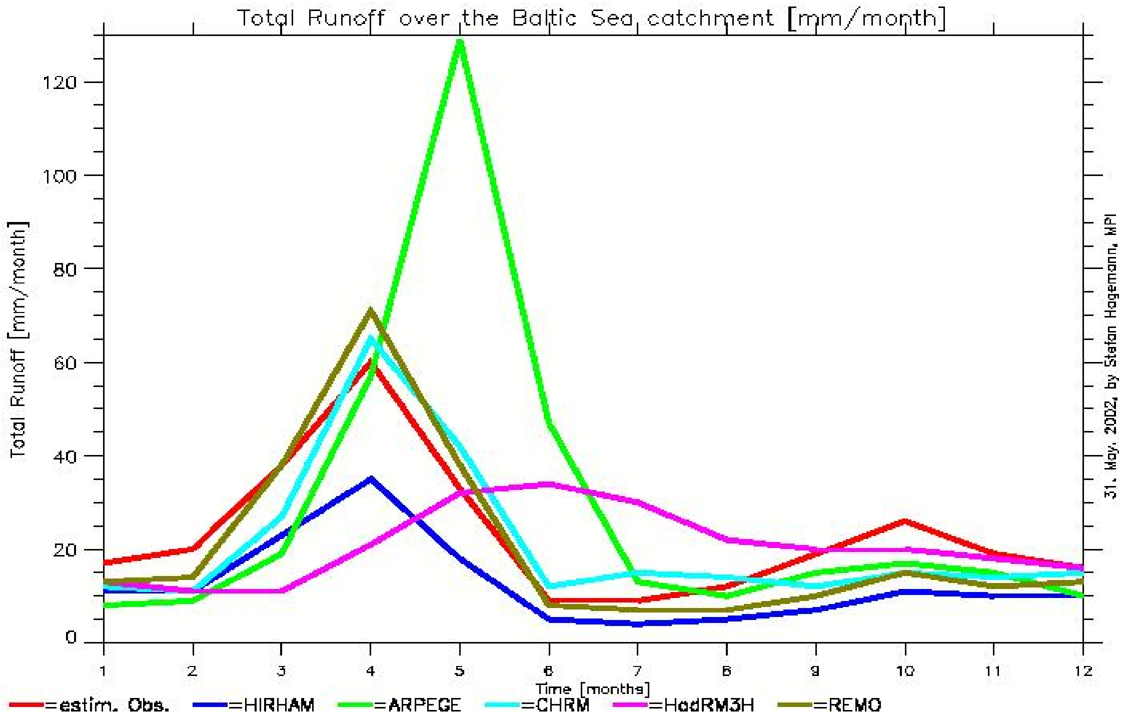


Figure 2.3: Annual cycle of precipitation over land (upper panel) and time series of average monthly precipitation for the period of 1979 to 1993 (lower panel).

Another possibility to quantify uncertainties is a model inter-comparison. As an example, a few results from different regional climate models and one global model (Arpeche) for the period 1979 to 1993 are shown in Fig. 2.4. The study was part of the EU-funded project, MERCURE.



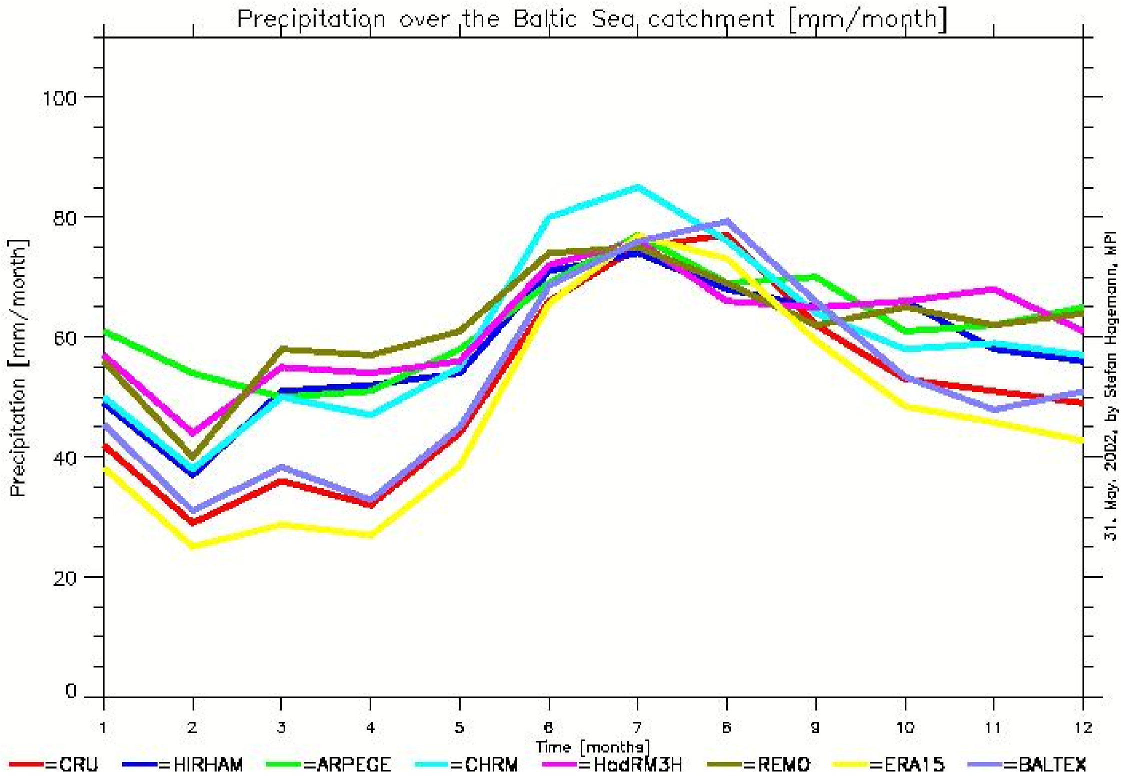


Figure 2.4: Mean annual cycle of total runoff (upper panel) and precipitation (lower panel) over the Baltic Sea catchment from different regional climate models and one global model (Arpeche), for the period 1979 to 1993.

2.4. Conclusions

Regional climate models, which have been developed during the last 10 years, play a major role in the definition and investigation of long term water budgets for the Baltic Sea drainage basin. They can be used to study today's long term means as well as annual and inter-annual variability. In addition, they can be used for climate change studies, which will estimate changes in means as well as in extremes. Changes in the annual cycle can also be detected.

However, the above results show that there are still large uncertainties in the estimations of the water budget. The annual cycle is quite well reproduced within the regional climate model simulations, but the accuracy of the long term budgets is still insufficient.

Detailed investigations using coupled regional climate model systems as well as all available observations are needed to reduce uncertainties and increase our understanding of the water budget for the Baltic Sea drainage basin.

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Chapter 3:

Baltic Sea

by

Anders Omstedt, Jüri Elken, Andreas Lehmann and Jan Piechura

3.1. Motivation

The Baltic Sea system, Figure 3.1a and b, constitutes a unique and important environment that is undergoing large changes due to eutrophication, pollution, misuse of natural resources such as over fishing, and climate change. The region shows large seasonal, inter-annual and regional variations primarily due to its location between the North Atlantic Ocean and Eurasia. In the Baltic Sea drainage basin about 85 million people live in 14 countries with rapid political, industrial and socio-economic changes. The Baltic Sea is highly dynamic and strongly influenced by large-scale atmospheric circulation, river runoff and by the restricted water exchange due to its narrow entrance area. Sea ice is formed every year with a long-term average maximum coverage of about half of the surface area.

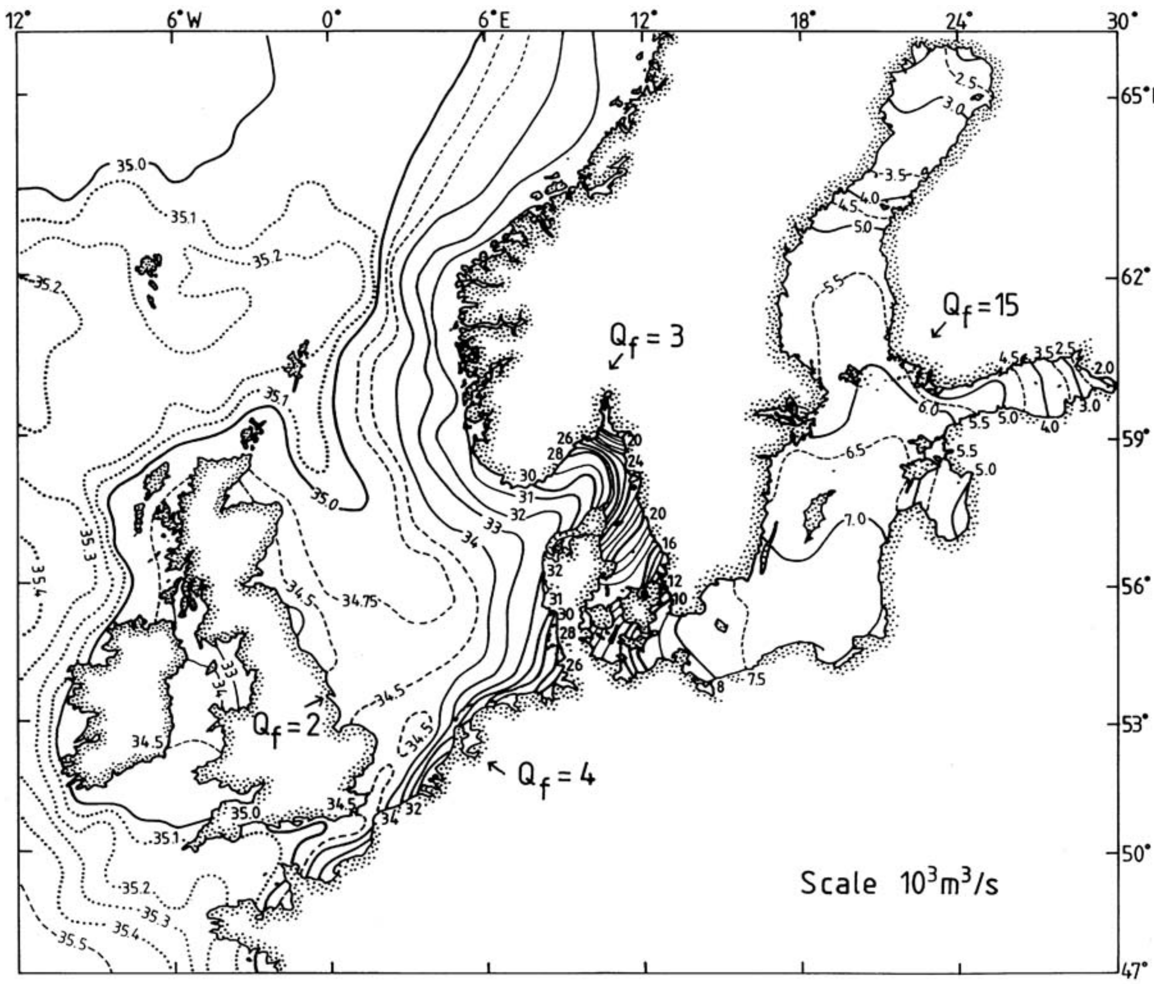

Figure 3.1a: Surface salinity distribution. Also indicated is runoff, Q_f , to the Baltic Sea (15000 m^3 s^{-1}), to Kattegat and Skagerak (3000 m^3 s^{-1}), to the Danish, German, Dutch, and Belgian coasts (4000 m^3 s^{-1}), and to the east coast of England (2000 m^3 s^{-1}). From Rodhe (1998).

How the Baltic Sea functions and how future changes will influence the Baltic Sea are major questions of concern. To answer these we need to build our understanding of the Baltic Sea and in particular how energy, water, and material are transported and transformed in the system. Thus we need to know how much fresh and saline water that enters and leaves the system, how energy is transformed from the atmosphere into the Baltic Sea, the load and how the load of different substances from the atmosphere and the rivers changes and how the transformation mechanisms in the Baltic Sea works.

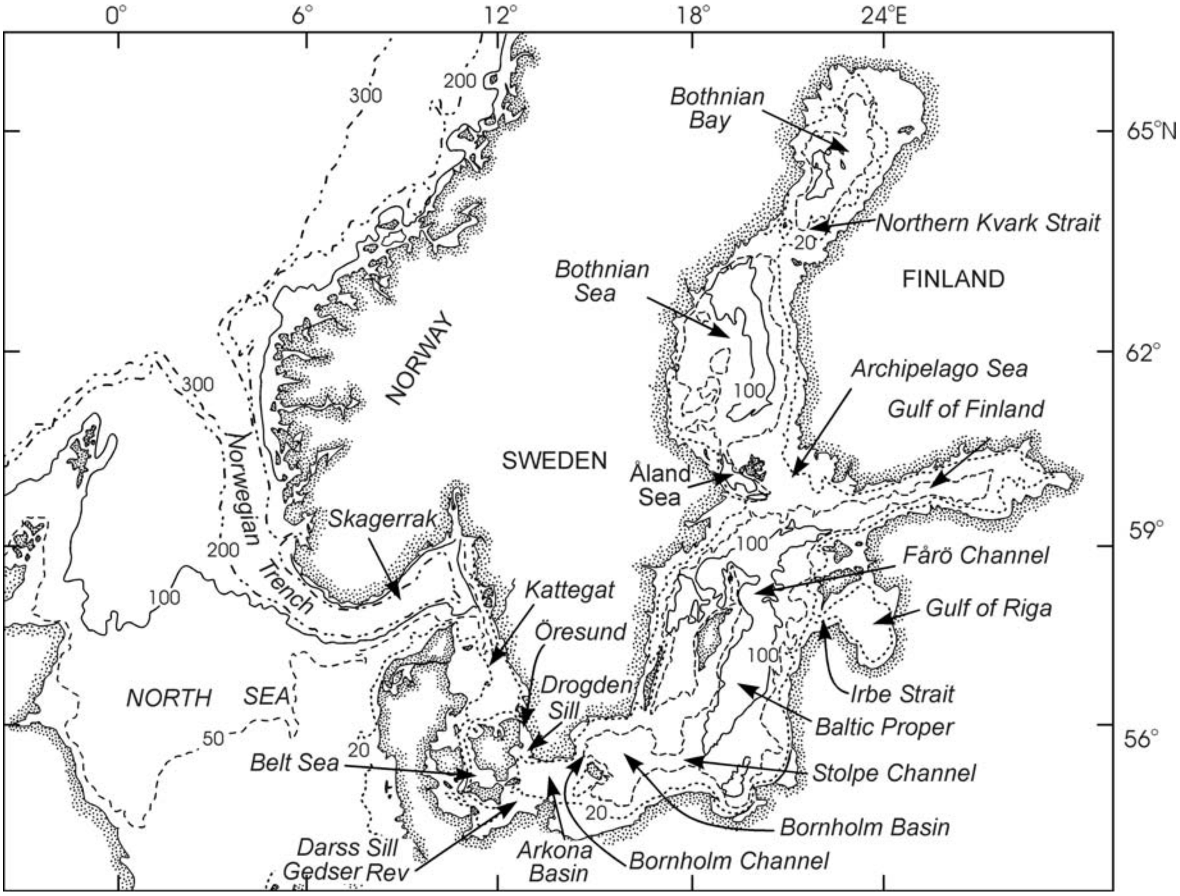

Figure 3.1b: The Baltic Sea – North Sea region with depth contours indicated.

Baltic Sea water and energy cycles were extensively studied in the twentieth century and major research efforts were made in the HELCOM (1986) and BALTEX (1995) projects. In 1986 the Helsinki Commission (HELCOM) summarized over ten years of joint efforts in determining the various terms of the Baltic Sea water balance. However, these terms were calculated in isolation, without modelling the Baltic Sea. In the late 1980s the Global Energy and Water Experiment (GEWEX) was developed within the framework of World Climate Research Programme (WCRP). The aims were to provide a better understanding of global, regional, and local processes that exchange energy and water in the climate system. Within GEWEX, six continental-scale experiments were initiated in various regions, with only one including an ocean component the Baltic drainage basin. The planning for BALTEX started in the early 1990s and the programme has now been running for 10 years (BALTEX, 1995, 1997). For information on BALTEX and its various data centres the reader is referred to the BALTEX Home page (http://w3.gkss.de/baltex/) and BALTEX (2004).

In the present chapter we aim: (1) to trace the development of Baltic Sea research, in particular into its water and heat cycles, and Baltic Sea modelling over the last 10 years; and (2) to indicate where we stand today: what is known and what seem to be the key questions for future Baltic Sea research. The view is based on results from the BALTEX Phase I period (1993–2002), but also includes results from other programs that have improved the understanding of how the Baltic Sea functions. Examples of such programmes are the Gulf of Riga-project funded by the Nordic Council of Ministers and the EU-funded project BASYS (Baltic Sea System Study).

3.2. The water and heat budgets of the Baltic Sea

The water and heat cycles of the Baltic Sea are affected by a number of small-scale features, for example, its complex coastlines and many islands. The complex bathymetry of the Baltic Sea with its narrow straits and channels, strong stratification, quite small radius of deformation of only several kilometres, and heterogeneous sea ice structure also influence the dynamics of the Baltic Sea. As a consequence, many physical processes at various time and space scales are involved when calculating the water and heat cycles (Figure 3.2). In general, there is insufficient knowledge of these cycles with regard to observations as well as models. For example, how wind and precipitation are affected by the Baltic Sea and how wind energy enters the Baltic Sea and powers deep-water mixing are matters not yet understood. Still, BALTEX Phase I has witnessed several important achievements.

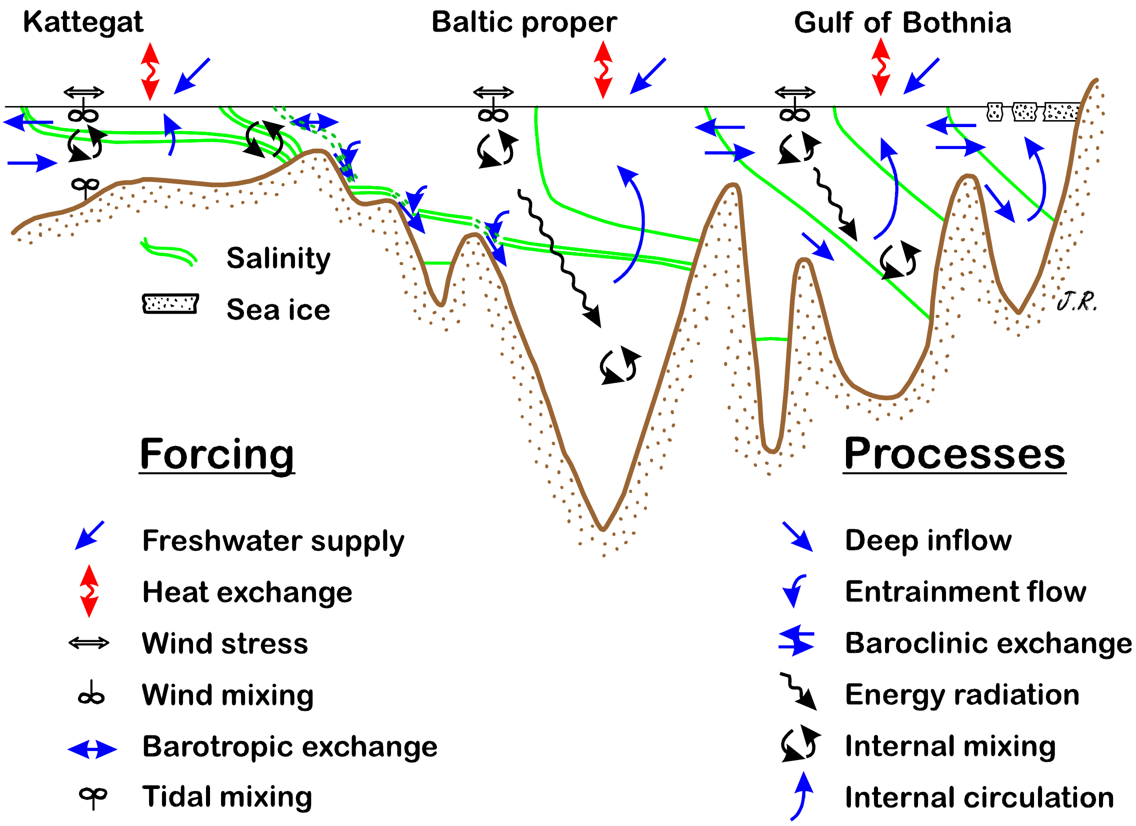

Figure 3.2: A conceptual model of the Baltic Sea. On the left are forcing, and on the right processes. Green lines show the salinity stratification, and the presence of sea ice is indicated in the Bothnian Bay (from Winsor et al., 2001).

BALTEX research mainly deals with water and heat cycles. Heat is, however, only one kind of energy involved in the energy cycle, which also includes various interactions between mean and turbulent kinetic energy, internal wave energy, and potential energy. Little is known about how external energy is transformed in the Baltic Sea (Axell, 2001).

Starting from the volume conservation principle, we can write the water balance equation as follows (Omstedt & Rutgersson, 2000; Stigebrandt, 2001):

$$A_s \frac{dz_s}{dt} = Q_i - Q_o + (P - E)A_s + Q_r + Q_{ice} + Q_{rise} + Q_T + Q_S + Q_g \qquad \{1\}$$

where A_s is the surface area of the Baltic Sea, z_s the water level of the Baltic Sea, Q_i and Q_o the in- and outflows through the Baltic entrance area, P and E the precipitation and evaporation rates, Q_r the river runoff, Q_{ice} the volume change due to ice advection from the Baltic Sea, Q_{rise} the volume change due to land uplift, Q_T and Q_S the volume changes due to thermal expansion and salt contraction, and Q_g the groundwater inflow.

In the discussion given below we will neglect contributions from Q_{ice} (order of 10^2 m^3/s, Omstedt and Rutgersson, 2000), Q_{rise} (order of 10^1 m^3/s, Omstedt and Rutgersson, 2000), Q_T, Q_S , and Q_g (order of 10^2 m^3/s, Peltonen, 2002).

An estimate of Q_S can be derived by considering that 1 salinity unit corresponds to about 1 cm change in sea level (the slope from Bothnian Bay to Skagerrak drops about 35 cm and the salinity increases from almost 0 to 35). Winsor et al. (2001, 2003) indicate that Baltic Sea salinity varies about 1 salinity unit per 30 years; using this number, we estimate that the volume change due to salt contraction on an annual basis is about 1/15 cm or in the order of 10^1 m^3/s (Baltic Sea surface area inside the entrance sills is about 370 000 km^2). The salinity in our paper is given according to the Practical Salinity Scale defined as a pure ratio without dimensions or units. This is the standard since 1981 when UNESCO adopted the scale. Thermal expansion due to heating and cooling may cause seasonal variation in volume flow in the order of 10^3 m^3/s (Stigebrandt, 2001), but on an annual scale the volume flow is at least one order of magnitude less. The left term in Equation (1) is the change in water storage and is important for short-term estimations of the water balance (Lehmann & Hinrichsen, 2001). See Table 3.1 for estimates of the various terms.

Table 3.1. Estimated annual mean volume flows for the Baltic Sea (order of magnitude). Unit 10^3 m^3 s^{-1}. The flows are denoted by: inflow (Q_i), outflow (Q_o), net precipitation (P-E), river runoff (Q_r), the volume change due to ice advection from the Baltic Sea (Q_{ice}), the volume change due to land uplift (Q_{rise}), the groundwater inflow (Q_g), the volume changes due to thermal expansion (Q_T)and salt contraction (Q_S). A_s denotes the Baltic Sea surface area.

Q_i (m^{3}s^{-1})	Q_o (m^{3}s^{-1})	Q_o-Q_i (m^{3}s^{-1})	(P-E)A_S (m^{3}s^{-1})	Q_r (m^{3}s^{-1})	Q_{ice} (m^{3}s^{-1})	Q_{rise} (m^{3}s^{-1})	Q_g (m^{3}s^{-1})	Q_T (m^{3}s^{-1})	Q_S (m^{3}s^{-1})
10^5	-10^5	-10^4	10^3	10^4	-10^2	-10^1	10^2	$\pm10^2$	$\pm10^1$

From heat conservation principles we can write the heat balance equation for the Baltic Sea according to Omstedt and Rutgersson (2000):

$$\frac{dH}{dt} = (F_i - F_o - F_{loss})A_s \tag{2}$$

Where $H = \iint \rho c_p T dz dA$ is the total heat content of the Baltic Sea, F_i and F_o the heat fluxes associated with in- and outflows, and F_{loss} the total heat loss to the atmosphere (note that the fluxes are positive when going from the water to the atmosphere). F_{loss} reads:

$$F_{loss} = (1 - A_i)(F_n + F_s^o) + A_i(F_w^i + F_s^i) - F_{ice} + F_r + F_g \tag{3}$$

where

$$F_n = F_h + F_e + F_l + F_{prec} + F_{snow} \tag{4}$$

The various terms in Equations (3) and (4) are denoted as follows: A_i is ice concentration, F_h the sensible heat flux, F_e the latent heat flux, F_l the net long wave radiation, F_{prec} and F_{snow} the heat fluxes associated with precipitation in the form of rain and snow, respectively, F_s^o the sun radiation to the open water surface, F_w^i the heat flux from water to the ice, F_s^i sun radiation through the ice, F_{ice} the heat sink associated with ice advection from the Baltic Sea, and F_r and F_g heat flows associated with river runoff and ground water flow. See Table 3.2 for estimates of the various terms.

Table 3.2. Estimated annual mean heat fluxes for the Baltic Sea (order of magnitude). The fluxes are denoted as: net heat flux (F_n defined in Equation 4), sun radiation to the open water surface (F_s^o), heat flow from water to ice (F_w^i), sun radiation through ice (F_s^i), F_{prec} and F_{snow} the heat fluxes associated with precipitation in the form of rain and snow, F_i the heat sink associated with ice advection from the Baltic Sea, F_r and F_g heat flows associated with river runoff and ground water flow, F_i and F_o the heat fluxes associated with in- and outflows, and F_{loss} (defined in Equation3) the total heat loss to the atmosphere (note that the fluxes are positive when going from the water to the atmosphere).

F_n (Wm^{-2})	F_s^o (Wm^{-2})	F_w^i (Wm^{-2})	F_s^i (Wm^{-2})	F_{prec} (Wm^{-2})	F_{snow} (Wm^{-2})	F_i (Wm^{-2})	F_r (Wm^{-2})	F_g (Wm^{-2})	$F_o – F_i$ (Wm^{-2})	F_{loss} (Wm^{-2})
10^2	$–10^2$	10^0	$–10^0$	10^{-1}	10^{-1}	$–10^{-1}$	10^{-1}	10^{-1}	10^0	$–10^0$

3.3. Major achievements during BALTEX Phase I and related programmes.

The rapid development of technology (internet, computers, and remote sensing) have improved our ability to access data and run numerical models, and introduced new scientific instruments (including new satellite sensors) and associated methods. Also, the dramatic political changes of the last decade have opened up new possibilities for communicating and performing field experiments in previously closed areas. These developments have strongly influenced Baltic Sea research over the last 10 years. The following sections outline and discuss some of the major achievements of Baltic Sea research of the last decade; together with some key scientific questions to be addressed in future research. From an oceanographic point of view, the major developments include the following:

1. Meteorological, hydrological, ocean and ice data are now available for the research community.
2. Progress in understanding of the strong impact of large-scale atmospheric circulation on Baltic Sea circulation, water mass exchange, sea ice evolution, and changes in the ocean conditions of the Baltic Sea.
3. Progress in understanding of the importance of strait flows in the exchange of water out from and within the Baltic Sea.
4. Progress in understanding of intra-basin processes.
5. Ocean models introduced into Baltic Sea water and energy studies.
6. Development of turbulence and 3-D ocean circulation models for application to the Baltic Sea.
7. Improved Baltic Sea ice modelling and increased understanding of the need for coupled atmosphere–ice–ocean–land models.

The major developments are discussed in more detail by Omstedt et al. (2004), below we will only illustrate some major BALTEX achievements.

The dynamics of inflows in the cascade of Baltic Sea deep sub-basins have been studied by several scientists. Experimental focus has been on the Stolpe Channel (Piechura et al., 1997) controlling the deepwater flow into the Gdansk/Gotland basins and further on. The complex dynamics of the

“2003” inflow to the Baltic Sea was described by Piechura & Beszczynska-Möller (2004) and are illustrated in Figure 3.3. The new observations illustrate several small-scale features, such as fronts, eddies, and internal waves. A general understanding of these processes is still lacking, and only a few results of modelling these processes are yet available (Zhurbas et al., 2003, Lehmann et al., 2004). The flow regime in the straits/connection areas is controlled by topography, rotation, and/or stratification and it is generally geostrophically balanced (Lilover et al., 1998; Stigebrandt, 2001; Omstedt and Axell, 2003) but shorter timescale behaviour is strongly modified by winds and water levels (e.g. Elken et al., 2003). In the wider connection areas (Irbe Strait to the Gulf of Riga, entrance to the Gulf of Finland, Åland Sea to the Gulf of Bothnia), bi-directional flows feed quasi permanent but migrating and self-restoring salinity fronts (Lilover et al, 1998; Pavelson et al., 1997) that are similar to the Kattegat–Skagerrak front controlling the major inflows to the Baltic Sea (e.g. Stigebrandt & Gustafsson, 2003).

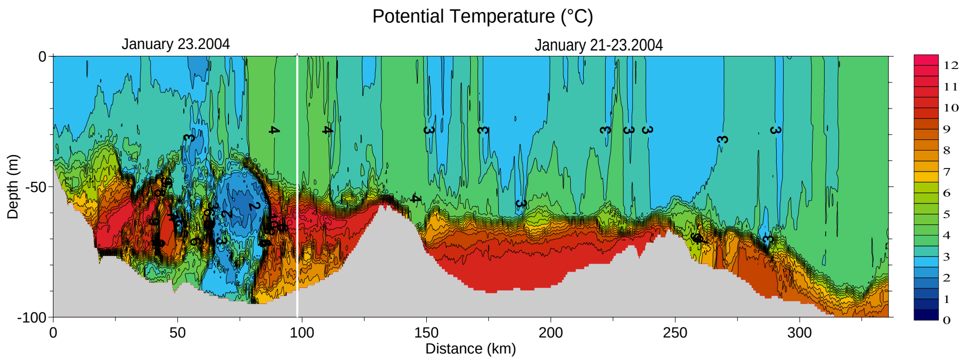

Figure 3.3: Measured temperatures in the Bornholm Basin (left) and the Stolpe Channel (right) during January 2003. The left illustrates a cold water inflow entering into warm bottom water. In the right figure one can notice a Stolpe Sill overflow with unusual warm temperatures. For details see Piechura & Beszczynska-Möller (2004).

Intrabasin processes are characterized by a much larger extent of scales. Traditional concepts consider the basins as good “mixers” of received water properties due to mesoscale eddies etc. However, investigations of juvenile freshwater patterns originating from the spring maximum of river discharge demonstrate clearly that their spreading is much faster than it would be expected from the quite slow mean circulation in the Baltic Sea (Eilola & Stigebrandt, 1998, Stipa et al., 1999). This is coherent with the modelling results by Lehmann and Hinrichsen (2000) who have shown that under realistic wind forcing, stable current bands exist in the several sub-regions. Stability of currents and excitation of low-frequency waves (transient Kelvin waves, coastal-trapped waves, basin-scale topographic waves) has recently again (after a boom of interest in the 1980-s) attracted several investigators (Fennel & Seifert, 1995, Raudsepp, 1998, Pizarro & Shaffer, 1998, Raudsepp et al., 2003, Stipa 2003). Their consequences on the water and heat balance in the changing climatic conditions have to be further evaluated.

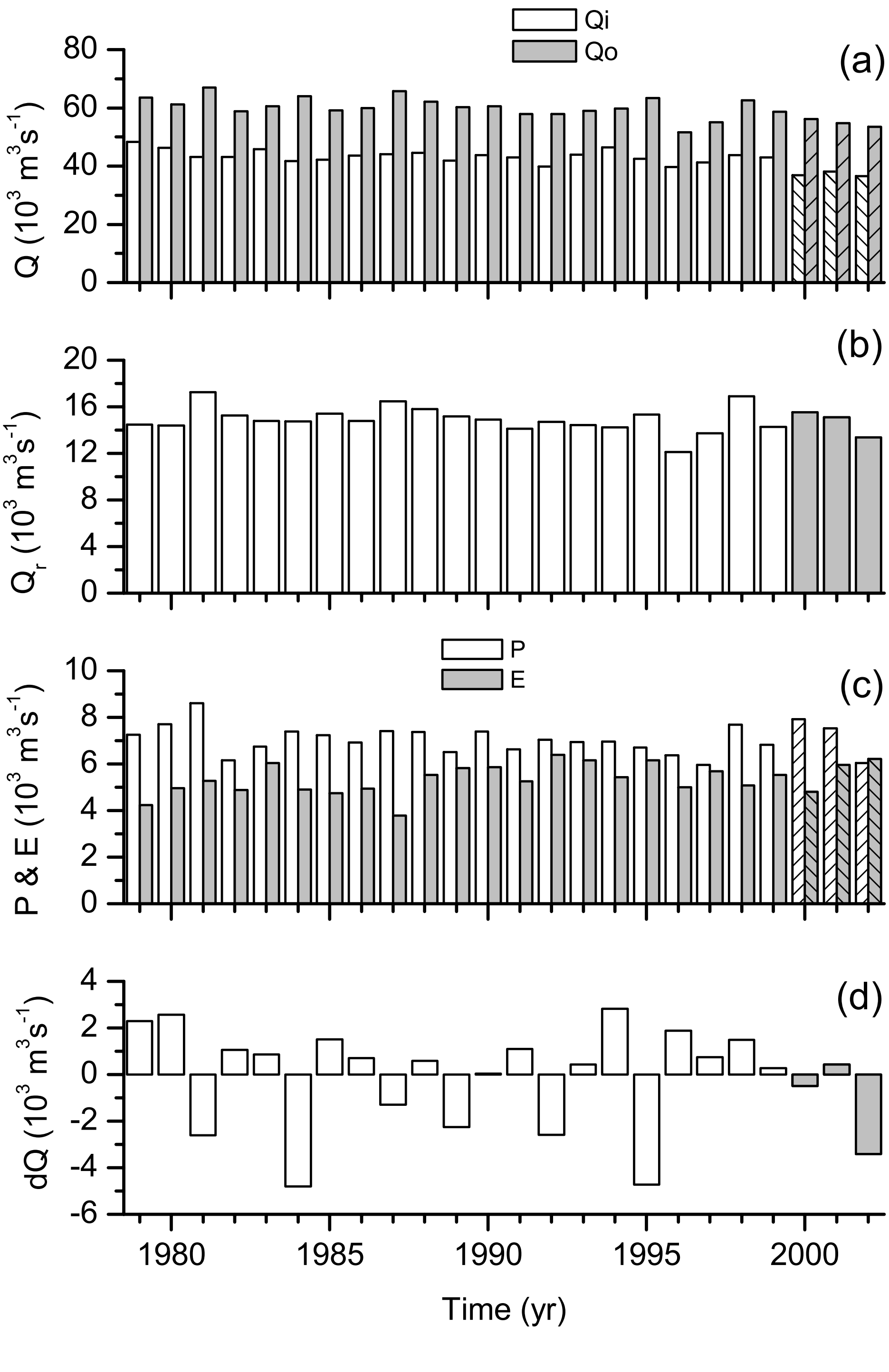

Figure 3.4: Baltic Sea (excluding the Kattegat and the Belt Sea) annual means of inflows and outflows (a), river runoff (b), net precipitation (c), and net volume change (d). The BALTEX/Bridge period is indicated. For details see Omstedt and Nohr (2004).

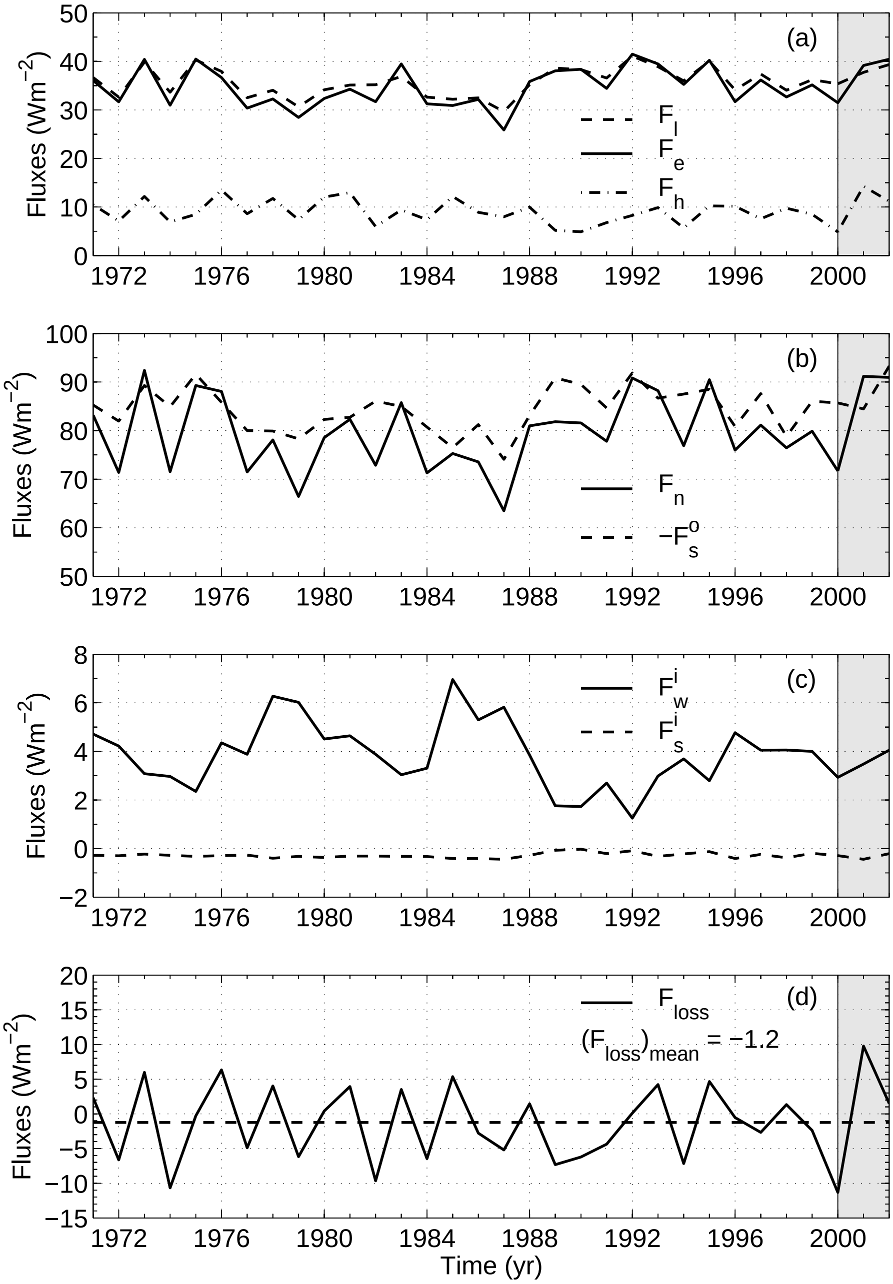

Figure 3.5: Annual means of: sensible heat (F_h), latent heat (F_e), net long-wave radiation (F_l), net heat flux ($F_n = F_h + F_e + F_l$), sun radiation to the open water surface (F_s^o), sun radiation through ice (F_s^i), heat flow from water to ice (F_w^i), and net Baltic Sea heat loss $F_{loss} = (1-A_i)(F_s^o + F_h + F_e + F_l) + A_i(F_s^i + F_w^i)$, where A_i is the ice concentration. For details see Omstedt and Nohr (2004).

Baltic Sea modelling has considerable been improved and introduced into water and heat-balance studies as a tool for synthesizing available data and building understanding (Omstedt et al., 1997; Gustafsson, 2000a,b; Lehmann & Hinrichsen, 2000; Schrum & Backhaus, 1999; Meier & Döscher, 2002). This is a great step forward, as meteorological, hydrological and ocean data often are sparse in terms of time and spatial resolution. Also, modelling the Baltic Sea allows consistent estimates of in- and outflows. Earlier studies often analysed individual terms in the water and heat cycles in isolation for various time periods. A recent up-date on modelling the water and heat cycles including an analysis of the BALTEX/Bridge period can be found in Omstedt and Nohr (2004). They also analyzed recent climate trends over the Baltic Sea and showed that climate change assessments should include trends and variability studies on the water and the heat balance components in addition to parameters such as temperature and wind. The annual variations of the various terms in the water budget and heat balance are illustrated in Figures 3.4 and 3.5.

Major achievements, partly done within the EU-funded project BALTEX-BASIS (Launiainen and Vihma, 2001) have been made in modelling ice temperature and ice–atmosphere fluxes, understanding and treating the effects of snow on ice (Launiainen & Cheng, 1; Cheng et al., 2001; Launiainen et al., 2001; Saloranta, 2000; Vihma & Brummer, 2002, Granskog et al., 2003).

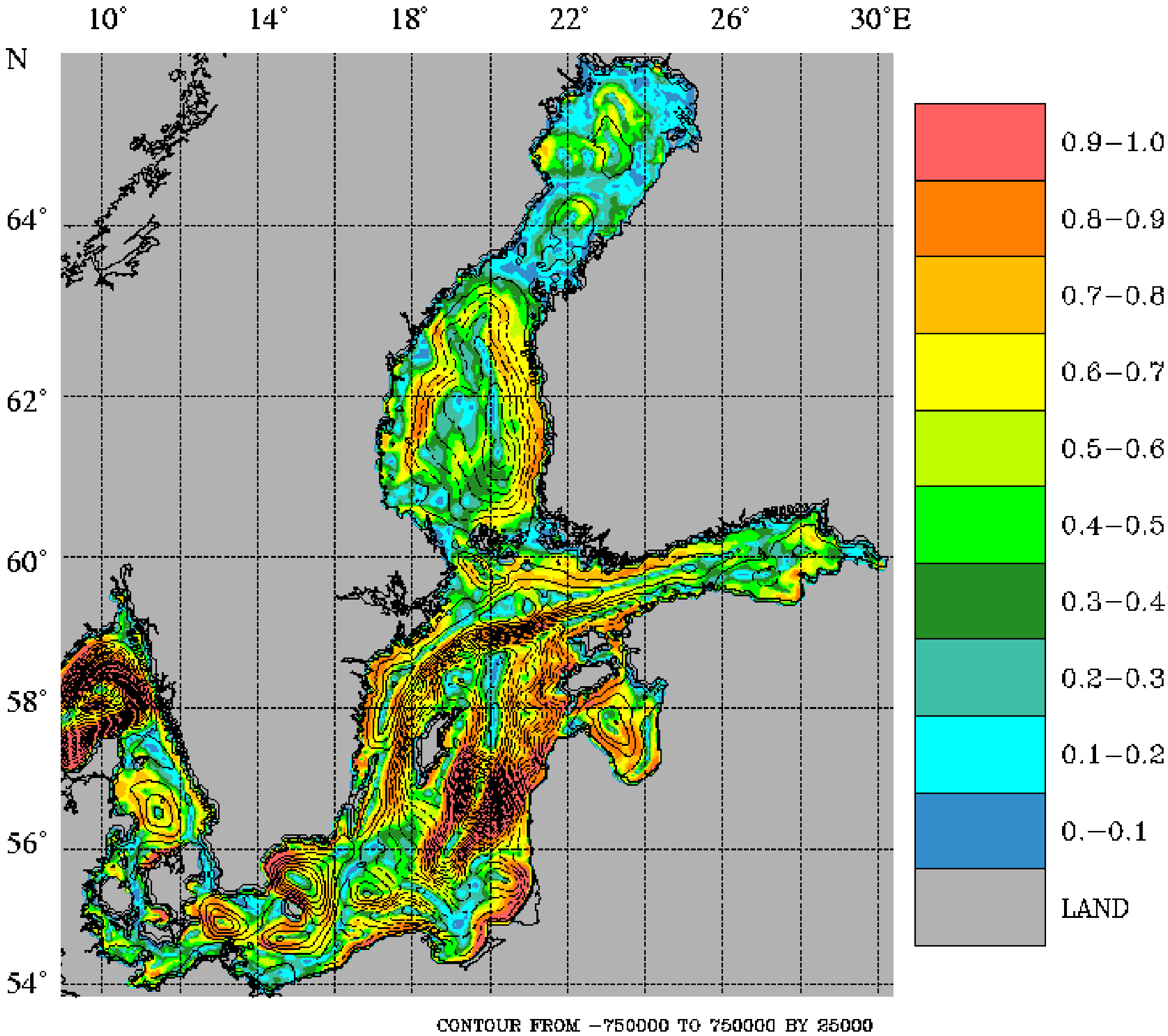

Figure 3.6: Stream function representation of the mean barotropic circulation for January, February, and March 1987, underlined by the stability of the barotropic flow. The colour bar represents stability values of 0–1. Contour interval is 0.25 x 10^5 m^3 s^{-1}. For details see Lehmann & Hinrichsen (2000).

3-D ocean modelling studies have improved the physics by including improve turbulence models, worked on atmosphere-ice-ocean coupling and building our understanding of three-dimensional circulation (Lehmann et al., 2002), decadal variability (Meier & Kauker, 2003a; Kauker & Meier, 2003), and climate change (Meier & Kauker, 2003b). Lehmann and Hinrichsen (2000) have shown using model simulations that under realistic wind forcing, stable current bands exist in the Baltic proper and the Bothnian Sea (Figure 3.6). Re-analysis of the Estonian mesoscale CTD database confirms the existence of these current loops in the Eastern Gotland Basin.

The development of coupled atmosphere–ocean models in BALTEX Phase I have taken several important steps. Initial work on atmosphere–ice–ocean coupling (Gustafsson et al, 1998) focused on operational forecasting aspects, and highlighted the need for data assimilation methods for sea surface temperatures when forecasting sea ice formation. Climate modelling was addressed by Rummukainen et al. (2001), where a regional coupled model for northern Europe was developed and used for downscaling general circulation model simulations. In this system, the Baltic Sea was modelled as coupled basins and lakes were introduced into the land surface scheme. Coupling the atmosphere and ocean using fully 3-D ocean models was studied by Hagedorn et al., (2000); further aspects of such coupling have more recently been studied by Döscher et al. (2002) and Schrum et al. (2003).

3.4. Summary and Perspective

Appendix A present both earlier and more recent estimates of the water and heat fluxes. The tables indicate that while several methods are now available, few of these take account of all components or provide estimates of uncertain factors. The values presented in the tables were produced using different methods and refer to different time intervals. Due to the large seasonal and interannual variability in the Baltic Sea system, all comparisons should be made for similar periods, which was one of the reasons for the BALTEX/BRIDGE period.

The major water balance components in the Baltic Sea are in- and outflows at the entrance area, river runoff, and net precipitation. Change in water storage also needs to be considered.

The outflowing water from the Baltic Sea is estimated as a long-term mean to 80,000 m^3/s, with an interannual variability of ±10,000 m^3/s. River runoff under current climatic conditions (the last 100 years) is estimated (the Belt Sea and the Kattegat excluded) at 14,000 m^3/s, with an interannual variability of ±4,000 m^3/s. Net precipitation over the Baltic Sea under current climatic conditions (the last 100 years) is estimated at 1,500 m^3/s, with an interannual variability of ±1,000 m^3/s. The accuracy in the different terms is not known but the mean error of net water balance on decadal time scale has been estimated to about 600 m^3/s (Omstedt and Nohr, 2004).

In terms of long-term mean, the Baltic Sea is almost in thermodynamic balance with the atmosphere. The dominating fluxes, as annual means, are the sensible heat, the latent heat, the net long wave radiation, the solar radiation to the open water and the heat flux between water and ice. The accuracy in modelling the different fluxes is not known but the net heat balance on decadal time scale can be modelled with a mean error of about some Wm^{-2} (Omstedt and Nohr, 2004).

Below the major achievements during last decade of Baltic Sea physical research are summarized together with some key questions to be addressed in future research:

- Meteorological data bases are available for the research community partly as station data and partly as gridded data. However, the gridded data sets are coarse and data sets that resolve the regional geometry are needed. The quality of the data, the data sets and the resolution are main topics for future research.

- River runoff data as monthly means to different sub-basins of the Baltic Sea are available. The observed data are however often delayed several years and more research related to the regional distribution and quality of the measurements is needed.

- Ocean and ice data are available from different data centres and data providers. The data are irregular in space and time and mainly some ice gridded data sets are yet available. New initiatives in generating gridded ocean and ice data sets are needed, together with assessments of data quality.

- The large interannual variability in the Baltic Sea region is mainly driven by large-scale atmospheric circulation. This can be seen in different time series, for example, ice and sea levels. Future research need to link our understanding of large-scale circulation above the Baltic Sea with global circulation and improved understanding of interannual, decadal and long-term variability.

- The Baltic Sea dynamics is strongly dependent on mixing processes in the entrance area as well as the Skagerrak-Kattegat ocean front. The modelling of this front and its consequences for the inflows needs further research efforts.

- Innovative ocean measuring methods have given insights into the dynamics and mixing of the inflowing dense bottom water to the Baltic Sea. A general understanding of these processes and how they should be parameterized or modelled are still lacking and need further research.

- The importance of the various straits in the Baltic Sea has been of increasing interest for the understanding of the water exchange and mixing. Of special interests are the straits in the Baltic entrance area, the Bornholm Channel, the Stolpe Channel, and the straits connecting the Gulf of Riga, the Bothnian Sea and the Bothnian Bay with surrounding sub-basins. New innovative measurements as well as new modelling efforts are needed.

- Understanding of the importance of intra-basin processes such as spreading of river run-off water, bottom pool dynamics, coastal-trapped waves, internal waves, Baltic Sea eddies, and up- and down-welling have been achieved. The importance of these processes for the water and energy exchange within the Baltic Sea needs to be addressed in the future research.

- Major improvements in modelling of the stratification in the ocean surface layer have been achieved by introducing two-equation turbulence models in Baltic Sea modelling. Also an increased understanding of the importance of deep water mixing has been gained. Several aspects as breaking surface waves, air bubbles, Langmuir circulation, internal wave breaking and deep water mixing need new research efforts.

- Ocean models have been introduced into Baltic Sea water and energy studies. They form the logical tool for integrating data from the atmosphere, river runoff and the Baltic Sea, reviewing present knowledge as represented by different models and parameterization schemes and closing the BALTEX box. New efforts in making in- and outflow measurements available are needed together with improved modelling.

- Major improvements in 3-D ocean modelling of the Baltic Sea-North Sea systems have occurred. New efforts in performing careful inter-comparison between the different 3-D models both with regard to long runs as well as climate sensitive processes are needed in the future work. The 3-D models should also be used to interpret observations and in motivating new observational programs for addressing processes needed to be included in the water and energy studies.

- Increased understanding related to the role of sea ice in the water and heat cycles. The complex structure of sea ice and snow need further considerations with regard both to dynamical (e.g. ice thickness distribution) and thermo dynamical (e.g. albedo) aspects. New observational programs related to sea ice are also strongly needed.

- Decadal and long-term modelling is now technically possible and interdisciplinary work concerning coupled modelling has started. These aspects have strongly improved our ability to address questions about the Baltic Sea climate and environment, topics that will be the further studied during BALTEX Phase II.

BALTEX is one of the major multidisciplinary research programs related to the Baltic Sea and have been a great success for particularly the ocean community. The programme has clearly showed the need for bringing meteorologists, hydrologists and oceanographers together. Still BALTEX research is needed and planned for a second phase from 2003 to 2012 (BALTEX, 2004). Visions in Phase II are to better understand the physical mechanisms that have caused the past and present climate variability and change and what will happen in the future. Major questions are: Will the Northern Europe become wetter or dryer? Will the Baltic Sea climate become fresher or more saline? The modelling work in Phase II aims to the development of a hierarchy of coupled atmosphere–land–ocean models with a horizontal resolution in the order of the internal Rossby radius (1–10 km). This will lead to improved description of the exchange flow through the Danish Sound between the North and Baltic Seas and between the deep basins of the Baltic Sea. Including the full range of meso-scale dynamics will improve our understanding of mixing processes and up- and downwelling along the coasts. The new BALTEX plan involves also an extension to nutrient, carbon and pollution modelling; research fields that are actively taken place since many years in the Baltic Sea. This will imply the need for reliable data sets on biochemical variables, atmospheric deposition and river load. It needs to be stated that in applying resources in research, a balance needs between the effort spent on modelling and the effort spent making new and innovative observations and process understanding. Despite the Baltic Sea having been more thoroughly observed than many other marine systems, there is a clear need for carefully designed observations to describe processes and provide new insight into the way the Baltic Sea functions. In this effort, to bring process understanding and numerical modelling together, BALTEX Phase II can play an important role.

3.5. Acknowledgements

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The BALTEX Phase I has not been possible without enthusiastic lead scientists who have given much spirit to the Baltic Sea research. We would therefore like to thank all the lead scientists who have made basic Baltic Sea research possible.

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3.7. Appendix: Measured and estimated water and heat flux components.

Table 3.3: Mean values of the different components in the water balance for the Baltic Sea (the Belt Sea and the Kattegat excluded). Unit 10^3 m^3 s^{-1}. The flows are denoted by: river runoff (Q_r), net precipitation (P-E), inflow (Q_i), outflow (Q_o), and storage change. A_s denotes the Baltic Sea surface area. Various investigation periods and methods have been used and ± indicates interannual variability.

AUTHOR	Q_i (m^3s^{-1})	Q_o (m^3s^{-1})	Q_o-Q_i (m^3s^{-1})	Q_r (m^3s^{-1})	A_s(P-E) (m^3s^{-1})	Storage Change (m^3s^{-1})
Early estimates						
HELCOM, -86, Table 11g			14.94	13.83	1.26	0.15
Runoff estimates						
Bergstöm and Carlsson (1994)				14±4		
COADS						
Lindau (2002)					0.70	
Ocean modelling						
Omstedt et al. (1997)					1.99	
Omstedt and Rutgersson (2000)	40.42	57.72	17.30	15.14	1.87	-0.29
Winsor et al. (2001)[1)]		80±10	15±5	14±4		
Omstedt and Nohr (2004)	42.75	59.41	16.76	14.96	1.70	-0.11
Rutgersson et al (2002)					1.5±1	
Meier and Döscher (2002)				15.07	1.8	
Lehmann and Hinrichsen (2002)	18.96	34.96	16.27	16.5		
PEP in BALTEX						
Hennemuth et al. (2002)					1.8±0.6	
Atmosphere modelling						
Jacob et al.(1997), run 1			19.09	15.32	3.77	0
Jacob et al.(1997), run 2			19.22	15.76	3.46	0
Jacob (2001)			16.39	13.92	2.47	
RCA-E [2)]				18.93	3.60	
RCA-H [2)]				24.64	5.69	
Coupled modelling						
Meier and Döscher (2002)				16.09	0.12	

1) Outflow was estimated as the mean of calculated outflow events only and not as the mean for the whole studied period (as was the case with other estimates).
2) Control runs using the Rossby Centre model from Rutgersson et al. (2002, Table 10)

Table 3.4: Mean heat balance of the Baltic Sea (the Belt Sea and the Kattegat excluded). The fluxes are positive when going from the water to the atmosphere. Unit: Wm^{-2}. The fluxes are denoted as: sensible heat (F_h), latent heat (F_e), net long-wave radiation (F_l), sun radiation to the open water surface (F_s^o), sun radiation through ice (F_s^i), heat flow from water to ice (F_w^i), net heat loss $F_{loss}=(1-A_i)(\ (F_s^o+F_h+F_{e+}F_l) + A_i(F_s^i+ F_w^i)$, F_o-F_i the difference between inflowing and outflowing heat through the Baltic sea entrance area. Various investigation periods and methods have been used.

AUTHOR	F_h (Wm^{-2})	F_e (Wm^{-2})	F_l (Wm^{-2})	F_s^o (Wm^{-2})	F_w^i (Wm^{-2})	F_s^i (Wm^{-2})	F_{loss} (Wm^{-2})	F_o-F_i (Wm^{-2})
Early estimates								
Henning, (1988)	18	39		-41[1)]			16	
COADS								
Lindau (2002)	12	42	69	-122			1	
Ocean modelling								
Omstedt and Rutgersson (2000)	7	35	43	-90	3	-0	-1	1
Omstedt and Nohr (2004)	9	35	36	-85	4	-0	-1	1
Meier (2001)	12	33	45	-91			-1	
Atmosphere modelling								
Jacob et al. (1997), run 1	7	32	44	-88			-5	
Jacob et al. (1997), run 2	11	36	44	-86			5	
Jacob (2001)	11	35	57	-119			-16	
Coupled modelling								
Meier and Döscher (2002)	10	41	53	-105			0	

1)Netradiation

Chapter 4:

Sea Ice

by

Timo Vihma and Jari Haapala

4.1. Motivation

The reasons to study ice in the Baltic Sea are related to two primary aspects: winter navigation and climate. The extent and thickness of the ice cover and the duration of the ice season are important for navigation and travel on the ice, and already for centuries there has been interest to monitor these variables (e.g. Sass, 1866). During BALTEX Phase I, research on the Baltic Sea ice conditions has become increasingly active, which is partly related to an increased interest in the climate and environmental changes. Also the winter navigation in the Baltic Sea has increased. For example, in Finland more than 80% of the international trade is transported via the sea, and ships need ice-breaker assistance for three to six months each winter. Operational ice services run dynamic sea ice models to forecast the ice conditions in the time scale of a few days. Both for operational services and climate research, we need basically the same knowledge on the physics of sea ice. Climate-related sea ice research can therefore apply the experiences gained from navigation-related research, and vice versa.

Through various mechanisms sea ice is an important factor in the climate system of the Baltic Sea region. First, sea ice has a high albedo. Sea ice is often covered by snow, and the albedo of a dry, new snow cover can be up to 0.9, while the albedo of melting bare ice is only of the order of 0.4 (or less, if the ice has become very thin). Even the latter is much higher than the albedo of the open sea, which is typically below 0.1. Changes on the snow/ice surface are accordingly associated with a strong feedback mechanism: a small reduction in the albedo can cause a large increase in the net solar radiation. Second, sea ice and its snow cover act as good insulators between the ocean and the atmosphere. In winter, the air-water temperature difference through the ice and snow can be up to 30 K. Sea ice cover is, however, seldom uniform, but broken by cracks, leads, and polynyas, which act as pathways for heat and moisture from the ocean to the atmosphere. In winter conditions, the sum of the turbulent fluxes of sensible and latent heat over the areas of open water can be several hundreds of Watts per square metre. This has a large effect on the thermodynamics of the atmosphere, sea ice, and the ocean. Third, the ice cover reduces, or even prevents, the air-sea exchange of momentum, water vapour, CO_2 and other gases. Fourth, the ice pack stores and advects fresh water, heat, atmospheric settling and sediments, and may release them far away from their original source. In addition, the extent and thickness of sea ice are highly sensitive indicators to climate variability and change.

Sea ice has been one of the central topics in BALTEX Phase I. In the EC-funded project ‘Baltic Air-Sea-Ice Study’ (BALTEX-BASIS, Launiainen and Vihma, 2001) from 1997 to 2000, the main emphasis was in the interaction between the atmosphere, sea ice, and the ocean, as well as in sea ice thermodynamics. Sea ice was also addressed in the EC-funded projects ‘Baltic Sea System Study’ (BASYS; Krauss, 2000) and ‘Ice State’ (Riska and Tuhkuri, 1999). The focus of the sea-ice research in BASYS was to model the seasonal and long-term evolution of the Baltic Sea ice pack. The objective of the ‘Ice State’ was a formulation of interconnection between the local and geophysical scales describing ice cover deformation. Sea-ice modelling issues have also been parts of the German and Swedish national research projects BALTIMOS (www.baltimos.de) and SWECLIM (Rummukainen et.al,. 2004). Imporant field observations have been carried out in the Gulf of Finland as a part of a Finnish-Japanese co-operative program (Kawamura et al., 2001; Granskog et al., 2004). In the field of Baltic Sea ice climatology, a regular series of workshops has been arranged every three years since 1993, and an international data bank has been created (Haapala et al., 1996). An EC-funded project 'Arctic Ice Cover Simulation Experiment' (AICSEX) paid attention also to the relation between the Arctic and Baltic Sea ice conditions. From the point of view of winter navigation, Baltic Sea ice is also studied in an ongoing EC-funded project 'Ice Ridging Information System for Decision Making in Shipping Operations' (IRIS).

Here we review the advance during BALTEX Phase I in the climate-related fields of sea ice research: ice properties, thermodynamics, and dynamics, as well as climatology of ice conditions. We have also witnessed a strong development in sea ice remote sensing. We will not review the technical advance in remote sensing, but refer to the recent summaries of the methods applying Synthetic Aperture Radar (Karvonen, 2003), passive microwave (Drobot and Anderson, 2003), and infrared (Chen et al., 2002) data. The advance in research on Baltic Sea physics, including aspects related to the sea ice, is summarized in Omstedt et al. (2004a). This paper is organized so that we first summarize the climatological ice conditions in the Baltic Sea and review the climate data analyses. Then we address the observations, process studies, and modelling of sea ice structure, properties and thermodynamics (Section 3) as well as dynamics (Section 4). Finally we review the advance in climatological sea ice modelling, in which both thermodynamics and dynamics play a major role (Section 5). A summary is given and perspectives for the future are discussed in Section 6.

4.2. Baltic Sea Ice Climate

The ice climate in the Baltic Sea can be characterized by several variables including the extent and thickness of the ice cover and the duration of the ice season.

4.2.1. Ice extent

Seinä (1994) and Seinä and Palosuo (1996) have summarized the annual maximum ice extent in the Baltic Sea utilizing the material of the Finnish operational ice service from winters 1941-1995 and information collected by Prof. Jurva from winters 1720-1940. The latter originated from various sources including observations at lighthouses, old newspapers, records on travel on the ice, scientific articles (Speerschneider, 1915; 1927), and air temperature data from Stockholm and Helsinki. Jurva himself never published the whole time series. In his last paper, Jurva (1952) showed the estimated ice extent from only 1830 onwards and commented the accuracy of the data as follows "I have tried to determine and estimate the general course of freezing and its different phases, e.g. in cold and correspondingly ice-rich winters from the winter 1829/30 to the eighties of the 19th century, from which period the knowledge of ice conditions in the outer sea is generally lacking. From about the year 1880 onwards we know the extension of the ice cover on the basis of notes made on board ships navigating the middle parts of the Baltic during many winters, or it may be rather easily and sufficiently accurately estimated on the basis of the time analysis of ice winters in the Archipelago." The time series was published as figures in Palosuo (1953), from where the ice extent has been later digitized by various authors (Lamb, 1977; Alenius and Makkonen, 1981; Leppäranta and Seinä, 1985). In the original figures, the ice extent is illustrated with bar diagrams, and an estimate of the uncertainty of the ice extent is denoted by dashed lines. The uncertainty is largest for severe ice winters, such as 1739/40, when the estimated range was as large as from 350 000 to 420 1000 km^2. In the most commonly used time series (Seinä and Palosuo, 1996; their appendices 1 and 2), only the maximum estimates are given. In any case, due to the high correlation between the air temperature and ice extent, even the early data are probably free of drastic errors (Seinä and Palosuo, 1996).

The extent of the sea ice cover varies a lot from year to year. Seinä and Palosuo (1996) classified the ice winters so that mild, average and severe winters contain the same percentage (~33%) of the winters in the period of 1720-1995. Mild and severe winters were further classified in extremely mild, mild, severe, and extremely severe ones (Figure 4.1). The extreme categories both contain ~10% of the winters. In extremely mild winters, only the Bothnian Bay, parts of the Gulf of Finland and Bothnian Sea, and shallow coastal regions in the Gulf of Riga are covered by ice, and the maximum ice coverage is only approximately 12% of the total area of the Baltic Sea (Figure 4.1). On average winters, the ice-covered region in March consists of the Gulf of Bothnia, Gulf of Finland, Gulf of Riga, northern parts of the Baltic Proper, and shallow coastal areas further south. In extremely severe ice winters, almost all the Baltic Sea freezes (Figure 4.1). According to the classification of Seinä and Palosuo (1996), during the last ten years all ice winters have been average, mild, or extremely mild. The latest extremely severe ice winter occurred in 1986-1987, and the latest winters with the Baltic Sea totally frozen have been in 1941-1942 (certainly) and 1946-1947 (most probably; Simojoki, 1952). According to Haapala and Leppäranta (1997), the maximum annual ice extent in the Baltic Sea (MIB) did not show clear trends during 1900s. In the time scale from 1720 to 2005 we see, however, a decreasing trend, and it is further discussed in section 4.

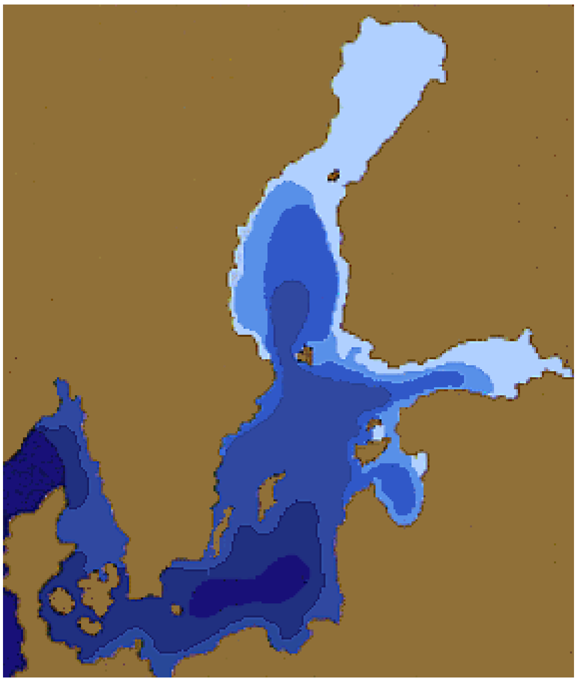

Figure 4.1. Annual maximum ice extent in the Baltic Sea: in extremely mild winters the maximum ice extent is at least the area marked by the lightest blue and at most that plus the area marked by the next-lightest blue. The maximum ice extent in mild, average, severe, and extremely severe winters is marked analogously with darker colours for the more severe ice winters (redrawn from Seinä and Palosuo, 1996).

4.2.2 Length of the ice season

In the Baltic Sea, the first sea ice typically forms in November (at earliest in the beginning of October) in the shallow coastal areas in the northernmost Bothnian Bay. The maximum ice coverage is usually reached in February or March, but sometimes already in January, and sea ice remains in the Bothnian Bay typically until mid-May. The latest remnants of individual ice ridges have been observed in early July. In the Skagerrag and the coastal areas of Germany and Poland, the probability of the sea ice occurrence is 25 - 75% (BSH, 1994). The ice season is accordingly very variable from year to year: in German coastal waters the latest dates of freezing are in early March, but in some winters the last ice has disappeared already by the end of December (Schmeltzer, 1999).

Most analyses on the length of the ice season have been based on local coastal observations. In the southern Baltic Sea, Sztobryn and Stanislawczyk (2002) have found large spatial differences in the sea ice climate along the Polish coast. In general for this region, according to Sztobryn (1994), the length of the ice season has decreased by 1-3 days per decade in the period 1896-1993 (see also Girjatowicz and Kozuchowski (1995). Girjatowicz and Kozuchowski (1999) analysed the ice conditions in the region of the Szczecin Lagoon in the period from 1888 to 1995, and found a statistically significant decreasing trend in the duration of the ice season.

In the nothern Baltic Sea, Haapala and Leppäranta (1997) analyzed ice time series from the Finnish coast, and concluded that the length of the ice season shows a decreasing trend, as also does the probability of annual ice occurrence in Utö (Northern Baltic Proper). Tarand (1993) and Tarand and Nordli (2001) have addressed the break-up dates of sea ice in the port of Tallinn. On the basis of time series over the last 500 years, they concluded that the break-up dates have become earlier since about the mid nineteenth century, and that the changes have been particularly large during the latest decades. This was found out also by Jaagus (2005), who analysed data from nine Estonian stations in the period 1949/50-2003/04. The largest decrease, by more than a month, in the duration of the ice season was observed in the West Estonian Archipelago, while on the southern coast of the Gulf of Finland the decrease has been insignificant. A statistically significant change towards later dates of freezing was detected only at four stations at the west coast of Estonia (Jaagus, 2005). Jevrejeva (2000) analyzed the sea ice and air temperature time series along the Estonian coast in the period of 1900-1990. The results indicated that, at the end of the study period, the date of a stabilized transition of the air temperature to sub-zero values was some 8-14 days later than in early 1900s, while the onset date of melting air temperatures has become 10-15 days earlier. The number of days with sea ice has decreased by 5-7 days in a century in the Gulf of Finland, and by 5-10 days in the Gulf of Riga. These changes have been associated with a climatic warming of 0.5-1.0°C in Estonia in November – April in the period of 1900-1990; the warming has, however, been statistically significant at 99.9% confidence level only at one of the eight stations analyzed by Jevrejeva (2000). Analyzing the historical record of ice break-up at the port of Riga in 1529-1990, Jevrejeva (2001) detected a decreasing trend of about 2.0 days per century for the break-up dates for severe winters (statistically significant at the 99.9% level). For mild and average winters, no statistically significant trends were detected.

Considering the whole Baltic Sea, Jevrejeva et al. (2004) did a comprehensive analysis of twentieth-century time-series at 37 coastal stations around the sea. In general, the observations showed a tendency towards milder ice conditions. They show that the largest change is in the length of the ice season, which has decreased by 14-44 days in a century, and it is largely due to the earlier ice break-up.

4.2.3. Ice thickness

Accurate data on the ice thickness is almost entirely restricted to the zone of land-fast ice. In the Bothnian Bay, the level ice thickness is typically 65-80 cm (Alenius et al., 2003), and it reaches 30 - 50 cm even in mild winters. In the Skagerrak and the coastal areas of Germany and Poland the annual maximum ice thickness varies from 10 to 50 cm (BSH, 1994).

In their analysis of 37 time-series from the coastal stations around the Baltic Sea, Jevrejeva et al. (2004) did not find any consistent change in the annual maximum ice thickness. According to Haapala and Leppäranta (1997), the level-ice thickness in the Baltic Sea did not show clear trends during the 20th century. Seinä (1993) and Launiainen et al. (2002) reported an increasing trend in the maximum annual ice thickness off Kemi (northernmost Gulf of Bothnia) during the 20th century until 1980s; in more southerly locations in the Gulf of Bothnia no clear trends were observed for the same period. In all stations, decreasing trends have been observed since 1980s. In the Gulf of Finland, the maximum annual ice thickness has had a decreasing trend off Helsinki and Loviisa (Alenius et al., 2003). From the point of view of winter navigation, an important climatological parameter is the distance that ships have to cruise in sea ice thicker than some threshold value. Launiainen et al. (2002) calculated the annual maximum distance from the harbour of Hamina (eastern Gulf of Finland) to a zone of sea ice less than 10 cm thick. The results for the period from 1951 to 2000 strongly depended on the air temperature with short distances in 1990s.

In the drift ice regions, where the most of the sea-ice mass locates, we do not have accurate data on the ice thickness. During the last ten years, many field studies have concentrated on the mapping of the ice thickness, but no systematic long-term measurements of the ice thickness have been carried out. Sea-ice thickness distribution is possible to observe with a fixed upward-looking sonar (which would allow long-term monitoring), from submarines, and by the airborne electromagnetic method (EM). Multala et al. (1996) showed that a fixed-wing aircraft EM-method is applicable to the Baltic Sea, but these measurements have not been continued. Haas (2004a,b) used helicopter-borne EM-instrument in the Baltic Sea during the winters of 2003 and 2004, and measured ice thickness characteristics along the Finnish coast. The results showed that, even in rather large regions, the mean deformed ice mass is often much larger than the undeformed ice mass. The observed mean sea-ice thickness averaged over an approximately 100-km-long flight track varied from 0.3 to 1.8 metres, with several sections where the mean ice thickness was more than 1.5 metres.

4.2.4. Large-scale atmospheric forcing on the ice conditions

During the last decade, an increasing attention has been paid on the relation between the inter-annual variations in the Baltic Sea ice conditions and the indices of the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO). The relationship between the large-scale atmospheric circulation and the Baltic Sea ice conditions can be illustrated by comparing the NAO winter index and the MIB (Figure 4.2). High positive NAO indices reflect strong westerlies over the North Atlantic, which bring mild and moist maritime air to the European continent. Negative NAO indices express a weakening or even blocking of the westerly airflow over the ocean. In that case, cold continental air masses over the Baltic Sea favour sea ice formation. Although the MIB is fairly well correlated with the winter NAO index (Figure 4.2), moving correlation analyses have demonstrated that the relationship is not constant in time (Omstedt and Chen, 2001; Janssen, 2002; Schrum and Janssen, 2002; Chen and Li, 2004). Meier and Kauker (2002) have interestingly pointed out that during two periods, around 1926 and 1966, the correlation has increased simultaneously with improvements in the observation methods for MIB, but changes in the NAO-MIB relationship can also be solely due to changes in the location of the atmospheric pressure patterns (Koslowski and Loewe, 1994; Chen and Li, 2004).

According to Yoo and D'Odorico (2002), NAO seems to affect mostly the late-winter temperature (January-March) with a significant impact also on the mid-spring (April-May) period, when the air temperature is strongly correlated to the ice break-up dates. The results of Jevrejeva and Moore (2001) suggest that, from the point of view of ice break-up in the Baltic Sea, AO is an index somewhat more essential than NAO: time series of ice break-up date reflect variations in the winter AO index in the 13.9-year period, but not in the NAO 7.8-year period. The application of wavelet calculations (Jevrejeva et al., 2003) has marked an advance in the methodology of ice climatology. Calculating cross-wavelet power for the time series, Jevrejeva et al. (2003) found out that the times of largest variance in the Baltic Sea ice conditions were in excellent agreement with significant power in the AO at 2.2-3.5, 5.7-7.8, and 12-20 year periods (previously Alenius and Makkonen (1981) had detected the most distinct cycles in the MIB at the periods of 3.5, 5.2, 8, and 13 years). It is noteworthy that Jevrejeva et al. (2003) found similar patterns also with the Southern Oscillation Index and El Nino sea surface temperature series (Nino3). Also according to Omstedt et al. (2004b), 90 % of the variance of the time-series is for the time scales shorter than 15 years. A concern of these studies is, however, that they have assumed the long-term time-series of the MIB as homogeneous in accuracy (compare to Section 4.2.1).

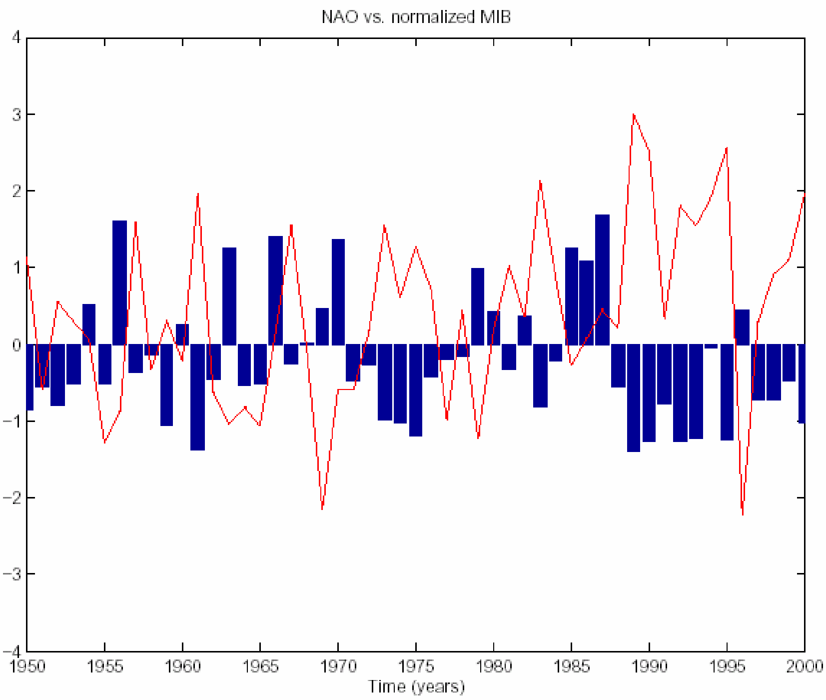

Figure 4.2. Time series of North Atlantic Oscillation index (Rogers, 1984) (line) and the annual maximum ice extent of the Baltic Sea, MIB (Seinä and Palosuo, 1996) (bars). The MIB is presented as an anomaly of the normalized time series.

Jaagus (2005) analyzed the freezing and break-up dates near the Estonian coast in relation to large-scale atmospheric circulation. NAO indices, the AO index, several teleconnection indices and frequencies of the circulation forms W, E and C, according to the Vangengeim-Girs classification, were used to describe circulation conditions. Generally, no correlation was found between the circulation and the date of the first appearance of sea ice. Only some indications revealed that the higher the intensity of westerlies in October, the later sea ice forms. The circulation has the strongest relationship with the date of ice break-up and the length of the ice season. They have a high negative correlation with the characteristics of the intensity of the zonal circulation. The highest value is present in the case of the sea ice break-up and the AO index for the total winter period (December - March): -0.73 as a mean of nine stations. According to Jaagus (2005), February is the key month, when the circulation plays a main role in determining sea ice conditions for the spring. High intensity of westerlies in winter (February) causes earlier ice melting in the Baltic Sea. The frequency of the meridional circulation form E in winter is positively correlated with the date of sea ice break-up. Using the conditional Mann-Kendall test, Jaagus (2005) demonstrated that the significant trends in sea ice near the Estonian coast during 1949/50-2003/04 are caused by the increasing intensity of westerlies in winter, especially in February, and by the corresponding decrease in frequency of meridional circulation types during the same time interval.

So far most studies have addressed the extent and duration of the sea ice cover. From the point of view of climatology, the most relevant parameter to describe the ice conditions is the total mass of ice, but we lack good data on it over large regions. Over a small region, such as the coastal areas of Schleswig-Holstein, the ice thickness and concentration can be observed sufficiently accurately. Koslowski and Loewe (1994) calculated the areal ice volume, which can be visualized as an equivalent ice thickness in a partly ice-covered sea. Analogously to degree days (accumulated degrees of frost), they further calculated the accumulated areal ice volume, and showed that in the period from 1879 to 1992 it was negatively correlated with the NAO winter index. Weak ice winters were related to a NAO winter index exceeding 1, and strong ice winters were related to a NAO winter index less than -1. Koslowski and Loewe (1994) also noteworthy pointed out that, depending on the exact location and size of the high- and low-pressure areas, in rare cases a strong ice winter in the southwestern Baltic Sea can develop even in spite of a high NAO winter index.

On the basis of the data on the accumulated areal ice volume from the 1878-1993 period, Koslowski and Glaser (1995) reconstructed the ice winter severity since 1701 for the southwestern Baltic Sea, and Koslowski and Glaser (1999) extended the calculations for the period from 1501 to 1995. The present-day ice winter regime has lasted since about 1860, while from ~1760 to ~1860 the ice winters were much more severe. Around 1800 the ice production in the southwestern Baltic Sea was three times larger than it is today (Koslowski and Glaser, 1999). According to Omstedt and Chen (2001), the shift towards a warmer climate took place in 1877 associated with a period of an increased low-pressure activity (Omstedt et al., 2004b). This shift in climate was identified as the ending of the Little Ice Age in the Baltic Sea region. Omstedt and Chen (2001) also found out that a colder climate is associated with higher variability in the ice extent and with a higher sensitivity of the ice extent to changes in winter air temperature. They further developed a statistical model that links the ice extent and a set of atmospheric circulation indices. Considering the possibilities to make climate-scale predictions for the future sea ice conditions, Omstedt and Chen (2001) argue that such a statistical model could be a useful tool in estimating the mean conditions of the ice extent on the basis of atmospheric pressure fields, which are produced applying a climate model. On the other hand, Launiainen et al. (2002) point out that the present-day large-scale atmospheric models are not particularly successful in reproducing the observed NAO index. Tinz (1996) found an exponential relation between the ice extent and the air temperature; applying it and climate model predictions, he forecasted a drastic decrease in the Baltic Sea ice cover in the next 100 years.

As the large-scale atmospheric forcing affects several cryospheric variables, statistical relationships have been found among them. Jaagus (1999) studied the interactions between the MIB and the annual snow cover duration in Estonia, and found a correlation coefficient of 0.68 between them for the period 1921-1996. The coefficient is not higher, because the correlation disappears during coldest winters.

4.3. Thermodynamics, Structure and Properties of Sea Ice

The structure, properties, thermodynamics and dynamics of sea ice are closely inter-related. Many basic studies on ice dynamics have, however, not addressed the other topics. We therefore organize this review with separate sections for (i) thermodynamics, structure and properties, and (ii) dynamics of sea ice. Sea ice and snow thermodynamics are controlled by the exchange of heat at the ice-ocean and air-snow interfaces (or, in the case of bare ice, at the air-ice interface), penetration of solar radiation below the snow/ice surface, and by the conduction of heat inside the snow and ice. The heat budget equation inside the ice is:

$$\frac{\partial}{\partial t}\left(\rho_i c_i T\right) = \frac{\partial}{\partial z}\left(k_i \frac{\partial T}{\partial z}\right) + q \qquad (1)$$

where ρ_i is the ice density, c_i is the specific heat of ice, T is the temperature, k_i is the heat conductivity of ice, and q is the internal heat source (e.g., absorption of solar radiation or release of latent heat of freezing). The boundary conditions are $k_i\, \partial T/\partial z = F_{net}$ at the surface and $T = T_f$ at the bottom. F_{net} is the net surface heat flux, and T_f is the freezing temperature of seawater. An analogous equation can be written for the snow cover. The net heat flux at the surface is:

$$F_{net} = (1-\alpha)(1-\beta)F_{sw\downarrow} + F_{lw\downarrow} + F_{lw\uparrow} + F_H + F_E + F_Q \qquad (2)$$

where $F_{sw\downarrow}$ is the downward shortwave radiation, α is the surface albedo, and β is the fraction of the absorbed shortwave radiation that penetrates through the surface. $F_{lw\downarrow}$ and $F_{lw\uparrow}$ are the downward and upward longwave radiation, respectively. F_H and F_E are the turbulent sensible and latent heat fluxes, respectively, and F_Q is the conductive heat flux at the surface.

Ice growth and melt at the bottom are determined by the difference between the conductive heat flux and the oceanic heat flux at the ice bottom:

$$\rho_i L \frac{\partial h}{\partial t} = k_i \frac{\partial T}{\partial z} - F_{wi} \qquad (3)$$

where h is the ice thickness, L is the latent heat of melting, and F_{wi} is the oceanic heat flux. In idealized conditions, analytical models for sea ice growth can be derived; Leppäranta (1993) reviewed them in the beginning of BALTEX Phase I.

4.3.1 Atmosphere-ice interaction

In BALTEX–BASIS, significant advance was made in the field of thermodynamic interaction between the atmosphere and sea ice. The studies can be divided in three categories: 1) local scale over land-fast ice, 2) spatial variations in different flow conditions, and 3) spatial averaging in the grid-scale of atmospheric and sea ice models.

In a local scale, the parameterization of the turbulent air-ice exchange of sensible heat (F_H) is sensitive to the effects of atmospheric stratification and the roughness lengths for momentum (z_0) and heat (z_T). Launiainen et al. (2001) analyzed the relation of the surface fluxes and the wind and temperature profiles, and obtained a new formula for the ratio of the roughness lengths: $z_0/z_T = 0.035\, Re^{0.98}$. The roughness Reynolds number $Re = (z_0 \cdot V)\nu^{-1}$, where V is the wind speed and ν is the kinematic viscosity of air. The result was found for smooth to moderately rough snow-covered sea ice.

Vihma and Brümmer (2002) studied the spatial variations in the atmosphere-surface exchange of heat and moisture (F_H and F_E) over the ice-edge zone. They showed that during a cold-air outbreak in the Gulf of Bothnia the atmospheric boundary layer (ABL) was strongly affected by the heat fluxes from leads. During such off-ice flows, the upwind snow/ice surface is typically close to a thermal equilibrium with the ABL, and in the downwind region, due to the large heat capacity of the sea, the surface temperature of the open sea is not much affected by the overflowing cold air. On the contrary, during advection of warm marine air-mass over sea ice, the snow/ice surface temperature is strongly affected (Cheng and Vihma, 2002), while an ice surface of a limited fetch does not always have any large thermodynamic effect on the ABL (Vihma and Brümmer, 2002). Cheng and Vihma (2002) applied a two-dimensional, coupled, mesoscale atmosphere–ice model to study the warm-air advection over sea ice. The model was run into a steady state under various flow conditions with respect to season, cloud cover and wind speed. If the turbulent heat flux from air to snow was large enough to compensate the radiative cooling of the surface, a downward conductive heat flux was generated in the upper ice and snow layers. The stronger was the surface heating, the larger was the region (downwind of the ice edge) where this downward flux occurred. The development of the stably stratified ABL downwind of the ice edge depended above all on the wind speed and cloud cover.

Except of the land-fast ice in coastal regions, the ice cover in the Baltic Sea is usually fractured. This reduces the representativeness of local point measurements, and aircraft observations are essential to measure spatially averaged fluxes in the ABL. The results of Brümmer et al. (2002a) revealed significant spatial and temporal variations in the surface fluxes; the fluxes depended above all on the large-scale weather conditions and on the state of the surface i.e. either open water, compact land-fast sea ice, or broken sea ice. The spatial variability of the heat fluxes in the ice edge zone was small during warm-air advection and large during cold-air advection. Even in the latter conditions, however, the spatial variability of the surface was often exceeded by the spatial variability of the net radiation flux caused by inhomogeneous cloud fields. The effect of leads is seen also in the diurnal cycle of air temperature: Niros et al. (2002) observed a much smaller mean diurnal cycle in winter over the Bothnian Bay than over the nearby land areas.

Considering the parameterization of turbulent surface fluxes over a heterogeneous surface, the so-called mosaic method has become increasingly common, and has also been applied over ice-covered seas (Vihma et al., 2005). In the method, each model grid cell is divided into patches of surface types (e.g., ice and open water), and the surface temperature of each patch is calculated. The grid-averaged surface fluxes result from area-averaging of the fluxes over the individual surface patches. Sometimes the division between surface types is, however, not so clear: in addition to thick ice and open water, several thin and intermediate ice types may exist. A simpler approach is to apply a flux-aggregation method, which is based on transfer coefficients for heterogeneous surfaces (the flux-aggregation method may, however, sometimes yield a wrong sign for F_H (Vihma, 1995)). Schröder et al. (2003) applied the BALTEX-BASIS aircraft data in parameterizing the turbulent surface fluxes using this approach. The data suggested a value of $(0.9\pm0.3) \times 10^{-3}$ (mean ± standard deviation) for the 10-m neutral heat transfer coefficient C_{HN10}. The aircraft measurements were made approximately at the height of the lowest atmospheric grid level of regional-scale models. The results are therefore applicable for such models, in which the lowest grid level may often locate above the constant-flux layer.

If uncoupled to atmospheric models, many sea ice models use simple parameterizations for the incoming radiative fluxes ($F_{sw\downarrow}$ and $F_{lw\downarrow}$). Considering longwave radiation, these parameterizations are typically based on easily observable quantities, such as the 2-m air temperature and humidity and the cloud fraction. In cold temperatures, various formulae presented in the literature differ a lot from each other (Launiainen and Cheng, 1998; Pirazzini et al., 2000). Many formulae underestimate $F_{lw\downarrow}$ under clear-skies, particularly in cold conditions, and simple parameterizations perform less well than multi-layer radiative transfer schemes (Niemelä et al., 2001a). Also for the cloud effect on $F_{sw\downarrow}$, simple schemes (usually dependent on the total cloud cover) perform poorly (Niemelä et al., 2001b). Atmospheric model output, based on the multi-layer radiative transfer schemes, can be recommended to be applied in sea ice models instead of simple parameterizations.

With a focus on the surface and near-surface temperatures and turbulent fluxes, operational meteorological models have been validated over sea ice by Ganske et al. (2001) and Pirazzini et al. (2002). Ganske et al. (2001) compared the BALTEX-BASIS rawinsonde and aircraft data with the analyses and 24-h forecasts of the regional model HIRLAM. The differences were largest during passages of cold and warm fronts. The model errors were largest near the surface, and the vertical gradients of air temperature and wind speed were too small in HIRLAM. In individual cases the surface temperature, wind speed and direction were strongly biased. Pirazzini et al. (2002) applied a data set from the Gult of Bothnia in March 1999. The comparisons indicated that the main discrepancies were related to the snow surface and 2-m temperatures: in cold nights the temperature inversions were too weak and delayed in HIRLAM. Experiments applying a two-dimensional mesoscale model suggested that HIRLAM results could be improved by updating the values of the surface albedo and the parameters of the surface temperature scheme on the basis of the snow age and temperature. Also the BALTIMOS data from winter 2001 (Brümmer et al., 2002b) offers possibilities for validation of the atmosphere-ice interaction in regional models.

4.3.2 Ice and snow

During BALTEX Phase I, significant advance has been made in studies on the penetration of solar radiation in snow and ice, subsurface melting, and formation of superimposed ice (refrozen snow melt or rain) and snow ice (snow transformed to ice due to flooding of seawater). Saloranta (1998; 2000) was the first to model the snow-ice formation demonstrating its importance for sea ice mass balance in the Baltic Sea. In BALTEX-BASIS, Lundin (2001) studied the snow influence on land-fast ice thickness, and found out that an increased mean snow thickness over a wide area leads to flooding, which increases the ice thickness via snow-ice formation. Snow thickness variations on smaller scales do not lead to flooding but affect the ice thickness, because the heat transfer through the snow is sensitive to the snow thickness. Granskog et al. (2003a) studied the land-fast sea ice on 15 sites along the Finnish coast, and observed that, on average, 18-21% of the total sea ice mass was composed of snow or precipitation. Granskog et al. (2004) observed large inter-annual variations in the contribution of snow-ice and superimposed ice to the total land-fast ice thickness (0-35% by ice mass) in the Santala Bay, Gulf of Finland. They concluded that the contribution strongly depends on the amount and timing of snow accumulation and timing of snowmelt-freeze processes, which all exhibit large year-to-year variation. Cheng et al. (2003) applied a one-dimensional model and BALTEX-BASIS data from the winters of 1998 and 1999: the results indicated that the refreezing of the surface melt water was the primary source of superimposed ice formation. In March 1999, both observations and model results indicated a sub-surface temperature maximum at the melting point due to solar radiation penetrating below the snow surface. The results of Cheng et al. (2003) suggested that sub-surface melting has an important (~20%) contribution to the total melting during early spring. In numerical modelling, the total melting is sensitive to the thermal properties of snow, while sub-surface melting is sensitive to the extinction coefficient. Launiainen and Cheng (1998) demonstrated that during the melting period in sprig, a layer of new snow can enhance the melting, although it initially has a large surface albedo. The melting starts because of the high volumetric extinction of solar radiation in the new snow.

During BALTEX Phase I, also Cheng et al. (2001) and Cheng (2002) have developed thermodynamic sea ice models. Cheng (2002) made sensitivity tests for both spatial (vertical) and temporal model resolution. In idealized cases he also compared the model results with analytical solutions. He found out that during the freezing season the influence of the resolution on model results is not significant, except for short-term predictions. During late winter and spring, when the solar radiation increases, the vertical resolution becomes much more important. In a coarse resolution model, the penetration of solar radiation into snow and ice is not described accurately enough; the absorbed solar radiation mostly contributes to the surface heat balance, the diurnal cycle of the surface temperature therefore becomes too large, and the sub-surface melting cannot be modelled. Cheng (2002) suggests that for process studies an ice model should apply a time step of about 10 minutes and a vertical resolution of

2 – 5 cm. If this is not possible in climate-scale studies, the ratio of time step to grid size should in any case remain small.

Prior to the BALTEX Phase I, there were very few studies on the relationships between the physical, chemical, structural, and optical properties of the Baltic Sea ice cover. The observations in the Santala Bay and various other locations on the land-fast ice have partly filled this gap. Kawamura et al. (2001) analysed the ice, snow and water samples collected at Santala Bay once a week from January to April 1999, and found out that the ice was composed of a granular upper layer, occupying approximately one-third of the entire ice thickness, and underlying columnar ice towards the bottom. The granular ice consisted of two layers with different origins, i.e. snow ice and superimposed ice. Granskog et al. (2004) analyzed the seasonal development of the structure, salinity, and stable oxygen isotopic composition ($\delta^{18}O$) of the land-fast sea ice. They concluded that the observed rapid changes in ice salinity were connected to changes in the ice thermal regime and flooding. The ice salinity was almost constant in depth, but $\delta^{18}O$ was lower close to the surface because of formation of snow-ice and superimposed ice. The shortwave radiation measurements of Rasmus et al. (2002) in spring 1998 demonstrated that the snow/ice surface albedo mostly depended on the condition of the surface, and especially on the presence of liquid water or snow, but also the cloud cover and forest shading had an effect. Ehn et al. (2004) made spectral irradiance measurements in the Santala Bay in March and early April 2000. The sea ice and seawater contained high amounts of dissolved and particulate matter, which effectively absorb radiation at wavelengths below 700 nm, and can potentially increase the ice melt rate. During the measurement period, the sea ice was snow-free, but highly scatterring surface layers were formed in conditions of melting and refreezing. In the case of very thin (10 cm), melting ice, the albedo was ~0.17 and 66-73% of the photosyntetically active radiation (400-700 nm) was transmitted through the ice (Ehn et al., 2004).

New studies have increased the knowledge on the chemistry of sea ice and its role as a moderator of biogeochemical cycling and budgets of elements in the Baltic Sea (Granskog and Virkanen, 2001; Granskog et al., 2003b; Granskog et al., 2004). The sea ice cover acts as a buffer for the accumulated substances. During the ice melt period increasing amounts of nutrients and other substances penetrate to the lower ice layers and further to the water below the ice. This may enhance the algal growth and other biological activity (Ikävalko, 1998; Haecky et al., 1998; Meiners et al., 2002). Granskog and Virkanen (2001) observed that both nutrients and trace elements were independent of sea ice salinity. Granskog et al. (2003b) found evidence that snow-ice formation, ice permeability, and ice algae all affected the nutrient status of the Baltic Sea ice.

4.3.3 Ice-ocean interaction

In BALTEX-BASIS, Shirasawa et al. (2001) made turbulence measurements below the land-fast ice. The results revealed some interesting features of the oceanic boundary layer (OBL): the momentum flux at the depth of 5 m from the ice bottom was ten times larger than at the depth of 0.5 m, and the heat flux from the water to the ice was very small, on average less than 1 W m^{-2}. Both these findings indicated an existence of a shallow very stable OBL below the ice. This seems to be related to an inflow of river water into the sea at the measurement site in Vaasa archipelago in the Gulf of Bothnia. A low-salinity layer was formed below the sea ice also in the Santala Bay (Ehn et al., 2004). There it was due to discharged meltwater, which stayed below the ice until the ice ablated in April. The water-ice heat fluxes were, however, much larger at the Santala Bay: mean oceanic heat fluxes were of 38-47 W m^{-2} for the ice growing period and 54-62 W m^{-2} for the ice melting period in winters 1999-2001 (Shirasawa et al., 2002). Also basin-scale observations (Omstedt, 2001) indicated oceanic heat fluxes larger than those observed in Vaasa archipelago. The BALTEX-BASIS data yielded a mean bulk heat transfer coefficient of 3.9 x 10^{-4} (Shirasawa et al., 2002). Due to the large spatial variability observed in the OBL, the representativeness of this result remains so far unclear.

4.4. Sea Ice Dynamics

4.4.1 Ice thickness distribution

Pack ice is a mixture of open water and several classes of undeformed and deformed ice. Each ice class has an inherent ice thickness distribution but ice classes also differ in their mechanical and thermodynamical properties. The ice thickness variability in a region is a result of the ice-ocean and ice-atmosphere heat fluxes, advection of non-uniform scalar fields and differential ice motion (Figure 4.3). The elementary variables of the ice pack are the ice thickness (h) and ice compactness (A). Ice characteristics in a scale larger than the typical length scale of individual features are described by the ice thickness distribution function g(h) (Thorndike et al., 1975):

$$\int_{h2}^{h1} g(h)dh = \frac{1}{R} f\left(h_1, h_2\right) \tag{4}$$

where R is the area under consideration and f (h_1, h_2) is a sub-area covered by ice with thickness from h_1 to h_2. The evolution equation for g(h) is,

$$\frac{Dg(h)}{Dt} = \Theta + \Psi \tag{5}$$

where the left side of the equation describes the Lagrangian change in g(h), Θ is the thermodynamic growth rate, and Ψ represents the redistribution of ice thickness due to deformation. The g(h) can be calculated from several observational data sets (Wadhams, 1998) but only a few numerical models resolve it. This is mainly due to difficulties in determining the redistribution function Ψ. In principle, Ψ depends on g(h) and the strain rate invariants.

In the classical Hibler (1979) model, g(h) is approximated with two ice thickness categories: h = h(h_0, H), where h_0 is the thin ice, interpreted as open water, and H is the thick ice (h > defined minimum ice thickness). Ridging of ice is taken into account since ice thickness can freely increase during the convergent ice motion, although ice concentration is constrained to be 1.0 at maximum. Most of the Baltic Sea ice models apply this approach.

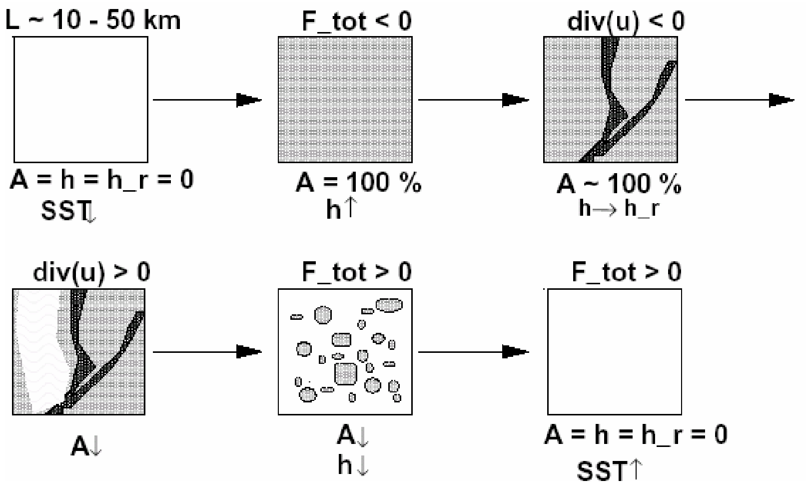

Figure 4.3. The life cycle of the pack ice. The evolution is characterized by the cooling of the ocean surface, freezing of the seawater, compression and opening of the ice pack, melting of ice and warming of the surface layer. F_tot denotes the total heat flux at the ocean/ice/atmosphere interface and div(u) is the divergence of the ice pack. The SST, A, h and h_r denote the sea surface temperature, ice compactness, level ice thickness and ridged ice thickness; the arrows indicate whether the variable is increasing or decreasing.

To solve g(h) numerically, several ice categories are needed (Hibler, 1980; Flato and Hibler, 1995). An alternative approach is to solve the ice concentration and mass for each ice category or ice type in a Lagrangian ice thickness space,

$$\frac{DA_i}{Dt} = \Theta_{Ai} + \Psi_i \qquad (6)$$

$$\frac{D\tilde{h}_i}{Dt} = \Theta_{hi} + \Omega_i \qquad (7)$$

where A_i is the concentration (i.e. areal fraction) of the ice category i, Θ_{Ai} denotes thermodynamical changes and Ψ_i is the change of ice concentration due to deformation (i.e. redistribution). $\tilde{h}_i$ is the mean thickness of ice per unit area, while Θ_{hi} and Ω_i are its changes due to thermodynamics and redistribution. Floe thickness h is obtained diagnostically since $\tilde{h}_i$ = hA. Multi-category sea-ice models apply redistribution functions to describe an average evolution of the pack ice deformation processes. Several deformation processes, such as compacting, rafting and ridging, are possible during a single time step. This mimics the real behavior of the pack ice in a continuum scale. The main uncertainty in multi-category models lies in the redistribution functions.

The first sea-ice models, in which the redistribution of ice was explicitly taken into account, were developed for operational purposes. Leppäranta (1981) made a distinction between undeformed and deformed ice. The prognostic variables of the model were the level ice thickness, ridge density, ridge sail height and total ice concentration. With minor modifications this scheme was used in several Baltic Sea ice models (Omstedt et al, 1994; Zhang and Leppäranta, 1995; Haapala and Leppäranta 1996; Schrum 1997). Shortcomings in the Leppäranta (1981) ice redistribution scheme are that the model does not include separate equations for the level ice and deformed ice concentrations, and it assumes that ridging occurs only when ice concentration reaches unity during convergence. Haapala (2000) presented a simplified ice thickness redistribution model where the pack ice was composed of open water, two different types of undeformed ice, as well as rafted ice, rubble ice, and ridged ice. The main advantage of the model is that it separates the ice types generated thermally and mechanically. The model results were compared to the operational ice charts and SSM/I remote sensing data, and the model was found to produce a realistic seasonal evolution of the pack ice. Both sub-basin and inter-basin ice characteristics were reproduced by the model. It was shown that the deformed ice production is a stepwise process related to storm activity. Most of the deformation was produced in the coastal zone, which also is an important region for thermodynamically produced ice because of the ice growth in leads. A shortcoming in the Haapala (2000) model is that it uses the Hibler (1979) parameterization for the ice strength (eq. 10) instead of Rothrock (1975) parameterization. The recent development (Haapala et al. 2004) overcomes this problem.

4.4.2 Momentum balance

In the field of sea ice momentum balance, the main scientific advance during BALTEX Phase I has been the studies by Leppäranta et al. (1998) and Zhang (2000). To better understand them, we look at the ice momentum equation in a horizontal plane: the motion of sea ice is driven by the wind stress, bottom stress due to the ocean current, and the sea surface tilt, and the motion is also affected by the internal stress of the ice pack and the coriolis force:

$$m\left(\frac{D\vec{u}}{Dt} + f\hat{k}\times\vec{u}\right) = A\left(\vec{\tau}^{\,a} + \vec{\tau}^{\,w}\right) + mg\nabla H + \nabla\cdot\sigma \qquad (8)$$

where m is the total ice and snow mass, $\vec{u}$ is the horizontal ice velocity vector, f is the coriolis parameter, $\hat{k}$ is the upward unit vector, $\vec{\tau}^{\,a}$ is the wind stress vector, $\vec{\tau}^{\,w}$ is the water stress vector, g is the gravitational acceleration, ∇H is the sea surface tilt and σ is the internal stress tensor. According to the scaling arguments (Leppäranta, 1998), the nonlinear advection terms and the sea surface tilt can be neglected in the calculation of the momentum balance.

The determination of the internal stress of the ice pack is the major problem in (8). The simplest assumption is the free drift law, i.e., there is no internal stress. It may hold locally but, if used in a numerical model, it leads to a large overestimation of the ice velocity and dynamic growth (Leppäranta et al., 1998). In climatological sea ice research, the viscous-plastic model (Hibler, 1979) is the most widely used scheme. The constitutive law is:

$$\sigma = 2\eta\dot{\varepsilon} + (\xi - \eta)tr\dot{\varepsilon}I + \frac{1}{2}PI \qquad (9)$$

where η is the shear viscosity, ξ is the bulk viscosity, $\dot{\varepsilon}$ is the strain rate tensor, *I* is the unit tensor and *P* is the ice strength. The viscous-plastic ice rheology implies that under very low strain rates the bulk and shear viscosities are constant and the model produces linear viscous behavior; otherwise the viscosities are calculated according to the plastic flow rule (Hibler, 1979). The ice strength parameter links the ice dynamics to ice thickness and compactness. For a two-level model with h = h(h_0, H) it is

$$P = P^*\tilde{h}e^{-C(1-A)} \qquad (10)$$

where P* is the ice strength constant, $\tilde{h}$ is the mean ice thickness over the grid cell and C is the compaction constant. A major difference between the two-level and multi-category ice models is that the ice strength parameter P is in multi-category models directly related to the energy consumed during deformation (Rothrock, 1975).

The ice strength constant P* and the aspect ratio of the yield curve are important model parameters but their values can only be determined experimentally. Zhang and Leppäranta (1995) and Leppäranta et al. (1998) showed that P* can vary from 1.0×10^4 N m^{-2} to 5.0×10^4 N m^{-2} depending on the ice conditions in the Baltic Sea. Leppäranta et al. (1998) used ERS-1-derived satellite data on ice motion for the verification of the modelled ice velocity fields, and noticed considerable stiffening of the ice pack as the minimum ice thickness increased from 10 to 30 cm. The results supported the assumption of a plastic rheology for thick (more than 30 cm) and compact ice, and Leppäranta et al. (1998) recommended a value of 2.5×10^4 N m^{-2} for a Baltic Sea ice model with a 10-km spatial resolution. Zhang (2000) applied a viscous-plastic sea ice model for the Bay of Bothnia and validated the results against remote sensing data and the drift of five GPS-tracked buoys in March 1997. He simulated ice motion with different yield curves (elliptical, tear drop, and triangular shapes) and found out that the classical elliptical yield curve produced the most accurate ice motion. He also concluded that 3.0×10^4 N m^{-2} is the most representative value for P*. Leppäranta et al. (2001) analysed the same data set, and ended up with a value of 4×10^4 N m^{-2} for P*. Leppäranta and Wang (2002) present additional aspects on high-resolution sea ice modelling.

4.4.3 Atmospheric forcing

In a local scale, the air-ice momentum flux $\vec{\tau}^a$ depends on the wind speed, z_0 of the snow/ice surface, and the thermal stratification in the atmospheric surface layer:

$$\vec{\tau}^a = \rho C_{DZ} V_Z^2; \quad C_{DZ} = \left(\frac{k}{\ln(z/z_0) - \psi_M(z/L_O)} \right)^2 \tag{11}$$

where ρ is the air density, C_{DZ} is the air-ice drag coefficient, k is the von Karman constant (≈ 0.4), and z indicates the reference height for C_{DZ} and V_{DZ}. The function ψ_M describes the stratification effect, and depends on the Obukhov length L_O. The results of Launiainen et al. (2001) from the land-fast ice in the Gulf of Bothnia indicated that the local z_0 did not depend on the wind speed. In a model parameterization of the momentum flux, the ice conditions have to be taken into account in the grid-scale, and C_{DZ} doest not depend solely on the local z_0 over ice. Modelling ice drift in the Gulf of Bothnia, Uotila (2001) calculated C_{DZ} on the basis of the ice concentration, surface roughness of ice floes, form drag due to floe edges (the freeboard depends on the ice and snow thickness), and the thermal stratification in the atmospheric boundary layer (ABL). The stratification effect was essential: the improvement in the model results by including this effect was comparable to the improvement achieved by increasing the grid resolution from 18 to 5 km. Uotila (2001) also showed that in the centre of the Gulf of Bothnia the ice drift was highly wind-dependent, and a linear relationship between the wind and drift velocities explained 80% of the drift's variance. Omstedt et al. (1996) studied the ice-ocean response to wind forcing using both an analytical and a numerical model. The numerical predictions agreed well with observations, but during conditions of variable winds the analytical model did not capture the wind-dependency properly. This was due to an application of linear stress laws.

Over sea ice, the stratification in the ABL is typically stable, which reduces $\vec{\tau}^a$. Localized convection may, however, occur over leads and polynyas (Vihma and Brümmer, 2002), and this enhances the turbulent mixing and $\vec{\tau}^a$. In the case of inaccurate model results for near-surface winds (as often in conditions of a stable background stratification with localized convection), Vihma (1995) proposed to parameterize $\vec{\tau}^a$ on the basis of the atmospheric pressure field and a geostrophic drag coefficient. Mesoscale circulations (Magnusson et al., 2001) may also contribute to the subgrid-scale air-ice momentum transfer. Vihma (1999) summarized various aspects of mesoscale variations in the wind stress over sea ice.

Recent observations of ice velocity in the Bay of Bothnia provide insight into the ice kinematics in highly compact ice conditions. Uotila (2001) showed that internal ice stresses were important close to the coast, and the modelling of the coastal ice motion was only successful by using a high-resolution (5 km) model with a realistic ice rheology. In the Baltic Sea, the main factors in the ice momentum balance are the wind stress and the internal stress of the ice pack (Leppäranta et al., 2001). When the compactness of the ice pack is high, the internal stress plays a major role, while it is negligible when the compactness is less than 0.8; then the ice velocity is close to the free drift velocity (Leppäranta et al., 2001). According to the plastic law, the internal stress of ice is linearly proportional to the ice strength (which is related to the ice thickness), and the wind stress is proportional to square of the wind velocity. This implies that, in addition to low compactness situations, there is a possibility for the ice velocity to reach the free drift velocity, if the wind stress is considerably larger than the internal stress. Leppäranta et al., (2001) found out that with wind speeds exceeding 15 m/s the observed ice velocities were closer to the free drift speed, and the deviation angle between the ice and wind directions reached a relatively constant value in agreement with the free drift law.

4.4.4 Operational modelling

Numerical modelling of the Baltic Sea ice conditions began in the early 1970's. In the beginning of BALTEX, the most advanced sea model applied for the Baltic Sea was that of Leppäranta and Zhang (1992), who implemented the viscous-plastic model of Hibler (1979) to the Baltic. Zhang and Leppäranta (1995) coupled the ice model to the storm surge model, and clearly demonstrated how variations in water elevations are reduced due to the internal friction of the ice pack. This model has been used for operational purposed in Finland during the latest years (Bai et al., 1995; Cheng et al., 1999). The same ice model was used in Sweden (Omstedt et al., 1994, Omstedt and Nyberg, 1995), but it was coupled to the ice-ocean box model of Omstedt (1990).

Another forecasting model (HIROMB) was developed by Kleine and Skylar (1995) and Eigenheer and Dalin (1998). It is presently used in several institutes around the Baltic Sea. Developments of the operational sea-ice models are ongoing within the IRIS project. The main objective of IRIS is to provide enhanced ice information for ship route selections, with a particular focus on ice ridges. In the project, the approach of Lensu (2003) to calculate ridge statistics has been implemented to the HIROMB and the Zhang (2000) model. In addition, a multi-category model of Haapala et al. (2004) has been applied in high-resolution sea-ice predictions.

4.5. Climatological Sea Ice Modelling

The first climatological sea ice models concentrated on the thermodynamic growth of ice. A pioneering work for climatological modelling in the Baltic Sea was done by Omstedt (1990), who developed a box model for the Baltic Sea. In this model the Baltic Sea was divided into various sub-basins. The vertical structure of the temperature and salinity was calculated in detail, and the horizontal advection of heat and salt was solved diagnostically. The ocean model was coupled to a one-dimensional ice model. During BALTEX, the model was further developed by Omstedt and Nyberg (1996). Due to its simplicity, the model allowed inter-annual simulations of ice conditions. Omstedt and Nyberg (1996) carried out decadal-scale integrations, and showed that ice conditions are largely controlled by the atmospheric forcing;

even minor changes in the air temperature can lead to large changes in the ice extent. Haapala and Leppäranta (1996) presented the first seasonal simulations of the Baltic Sea ice conditions with the evolution of sea ice calculated in two dimensions. Their model was based on the Hibler (1979) viscous-plastic rheology, the Semtner (1976) thermodynamic model, and the Leppäranta (1981) ice thickness redistribution schema. The ice model was coupled to a simple ocean model.

In the most advanced Baltic Sea models, a three-dimensional primitive-equation ocean model is coupled to a two-dimensional dynamic-thermodynamic ice model. The first such modelling results were presented by Lehmann and Krauss (1995), who coupled a high-resolution free-surface ocean model (Lehmann, 1995) to a viscous-plastic ice model (Hibler, 1979; Stössel and Owens, 1992). The model (BSIOM) has been used to simulate the general characteristics of the Baltic Sea (Lehmann and Hinrichsen, 2000a,b; Lehmann et al., 2002). Other high-level models were presented by Schrum (1997) and Meier et al. (1999). Schrum (1997) coupled a three-dimensional shelf ocean model (Bachhaus, 1985) to an extended version of Leppäranta and Zhang's (1992) model. The model has been used in analyzing the influence of the NAO on the circulation of the North Sea and the Baltic Sea (Schrum, 2001). The model was recently coupled to an atmospheric model (Schrum et al., 2003).

The approach of Meier et al. (1999) was to develop a numerical model suitable for parallel computing. They coupled a highly optimized primitive-equation ocean model (Webb et al., 1997) to an elastic-viscous-plastic ice model (Hunke and Dukowicz, 1997). Meier (1999) presented results of a 13-year hindcast simulation, and showed that the ocean temperature and salinity fields and ice conditions were generally well reproduced by this Rossby Center ocean model (RCO).

The RCO has been used for estimation of the future hydrographic and ice conditions in the Baltic Sea (Meier, 2000). In these predictions, the RCO was forced by the Rossby Center regional atmospheric climate model (Rummukainen et al., 1999). Comparable simulations were made with the Haapala (2000) model by Tuomenvirta et al. (2000; 2001). A comparison of these two model predictions was presented in Haapala et al. (2001b). Present-day climatological ice conditions and inter-annual variability were realistically reproduced by the models, except that the production of deformed ice was underestimated due to the underestimation of surface winds in the forcing data. The simulated MIB ranged from 180 x 10^3 to 420 x 10^3 km^2 in the control simulation of both models, and from 45 x 10^3 to 270 x 10^3 km^2 in the scenario simulation with a 150 % increase in the atmospheric CO_2 concentration. The range of the maximum annual ice thickness was from 32 to 96 cm and from 11 to 60 cm in the control and scenario simulations, respectively. In contrast to earlier climate change estimates (Tinz 1996; Omstedt et al. 2000), sea ice was still formed every winter in the Northern Bay of Bothnia and in the easternmost parts of the Gulf of Finland (Figure 4.4). Overall, the simulated changes in quantities such as the ice extent and thickness, as well as their inter- annual variations, were relatively similar in both models. This is remarkable, because the two coupled ice-ocean model systems were independently developed and different in many aspects. This increases the reliability of future projections of ice conditions in the Baltic Sea. The most recent predictions with the Rossby Center coupled atmosphere-ocean model do not change these conclusions (Meier et al. 2004).

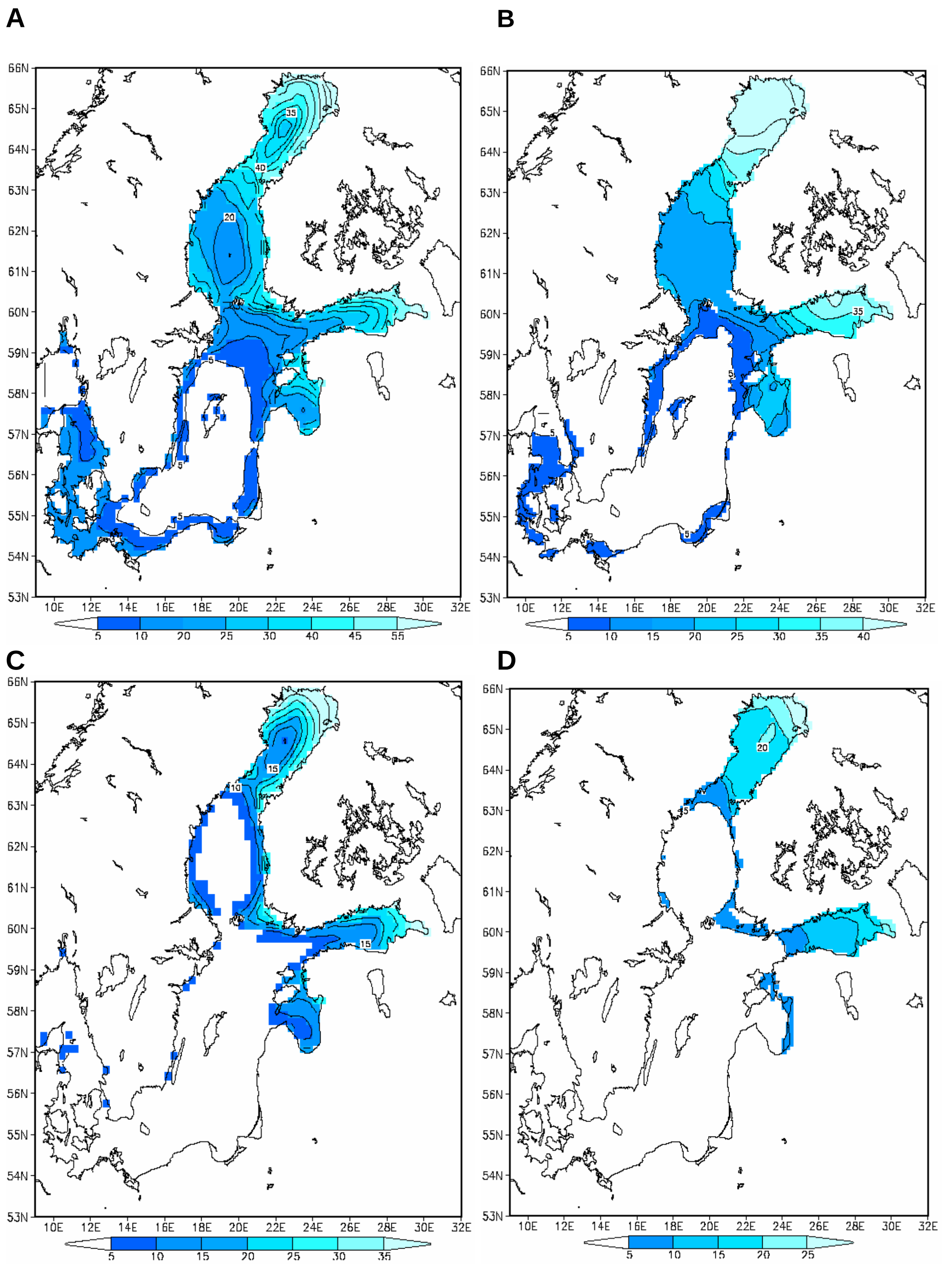

Figure 4.4. Modeled mean total ice thickness on 1 - 10 March in a pre-industrial (A and B) and future (C and D) climate conditions by the Helsinki ice model (A and C) (Haapala, 2000) and Rossby Center ocean model (B and D) (Meier, 2000). The models were forced by ten-year simulations of the Rossby Center regional atmospheric model. The future climate scenario simulation assumed a 150% increase in the atmospheric CO_2 concentration (redrawn from Haapala et al. 2001b).

RCO has also been used for long-term hindcast simulation of the Baltic Sea. Meier and Kauker (2002) simulated the period of 1902 – 1998 with the reconstructed atmospheric forcing. Their results are outstanding in respect of the reproduction of the vertical structure of the hydrography, salt water inflows, and the inter-annual variability of the ice conditions in the Baltic Sea.

4.6. Summary and Perspectives

BALTEX Phase I has marked a significant advance in several fields within sea ice research. Above all, we have obtained an improved understanding on the complex interactions between the following processes.

1. The atmosphere, sea ice, and the sea are closely coupled via thermodynamic and dynamic processes. BALTEX field experiments and modelling studies have yielded new results on the local and regional surface fluxes and the interaction of the ABL, sea ice, and the open water.
2. Sea ice thermodynamics and dynamics are closely interrelated. Sea ice dynamics results in opening and closing of leads, while thermodynamics results in ice formation, growth, and melt. Ice dynamics depends on the ice thickness distribution, and in turn redistributes the ice thickness. Results from 1 above and experiences with multi-category ice models have increased our understanding in this field.
3. The structure, physical properties and thermodynamics of sea ice are closely interrelated. Advance has been made in studies on sea ice structure, surface albedo, penetration of solar radiation, subsurface melting, and formation of superimposed ice and snow ice.
4. Physics, chemistry, and biology of sea ice are closely interrelated. Studies during BALTEX Phase I have addressed the solar radiation, nutrients, infiltration of matter through the ice, and the algae growth.
5. A few observations have demonstrated how the river discharge and ice melt affect the stratification of the oceanic boundary layer below the ice and the oceanic heat flux to the ice bottom. In general, process studies on ice-ocean interaction have been rare.
6. The Baltic Sea ice conditions are strongly affected by large-scale atmospheric circulation: the indices of AO and NAO correlate with the ice extent, the date of ice break-up, and the length of the ice season.
7. Increasing experience in climate modelling has improved our understanding on the role of sea ice in the regional climate system.

A major challenge for BALTEX Phase II is to deepen and further integrate the knowledge on these processes, and to well organize further research efforts. Our perspectives on the future research can be summarized as follows.

a) Increasing amounts of remote sensing data on sea ice will be available, and the most effective utilization of these data in climate-related studies is a challenge. Above all, we need to study all possibilities of applying remote sensing data to estimate the sea ice thickness distribution. Remote sensing data can also be utilized to detect individual ice ridges or clusters of them. In addition, high-resolution remote sensing data on sea ice concentration (and the data assimilation) are essential for modelling of the ice, ocean, and the atmosphere (Kaleschke et al., 2001).
b) Climate-scale variations in the three-dimensional morphology of deformed ice have not yet been studied in the Baltic Sea, because statistics on ridge density, sail height, and keel depth have been collected only recently. When more data become available, climate-scale studies should have more focus on deformed ice.

c) More co-operation between physicists, chemists, and biologists studying sea ice is needed to deepen our understanding on the complex interactions inside and below the sea ice cover. In spite of some advance (Ehn et al., 2004), little is so far known on how the ice structure, texture, chemical composition, dissolved and particulate matter, as well as biota affect the absorption of solar radiation and heat conduction.
d) The snow cover on sea ice deserves more attention, in particular during the spring melt season, which is often interrupted by periods of re-freezing. Snow-ice and superimposed ice are essential for the total ice thickness in the Baltic Sea, and we need more observations and modelling efforts focusing on them. Also the permeability of sea ice deserves more attention; it is important for the infiltration of seawater through the ice, and therefore affects snow-ice formation.
e) The snow/ice surface albedo is a critical parameter for climate modelling. In addition to its dependence on the state of the snow and ice cover, the snow/ice albedo interacts with the cloud radiative forcing, the partitioning between direct and diffuse radiation, and the multiple reflections between the snow/ice surface and the cloud base.
f) The main bottleneck of the development of the sea-ice models is the lack of proper validation data. In operational ice charts we have very good information on the ice extent and the thickness of coastal land-fast ice. The latter can be used for validation of thermodynamic models. Two important ice variables are, however, missing from the monitoring activities, namely the ice velocity and the thickness of drifting ice. In principle both variables could be observed with a reasonable accuracy. Ice velocity can be measured with drifters or derived from consecutive satellite images. Ice thickness is more difficult to map in a synoptic scale, but an upward-looking sonar in a fixed position would provide valuable statistics of the ice thickness distribution.
g) An obvious shortcoming in the present-day Baltic Sea ice and ice-ocean models is their horizontal resolution, which does not enable to resolve eddies and fine structures of the pack ice. The Finnish operational sea-ice model presently uses a resolution of 1 nm (~2 km). In this scale the model produces much stronger gradients in the ice thickness field than the same model used with a resolution typical for climate simulations. Compared with satellite data and ice charts, the model with a 1-nm resolution is, however, still too coarse. To capture coastal leads and narrow deformation zones, the ice model should have a resolution higher than 250 metres. Within the next five years, we probably will not see a coupled ice-ocean model of the entire Baltic Sea with such a resolution, but nested models or models with curvi-linear co-ordinates can be developed, with a certain region modelled with a very high resolution.
h) All sea-ice models presently used in the Baltic Sea are finite difference models. For the Arctic, Hopkins et al. (2004) have developed a finite-element sea-ice model. This model explicitly calculates the evolution of single ice floes, interaction between the ice floes, and ridge build-up. Utilizing this or a comparable model in the Baltic Sea would certainly yield new important results.
i) Increasing computational power is supposed to yield continuous advance in both operational and climate-scale sea ice modelling. We may foresee that during BALTEX Phase II operational atmospheric models will reach a horizontal resolution of the order of 1 km, and an improved vertical resolution will provide better possibilities to model stably stratified ABL and OBL. Better forcing fields for sea ice models will accordingly be available. Sea ice modelling can develop in the above-mentioned directions, and even climate models can have several layers in the ice and snow, which will allow realistic modelling of the complex thermodynamic processes.

4.7. References

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Chapter 5:

Land-atmosphere interaction in the Baltic Region

by

Bart vd Hurk

5.1. Introduction

The cycles of water and energy in the Earth climate system are greatly affected by processes at the land-atmosphere interface. These processes reflect a two-way coupling between the state of the soil and land surface on one hand, and the atmosphere on the other. For instance, evaporation from vegetated areas affects the water stored in the subsoil zone, but also modifies the atmospheric water content, thereby affecting the thermodynamic structure and precipitation. The precipitation in turn modifies the soil water content and evaporation, closing the water feedback loop.

A particularly complicated aspect of this two-way coupling is the existence of potential positive feedback loops. A well-known phenomenon is the drying cycle over continental summers, in which soil depletion reduces evaporation and consequently precipitation, exaggerating even further the dry state of the soil. Alternatively, systematic cool biases are attained in cases where excessive cloud formation inhibits radiation to reach the surface, giving rise to a cold bias in the atmospheric temperature, which may enhance low level cloud formation by condensation even further. Positive feedback loops of this kind are difficult to represent realistically in numerical models of the (regional) climate system. Under particular conditions dependencies of fluxes on states (precipitation as function of water content and thermodynamic structure, evaporation as function of soil water content, radiation as function of cloud cover) may be very strong and non-linear, and drive the system to a given state from which it is difficult to recover without strong external forcing.

For that reason, research on land-atmosphere interaction is not only aiming at the primary land-surface processes (evaporation and runoff, momentum exchange, radiative properties), but gradually focusing on the representation of the land-atmosphere *feedback* processes using coupled models (Van den Hurk *et al*, 2002b).

In the context of the 1st phase of the extensive BALTEX project, a few studies have been carried out that can be regarded as partial exponents of this new focus on feedback analysis. These studies are normally designed as modelling exercises in which sensitivities of the whole hydrological cycle to modifications in land-surface and/or atmospheric parameterisations are explored. Parallel to these numerical experiments observations have been used to improve the quality of land-surface models or to enable the detection of changes in land surface conditions on a climatological time scale. This chapter provides an overview of these observational and modelling studies, and makes suggestions for future research needs in the framework of the follow-up of the BALTEX project.

5.2. Observational studies and offline model evaluation

The PILPS2E-experiment

A classical methodology to evaluate land surface models has been developed in the so-called PILPS (Project for Intercomparison of Land-surface Parameterisation Schemes) series of experiments. Observations of radiative, atmospheric and precipitation forcings are used to drive offline land-surface schemes, and resulting fluxes and state variables are subsequently compared to each other or independent observations. In the Baltex area the PILPS-2E experiment (Bowling et al, 2002) has been designed to evaluate approximately 20 surface models under high-latitude climate conditions, dominated by snow processes and short growing seasons. In PILPS-2E a 20-year forcing was prepared covering a 58000 km^2 area comprising the Torne and Kalix river catchments. After 10 years of spin-up, models were compared to observed snow extent, runoff, evaporation estimates and in situ fluxes. Of particular importance for the representation of the hydrological and energy processes at the land-surface appeared to be the treatment of snow sublimation and melt. Differences in this treatment resulted in significant inter-model differences of averaged seasonal cycles of the important fluxes, in particular during Spring (see, e.g. Figure 5.1, comparing the number of days with snow cover to satellite derived estimates). A special issue of Global and Planetary Change is devoted to studies carried out in the context of the PILPS-2E experiment.

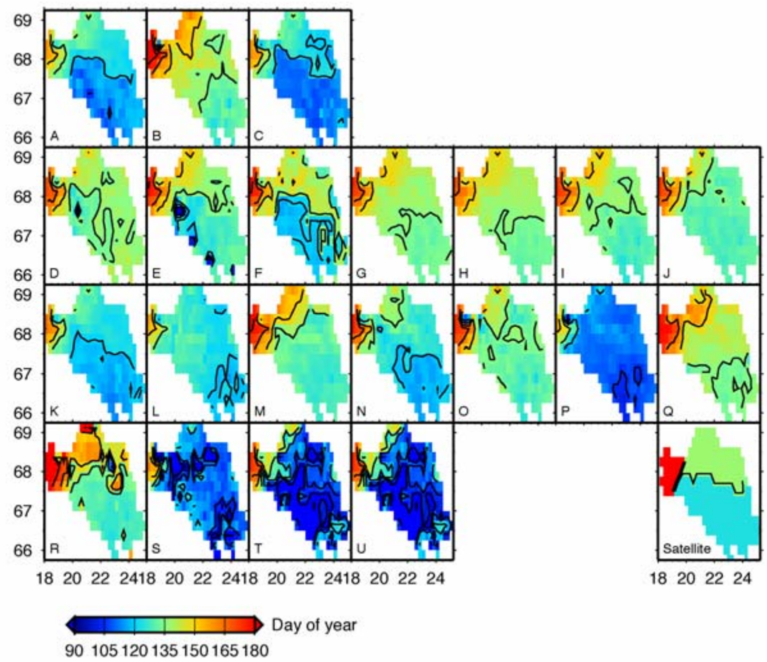

Figure 5.1: Number of days with snow cover for models participating in PILPS-2E. Lowest right panel shows a satellite derived estimate (after Nijssen et al, 2002).

Evaluation of the ECMWF land surface scheme using NOPEX data

Gustafsson et al (2003) used NOPEX data to evaluate the performance of changes made to the land surface parameterisation scheme of the European Centre for Medium-Range Weather Forecasts (ECMWF) for the 40-year Reanalysis project. They confirmed the conclusions by van den Hurk et al (2000) that modifications to the treatment of snow in forest areas resulted in a systematic improvement of the annual cycle of the land surface fluxes and state variables. However, the modelled relation between soil water and evaporation appeared different from the observations (too little transpiration in summer at too high soil water contents), which could be improved by adjusting canopy and soil properties in the model. This study provides a powerful illustration of the use of observations to optimise the *sensitivity* of land surface fluxes to state variables, rather than the optimisation of either of the model components.

Soil moisture observations from space

Soil moisture is an important storage reservoir in the hydrological cycle. Its spatial and temporal variability put severe limitations on systematic regional scale monitoring using in situ measurements only, and spaceborne observations techniques based on active and passive microwave sensing are being developed. Lindau et al (2002) explored the use of the C-band radiometer data on board of the SMMR satellite (which has collected surface brightness temperature and inferred soil moisture data between 1978 and 1987). They carefully analysed the degree of correlation one may expect from comparing point measurements derived from in situ samples to satellite pixels at an order 100^2 km^2 resolution. Using observations from a routine Estonian soil moisture network they showed a good correlation between a polarization index (ratio of horizontally and vertically polarized brightness temperatures) and in situ soil moisture, demonstrating the capacity of even C-band observations to construct a regional scale soil wetness database. Future satellite missions (e.g. SMOS from ESA) aim at soil moisture monitoring using observations taken in the L-band, which is hardly affected by atmospheric absorption and scattering and therefore superior over the C-band data from SMMR and similar instruments.

Surface radiation

Also satellite derived surface radiation estimates in the Baltic region are being explored. Hollmann and Gratzki (2002) explain the methodology to be followed in the so-called Climate Satellite Application Facility, installed by EUMETSAT. Meteosat Second Generation (MSG) will allow sophisticated cloud detection and radiative transfer calculations on a high temporal and spatial resolution. MSG was launched early in 2002, and availability of operational products is to be expected soon.

5.3. Numerical studies with coupled models

Comparison of regional atmospheric models during the PIDCAP period

Insight in the contemporary behaviour of processes governing the energy and water cycles in the Baltic area is gained by comparing coupled land-atmosphere models to each other and to observations in well-designed and devoted experiments. Over the Baltic area, such an intercomparison was carried out during the 3-month PIDCAP (Pilot Study of Intense Data Collection and Analysis of Precipitation; Aug – Oct 1995) period by Jacob et al (2001) and Lorant et al (2002). In a unique set-up, a number of limited area models was operated using a common vertical and horizontal grid, atmospheric forcings as lateral boundary conditions and sea surface temperatures. Comparisons were carried out between models and observations of cloud cover, water vapour amount, surface radiation and synops parameters, runoff and turbulent surface fluxes over sea. Not surprisingly, a great sensitivity of surface evaporation and runoff was found to the initialisation of soil water content, which was not prescribed and varied considerably among the participating modelling systems (see Figure 5.2). Long spin-up periods are required for initialisation of the slow soil moisture reservoir (see the PILPS-2E study by Bowling et al (2002)), in order to obtain a moisture content compatible with the model-specific mutual dependencies between soil water and resulting fluxes. Although the comparison period was relatively short and available observations were not exhaustive, many modelling groups were able to use the results of the experiment in order to detect and repair deficiencies in their formulations, serving post-experiment applications of the limited area models.

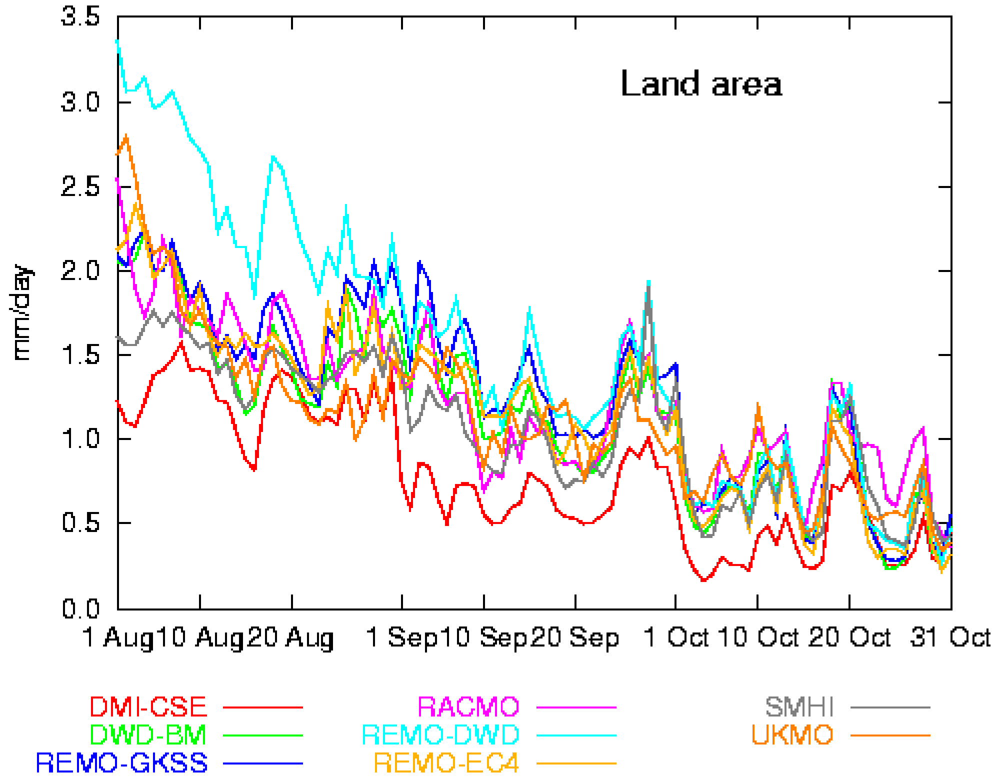

Figure 5.2: Time series of surface evaporation over land in the Baltic Sea catchment, as predicted by the limitedarea models participating in the PIDCAP-intercomparison (Jacob et al, 2001). Soil moisture initialization appeared to be responsible for the major portion of the variability.

Evaluation of the impact of land surface schemes on the regional hydrological cycle

Similar to the abovementioned study, Van den Hurk et al (2002a) carried out a model intercomparison over the Baltic area, but focussed on the impact of the choice of land-surface model on the hydrological cycle. They did so by running a limited area model for a full annual cycle over the same domain as the PIDCAP intercomparison experiment, but used a common atmospheric host model in which two different land surface schemes were coded, mainly different with respect to the formulation of runoff and spatial variaibility of soil and vegetation parameters. A simulation with the HBV-hydrological model, forced by observed precipitation, served as reference here. Although (again) soil moisture spin-up appeared an issue not optimally resolved, they found that the partitioning of precipitation over runoff, soil storage and runoff was very different in the two land-surface schemes included in the simulation. Comparisons to the HBV-simulation showed the explicit treatment of spatial variability of soil infiltration capacity to result in superior temporal characteristics in the modelled total runoff to the Baltic Sea (Fig. 5.3). But, one step further they concluded that this difference in rainfall partitioning had a well-detectable impact on the water recycling in the domain, by a close connection between surface evaporation and precipitation on the regional scale. In their results, this feedback acted to reduce the differences between the schemes in terms of total simulated runoff, in spite of considerable differences in the temporal characteristics.

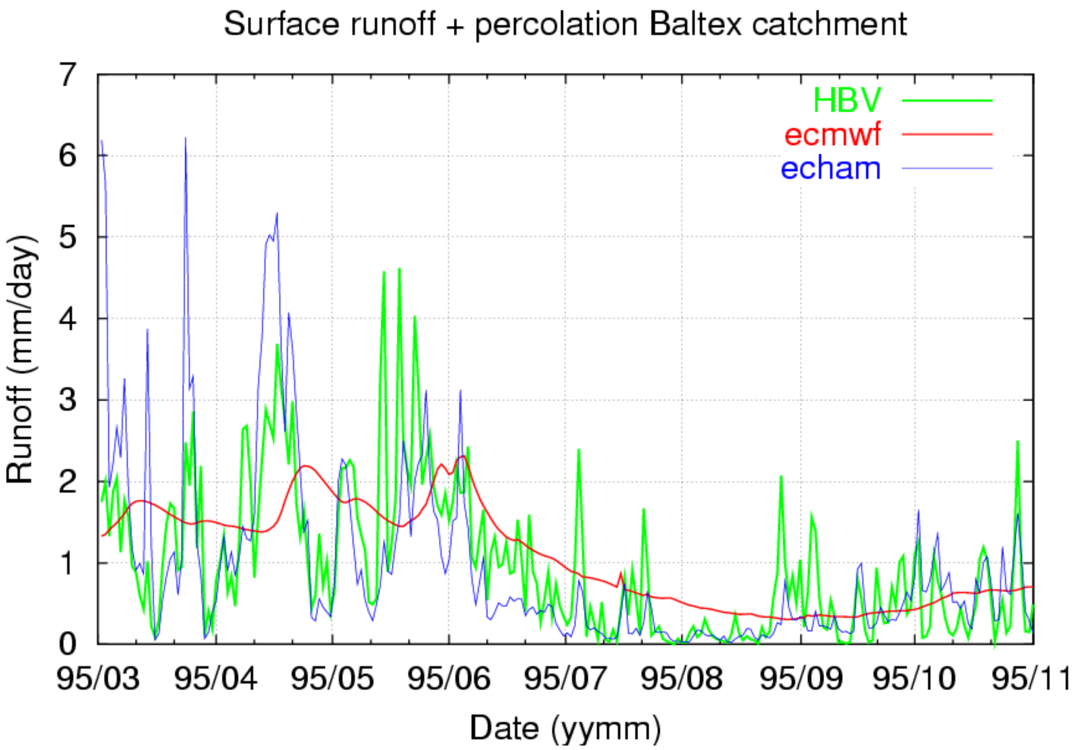

Figure 5.3: Comparison of daily runoff from the HBV-simulation, and two land surface schemes in a common host atmospheric model: one with explicit surface (echam) and one without (ecmwf) (Van den Hurk et al, 2002a).

Global water cycling

An interesting study on land-atmosphere interaction is the global water tracing experiment by Bosilovich and Schubert (2002), in which continental scale sources and sinks of water vapour are simulated in a tracer formalism. Using “labelled” water particles followed in a GCM-simulation, they estimated the source of precipitation falling in the Baltic area. In winter more than 50% of the precipitation falling in the Baltic area originates from the North-Atlantic area, and, as expected, summertime precipitation is increasingly originating from the European continent. Local recirculation of precipitation could not be calculated from their results, as the Baltic catchment was not identified as a separate source area. However, from inspecting the source/sink distribution of Europe as a whole it is evident that local recycling is stronger in summer and amounts up to 45% of the total precipitation. This implies again that sensitivity analyses of parameters affecting the hydrological cycle (land surface parameters, precipitation, cloud cover etc) should preferably be considered in coupled models, since a strong mutual interaction of these components is present.

5.4. Conclusions and suggestions for future directions

Of coarse, a careful evaluation of the skill of any parameterisation scheme operated stand-alone is justified, but an analysis using coupled models enables an evaluation in the context of the application in which this stand-alone parameterisation scheme will eventually play a role. Many feedbacks in coupled systems may affect the actual performance of the modelling systems. Therefore, analysis of model performance should go beyond the validation of individual fluxes or state variables. Of particular relevance is to analyse diagnostic output that reflects the sensitivities of fluxes to state variables explicitly or implicitly incorporated in the coupled modelling systems. For instance, the relation between soil water and evaporation is probably more meaningful to evaluate the skill of a model system to represent the regional hydrological cycle than is the separate analysis of fluxes or soil water content.

This implies that the design of model intercomparison or evaluation studies must be reconsidered. The GEWEX Land Atmosphere System Study (GLASS) panel devoted a special workshop to the issue of land-atmosphere coupling and future experimental design (Van den Hurk et al, 2002). Their suggested experimental design is based on the fact that "optimal" model parameters may be affected by land-atmosphere feedback. A controlled model intercomparison experiment like the PILPS set-up is not as straightforward with coupled models. Probably, starting from a well-defined single column set-up, and development of (additional) relevant diagnostic outputs are the primary research tasks to be initiated.

Perhaps the most challenging aspect of coupled land-atmosphere studies is the extraction of relevant information from available or newly derived observation types. It is apparently easier to measure soil moisture or fluxes of energy and water, than to measure a quantity expressing the degree and nature of the coupling between land surface and the overlying atmosphere. Continuation of the current long-term monitoring programs is mandatory in order to be able to capture the relevant temporal and spatial time scales in the observations. But, as with the design of numerical experiments, a (re)consideration of combinations of observations is needed to improve the amount of information that can be extracted from the data.

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Chapter 6:

Fluxes of Latent and Sensible Heat over the Baltic Sea

By

Ann-Sofi Smedman and Sven-Erik Gryning

6.1. Introduction

Our ability to understand and predict the 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 changes the surface albedo, and the availability of water in the ground affects the way heat and moisture enters 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.

The BALTEX experiment and some results are described in Raschke et al. (2001).

As stated above, determination of the water budget over the Baltic Sea and its catchment area is the major objective of BALTEX. The three main components of the water balance are: river run-off, the exchange of water through the Danish Straits and precipitation minus evaporation over the Baltic Sea itself. The first two components are fairly well-known, but reliable and representative estimates of precipitation and evaporation for the Baltic Sea were lacking at the onset of the BALTEX project. Thus the project PEP in BALTEX (Pilot study of Evaporation and Precipitation in the Baltic Sea) was designed to bridge this gap of knowledge.

The specific scientific objectives of PEP were defined in the following manner

- Direct measurements of water vapour flux (evaporation) at 4 sites in the Baltic Sea during an 18 month period.
- Use of the above measurements for validation of evaporation routines in regional and meso-scale models
- First steps towards improvement of parameterizations for evaporation in the models used in the validation study
- In-situ measurements of precipitation by advanced methods on islands and on ships, also during an 18 months period
- Validation of precipitation estimates from regional models for the special measuring sites
- Improvement of algorithms to estimate precipitation from weather radar data over the Baltic Sea
- Estimation of evaporation and precipitation over the entire Baltic Sea for a one-year period, carried out with 4 models for evaporation and 4 for precipitation.

In the following only the sensible and latent heat exchange over the Baltic Sea is considered.

6.2. Sites and measurements

Direct heat and evaporation measurements from the following sites are analysed:

1. Kopparnäs, on the Finnish south coast (operated by FMI)
2. The island Christiansø (operated by Risø)
3. The island Östergarnsholm, east of Gotland (operated by MIUU)

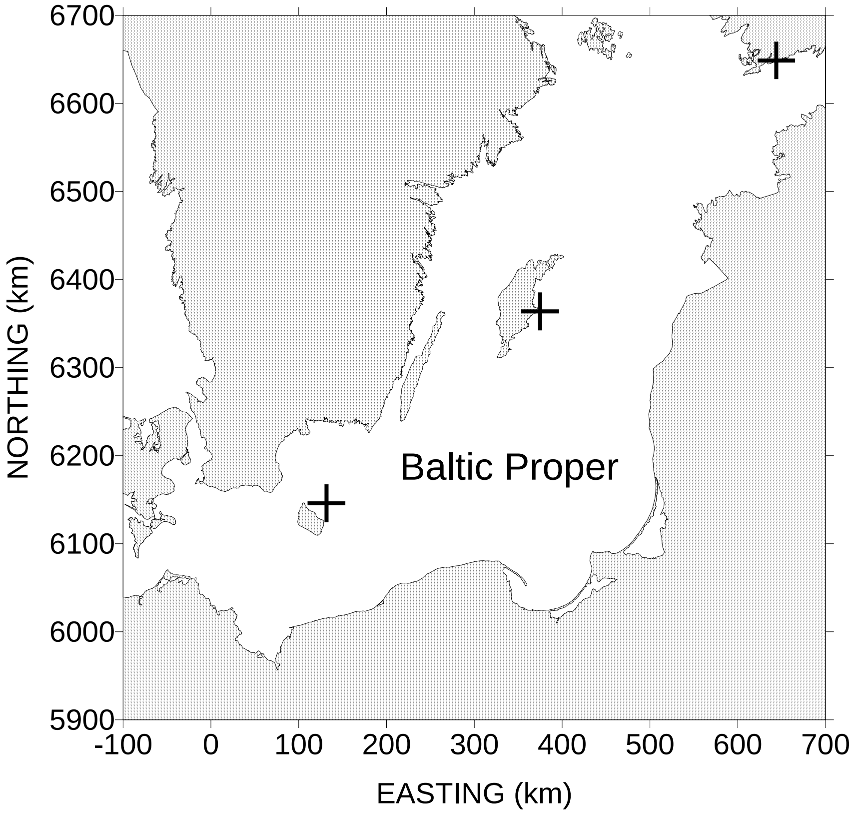

Figure 6.1: Map of the Baltic Proper with land surfaces and islands dotted. Crosses show the locations of Christiansø (east of Bornholm), Östergarnsholm (east of Gotland) and Kopparnäs at the Finnish coast. The co-ordinate system refers to UTM34.

6.2.1 Kopparnäs

6.2.1.1 Site

The main site in Finland is Kopparnäs, where two masts (Figure 6.2) were instrumented. Kopparnäs site is located on the southern coast of Finland. The water fetch at the site is obstructed by several islands with an undisturbed water fetch for wind directions of 150 – 250 degrees, Figure 6.3.

Figure 6.2: Kopparnäs. In the front the 50 m tower, and in the back the 33 m tower. The temperature of the sea water is measured at 0.5 m depth.

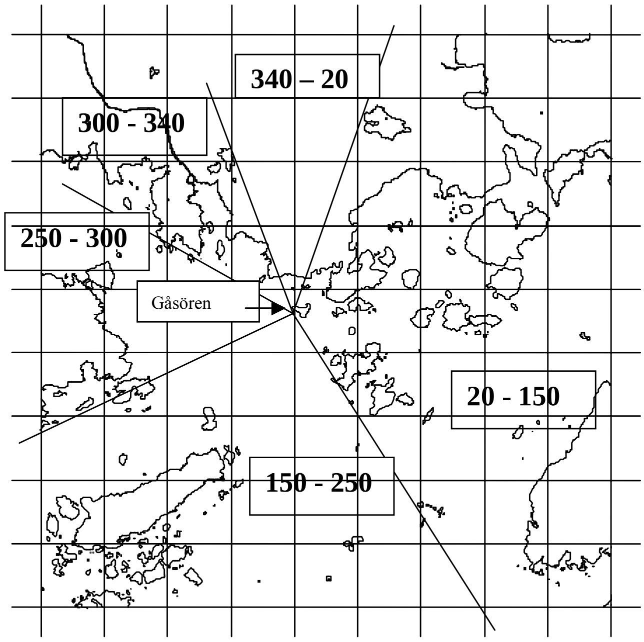

Figure 6.3: A map of Kopparnäs site. The wind sectors used in this report are indicated.

The main mast for the PEP project is located on a small island Gåsören seen in Fig. 6.3. The height of the mast is 33 m and it is sited on the western part of Gåsören some 20 m from water.

6.2.1.2 Measurements

Evaporation was measured in three ways: continuous 10 min averages for the bulk method, continuous 1 Hz measurements using a special humidity sensor, occasionally performed direct evaporation measurements by the open path fast response water vapour hygrometer, model M-100 (Applied Technology Inc. USA).

The wind measurements were made by ordinary non-ice-free anemometers of type Vaisala WAA15. In this type of sensors the shaft is heated, but it does not prevent the icing of the cups. Shaft heating was not implemented in this installation.

To get accurate temperature measurements a QLI50 Sensor Collector system (from Vaisala) with PT100(1/10DIN)-sensors and carefully built cable without extra connecting box were used at Gåsören since 25.11.1998.

Turbulence data was collected by PC-measurement system continuously at 10 Hz frequency. Hygrometer M-300 and Metek USA-1 sensors were measured at 10 Hz frequency. Data was saved on the PC´s hard disc and during the visit to the island it was copied to CD-RW (Tammelin and Hyvönen, 2000).

6.2.2 Christiansø

6.2.2.1 Site

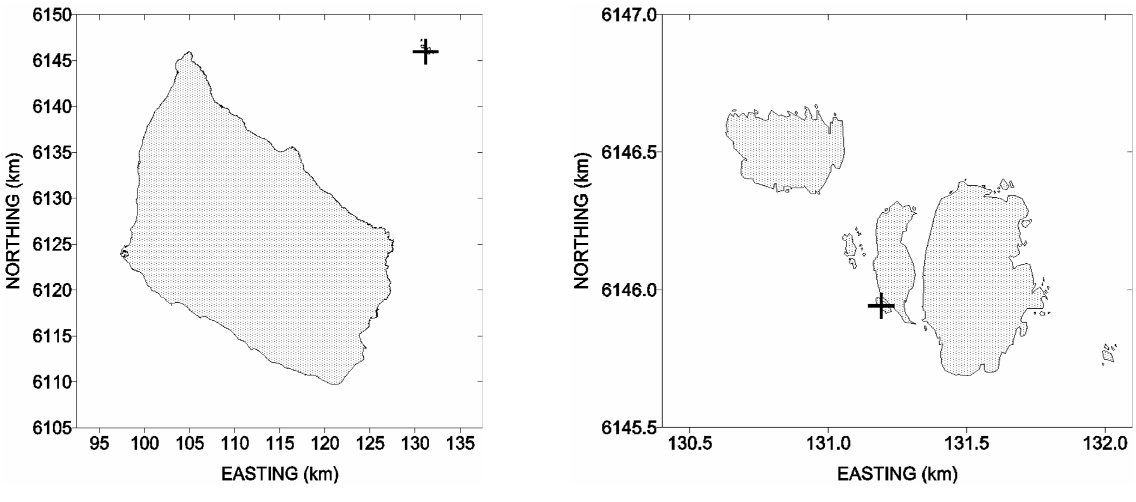

Figure 6.4: The left panel shows the island of Bornholm. Christiansø is the group of islands northeast of Bornholm that can be seen in the upper right corner of the frame and it is marked by a cross. Right panel is a map of Chrisatiansø with the position of the meteorology mast indicated by a cross. The co-ordinate systems refer to UTM34.

The measuring activities were concentrated at a cluster of small granite islands in the Baltic Sea known collectively as Ertholmene. Figure 6.1 shows a map of the Baltic Proper with the position of Ertholmene marked with a cross. For wind directions in the sector 190 to 270 Ertholmene lies about 20 km downwind of Bornholm, Figure 6.4 (left panel). In the sector 270 to 45 degrees the water fetch to the Swedish coast is about 100 km. The biggest island - Christiansø, is a ≈0.2 km^2 large, beautifully preserved 17th century island fortress, Figure 6.4 (right panel). It forms, together with its smaller, ≈0.04 km^2, sister island, Frederiksø a natural harbour. The number of people living on the islands is about 100 and restricted. The islands are cultural and environmental protected areas. Græsholm, northwest of Christiansø, is a wildlife refuge. Ertholmene are rather flat, although Christiansø reaches 20 metres in its central parts. Commonly the group of islands is also named Christiansø, and this practise will be used here.

6.2.2.2 Measurements

Long term measurements (April 1998 through December 1999) of atmospheric turbulence and evaporation were carried out at an 8-meter mast placed on a small granite island with an open sector to the sea of 120° to 300° through south, Figure 6.2. The measurements of heat and momentum fluxes were performed with a Kaijo-Denki DAT/TR-61B three-dimensional sonic anemometer. The fluctuations of water vapour content in the air were measured with an open path infrared optical hygrometer (OPHIR), Figure 6.5. The signals from the instruments were sampled with a frequency of 10 Hz. All mean values, variances and covariances are derived as 30-minute averages with software developed at Risø (Risø National Laboratory). All measurements including the raw data have been transferred to Risø by use of internet and stored for subsequent analysis.

Figure 6.5: The meteorology mast. The picture is taken looking towards southwest.

Synoptic data were measured near the lighthouse at Christiansø, a few hundred meters from the meteorology mast. Sea surface temperature (bucket temperature) is measured once a day.

During an extensive observation period from 24 October to 5 November 1998 the measurement programme was extended with radiosoundings, with a total of 24 radiosondes released at Christiansø. The soundings were performed by an AIR system (Atmospheric Instrumentation Research Inc.) with radiosondes of type IS-5A Intellisonde, measuring temperature, humidity and pressure (can be converted to height) with data sampling every two seconds. The soundings were performed with an ascent velocity of about 1-3 m s^{-1} . Most of the sondes were launched under very difficult conditions due to very strong winds. During the days from 31 October to 2 November the radiosounding programme was further intensified to 4 to 6 soundings per day.

The depth of the boundary layer was subjectively estimated from the soundings, based mainly on the profile of the potential temperature, and taken as the height where the potential temperature starts to increase, simultaneously considering the humidity profile. Figure 6.6 shows examples of potential temperature profiles from radiosoundings at 9, 15 and 24 GMT on November 1, 1998. It can be seen that the potential temperature is near constant as function of height above the sea and up to typically 500 metre, where it starts to increase marking the top of the boundary layer. The bullet depicts the subjectively estimated top of the boundary layer.

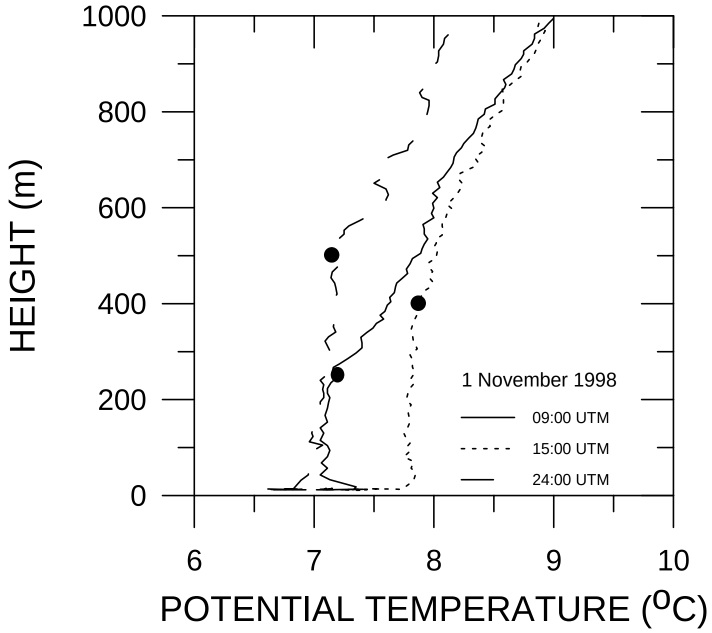

Figure 6.6: Examples of radiosonde profiles of potential temperature on November 1, 1998. Bullets indicate the subjectively estimated boundary-layer heights (Gryning and Batchvarova 2002).

6.2.3 Östergarnsholm

6.2.3.1 Site

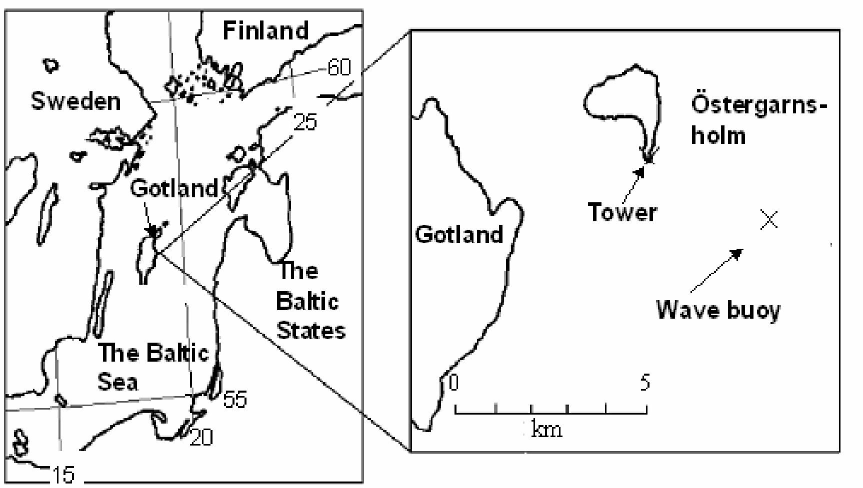

Figure 6.7: Map with indication of Gotland (left) and the Östergarnsholm site (right).

Figure 6.8: Arial photography of the meteorological station at Östergarnsholm.

The small island Östergarnsholm (2 x 2 km), is situated about 4 km east of the island of Gotland in the middle of the Baltic Sea (Figure 6.7). On this island, semi-continuous measurements have been performed on a 30 meter tower, since May 1995. Östergarnsholm is a very flat island, with only sparse vegetation and no trees.

The slope of the sea floor outside the island permits an undisturbed wave field for most conditions (Smedman et al., 1999). However, during high wind speeds, a minor correction for limited water depth has to be applied. The slope is approximately 1:30 at 500 m from the shore, and about 10 km from the peninsula, the depth is 50 m, reaching below 100 m further out. The flux footprint analysis performed by Smedman et al. (1999) showed that for measurements at approximately 10 m height during neutral conditions, 90% of the fluxes originate from areas beyond 250 m, 50% originates from beyond 670 m and 70% from areas between 250 and 1700 m. And it was concluded that the shallow water effects to be seem small even during gale conditions.

The base of the tower is situated at about 1 m above sea level, Figure 6.8. In the sector approximately 100-220° the water fetch is undisturbed, and the distance to the shoreline in this direction is normally no more than a few tens of meters. Östergarnsholm will therefore represent open sea conditions of the Baltic Sea for most of the time when the wind is from the sector 100-220°.

6.2.3.2 Measurements

Turbulence instruments (Solent Ultrasonic Anemometer 1012R2, Gill Instruments, Lymington, United Kingdom) are placed at 9, 17 and 25 m above the tower base and recorded with 20 Hz. Slow response ("profile") instruments are placed at five heights on the tower, at 7, 12, 14, 20 and 29 m above the tower base, measuring wind speed, wind direction and temperature with 1 Hz.

The temperature measured by the sonic anemometers T_s is very close (about 0.20%) to the virtual temperature T_v (Dupuis et al., 1997, Sjöblom and Smedman, 2001). The virtual heat flux $\overline{w'\theta_v'}$ has been corrected for "cross-wind" velocity contamination, since the signal is contaminated by the wind components normal to and along the path (Kaimal and Gaynor, 1991).

In addition to the tower instruments, a Wave-Rider Buoy (owned and run by the Finnish Institute of Marine Research) is deployed about 4 km from Östergarnsholm (direction 115°, Figure 6.7). The buoy is moored at 36 m water depth, and it is placed in the upwind fetch of the measurements, thereby representing the wave conditions in the "footprint area" outside Östergarnsholm. It measures sea surface (bucket) temperature, significant wave height, wave direction and the energy spectra of the wave field.

6.3. Fluxes of latent and sensible heat

6.3.1 Brief outline of methods

The most direct method for determination of evaporation over the sea is the *eddy correlation technique*. It essentially amounts to measuring the net difference between upward and downward transfer of humidity by the vertical component of the turbulent wind at some low height above the water surface. It is generally accepted that this turbulent flux is close to the water vapour flux from the surface, i.e. the evaporation. With measurements at 10 m this approximation is usually better than 10 percent. In mathematical terms, the eddy flux of water vapour is simply

$$E = \overline{w'q'} \qquad (1)$$

Here E is evaporation (kg m^{-2} s^{-1}), w' instantaneous value of the vertical wind component (m s^{-1}) and q' is instantaneous deviation of absolute humidity (kg m^{-3}) from its mean value for the averaging period of 30 or 60 minutes. The overbar means an average over this period of time.

The eddy correlation technique was employed at the sites Christiansø, Östergarnsholm and Kopparnäs.

Regional-scale and meso-scale models employ a so-called *'bulk formulation'* for calculating evaporation over the sea:

$$E = C_e(q_{10} - q_0)u_{10} \qquad (2)$$

where E is evaporation (kg m^{-2} s^{-1}), C_e is a dimensionless parameter, q_{10} is absolute humidity (kg m^{-3}) at 10 m above the water surface, q_0 is the corresponding absolute humidity at the water surface, which is assumed to equal the saturation absolute humidity at the sea surface temperature (T_s), and u_{10} is wind speed (m s^{-1}) at 10 m. All quantities in in Eq. (2) are mean values over a time period of the order 30 to 60 minutes. Provided C_e is known, evaporation can be obtained from Eq. (2) with values for q_{10} , T_s and u_{10} generated by the model. Many field studies have provided information on C_e, but the results are not conclusive. Few, if any, previous studies have provided so comprehensive data for this parameter as the present study. In the comparisons presented below are given not only results for the water vapour flux E but also for the corresponding turbulent *flux of sensible heat*, H, which is technically easier to measure. This quantity is obtained with the eddy correlation technique and Eq. (1) after substitution of $\rho c_p T'$ for q', where ρ is air density (kg m^{-3}), c_p is specific heat of air (j kg^{-1}K^{-1}) and T' is instantaneous deviation of temperature (K) from its mean value for the averaging period. H is thus obtained in W m^{-2}. Often evaporation is given as an energy flux equivalent as well, after multiplication of E with L_v, the specific heat of vaporization. L_vE is then termed *the flux of latent heat*. In some graphs the Greek letter λ is used instead of L_v.

The bulk formula for H is

$$H = \rho c_p(\theta_{10} - \theta_s)C_H u_{10} \tag{3}$$

where θ_{10} is the potential temperature at 10 m, which is close to ordinary temperature at that height, θ_s = T_s, the sea surface temperature. C_H is a dimensionless parameter and the other quantities have the same meaning as before.

The parameters C_e and C_H can both be written as the product of a stability function $f_{e,H}(z/L)$, where z is height above the surface and L is the Monin-Obukhov length (definition: see below), and the value of C_e and C_H at neutral stability (z/L= 0), C_{eN} and C_{HN} respectively, i.e.

$$C_e = f_e(z/L)C_{eN} \tag{4a}$$

$$C_H = f_H(z/L)C_{HN} \tag{4b}$$

Here the functions f_e and f_H may, in principle, be different but are usually assumed to be equal, i.e. $f_e = f_H = f(z/L)$. The Monin-Obukhov length is defined accordingly:

$$L = -\frac{u_*{}^3 T_0}{gk\overline{w'\theta'}} \tag{5}$$

where u_* is the friction velocity (ms^{-1}), T_0 the mean temperature of the surface layer (K), g is acceleration of gravity (ms^{-2}), k is the von Karman constant = 0.4, and $\overline{w'\theta'} = H/\rho c_p$.

6.3.2 Comparison of bulk estimates against turbulent flux estimates

Figure 6.9 compares sensible heat flux H, obtained with the eddy correlation technique, H_{direct}, with H_{bulk} from measurements at Östergarnsholm. Here C_H has been calculated with $C_{HN} = 1.1 \cdot 10^{-3}$ and standard formulas for $f(z/L)$. The agreement is quite good for positive fluxes, but for negative fluxes - H_{direct} is about half - H_{bulk}, see below. Figure 6.10 shows a corresponding comparison of the latent heat flux derived from eddy correlation (ordinate) against bulk estimate from the Kopparnäs site.

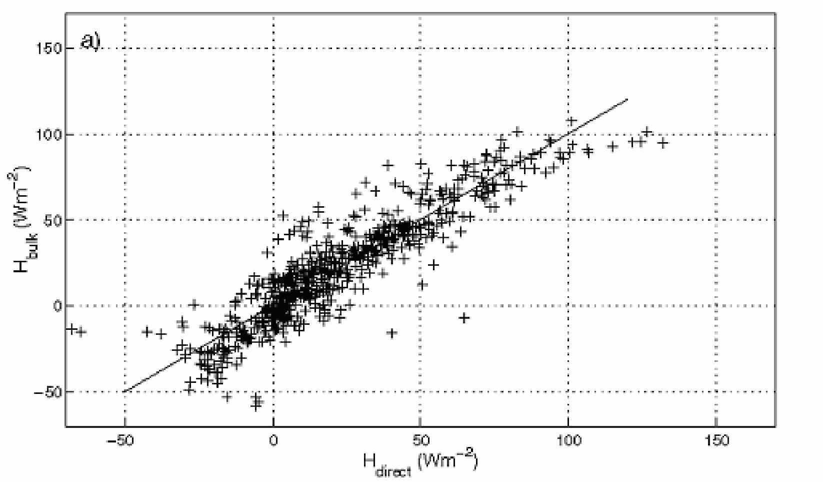

Figure 6.9: Sensible heat flux calculated by bulk formulation compared to corresponding measured values at Östergarnsholm, May to December 1998. Solid line is the 1:1 relation. After Rutgersson et al. (2001b).

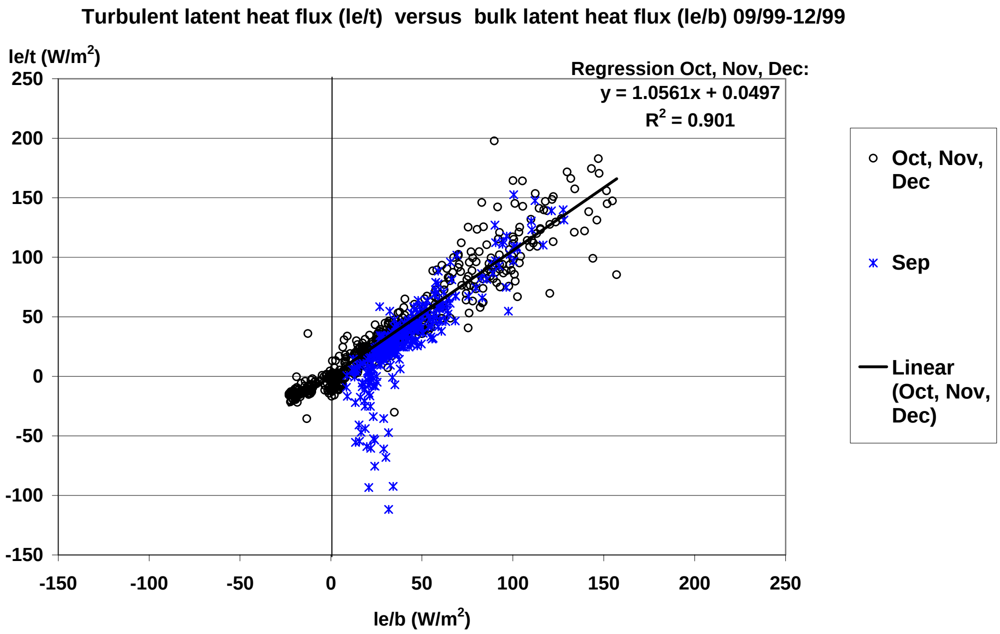

Figure 6.10: Latent heat flux measured with eddy correlation technique(on the ordinate) versus calculated values with the bulk method at Kopparnäs. Period: Oct. – Dec. 1999.

Apart from some of the crosses, the data appear to correlate very well, the correlation coefficient being 0.95. There is, however a slight tendency for the bulk method to underestimate the fluxes, at least for large fluxes.

Figure 6.11 shows C_{HN} plotted against the stability parameter z/L for data from Östergarnsholm. The filled symbols are data measured with MIUU turbulence instruments and the open symbols with sonic anemometers.

For unstable conditions, ($z/L < 0$), the mean value of C_{HN} is around $1.1 \cdot 10^{-3}$ but with large scatter close to neutral. But for stable stratification ($z/L > 0$) the values are very small around $0.6 \cdot 10^{-3}$. So there is a 'jump' around neutral stability. This indicates that the stability correction is wrong.

This result was also reported by Large and Pond (1982) but seems to have been overlooked by subsequent authors. Recently the same result was, however, found by Oost et al. (2000).

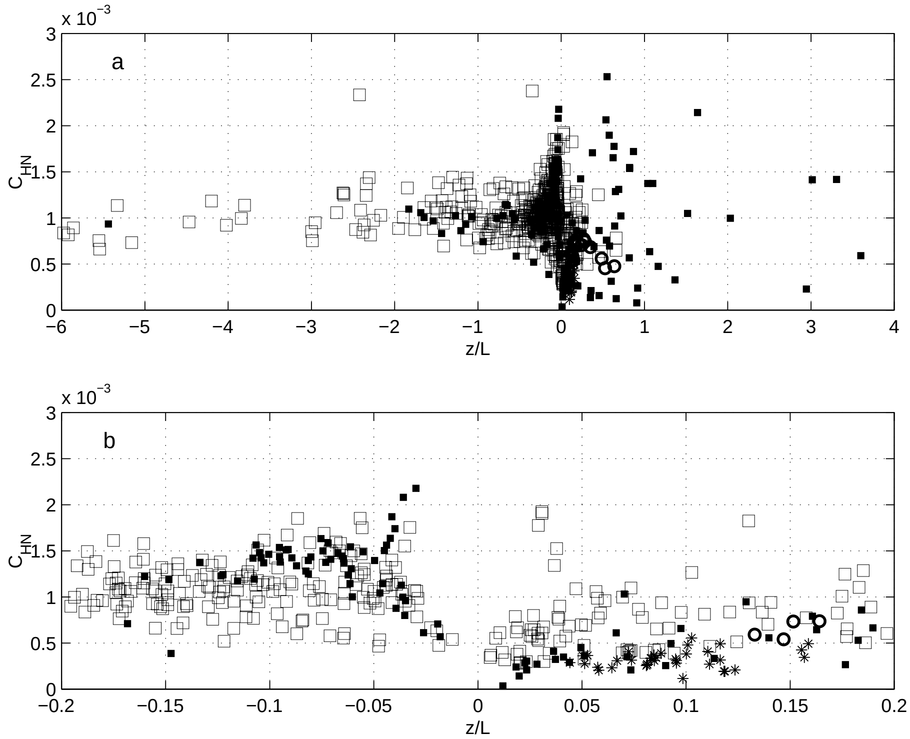

Figure 6.11: C_{HN} plotted as a function of z/L in two stability ranges. Open symbols represent measurements with sonic anemometers and filled symbols with the MIUU turbulence instrumentation.

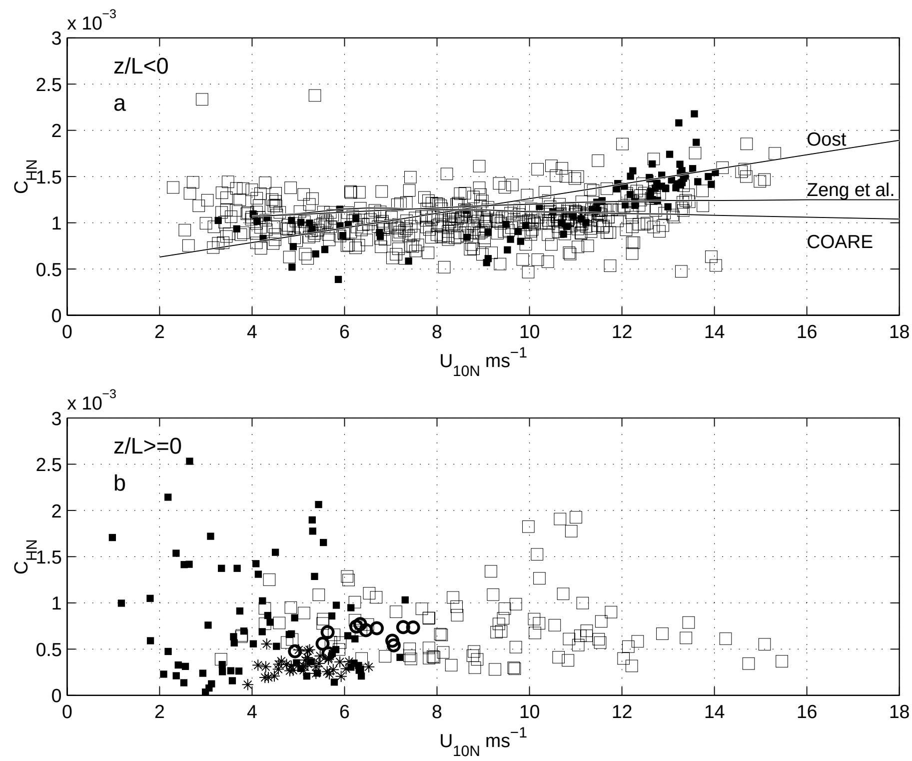

Figure 6.12: C_{HN} plotted as a function of wind speed at 10 m for a) $z/L < 0$ and b) $z/L > 0$. The curves represent expressions from Oost et al. (1999), Fairall et al. (1996a) (denoted COARE) and Zeng et al. (1998) respectively. Symbols as in Figure 6.4.

In Figure 6.12 (after Guo Larsen et al., 2004) an increase in C_{HN} with increasing wind speed can be seen for $z/L < 0$. Andreas and DeCosomo (2002) assume that the surface renewal theories by

Fairall et al., (1996a) and of Zeng et al. (1998) are basically correct and they derive spray-mediated contributions to the flux of latent and sensible heat. They find that for high wind conditions the spray contribution is “about 10% of the total flux”.

It is a reasonable assumption that the observed deviation of our data at high wind speed from the prediction of the two ‘surface-renewal’ models (the ‘Zeng’ model and the ‘COARE’ model) is due to the effect of spray on the sensible heat flux.

Note that when the wind speed is in the range 14 – 16 ms^{-1} and stability goes from slightly unstable to slightly stable, C_{HN} changes dramatically, from about $1.6\cdot10^{-3}$ to $0.5\cdot10^{-3}$. This is an effect that can be easily understood in terms of the theory for the spray-mediated flux contribution. As shown in Andreas (1992) and Andreas and DeCosomo (2002), the contribution from spray evaporation to the sensible heat flux is proportional to (T_w-T_{ev}), where T_w is the sea surface temperature and T_{ev} is “a quasi-equilibrium temperature that the droplet falls to before evaporation begins at earnest”. The factor of proportionality contains the spray generation function and is positive. Thus, we expect that, when in high wind conditions, the temperature gradient near the surface changes from very slightly unstable to very slightly stable, other factors remaining essentially unaltered, the spray-mediated contribution to the sensible heat flux remains the same, i.e. it is expected to increase the upward directed flux in the unstable case and reduce the downward directed flux to virtually the same extent.

6.3.3 Comparisons of model estimates of evaporation and sensible heat flux with measurements

Simulations of evaporation and sensible heat flux with the following models have been compared with eddy correlation data:

- The HIRLAM regional weather forecast model.
- The PROBE-Baltic model

6.3.3.1 HIRLAM model

The HIgh Resolution Limited Area Model HIRLAM is a complete model system for operational weather forecasts maintained by national meteorological services in several countries. It covers Northern Europe. The baseline forecast model is a hydrostatic, semi-implicit limited area Eulerian model (Källén, 1996). The model is based on the primitive equations with temperature, pressure, humidity and horizontal wind velocity components as prognostic variables. Operationally, different local versions of the HIRLAM model are used, and in this study we use HIRLAM data provided by the Swedish Meteorological and Hydrological Institute. Sea surface temperature and ice cover measurements in combination with satellite data are used as surface boundaries for the Baltic Sea area. Outside the Baltic area, analysed data from ECMWF (European Center for Medium range Weather Forecast) are applied. At the lateral boundaries the model is forced with operational analyses from the global models at the ECMWF.

6.3.3.2 PROBE-Baltic oceanographic model

The Baltic Sea model PROBE-Baltic (Omstedt and Nyberg 1996) is a process-oriented ocean model in which the Baltic Sea is divided into 13 sub-basins based upon data on bottom topography. As a meteorological input to the model the SMHI(1x1)˚. Data-base is used. The model calculates the horizontal mean properties of sea surface temperature, ice concentration and thickness in each sub-basin. The turbulent fluxes are calculated from bulk-formulations.

6.3.3.3 Comparison

Figure 6.13 shows, for Christiansø, latent heat flux comparisons in Figures 6.13a and 6.13c, and sensible heat flux comparisons in Figures 6.13b and 6.13d. The figures in the first line, Figures 6.13a and 6.13b, compare HIRLAM simulations (Swedish version) with measurements, and those in the second line, Figures 6.13c and 6.13d, compare PROBE-Baltic simulations with the same measurements. Generally speaking, the graphs for sensible heat flux show less scatter than those comparing latent heat flux, cf. below. It appears from Figure 6.13a,b that this version (the Swedish) of HIRLAM gives systematically higher evaporation but predicts sensible heat flux quite well compared to the measurements. PROBE-Baltic also gives evaporation higher than measured, Figure 6.13c, but to a less extent than HIRLAM, but underestimates sensible heat flux. Figure 6.14 compares predictions of latent heat flux with the Finnish HIRLAM version with eddy correlation measurements at Kopparnäs. The correlation coefficient is quite high, 0.81, but the model gives slightly higher values compared to the measured flux (about 12%).

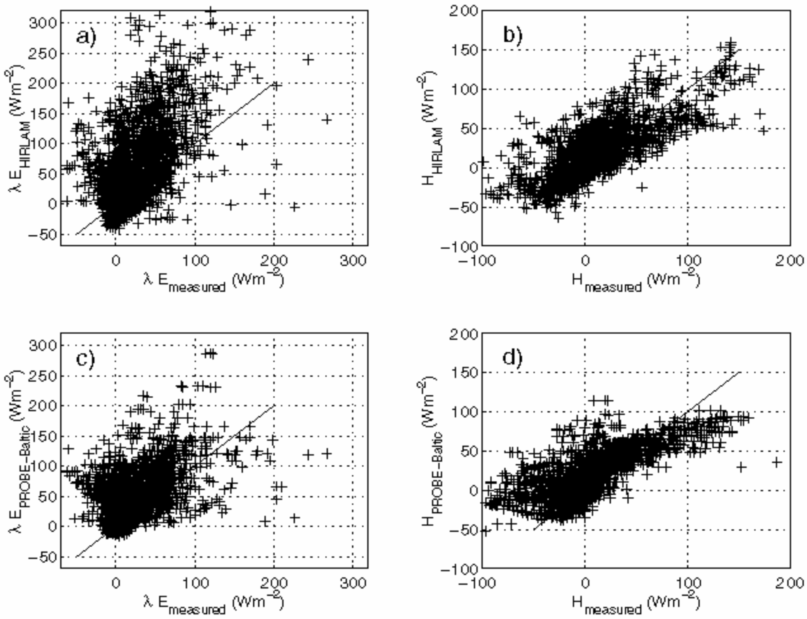

Figure 6.13: Measured and calculated latent and sensible heat flux for the period May 1998 to Dec. 1998 from Christianø. (a) measured latent heat flux (λE) is compared to HIRLAM model estimates; (b) corresponding comparison for sensible heat flux (H); (c) latent heat flux (λE) measurements compared to PROBE-Baltic; (d) corresponding comparison for sensible heat flux (H), Rutgersson et al. (2001).

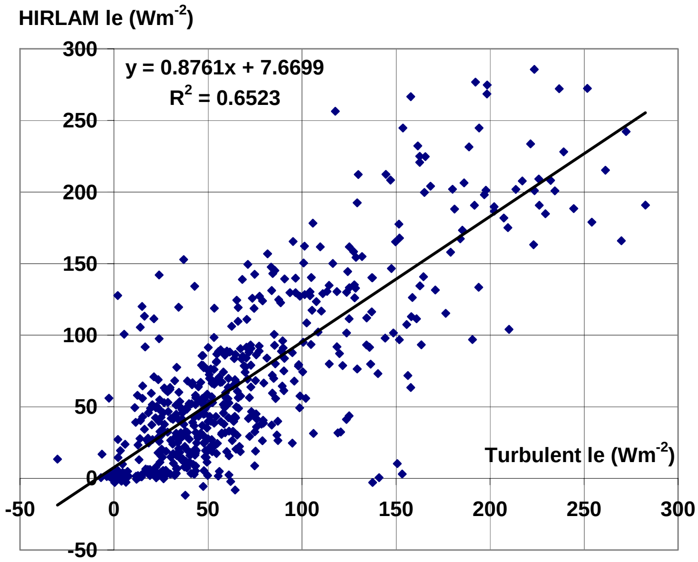

Figure 6.14: Comparison of model estimates of the latent heat flux obtained with the Finnish HIRLAM against corresponding flux measurements at Kopparnäs. Time period: 5 June 2000 –23 September 2000. Only data with wind from open-sea-sector are shown.

6.3.4 Simulations of areal and temporal variation of evaporation over the Baltic Sea

Figure 6.15 shows monthly evaporation fields, covering the period December, 1999 to October, 2000, obtained with the Finnish HIRLAM version (Tammelin and Hyvönen, 2000).

Evaporation over the Baltic Sea is maximum during the autumn, but as shown in the December, 1999 and January, 2000 plots of Figure 6.15, there is a strong secondary maximum of evaporation during the winter in the northernmost part of the Baltic Proper, with values above 100 Wm^{-2} south of the Åland islands.

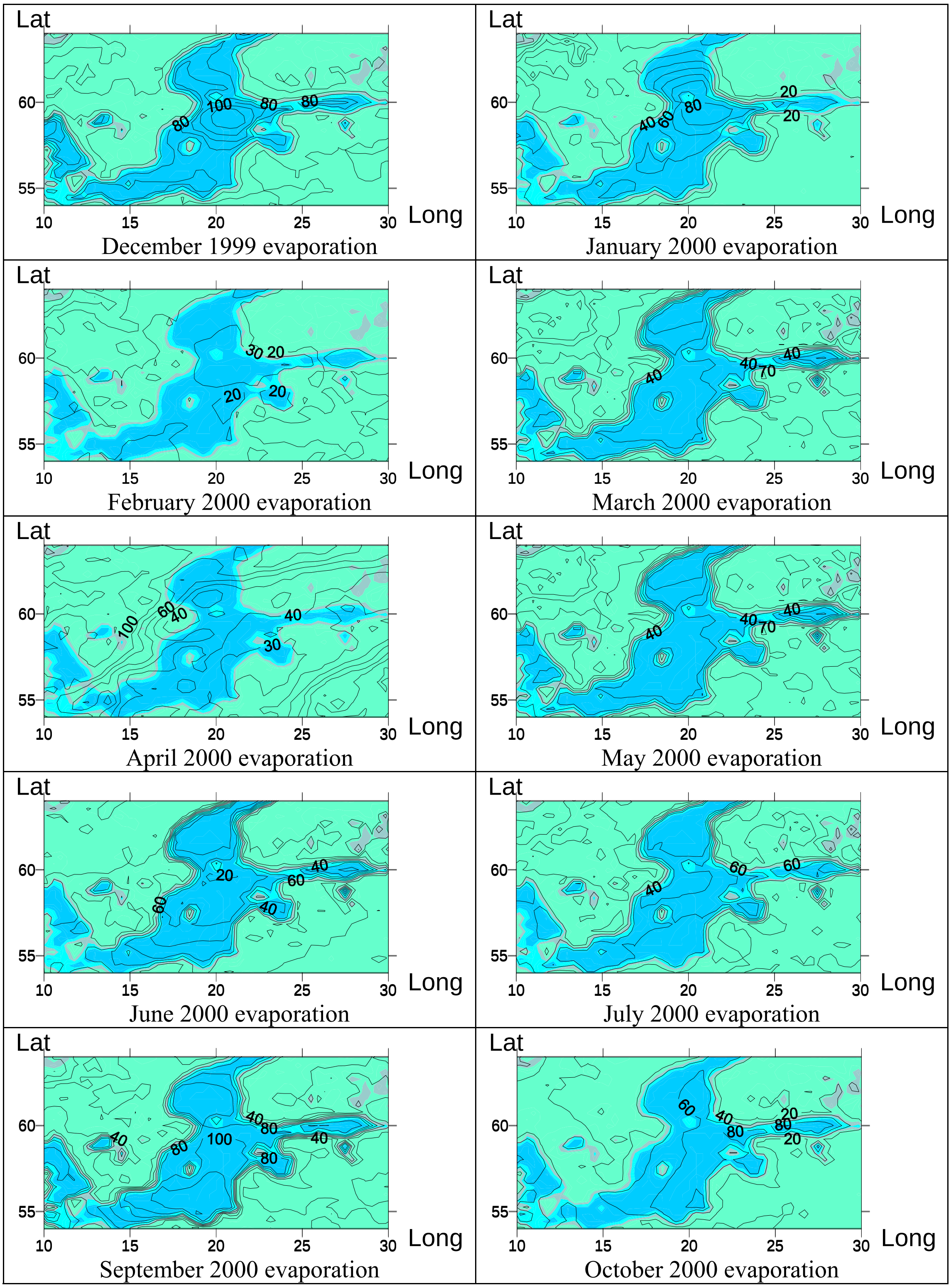

Figure 6.15: Monthly accumulated evaporation December 1999 –October 2000 derived from the HIRLAM model simulations.

6.3.5 Boundary layer height over the Baltic Sea

A possible source of the rather large scatter in all plots comparing measured and modelled fluxes may be an influence of the boundary layer height (z_i) on the stability functions (Eq. 4). It has been shown from measurements over land (Johansson, 2002) that the stability expression for momentum, which is included in Eq. 4, is a function of z_i/L. An attempt was made to compare measured and modelled boundary layer heights over the sea to come up with a reliable method to estimate z_i from models.

From radiosonde measurements the boundary-layer height over Christiansø during the period with intensified measurements was found to be about 500 meters, Figure 6.16 The boundary layer grows in response to the sensible heat flux, and its predictability therefore is closely connected to investigations on the sensible heat flux over the sea. The meteorological conditions during the simulated period are characterised by high wind speed and positive heat flux over the sea.

The boundary-layer height was simulated with two models, a simple applied high-resolution (2 km times 2 km) model (Gryning and Batchvarova, 1996), and the Swedish HIRLAM model (grid resolution of 22.5 km times 22.5 km). At south-westerly winds it was found that the boundary-layer height is influenced by a relatively large island (Bornholm) lying 20 km upwind of the measuring site. In this situation the high-resolution simple applied model reproduces the characteristics of the boundary-layer height over the measuring site quite well, Figure 6.16. Simulations with the HIRLAM model gives too high values, likely because the water fetch between Bornholm and the measuring site is about the size of the grid resolution of the HIRLAM model, and therefore poorly resolved. At northerly wind (last 30 hours in Figure 6.16), the water fetch to the measuring site is about 100 km. Then both models reproduce the characteristics of the height of the marine boundary layer equally well , Figure 6.16. This suggests that the HIRLAM model with respect to predictions of the height of the marine boundary layer adequately resolve a water fetch of 100 km. See also Gryning and Batchvarova (2002).

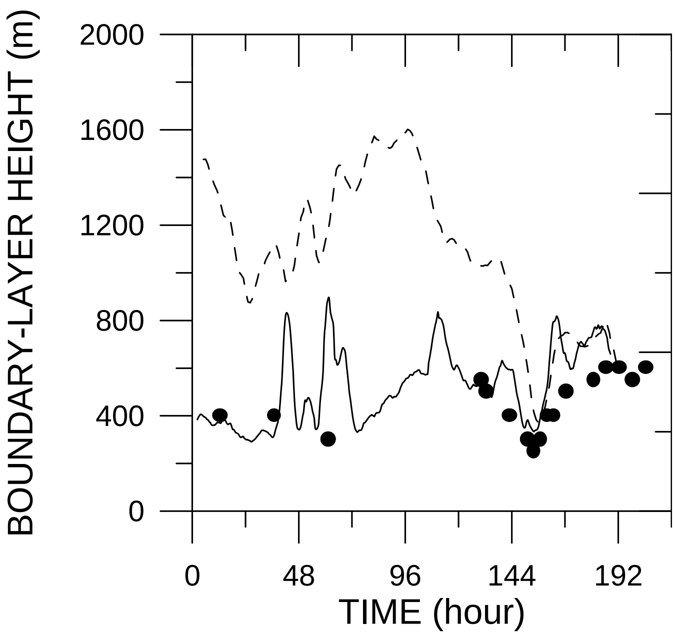

Figure 6.16: Time evolution of boundary layer height at Christiansø; measurements, dots, and from two model simulations, HIRLAM, dashed line, and the simple applied model, full line. Time 0 of the graph is 00LST 26 October 1998. During the first 160 hours, the wind had passed the 20 km distant island of Bornholm before arriving at Christiansø; during the remaining time period the upwind fetch was free of obstacles for more than 100 km.

6.4. Outlook

It is clear that PEP in BALTEX has given a very substantial contribution to the knowledge of the evaporation regime over the Baltic Sea. Nevertheless, it is also evident that much remains to be done. The project has thus highlighted how difficult it is, even with the extensive and sophisticated methods employed here, to get an accurate estimate of the fluxes over the Baltic Proper for a one year period. This uncertainty is highly relevant not only in the special BALTEX context but also in the wider context of climate change studies globally, as it gives an indication of how uncertain energy and water balance estimates over the ocean really are. Concerning the water balance of the Baltic Sea, the PEP project has clearly indicated the needs for future studies in the area.

Simulations of the spatial and temporal variation of evaporation over the Baltic Sea within PEP show interesting features, with very low evaporation over the entire Baltic during spring and summer and large spatial variations during autumn and winter. Especially the observed switch of the maximum from the south-eastern parts to the northern parts of the Baltic Sea Proper from autumn to winter warrants detailed studies, as it is likely that the strong winter maximum south of Åland may be partially responsible for the heavy snow falls often encountered in the eastern parts of Sweden during this time of year.

A main message from PEP is that there are still large uncertainty in modelling turbulent fluxes over the sea as well as proper parameterization of the air-sea boundary layer processes. Also there is large differences between models. The measurements from PEP provide an invaluable data base that should be used for further validation of models.

6.5. Acknowledgements

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Chapter 7:

Precipitation over the BALTEX area

by

Karl Bumke and Franz Rubel

7.1. Motivation

Although precipitation is one of the main components of the hydrological cycle, it is still a scientific problem to derive high quality precipitation fields.

Even today there is a lack of accurate precipitation measurements (Bumke and Clemens, 2001), since conventional rain gauges show a number of systematic errors caused by flow distortion, wetting and evaporation losses (Sevruk, 1982, or Førland, 1996). Flow distortion is also mainly responsible for the deficiency in number of reliable precipitation measurements over the sea (e.g. Reed, 1977). Therefore, methods have been developed to derive precipitation rates over sea from visual observations of the present weather (e.g. Tucker, 1961, or Lindau, 2002).

Another problem with respect to analyse fields is the high variability of precipitation in space and time. This was investigated by Rubel (1996) in general and by Clemens and Bumke (2002) for the Baltic Sea area. Consequently dense observation networks are needed to get accurately interpolated precipitation fields. Unfortunately due to financial reasons the precipitation network will deteriorate in future, thus, alternative methods have to be developed to fill in the gaps, mostly based on remote sensing techniques like weather radars or micro wave meteorology. However, these techniques as well as numerical model output used for weather prediction or climate modelling, necessitates the validation by in-situ measurements to allow well-founded statements about their quality.

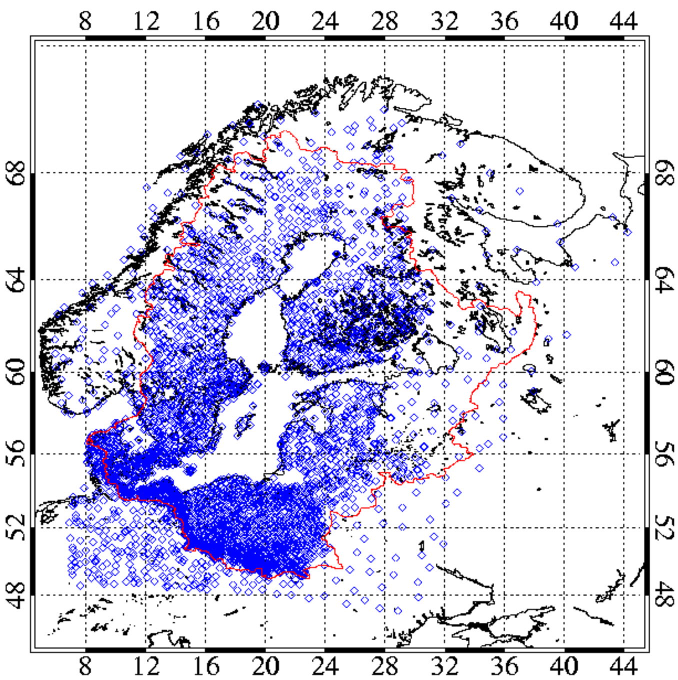

Figure 7.1: Spatial distribution of the synoptic precipitation data.

7.2. Collection and on-event bias correction of existing precipitation measurements

In the frame of BALTEX most of the available precipitation measurements and other meteorological data in the BALTEX catchment area were collected at the BALTEX Meteorological Data Center (BMDC), located at the German Weather Service (Lehmann et al., 2000). The total number of precipitation gauges with daily observations is about 4000 (Fig. 7.1). Rubel and Hantel (1999) corrected these daily observations for systematic measurement errors caused by aerodynamic effects as well as wetting and evaporation losses. The meteorological information needed for the correction procedure is mostly unknown at the location of the precipitation gauges. Therefore, meteorological information was taken from the closest synoptic stations. In the Baltic Sea drainage basin most rain gauges are in the local vicinity of a synoptic station, not more than 45 km away; the mean distance to the closest synoptic station is 30 km. Allerup et al. (2000) applied a similar correction method to the Danish precipitation database to investigate the influence of off-site weather information. They concluded that wind speed can be extrapolated from remote sites not farther away than approximately 50 km, while information on rain intensity and temperature can be safely extrapolated across longer distances.

The annual averaged precipitation deficit of the raw rain gauge observations is about 13% (Rubel and Hantel, 2001). The bias-corrected precipitation measurements can serve as ground truth for precipitation over land (Rubel, 1998) and are invaluable for example in the design of new algorithms for remote sensing techniques.

7.3. Introduction of new instruments to measure precipitation

Simultaneously the development of several new kinds of instruments to measure precipitation have started. Two instruments were constructed to measure precipitation especially under high wind speeds as they occur usually on moving platforms like ships or in mountainous areas. These are a new kind of a ship rain gauge (Hasse et al. 1998) and an optical disdrometer (Großklaus et al., 1998), which gives drop size distributions, too. Predominantly for the use on land a vertical looking micro rain radar (Peters et al., 1998) and a new mini sodar were developed.

Within the Pilot study of Evaporation and Precipitation (PEP, Smedman et al., 2002) in BALTEX and APOLAS (Accurate areal Precipitation measurements Over Land And Sea) in DEKLIM (Deutsches KLIMaforschungsprogramm) the ship rain gauges have been used routinely on several merchant ships to measure precipitation along their sea routes from Germany/Denmark to Finland/Poland/Russia. These measurements produce a new set of in-situ precipitation data over the Baltic Sea (Fig. 7.2), an area not covered by the existing synoptic precipitation gauge network (Fig. 7.1). The micro rain radar was used at several sites, for example in Zingst, Germany, and on the small islands Christiansø, Denmark, and Östergarnsholm, Sweden (Fig. 7.2). Within the frame of the DEKLIM program all these instruments are mounted at Westermarkelsdorf and most of them in Zingst, both Germany, to allow extensive comparisons with conventional gauges and other instruments like the Joss Waldvogel disdrometer to test their suitability for routine observations of precipitation (Fig. 7.2).

As mentioned above it is also possible to derive precipitation rates over sea from visual weather observations, where the present weather code is taken as an indicator for the precipitation rate. This method has their own problems (Dorman and Bourke, 1978), but it is the only possibility to investigate precipitation from observations over the recent decades. For the Baltic Sea area Lindau (2002) improved and used this method to estimate precipitation from the Comprehensive Ocean and Atmosphere Data Set (COADS).

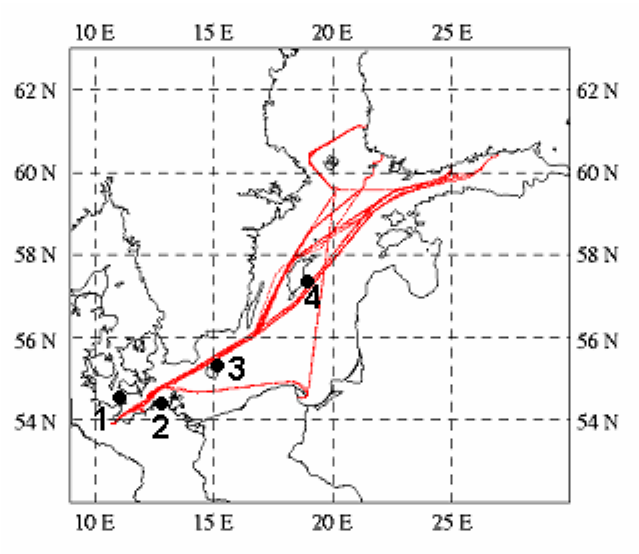

Figure 7.2: The red lines give the spatial distribution of the rain fall measurements by the observing ship rain gauges during autumn 1998. The symbols mark those locations (1 = Westermarkelsdorf, 2 = Zingst, 3 = Christiansø, 4 = Östergarnsholm), where additional precipitation measurements have been performed during PEP and APOLAS.

7.4. Interpolation of precipitation measurements

To get precipitation fields from in-situ measurements three different methods have been developed within BALTEX. One is the MESAN (MESoscale ANalysis) of the Swedish Meteorological and Hydrological Institute (SMHI) which analyses precipitation fields on the base of synoptic observations, distributed via the Global Telecommunication System (GTS), and, at a lower degree, from the BALTRAD radar estimates (Michelson et al., 2000b). For that purpose spatial structure functions of each synoptic station in terms of correlation functions have been estimated which serve as weighting functions in the analysis scheme. Radar estimates of precipitation were checked for their reliability and merged with synoptic observations to get realistic precipitation fields. The precipitation measurements were not corrected for systematic errors like wind distortion, wetting and evaporation losses. Due to missing in-situ measurements of precipitation over sea it is to expect that the uncertainties of MESAN are increasing over the Baltic Sea area.

Another interpolation scheme uses all available precipitation measurements in the BALTEX area. To get unbiased estimates Rubel and Hantel (1999) used those measurements, which were corrected for systematic errors. Interpolation was done by applying a statistical method, the block kriging, on the data. Resulting errors over land are small, but over the Baltic Sea they may reach about 40% (Fig. 7.3).

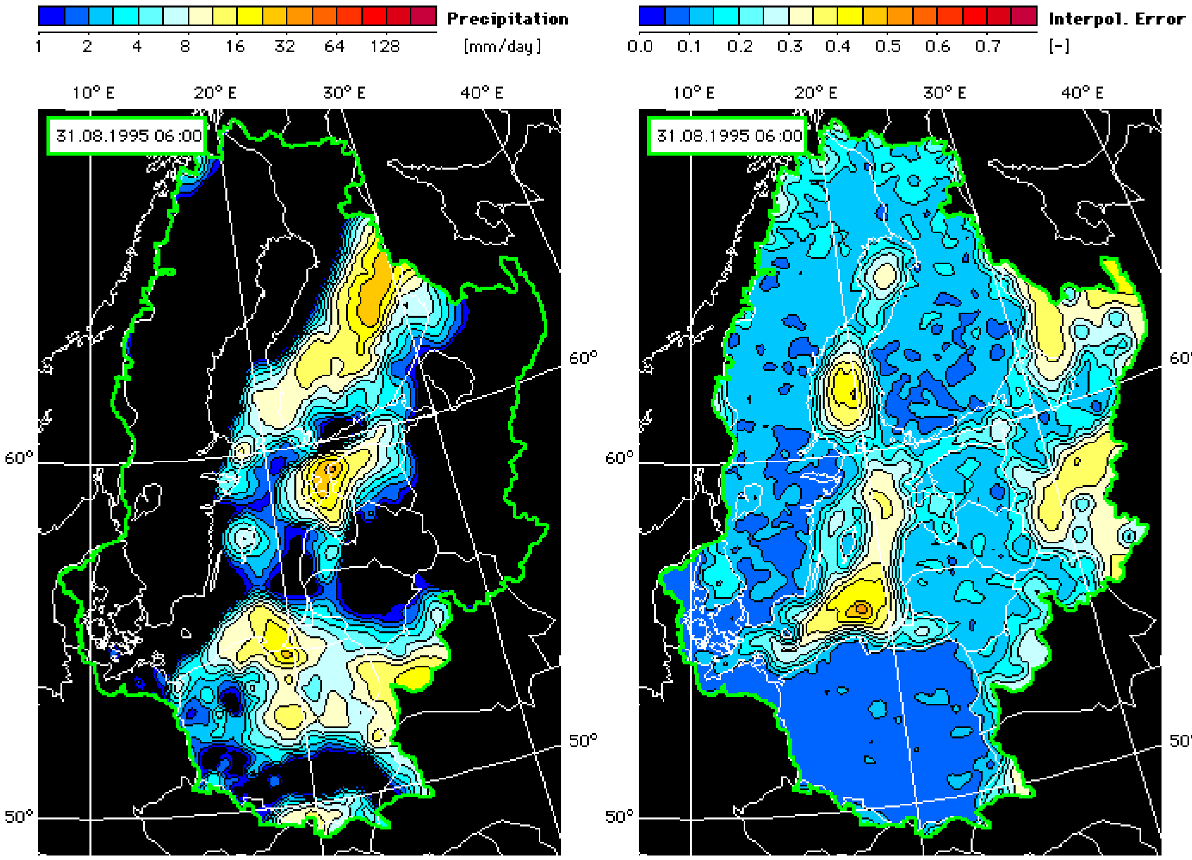

Figure 7.3: Objectively analysed precipitation field and the normalised interpolation error (Rubel, 1998)

Recent data sets collected in the framework of the ELDAS project comprise more than 21,000 gauges over Europe (Rubel, 2004). Improvements concerning the precipitation analysis in the Baltic Sea drainage basin result from additional Norwegian precipitation gauges collected during ELDAS (Rubel et al, 2004a).

A third method makes use of ship rain gauge measurements on merchant ships to estimate precipitation over the Baltic Sea, only. This interpolation scheme (Clemens, 2002) bases also on the Kriging method and allows to estimate seasonal precipitation fields along the main ships' routes with an accuracy of about 15% (Fig. 7.4).

No efforts were made so far to combine in-situ measurements over land and sea to estimate precipitation fields. Depending on the chosen interpolation system this will necessitate the investigation of spatial structure functions of precipitation fields in coastal areas.

7.5. Remote sensing techniques

A different approach to estimate precipitation fields over land and sea is to use remote sensing techniques. The most prominent example is the composition of BALTRAD, which is a network of Swedish, Finnish, Norwegian, Danish, German, and Polish weather radars combined with some synoptic stations mainly in Poland and over the Baltic states by the SMHI (Michelson et al., 2000a). BALTRAD gives a good insight in the actual precipitation patterns (Fig. 7.5) due to their excellent spatial and temporal resolution. But it fails on longer time scales (Strümpel, 2001). One reason is that the derivations of these fields demand the use to full distance range of a radar, also outside the doppler radius, which causes consequently a number of problems due to a possible occurrence of artefacts. Other problems may arise from refraction in the marine atmosphere, typically following from stable atmospheric conditions as they are frequent in spring.

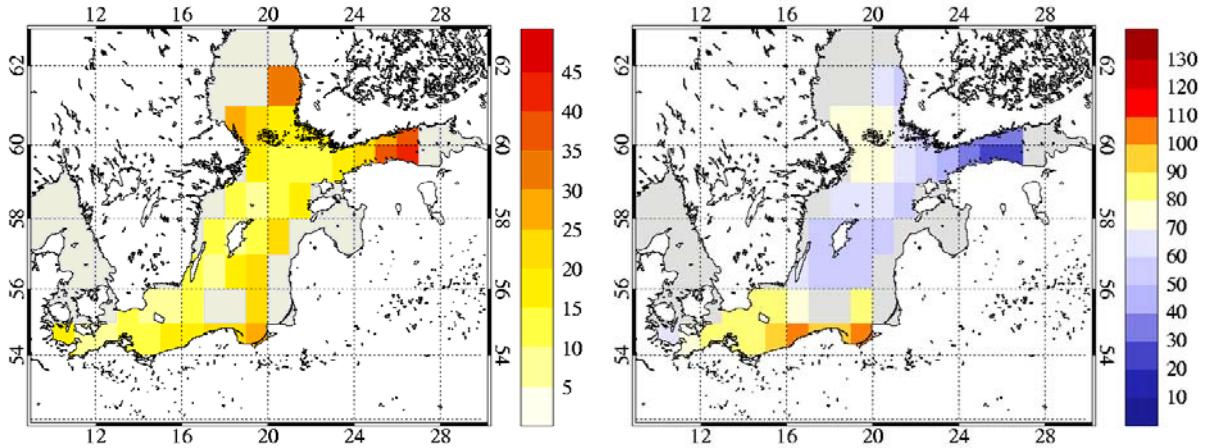

Figure 7.4: Spatial distribution of precipitation estimates (in mm/month, left) and of relative error estimates (in %, right) for autumn 1998 resulting from the kriging method. (Clemens, 2003)

Vertical-looking micro-rain-radars (MRR) can also be used to estimate precipitation. The measured vertical profile of rain rate and drop size distribution allows to link the weather radar measurements aloft with surface precipitation measurements. Figure 7.6 shows a first attempt of simultaneous measurements of radar reflectivity obtained at Zingst with a MRR-2 and the Rostock weather radar. The MRR-2 data have been converted into equivalent Rayleigh reflectivity on the basis of retrieved drop size distributions.

A new 3-hourly precipitation data set has been presented by Rubel et al. (2004a, b). 3-hourly precipitation fields have been estimated by disaggregating daily gauge analyses with radar data from quality controlled BALTRAD (Michelson, 2003; Michelson, 2004) and CERAD (Brugger, 2004) data, respectively. This dataset is available for the period Oct. 1999 to Dec. 2000 and has been designed for both, NWP data assimilation and model verification studies.

Another remote sensing method, developed for nowcasting applications has been presented by Bennartz et al. (2002). Based on data obtained from the Advanced Microwave Sounding Unit (AMSU) onboard NOAA-15, this satellite product provides categorical precipitation estimates. Precipitation is divided into the 4 categories: precipitation-free, risk of precipitation, precipitation between 0.5 and 5 mm/h, and precipitation higher than 5 mm/h. Algorithm for the scattering-based precipitation identification were employed for land and sea areas. Algorithm used for coastal areas is a average of both, weighted by the fraction of land in the footprint.

Global monthly precipitation fields with a spatial resolution are available from the GPCP project (Huffman et al., 1997; see also Rubel and Hantel, 2004). These fields are based on various satellite products merged with the precipitation database of the GPCC. These dataset has been designed for use in climatological studies. It covers the period 1979-2002. A daily precipitation product estimated from multiple satellites is also available from the GPCP project (Huffman et al., 2001). These daily satellite estimates cover the period 1997-2002.

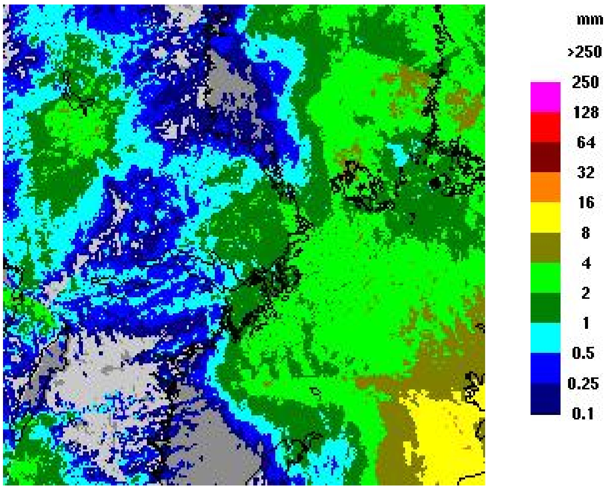

Figure 7.5: 12-hour accumulated precipitation from gauge adjusted radar for an area covering eastern Sweden, south western Finland, and part of the Baltic Proper. February 7, 2000, 18 UTC. (Smedman et al., 2002)

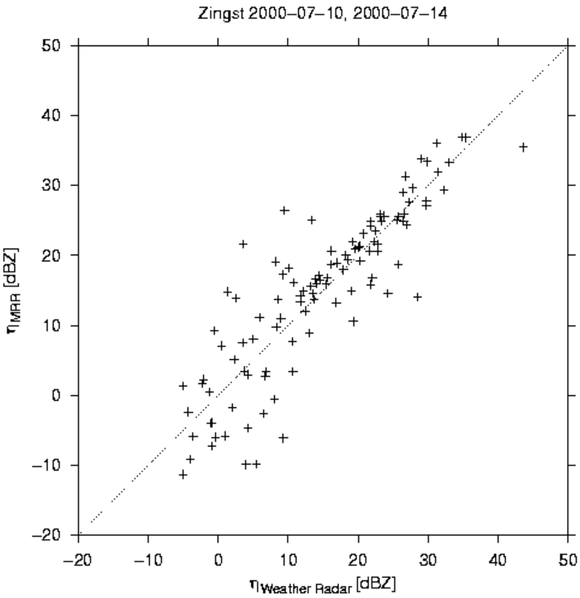

Figure 7.6: Radar reflectivity, MRR" versus Rostock weather radar (Peters, pers. communication).

7.6. Numerical models

A prerequisite for a lot of applications is that data are continuously available on regularly distributed grid points. Due to a lack of other data this can be achieved by the use of numerical models to compute precipitation rates. Precipitation is part of the forecast, thus, numerical models of weather prediction ought to be used for that purpose. Such models differ considerably in the spatial resolution, for the BALTEX area it typically ranges from about 1° for the SMHI to 0.1° latitude/longitude for the HIRLAM model (Rutgersson et al., 2001). These models are suitable to give precipitation estimates over the Baltic Sea for recent years, e.g. for September 1998 until 1999 (Fig. 7.7). Annual precipitation ranges for this 12 month period between 620 and 800 mm/y, depending on the chosen model. As an 18 years average for the period 1971 until 1988 Rutgersson et al. (2002) give 585 mm/y, which is close to the value of 50 mm/month estimated from COADS (Lindau, 2002). Alternatively products like the NCEP/NCAR reanalysis project have to be used. These allow an insight in precipitation for the last 50 years.

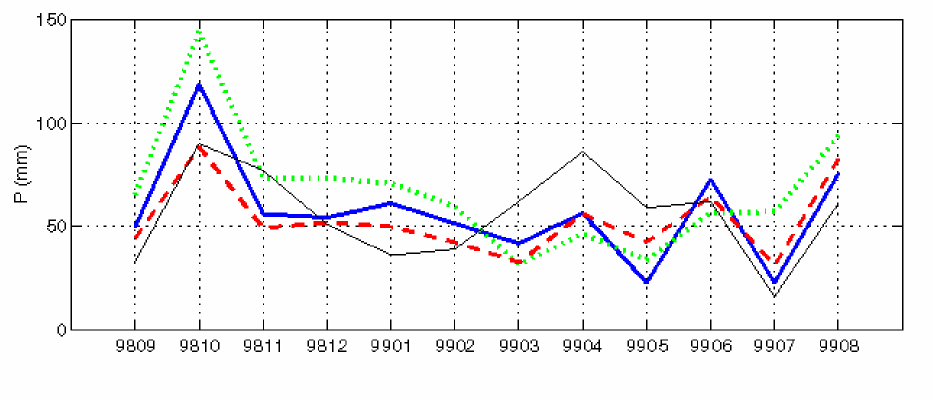

Figure 7.7: Monthly averages of precipitation (in mm/month) for the Baltic Proper using different methods. Thick full line is the REMO-DWD model, dotted line is the HIRLAM (Swedish version) model, dashed line is the PROBE-Baltic model and thin solid line is the 'ships model'. The time period is September 1998 to August 1999. (Smedman et al., 2002)

For investigation of climate change climate models like the REgional MOdel REMO were developed. During BALTEX the progress in the model development was tremendous especially on the field of air sea interaction. Therefore, atmospheric models were coupled with models of the Baltic Sea (Omstedt et al., 1997, and Hagedorn et al., 2000) to get better estimates of air sea fluxes like evaporation. But with regard to precipitation all models are hampered by the fact that they were often validated over land, only. Due to missing in-situ data no direct comparisons over sea were performed. Now available precipitation fields over the sea from in-situ measurements on merchant ships have been used for first comparisons to numerical model output (Rutgersson et al., 2001). That study clearly depicts the must of an improvement of precipitation predictions in numerical models.

7.7. Snow

Still a problem is the measurement of snow, since conventional gauges fail in measuring snow (Sevruk, 1982). Also remote sensing techniques like radar are hampered by differences in physical properties of snow and rain.

7.8. Conclusions

Precipitation over the Baltic Sea is still not exactly known. The uncertainties are of the same order as uncertainties in evaporation (Smedman et al., 2001, Hennemuth et al., 2003). Thus, it is still an open question whether precipitation exceeds evaporation or vice versa.

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Chapter 8:

Runoff in BALTEX

by

L. Phil Graham

8.1. Motivation

Runoff is a key variable of the water balance that integrates precipitation, evapotranspiration and storage at the outflow point of any given drainage area (or catchment). Although the term runoff generally applies to the excess water available after losses and storage are accounted for, the value that is measured at gauging stations is actually river flow (or river discharge), usually expressed in units of volume over time (typically m^3s^{-1}). River flow includes the effects from horizontal transport in lakes and river channels.

As the Baltic Sea has only one outflow point to the world ocean, all runoff from the total basin land area accumulates at this point. This provides an excellent opportunity for solving the water balance of the basin, which in principle is straightforward. In practice, this is not so simple, particularly during early years of BALTEX when less was known about both precipitation and evaporation over the sea. Obtaining good estimates of river flow to the Baltic has thus been an important contribution to BALTEX and will continue to be so in the future.

Before BALTEX was established, there was no common database of observed river flow to the Baltic Sea. Individual countries within the basin maintained national databases containing only their own observations of river flow and there was no organised coordination between them. However, an early report of observations and estimated total inflow to the Baltic was made by Mikulski (1982).

8.2. Progress made within BALTEX

A database of monthly river flow to the Baltic for much of the 20th century was compiled and published by Bergström and Carlsson (1994). This database developed into the BALTEX Hydrological Data Centre (BHDC; (Carlsson, 2000). Although this database still consists mainly of monthly data, it is maintained and updated. Observation updates, however, are received on a sporadic basis with lag times of up to several years for some parts of the basin. Figure 8.1 shows the available river flow from the database summarised for the main sea basins of the Baltic. It currently extends to the end of December, 1996 for the total basin. As seen in the figure, the status of updated river flow varies among different sub-regions of the Baltic Basin.

A large-scale hydrological model of river flow to the Baltic was developed for use in BALTEX (HBV-Baltic; (Bergström and Graham, 1998; Graham, 1999). As this model is run with synoptic observations of precipitation and temperature, it can be used to provide an estimate of river flows for those years not covered by the BHDC. It is updated once a year and currently covers the period 1981-2004, as shown in Figure 8.2. Results from this model have been used in combination with observations to extend the record for the total Baltic, shown as a dashed line in Figure 8.1 for the years 1997-2002. Aside from filling in for missing data, HBV-Baltic has been used as a validation tool for climate models and contributed to improvements in land surface modelling (Graham and Bringfelt, 2001; Graham and Jacob, 2000; Jacob et al., 2001; van den Hurk et al., 2002).

Many rivers flowing to the Baltic Sea are regulated by dams. This is particularly true for the northern rivers in Sweden and Finland where hydropower generating facilities are well developed. This does not typically affect values of annual river flow, but seasonal flow is highly affected. The dams tend to dampen spring peak flows by storing a large part of the spring snowmelt and enhance winter flows by releases to generate electricity during the cold season. Both Figures 8.1 and 8.2 represent observed river flow including the effects of dam regulation. Figure 8.3 shows corresponding results from hydrological modelling that represents natural conditions (simulations where the effects of dams are artificially taken away). This has been done only for the Bothnian Bay and Bothnian Sea drainage basins, but this in turn affects the total Baltic, as shown in Figure 8.3. Use of natural flow conditions is beneficial when analysing hydrological processes in climate models.

Communication and cooperation between meteorologists and hydrologists has significantly increased with BALTEX activities, resulting in better understanding of the water cycle and the modelling of it (Graham and Bergström, 2000; Graham and Bergström, 2001). This cooperation continues today in both EU financed projects and national efforts.

Representation of the lateral transport of runoff by using runoff routing techniques has been included in climate models applied to the BALTEX region (Graham, 2002; Hagemann and Dümenil, 1999). This converts runoff to a variable that can be directly compared to observations by taking into account transformation for groundwater, lake and channel storage, and transport time. It also contributes to coupling between atmospheric and ocean models (Döscher et al., 2002).

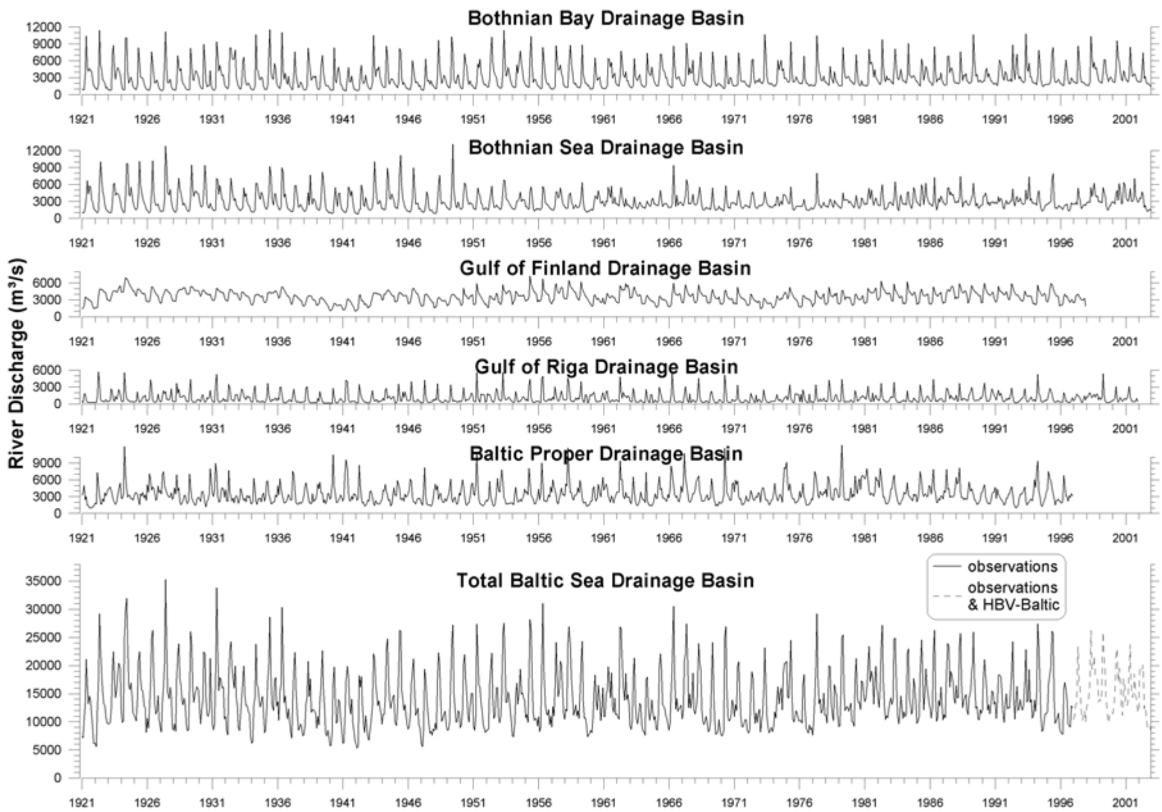

Figure 8.1: Observed monthly river discharge from the main drainage basins of the Baltic Sea for the period 1921-2002. Note that in some basins observations are not available for the full time period. Shown for the total Baltic are also extended values (1997-2002) that combine all available observations with HBV-Baltic simulations (where observations are not available).

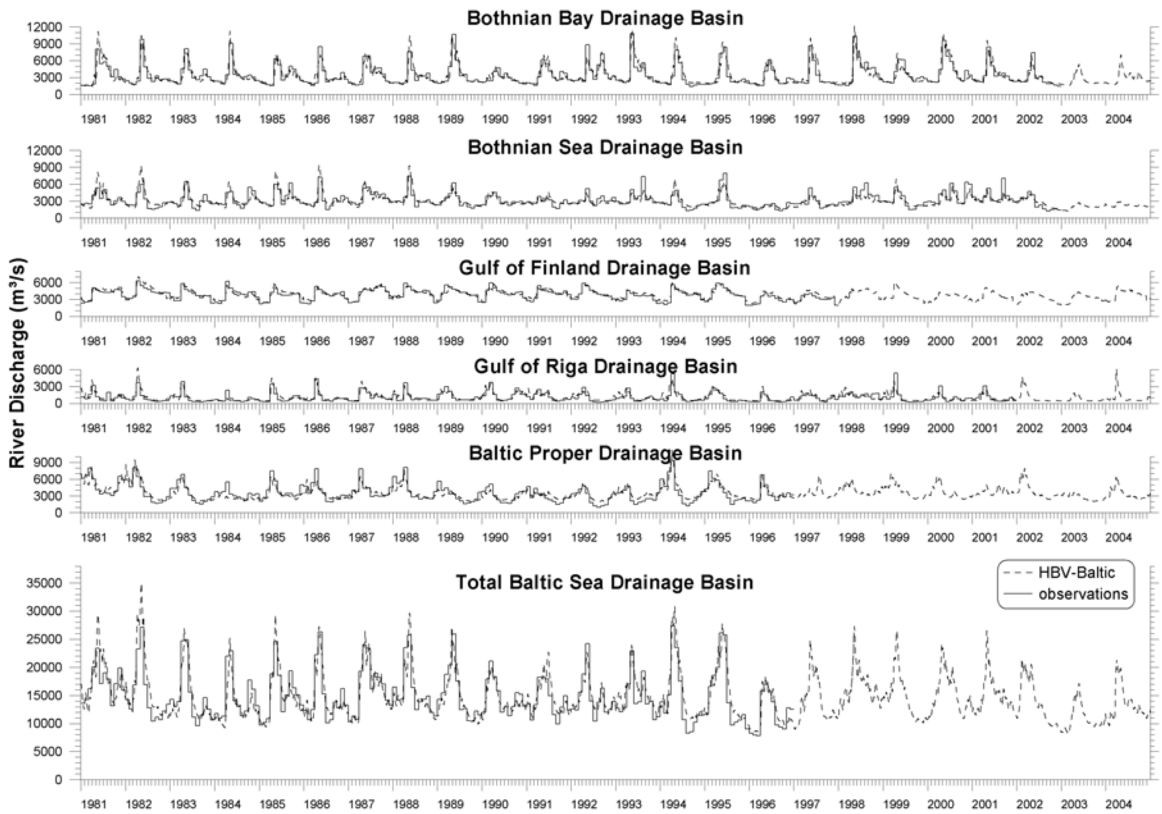

Figure 8.2: HBV-Baltic modelled daily river discharge from the main drainage basins of the Baltic Sea. The observations are the same as those shown in Figure 1.

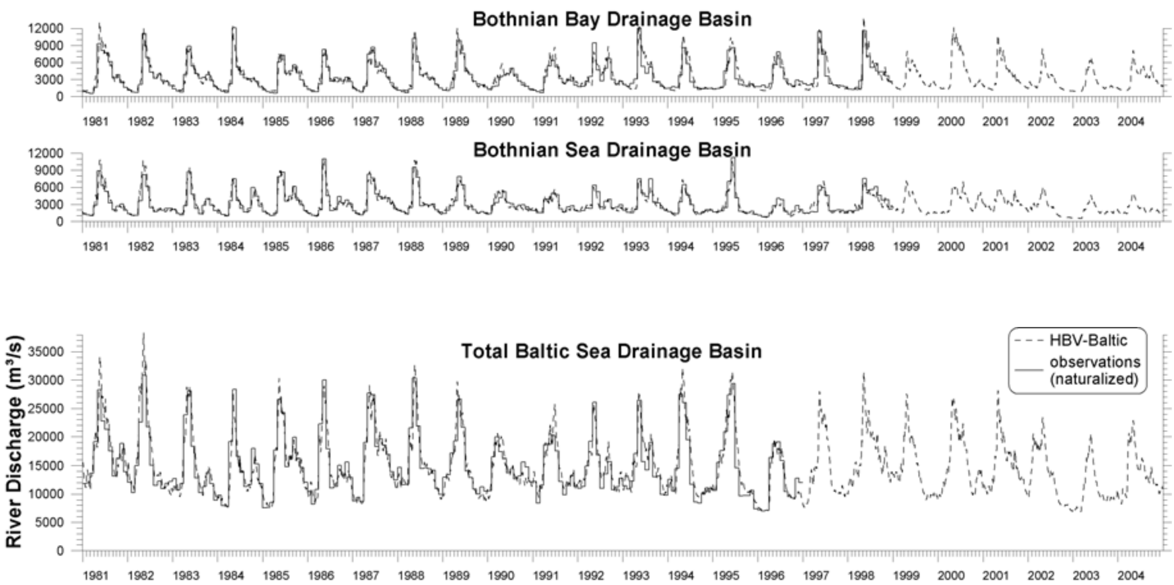

Figure 8.3: HBV-Baltic modelled daily river discharge under natural conditions from the Bothnian Bay, Bothnian Sea and corresponding total Baltic Basin. The observations shown have been naturalized to take away effects of river regulation.

Efforts to improve flood forecasting with the help of regional atmospheric models for specific river basins have been made. Klein et al. (2001) developed a forecasting system for the Odra drainage basin. This combines atmospheric modelling, hydrological modelling and river hydraulics modelling to better forecast flooding events.

Studies on the effects of climate change on river flow in the Baltic Basin have been made (Bergström et al., 2001; Gardelin et al., 2002; Graham, 2004; Graham et al., 2001). Although not officially part of BALTEX Phase I, this work was greatly aided by the development and cooperation that occurred during BALTEX projects. This provides a headstart for the more applications-oriented BALTEX Phase II.

8.3. Has BALTEX met its objectives?

BALTEX has come a long way toward meeting many of its objectives in regards to runoff and hydrological modelling. Establishment and maintenance of the BHDC together with hydrological modelling for missing data provide important inputs for investigation of the water balance over the Baltic Basin. Common analysis and communication between hydrologists and meteorologists has resulted in improved representation of hydrological processes in climate models. However, the level of hydrological modelling activities has generally been lower than originally anticipated.

An area that has not been adequately addressed is how to transfer improved models, databases and knowledge to practical applications within water resources management. Only a few applications have been made. In addition, a specifically stated objective of the BALTEX Phase I Implementation Plan (Section 7.7.8) has not been addressed. This is the "intercomparison of hydrological models," which was to be carried out for selected river basins within the Baltic Basin. Some aspects of this intercomparison were addressed by the PILPS 2e work on the Torne-Kallix basin where different land surface schemes participated (Bowling et al., 2003). However, PILPS 2e was not aimed specifically at hydrological models, but rather at land surface schemes.

8.4. Summary and Perspective

BALTEX has thus far established a hydrological data centre and strives to update runoff data in a timely fashion. Models have been developed to complement this function and fill in where data is missing. Models have also been used in a variety of other studies with the goal of improving our understanding of the water balance in the Baltic Basin and providing hydrological inputs to applications. Therefore, there is now a good basis of knowledge about runoff to the Baltic Sea, but more is needed.

Although river discharge observations for much of the Baltic Basin are made available to the BHDC in a timely fashion, there are sub-regions where the lag time is too long, as seen in Figure 8.1. We still do not have a comprehensive database of *daily* river flow to the Baltic Sea, nor do we have comprehensive measurements of evapotranspiration or soil moisture, which would complement this database. We have not fully exploited other sources of verification data that do exist, such as extensive snow water equivalent measurements from Finland and Estonia. Analysis of such combined measurements together with river flow and precipitation observations would help improve our understanding of precipitation partitioning and runoff processes. Furthermore, to date there is still only one large-scale hydrological model that can provide estimates of runoff to the Baltic. The use of additional models would be of benefit in helping to identify errors and uncertainty estimates.

BALTEX should strive for continued functioning of the research networks that have been built up over the years and try to get all Baltic Sea countries more actively involved. Data gathering activities should continue and more timely updating of river discharge observations should be emphasised. Additional measurements of evapotranspiration under varying climates and seasons should have a high priority. We should attempt to better quantify the uncertainty of our results, both modelled and measured. Practical applications of the benefits of BALTEX research should be methodically explored. If intercomparison projects are pursued, they should be formulated to address specific hydrological applications, such as flood forecasting. Lastly, hands-on cooperation with other continental scale experiments should be established or expanded.

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Chapter 9:

Satellite Applications

by

Jürgen Fischer and Clemens Simmer

9.1. Motivation

BALTEX as a continent-scale experiment needed measurements which where able to cover homogeneously the complete Baltic sea catchment area including the even larger modelling area surrounding the catchment. Satellites were and still are the only appropriate tool for this purpose. Satellite measurements have been used in BALTEX Phase I for a range of purposes reaching from radiation budget studies, cloud and precipitation analysis, to the determination of surface properties of the Baltic Sea and the surrounding land surface. BALTEX also made major contributions by developing new and improving available retrieval algorithms for operational and new satellites. New techniques for assimilation of satellite data into weather forecast models were also developed in BALTEX Phase I. The dominant use of satellite data was, however, the evaluation of dynamic models applied or developed during BALTEX.

9.2. Application Areas and Results

9.2.1 Overview

The energy and water cycle of the BALTEX region varies strongly with the season and might be subject to climate change. The goal of GEWEX to estimate the energy budget within the order of 10 W/m^2 is very ambitious but necessary to quantify the different processes in the earth system. The most uncertainties are still due to clouds, precipitation and soil moisture. Since the total water vapour will change with increasing temperatures, its variability has to be observed as well. A long-term monitoring of water vapour, clouds, precipitation and soil moisture is only feasible by means of satellites. There is a fleet of satellites in space with different instruments which can be used to monitor the BALTEX region. The quality of the products depends on the instruments as well as on the algorithms.

The first generation of Meteosat geostationary satellites (MFG), the first one launched in 1978, suffer from poor spectral and radiometric resolution, however, for long-term analysis, i.e. of cloud cover, they are extremely valuable. The Meteosat second generation (MSG), launched in August 2002, carries the multi-channel spectrometer SEVIRI which enables the retrieval of atmospheric properties with a much higher accuracy. The main drawback for the use of the geostationary orbit for BALTEX is the increasingly oblique view with increasing latitude; actually a major part of the Baltic Sea and its catchment cannot be adequately sensed by geostationary orbiting satellites. This deficiency can be compensated for by use of polar orbiting satellites. Besides having higher spatial resolutions their temporal coverage increases with latitude. The new generation of polar orbiting satellites, such as ESA's ENVISAT, NASA's Terra, Aqua, and Aura, and the US Navy DMSP satellites are all carrying suitable instruments to observe the relevant atmospheric and surface properties.

9.2.2. Radiation Budget Components

The knowledge of the radiation budget, especially the radiative exchange processes between atmosphere, land and ocean, is important for studying the driving mechanisms of weather and climate. Satellite measurements alone allow us to determine rather directly the amount of energy emitted and reflected by the Earth system. Several satellite experiments, like earth radiation budget experiment ERBE and the Clouds and Earth's Radiant Energy System (CERES) [NASA, 2004], are dedicated to establish a climatology of the radiation budget at top of the atmosphere. These instruments have spatially coarse but radiometrically precise broadband channels to provide observations of the radiation budget. In addition to these continuous global measurements, observations on higher spatial resolution together with information of the atmospheric state are needed, to increase our understanding of the variability of the radiation budget and to estimate it with a higher degree of accuracy. The Free University of Berlin developed a method to utilise narrowband solar channels of NASA's Terra-MODIS for radiation budget studies. MODIS yields higher spatial resolution than CERES and allows to account for atmospheric water vapour and cloud properties by using specific channels. For the development of the algorithm the radiative transfer model (MOMO) [Fell and Fischer, 2001] has been used to simulate upward radiance of arbitrary chosen cases that represent the natural variability of the atmosphere. The dataset is used to derive a narrow-to-broadband radiometric flux conversion by means of multidimensional nonlinear regression (or artificial neural networks). A comparison of the new product has been performed with the shortwave albedo product of CERES also onboard the Terra satellite. The results of the comparison show an excellent agreement in terms of the backscattered radiation within less than 10 W/m². Fig. 9.1 exemplarily shows a scatter plot of the upward short-wave radiation over Europe measured by CERES and converted from MODIS measurements. The higher resolution of MODIS compared to CERES allows for studying small scale cloud albedo variations.

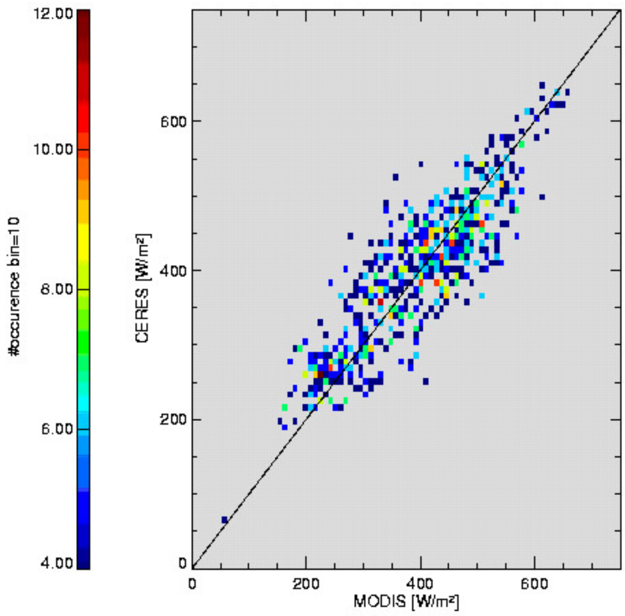

Figure 9.1: Upward short-wave radiation over clouds within the region [35N-70N, 20W-25E] at July16, 2002, 9:32 UTC; mean (CERES) = 453.9 W/m², mean (MODIS) = 449.8 W/m², rmse=107,84 W/m² and bias = -4.13W/m².

9.2.3. Atmospheric Water Vapour

Our knowledge of atmospheric water vapour is still limited, albeit this natural greenhouse gas is very important for the vertical energy balance of the atmosphere and precipitation forecasts. The most accurate way to derive total water vapour content of the atmosphere from satellite is by using passive microwave observations. The data does, however, only lead to usable information above water surfaces. Another problem with satellite based passive microwaves sensors is their large foot print, which spans tens of kilometres and additionally includes effects from larger distances due to antenna side lope effects. The latter is especially serious in coastal areas, where the strong land surface emission influences noticeably the ocean signal. As the spatial resolution of the relevant channels of the used satellite sensor SSM/I is especially low with about 50 km a considerable part if not all of the retrievals over the Baltic Sea is land surface influenced. Lindau and Ruprecht (2000) solved this problem by developing a special correction scheme for coastal areas, which allows for retrievals e.g. of atmospheric total water vapour content even close to the coast. Thus the area of useful retrievals with passive microwave sensors was significantly enlarged driven by the special conditions of BALTEX.

MERIS onboard ENVISAT and MODIS onboard Terra and Aqua also have dedicated channels to observe atmospheric water vapour using the backscattered solar radiance. The radiance measurements are, in contrast to passive microwave observations more suited to observations above land than above ocean surfaces, and provide also a much higher spatial resolution. The methods used to retrieve integrated water vapour from backscattered sunlight are based on the 'differential absorption technique'. Water vapour is estimated from the radiance ratio of measured radiances in the H_2O absorption band at 900 nm and a reference channel. The actual relation between the measured radiance ratio and the integrated water vapour is calculated by means of a radiative transfer model taking into account a large variety of different atmospheric profiles, surface and aerosol properties. The inversion is performed by an artificial neural network (Bennartz and Fischer, 2001).

For validation exercises, MODIS and MERIS measurements were compared to measurements of integrated water vapour contents taken by the ground based Microwave Water Radiometer (MWR) at the ARM site in Oklahoma, USA and radio soundings over central Europe. The agreement with MWR retrievals is very good with an *rms* difference between ground based and satellite based observation of 1.7kg/m² and a bias of 0.6 kg/m². The analysis of radio soundings and MODIS data above central Europe results in an *rms* deviation of 2.0 kg/m² and a bias of 0.8 kg/m² (see Figure 9.2). More details of this investigation are given in Albert et al. (2005). This algorithm has been applied to MODIS data above the BALTEX region for 2001 to 2003, estimating monthly means.

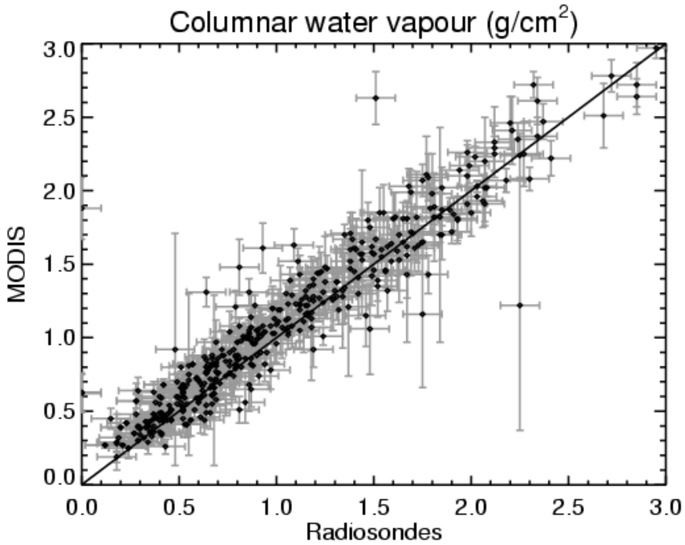

Figure 9.2: Scatter plot of integrated water vapour measured by radio soundings and retrieved from MODIS over central Europe from July 2002 to April 2003.

SEVIRI onboard the geostationary satellite MSG provides measurements of the full disk every 15 minutes. This enables to observe the diurnal variation of relevant atmospheric properties with an accuracy not reached so far. SEVIRI provides measurements in the thermal infrared which contains information on the atmospheric columnar water vapour content. An algorithm has been developed using data from the channels 6.2µm, 7.3µm, 8.7µm, 10.8µm, 12.0µm, and 13.4µm based on differential absorption parameterized by neural network techniques. The algorithm is applied for cloud free SEVIRI pixels at day and night time. It has been validated against independent satellite remotely sensed columnar water vapour measurements. The rms difference between MODIS and SEVIRI is estimated to 3.6 kg/m^2 with a bias of -1.3g/m^2. An example of the comparisons between MODIS and SEVIRI is shown in Fig. 9.3.

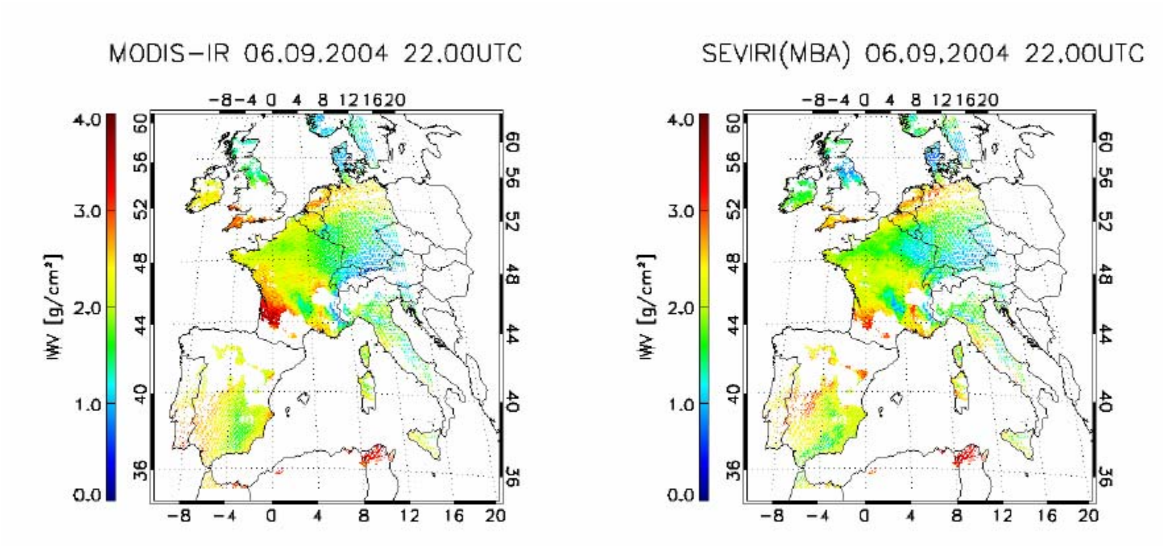

Figure 9.3: Total water vapour retrieved from MODIS (left) and SEVIRI (right) September 6, 2004.

The use of satellite based positioning systems like GPS for the retrieval of vertically integrated water vapour has been an issue in BALTEX (e.g. Stoew et al. 2001) from the beginning for the evaluation of atmospheric models. Applications of GPS technology concentrate on static networks, thus reference stations, which do not change their position. This procedure simplifies the parameter estimation and leads to a high accuracy from 1 to 2 kg/m² of the water vapour content. The efforts in BALTEX started with using the GPS stations around the Baltic Sea coast originally dedicated to detect the post-glacial uplift of Scandinavia. The so-called wet delay by atmospheric water vapour – an unwanted "noise" figure for position determination – has been transferred into usable atmospheric information, and is approaching operational use by the national weather services. While the GPS-based water vapour estimation in static networks in the meantime has become an established application, the measurement of this value on kinematical platforms represents a big challenge: On moving carriers the coordinates of the GPS antenna cannot be expected to be known, but must be estimated additionally to the water vapour content at every time of the measurement as new parameters. In spite of complicated evaluation methodology the results within BALTEX show that the water vapour content of the atmosphere can be successfully determined with GPS also on woving platforms like ships. First results have been obtained from instruments deployed on ships crossing the Baltic Sea (Figure 9.4). The GPS solution has several outliers (marked with circles), but reproduces the trend of the IWV well. The results of measurements with a radiosonde are also plotted as well as the values computed from weather fields produced by National Center of Environmental Prediction (NCEP) of the U. S. National Oceanic and Atmospheric Administration (NOAA) and the IWV values computed by REMO climate model.

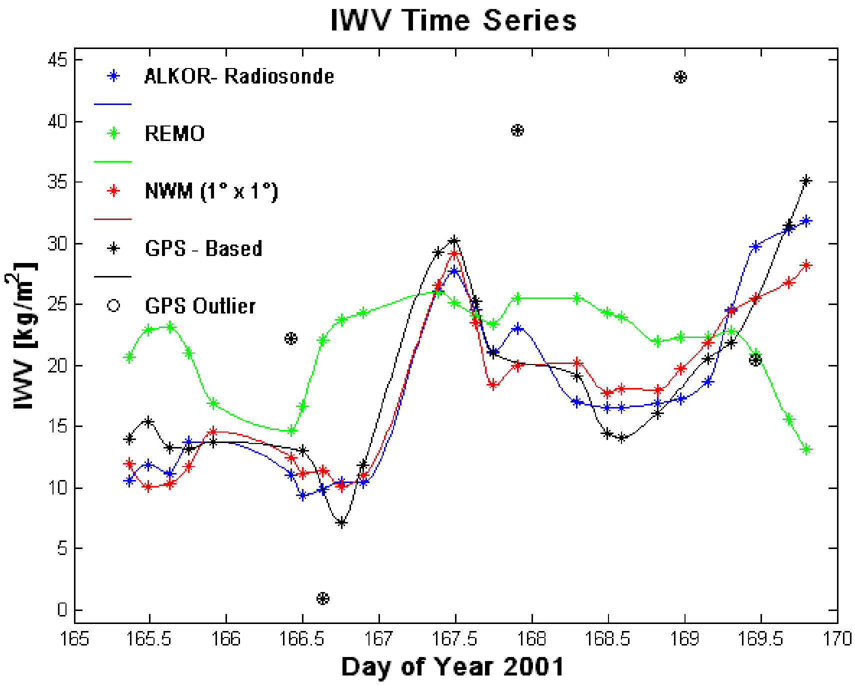

Figure 9.4: Comparison between radiosondes, static and kinematic GPS retrievals of total atmospheric water vapour content with analysis of NCEP ad the regional climate model REMO

9.2.4. Clouds

A cloud cover climatology above the BALTEX region has been estimated from geostationary METEOSAT First Generation (MFG) measurements. The time series is based on hourly MFG thermal infrared data from January 1992 to December 2001. The investigated region covers most of Europe and parts of the Atlantic and North Africa. The algorithm was designed for the analysis of historical MFG data and day and night application. For the cloud detection in one image not only prior images, but also following images have been used. The algorithm determines a theoretical cloud free brightness temperature of every pixel and compares it to the current measurement. High differences indicate high probabilities for cloud cover, while low differences indicate the contrary. The method to estimate clear sky brightness temperatures is based on an interpolation between highest temperature values at each pixel and time of day. This method can be understood as a dynamical threshold test. The algorithm has been validated against synoptic observations. The main outcome of the long term observation is, that the 10 year mean cloud coverage over the Baltic region is about 67%. No trend in cloud cover was found within the analyzed period. Mean diurnal and annual cycles and also regional effects like mountains or land/sea surface have been studied as well (see Figure 9.5).

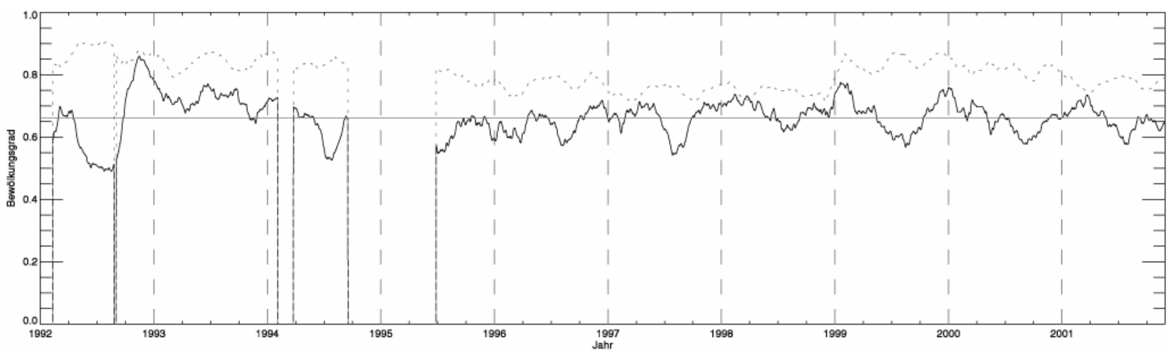

Figure 9.5: 60 day running mean of cloud cover derived from MFG from 1992 to 2001

The successor of MFG, MSG, features significant improvements in the instruments skills. SEVIRI onboard MSG is an imaging spectrograph with 12 channels in the visible, near infrared and thermal infrared region with a spatial resolution of 3 by 3 km^2. Several algorithms developed by different institutions exist to generate cloud products from SEVIRI measurements. E.g. the Free University of Berlin developed a whole series of meteorological level2 SEVIRI products, which partly showed superior quality compared to the operational EUMETSAT products.

Methods to obtain cloud optical thickness from the NOAA-AVHRR were refined with improved surface characterisation at the Dutch Weather Service (Feijt et al. 2005) together with estimates of cloud liquid water content, which was also estimated over ocean areas from passive microwave methods applied to AMSU observations. Other parameters derived from satellites for BALTEX are cloud-top pressure from several satellites using the oxygen A-Band technique (Albert et al., 2004, Preusker et al., 2004), the effective radius of cloud droplets and even droplet number concentration and geometrical thickness (e.g. Schüller et al. 2005) based on assumptions on the vertical profile of clouds.

Cloud Classification was another important topic in BALTEX Phase I with the development and continuous improvement of the SCANDIA scheme at SMHI, which was e.g. used to derive a 10 year climatology from NOAA AVHRR (Karlsson, 2003). The scheme has already found its way into the Eumetsat Satellite Application Facility on Nowcasting and Very Short Range Forecasting (SAFNWC, e.g. Dybbroe et al., 2005a,b), where the NOAA-AVHRR data are now combined with observations from the geostationary METEOSAT satellite.

9.2.5. Ocean Surface

Sea surface temperature and ice cover are standard products from satellites and have been used within BALTEX extensively. Ocean salinity cannot be retrieved from current sensors due to the still missing L-band observations. Larger scale ocean surface winds from scatterometer and wave spectra from Synthetic Aperture Radar (SAR) have not yet played a role in BALTEX, possibly due to the large influence of neighbouring land surface on the signal. The Baltic Sea as an inland sea is dominated by coastal areas. Due to the roughness change wind is one of the parameters mostly influenced by this contrast leading to large and systematic changes, which depend on wind direction relative to the coastline direction. Especially for off-shore industry knowledge about the wind regime in this region is of major importance. T is by no means known how accurate atmospheric models perform in this region of special interest for BALTEX. Hasager et al. (2004) have made first attempts to use the roughness signal from ERS-2 SAR measurements to estimate coastal wind speed. Results for an area at the North Sea coast demonstrated the potential and current problems of the method. Both the different effects of the coast for off- and onshore wind directions and the influence of off-shore buildings on the wind regime could be shown.

9.2.6. Land Surface Properties

Bonn University developed a retrieval algorithm for soil moisture within the uppermost meter of soil to use it as validation tool for the coupled BALTEX model system (BALTIMOS). As calibration data, longterm soil moisture measurements from the former Soviet Union are used. The retrieval works in two steps: First, the distribution of longterm mean soil moisture is derived by using precipitation, soil texture, vegetation density and terrain slope. In a second step, the temporal variability at each location is deduced by using microwave radiation measurements available from DMSP satellites (SSM/I sensor) together with precipitation and air temperature data. The major part of soil moisture variance originates from spatial differences between long-time means at each location. The algorithm is capable to reproduce this variance to a large extend by using easily available data, i.e. precipitation, vegetation density, soil texture and terrain slope. In the second step the temporal variance is explained so that the retrieved annual cycle is found to be in good agreement with the measurements. Independent soil moisture measurements from Illinois confirmed the quality of the retrieval algorithm.

The Free University of Berlin did satellite retrievals values of surface properties to be used for the coupled model BALTIMOS. To obtain a better adaptation to real conditions the estimation of the annual changes in vegetation, e.g. deciduous forests, which significant influence to the boundary layer processes and the moisture budget were derived for use in the model. During the vegetation period (April-September) LAI was predicted from the Normalized Difference Vegetation Index (NDVI) for 1/100 degree resolution. The regional variability of the NDVI values is not very large. However, the time dependent variability of LAI exhibits the activity of vegetation and biomass production. These LAI data sets for the whole BALTEX region has been compared to the existing model scheme and used to test the sensitivity of the model against yearly cycle of vegetation. In the Baltic Sea area the surface and the sea is partly covered with snow and ice for several months. Therefore the snow cover was analysed by synoptic observations from weather services for model comparison and in combination to the LAI. The comparisons to model simulations present distinct deviations at the start and end of the winter season, which will lead to further model improvements of the coupled model system.

9.2.7. Model Use and Validation

The observational programme PIDCAP executed actually before the official start of BALTEX Phase I was truly a jump-start for BALTEX in many aspects. Dedicated to precipitation it provided for a variety of measurements over the Baltic Sea catchment area, which has been used in the succeeding time a lot for model validation. In Jacob et al. (2001) a comparison of 8 regional atmospheric model systems was carried out for the PIDCAP period (a three-month late summer/early autumn period in 1995) over the Baltic Sea and its catchment area.

All models were configured on a common grid using similar surface and lateral boundary conditions, and ran in either data assimilation mode (short term forecasts plus data assimilation), forecast mode (short term forecasts initialised daily with analyses) or climate mode (no re-initialisation of model interior during entire simulation period). Daily averaged quantities, separate for land and sea areas was compared against the available analyses or observations of cloud cover, precipitation, vertically integrated atmospheric specific humidity, runoff, surface radiation and near surface synoptic observations. Satellite observations played a key role in these comparisons. The models operated in climate mode generally displayed slightly larger deviations from the observations than the data assimilation or forecast mode integration, but in all cases synoptic events were well captured and correspondence to near surface synoptic quantities was good. Significant disagreement between model results was shown in particular for cloud cover and the radiative properties, average precipitation (and runoff).

A combined validation of water vapour over land and over sea simulated by the regional climate model REMO has been performed by using GPS (Global Positioning System) observations together with SSM/I. Over land, GPS stations are able to measure the total water vapour content of the atmosphere by exploiting the signal delay due atmospheric moisture. Over sea, passive microwave observations from SSM/I are used to derive total atmospheric water content, employing the method by Lindau and Ruprecht (2000). A comparison of both observation sources with the modelled water vapour from REMO (Figure 9.7) revealed that the model is too wet over land as well as over sea. A bias of about 2 kg/m^2 was found against both, GPS and SMM/I. A similar validation study with a weather forecast model has been published by Koepken (2001). The compared models of the German Weather Service (DWD) did reproduce the observed temporal and spatial variability of the remotely sensed total water vapour fields accurately, but a systematic bias of +2.5–3 kg m^{-2} was diagnosed versus GPS. However, radiosondes indicated a smaller bias of about 1.5–2 kg m^{-2} and hint at a slight dry bias in the GPS data. The model bias slightly depends on the amount of humidity, being smaller in relative and absolute terms for higher IWV values. A comparison of the results from the models versus GPS and SSM/I retrievals showed an encouraging correspondence between the two independent data sources. A preliminary evaluation of the then new operational Lokal Model (LM) indicated a reduced bias of about 1 kg m^{-2} when compared with observations from German GPS sites.

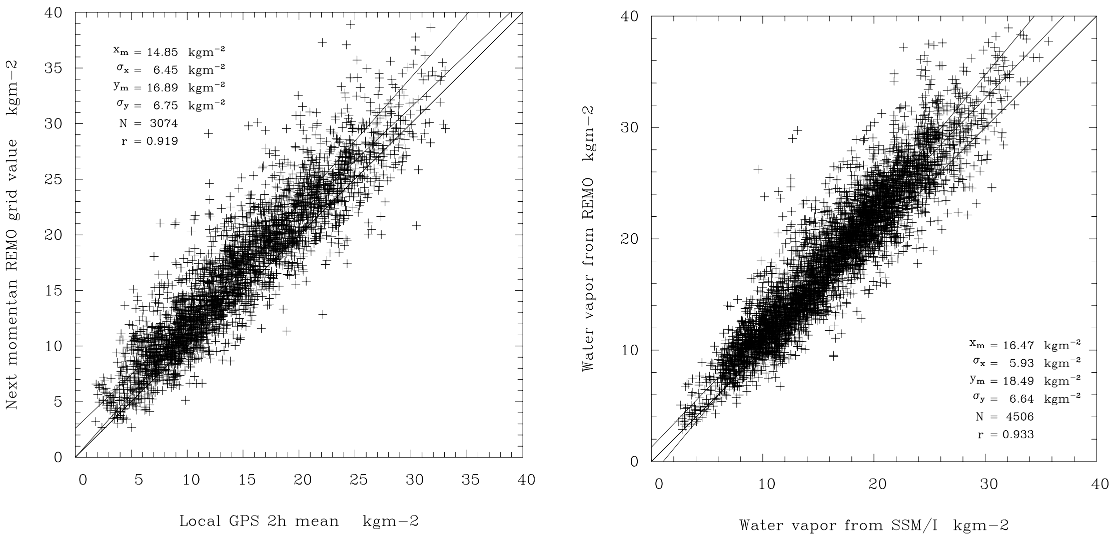

Figure 9.6: (Left) Comparison of total water vapour from GPS and from REMO for the period August 20 to October 31 1995. (Right) Total water vapour from SSM/I and from REMO. In order to make the variance comparable, both data sets are averaged over 6 by 6 REMO grid points.

Soil moisture has been one of the parameters determined from satellites, which has been also used for model validation. University Bonn applied their soil moisture algorithm (see above) to the entire model area of the BALTIMOS coupled model (Fig. 9.7). Large differences between model and observation occur in both, the regional distribution of long term mean soil moisture and its temporal variance. The long time means for the entire model area are, however, in good agreement: e.g. they differ only by about 10 mm (262 mm/ 274 mm). This result was not expected because both data sets have been derived from totally independent information. As the soil moisture retrieval is based on rather coarse data, it cannot resolve the details in the fine structures of the modelled long term mean soil moisture pattern. To compensate for the different resolutions of model and retrieval both data sets were averaged over 10 by 10 grid boxes (180 km by 180 km) resulting in a correlation coefficient of 0.457. The ability of the BALTIMOS coupled model to reproduce the temporal evolution of soil moisture has been studied for the Oder catchment. Almost nine years of data are exploited. The average soil moisture for this particular region is reproduced very well by the model, with 231 mm compared to 233 mm derived by the retrieval. However, the model exhibits a much stronger annual cycle reflected in a standard deviation twice as high as retrieved by the algorithm. Moreover the annual cycle of the model is shifted backward in time compared to the observations. The model seems to be delayed by about one month.

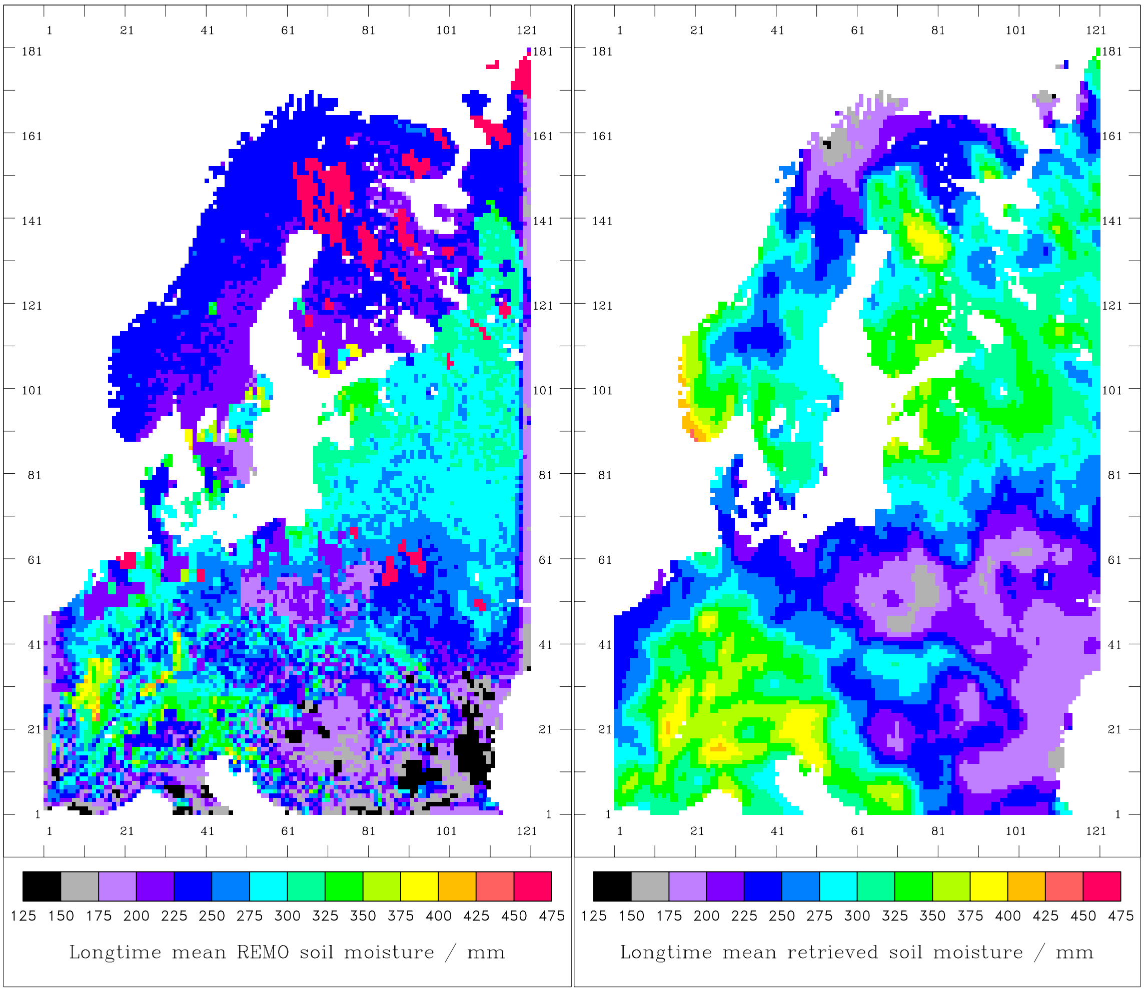

Figure 9.7: Long-term root zone soil moisture from REMO (left) and retrieved (right)

9.2.8. Assimilation of Satellite Data into Atmospheric Models

The assimilation of satellite data into atmospheric models to improve the model initial state has been pioneered in Europe by ECMWF. ECMWF has shown, that e.g. the assimilation of atmospheric humidity from satellites has increased model prediction considerably by increasing the quality of Southern hemisphere forecasts up to the quality of the Northern hemisphere forecasts. Within BALTEX extra efforts has been put into the assimilation of land surface parameters. Soil moisture has been assimilated indirectly also by national European weather services by using screen level observations. Seuffert et al. (2003) have shown however, that the direct assimilation of satellite passive microwave radiances e.g. of the future SMOS satellite might lead to improved and more physical soil moisture analysis. First attempts are made to also include satellite derived snow estimates in the surface analysis (Drusch et al, 2003).

9.3. Summary and Perspective

In BALTEX Phase I satellite observations mainly played a role in the concerning the development of new and improved retrieval methods. Attempts to use the data for climatologic aspects of the BALTEX region has been somewhat hampered by unresolved problems concerning drifts, effects on solar illumination on derived diurnal or seasonal variability. Nevertheless first attempts have been made to derive regional climatologies and in comparing the data with model results. Especially the latter has led to new insights into problems of both models and satellite data. Due to model improvements by improved spatial resolution and by taking into account more detailed cloud and precipitation physics new methods of comparison will be applicable by simulating satellite measurements from model results. By this approach climatological assumptions inherent to any retrieval algorithm avoided at the expense, however, of a more elaborate analysis of the comparisons, because descrepencies might be caused by a range of reasons.

BALTEX Phase II will also profit from vastly improved sensors with higher spatial and temporal resolution (MODIS, MERIS SEVIRI). More intense use of satellite data will follow from the Climate and Nowcasting Satellite Application Facilities of EUMETSAT, which will concentrate on the use of MSG and its combination with polar orbiting satellites. Another thread along which improved use of satellite data will be fostered is the combination with other atmospheric and earth surface observations. One example is the planned regional reanalysis by SMHI combining the MESAN approach (Häggmark et al., 2000) with the SCANDIA cloud analysis.

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Chapter 10:

BALTEX Weather Radar Achievements

by

Günther Haase, Jarmo Koistinen, and Daniel Michelson

10.1. Motivation

Accurate precipitation measurements are essential to improve scientific understanding of energy and water cycles, and to develop forecasting systems to both warn of hazards and enable the optimization of management procedures. Weather radars are the only sensors which are able to provide precipitation observations, with high spatial and temporal resolutions, simultaneously over both land and sea. The activities of the BALTEX Working Group on Radar (WGR; Brandt et al. 1996) have led to the establishment and operation of the BALTEX Radar Data Centre (BRDC), designed to collect data from those radars in and proximate to the Baltic Sea and its drainage basin, to process these data into series of homogeneous products, to disseminate these products to BALTEX data users, and to archive all data and products (Michelson et al. 2000).

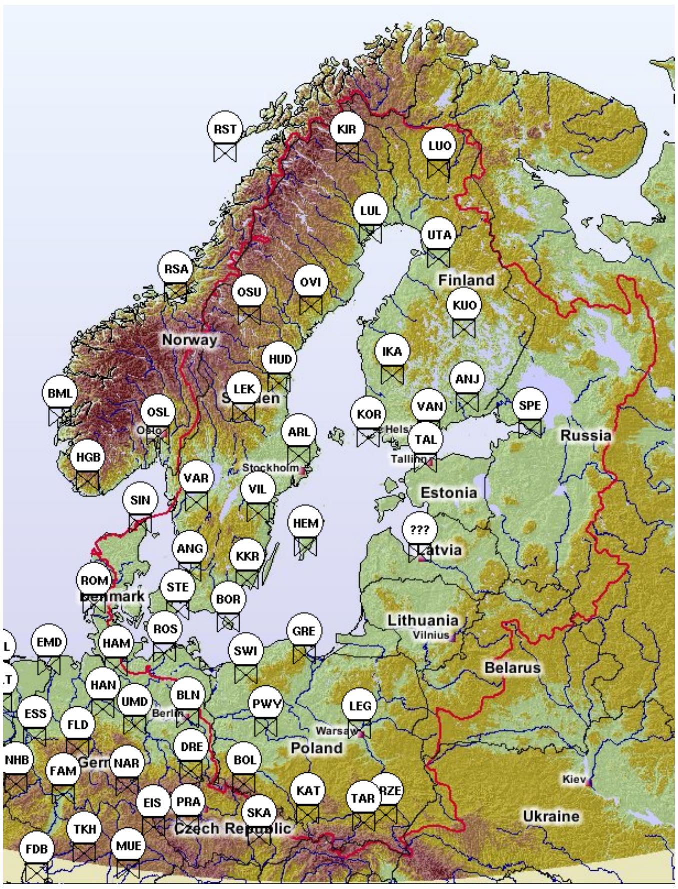

Figure 10.1: Existing and potential BALTRAD radars. The Baltic Sea’s drain basin is outlined by a thick red polygon. Background map courtesy of UNEP GRID-Arendal.

The BALTEX Radar Network (BALTRAD) consists of around 30 C-band, mostly Doppler, weather radars in Norway, Sweden, Finland, Denmark, Germany, The Netherlands, Poland, and Estonia (Fig. 10.1). This network provides BALTEX with composite images of radar reflectivity factor every 15 minutes with 2 km horizontal resolution. Three- and 12 hour radar-based accumulated precipitation products are also generated at the same horizontal resolution using an adjustment technique employing gauge observations. The WP product contains vertical profiles of wind speed, wind direction, reflectivity factor, and other associated variables, with a temporal resolution of 15 minutes and a vertical resolution of 200 m (Koistinen and Michelson 2002). The two methods used are the Velocity Azimuth Display technique (VAD; Andersson 1998) and the Velocity Volume Processing (VVP; Waldteufel and Corbin 1979) technique. WP products are disseminated automatically to the CWINDE (COST Wind Initiative for a Network Demonstration in Europe) data centre for EUMETNET WINPROF. All BALTRAD products are available to BALTEX data users on CD-ROM from October 1999 to March 2002. Production of data sets is still ongoing with new forms of distribution.

Two major achievements of the BALTEX WGR may be highlighted here: (i) the establishment of a unique radar data base comprising measurements and products from many different countries, and (ii) the stimulation of new radar related projects within COST 717 (Rossa 2000) and EUMETNET OPERA (http://www.chmi.cz/OPERA). Additionally, BALTEX has initiated the improvement of many national radar networks. However, BALTEX itself benefited also from data quality work in the Nordic Weather Radar Network (NORDRAD) which is a cooperation project between Finland, Norway, Sweden, and Estonia. Therefore, it is sometimes difficult to distinguish between BALTEX and NORDRAD achievements.

10.2. Data quality control

10.2.1. Calibration and monitoring

After several years of operational use, it became clear that in the BALTEX network individual radars did not perform at a common calibration level. The magnitude of the reflectivity level differences, particularly those between neighboring Swedish and Finnish radars, could even be of the order of 10 dBZ. A three-year joint project was established to determine the main causes of the permanent and substantial observed differences (Koistinen et al. 1999).

Two identical sets of calibration experiments were performed at two overlapping radars: Ikaalinen in Finland and Hudiksvall in Sweden. The methods included reference feedhorn tests with an independent signal generator and sphere calibrations (Gekat et al. 2003). These special calibrations were preceded by ordinary receiver calibrations using the output of a signal generator injected into the waveguide. The project clearly revealed that a careful system analysis of signal processing and calibration routines is very important in any radar network. A feed horn calibration is recommended to calibrate the receiving part of the system. A sphere calibration is ideal, but a quite laborious and inaccurate tool so far in practice.

When the main causes for the permanent discrepancy between Swedish and Finnish radars had been removed, a follow-up project was then set up with the aim of improving the intensity level harmonization to within ± 2 dBZ and establishing workable and efficient quality assurance and maintenance practices. The main task was the creation of a numerical analysis program by which estimates of the calibration difference of the radars and difference of the lowest elevation angles used by the radars are obtained (Huuskonen 2001). Altogether, 15 radars were chosen for the study. The input data in the paired-radar analysis is the pseudo-CAPPI (Constant Altitude Plan Position Indicator) reflectivity data projected onto a polar stereographic grid. Products at 15 minute interval were processed to create estimates of the average reflectivity difference on the common field-of-view of the radars.

The concept of using an external reference target for calibration and monitoring of calibration stability becomes more attractive if the same target may be shared by several radars, hence the interest in using the sun as such a target. Another form of external reference target may be in the form of conventional precipitation measurements by gauges. The principle is that overlapping radars have common coverage areas with common gauges, and that comparing gauge and radar data may reveal systematic differences between different radars' calibration levels. This knowledge could then be used to derive a means of normalizing radar data to a common level defined by the gauge measurements.

This type of gauge-radar comparison was conducted using radar data from Norway, Sweden, Finland, and Danish data from Copenhagen, along with daily measurements from around 1600 gauges in the climate station networks in Norway, Sweden and Finland (Michelson 2001). In order for this kind of comparison to be meaningful, long integration periods must be used. Doing so has the effect of smoothing out much of the noise in both data sources. If there are no known climatologically forced precipitation gradients in a given radar's coverage area, then a long radar data integration in an ideal case will be isotropic about the radar itself while the gauge data integration will be more-or-less uniform in space. The basis for the comparison becomes the gauge-to-radar ratio (*F*), according to Eq. (1), as a function of distance from the radar.

$$F(dB) = 10 \log(G/R) \qquad (1)$$

In terms of radar calibration, the most valuable piece of information in such a derived relation becomes the y-axis intercept, which can in such a context be referred to as the system bias. This value gives the difference in calibration level between the gauges and the radar at the radar's location. Deriving the system bias for each radar provides the most elementary basis for normalizing radar data. The shape of the curve illustrates the bias as a function of distance from the radar. If the relations from several radars are reliable enough, then the combined use of the system and distance biases may be incorporated into the normalization process.

10.2.2. Non-precipitation echoes

Propagation of electromagnetic waves has been comprehensively addressed in a weather radar context (e.g. Alberoni et al. 2001). Figure 10.2 illustrates normal propagation and ducts giving rise to echoes from the earth's surface. This entrapment and propagation of a small amount of radiation is referred to as being anomalous (AP) and the echoes are referred to as AP echoes. Such echoes are strong and highly variable on small spatial scales over land. Over sea, where they are referred to as sea clutter, they are more homogeneous and generally weaker in strength. Other types of non-precipitation echoes originate from insects, birds, aircraft, chaff, military jamming, and the sun. All types of non-precipitation echoes are referred to as being spurious (Koistinen et al. 2003).

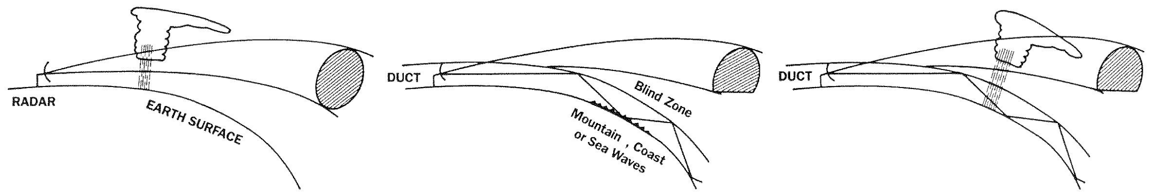

Figure 10.2: Normal propagation conditions with precipitation (left) and anomalous (superrefraction) propagation conditions giving rise to radar echoes from the earth’s surface with (right) and without precipitation (middle) (from Alberoni et al. 2001).

Radar systems with good coherency and effective Doppler filtering to full measurement range do not suffer from ground clutter even in common cases when unfiltered reflectivity is severely contaminated by clutter. However, systems with limited Doppler range suffer from ground clutter and even the coastal Doppler systems suffer from sea clutter contamination. The operational experience in the Nordic countries shows that major part of clutter generated by anomalous propagation in ducting conditions occurs in spring and summer (April–August). The dominating favorable factor is a warm air mass above the cold Baltic Sea, generating a cool, moist and shallow ducting layer of air at the surface. In operational use, Doppler filtering mitigates almost all AP ground clutter. The main remaining problem in Doppler radars is sea clutter and ships. They can't be filtered with the existing signal processors since reflectivity, Doppler spectrum width, and average Doppler velocity are similar to those from precipitating echoes. As long as operational Doppler signal processing or polarimetric measurements are incapable of diagnosing sea clutter and other non-meteorological echoes, we have to use post-processing methods on radar data together with multisource meteorological data for echo type classification.

10.2.2.1 Image analysis method

A recently developed scheme applies a set of detection algorithms listed in Tab.10.1. Each detector concentrates on specific visual features in the image.

Table 10.1: Detectors and their primary targets

Detector	Target
BIOMET	birds and insects near the radar
SPECK	noise, distinct specks
EMITTER	line segments
SUN	long line segments
SHIP	ships (and aircraft)
DOPPLER	non-continuous Doppler data

Anomaly detection and filtering tasks are carried out separately. In the detection stage, each detector provides a response image which presents the spatial probabilities of an anomaly class. Here, "probability" means a degree of confidence computed from detection sensitivity parameters set by an expert. More specifically, each such parameter is essentially a 50–50% threshold of anomaly vs. precipitation; each detector typically needs a couple of such thresholds for reflectivities or visual features. Continuity is achieved by using fuzzy logic, i.e. continuous probability functions for classification instead of strict reflectivity thresholds (Sonka et al. 1993). Finally, the total probability of spurious echo occurrence is obtained by taking the maxima over the specific response images.

The continuous-valued response image, having equal dimensions with the original data, allows cutting off anomalies with a tunable threshold. This is useful because the filtering always involves the compromise of removing anomalies and true precipitation, and applications have varying requirements on this compromise. For example, generation of warnings often requires conservative anomaly removal whereas strongly filtered (yet sparse) precipitation data are preferred when computing motion vectors. Peura (2002) gives a detailed discussion of all detection algorithms. A goal of BALTEX Phase II (Graßl et al. 2004) is to apply the image analysis method to BALTRAD products.

10.2.2.2 Multisource method

A simple and pragmatic method, utilizing the difference between and analyzed near-surface and Meteosat IR temperatures (ΔT), has been developed and applied with the intent to identify and remove non-precipitation echoes (like AP, ground and sea clutter) in weather radar composite imagery (Michelson and Sunhede 2004). Despite inherent deficiencies in these multisource data, such as lower spatial and temporal resolutions relative to the radar data, ΔT is demonstrated to efficiently identify areas void of potentially precipitating clouds, and remove radar echoes in them.

A set of 243 manually analyzed composites from the summer of 2000 was used to evaluate the method. False alarm rates (FAR), percent correct (PC), and Hanssen-Kuipers skill (HKS) scores (Wilson 2001) were calculated from standard contingency tables for five echo classes: weak, strong, land, sea, and all. FAR was lowered in all classes, PC was generally raised by a few percent to be over 95%, while HKS either remained unchanged or was slightly lowered through the application of ΔT. These results indicate that ΔT successfully removes a significant amount of non-precipitation, sometimes at the expense of a small amount of true precipitation. This penalty is larger over sea which may indicate a need to tune the method differently for land and sea environments.

This method may act as a foundation on which improvements to radar data quality control may be introduced with the introduction of new and improved satellite instrumentation such as that found onboard Meteosat Second Generation. However, this type of method should remain a compliment to improved signal processing and radar data analysis techniques.

10.2.2.3 Three-dimensional correction method

With improved computer performance, a new filtering method has been applied to Swedish polar volume data (Alberoni et al. 2001). It is based on analysis of the vertical variability of radar echoes above a given point. The results from case studies show that AP echoes can be identified and removed using the three-dimensional information available in original polar volume data but that the method is subjected to the same kind of difficulties as with other methods, i.e. tuning it to gain optimal effect.

10.2.3 Precipitation measurements

The estimation of surface rainfall from reflectivity data derived from weather radar has been much studied over many years. It is now clear that central to this problem is the adjustment of these data for the impacts of vertical variations in the reflectivity.

10.2.3.1 Vertical profile of reflectivity

a) Vertical profile of reflectivity correction

Radar measurements are made at increasing height and with an increasing measurement volume with increasing range, making them decreasingly representative for surface conditions. A radar measurement (Z_e), and possibly even the precipitation intensity, can be accurate aloft, at the height of radar measurement, but it is not necessarily valid at the surface. This inaccuracy is not a measurement error but a sampling difference. The Vertical Profile of Reflectivity (VPR) above each surface location can be denoted as $Z_e(h)$, here h is height above the surface. The shape of the VPR determines the magnitude of the sampling difference.

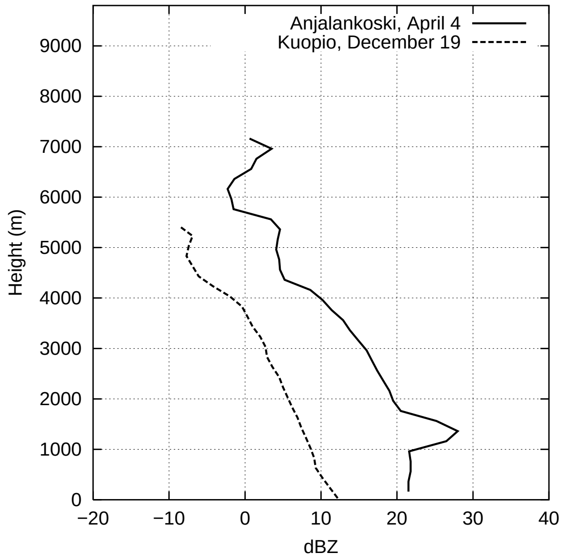

Figure 10.3: Two vertical profiles of reflectivity averaged from single polar volumes at ranges of 2-40 km from the radar. The solid line represents rain and the dashed line snowfall.

Figure 10.3 shows an example of two measured VPRs. As we know the shape of the radar beam pattern f^2 and the height of the beam centre h at each range r, it is easy to calculate from a VPR what the radar would measure at each range, $Z_e(h, r)$:

$$Z_e(h,r) = \int f^2(y) Z_e(y) dy \,, \qquad (2)$$

where the integration is performed vertically (y) from the lower to the upper edge height of the beam (Koistinen 1991). The vertical sampling difference c (in decibels) is then:

$$c = 10 \; log \frac{Z_e(0)}{Z_e(h,r)} \;, \qquad (3)$$

where $Z_e(0)$ is the reflectivity at the surface in the VPR. Hence, by adding the sampling difference (c) to the measured reflectivity aloft (dBZ) we get the reflectivity at the surface, dBZ (0):

$$dBZ(0) = dBZ + c \,. \qquad (4)$$

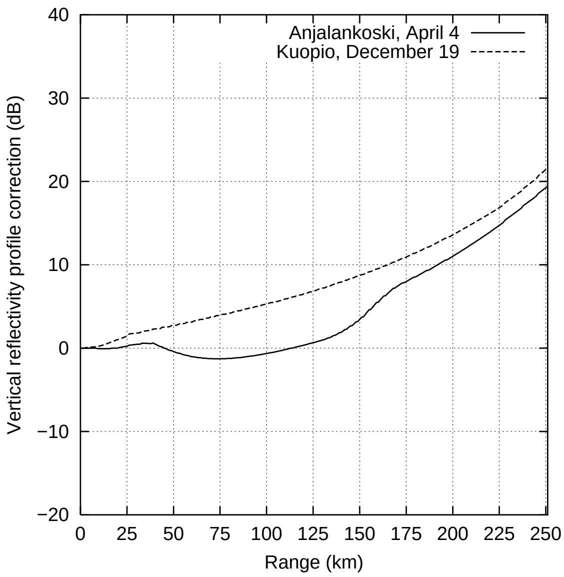

Figure 10.4: Sampling difference (dB) between the measured reflectivity and actual reflectivity at surface level as a function of range. The graphs represent the vertical profiles of reflectivity in Fig. 10.3. The elevation angle is 0.4° and one-way beamwidth is 0.95°.

When we apply Eq. 3 to the reflectivity profiles in Fig. 10.3, the resulting sampling difference can be seen in Fig. 10.4. In snowfall, the difference increases monotonously as a function of range, indicating significant underestimation of surface precipitation already at close ranges. In rainfall, the radar measurement is relatively accurate up to the range 130-140 km. It should be noted that the overestimation introduced to the ground level precipitation estimate due to the bright band in Fig. 10.3 is very small in Fig. 10.4 (at 50-110 km). By comparing the two curves in Fig. 10.4 we can conclude the following: when the height of the bright band is more than approximately 1 km above the antenna, the overestimation due to the bright band will compensate the underestimation effect of snow in the beam. As a result a radar measurement is more accurate to longer ranges than it would be without a bright band. If the bright band is located at a low altitude (0-500 m) the resulting overestimation of surface precipitation will be much larger (typically 2-8 dB) but restricted to a short range interval close to the radar.

Koistinen et al. (2003) showed that the sampling difference is by far much more important factor in the accuracy of operational radar-based precipitation measurements than the effect of an “optimal” relation between radar reflectivity factor and precipitation intensity. Due to the shallow structure of precipitation with generally large negative reflectivity gradients from the surface level upwards, especially in snowfall, this conclusion is even more valid in a cold climate. If the radars in such regions are ideally sited (like in Finland), the sampling bias is the only really significant factor influencing the accuracy of quantitative ground level precipitation measurements at 50-250 km ranges from radar. For non-optimally sited radars in areas of complex terrain in Sweden, Norway and elsewhere, siting issues strongly affect data quality. In wintertime, the sampling bias at longer ranges is quite often so large (20-40 dB) that the reflectivity signal is lost completely and the real detection range of precipitation is only 100-150 km. There are at least two solutions to correct the sampling biases (provided that some reflectivity level is measured). Gauge adjustment techniques can be applied for longer integration periods (12 hours and longer), since the amount of gauge data is usually representative only for longer periods. For shorter periods, VPR correction schemes (Eq. 3) based on measured or estimated VPRs can be applied.

b) “Down-to-Earth” method

At SMHI a new experimental procedure (known as Down-to-Earth, DTE) has been developed and tested for combining radar measurements aloft with information from a Numerical Weather Prediction (NWP) model and a mesoscale analysis system (Michelson et al. 2003). The procedure involves the exploitation of moist cloud physics in an attempt to account for physical processes impacting on precipitation during its descent from the height of radar echo measurements to the surface. The application of DTE leads to increased underestimation in the radar measurements compared to precipitation gauge observations at short and intermediate radar ranges (0-120 km), but is successful at reducing the bias at further ranges. However, the application of DTE does not lead to significant decreases in measurement variability. It is concluded that further work on radar data quality control, along with improvements to the NWP model, are essential to improve upon results using such a physically-based procedure.

The BALTEX WGR suggested at their latest meeting on Bornholm (May 2004) to combine FMI’s VPR correction algorithm with the evaporation scheme employed in the DTE technique. It is expected that this will improve the surface rainfall estimation further.

10.2.3.2 Dynamic Z-R relations

If the size and water phase distribution of hydrometeors is known, the precipitation intensity can be calculated:

$$R = 10^{\frac{(dBZ - 10\log a)}{10\,b}} \qquad (5)$$

where a and b are factors depending on the water phase and size distribution of the hydrometeors (Marshall and Palmer 1948). It should be noted that the unit of R is mm/h but the measured value is instantaneous, representing the 0.1 second long period when each bin was measured. In BALTRAD precipitation products a = 400 and b = 2, assuming all precipitation is solid in winter (October-March). During the rest of the year a = 200 and b = 1.5 (rain).

When reflectivity measurements are transformed into precipitation estimates two additional sources of inaccuracy will be added to those related to reflectivity only. The effective radar reflectivity (Z_e) is accurately measured but the scatterers may not be precipitating hydrometeors. Assumptions and selected constants in Eq. (5) may not be valid everywhere.

The natural variability of hydrometeor distribution is wide and rapid in time and space. As a consequence, any “optimal” *Z-R* relationship, measured directly e.g. with a disdrometer, will not implicate statistically significant improvement in radar precipitation measurements unless the integration period is very long (Joss and Germann 2000). Hence, it is reasonable to use a fixed *Z-R* relation, based on very large hydrometeor samples, separately for rain and snow and possibly for convective and stratiform rain (Smith and Joss 1997). Saltikoff et al (2000) applied a real-time selection of *Z-R* factors based on the analysis of ground level hydrometeor phase (rain, sleet, snow) and, as a reference, a fixed *Z-R* for rain. The resulting 12 hour accumulated precipitation (*R*) was compared to gauge measurements (*G*) at the same locations. As the selection between the two choices introduces only minor changes to gauge-radar comparisons, while the difference itself remains large, it can be concluded that improvements gained through optimal *Z-R* relation between radar reflectivity factor and precipitation intensity are masked behind other, much larger sources of bias. Thus the selection of the *Z-R* relationship in the BALTRAD production is not critical from the point of areal and long term average accuracy. The most outstanding violation will appear in cases of wet hail, which will introduce very high reflectivities (55-70 dBZ). In such cases Eq. (5) will lead to overestimation of rain by a factor of 3-10. The time-space fraction of hail occurrence is very small, usually covering an area of the order of 10 km^2 and time period of 30 minutes. Still the practical consequence is that without a hail detection algorithm we can’t use radar reliably for a local, urban-scale flood warning. For larger areas (1000 km^2 or more) the radar-based flood warnings are much more reliable without hail detection.

Michelson (2001) developed a method where information from an NWP model is used to diagnose the precipitation phase and assign appropriate *Z-R* relations to radar data. This approach considers also the height and thickness of the bright band and those parts of it which are located within the radar beam. The diagnosis of precipitation phase and the application of phase-dependent *Z-R* relations do not lead to improvements in the accuracy of the DTE results (Michelson et al. 2005).

10.2.3.3 Gauge adjustment

Precipitation gauges are commonly viewed as providing accurate point measurements. Weather radar is commonly perceived as being able to capture precipitation's spatial distribution well in relative terms. Numerous studies over the past few decades have sought to integrate radar data (R) with gauge observations (G) to arrive at quantitatively accurate and spatially continuous radar-based precipitation measurements (Gjertsen et al. 2003).

G/*R*-based techniques are generally well suited for operational real-time use since they are robust and generate results which are more quantitatively useful than unadjusted radar data. The gauge adjustment technique applied at the BRDC (Michelson et al. 2000, Michelson and Koistinen 2000), for the purposes of generating precipitation datasets for the BALTEX is a further development of a technique for use with Finnish single-site radar data and a high density gauge network (Koistinen and Puhakka 1981). Their technique, in turn, is based on improvements to that developed in the United States (Brandes 1975) and an application of the improved Barnes analysis technique (Barnes 1973).

In short, the gauge adjustment technique involves the derivation and application of the logged gauge-to-radar ratio log (*G*/*R*). This variable is used to derive a uniform distance-dependent relation between radar and gauge data, and a spatially analyzed *F* field. The final adjustment factor applied to a given radar-based value is a weighted combination of the uniform and spatial adjustment factors, based on observation density; the spatial adjustment is given that proportion of the total weight which the local observations can support. The primary innovations of this adjustment technique are:

- Radar sums, and the distance information, are managed as composites.
- Individual radar sums are subjected to a preliminary adjustment to normalize their content to a common level throughout the network. This step is also designed to minimize the bias between radar and gauge sums at each radar site due to systematic errors such as differences in calibration.
- *G*/*R* point pairs are collected in a moving time window to ensure a large enough sample such that the risk of overfitting in the relation with distance is minimized. Also the use of a quality control routine is used whereby individual point pairs are assigned a variable quality weight [0-1] within an accepted quality interval.
- A second-order polynomial between log (*G*/*R*) and ground distance from the radar is the basis for the adjustment.
- The gauge adjusted radar sums are integrated with results of an optimal interpolation of corrected gauge sums in areas without radar coverage.

An additional innovation is the use of systematically corrected gauge observations through the application of a statistical model driven by MESAN (Häggmark et al. 2000) fields (Førland et al. 1996, Michelson et al. 2000, Michelson 2004).

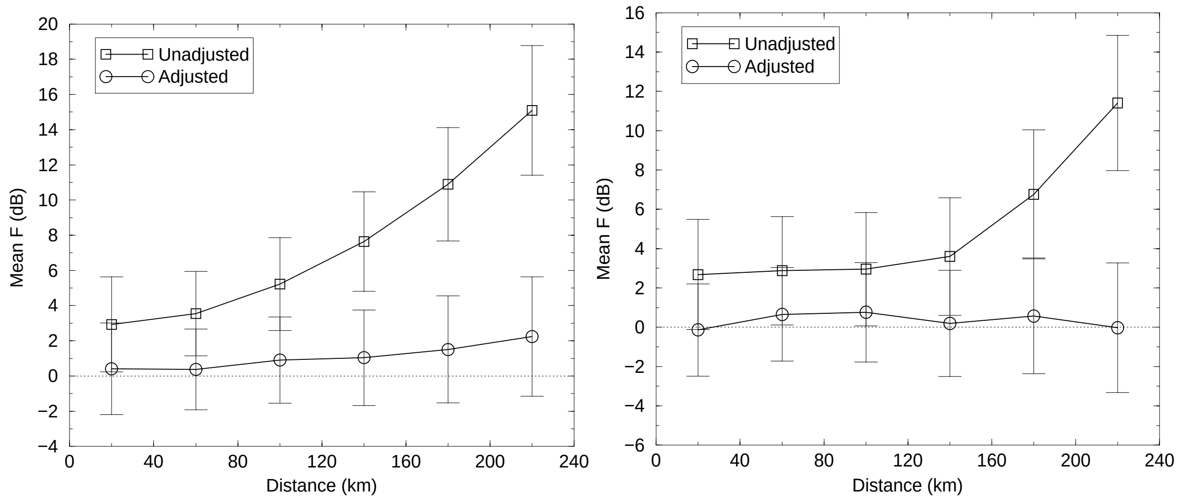

Figure 10.5: Bias as a function of distance with daily accumulations before and after gauge adjustment. Left: December 1999 - February 2000. Right: June - August 2000. Error bars denote one standard deviation. Note the difference in y-axis scales.

The gauge adjustment technique was evaluated using the three-month winter and summer periods, and independent climate station gauge data (Koistinen and Michelson 2002). This was done by binning the *G*/*R* point pairs into 40 km strata and deriving averages, standard deviations, and histograms of *F* for each stratum (Figs. 10.5-6).

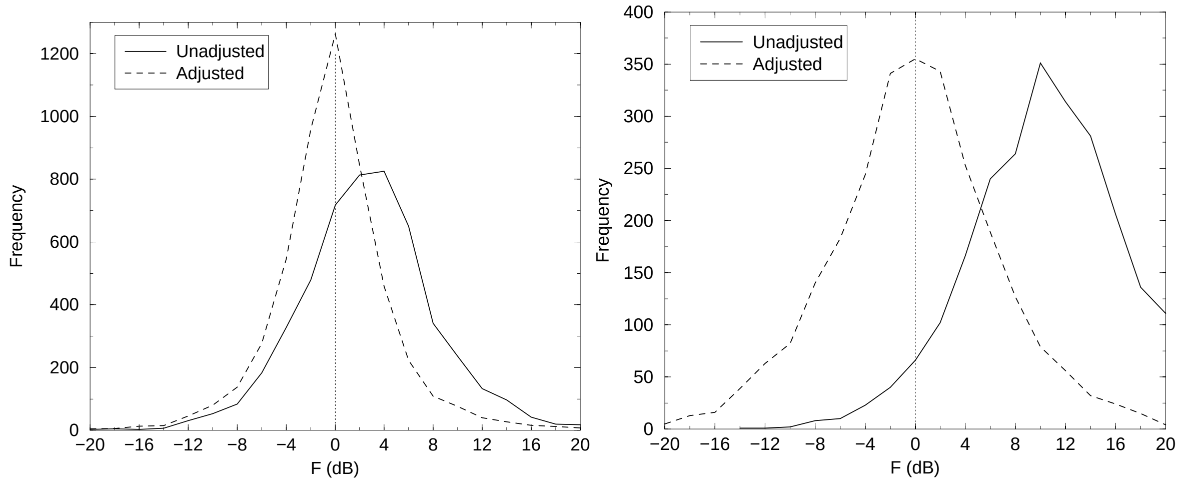

Figure 10.6: F (dB) histograms for the period June-August 2000 for the most proximate and the most distant of the six 40 km wide distance strata. Left: 0-40 km. Right: 200-240 km.

The histograms in Fig. 10.6 show that the mean biases are minimized, while the variabilities in all but the most proximate 40 km stratum are also reduced. In all but the most distant couple of strata for the winter evaluations, the mean bias is minimized to within one dB which is around a 25% loss. Only in the most distant winter stratum does the bias exceed 2 dB, which is roughly a 60% loss, where the corresponding unadjusted bias exceeds 3000%! Standard deviations are lower for adjusted data in all but a couple of strata. This means that significant improvements to the accuracy of radar-derived accumulated precipitation are gained out to full operational range resulting from the use of this gauge adjustment procedure.

These results show the value of gauge adjustment in improving the quantitative value of radar-based accumulated precipitation estimates by addressing the issue of bias against gauge observations (Koistinen et al. 2003). Further improvements may be gained, in the form of reduced scatter in the comparison with gauges, if a precipitation phase type-dependent *Z-R* relations and VPR corrections are applied. This combination of strategies has been identified (Collier 1996) as a means of improving the accuracy of radar data; it is the subject of ongoing research within BALTEX and elsewhere.

10.2.4 Wind measurements

10.2.4.1 De-aliasing

Aliasing of Doppler radar velocities is a well-known problem and has been addressed by many authors during the last decades. Based on the idea of Siggia and Holmes (1991) to integrate unfolding into the VVP algorithm, a new de-aliasing algorithm has been developed at SMHI (Haase and Landelius 2004, Haase et al. 2004). It is an accurate and robust tool based on a linear wind model and designed to eliminate multiple folding. The innovation of the new technique is that it maps the measurements onto the surface of a torus. Unlike many other concepts, it does not depend on wind information from a nearby sounding (e.g. radiosonde or wind profiler) or from an NWP model. Since volumetric radial wind data from Finnish radars are strongly affected by aliasing problems (but solved in operational VVP products by using commercial post-detection aliasing algorithms) we applied the new unfolding algorithm to Doppler winds measured with the Vantaa radar (60.27°N, 24.87°E) during the winter storm of 4 December 1999.

a) Wind profiles

Wind profiles have been generated based on the VVP technique. It is typically applied to thin layers of data at successive heights. In the case study presented here, radial wind observations within a layer of 200 m thickness and a horizontal radius of 40 km has been used. Wind speed and direction can be extracted via a multi-dimensional and multi-parameter linear fit of all observations in a certain height interval. If the azimuthal data coverage is less than 1/3 the wind retrieval is rejected at this height level.

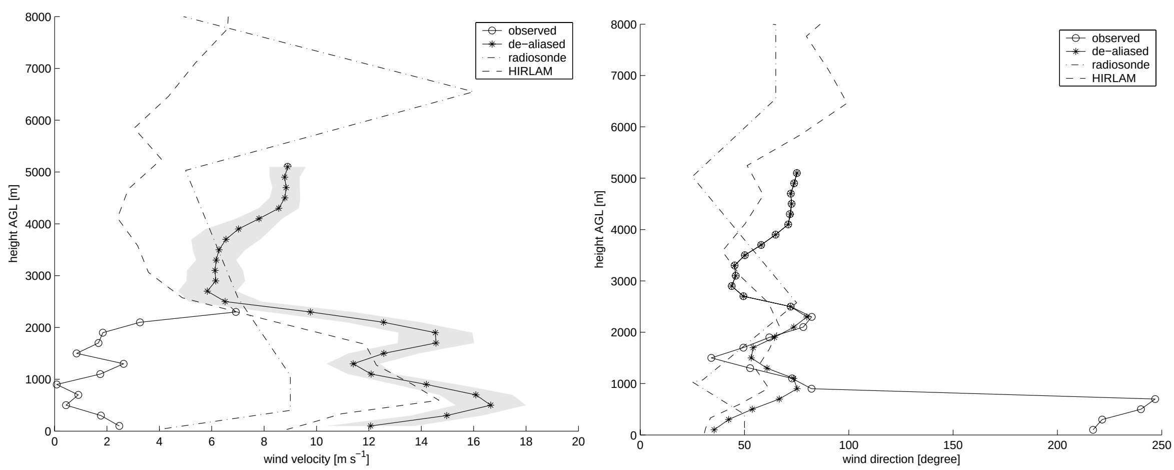

Figure 10.7: Vertical profiles of wind velocity (left) and direction (right) derived from observed and de-aliased radial wind velocities for Vantaa radar on 4 December 1999 at 1200 UTC. The grey-shaded area indicates the one-σ-deviation of the de-aliased velocity observations from the VVP solution. Additionally, wind profiles from a six hour HIRLAM forecast for the closest grid point to Vantaa and a radiosonde sounding for Tallinn are shown.

Figure 10.7 shows vertical profiles of wind velocity and direction derived from observed and de-aliased radial wind velocities for Vantaa radar on 4 December 1999 at 1200 UTC. Aliasing effects are clearly visible up to 2500 m AGL. This is due to the fact that for the lowest four elevation angles (0.4°, 1.3°, 2.3°, and 3.3°) the Nyquist velocity is only 7.55 m s^{-1}. The grey-shaded area indicates the one-σ-deviation of the de-aliased velocity observations from the VVP solution. Its narrow shape confirms that the unfolding method is quite stable in this case study.

Unfortunately, there is no radiosonde sounding available for the radar location in Vantaa. Instead, the radiosonde observation for Tallinn (59.38°N, 24.58°E), Estonia, is shown in Fig. 10.7 (approximately 100 km distance from Vantaa). Although the vertical resolution is much lower than for the radar measurements, structures in the wind speed and direction profiles are similar. The High Resolution Limited Area Model (HIRLAM; Undén et al. 2002) forecast (22 km grid point spacing, no assimilation of radar winds in 1999) reveals the same trend as the de-aliased wind profiles, however not as detailed.

b) Super-observations

A super-observation (SO) is an intelligently generalized observation created through horizontal smoothing in polar space based on high resolution data. It includes also a number of derived variables which collectively serve to describe the characteristics of a given observation (Michelson 2003). A method for generating of radial wind SOs is implemented at SMHI.

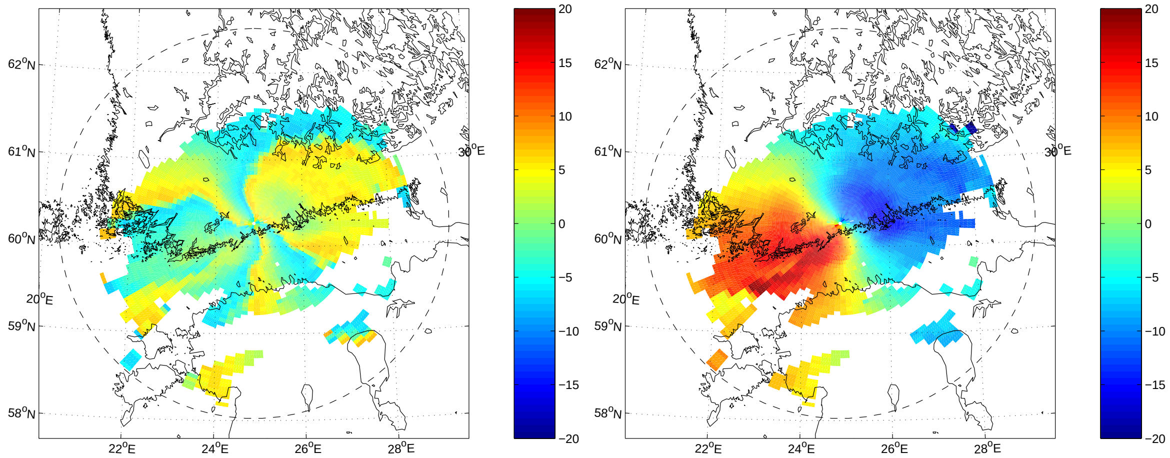

Figure 10.8: SO of observed (left) and de-aliased Doppler winds (right) in m s^{-1} for Vantaa radar on 4 December 1999 at 1200 UTC (0.4° elevation angle). Negative values refer to radial winds towards the radar. The dashed line indicates the 250 km range ring.

Figure 10.8 illustrates how radial wind SOs benefit from the new de-aliasing technique. The generalized treatment of the original high resolution polar data can be clearly discerned, as can the preservation of the polar nature of the derived SO product (4° azimuthal and 5 km radial resolution). In the output bins with only few high resolution input bins, the SO generator has the effect of filling in gaps which leads to more complete and smoothed results.

10.3. Applications

10.3.1 Use of radar data in hydrological modeling

Currently, weather radar data is not used operationally in large scale hydrological forecasting systems in Europe, although research work on this topic has been quite active for some years. A comprehensive COST 717 report about using radar data in hydrological modeling is forthcoming.

In Finland weather radar data has been used in hydrological applications pre-operationally e.g. for the Kyrönjoki basin (4000 km^2) since 1998 (Vehviläinen et al. 2002). For this catchment only three rain gauges are available in real-time. Additionally, areal precipitation is estimated by the radar in Ikaalinen outside the catchment. The main results and experiences using radar data in the hydrological forecasting system can be summarized as follows (Vehviläinen et al. 2004):

- Average correction terms for radar precipitation can been estimated through the water balance simulation of the hydrological model.
- During summer, practically no differences were observed in the hydrological forecasts made by the two model versions; one using radar and one using rain gauge estimates as input.
- Weather radar gives more accurate or realistic rainfall distribution estimates, but so far this improvement has not increased the accuracy of discharge and water level forecasts.
- In summer, rain gauge measurements can be replaced by radar precipitation measurements without deteriorating forecast accuracy.
- In winter, snow accumulation simulation using only radar data is not possible.
- The simulation time-step in the hydrological model is currently one day which is too long to get full benefit from radar precipitation data.
- Soil moisture error, common after dry rainless period, affects strongly to flood forecast accuracy.

Note that the hydrological model has been calibrated with rain gauge data and the radar data are more or less uncorrected. However, it is clearly visible that even raw radar data can improve hydrological forecasts.

Currently, two research projects within the 5th Framework Programme of the European Union are addressing the use of radar data to improve hydrological forecasts: CARPE DIEM (Critical Assessment of Available Radar Precipitation Estimation Techniques and Development of Innovative Approaches for Environmental Management; Alberoni et al. 2002) and ELDAS (Development of a European Land Data Assimilation System to predict Floods and Droughts; http://www.knmi.nl/samenw/eldas).

In the CARPE DIEM project, areal precipitation estimates from radar, rain gauges, NWP model simulations, and different versions of a mesoscale analysis system have been compared (Olsson et al. 2004). Radar data has been adjusted by the gauge adjustment procedure presented in this chapter. For the comparison study, data from 2002 for the Gimån catchment (4300 km^2) in Central Sweden has been used. For most of the period the radar data agreed well with data from the gauge-derived sources, but during a few months the radar produced unrealistically high values over a part of the catchment, possibly owing to temporal malfunctioning. In a second phase the different areal precipitation estimates were used to drive the hydrological HBV model (Bergström 1976), set up for the catchment. The resulting runoff was compared with the observed, both for the entire catchment and for a smaller sub-catchment. Generally, the accuracy of the radar-generated runoff was similar to the gauge-generated (Fig. 10.9). The inhomogeneities found in the radar-estimated areal precipitation did not significantly deteriorate the generated runoff as they occurred in a period with low-flow conditions and affected only a remote part of the catchment.

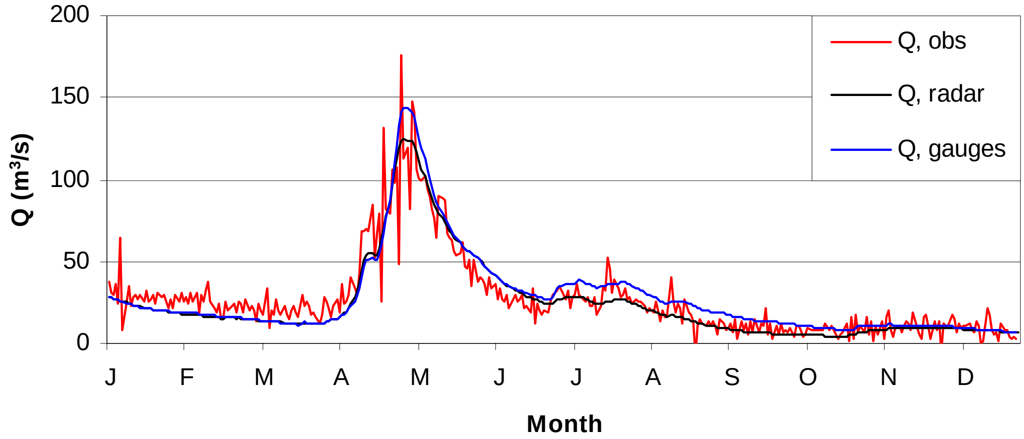

Figure 10.9: Runoff from catchment Gimån during 2002: observed and simulated using precipitation estimated from rain gauges and radar, respectively (from Olsson et al. 2004).

The focus of the ELDAS project is to develop a general data assimilation infrastructure for estimating soil moisture fields on the regional (continental) scale, and to assess the added value of these fields for the prediction of the land surface hydrology in models used for NWP and climate studies. SMHI contributes with an investigation of the potential use of radar-derived precipitation for improving real-time hydrological forecasting in critical flooding situations. The objective is to assess whether the high temporal and spatial resolution of radar data would have improved the forecasting and possibly affected decisions during rescue operations.

10.3.2 Use of radar data in NWP models

Data assimilation in NWP optimally blends observations with an atmospheric model in order to obtain the spatial distribution of atmospheric variables and to produce the best possible model initial state. The number of observations is generally small compared to the number of degrees of freedom in the initial state of the forecast model. This problem is overcome by introducing some a priori information. This a priori information is usually a short-range forecast, supplemented with statistical information about its errors, in addition to statistical information about the observation errors.

Because of improved assimilation techniques, increased model resolutions, and more developed infrastructure for data communication, the interest of Doppler weather radar wind data assimilation has increased. Moreover, wind is also a primary prognostic variable of NWP models (Macpherson et al. 2003). The radial wind data can in principle be utilized directly to obtain detailed initial model states. However, for mesoscale models, the practice is to apply different processing methods before passing the data to atmospheric models.

The VAD technique can be used as one such processing method; like the VVP algorithm it provides vertical profiles of horizontal winds from the Doppler radar radial wind data (Section 2.4.1). Another form of processing is to generate Doppler radar radial wind SOs through methods based on spatial averaging (Section 2.4.1). The observation handling system of the HIRLAM three-dimensional variational data assimilation (3DVAR) is designed to handle a variety of different data types and computer architectures and to manage data volumes associated with a limited-area data assimilation system. It has been complemented to handle also radar wind data, either in the form of SO or VAD (Lindskog et al. 2004).

A 10-day HIRLAM assimilation and forecast experiment, extending from 1 to 10 December 1999, has been performed over an area covering northern Europe and the northern Atlantic. Synoptically, the period is characterized by deep cyclones passing over the Baltic Sea. The three parallel data assimilation experiments are configured as follows:

- Only conventional observations are used (referred to as "control assimilation")
- Conventional observations and VAD profiles based on data from the SMHI radar network are used ("VAD assimilation")
- Conventional observations and SOs based on data from the SMHI radar network are used ("SO assimilation")

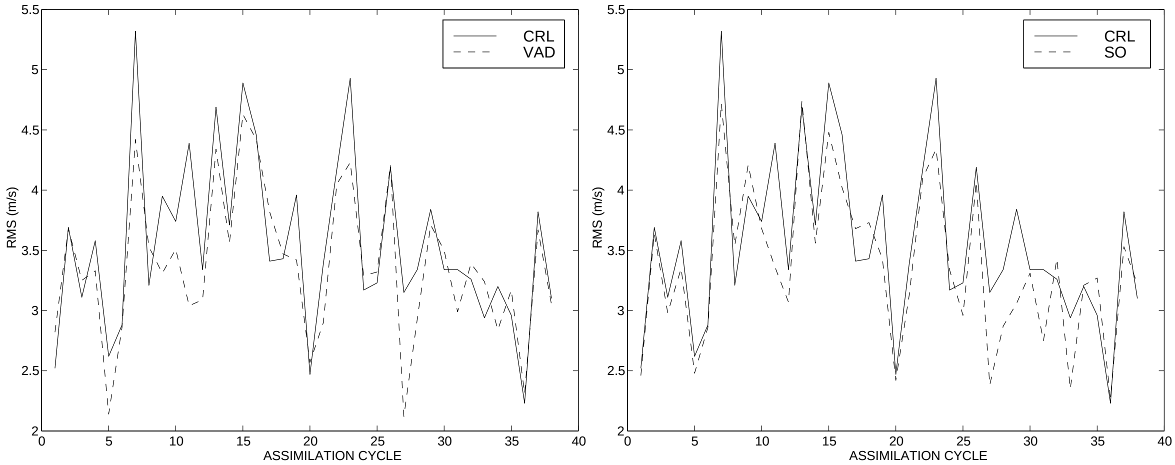

Figure 10.10: Day-to-day variability of the rms scores of the 24-h wind speed forecasts at the 850-hPa level for the control run (CRL), the VAD run (left), and the SO run (right) (from Lindskog et al. 2004).

There is a large day-to-day variability of the bias and the rms scores with the configurations described above. Figure 10.10 shows the rms values of the 24-h wind forecasts at the 850-hPa level, in comparison to the verifying observations for the 10-day period. It is evident that for almost all 24-h forecasts during the period, the scores of the VAD and SO runs are better than the scores of the control run. This is encouraging for the potential benefits in exchanging VAD profiles within Europe for assimilation into the current generation of regional models, with resolutions of 10-20 km (Macpherson et al. 2003).

An important goal of the proposed de-aliasing algorithm (Section 2.4.1) is to improve the quality of Doppler radar wind profiles and SOs used for data assimilation. In order to evaluate the performance of the new technique on a more statistical basis, we are currently preparing a de-aliasing experiment for a representative summer and winter period including all Finnish radars. The unfolded polar volume radar data will be applied to the HIRLAM 3DVAR through the generation of wind profiles and SOs. Their use is expected to improve substantially with the introduction of the proposed de-aliasing method.

10.3.3 Use of radar data for validation

a) NWP validation

Within the NWP community, gauge-adjusted BALTRAD products have been used in validation exercises using several model systems. For example, comparisons between BALTRAD and HIRLAM precipitation estimates have showed high degrees of correspondence both in terms of amounts and spatial distributions (Fortelius et al. 2002, Fortelius 2005 this report).

b) Satellite validation

BALTRAD composites have been comprehensively used in the development of the precipitation analysis algorithm within the framework of the EUMETSAT Satellite Application Facility (SAF) to support Nowcasting and Very Short Range Forecasting.

The Tropical Rainfall Measurement Mission (TRMM) has been quite successful (e.g. Gabella et al. 2004). TRMM covers latitudes reaching the middle part of the Mediterranean in the north. The future NASA/JAXA satellite mission (Global Precipitation Measurement, GPM) together with the European (still tentative) ESA mission (European contribution to the GPM mission, EGPM) will reach latitudes up to 65-68ºN. The onboard equipment of the GPM/EGPM satellite constellation includes e.g. active K-band radars and passive microwave radiometers. The sensitivity of the planned radars has been improved compared to TRMM so that they can measure weak rainfall and even major part of accumulated snowfall (not necessarily occurrence of very weak snowfall). Optimal ground validation data for GPM measurements of nimbostratus-type rain and snowfall will be provided by the BALTRAD products as they cover a wide northern area of land and sea in a climate where snowfall is a frequent phenomenon. It should be noted that at the time of the GPM launches the BALTRAD data archive will be extraordinary large, which will facilitate derivation of climatological representative horizontal and vertical structures of precipitating weather systems, especially those of snowfall.

Bennartz and Michelson (2003) described the evaluation of a combined radar and passive microwave dataset obtained during the BALTEX Pilot Study for Intensive Data Collection and Analysis of Precipitation (PIDCAP), where three-dimensional volumes of data from the Gotland radar were obtained timed according to the overpasses of the DMSP-satellites F10 and F13. Both satellites are equipped with a Special Sensor Microwave/Imager (SSM/I), suitable for precipitation retrievals.

They compared radar precipitation estimates, convolved to the native resolution of the SSM/I, at different altitudes with polarization and scattering indices (S_{85}) derived from the SSM/I. For all 22 overpasses investigated here radar precipitation estimates at 3 to 4 km altitude are well correlated with the SSM/I-derived S_{85} (average correlation coefficient = 0.70). Although more directly linked to surface precipitation, polarization indices have been found to be less correlated with radar data, due to limitations inherent in the remote sensing of precipitation at higher latitudes.

A stratification of the dataset into frontal and convective events revealed significant variations in these relationships for different types of precipitation events, thus reflecting different cloud microphysical processes associated with precipitation initialization. The relation between S_{85} and radar rain estimates at higher altitudes varies considerably for different convective and frontal events. The sensitivity of S_{85} to radar-derived rain rate ranges from 3.1 K mm^{-1} h^{-1} for a strong convective event to about 25 K mm^{-1} h^{-1} for the frontal and about 70 K mm^{-1} h^{-1} for the small-scale convective events. For extrapolated surface precipitation estimates, sensitivities decrease to 14 K mm^{-1} h^{-1} and 25 K mm^{-1} h^{-1} for frontal and small-scale convective precipitation, respectively.

10.4. Summary and perspective

This chapter has summarized the major radar developments within BALTEX during Phase I (1993-2002). All activities aim to optimize the BALTRAD radar network and its products. However, a poor radar site will have a devastating affect on data quality in general and on the ability to perform activities such as those outlined in this chapter. Common to all radar sites is the necessity of avoiding obstacles proximate to the radar, such as buildings, towers, trees, and higher terrain, since these will cause partial or total beam blockage, thus corrupting entire sectors of radar coverage. Paradoxically, data from a radar with a completely free horizon may also be contaminated by echoes generated from side-lobes. An ideal site would place the radar antenna slightly higher than surrounding vegetation which serves to absorb side-lobe radiation (Gekat et al. 2003). Poor siting has been experienced with several Swedish radars and has resulted in decisions to move the radar previously located in Gothenburg to a new site called Vara (2002), and the radar in Norrköping to a new site called Vilebo (2003). The radar in Luleå has been moved in spring 2005.

Currently, radar data quality issues are much discussed within the NORDRAD and COST 717 communities (e.g. Saltikoff et al. 2004, Michelson et al. 2004, and Alberoni et al. 2003). Detailed information can be found on the respective websites http://nordrad.fmi.fi/methods and http://www.smhi.se/cost717. BALTEX will definitely benefit from these discussions. A milestone in the convergence of BALTEX and NORDRAD was the first joint workshop in Norrköping (2003). The scope was to identify commonly prioritized quality control and product generation methodologies and organize their introduction to the NORDRAD/BALTRAD network. During the workshop a list of challenges was composed, and each challenge classified with star rating, and estimates of magnitude and frequency in Northern Europe. The following joint workshop in Gudhjem on the island of Bornholm (2004) was devoted to the distribution of work packages among NORDRAD/BALTRAD member countries. Two data quality projects have been prioritized: (i) VPR correction and (ii) beam propagation. Both have been started at the beginning of 2005.

Finally, the science plan for BALTEX Phase II (Graßl et al. 2004) provides excellent opportunities for using radar data in atmospheric and hydrological models. Especially real-time flood forecasting is highly prioritized.

10.5. Acknowledgements

The authors gratefully acknowledge Bertel Vehviläinen, Jonas Olsson, and Magnus Lindskog for their input regarding the use of radar data in hydrological and NWP models.

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Chapter 11:

Ground-Based GPS for Remote Sensing of Water Vapour

by

Gunnar Elgered

11.1. Motivation

Water vapour is an important green-house gas. Accurate measurements of water vapour in the atmosphere are in general difficult and costly to carry out with high temporal and spatial resolution over long time. The ability of the Global Positioning System (GPS) to provide estimates of the atmospheric water vapour content above receivers on the ground is therefore a promising application. The ground-based GPS receiver networks provide measurements of differences in time of arrival. Since time is a physical parameter which we can measure with high accuracy, also over long time periods, it is a promising method for providing an observational system for climate monitoring. As continuously operating GPS receivers are increasing in numbers the spatial resolution will continue to improve. Many countries in the BALTEX area today have networks with typical baseline lengths from 100 to 200 km.

Here we will first in Section 2 discuss the scientific background for the application of ground-based GPS for water vapour measurements. The focus will be on the factors limiting the accuracy. Thereafter, we mention some of the accomplishments relevant for climate research in Section 3. In Section 4 some suggestions for investigations over the next years are summarized.

11.2. Scientific background

In the seventies it was recognized that variations in the atmosphere have an impact on the performance of space geodetic techniques. At that time Very-Long-Baseline Interferometry (VLBI) was the method which offered a potential positioning accuracy of the order of centimetres meaning that the varying signal delay caused by water vapour could be the major error source (Shapiro1976). When the Global Positioning System (GPS) was established the geodetic application was immediately recognized (Counselman and Shapiro 1979). Since the contribution of water vapour to the refractive index is independent of frequency the influence on the signal delay is identical in the geodetic applications of VLBI and GPS. Therefore water vapour in the atmosphere was identified as an important error source — at least for the most accurate technique using observations of the carrier phase of the GPS signal — and several impact studies were carried out (Blewitt 1993).

The normal situation in geodetic surveying is that no independent information is available on the water vapour content, and its variability, and the atmospheric influence must be estimated from the GPS data themselves. By spreading the observations over a large range of elevation angles the correlation between the estimates of the clock drifts and the atmospheric variations is reduced and both of these effects can be estimated with sufficient accuracy. Since the atmospheric water vapour content is difficult to measure with high temporal and spatial resolution this opened up for a new application — the use of these estimates of the atmospheric influence on the signal in the area of meteorology.

The atmospheric parameter normally estimated from the GPS data is the equivalent Zenith Total Delay (ZTD). The estimated ZTD is an average parameter, referred to the zenith direction, inferred from the integrated refractive index along all the propagation paths from the observed GPS satellites to the receivers on the ground. Most of the variability in the ZTD is caused by the water vapour. This "wet" part of the propagation delay is often referred to as the Zenith Wet Delay (ZWD) and can be calculated from the ZTD by removing a component which can be estimated with high accuracy from the total ground pressure. An uncertainty of 1 hPa in the pressure corresponds to an uncertainty of 2 mm in the ZWD. The estimated ZWD has an additional uncertainty of approximately 1% from the equation used for the refractive index (Boudouris 1963; Rueger 1999). If we want to derive the water vapour content (rather than the ZWD) an additional conversion must be made. The size of the uncertainty introduced here depends on how well the physical temperature of the water vapour is known. Using ground observations of temperature together with simple models typically give an extra uncertainty of just above 1% (Emardson and Derks 199. Most often it is the uncertainty in the ZTD from the GPS data analysis that will dominate over these mentioned conversion errors.

The accuracy of the ZTD estimates depends on many other parameters. Most important are the uncertainties in the orbit parameters of the satellites, the geophysical models used for the receiver coordinates, and the minimum elevation angle used for the observations.

The uncertainties in the satellite orbits are reduced by using a large tracking network. The International GPS Service for Geodynamics (Beutler et al. 1996; Beutler et al. 1999) provides different products of different quality, where the most accurate orbit parameters are available many days after the time of the data acquisition. The ZTD errors caused by orbit uncertainties are correlated both temporally and spatially meaning that observed rapid changes and differences between nearby GPS sites have a high common mode rejection of orbit induced errors. Uncertainties in the orbit parameters are the main difficulty encountered in the application for using the ZTD in weather forecasting where the requirement of data availability in near real time often means within 1–2 hours from data acquisition. The ZTD obtained from post processing, using the most accurate orbit parameters, is the obvious choice for all applications which do not require results in near real time. For example, when the ZTD is used as an independent source of information for validation of climate models and climate monitoring.

In continuously operating GPS networks the site coordinates are often well known and by fixing coordinates to these values the formal uncertainties of the ZTD is improved. Models for short term variations such as earth tides, ocean and atmospheric loading effects need to be included (see e.g. Dach and Dietrich 2000). This is also true when site coordinates are estimated if the update period is 24 hours or longer.

The value of the elevation angle cut off angle is not an error source in itself but can introduce systematic biases due to multipath effects, a changing phase pattern of the antenna, and a different satellite constellation. All these effects can change with the elevation angle. If this is not correctly modeled the residuals will be interpreted as atmospheric signals through the mapping function used in the ZTD estimation process (Niell 1996).

Let us conclude this background discussion by noting that the absolute accuracy of ZTDs estimated from ground-based GPS networks is poor although comparable to other existing instruments and techniques, such as microwave radiometry, radiosondes, et cetera. The major part of this unknown bias type of error should, however, be possible to keep constant over time scales of many years. The strength of the method is the possibility to observe continuously with a good temporal resolution.

The horizontal resolution is simply determined by the distance between the GPS sites in the network.

11.3. Major developments in relation to the objectives in the science and implementation plans

11.3.1 Monitoring Long Term Variations

One application of the ground-based GPS networks is long term monitoring of the ZTD and the Integrated Precipitable Water Vapour (IPWV). A study focusing on the possibilities to detect climate change from IPWV measurements was presented by Yuan et al. (1993). A more recent investigation was made by Vedel and Stendel (2004) where they study how to use both ground-based and space-based GPS data for climate monitoring. They also point out the advantage of using the raw GPS data (ZTD) rather than the derived IPWV. Up to now the available time series of GPS data are, however, too short to provide climate monitoring results. Instead the focus of the research has been on the assessment of the usefulness of GPS technique for this application.

Our contributions to the BALTEX project have mainly been within the framework of the two EC supported projects NEWBALTIC and NEWBALTIC 2 in the late nineties. Especially data from the PIDCAP experiment were used for comparisons of GPS results from Sweden and Finland with those from other independent data sources such as radiosondes, microwave radiometry, and Numerical Weather Prediction (NWP) models (Emardson et al. 1998; Yang et al. 1999). Thereafter, we have used nine years of data from the Swedish GPS network to assess the stability of estimated linear trends in the IPWV (Gradinarsky 2002). The Onsala Space Observatory, on the Swedish west coast, is a special site in these studies. Here we also have access to microwave radiometer data and nearby radiosonde launches from the same time period. Figure 11.1 shows a comparison of these time series where we also see a good agreement in the estimated trends. The over all results are shown in Figure 11.2. The estimated trends are here very small. In fact the largest trend, of the order of 0.2 mm/yr is seen at the Onsala site.

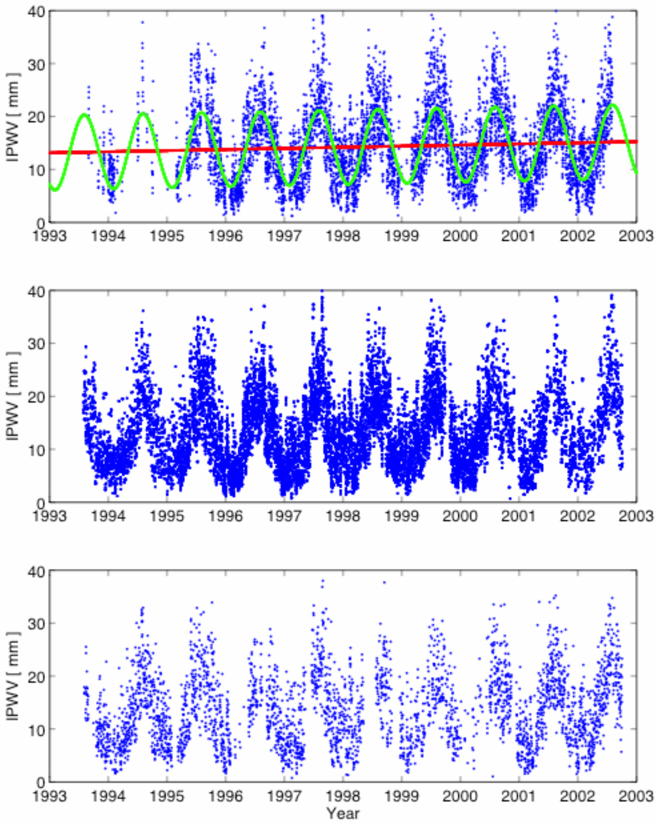


Figure 11.1. Time series of the water vapour content measured by GPS (top), microwave radiometry (middle) at the Onsala site, and radiosondes (bottom) at the Gothenburg-Landvetter Airport (37 km distance from Onsala). When estimating the linear trends we obtain 0.21±0.02 mm/yr (GPS), 0.20±0.02 mm/yr (microwave radiometry), and 0.22±0.02 mm/yr (radiosondes) (Gradinarsky 2002).

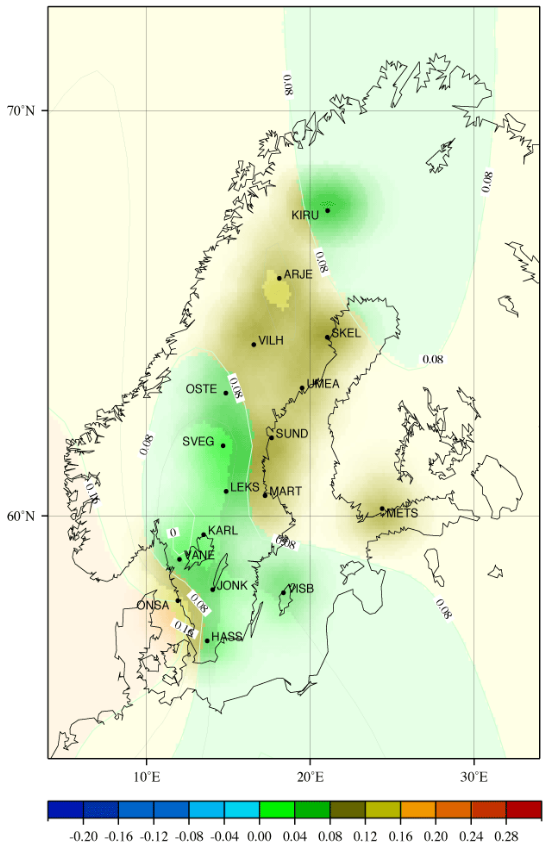
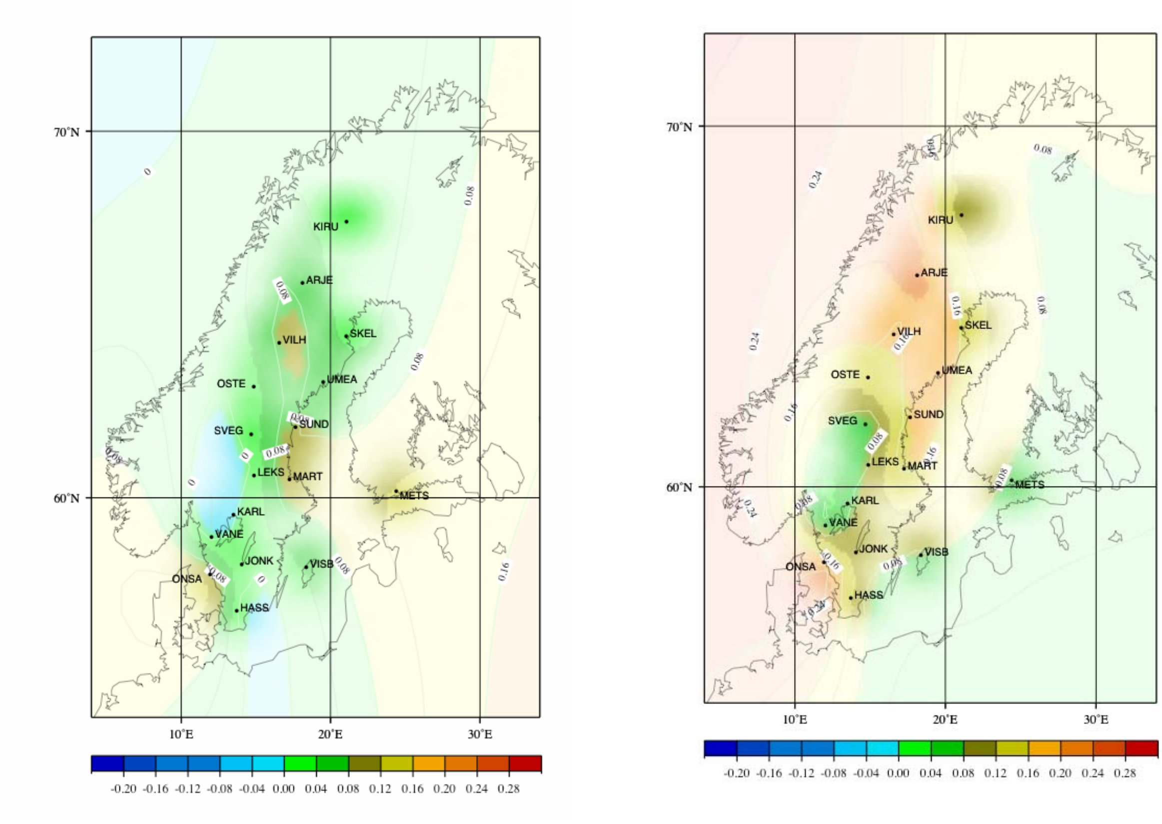


Figure 11.2. Estimated linear trends in the water vapour content for the time period August 1993–August 2002. The scale is in mm/yr (Gradinarsky 2002).

Geographical patterns are evident when for example different seasons are studied independently (see Figures 11.3a and 11.3b). Furthermore, the patterns change when 1 or 2 years of data are ignored in the nine year long time series. Such results are of course related to the interannual variability and the systematic behaviour of weather patterns over time scales of years and these results confirm the well known fact that it is necessary to study long periods in order to make statements about the climate in a specific region. Often averages over 30 years are used in climate studies and the history of continuously operating GPS networks is now of the order of ten years. However, as the time series grow longer, we expect the GPS data to be able to provide independent information with a good spatial resolution.



A **B**

Figure 11.3. Estimated linear trends in the water vapour content for the time period August 1993–July 2003 for (A) the winter data, and (B) summer data. The scale is in mm/yr (personal communication Gradinarsky 2003).

11.3.2 The diurnal cycle in the atmospheric water vapour content

The diurnal cycle in the IPWV is driven by the solar radiation. Therefore, we expect a dependence on the time of year and the site's latitude. Dai et al. (2002) studied data from 54 GPS sites in North America (typical latitudes were 25–45°N) and found amplitudes in the range 1.0–1.8 mm IPWV for the summer period.

We used GPS data from 26 sites in the north of Europe to estimate the diurnal cycle. The latitude range was 55–70°N. Typical amplitudes of the diurnal cycle were here from 0.1 to 0.6 mm for the three summer months June, July, and August and the time period 1995–2000 (Bouma 2002). These results also show a good agreement with the climate model (version 2) of the Rossby Centre of the Swedish Meteorological and Hydrological Institute (see Figure 11.4). For the other parts of the year the diurnal cycle is too small to be detected given the much larger variations in IPWV introduced by the moving weather systems. These results are consistent with the work carried out analyzing data from the German GPS network, consisting of more than 200 sites in 2002 (Gendt et al. 2004). Here slightly larger diurnal amplitudes are found due to the lower latitudes of the sites. A clear seasonal dependence is also seen in this data set.

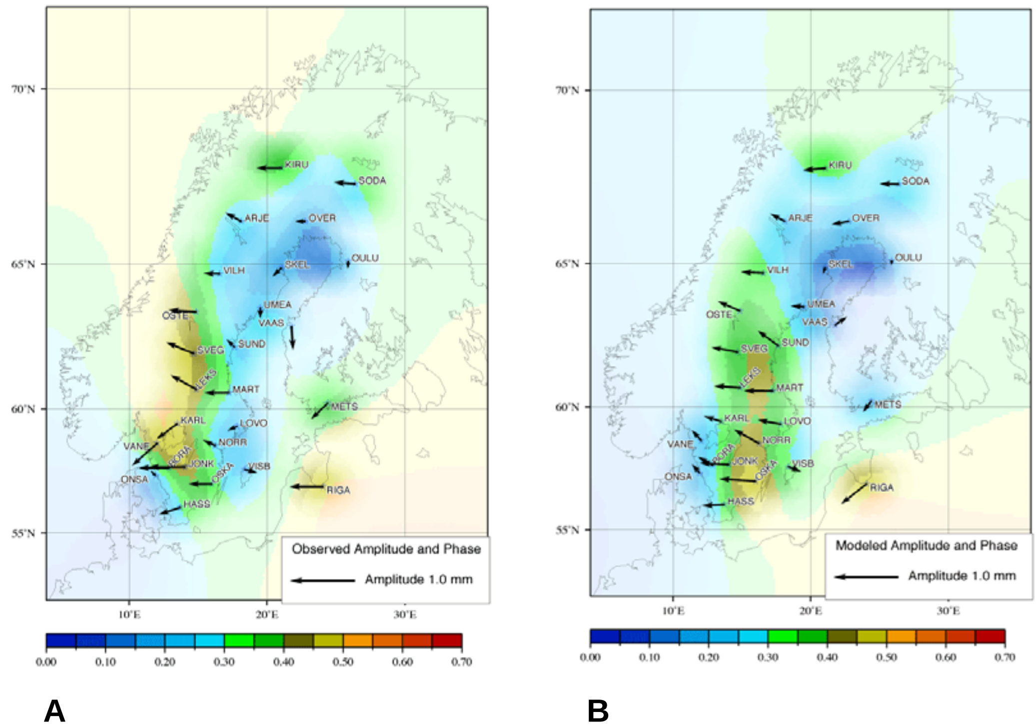


Figure 11.4. Estimated amplitude and phase of the diurnal component in the IPWV for five consecutive summers from (a) GPS data (b) a climate model (Bouma (2002). The amplitude is presented both with the background colour and the length of the vectors. The phase is illustrated by the vector direction in a clock-wise sense and up means 0 hours UT. The true solar time is approximately 1 hr ahead of the UT for the sites shown.

11.4. Summary and Perspective

The relevant goal in the science plan for BALTEX phase 2 is ”To obtain better and more comprehensive observations from the entire Baltic Sea basin, including new satellite data” (BALTEX, 2004).

The continuously operating GPS networks continue to improve both in terms of reliability and the number of sites. An example of the present situation and the future plans for Sweden is summarized in Figure 11.5. In terms of improving the quality of the existing data set, with the addition of new data and new sites, we propose that the best approach is to reprocess the entire ground-based GPS data set and at the same time implement and assess new improved models for correction of some of the effects mentioned above.

The more important issues are:

- Possibilities to correct for second order propagation effects caused by the free electrons in the ionosphere.
- Studies of adding information on the geopotential height (taken from global analyzed fields, e.g. by ECMWF) to the mapping functions used to describe the elevation dependence of the propagation delay.
- Improve the knowledge of, and models for, GPS antenna phase centre variation and their dependence on the local electromagnetic environment.

Plans for this work exist and proposals for funding are pending. In the more distant future the addition of the European Galileo satellite constellation will imply a much better sampling of the atmosphere. This addition will approximately double the amount of satellites and will consequently also reduce the impact of orbit errors in an averaging sense. At the same time the Galileo system will introduce systematic changes to the relative distribution of satellites on the sky. Therefore, it will be a challenge to combine IPWV data estimated using different combinations of Global Navigational Satellite Systems (GNSS). It is likely that raw GNSS data must be reprosessed for entire time periods using consistent models for e.g., antenna phase centres, ionospheric effects, and geophysical models for crustal loading effects.

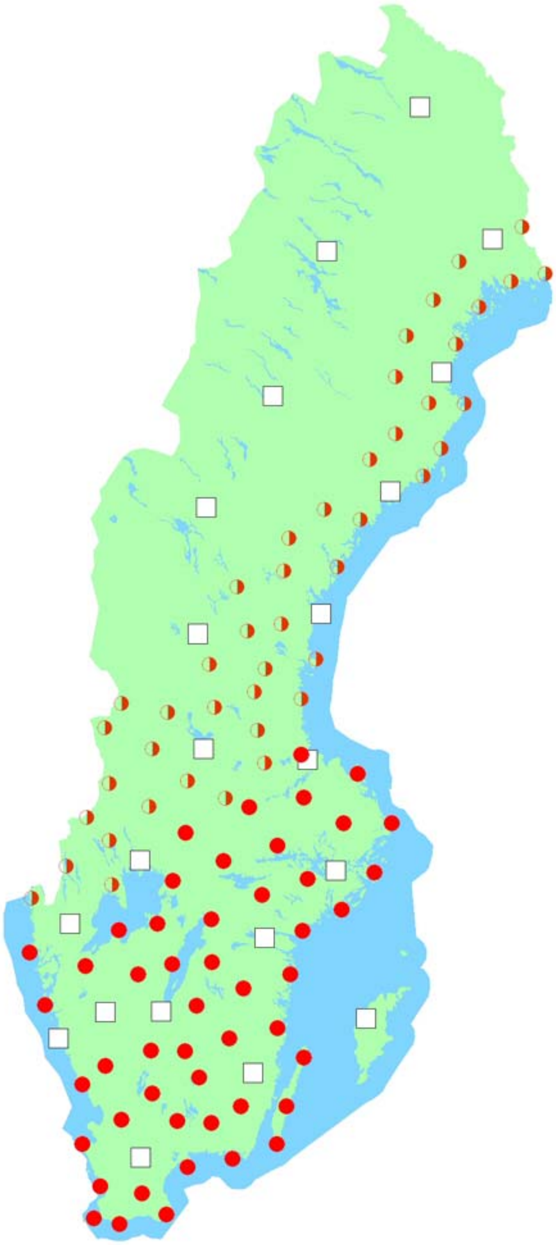


Figure 11.5. The status of the continuously operating GPS network in Sweden (SWEPOS). White squares denote the original 21 sites established in the early nineties. It is mainly data from these sites that have been used for meteorological research carried out so far in this area. The filled red circles denote operating stations for RTK (Real Time Kinematic) applications. They are typically mounted on buildings but will be useful also for meteorological applications. The partly filled red circles are new sites planned to be installed during the next few years (personal communication G. Hedling, National Land Survey of Sweden).

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Chapter 12:

Data assimilation and analysis

by

Carl Fortelius

12.1. Motivation

Numerical simulation of the atmosphere has a long history in weather prediction and climate research, and models may be as important as measurements, when it comes to forming our present understanding of the processes which drive the general circulation of the atmosphere and oceans, and ultimately control the climate (Browning and Gurney 1999).

Data assimilation refers here to the methods used for combining observations (data) and a numerical weather prediction (NWP) model to esitmate the state of the climate system. The main application of data assimilation is in providing initial conditions for NWP, but the products of a data assimialtion system are not limited to these initial conditions, but only by the complexity of the applied NWP model. Thus they typically include many processes and phenomena related to the climatic energy and water cycle, which are not generally well observed, such as diabatic heeting and cooling within the atmosphere, condensation and precipitation formation, evaporation, turbulent and radiative heat fluxes at the surface and in the atmosphere et c.

Outside everyday NWP, data assimilation may be seen as a way of constraining the state of a model to follow as closely as possible the observed evolution of the climate system. Such re analysis of historical data, employing global assimilation systems and spanning many decades has been undertaken by several research centres, such as the National Centers for Environmental Prediction (NCEP) and The National Center for Atmospheric Research, (NCAR) in the United States (Kalnay et al. 1996) and by the European Centre for Medium-Range Weather Forecasts (ECMWF, Gibson et al. 1999, Simmons and Gibson 2000).

These global data sets have too coarse spatial resolution for resolving topographic features on scales of tens of kilometers, such as many river catchments, large lakes or even the bays of the Baltic Sea. As a complement to the global systems, regional high resolution data assimilation for climate studies is therefore undertaken at NCEP for North America (Mesinger et al., 2003), and by the European HIRLAM-community for the BALTEX-area (Fortelius et al., 2002). These projects use data assimilation systems based on Limited Area Models (LAMs). A LAM is an atmospheric model applied to only a part of the globe. Unlike a global model, a LAM requires externally specified boundary conditions at the lateral boundaries of its domain. These latter typically consist of predicted or analyzed data from a global system or from another LAM. LAMs are used extensively in short range weather prediction and for dynamical down-scaling of global climate simulations.

12.2. Principles of data assimilation

Numerical weather prediction is an initial value problem, and data assimilation is the process whereby the initial conditions (known as an analysis) are determined. Zupanski and Kalnay (1999) offer a concise and accessible treatment of the subject, and only an outline is given below. Since NWP models are designed to simulate the climate system, or at least parts of it, the initial conditions should represent well the true state of the same system. NWP models in use today may be highly sensitive to subtle details of the initial state. For example, initial conditions which are inconsistent with the quasi-geostrophic balance of the atmosphere will give rize to inertia-gravity waves of unrealistically high amplitude in the forecast. Thus some kind of balancing of the initial state has to be included in the process.

It is clear that the initial state should be based on observatoins and fit them well. But in practice not nearly enough observations are available to initialize all scales of motion and phenomena simulated by a state-of-the-art NWP-model, as the number of observations available at a given time is typically two orders of magnitude less than the degrees of freedom of the model. The missing information must be provided by a background field, representing the best possible estimate in absence of any observations. In everyday weather forecasting, data assimilation is carried out periodically, and a short range forecast initiated from the previous analysis is used as background field. This is an optimal way of allowing past observations to influence the analysis through the forecast model. In particular, data gaps are partially filled by information carried from more favoured regions by the atmospheric flow. An unavoidable consequence of using a short range forecast (model state) for background is, that the analysis becomes srongly influenced by the forecast model, and poorly observed phenomena or scales of motion are essentially determined by the model alone.

Widely-used assimilation methods are Optimal Interpolation (OI) and 3-dimensional variational assimilation (3DVAR) . Both methods seek to minimize a cost function of the form:

$$J=\frac{1}{2}\left(H(x)-y\right)^T R^{-1}\left(H(x)-y\right)+\frac{1}{2}\left(x-x^b\right)^T B^{-1}\left(x-x^b\right)\,, \tag{1}$$

where **y** denotes a vector of all observations, **x** is the model state vector to be found, and $\mathbf{x^b}$ is the bacground. *H* is the transformation from the regular model space to the irregular observtional locations and to observed parameters. The superscript T denotes a transpose.The most interesting part of 1 are the error covariance matrixes for the observations **R,** and background **B.** These matrixes determine how much weight is put on the observations and how much on the background, but also serve the vitally important purpose of distributing information in space and between variables.

The OI method is based on finding an explicit solution to the linearized optimization problem (3.1), whereas 3DVAR seeks an iterative solution to the full problem. The latter approach is rapidly replacing OI in operational weather forecasting because of its many advantages. In particular, the possibility to use a nonlinear transformation *H*, allows the use of remotely sensed data without first solving the inverse problem of projecting the data onto the model variables

A common deficiency of OI and 3DVAR is the use of a fixed background error covariance matrix, neglecting the fact that the forecast eror characteristics depend on the weather and vary from day to day. More advanced methods like, 4DVAR or Kalman filtering, seek to improve things by solving the analysis problem over a finite period of time taher than just one instant, using the model to project the background state forward in time.

12.3. Findings from the BALTEX regional reanalysis project

The BALTEX regional reanalysis project (Fortelius et al., 2002) was carried out jointly by the Finnish (FMI) and Swedish (SMHI) national meteorological services as an ECMWF special project with the objective to carry out high resolution data assimilation around the Baltic drainage basin (Fig. 12.1) over one year (Sept. 1999-Oct. 2000) during the BALTEX main experiment BRIDGE (Bengtsson 1998), and thereby to promote the use of assimilation products in regional climate system research. A specific objective is to produce gridded fields of all components needed to close the energy and water cycles, with a spatial resolution of approximately 22 km and a temporal resolution of six hours. The computational domian is shown in Figure 12.1. More details are given on the project home page, which is linked to the BALTEX web site http://w3.gkss.de/baltex/.

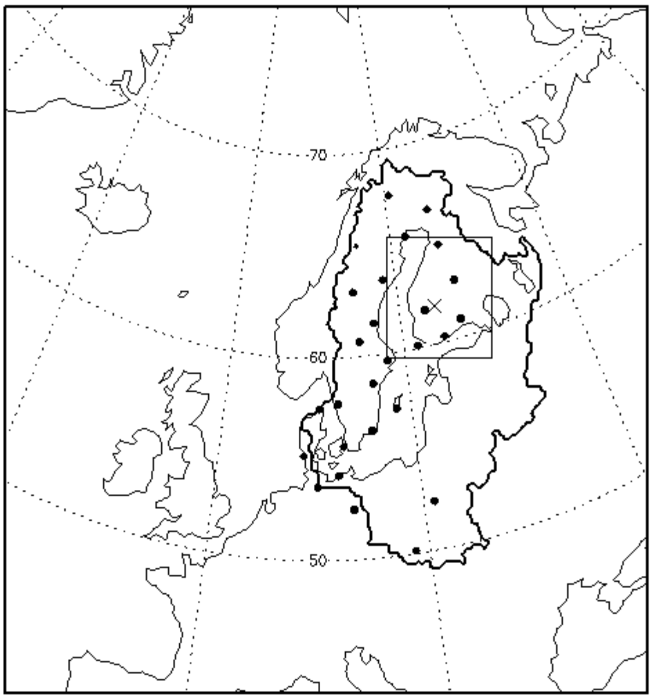

Figure 12.1. Domain of the BALTEX regional reanalyses. The black dots and the cross indicate the sites of weather radars and Hyytiälä field station, respectively.

12.3. 1 The assimilation system

The assimilation system used is a specially designed version of the HIRLAM numerical weather prediction system (Undén et al. 2000) maintained by the international HIRLAM consortium, consisting of the national meteorological services of Denmark, Finland, France, Iceland, Ireland, The Netherlands, Norway, Spain, and Sweden. The system consists of a forecast model and analyses modules for the atmosphere and the surface. Prognostic variables of the atmosphere-model are surface pressure, horizontal wind, temperature, specific humidity, specific cloud condensate, and the kinetic energy of small-scale turbulence. Physical processses explicitly treated in the atnosphere-model are radiative tranfer, small scale turbulence, convection, and condensation and cloud micro physics. The atmopshere is coupled on every time step to a soil/vegetation model via the ecxchange of momentum, heat and water between the atmosphere and the surface. The surface temperature and ice cover of lakes and seas are kept at their initial values during a forecst.

Boundary conditions at the lateral edges of the domain are specified using analyses from the ECMWF, updated every 3 hours, and interpolated linearly in time to every time step of the forecast model.

The analysis of atmospheric variables is performed using 3DVAR, employing six-hourly cycling. The observations consist of surface data from reporting weather stations, ships and drifting buoys, and upper air data from radio soundings and reporting aircraft. The analyzed atmospheric state is filtered with respect to gravity waves using a diabatic digital filter to get a balanced initial field for the prognostic model.

On land surfaces, only the snow-cover is analysed based on observations, while the temperature and moisture in the soil and vegetation are described by the soil-model. Analogously, the numerous inland lakes in Scandinavia are described with a separate lake model (Ljungemyr et al. 1996). The surface temperature (SST) and ice evolution in the Baltic Sea are described with a coupled ice-ocean model (Gustafsson et al. 1998), forced by the atmosphere-model via fluxes of heat and water vapour, and relaxed towards the observed SST-distribution. Elsewhere, analysed STT and ice distributions from the ECMWF are used.

12.3.2. Water balance of the Baltic drainage basin

Barring chemical reactions, the amount of water substance in any volume can change only by fluxes through the boundaries of the volume. For a column of air, these fluxes consist of precipitation (*P*), phase transitions at the surfcae (evaporation, dew formation et. c., *E*), and horizontal transports through the lateral boundaries. The net effect of these transports is given by the convergence of the vertically interated horizintal flux of water vapour and cloud condensate (*C*). In most cases the contribution from the cloud condensate is so small as to be entirely negligible. Symbolically we may write:

$$W = C + E - P, \tag{2}$$

where *W* stands for the rate of change of water substance within the atmospheric column.

For the soil, vegetation cover and snow pack, we may write the analogous equation

$$W' = C' + P - E, \tag{3}$$

where *W'* is again the rate of change of water substance in the system, and *C'* stand for the convergence of runoff and ground water movement.

All the terms in (2) are easily obtained from the BALTEX reanalysis data. Terms *E* and *P* are included in the model output as accumulated within each forecast. Term *W* is readily computed by taking the difference of appropriate model states. Term *C* is often evaluated using the state variables of surface pressure, wind and specific humidity, (e.g. Fortelius, 1995). This method is cumbersome and usually inaccurate, since many numerical approximations of derivatives and integrals are involved. A much simpler approach is to evaluate *C* as a residual term in (2). If this is done in such a way, that all the remaining terms in the equation refer to the same forecast, i.e. the change predicted by the model for a given period is compared to the accumulated precipitation and evaporation during the same period, then the residual is actually equivalent to the accumulated flux convergence as given by the forecast model during the same period.

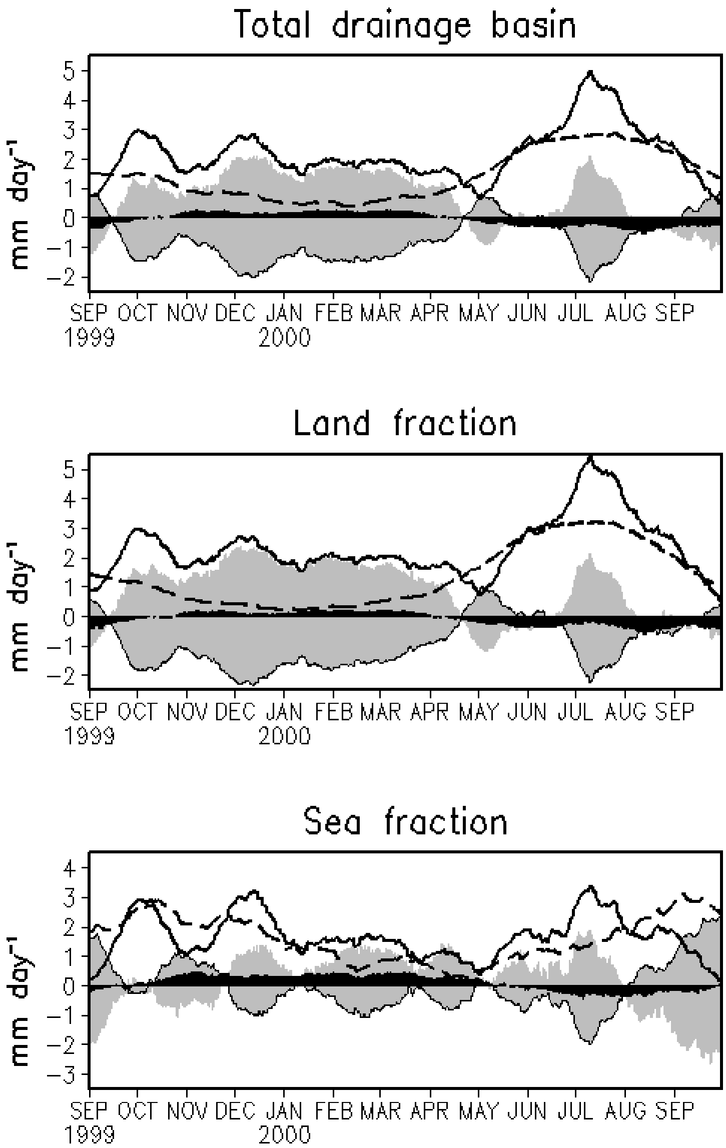

Figure 12.2. Terms in the atmospheric water budget over the drainage basin of the Baltic Sea. Graphs represent 30-day running means based on forecast hours 6-12 of four forecast cycles each day. Precipitation and evaporation are shown as heavy solid and dashed lines, respectively, and the difference between evaporation and precipitation is shown by the solid line at the edge of the grey shaded band. The unmarked edge of this band shows the net convergence of lateral water transport in the atmosphere. The black shaded band gives the bias of the predicted rate of change of the atmospheric water content relative to the analysed one.

Figure 12.2 illustrates the atmospheric water budget of the Baltic drainage basin from September 1999 through September 2000, as given by the BALTEX reanalysis system. The graphs present 30-day running means based on hours 6 – 12 of four forecast cycles each day. For the basin as a whole (top panel), precipitation (Heavy solid line) dominates over evaporation (dashed line) except for shorter periods during spring and autumn. The deficit (surplus), indicated by the line at the edge of the grey shading, is nearly balanced by convergent (divergent) flux of water vapour flux (the unmarked edge of the same grey shading) so that the rate of change (not shown) is usually small. Averaged throughout the year, the region is clearly one of net imported water vapour.

Comparing the predicted rate of change of the water content to the one that may be deduced from analyses valid at the corresponding times sheds some light on the reliability of these results. The
black shaded area shows the difference between these tendencies, which is seen to be small in magnitude compared with either *E-P* or *C*. Nevertheless, positive values, indicating excessive accumulation of water in the forecasts, prevail in winter, while the opposite is true in summer. The pattern is consistent with the systematic error of the surface pressure (not shown), reflecting the tendency of the model to spuriously accumulate mass in the region during winter and disperse mass during summer.

Conditions over the land fraction of the drainage basin (middle panel) are similar to those prevailing over the total basin. This is not surprising, as most of the area is covered by land. It is interesting to note, that even the land-part of the basin may serve as a net exporter of water vapour on a monthly time scale. This happens in September 1999 and in May 2000, and again in September 2000.

Over the Baltic Sea itself (Fig. 12.2, bottom panel), conditions look rather different from those over the continental parts. Precipitation and evaporation both follow a similar annual cycle, but the former is more variable on a monthly time scale. Hence sometimes one and sometimes the other dominates the scene, and periods of net import and export of water vapour follow each other at irregular intervals throughout the year without any obvious annual cycle.

12.3.3. Heat fluxes at the surface

The heat balance equation at the surface can be written:

$$R = L + H + G, \qquad (4)$$

where *R* stands for the net radiation with contributions from both solar and thermal fluxes, *L* and *H* are the turbulent fluxes of latent and sensible heat, respectively, and *G*, finally, the flux of heat into the ground or water.

Figure 12.3 illustrates the surface heat balance of the Baltic drainage basin from September 1999 through September 2000, as given by the BALTEX reanalysis system. The graphs present 30-day running means based on hours 6 – 12 of four forecast cycles each day. Looking first at the land fraction of the basin (middle panel), the net radiation *R*, shown by the heavy solid line, is clearly the most dynamical term in (4), and follows a well defined annual cycle, being strongly positive from March to October, and weakly negative from November to February. At all times *R* is nearly balanced by *L* (light solid line) and *H* (dashed line), the storage term *G* (shaded area) being clearly of minor importance on a monthly time scale. In winter the negative net radiation is balanced by a flux of sensible heat from the air to the ground, while the flux of latent heat still acts to cool the surface. While the direction of the latent heat flux is probably right, the magnitude is probably too large. In early spring the sensible heat flux is first in reacting to the increasing net radiation, and changes its sign in March. The latent heat flux starts increasing a bit later, but continues to grow until July, while the sensible heat flux peaks at a lower level already in May. The storage term peaks in April, when it is of comparable magnitude with *L* and *H*. The positive annual average of the storage terms shows that a net storage of heat in the soil takes place during the re-analysis period.

Conditions over the basin as a whole (Fig. 12.3 top panel) tend to follow those over land, but the storage term is clearly more important here. The situation over the Baltic Sea itself (Fig. 12.3, bottom panel) looks different. Heat storage here plays a major role in balancing the summertime positive net radiation and in maintaining the heat fluxes in winter despite the negative net radiation prevailing then. The fluxes of sensible and latent heat correlate more closely than over land, and the latter is generally the dominating one.

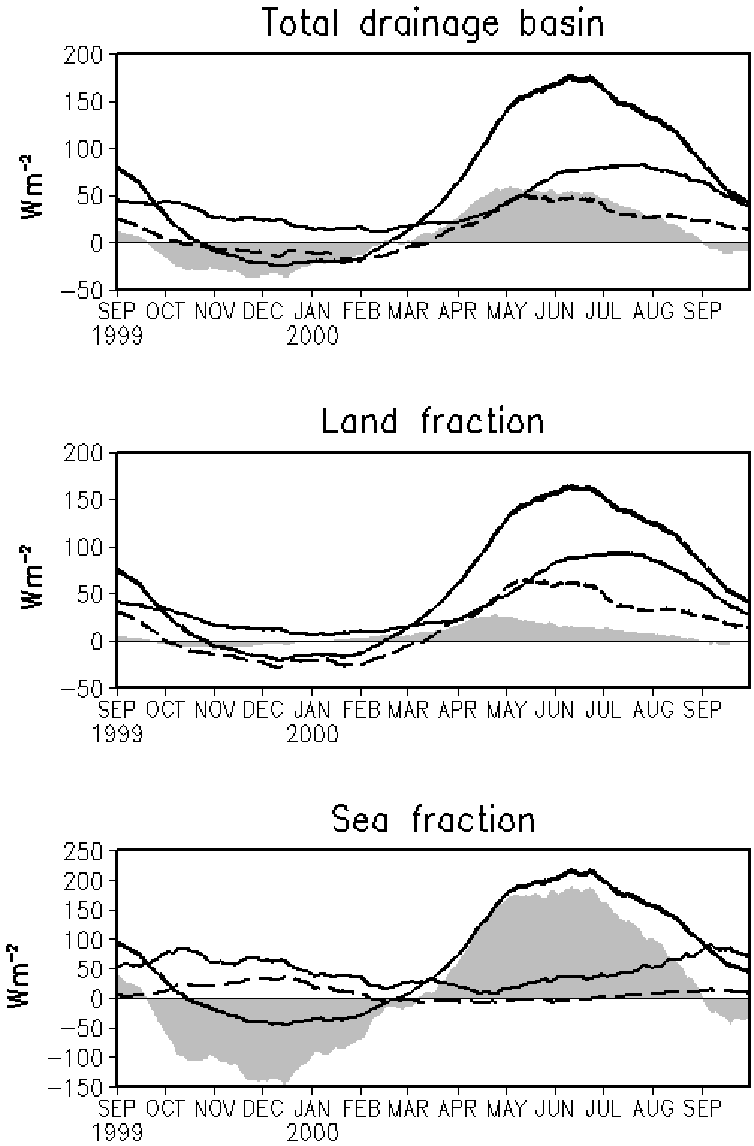

Figure 12.3. Terms in the surface energy balance over the drainage basin of the Baltic Sea. Graphs represent 30-day running means based on forecast hours 6-12 of four forecast cycles each day. The heavy solid line represents net radiation. Thin solid and dashed lines denote fluxes of latent and sensible heat, respectively. The grey shaded area shows the heat storage into the ground or water

12.3.4. Heating and cooling of the atmosphere

An equation for the specific enthalpy, or temperature multiplied by the specific heat of air at constant pressure, may be written for a column of air in analogy with equation 2:

$$D = A + Q_r + Q_c + Q_t + Q_f, \quad (5)$$

where D stands for the rate of change of the total enthalpy of the air column, A is the net effect of the flux convergence of enthalpy into the column and the work done by the pressure force, which is also equivalent to the flux convergence of potential energy. Thus the term *A* may alternatively be interpreted as the flux convergence of dry static energy, or the sum of enthalpy and potential energy. The remaining terms Q_r , Q_c , Q_t and Q_f represent diabatic heating by radiation, latent heat release, convergence of turbulent heat fluxes, and frictional dissipation of kinetic energy in the air column, respectively. Heating by radiation is equal to the difference between the downward radiative heat fluxes at the surface and at the outer boundary of the atmosphere. Analogously, heating by turbulence is equal to the flux of sensible heat into the atmosphere at the surface. The frictional dissipation is usually small in magnitude, and often neglected as a heating term. When looking at the atmosphere as a heat engine, however, this term plays a crucial role in closing the atmospheric energy cycle (e.g. Rosen, 1999).

The BALTEX reanalysis data include all the heating terms, except frictional dissipation. Neglecting this term, the adiabatic term *A* may be computed in the same way as the convergence term *C* in the water budget. Figure 12.4 shows heating and cooling terms obtained in this way over the Baltic drainage basin. As for the water budget, the graphs represent again 30-day running averages based on forecast hours 6-12 of four forecast cycles each day. Looking first at the conditions for the basin as a whole (top panel), we see that the atmosphere is cooled by radiation (dashed line) throughout the year at a rather constant rate on the order of 100 W m^{-2}, corresponding to a temperature change on the order of 1 K day^{-1}. The radiative cooling is partially offset by the much more variable latent heat release (heavy solid line). The surface sensible heat flux (dashed line) is important mainly during late spring summer.

The net effect of the diabatic terms (solid line at the edge of the grey shaded area) is to cool the atmosphere during most of the year except of the period from May to Aug 2000, when heating of a similar magnitude prevails. On a monthly time scale the diabatic cooling (heating) tends to be balanced by import (export) of dry static energy (the unmarked edge of the grey shaded area), but this is not true for shorter time scales, where strong fluctuations in the adiabatic term cause rapid changes of the air temperature associated with fluctuating weather patterns. This is reflected in the irregular shape of even the 30-day running mean. It is worth noting, that these fluctuations are generally very well predicted by the assimilation system, so that there is no reason to doubt the essential correctness of the adiabatic term. In analogy with Figure 12.2, the black shaded area shows the difference between the predicted and analysed rates of change of total enthalpy. The difference is mainly small in magnitude compared with the leading terms, but shows a well defined annual cycle. Positive difference indicating excessive warming of the air prevails during the cold season, while the error is much in the warm season. Unlike in the case of the water budget discussed in section 3.2, this error cannot be explained by the bias in the surface pressure alone.

Conditions over land are very similar to those over the basin as a whole, but more differences are seen over the Baltic Sea itself (Fig. 12.4, bottom panel). The latent heat flux is here important only in autumn and early winter, but gets weaker as the ice cover grows in extension during the winter months. Even more strikingly, the period of strongly positive diabatic heating seen over the land-parts of the basin in the summer months is lacking over the sea. This is because the summertime convection with its associated latent heat release occurs mainly over the land.

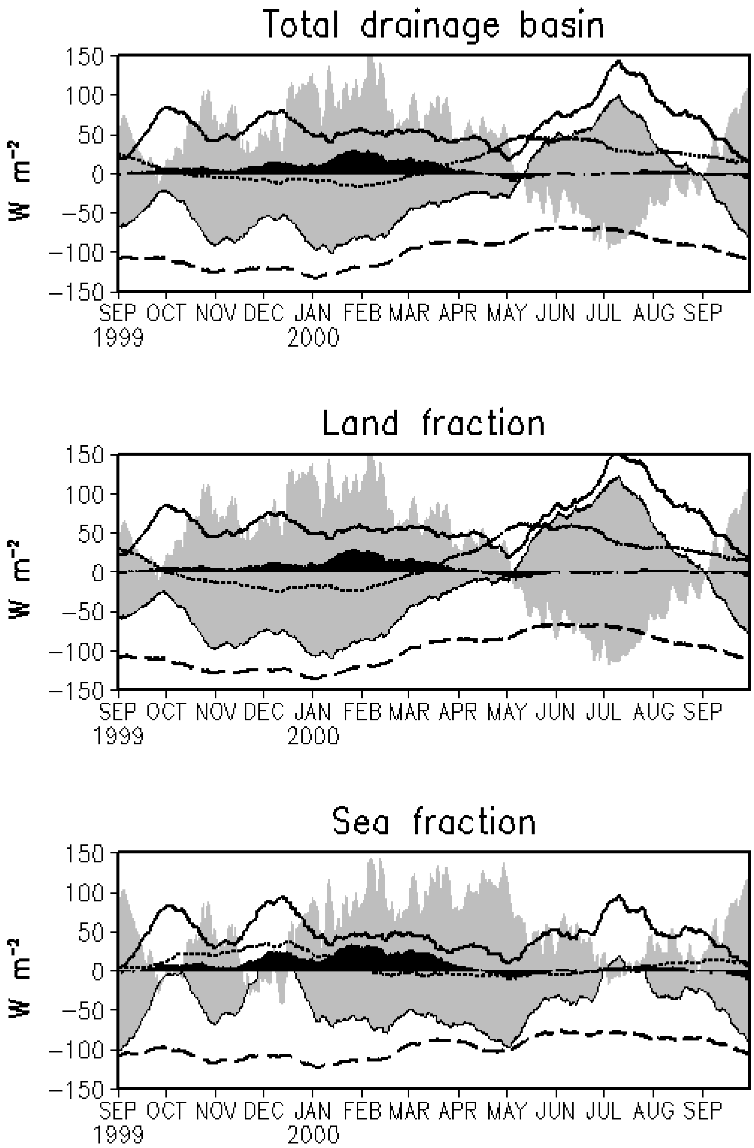

Figure 12.4. Atmospheric heating and cooling terms over the drainage basin of the Baltic Sea. Graphs represent 30-day running means based on forecast hours 6-12 of four forecast cycles each day. Latent heat release and radiation are shown as heavy solid and dashed lines, respectively. The dotted line shows the surface sensible heat flux. The net diabatic heating is shown by the solid line at the edge of the grey shaded band. The unmarked edge of this band shows the adiabatic heating, or the net convergence of dry static energy. The black shaded band gives the bias of the predicted rate of change of the total atmospheric enthalpy relative to the analysed one.

12.3.5. Comparison with independent data

No model result ought to be trusted without a critical examination in the light of independent data. Wihtin the BALTEX reanalysis project, surface heat fluxes were compared to field mesurements at a Finnish research site, and precipitation amounts were compared to products from the BALTEX Radar Data Centre.

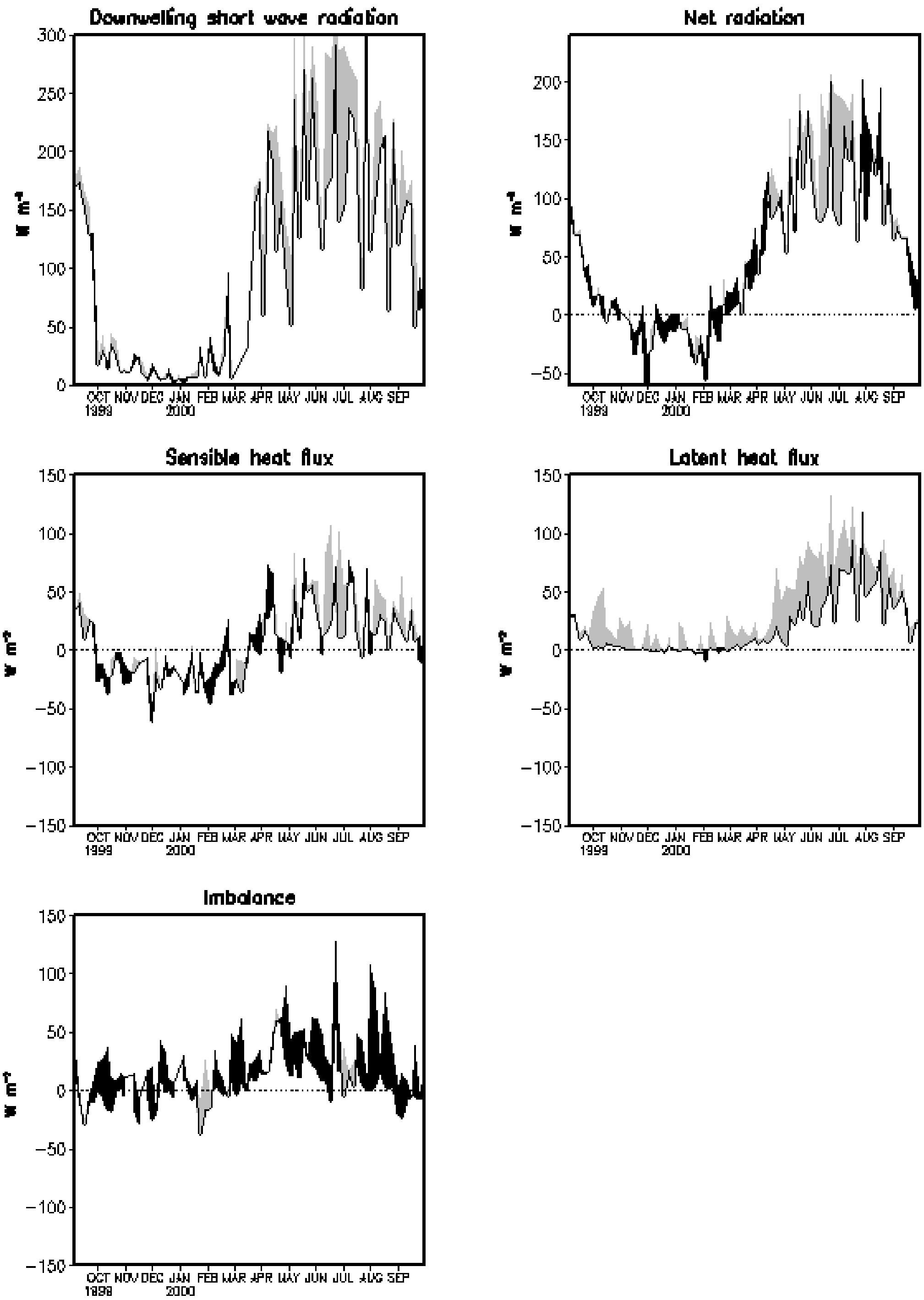

Figure 12.5. Components of the daily mean surface energy balance at Hyytiala field station, marked by the cross in Fig. 12.1. Solid lines give the observed fluxes, while grey and black shading indicate psoitive and negative differences between the BALTEX reanalysis model and the data, respectively. Model results refer to forecast hours 6-12 of four forecast cycles each day.

In Fig. 12.5 daily averages of model-generated surface heat fluxes are compared to direct measurements at a SMEAR 2 field station in Hyytiälä in southern Finland. The station, indicated by a cross in Fig. 12.1, belongs to the European-wide CARBOEUROFLUX network, and is described in Vesala et al. (1998). They are used with the kind permission of Prof. Timo Vesala at the University of Helsinki (Department of physical sciences, Division of atmospheric sciences). The fluxes are obtained from eddy covariance measurements above of a pine forest at a height of 23 m above ground. The model-fluxes represent a grid box with a mixture of 78 % forest 14 % open land and 8 % lake. The model is obviously able to reproduce the annual cycle as well as day to day variability of most components of the surface heat budget, but systematic differences are seen as well. Thus the linear correlation coefficient between measured and modelled daily downwelling short wave radiation is as high as 0.94, but the model neverthelsess cleary overestimates the downwelling short wave radiation during summer, (grey shading). High correlation is found also for the net radiation (0.90) , but the model tends to be to overestimate the annual cycle, beeing too negative or too small (black shading) during the cold season, and too positive in summer. A similar systematic difference is seen in the sensible heat flux, but the correlation coefficient is lower here,amounting only to 0.77. A similar level of correltaion (0.82) is found for the latent heat flux, but the model gives persistently larger values than are observed. Finally, it must be noted that there is a substantial annual imbalance of 27 Wm^{-2} in the measured fluxes, compared to 7.1 Wm^{-2} for the model. Formally, the imbalance should equal the storage of heat in the soil and vegetaiton, and it should be close to zero on an annual level. Despite their persistent difference, model results and data are still positively correlated at a level of 0.54 in the correlation coefficient.

The verification of precipitation forecasts in general is made difficult by the huge variability of precipitation in time and space. In general a large number of in situ measurements is needed to estimate the average precipitation over a model grid box. A network of radars provides virtually continuous observations, but obtaining accurate estimates of the precipitation at the surface using radars alone is very problematic. The BALTEX Radar Data Centre combines corrected rain gauge data with radar measurements over the catchment basin of the Baltic Sea. These data were used for verification of the predicted precipitation. Products and methodologies of the BALTEX Radar Data Centre (BALTRAD) are described in Michelson et al. (2000). The data used here consists of gridded consecutive 12-hourly precipitation sums with a horizontal resolution of 2 km. For the purpose of this study, the BALTRAD data are transformed by box-averaging to the HIRLAM-grid having a grid length of 22 km.

Figure 12.6 shows time series of 7-day running mean precipitation totals over the rectangular area shown in Fig. 12.1. This area was chosen mainly because the of the high quality of the radar network there. As before, the model output consists of hours 6-12 of four forecast cycles each day. The correspondence between the two totally independent estimates is quite remarkable on all time scales, and the linear correlation coefficient is as high as 0.95. Even for half-daily precipitation sums (not shown), the linear correlation coefficient between the two estimates is as high as 0.91. Annual totals differ by only 6%, amounting to 744 mm for BALTRAD and 788 mm for HIRLAM, so the difference is definitely within the observational uncertainty.

Although important, the total amount is only one aspect of precipitation. It is also important how the precipitation is distributed in space and time. Fig. 12.7 shows frequency-histograms of semi diurnal precipitation in different seasons for all (22 by 22 km) grid-boxes within the control area. The main features of the observed distributions, including their seasonal changes, are well reproduced by the reanalysis products, especially in spring and summer. In autumn and winter the occurecnce of weak precipitation is overpredicted by the system at the cost of cases with no precipitation at all (note that the leftmost columns in Fig. 12.7 have been divided by a factor of 10 for greater readability).

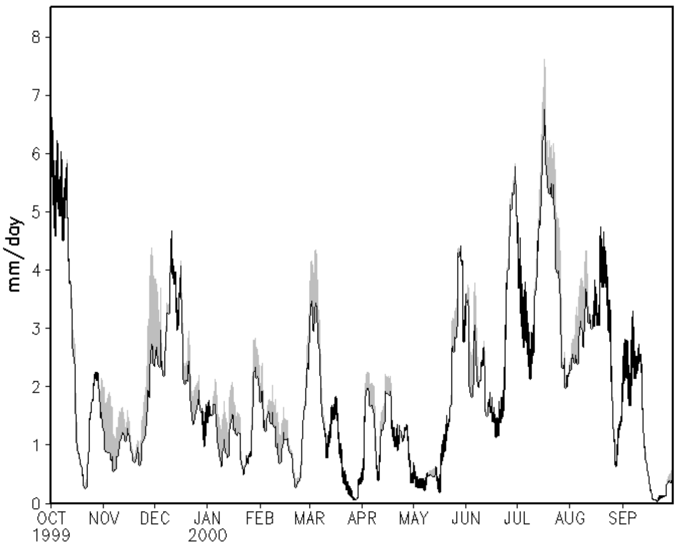

Figure 12.6. Areal 7-day running mean precipitation totals for the rectangular area shown in Fig. 12.1. The solid line shows precipitatoin retrievals from the BALTEX Radar Data Centre. Grey and black shading, respectively indicate positive and negative differences between the BALTEX reanalysis system and the BALTRAD retrieval. Model results refer to hours 6-12 of four forecasts each day.

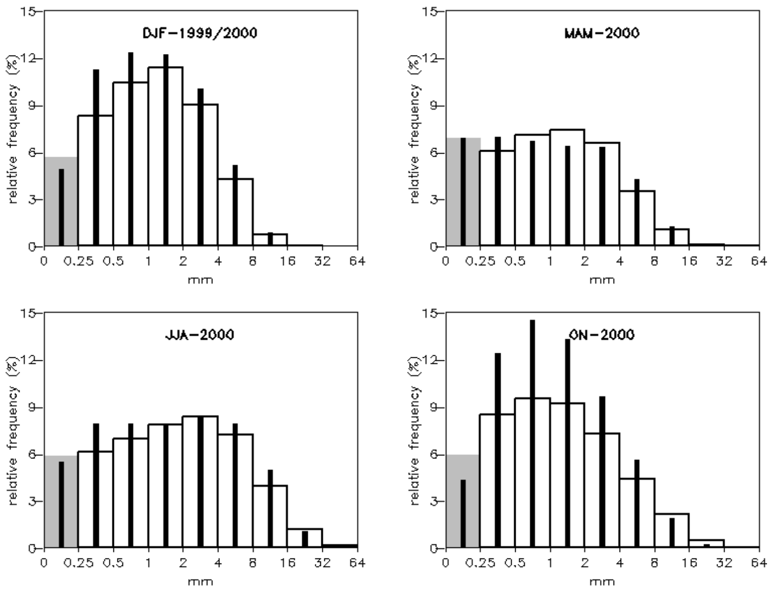

Figure 12.7. Relative frequency distributions of semi siurnal precipitation totals for all grid-boxes within the rectangular control area in Fig. 12.1. The thin black columns refer to the BALTEX reanalysis system, while the wide unfilled columns show precipitation retrievals from the BALTEX Radar Data Centre. Different panels refer to different periopds, as indicated by the letters and numbers. The leftmost columns have been divided by 10 for greater readability.

12.4. Summary and Perspective

The BALTEX regional reanalysis project has demonstrated that data assimilation using a modern limited area numerical weather prediction system is a feasible way to determine the essential features of the energy and water cycles of the Baltic drainage basin.

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Chapter 13:

Cloud observation and modelling

by

Susanne Crewell

13.1. Motivation

Clouds affect our daily life in many ways. Much more than air temperature clouds dominate our perception of weather and thus have an enormous influence on our daily activities and our health. This fact is completely at variance with our knowledge about clouds, their representation in climate and weather forecast models and our ability to predict clouds. It is their high variability in time and space, which makes clouds both hard to monitor and to model. It is well-known, that clouds are directly linked to the dynamics of the atmosphere. The most important parameter linking dynamics to clouds, in both the real world and in forecast models is the water content of clouds. Passive microwave remote sensing is by far the most direct and accurate method to estimate cloud water content. Unfortunately, from satellite this technique only works over ocean areas. Over land areas satellite remote sensing methods must rely on very indirect information taken from cloud reflection of solar radiation. Thus, important cloud information does not get into our models in the area where people live.
As stated by the Intergovernmental Panel on Climate Change (IPCC)'95: "the most urgent scientific problems requiring attention to determine the rate and magnitude of climate change and sea level rise are the factors controlling the distribution of clouds and their radiative characteristics....". The same was concluded in the AMIP project (e.g. Gates et al., 1999) in which the outputs of 30 atmospheric models were compared for a ten-year run. Furthemore, the latest IPCC report (2001) states that "there has been no apparent narrowing of the uncertainty range associated with cloud feedbacks in current climate simulations" and moreover that "there are particular uncertainties associated with clouds and their interaction with radiation and aerosols"; as a result it further recommends that "the only way to obtain progress in this complex area of atmospheric science is by consistently combining observations with models" and that "a more dedicated approach is needed".

The BALTEX Cloud Liquid Water Network: CLIWA-NET project (Crewell et al., 2002 and 2003) aimed at a better cloud representation in atmospheric models by an advanced observational program leading to improved parameterizations. For this purpose a prototype of a European cloud observing system was established by co-ordinating the use of existing, ground-based passive microwave radiometers and profiling instruments. The data from the ground-based remote sensing instruments were used to improve the satellite-based estimates of cloud water content. New procedures have been developed to exploit this synergy.

13.2. Ground-based observations

In total six months of continuous observations were carried out divided into three campaigns overlapping with the BRIDGE enhanced observation periods. The primary goal of the ground-based stations was the continuous observation of cloud liquid water path from multi-frequency passive microwave measurements. In order to derive information about the vertical cloud structure and to enhance LWP accuracy the additional instruments, e.g. lidar ceilometer, IR radiometer, or cloud radar were used. The first two campaigns involved distributed sites in the BALTEX modelling area (Fig. 13.1) while the third concentrated on a smaler scale focussing on the Netherlands.

13.2.1. CLIWA-NET Network (CNN) campaigns

The ground-based network for the CNN campaigns consisted of 12 individual stations located within the Baltic Sea Experiment (BALTEX) area (Fig. 13.1) with a microwave radiometer as a central instrument. CNN I covered August/September 2000 and CNN II /April/May 2001. Details of the instruments at the individual stations can be found at http://www.knmi.nl/samenw/cliwa-net.

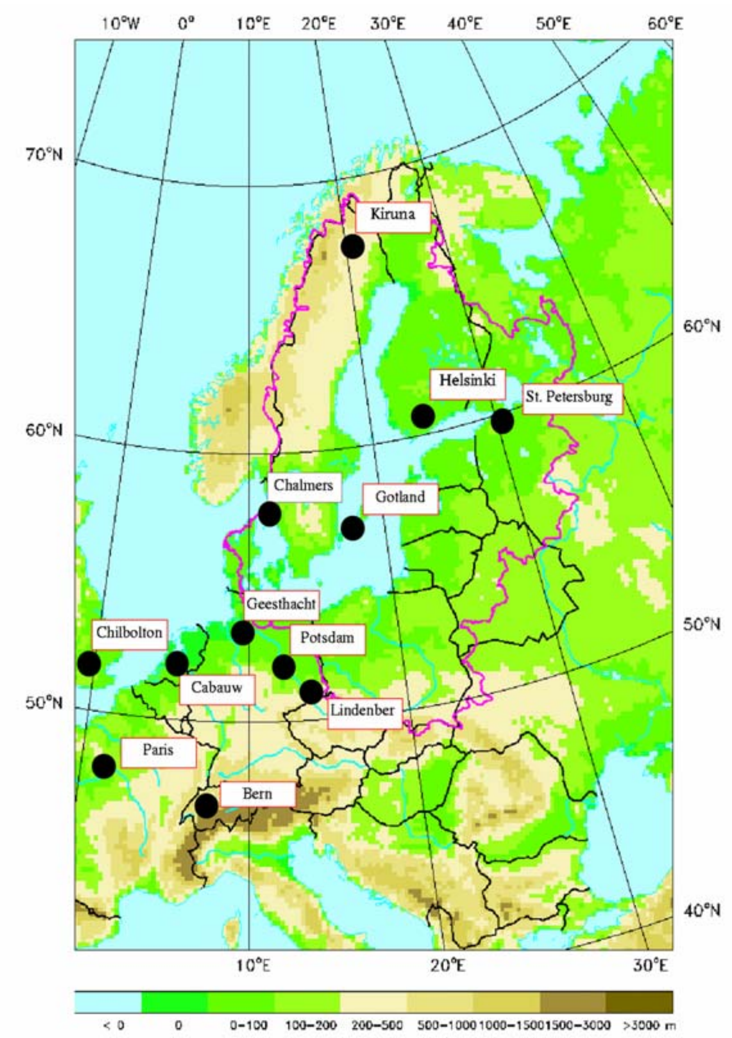

Figure 13.1: Position of stations during the CLIWA-NET observation periods (CNN I and II)

The liquid water path can be estimated from atmospheric emission in the microwave region since in this spectral region the cloud contribution strongly increases with frequency. Therefore standard dual-channel systems measuring at two frequencies with one close to the 22.235 GHz water vapour line and the other in a window region at higher frequencies can simultaneously observe LWP and the integrated water vapour (IWV) (Westwater, 1993). Within CLIWA-NET existing microwave radiometers of very different design and specifications were used. For each radiometer the uncertainty of the direct observable, the brightness temperature, was determined. Algorithms for LWP and IWV individually adapted to the different instruments were derived. For each station long-term radiosonde data sets were used for the derivation of statistical retrieval algorithms. The uncertainty of the different radiometers varies between 15 and 35 gm^{-2}.

While the microwave radiometers were relatively diverse in design, infrared radiometer (IR) and lidar ceilometer were more or less standardized. The combination of a lidar ceilometer and IR radiometer is useful in characterizing cloud base height to an accuracy of ~30 m and cloud base temperature to an accuracy of 1–2 K after subtracting the atmospheric contribution from the IR measurement. At three stations cloud radars were operated. In order to detect small cloud droplets, cloud radars usually operate at higher (for example 95 GHz) microwave frequencies. Because attenuation is relatively strong at these frequencies cloud radars typically point vertically and gather time-height series. The radar signal is proportional to the sixth moment of the drop size distribution (DSD) and therefore the derivation of the liquid water content, which is proportional to the third moment of the DSD, is highly uncertain. Weather radars, intended for precipitation measurements, use much lower frequencies (e.g., 1–9 GHz) and continuously scan the horizon at very low elevation angles. The Baltex radar network (BALTRAD, Koistinen and Michelson, 2002) provided time series of the radar reflectivity factor for rain detection.

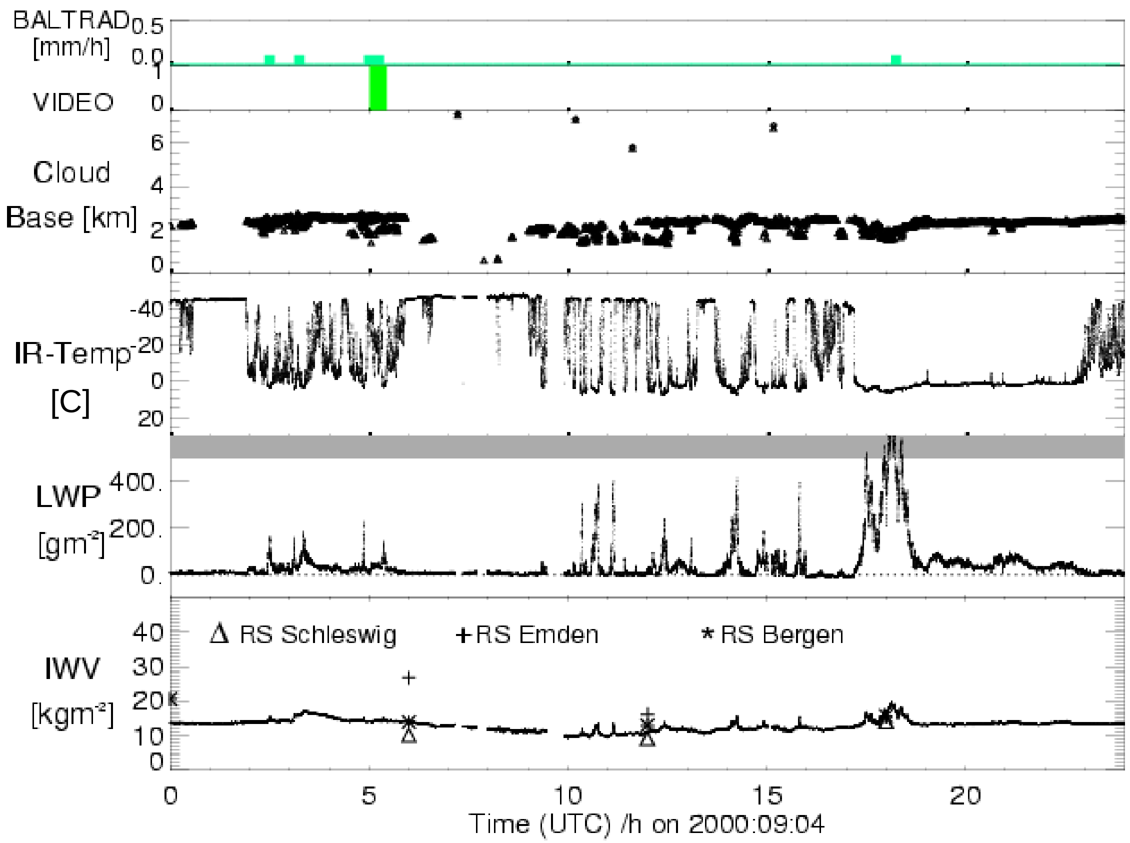

Figure 13.2: Example of a daily time series observed at Geesthacht on 4 September 2000 during CNNI.

The microwave and IR measurements at Geesthacht (Fig. 13.2) reveal cloud variability on different scales. The correlation between cloud base height and IR temperature is high: During the presence of clouds, IR temperatures are high, while in the absence of clouds the IR temperature of the atmosphere drops to –30 to –55^o C. From 17:30 to 19:00 UTC cloud base height increases and the IR temperature decreases. As ceilometer and IR radiometer measurements contain the cloud base information, they show a different behaviour than LWP, which is a vertically integrated quantity. For example, the periods from 13:45 to 14:30 UTC and 17:30 to 18:30 UTC in the time series are characterized by almost identical values for the cloud base height (1.5 to 2.5 km) and IR temperatures (0 to 10^o C). The corresponding peak LWP value for the first period, however, is much lower than for the second period. Ice clouds are transparent at the microwave frequencies used in this study; they do not contribute to the microwave radiances. Since no useful LWP and IWV retrievals can be performed during rain, these conditions have to be identified (van Meijgaard and Crewell, 2005). Therefore several precipitation indices from different sensors were acquired.

13.2.2. BALTEX BRIDGE Campaign (BBC)

The BBC campaign in August/September 2001 included intensive remote sensing observations at the Cabauw site (Fig. 13.3) including three cloud radars. Within a regional network (120x120 km^2) lidar ceilometers, infrared radiometers and pyranometers were operated at six stations (Fig. 13.4). After a microwave radiometer intercomparison campaign (MICAM) during the first two weeks of August at Cabauw the radiometer were distributed to the stations in the regional network. Originally initiated by CLIWA-NET, the campaign grew considerably by the inclusion of e.g. four aircrafts and two tethered balloons by other European partners.

The combination of different advanced remote sensing instruments at the Cabauw site during the BBC campaign allowed the application of a newly developed synergetic algorithm (Löhnert et al., 2004) to derive simultaneously temperature, humidity and temperature profiles and their respective uncertainties.

13.3. Satellite observations

Figure 13.3: Set-up of the remote sensing site in Cabauw showing the microwave radiometer MICCY and three cloud radars. The 200 m mast is visible in the background.

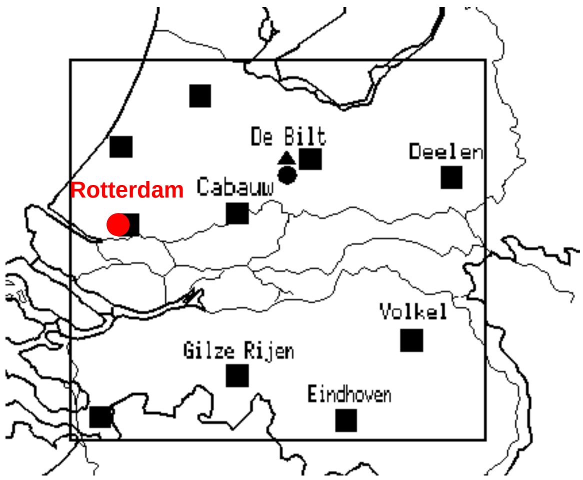

Figure 13.4: Distribution of stations in the Cloud Detection System. Stations labelled in black were additionally equipped with microwave radiometers. Aircrafts were based in Rotterdam.

Within CLIWA-NET a prototype of the space based component of the European cloud observing system for liquid water path fields was developed. Instruments involved were the passive imager onboard of the NOAA polar orbiting satellites, Advanced Very High Resolution Radiometer (AVHRR) and the Advanced Microwave Sounding Unit (AMSU) onboard the same platform,. The final aim was to obtain fields of spatial distributions of liquid water path from a combination of satellite images and time-series from the ground-based network.

The time-series from ground based measurements are not always representative for the cloud field as seen from satellite. This is due to the fact that cloud field properties change in time and space. Therefore, we never know which part of the time series that is measured at one location is representative for which part of the spatial distribution that is measured at one moment in time. Spatial and temporal variability are illustrated using the Russian-doll method, where the mean and the standard deviation are calculated over increasingly larger area / time intervals (in a way resembling how Russian dolls fit into each other). For example on August 4 there is a field of small scale cumuli over the Netherlands at the time of satellite overpass (Fig. 13.5). The spatial LWP average ranges from 70 g m^{-2} to 215 g m^{-2} for the different areas considered while one observed from ground increases from 40 g m^{-2} for a short integration time to about 150 g m^{-2} for a 6 minute interval. These results show that satellite retrieval quality can not be assessed for an individual case but a large number of overpasses need to be analysed.

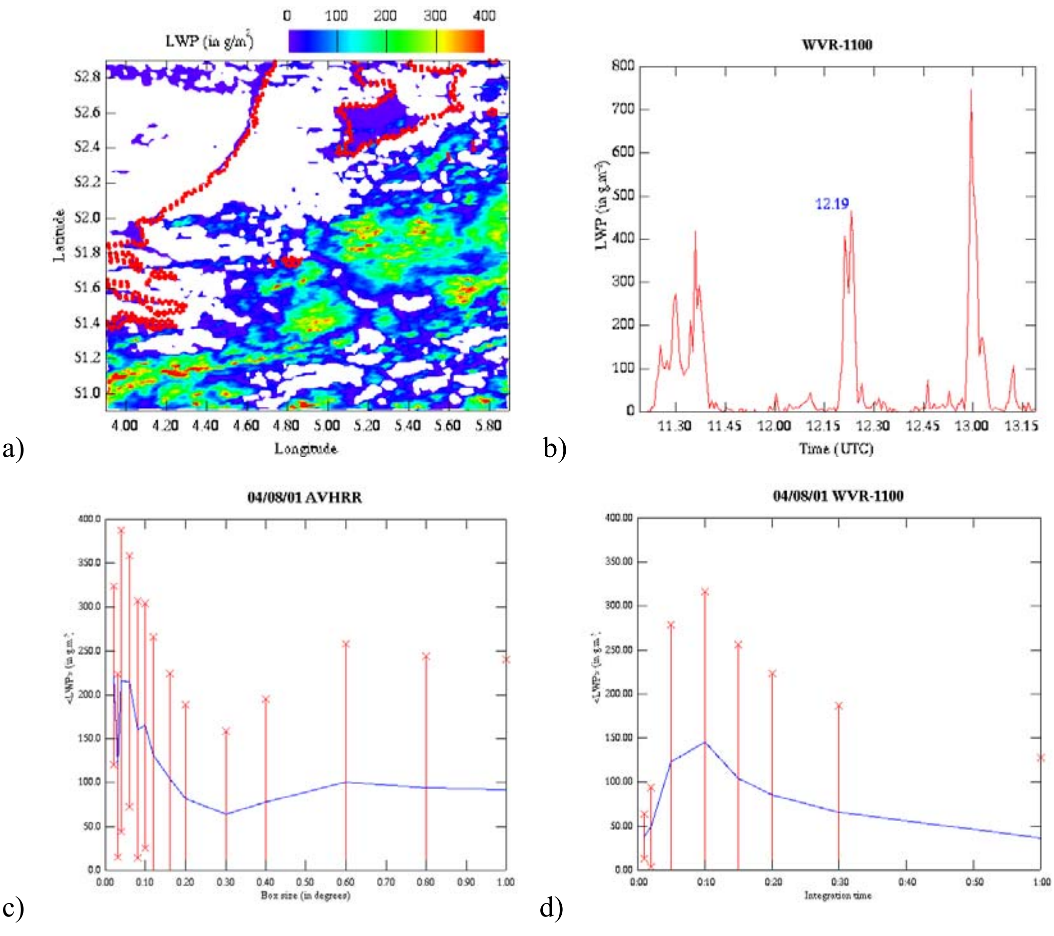

Figure 13.5: LWP as measured from satellite (a) and ground (b), averaged over space (satellite, c) and time (ground, d) on 4 August 2001.

13.4. Model evaluation

Within the CLIWA-Net project four European institutes participated in the evaluation of model predicted cloud parameters: the European Center for Medium-range Weather Forecast (ECMWF), Deutscher Wetterdienst (DWD), the Swedish Rossby Center, and the Royal Netherlands Meteorological Institute (KNMI). The ECMWF participated with the global forecast model (version CY24R1) operated at an effective horizontal resolution of 40 km and with 60 layers in the vertical. It employed the prognostic cloud scheme of Tiedtke (1993) in which cloud content and cloud fraction are both treated prognostically. The DWD contributed with the recently developed Lokal Modell (LM; Doms and Schättler, 1999) operated in non-hydrostatic mode at a resolution of 7 km and with 35 layers in the vertical. At this resolution convection is still parameterised, but stratiform clouds are assumed to be resolved, implying that the cloud fraction of an entire grid box is determined by an all-or-nothing scheme. The Rossby Center has developed a climate version of the numerical weather prediction model HIRLAM, hereafter referred to as the RCA-model (Jones, 2001). In this model cloud parameters are represented by the convection scheme of Kain and Fritsch (1991) and a stratiform cloud scheme proposed by Rasch and Kristjansson (1998). KNMI operated a regional version of the ECHAM4 GCM, hereafter referred to as RACMO (Regional Atmospheric Climate Model; Christensen *et al.* 1996). Cumulus convection is represented by a mass-flux scheme and stratiform processes by a modified version of a scheme originated by Sundqvist *et al.* (1989) in which the sum of cloud and ice water content is a prognostic variable. Details can be found in Roeckner *et al*. (1996).

Model time series were calculated for sub-domains centered around the CLIWA-NET site. The sub-domain size was chosen to be in the order of 50x50 km. For ECMWF this leads to just one grid cell, for RCA and RACMO to 3x3 grid cells, and for the LM to 7x7 grid cells. The model output refers to a 12 to 36 hour window taken from each daily forecast initiated at 12:00 UTC the previous day. The RCA-model and RACMO were operated in as much an identical fashion as possible. The two models shared the same domain, where the horizontal resolution was 18 km and the number of model layers was 24. For the BBC-campaign the RCA vertical mesh was increased to 40 levels. Both models used the same set of ECMWF analyses to initialise the atmospheric component of the model and to drive the model from the lateral boundaries. The LM initialization has its own data-assimilation; the LM boundaries are forced from large-scale forecasts operated by DWD. A number of comparison between model output and ground and satellite observations has been carried out. In the following we will exemplarily give information on the evaluation of the mean liquid water path and the vertical structure of clouds.

13.4.1 Mean liquid water path

For each CLIWA-Net site the mean values for LWP and IWV inferred from observations and derived from model predictions were compared. Large efforts were made for a proper match of observations and model results. Because microwave radiometer measurements are unreliable when the instrument becomes wet, it is essential that events of precipitation be accurately identified in the observations and model values are effectively filtered out. Non-zero or even negative values of observed LWP in cloud free situations were effectively dealt with by a time-dependent correction based on information of supporting instruments for cloud detection. Temporal aggregation or, equivalently, conditional averaging in time, was used to bring the observations to scales matching the grid-box mean model predicted values. Furthermore, additional information by auxiliary sensors was used to identify specific conditions like low level water clouds or overcast conditions. The procedures and results are described in detail by Van Meijgaard and Crewell (2005). The mean observed LWP averaged over the scenes with water clouds present reduces from about 90 g/m^2 for temporal scales of 5 minutes to about 40 g/m^2 at scales of one hour (Fig. 13.6). All models, but in particular the

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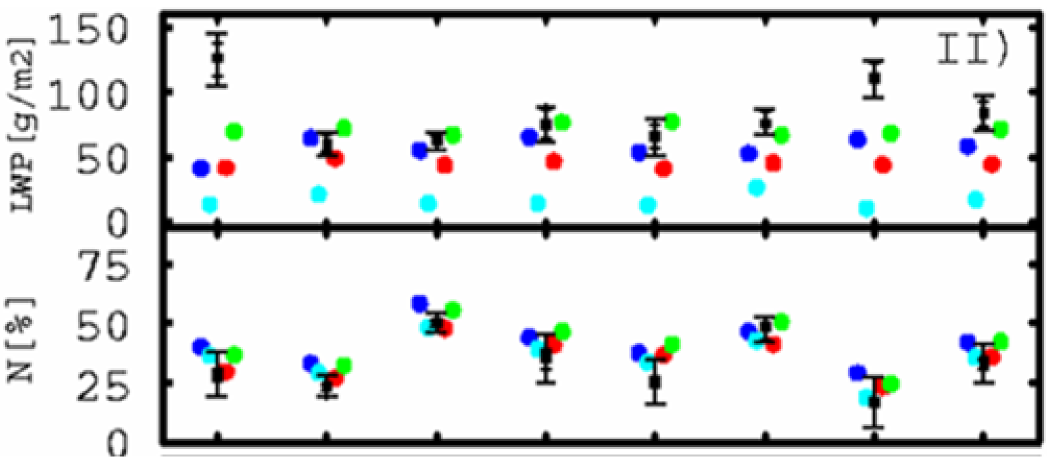

Figure 13.6: Observed (black) and model predicted mean LWP for cases of low level water clouds for the stations Gotland (GO), Onsala (ON), Potsdam (PO), Lindenberg (LI), Cabauw (CA), Chilbolton (CH) and Bern (BE) during CNN II. Model results are given for ECMWF (blue), RCA (red), RACMO (green) and LM (light blue). Black bars give the variation due to temporal aggregation.

RCA-model, tend to overpredict frequency and duration of precipitation. Different models differ most in their predictions of LWP illustrating the scarcity of LWP observations so far. The geographical differences evident in the observations are not visible in the model predictions. The ECMWF model and, to a lesser extent, RACMO are found to overestimate mean LWP, while the RCA-model predicts values close to what has been observed. The LM-model tends to greatly underestimate the observed values.

13.4.2 Cloud vertical structure

The cloud radar observations during the BALTEX Bridge Campaign allowed to study the cloud vertical distribution and overlap in the four models described above. Ceilometer observations of cloud base height were used to eliminate the contamination of the radar measurements by insects. We will concentrate on the sensitivity of simulated cloud fields and associated cloud process (e.g. diurnal cycle of clouds, cloud-radiation interaction) to increasing model vertical resolution. It is generally expected that a more accurate representation of cloud processes will occur as model vertical resolution increases. As motivation, Figure 13.7 shows the vertical structure of the cloud field, observed by the KNMI radar over Cabauw, through the day of September 18th 2001. The raw KNMI radar reflectivities have been temporally averaged to produce a cloud fraction representative of ~20 km spatial resolution. During the day a frontal system passed over Cabauw, this is clearly seen in the gradual transition from high clouds to low clouds as the day progressed. Early in the morning a fog layer was present gradually turning into a low-level cloud layer. This layer lifted and thinned through the morning, attaining a cloud base of ~750 m by 12 noon. Late in the evening a second period of upper level clouds (above 5 km) was observed. All models simulate the 3 observed cloud structures with varying degrees of success. In the plot, RCA24 and the RACMO models used identical vertical layering (24 levels) while RCA40 and ECMWF both used an identical 40 layer structure. The RCA model was the exact same model in both simulations except for the increased vertical resolution. The improvement in the RCA simulation of the frontal cloud system, as vertical resolution is increased, is clearly visible, especially in the mid-troposphere. In fact, the model cloud fields look more common grouped by vertical resolution, ECMWF with RCA40 and RACMO with RCA24, than if they were grouped by common model physics (in this case the two RCA models).

In general this picture is confirmed over the whole BBC campaign. Relative to the observations all models underestimated the height of the lowest cloud base. Clouds occurred more frequently in the models but with smaller amounts of cloud fraction below 7 km. The findings confirm previous cloud radar studies, which found that models overestimate high

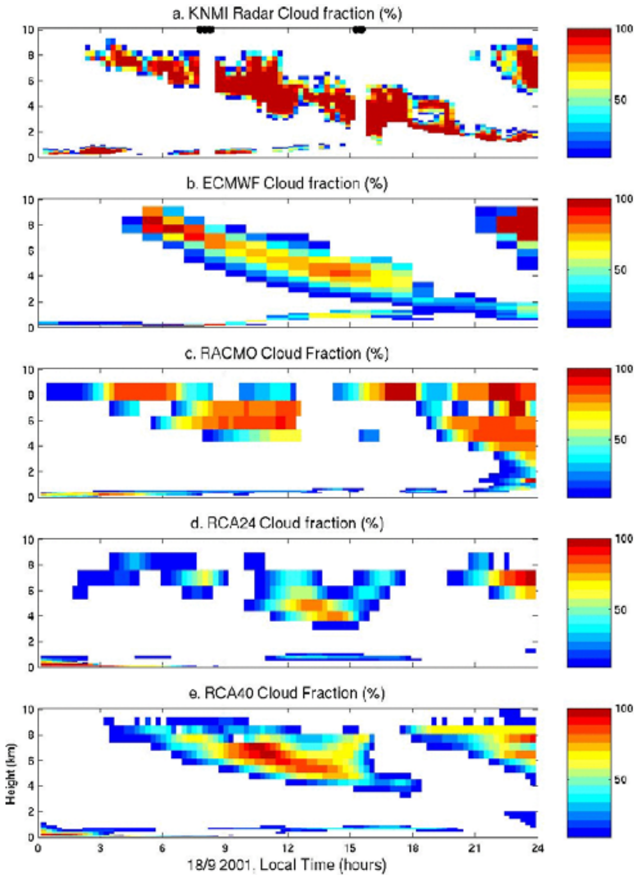

Figure 13.7: Diurnal cycle of cloud fraction over Cabauw during 18th September 2001. Panel a) Cloud fraction derived for ~20 km spatial resolution from KNMI Cloud Radar b-e) CLIWA-NET model derived cloud fractions for grid box collocated with Cabauw.

clouds above 7 km. Furthermore, the radar-observed clouds were often thinner than the model vertical resolutions, which can have serious implications on the cloud overlap and radiation fluxes. The radar-derived cloud overlap matrix, taking into account the overlap of all vertical layers, was found to be close to maximum-random overlap. Details about the comparisons and further results are given in Willen et al. (2005).

13.5. Summary and Perspective

The prototype of European Cloud Observation network (ECON) was successfully implemented during three enhanced observational (CNN I: August/September 2000; CNN II: April/May 2001 and BBC: August/September 2001). To achieve this, existing observation systems (microwave radiometer and auxiliary instruments) were distributed in a continental over the BALTEX modelling region and a regional scale network in the Netherlands. In the following we provide some results which have major consequences for future research.

13.5.1. Observational aspects

- Harmonized retrieval algorithms to derive the liquid water path (LWP) and the integrated water vapour (IWV) were developed for all stations and campaigns. The addition of several other sensors like ceilometer and infrared radiometer was found very valuable for quality checking and further constraining the atmospheric state (e.g. radiation and wind). The exact detection of rain events is extremely important as many instruments are unreliable in these conditions. Due to the high variability of precipitation rain detection by rain gauges is not sufficient.
- The microwave intercomparison campaign (MICAM) verified the good quality of liquid water path measurements during the previous CNN campaigns. However, the uncertainty of current gas absorption models and the inherent retrieval ambiguities still limit the accuracy of standard dual frequency systems to about 30 g m^{-2}. These models need to be further constrained.
- The combination of different advanced remote sensing instruments at the Cabauw site during the BBC campaign (Crewell et al., 2004) allowed the application of a newly developed synergetic algorithm to derive simultaneously temperature, humidity and temperature profiles and their respective uncertainties (Löhnert et al., 2004). This kind of information is extremely useful for model evaluation.
- For a future long-term implementation of ECON a low-cost microwave radiometer (Rose et al., 2005) which also takes into account requirements from the modelling community has been designed. Thanks to external funding the first system was already built.

13.5.2. Satellite and integration aspects

- The satellite data acquisition system obtained data from nearly all possible satellite overpasses. Cloud classification was performed for more than 1000 scenes. The cloud classification scheme showed in general a very high quality during all observational campaigns. Problems in the estimation of cloud coverage mainly occur during twilight where the cloud amount from AVHRR is less reliable and mostly tend to be slightly underestimated. In addition there is an inherent difference in the cloud scheme and in the AVHRR sensitivity in general between land and sea surfaces. This results in a slight overestimation of the cloud cover but higher reliability over sea and a slight underestimation and lower reliability over land. This inherent discrepancy between sea and land in cloud amount combined with an observed ambiguity between separation of fractional water clouds (small cumuli and cloud edges) and thin cirrus, made post-processing necessary before the data could be used for studies of diurnal cloud cover and model comparison in general.
- Improvement in satellite estimates made from NOAA-AVHRR of LWP were possible due to the newly developed analysis methods that utilize the additional information from the near infrared channel of NOAA-16. The new method includes analysis of the cloud thermodynamic phase (ice or water) and estimates of the size of the cloud particles. Comparison with ground observations indicates reasonable accuracy at lower LWP values.

13.5.3 Modelling aspects

Methodologies focusing on the evaluation of model predicted cloud parameters with CLIWA-NET inferred observations have been developed and examined in various applications, e.g. a statistical evaluation of predicted liquid water path (LWP). Furthermore, the influence of horizontal resolution (down to 1 km) was studied for the Lokal-Modell.

- Models overpredict frequency and duration of precipitation. Models overpredict the amount of liquid water clouds. On average, models predict LWP in the right order of magnitude, but the spread among the models is considerable (Van Meijgaard et al., 2005).
- On average, models provide a reasonable representation of the LWC vertical distribution, but variations among the models in amount and height of the maximum value are huge. For individual events, modeled vertical structure of LWP has no prediction value.
- Model relations between solar transmissivity and LWP are compared with the observed relation. Some models represent inadequate relations with transmissivity falling off to steeply with increasing LWP. Owing to a compensating error, i.e a significant underprediction of LWP, one model still provides a reasonable radiative forcing at the surface.
- Numerical experiments have been conducted with a meso-scale model, e.g. the Lokal- Modell, to examine the sensitivity of cloud and precipitation parameters on the horizontal resolution in the range of 10 to 1 km. Domain averaged LWP, and, in particular, precipitation are found strongly enhanced by increasing horizontal resolution while domain averaged IWV, cloud cover, and surface energy fluxes are hardly affected by the resolution refinement for short-term integrations in forecast mode. Size distributions of model resolved convective cells depend strongly on the employed horizontal resolution. The dominant size scales with the grid spacing rather than a model-independent physical scale. At the smallest grid-spacing a resolution independent distribution starts to develop. There are indications that the application of fully parameterised turbulence without horizontal exchange between grid boxes is no longer adequate in this range of grid spacings.
- The total cloud amounts derived from two satellite systems, i.e. ISCCP and AVHRR, are found to be significantly different with the ISCCP cloud amount being much larger than the AVHRR cloud amount. The AVHRR amounts, in turn, are found to be larger than ground-based (synop) estimates. Model predicted cloud amounts from different cloud schemes fall between the observations and AVHRR.
- Refinement of the vertical model mesh results in a better representation of cloud processes. In general, it also results in a better representation of macroscopic cloud parameters like cloud amount and the vertical distribution of clouds. Typical errors like a tendency to simulate cloud base height at too low altitudes are not remedied completely (Willen et al., 2005).

In summary, the BALTEX Cloud Liquid Water Network has provided a very useful data set during its six months of operations. These unique data were used for model evaluation and revealed that the atmospheric models have large deficits in representing the liquid water content and also cloud vertical structure. However, to pin down the deficits to certain model assumption more observations over the full annual cycle are necessary. In addition, these observations should focus on stations where the atmospheric state is derived as complete as possible by the synergy of different sensors.

13.6. Acknowledgements

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Chapter 14:

Development of coupled regional climate models within BALTEX

by

Daniela Jacob

14.1. Motivation

The investigation of the water and energy cycles within the Baltic Sea and its drainage region has to take into account different compartments of the Earth system. The atmosphere, the Baltic Sea itself and the land hydrology are all contributing to the water and energy cycles. Therefore atmosphere/land surface/ocean coupling is still a major activity within BALTEX (Lawford et al., 2004).

From the very early years of BALTEX the development of coupled modelling systems was seen as a major challenge. In the BALTEX Initial Plan (Bengtsson, 1995) is it said:

…*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. The regional models will be coupled to a large-scale hemisphere 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 know whether precipitation (P) minus evaporation (E), even on an annual basis, is negative or positive.…*

Theses words are still valid and much progress has been made to establish regional modelling systems and to judge their quality by using as many different observations as available. However, several of the water and heat components and their variability in time and space need further research efforts.

14.2. Major achievements of the Baltex Phase I and related programmes

During the last years atmosphere, land surface and ocean coupling efforts succeeded in the establishment of two regional coupled modelling system: the RCAO developed at the Rossby centre (Döscher et al, 2002) and BALTIMOS from MPI-M (Jacob et al, 2003, Lehmann et al, 2004)). Both systems are currently under validation and further development. They are designed for climate studies and similar to global coupled atmosphere ocean general circulation models.

In both systems the Baltic Sea is interactively coupled to the atmosphere. Using the atmospheric fluxes to force the ocean component sea surface temperatures are calculated realistically. The systems are free of drift, flux correction is not needed.

Over land areas radiation, sensible and latent heat fluxes as well as precipitation are given to the land surface modules, which in turn deliver soil temperature and soil moisture as surface boundary conditions to the atmosphere model. Runoff is also produced by the land surface modules: this includes vertical distribution as well as lateral transport of water in the soil. The latter one contributes to river discharge, which enters the Baltic Sea.

For validation purposes both systems have been used for hind-cast experiments, which include always two simulations, a coupled and an uncoupled one. RCAO has been driven by ERA data for 1989 to 1993 (for details: Döscher et al., 2002), whereas BALTIMOS was run for 1999 to 2003 (for details: www. baltimos .de, special issue TAC under preparation).

Longer term simulations are under way with BALTIMOS for today's climate conditions for the period from 1979 to today. RCAO as been used within the PRUDENCE project to simulate an IPCC A2 climate change scenario for 2071 to 2100 (see: special issue Climatic Change under preparation)

14.3. Summary and Perspectives

Two coupled regional climate modelling systems have independently been developed and successfully validated against observations. They build a solid basis to investigate the variability in the water and energy cycles in BALTEX phase II and fill the gaps where observational data are missing. The challenges for the future are to investigate the coupling character of processes between different compartments in the regional climate system and to analyse results from these modelling systems in detail. The question of the variability and magnitude of the individual components of the water and energy budgets can now be tackled again.

During phase II, both modelling systems can be used to study the climate from 1800 to 2100 as well as their relation to global circulation changes. The extension of physical systems, currently represented in RCAO and BALTIMOS, to the interaction between physical, and biogeochemical processes will be one of the most challenging activities in BALTEX phase II.

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Chapter 15:

Synthesis

by

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BALTEX Phase I (1993-2002) has generated an active research covering the whole field of advanced modelling and data studies in meteorology, hydrology and oceanography. Major research elements of BALTEX include the collection of *in situ* and remote sensing data, re-analysis of existing data sets, data assimilation, numerical experiments and coupled modelling, and process studies including field experiments. It has brought major results both in scientific knowledge and research infrastructure at the European level. Examples include the first coupled regional models for the entire Baltic Sea basin with improved water budget estimates through newly assimilated data sets. Also special observing periods (such as the Pilot Study for Intensive Data Collection and Analysis of Precipitation, PIDCAP) 1995, and BRIDGE, the major enhanced observational period within BALTEX from 1999 to 2002) with dedicated additional observations were conducted in the frame of BALTEX. BALTEX projects are still ongoing in different countries, funded by institutional and national sources.

In the following major achievements are listed.

For the atmosphere:

- Improved understanding of the land-atmosphere interaction in the Baltic Sea basin through observational studies, offline model evaluation and through numerical studies with coupled models.
- Improved knowledge on precipitation and evaporation over the BALTEX region through new instruments, observational data, radar estimates and satellite sensors.
- Development of improved remote sensing techniques to determine e.g. precipitation rates by weather radar, precipitable water by GPS, and cloud climatologies by AVHRR.
- Development of fully coupled atmosphere-land-ocean models of the Baltic Sea basin for present day and climate change applications.

For hydrology and runoff:

- A database of monthly river flow for the entire basin and its major sub-basins has been compiled and is being used extensively for e.g. budget studies and modelling purposes. .
- Large-scale hydrological models of river flow to the Baltic Sea exist.
- Lateral transport of runoff through runoff routing has been applied in climate models.
- Efforts to improve flood forecasting with the help of regional atmospheric models for specific river basins have been made.
- Climate change scenarios of impacts to the water cycle in the Baltic Sea basin have been performed.

For the Baltic Sea:

- Meteorological, hydrological, ocean and ice data are now available for the research community through BALTEX data centres.
- Progress in understanding of the strong impact of large-scale atmospheric circulation on Baltic Sea circulation, water mass exchange, sea ice evolution, and changes in the ocean conditions of the Baltic Sea.
- Progress in understanding of the importance of strait flows in the exchange of water into and within the Baltic Sea.
- Progress in understanding of intra-basin processes.
- Ocean models introduced into Baltic Sea water and energy studies.
- Development of turbulence models and 3D ocean circulation models for application to the Baltic Sea.
- Improved Baltic Sea ice modelling and increased understanding of the need for coupled atmosphere-ice-ocean-land models.

For sea ice:

- Advances of thermodynamic and dynamic coupling between the atmosphere, sea ice, and the sea. Field experiments and modelling studies have yielded new results on local and regional surface fluxes and the interaction of the atmospheric boundary layer, sea ice, and open water.
- Progress in understanding the interaction between sea ice dynamics, thickness distribution, and thermodynamics.
- Progress in understanding the interaction between the structure, physical properties and thermodynamics of sea ice.
- Some advance in understanding the effects of river discharge and ice melt on the oceanic boundary layer below sea ice.
- Advanced understanding of effects of the large-scale atmospheric circulation on the ice conditions in the Baltic Sea.

In spite of the impressive list of achievements within BALTEX Phase I, deficiencies in our knowledge of individual parts of the Baltic Sea climate still exist. The following list presents a few of the open questions and topics, which are bridging into BALTEX Phase II:

- Budgets

A detailed analyses of the water and energy budgets as well as their variability is still missing. Several authors are presenting estimates for individual components of the budgets or budget calculations from measurements or global re-analyses data, which need to be investigated further. Uncertainty ranges should be added on the individual components of the budged and an overall quality measure of the reliability should be developed

In addition the extension of the time period under investigation from 1980–2002 to 1800-2100 provides the opportunity to analyse ongoing and future climate changes in this region. It also allow to investigate trends in the single components of the water and energy budgets. How do these trends influence the trend in the budget? Do they cancel each other? Which component is the dominant one?

- Large scale flow vs local recycling

It is still not fully understand how strong the large scale flow dominates the weather and climate in the individual parts of the Baltic Sea study area. The climate in Northern Europe is strongly dominated by synoptic scale variability on many time scales and hardly any predictability seems to exist beyond a few weeks. A clear understanding of the coupling processes and their time and scale scales is needed to separate the large scales from the local and regional scales. Further studies should address this topic for different seasons and part of the area.

- Regional climate change

State of the art regional climate models indicate that global climate change will also effect the Baltic Sea region. Depending on the strengths and speed in air temperature rise the regional mean temperatures and precipitation pattern will changes as well as their variability. The possible changes of so-called extreme events needs to be better understood and simulated. In addition uncertainty ranges and probability indices have to developed and communicated to associated scientific and public communities.

The influence of global warming on the melting rate of the Greenland ice sheet needs to be understood and modelled. This freshwater inflow to the North Atlantic might cause a slow-down effect of the thermo-haline circulation. Up to now it is not clear how the seas surface temperatures will develop in the future in the North Atlantic and if this will also influence the water in the Baltic Sea itself. This again will influence the climate of the surrounding land areas.

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Appendix B: BALTEX main references

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