The Baltic Sea Experiment (BALTEX): A European Contribution to the Investigation of the Energy and Water Cycle over a Large Drainage Basin

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ABSTRACT

The Baltic Sea Experiment (BALTEX) is one of the five continental-scale experiments of the Global Energy and Water Cycle Experiment (GEWEX). More than 50 research groups from 14 European countries are participating in this project to measure and model the energy and water cycle over the large drainage basin of the Baltic Sea in northern Europe. BALTEX aims to provide a better understanding of the processes of the climate system and to improve and to validate the water cycle in regional numerical models for weather forecasting and climate studies. A major effort is undertaken to couple interactively the atmosphere with the vegetated continental surfaces and the Baltic Sea including its sea ice. The intensive observational and modeling phase BRIDGE, which is a contribution to the Coordinated Enhanced Observing Period of GEWEX, will provide enhanced datasets for the period October 1999–February 2002 to validate numerical models and satellite products. Major achievements have been obtained in an improved understanding of related exchange processes. For the first time an interactive atmosphere–ocean–land surface model for the Baltic Sea was tested. This paper reports on major activities and some results.

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1. Introduction

In the late 1980s the Global Energy and Water Cycle Experiment (GEWEX) was developed within the framework of the World Climate Research Programme (WCRP) (e.g., Chahine 1992). GEWEX aims to provide a better understanding of global, regional, and local processes that exchange energy and water in the climate system of the earth. This improved understanding is needed to overcome the problems of global and regional numerical models that try to reproduce the observed regional transports of water in the atmosphere and at the ground (e.g., Gates 1999; Lau et al. 1996). Six continental-scale experiments (CSEs) were initiated in different climate zones to supply validated tools for numerical forecasting of various branches of the hydrological cycle over all regions of the earth (e.g., Stewart et al. 1998). Since the most accurate measurement of hydrological quantities is river discharge, all these experiments focus on large river basins. Besides climate research many more applications will benefit from this effort, for example, weather forecasting, water management, and agriculture.

In the Baltic Sea Experiment (BALTEX) the entire Baltic Sea drainage basin (Fig. 1) is investigated (e.g., Raschke et al. 1998). This drainage basin extends over a region of about 2.14×10^6 km^2 and ranges from the subarctic climate in northern Finland (~69°N) to the temperate and more continental climate in southern Poland (~49°N). In its longitudinal direction it extends from about 8° to 40°E. The Baltic Sea itself covers an area of about 394 000 km^2. Tributaries from the territories of 14 countries discharge about 450 km^3 yr^{-1} freshwater into the Baltic Sea (see section 4). Major freshwater contributors are the rivers Neva, Vistula, Odra, Kemijoki, Luleälv, and Torneälv, among others. The coexistence of large continental surfaces with many lakes in Finland and Sweden and with the Baltic Sea provides the challenge of a close collaboration between atmospheric physicists, hydrologists, and oceanographers.

This region, home to about 90 million inhabitants, has experienced drastic political and economic developments, which often were related to climate events (e.g., Neumann and Kington 1992). The recent political situation is the basis of rapid economic and societal changes with all their advantages and disadvantages for the environment.

The primary scientific objectives of BALTEX, as defined in several workshops, are

- to develop and validate regional models coupling interactively the atmosphere to continental surfaces and the Baltic Sea, which can later be transferred to other regions;
- to provide a more reliable understanding of relevant physical processes; and
- to investigate the climate in this region and its dependence on large-scale circulation anomalies of our global climate system.

To reach these goals, data from in situ networks and satellite observations are analyzed. Models of meteorological and hydrological services, as well as research centers and universities, are improved and coupled. Where needed, field campaigns are conducted to understand climate processes. Hereby, the transferability of models and methods to other

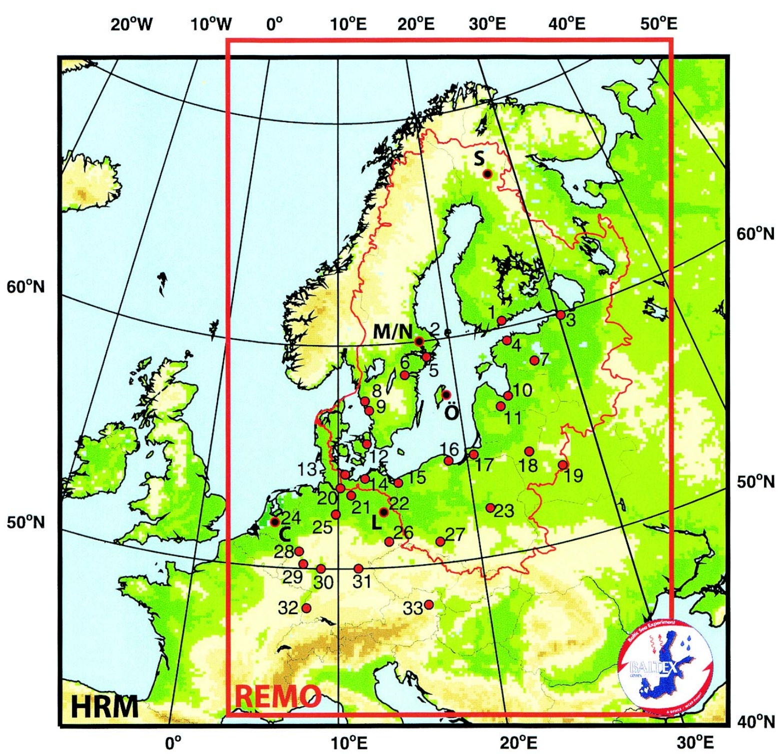

FIG. 1. The Baltic Sea catchment and locations of research groups, contributing to BALTEX. Names of the institutes are given in the appendix. The red lines indicate the area covered by regional numerical models. The letters C, L, Ö, M/N, and S describe the location of a major observational station [see section 3c(1)].

basins is a major objective. Immediate products of this research are improved short-term and medium-range weather forecasts and water management applications.

More than 50 research groups and operational services from 14 European countries (Fig. 1) participate in BALTEX-related research with numerical modeling, field studies, operational observations, and analyses of satellite data. The research and operational activities within BALTEX are coordinated by a science steering group. An international project office (http://w3.gkss.de/baltex/) links all groups and activities. Four data centers established at national services are responsible for the collection and dissemination of hydrological and radar [both at Swedish Meteorological and Hydrological Institute (SMHI) in Norrköping, Sweden], oceanographic [Finnish Institute of Marine Research (FIMR) in Helsinki, Finland], and meteorological [Deutscher Wetterdienst (DWD) in Offenbach, Germany] data. The BALTEX activities began in 1992 and will continue until the end of 2005. Its second phase, named BRIDGE, is concentrating on enhanced data collection and on dedicated process-oriented studies. Figure 2 shows the major steps of its development and planned activities.

This paper provides an overview of the scientific challenges investigated within BALTEX. First, an overview of the Baltic Sea drainage basin is given. This is followed by a description of the data acquisition and analyses carried out in the frame of BALTEX. The numerical models used are briefly introduced and some results of the model simulations and their comparison with measured data are discussed. First attempts are undertaken to quantify the water and energy cycle over the Baltic Sea.

2. Climate in the BALTEX area

Weather and climate in the BALTEX area are controlled by the circulation of the atmosphere over the North Atlantic in the west and over the Eurasian continent in the east. The BALTEX area belongs to the transition zone between the maritime climate of western Europe and the strongly continental climate of Siberia. Therefore, the climate of the northern part is dominated by boreal forests in contrast to the temperate humid climate in the south (Johannessen 1970). The seasonal temperature amplitudes from south to

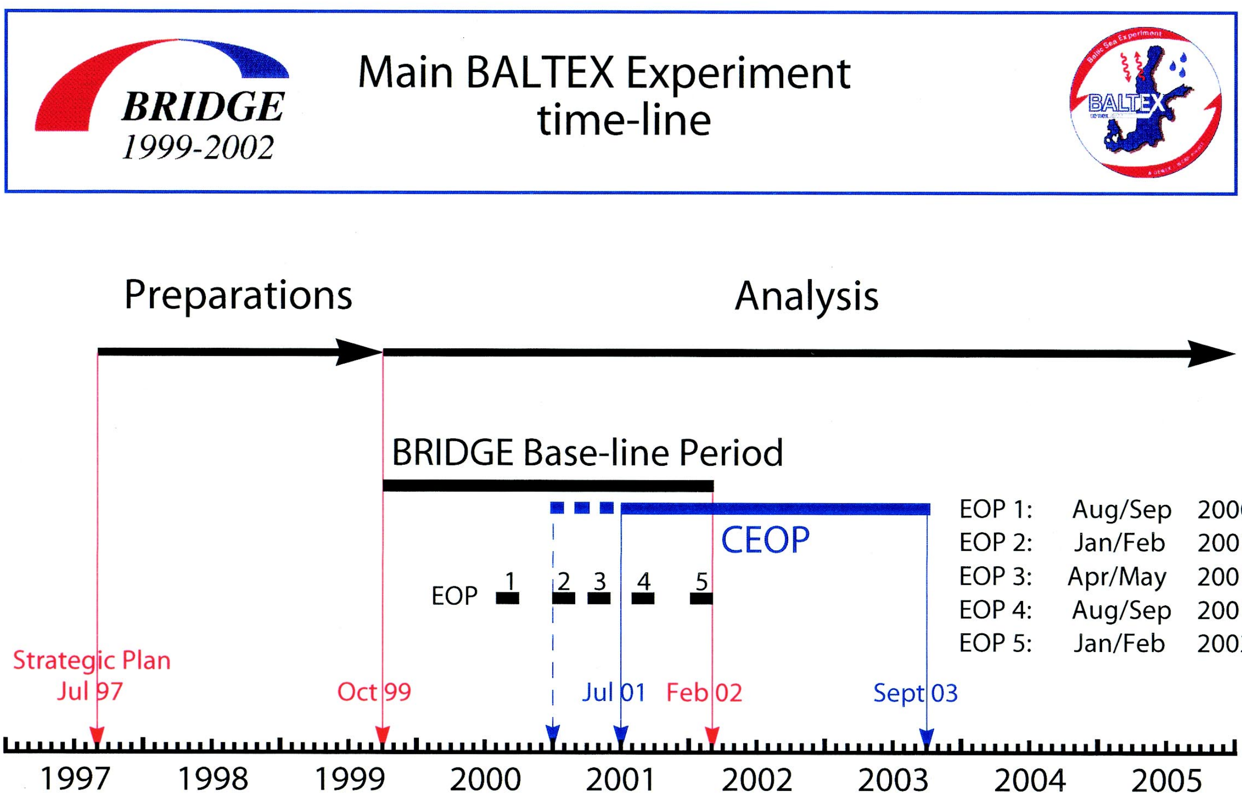

FIG. 2. Major activities within the BALTEX. Enhanced Observing Periods (EOPs) are defined to concentrate on specific process-oriented studies. CEOP is the Coordinated Enhanced Observational Period of all CSEs.

north are displayed in Table 1. The increase in amplitude is mainly caused by a decrease of the average winter temperatures. These temperature differences also provide a hint about the influence of the Baltic Sea on adjacent land areas.

The effect is also found in the pressure analysis performed by Speth and Skade (1977) who find a surface pressure minimum over the northern Baltic Sea during all seasons except in fall. This minimum is, however, very shallow. It cannot be found above the 850-hPa level. Thus, the earlier analyses by Defant (1972) are not incompatible with the latter ones, showing that at 850 hPa the winds are predominantly from the west (270° ±25°).

The main control of weather and climate of the BALTEX area is provided by cyclones that migrate from the North Atlantic toward the east (Johannessen 1970). Thus one can assume that a link must exist between the North Atlantic oscillation (NAO) and the temperatures over Scandinavia, in particular during winter. Van Loon and Rogers (1978) confirmed that the so-called temperature seesaw between northern Scandinavia and Greenland is related to the NAO. Koslowski and Loewe (1994) also show that the ice volume in the western Baltic Sea is negatively correlated with the NAO index. Recent investigations reveal a change in that relation. Hilmer and Jung (2000) discover that the centers of action of the NAO, in particular the northern part, have shifted toward the east during the last 20 years. As a consequence the correlation between the NAO and the winter temperatures [Dec–Jan–Feb–Mar (DJFM); see Fig. 3], has significantly increased from the period 1958–77 toward the period 1978–97. Over Estonia some significant trends occurred during the second half of the twentieth century (Keevallik et al. 1999). Snow cover has decreased during the last 40 years by 15–16 days in March and April (Tooming 1996). March temperature has increased by 4°C and in the same month the amount of low clouds has increased. Tiesel (1984) studied several shallow heat cyclones over the Baltic Sea.

The effect of the Baltic Sea as a heat source for the surrounding land areas is also evident in the distribution of the sensible heat flux. Henning (1988) calculated the fluxes from individual observations (1862–1978) for the weather stations around the Baltic Sea and ships of opportunity. He obtained a maximum of the sensible heat flux for the Baltic proper (see his Fig. 13) in December and January. Studies with data from more recent years by Bumke (2001, unpublished manuscript) and by Omstedt and Rutgersson (2000) confirm these earlier results of Henning (1988).

Isemer and Rozwadowska (1999) extracted cloud observations of voluntary observing ships from the Comprehensive Ocean–Atmosphere Data Set (COADS; Woodruff et al. 1987). They found that the mean annual cycle of total cloud cover over the Baltic proper shows a pronounced annual amplitude with lowest monthly values of 50% during May–July and highest values of 75% during the winter months.

Radiation fluxes at the Baltic Sea surface have usually been estimated by either extrapolation of the coastal actinometric measurements to the open sea area or by application of radiation parameterizations to marine meteorological observations. Rozwadowska and Isemer (1998) calculated monthly and annual estimates of incident solar radiation flux at the surface of the Baltic proper for the years 1980–92 using several parameters from the COADS datasets. Surface solar radiation at the Baltic proper shows a dominant annual cycle with mean monthly values ranging from 20 W m^{-2} in December to 250 W m^{-2} in July. Kaczmarek and Dera (1998) calculated the solar irradiance reaching the sea surface for 20 subregions using monthly mean input data from the period 1970–90. They find for the southernmost part an annual average

TABLE 1. Annual mean near-surface air temperature and its annual amplitude across the BALTEX area indicating the influence of SSTs on local climate (from Müller 1979).

Name	Lat (N)	Long (E)	*T* amplitude (K)	Mean temperature (°C)
Greifswald	54°06'	13°27'	19.1	+8.3
Sandvig	55°17'	14°47'	17.6	+8.2
Stockholm	59°21'	18°04'	20.9	+6.6
Härnosand	62°28'	17°57'	22.8	+4.4
Haparanda	65°50'	24°09'	27.4	+1.6
Sodankylä	67°22'	26°36'	28.2	–0.4

of 143 W m^{-2} with only very little spatial variability (1.5%). Maximum values of irradiance are found in June (293 W m^{-2}) and minimum values are calculated to be 14 W m^{-2} in December.

The Baltic Sea drainage basin represents a typical continental scale and can thus be used as a huge rain gauge or test site for coupled atmosphere–land–ocean modeling. The atmospheric water and energy budgets can be determined by considering the net flux through the Danish straits, the entrance area of the Baltic Sea, which amounts to about 450 km^3 yr^{-1}. More than 50% are discharged by rivers during the melting season only (Fig. 4).

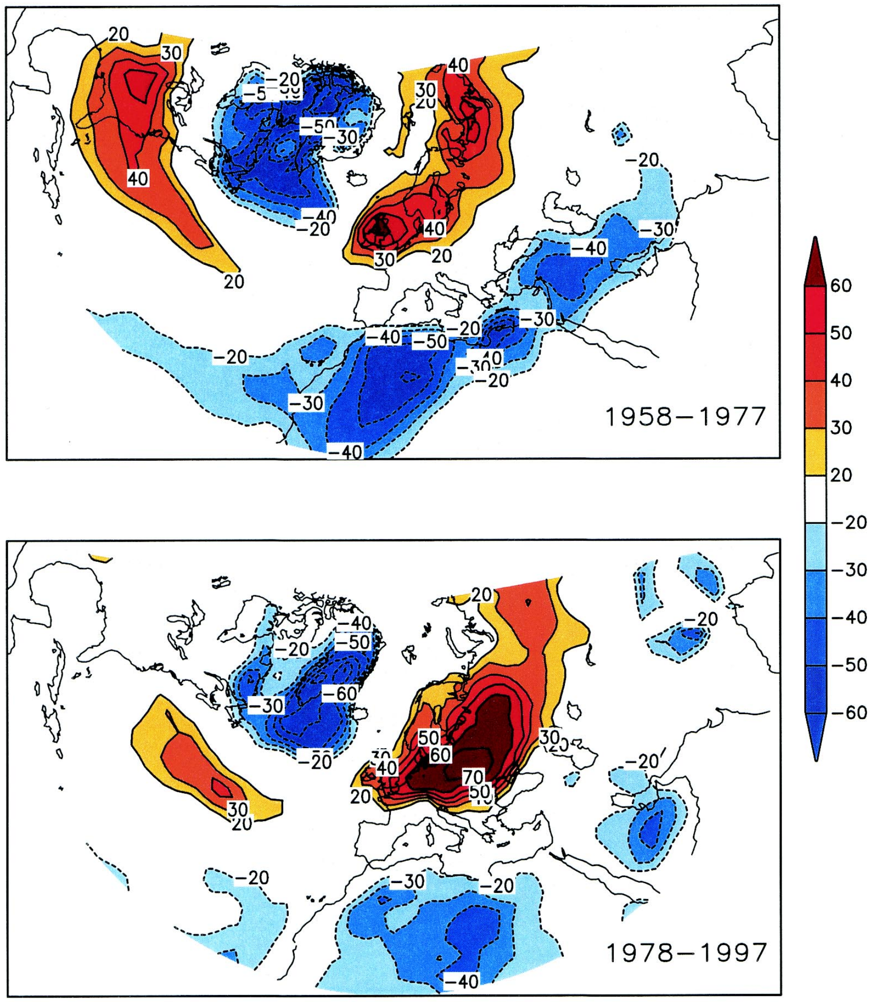

Fig. 3. Squared correlation coefficient between the NAO index and winter (DJFM) temperatures over the Northern Hemisphere for the periods (top) 1958–77 and (bottom) 1978–97 (from Hilmer and Jung 2000). Only values above (below) +20%(–20%) are shown.

During major saltwater intrusions, which tend to occur after a long-lasting (about 3 weeks) high pressure system over the Baltic Sea followed immediately by strong westerlies, often more than 300 km^3 of saltwater from the North Sea can penetrate into the sea within a few days. This heavier and oxygen-rich water then can penetrate near the bottom of the Baltic Sea farther northeast providing oxygen for life in the lowest layers. Figure 5, from Lass and Matthäus (1996), shows the occurrence of such major intrusions since 1900. Note, apart from a major event in 1993, there had been no major saltwater intrusions since 1983. The length of each column represents both the salinity of the intruding water and the duration of the event. The correlation between large-scale atmospheric circulation and maximum annual ice extent in the Baltic Sea has recently been investigated by Omstedt and Chen (2001). They showed that the ice extent is fairly well correlated to the NAO index during winter. However, the moving correlation analysis showed that the relationship is not stationary over time. The authors also showed that the significant long-term (1720–1997) decreasing trend in the maximum ice extent is associated with a significant regime shift in 1877. The change indicates a shift from a relatively cold climate (Little Ice Age) to a relatively warm one.

3. Data acquisition and analysis

It is of vital importance for the scientific goals of BALTEX to use as many observations as possible to 1) better understand the physical processes governing the exchange of water and energy between the land surface, the Baltic Sea, and the atmosphere; and 2) initialize, test, and run coupled regional models that quantify the water and energy budget of the Baltic drainage basin. Therefore, one major goal of BALTEX is to collect as much data as possible from

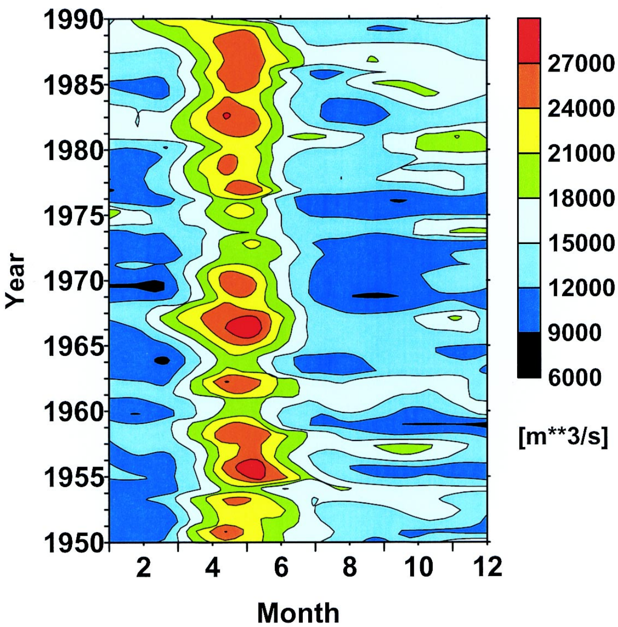

FIG. 4. Seasonal runoff (in m^3 s^{-1}) into the Baltic Sea, showing a strong interannual variability during the summer and fall (Bergström and Carlsson 1994).

existing networks like the Global Telecommunication System (GTS) of the World Meteorological Organization and other sources. In addition, specific field experiments are conducted to develop and test better parameterizations for the exchange of energy and water. While most of the mentioned data sources provide point measurements, remotely sensed data (from satellite and ground based) give either areal coverage or vertical profiles.

a. In situ measurements

The BALTEX area and its neighborhood are well covered with ground-based synoptic and radiosounding stations. Most of the data used for BALTEX are distributed via GTS on a routine basis. There is also a very dense network of Global Positioning System (GPS) receivers. In addition many hundreds of rain and river gauges exist in national networks. All available data are collected within the frame of BALTEX. They are quality controlled, archived in the respective data centers, and made available to the entire BALTEX community.

1) Ground stations

Several continuously measuring sites with special equipment are actively contributing to BALTEX. These are the field sites near Lindenberg (L) Marsta and Norunda (M/N), Cabauw (C), Sodankylä (S), and Östergarnsholm (Ö). The location of the sites is shown in Fig. 2. Towers and profilers have been in operation for a few years and measure, for instance, vertical fluxes of water vapor. This information is routinely used in forecast models and process studies.

Measurements representative of the conditions over the Baltic Sea are those from Östergarnsholm in the middle of the Baltic Sea. Other stations represent typical conditions over agricultural land and forests in the center of the Baltic Sea drainage basin (Marsta and Norunda), typical features of the southern part of the drainage basin (Lindenberg and Cabauw), and over the northern part with long winter periods (Sodankylä).

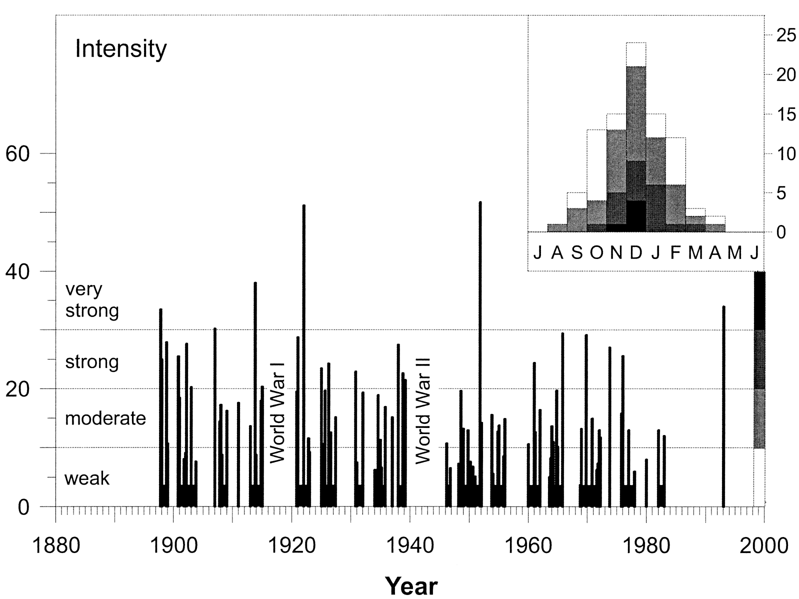

FIG. 5. Frequency of major saltwater intrusions through the Danish belts and straits into the Baltic Sea after the year 1900 (from Schinke and Matthäus 1998). The histogram on top right explains the seasonal distributions of these events.

2) Precipitation correction and analysis

Existing long-term precipitation climatologies for the Baltic Sea or the Baltic Sea drainage basin have been calculated from routinely available synoptic data (e.g., Omstedt et al. 1997) or have been extracted from merged global satellite–gauge products. The annual mean precipitation in the Baltic Sea drainage basin is about 2 mm day^{-1} with a maximum in August (2.7 mm day^{-1}) and a minimum in April (1.3 mm day^{-1}).

During the period 1 August to 31 October 1995 (Isemer 1996), the BALTEX Meteorological Data Centre collected rain gauge data from national climate networks, and Rubel (1998) compiled high-resolution daily precipitation fields. A precipitation correction and analysis model has been developed to calculate the areal precipitation. This model consists of a dynamical bias correction module and a geostatistical module. The bias correction reduces the systematic undercatch of the rain gauges due to wind-induced evaporation and wetting losses taking instrument specifics into account (Rubel and Hantel 1999). The dimensionless mean correction factor shows a maximum in February (1.25–1.50) and a minimum in August (1.02–1.05). The present high-resolution climatology includes area-averaged time series of daily precipitation (Fig. 6) and time-averaged distributions of annual precipitation, valid for the BALTEX catchment. These data have been used to verify the NWP models improved during BALTEX and of the products of the Global Precipitation Climatology Project of GEWEX (Rudolf and Rubel 2000). A similar bias correction has been implemented by Michelson et al. (2000b) on 12-h synoptical gauge observations prior to gauge adjustment of radar data [section 3a(1)]. Results of the mesoscale analysis system (Michelson et al. 2000a), developed by SMHI, have been compared to precipitation fields derived from shipborne rain gauge measurements (Hasse et al. 1998; Clemens and Bumke 2000), which have been conducted since 1996 onboard several ferry boats cruising between Germany, Poland, and Finland. Generally, precipitation fields based on direct measurements on ships are higher than those calculated by the mesoscale analysis system (MESAN). This can be partly explained by 1) a too small gauge correction to account for wind speed, wetting, and evaporation losses for stations used in MESAN; and 2) the interpolation assumption in MESAN that is not quite correct for areas over the Baltic Sea. A comparison to nearby coastal synoptic stations, which have been corrected according to Rubel and Hantel (1999), again shows an underestimation of precipitation by MESAN by about 10 mm month^{-1}, while the interpolated fields based on ship rain gauge measurements underestimate precipitation by only 3 mm month^{-1}. This dataset is then considered to be the truth for further use.

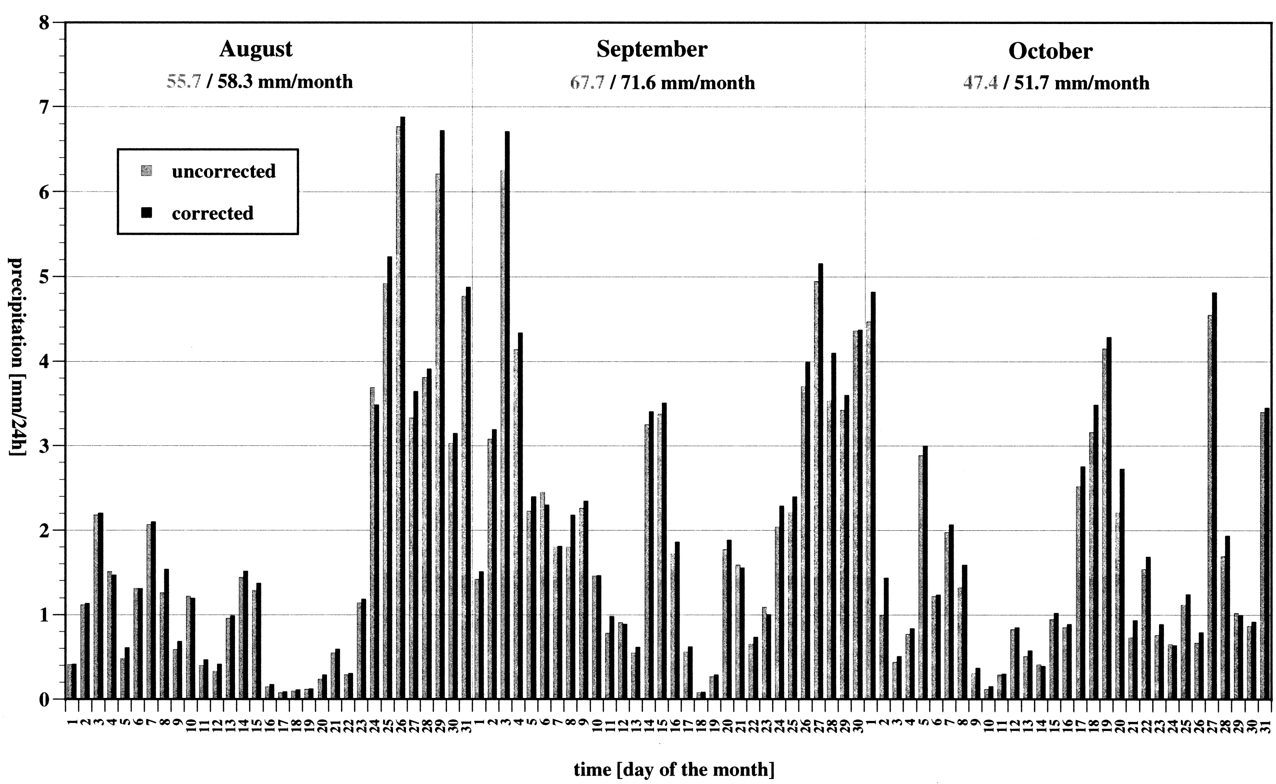

FIG. 6. Time series (1 Aug–31 Oct 1995) of daily precipitation averages (mm day^{-1}) within the Baltic Sea drainage basin based on both uncorrected (gray) as well as corrected (black) rain gauge data.

b. Remote sensing

Remotely sensed data support BALTEX field campaigns, model validations, and climate studies. They are supported by the large amount of ground truth data, which also can serve as a test bed for the development of new remote sensing schemes. In this section we show three examples from ground-based remote sensing, the weather radar to determine precipitation rates and amounts, GPS data to estimate precipitable water, and Advanced Very High Resolution Radiometer (AVHRR) analysis to calculate cloud climatologies over the Baltic Sea area.

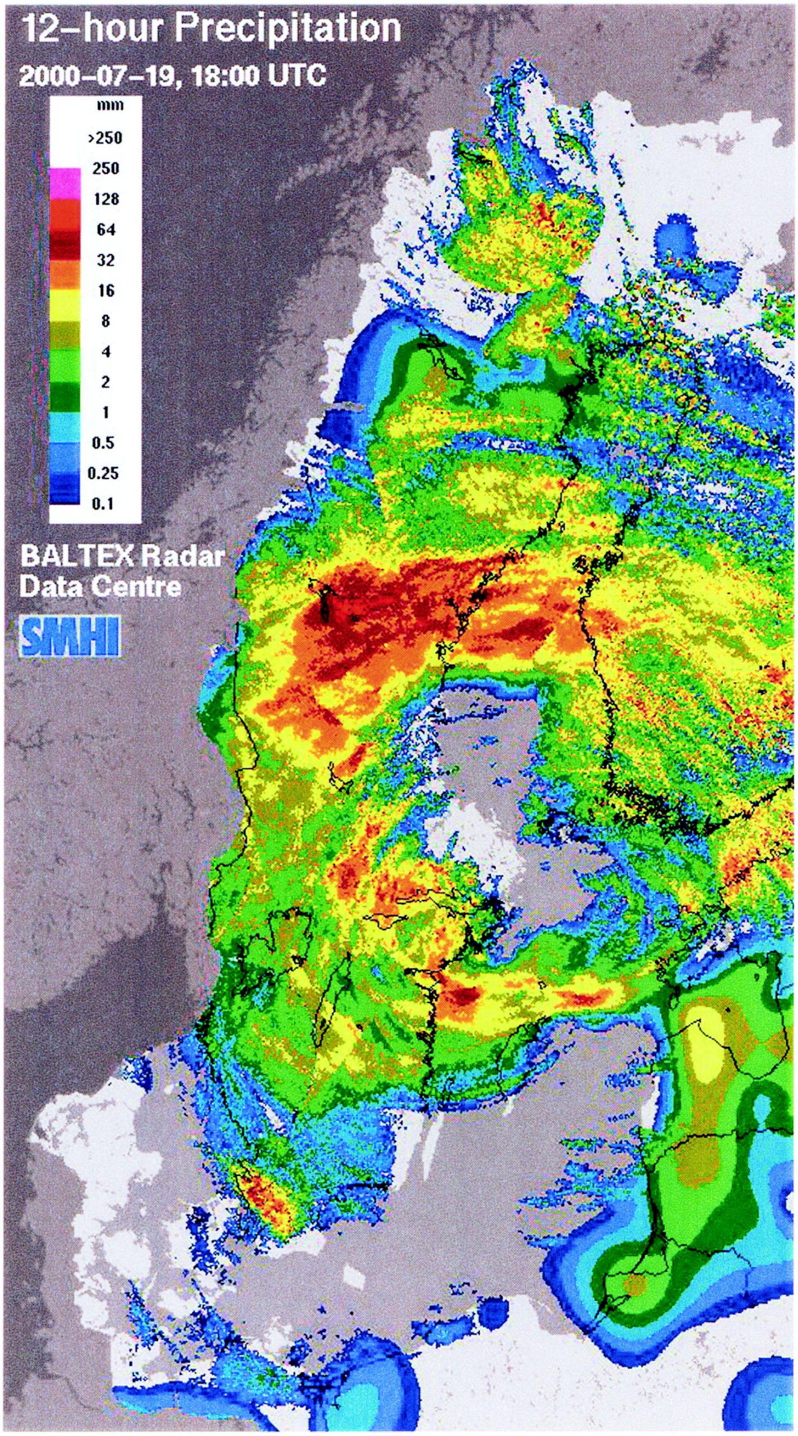

FIG. 7. Image of a 12-h, gauge-adjusted, accumulated precipitation product (Michelson and Koistinen 2000) from 19 July 2000 at 1800 UTC. This event, together with a sequence of others, caused severe and widespread flooding in central Sweden.

1) WEATHER RADAR

The BALTEX radar network (BALTRAD) consists of 29, mostly C band, radars in six countries. Data transmission to and from the BALTEX Radar Data Centre (BRDC) in Norrköping, Sweden, is achieved by operational lines and through provisional Internet-based solutions. The BRDC operates in near–real time, and its datasets (Michelson et al. 2000b) are available to users on CD-ROM throughout the BRIDGE period. More radars will be installed in Estonia, Latvia, and Poland. The BRDC applies and evaluates new product and quality control algorithms, a simple example of which is hybrid radar imagery, where Doppler data, covering part of the radar coverage area, are merged with non-Doppler data covering the remainder of the area. Multiscore methods for identifying and removing spurious radar echoes integrate Meteosat IR data with operationally analyzed 2-m temperatures. Vertical wind profiles are also BRDC datasets and these are generated using well-known techniques.

The highest-level precipitation product in the BRDC datasets is the gauge-adjusted accumulated precipitation, with 3- and 12-h (Fig. 7) accumulation times. A detailed description of the algorithms used is given in Michelson and Koistinen (2000).

In addition, new methods are developed to assimilate the radial winds from weather radar into NWP models. Lindskog et al. (2000) present a method for deriving radar radial wind observations, along with the methods used to assimilate them into a limited-area NWP model using a 3D variational approach. In a case study, it is shown that the model is unbiased with respect to the radar observations, and that the rms's of the analysis departures are smaller than the rms's of the background departures.

2) GPS PRODUCTS

A dense network of geodetic and meteorological GPS receivers over Scandinavia encouraged early comparisons of measured and modeled amounts of total atmospheric water content at several locations. Water vapor in the atmosphere is changing the speed of the GPS signals. Hence it is possible to estimate the water vapor content through determining these time differences. Figure 8 shows such a comparison, indicating that models tend to overestimate the atmospheric water vapor content.

3) AVHRR CLOUD CLIMATOLOGY

A cloud climatology based on four National Oceanic and Atmospheric Administration (NOAA) AVHRR overpasses per day over the area has been derived from a 10-yr period. The basic method is described in Karlsson (1997) and results can be found in Karlsson (2000a,b).

Figure 9 shows a 10-yr analysis (1991–2000) of cloud frequencies for the summer season (Jun–Aug). The most striking feature of this time series is the large interannual variability of cloud cover and related weather. Furthermore, the effect of heat and moisture exchange on lower clouds and on convection is clearly visible. The relatively cool sea surfaces generally suppress cloud formation. This does not appear to be true over the North Atlantic Ocean, visible in the upper-left corner of each panel of the figure, where the uplifting enhances the cloudiness.

The annual cycle of cloudiness extracted from the satellite dataset has been found to agree well with the corresponding cycle found from studies of ship observations (Isemer and Rozwadowska 1999). Results will be used to validate regional climate model simulations at the SMHI Rossby Centre and special attention will be given to studies of the diurnal and annual cycle of cloudiness and to the testing of various cloud parameterization schemes.

c. Specific field campaigns

Several specific field studies have been carried out to better understand exchange processes of water vapor and energy in the area. All of the experimental sites, listed below, are equipped with flux towers, estimating the turbulent heat and momentum fluxes at different altitudes above the ground.

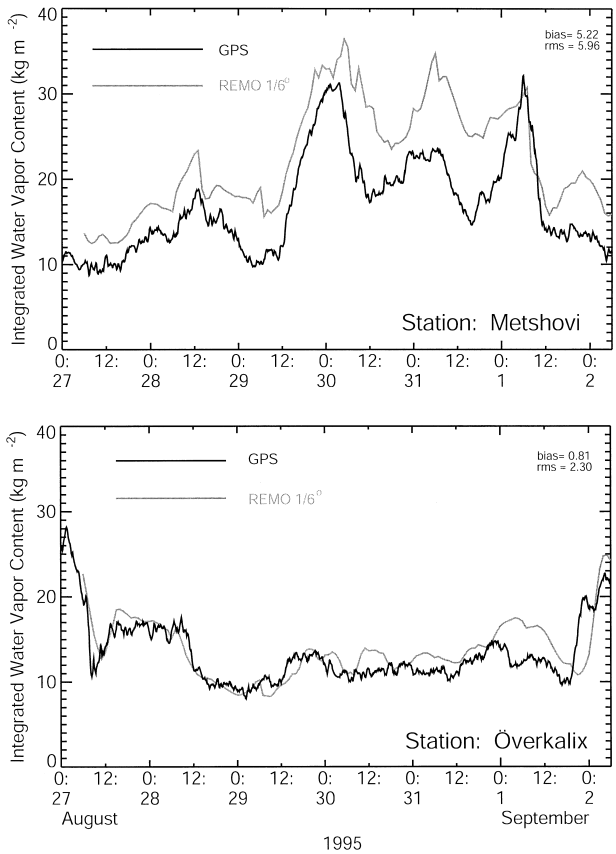

FIG. 8. Total atmospheric water vapor at two stations in Sweden as derived from GPS signals (from G. Elgered, Chalmers University) and simulated with the model REMO during a 5-day period in fall 1995.

1) Northern Hemisphere Climate Processes Land-Surface Experiment (NOPEX-Summer): This experiment was based over a typical northern European landscape near Uppsala. The experimental region represents the southern part of the boreal zone with a mixture of forests, agricultural fields, mires, and lakes. It covers about 50×50 km^2. The experiments took place in the summer of 1994 and spring/summer of 1995 (Halldin and Gryning 1999).
2) NOPEX-Winter, also called the Winter Experiment: This experiment was based at the Sodankylä Meteorological Observatory in Finnish Lapland during March and April 1997, representing the northern part of the boreal zone, and at the NOPEX

site representing the southern boreal zone (Harding et al. 2001).

3) Lindenberg Inhomogeneous Terrain-Fluxes between Atmosphere and Surface—A Long-Term Study (LITFASS): LITFASS was based near Lindenberg, southeast of Berlin, Germany. This area exhibits a slightly undulating landscape with patches of forest, agricultural land, and lakes, which is typical of the southeastern part of the Baltic Sea drainage basin. A major field experiment was conducted in 1998 (Beyrich et al. 2000).
4) Tropospheric Energy Budget Experiment: This experiment took place over an area of 100×100 km^2 around the tall (213m) meteorological mast at Cabauw, Netherlands. The existing meteorological operational network at Cabauw was extended with a cloud detection network (van Lammeren et al. 2000) and upward-looking infrared instruments as well as a profiler–Radio Acoustic Sounding System system in order to determine cloud microphysical properties and their impact on the energy budget. The experiment was performed during 1995–96 (Fejit and van Lammeren 1996).
5) Baltic Air–Sea–Ice Study: This experiment was based over the Gulf of Bothnia to improve parameterizations of air–ice–ocean interaction processes. The field experiments were conducted from a research vessel in the sea ice edge zone of the Baltic Sea until recently (Launiainen and Vihma 2001).
6) Pilot Study of Evaporation and Precipitation in BALTEX (PEP): This experiment was held over the Baltic Sea along a transect from the northern coast of Germany to southwestern Finland. For an 18-month period (1998–2000) PEP provided a comprehensive set of actual evaporation data, measured with the eddy correlation technique at four sites, as well as precipitation, measured by a micro–rain radar.
7) Diapycnal Mixing in the Stratified Ocean (DIAMIX): The surveys of DIAMIX aim at a better understanding of diapycnal mixing and improved parameterizations of mixing processes in the Baltic Sea. The study area east of Gotland in the Baltic is chosen for its lack of tides while different modes of wind exerted motions can be studied. Surveys of 10–15 days have been carried out during two summer periods—June 1998 and September 2000—and one winter period—March 1999.
8) BALTEX Cloud Liquid Water Network (CLIWANET): This experiment measures micro- and macrophysical cloud field properties by coordinating existing, ground-based passive microwave radiometers and profiling instruments. This network was operated during the first enhanced observing period (EOP1) of BRIDGE (Aug/Sep 2000) and will be operated during the third EOP (April/May 2001).

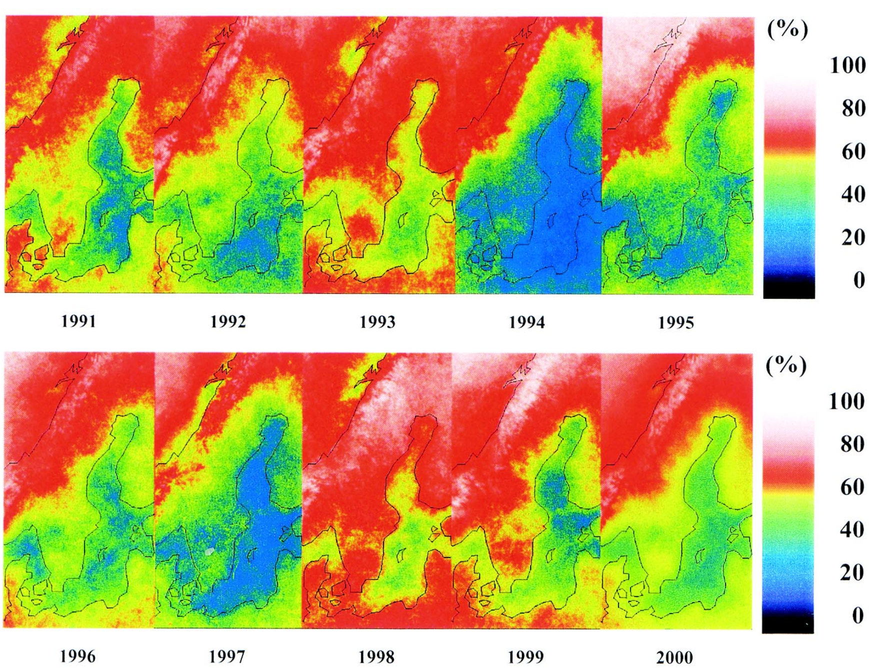

FIG. 9. Summer cloud frequencies (%) over Scandinavia in the period 1991–2000 derived from NOAA AVHRR data.

4. Numerical modeling

Numerical models of the atmosphere, land surface, rivers, lakes, oceans, and sea ice are used and some of them are coupled interactively to study the energy and water cycle components in the Baltic Sea drainage basin. Various studies have been conducted to validate model results using, for example, data as described in the previous section to look for the sensitivity of results on the input analyses, to study long time series, and to close the water and energy budget. This section introduces some of the models and results from simulations of specific time periods.

Several of the models in use within BALTEX have been applied to other regions on the globe within the framework of the GEWEX projects: the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS; Henderson-Sellers et al. 1995), the GEWEX Cloud System Study (GCSS; e.g., Ryan et al. 2000), and the Project to Intercompare Regional Climate Simulations (Takle et al. 1999).

a. Regional models of the atmosphere

To enable an effective feedback with operational weather services in the BALTEX area, their numerical regional models are used in the framework of BALTEX. This allows to use operational field analyses and to avoid uncertainties in model interfaces. The models originate from the German Weather Service (DWD) and from the national weather services of the Nordic countries. The numerical models are the regional model (REMO) based on the Weather Forecast Model of the DWD (Majewski 1991) and the High Resolution Limited Area Model (HIRLAM) maintained by the national meteorological services of Denmark, Finland, Iceland, Ireland, Netherlands, Norway, Spain, and Sweden (Källen 1996). Both models are available in the forecast and the climate mode.

The main period of interest for the model simulations in the forecast mode was the during the Pilot Study for Intensive Data Collection and Analysis of Precipitation (PIDCAP; Aug–Oct 1995). During PIDCAP all available data were collected over the BALTEX area with inclusion of those not available in the operational GTS messages. These are data from all synoptic and precipitation stations, from ship measurements, and water vapor from GPS and the Special Sensor Microwave/Imager; cloud cover and cloud water from International Satellite Cloud Climatology Project-DX (ISCCP-DX) dataset; and runoff data from river gauges. Some comparative studies were carried out within projects funded by the European Union: Numerical Studies of the Energy and Water Cycle in the Baltic Region I (NEWBALTIC; Bengtsson 1998) and NEWBALTIC II (Bengtsson 2000). Climate studies focus on the period of 1979–94.

1) Simulations with REMO-GKSS in the forecast mode

The GKSS Research Centers version of REMO (hereafter called REMO-GKSS) is based on the Europa Model (EM) of DWD. Some modifications were introduced concerning prognostic variables and the model diagnostics. The hydrostatic model is used in a 0.5° horizontal grid version covering Europe and the North Atlantic, in which a 1/6° version covering the BALTEX area is nested. Depending on the case study, initial and boundary conditions were taken from the DWD, the HIRLAM, and the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses. REMO-GKSS was validated with data from several target periods of the years 1993–95. Consecutive 30-h forecasts are performed starting each day at 0000 UTC. This procedure facilitates a comparison with measurements of high resolution in space and time.

Some results are briefly summarized here. For the PIDCAP period the total precipitation is overestimated by REMO-GKSS by about 20% but is modeled differently with slightly different input (Fig. 10). The near-surface winds are too high by about 1 m s^{-1}. Generally there is a fair agreement of the total atmospheric water vapor content between in situ observations and GPS-derived data, where the models tend to be too moist.

For March 1994 radiative fluxes at the top of the atmosphere derived from measurements by the Scanner for Radiation Budget (ScaRaB) were used to evaluate fluxes calculated by REMO-GKSS (Hollmann et al. 1999). The areal and monthly averages of outgoing longwave fluxes were too low by 4 W m^{-2} with maximum values deviations of 10 W m^{-2} over the Alps and Norway since too many high clouds are simulated by the model. This was improved by implementing a new cloud scheme into REMO-GKSS (Zhang et al. 2001) leading to an average overestimation of the longwave fluxes by 2 W m^{-2} with maximum differences of 5 W m^{-2}, that is, remaining within the error range of ScaRaB.

Since 1999 an updated version of the EM, the High Resolution Model (HRM), is available and used instead of REMO-GKSS. Johnsen and Rockel (2000) showed that the HRM produces an overall too moist atmosphere, since the operational analyses taken as initial and boundary data have also been too moist. Comparisons of simulated (HRM) and satellite-derived (ISCCP-DX data) cloud properties show that the simulated total cloud cover is 10%–15% higher than the satellite-derived values. In contrast, the simulated cloud water path is about 200 g m^{-2} smaller than the ISCCP values. In this context the investigation of the vertical cloud structure is important. The simulated values of high- and low-level clouds are 10%–30%

larger than the ISCCP values at these levels. However in the medium level there are about 5%–25% fewer simulated clouds than ISCCP-derived clouds (I. Meinke 2000, personal communication). This is in agreement with the results from an intercomparison within the framework of the GEWEX Cloud System Study showing that most regional models produce too many high-level and too few medium-level clouds (e.g., Ryan et al. 2000).

2) Data assimilation with the HIRLAM system

HIRLAM is a limited-area model system for operational weather forecasting. The baseline forecast model is a hydrostatic three-time-level, semi-implicit, limited-area gridpoint model (Källen 1996). Together with the REMO this model was tested in the projects NEWBALTIC I and NEWBALTIC II (Bengtsson 1998, 2000). Additionally to a model intercomparison carried out in three projects HIRLAM was coupled to a lake model in NEWBALTIC II (see section 4d). In the framework of BALTEX a special version of HIRLAM is now in development. It quantifies water and energy budgets by data assimilation and will be essential during BRIDGE. Recent modifications include the parameterization of large-scale condensation (Rasch and Kristjansson 1998) and convection (Kain and Fritsch 1998). The convective part uses the turbulent kinetic energy (TKE) as a trigger and is closely linked to the turbulence scheme, which is based on the TKE as a prognostic variable (Cuxart et al. 2000). Radiation is treated according to Savijärvi (1990). Parameterization of soil moisture and runoff is based on soil moisture variability functions used in hydrological models.

At the lateral boundaries the model is forced with ECMWF operational analyses updated every 3 h. The analysis of atmospheric variables is based on a variational formulation (e.g., Lindskog et al. 2000). 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 (Lynch and Huang 1992).

At the surface, snow and sea surface temperature (SST) observations are assimilated. The SST and ice evolution in the Baltic Sea are computed with an ocean–ice model (Gustafsson et al. 1998). The numer-

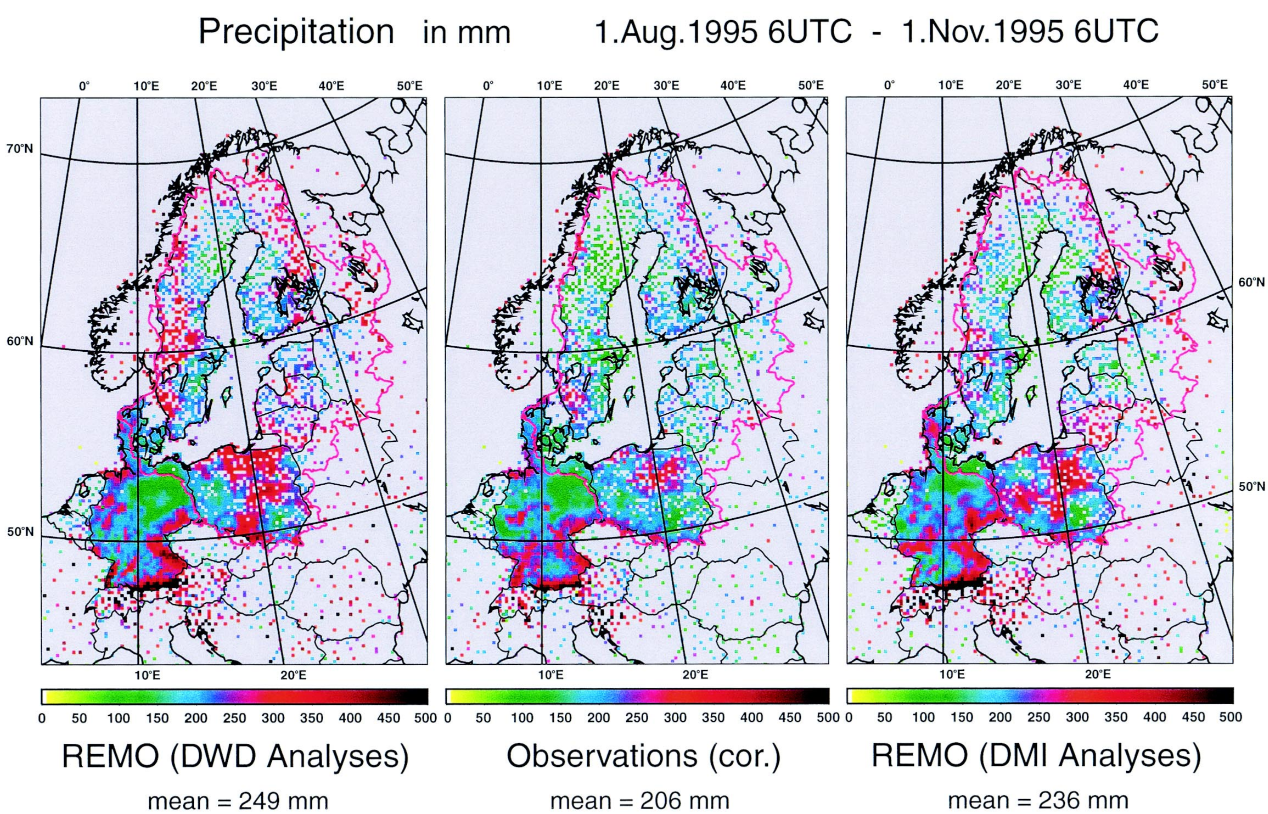

Fig. 10. Precipitation during the PIDCAP period (1 Aug–31 Oct 1995), measured and corrected data (center) and modeled with analyses of the DWD (left) and DMI (right). Each dot indicates a grid area with at least one rain station. The precipitation was corrected with the dynamic correction model by Førland et al. (1996).

ous lakes in Scandinavia are described with lake models (Ljungemyr et al.1996), which are forced with atmospheric data from the forecast model, and coupled through updated temperature and ice fields.

3) Simulations with REMO in climate mode

To investigate the annual and interannual variability of the water budget for today's climate, several experiments with a climate mode of REMO have been performed (Jacob et al. 2001). The baseline experiment is a continuous simulation for the years 1979–94 using REMO with a horizontal resolution of 0.5°, which has been carried out and validated against observations. REMO is initialized once and continuously driven with ECMWF reanalyses data at the lateral boundaries. Figure 11, taken from Jacob (2001), shows the time series of observed and simulated total precipitation (monthly values in mm) in the Baltic Sea drainage basin. It can clearly be seen that the simulated time series shows no systematic trend, which has not been corrected for undercatch (the correction is about 5%–10%). The model overestimates the long-term mean precipitation by 5%–8%. A stronger overestimation of precipitation in spring can be observed. This can either be initiated by advection of too much moisture through the boundaries (too moist ECMWF reanalyses in spring) or it can be related to strong convective activity over soils, which are too wet due to an unrealistically early start of the snowmelt season. These results are under further investigation (see also Jacob 2001). Long-term measurements of water vapor in the atmosphere (e.g., from ground-based GPS data) could help to identify the processes causing the systematic error. Here the importance of validating against all hydrological components becomes obvious.

b. *Link between the atmosphere and rivers: Land surface models*

Land surface models [LSMs; see summary by Koster et al. (2000)] provide the lower boundary conditions for atmospheric circulation models and calculate the water fluxes within the unsaturated soil for hydrological models. Their complexity ranges from simple bucket models to sophisticated soil–vegetation–atmosphere transfer (SVAT) schemes with multiple vegetation, soil, and snow layers. Recent developments in land surface modeling include the representation of subgrid heterogeneity in surface characteristics, photosynthesis–transpiration physics,

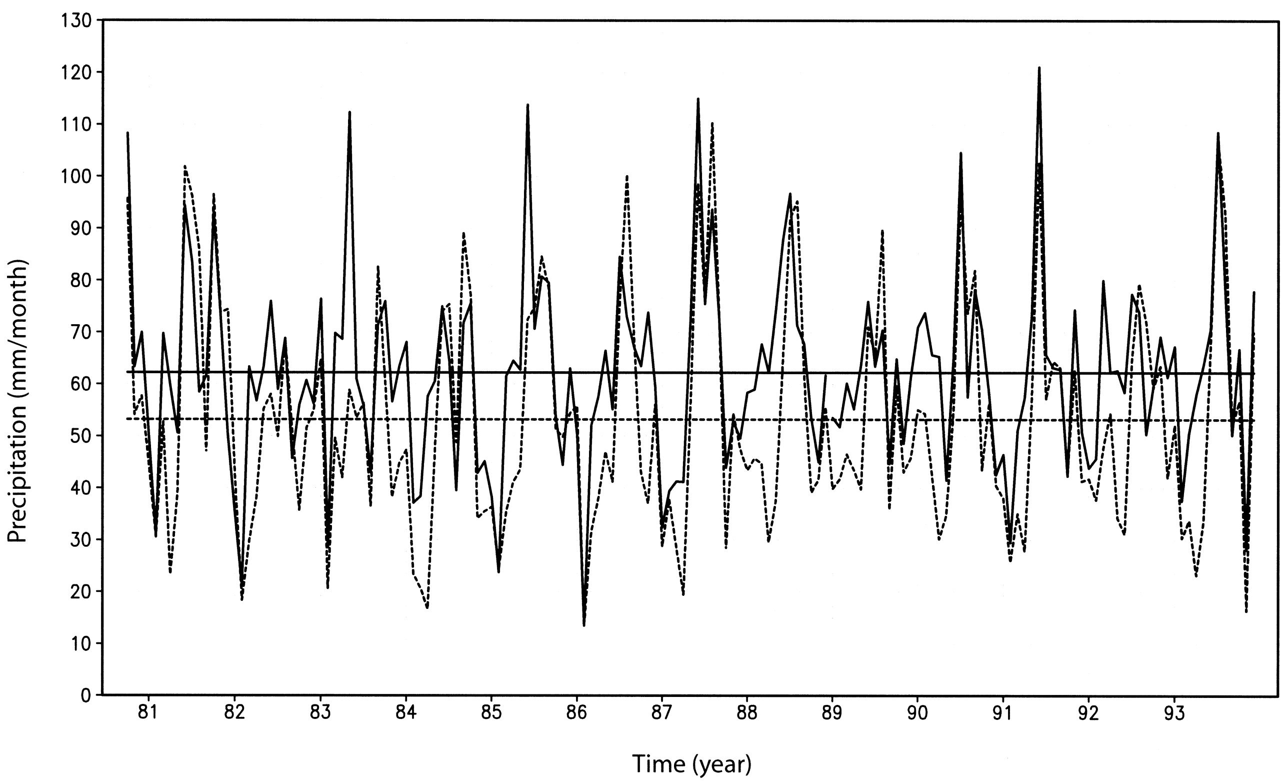

Fig. 11. Time series of calculated (solid lines) and measured (broken lines) uncorrected mean precipitation budget of the entire BALTEX model area. Horizontal lines mark the averages.

a treatment of dynamic vegetation, and the inclusion of hydrological processes.

In the GEWEX project PILPS (Henderson-Sellers et al. 1995) a wide disparity in LSM behavior was found in a number of environments (Chen et al. 1997; Wood et al. 1998). It was found that runoff and evapotranspiration are strongly related and that a poor runoff calculation may result in unrealistic values for the evapotranspiration.

Mengelkamp et al. (1999) and Warrach et al. (1999) extended the one-dimensional land surface Surface Energy and Water Balance (SEWAB) scheme with parameterizations of hydrological processes and verified the model with various datasets from different PILPS phases (e.g., Lohmann et al. 1998a). SEWAB includes also the processes of soil freezing and thawing and the seasonal snow cover (Warrach et al. 2001, manuscript submitted to *Theor. Appl. Climatol.*). There are various optional versions of SEWAB. These include

- the assumption of a variable infiltration capacity (e.g., Dümenil and Todini 1992);
- areas with a large contribution of slow base flow to the streamflow (e.g., Odra basin), which might require a model concept to delay the calculated runoff; in SEWAB this is approached with the attachment of a slow and fast flow storage;
- the TOPMODEL approach by Stieglitz et al. (1997), which utilizes the distribution of the orography within a land surface segment to account for the heterogeneous soil moisture; and
- the concept of ponding at the surface, which allows for the simulation of immediate streamflow responses to precipitation events (Mengelkamp et al. 2001b).

Horizontal runoff processes and the horizontal distribution of soil moisture are often not explicitly described in the SVAT model.

To test these various runoff parameterizations (apart from the TOPMODEL approach) SEWAB was run for 1 yr with a 20-min time step for a 14-ha grassland area near Cork, Ireland, where meteorological measurements and runoff data were available. Simulated runoff is compared to the observations. As a measure for the performance of the model NASH and Sutcliff (1970) defined the efficiency, which is shown as a function of the averaging period in Fig. 12. The error becomes smaller with increasing length of the averaging period, since during a longer period, more water from a precipitation event can enter the river. For periods of less than 5 days the ponding process is most important in simulating the immediate response to a precipitation event. The introduction of a depth-dependent saturation hydraulic conductivity would improve the accuracy.

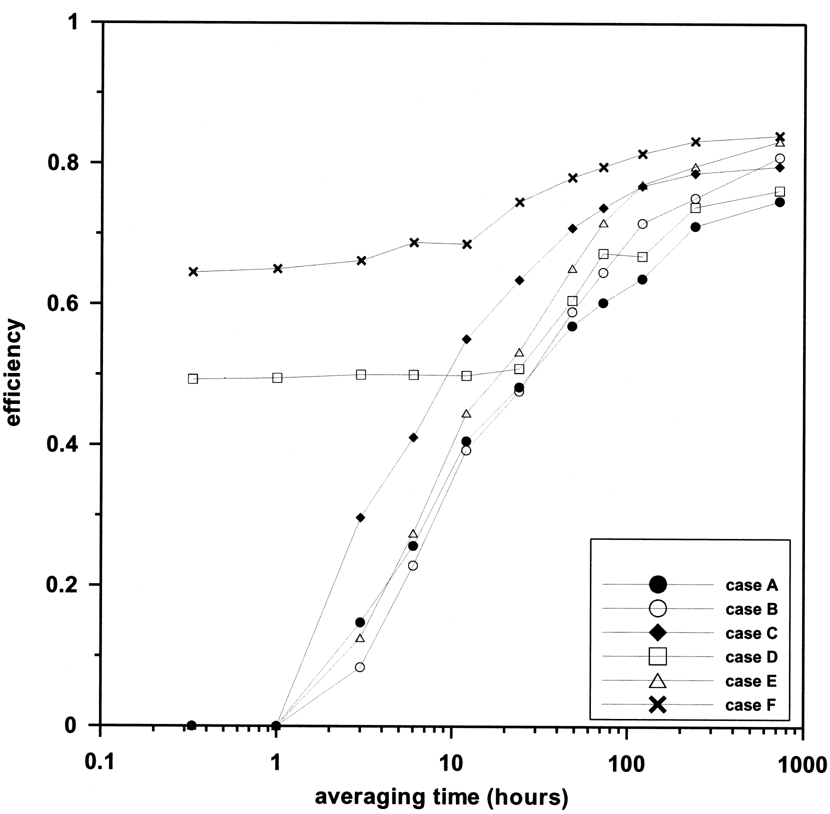

FIG. 12. Efficiency (a measure dependent on volume and timing) of an observed and simulated hydrograph for a 14-ha catchment near Cork, Ireland, as a function of the averaging period. Case A: saturation excess runoff and free drainage. Case B: as in case A but with depth-dependent saturation hydraulic conductivity. Case C: saturation excess runoff and baseflow storages. Case D: ponding and baseflow storages. Case E: as in case C but with depth-dependent saturation hydraulic conductivity. Case F: as in case D but with depth-dependent saturation hydraulic conductivity.

c. *Regional modeling of river discharge*

Within the framework of BALTEX the large-scale hydrological model HBV-Baltic has been developed and used to

- assess the major water balance components of the Baltic basin (Bergström and Graham 1998);
- evaluate the hydrological parameterizations of climate models (e.g., Graham and Jacob 2000);
- simulate in near–real time the freshwater contributions to the subbasins of the Baltic Sea; and
- simulate impacts of climate change on the river flow to the Baltic Sea (e.g., Graham et al. 2001).

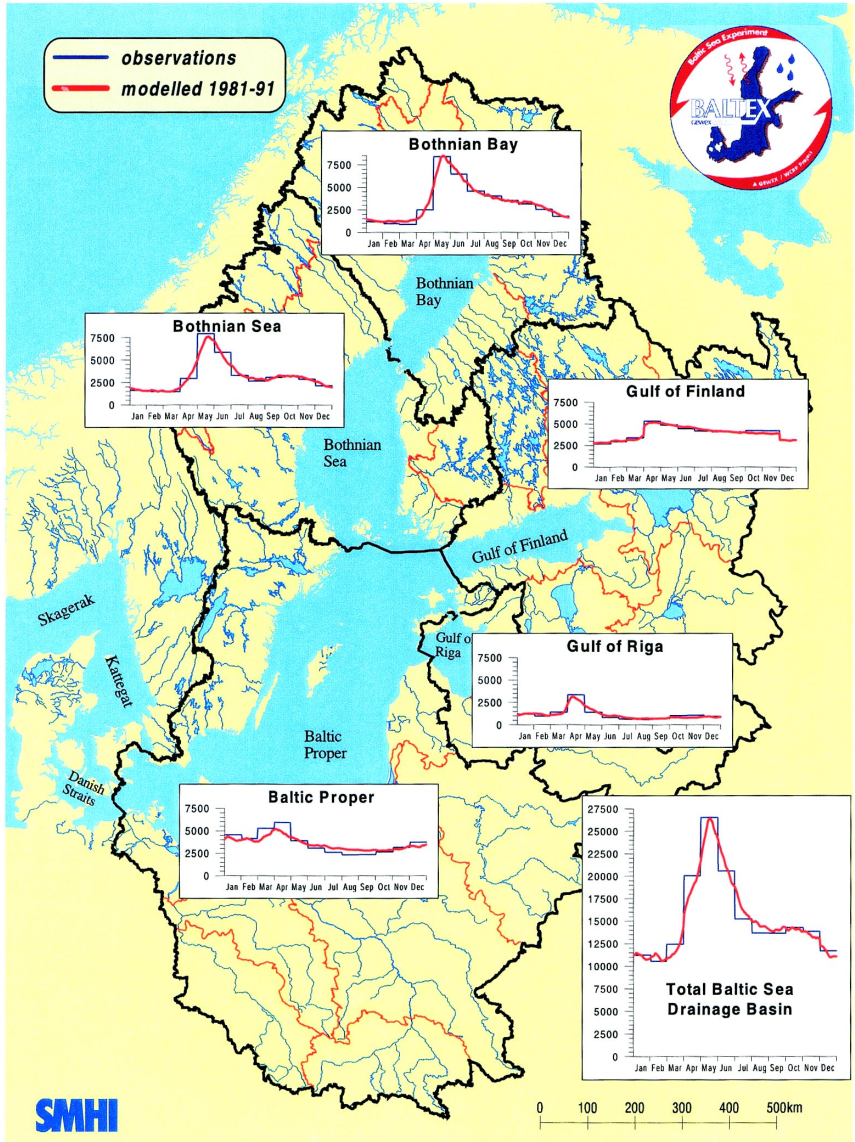

FIG. 13. Monthly averages (in $m^3 s^{-1}$) of freshwater flow into the major subbasins of the Baltic Sea, calculated with the HBV model using meteorological input data. Note that major contributions are available during the melting season.

Figure 13 illustrates the annual cycles of the contributions from all rivers in different subbasins of the Baltic basin and how this was modeled by HBV-Baltic. The use of HBV-Baltic has been instrumental in harmonization between regional climate models and hydrological models. In particular, compensating errors in snow modeling have been identified and the soil moisture routines have come a step closer to being consistent.

A distributed hydrological model is used to describe the horizontal transport of water in the river system (Lohmann et al. 1996) where the generated total runoff is routed to the outlet of the grid box, and afterward transported to a prescribed outlet of a catchment. The time delay is characterized by the unit hydrograph. The routing for the river network is done by solving the linearized St. Venant's equation. First results have been obtained for the rivers Elbe, Weser, and Odra coupling the routing scheme with an LSM, which calculates the runoff of a grid box (see sections 4b and 6). Simulated and measured streamflow at selected gauge stations compare to within ±10%–15% (Lohmann et al. 1998b; Lobmeyr et al. 1999).

In a study of the Daugava basin (Ziverts and Jauja 1999) the Latvian model METQ98 divides this basin into 22 subbasins and considers in each subbasin five types of hydrological response units: agricultural lowlands, agricultural hilly land, forest, swamps, and lakes. Simulations were made for a period of 39 yr (1956–94) using recorded data (daily precipitation, air temperature, and vapor pressure deficit) from 16 meteorological stations. The river channel is represented by a series of 43 linear reservoirs. The measured and simulated discharge in the Daugava River basin for the 5-yr period 1983–1987 at Plavinas is shown in Fig. 14. The correlation is 0.94. The main error source has been the small data sample for precipitation.

d. Modeling lakes in BALTEX

There are many lakes in the Baltic Sea drainage basin. In Sweden the number of lakes larger than 100 $\times$ 100 m^2 is above 90 000. In recent years lake models have been coupled to meteorological models (Ljungemyr et al. 1996; Omstedt 1999; Rummukainen et al. 2001). The lakes in each grid cell of the meteorological model are classified according to their depths and surface area. For shallow lakes, slab models are used while for deeper lakes vertically resolved lake models are applied. Of special interest to the modeling of the water and heat cycles of the atmosphere are the moisture flux from lakes during open lake conditions and their change in albedo during ice-covered conditions. In NEWBALTIC II (Bengtsson 2000) a 1D lake model allowing for ice formation was coupled to the atmospheric model HIRLAM. A simulation of February 1998 shows clearly that more lakes are ice covered in the coupled model simulation than were observed.

e. Modeling the Baltic Sea

Within BALTEX, the Baltic Sea is modeled using both process-oriented (Gustafsson 2000a,b; Omstedt and Axell 1998) as well as three-dimensional ocean models (Lehmann 1995; Meier 1999; Schrum and Backhaus 1999). Several studies related to the water and energy cycle of the Baltic Sea have been performed with the process-oriented model PROBE-Baltic (Omstedt and Nyberg 1996). An example is shown in Fig. 15, where the ice classification follows that by Seinä and Palosuo (1993), and the figure illustrates the period 1980–95, which includes both mild, normal, and extremely severe ice winters. The model simulation shows high skill, with a mean error of 13 $\times 10^3$ km^2 (average model overestimation is about 7%) and a root-mean-square error of 32 $\times 10^3$ km^2.

Some model-based estimates of the Baltic Sea water budget are summarized in Table 2. Omstedt and Rutgersson (2000) calculated evaporation rates using the PROBE-Baltic ocean model forced by observed data for the period 1981–95. The ECHAM4 simulations for the Baltic Sea were described by Jacob et al. (1997). The water balance components from the Rossby Centre Atmosphere model (RCA) simulations (Rummukainen et al. 2001) are calculated using the HBV-Baltic model and a climate version of the HIRLAM model. From the table one may notice that the present climate models are too wet in control runs.

Meier (2000) simulated at 13-yr period using a three-dimensional ocean model. His results are quite close to the results from the PROBE-Baltic model. This is due to the fact that almost the same forcing fields were applied and quite similar atmosphere–ocean flux parameterizations were used in both ocean models. Both ocean models predict a net heat gain of 1 W m^{-2} to the Baltic Sea, illustrating that the Baltic Sea water body is almost in balance with the atmosphere and could, from a thermodynamic point of view, be regarded as a closed basin.

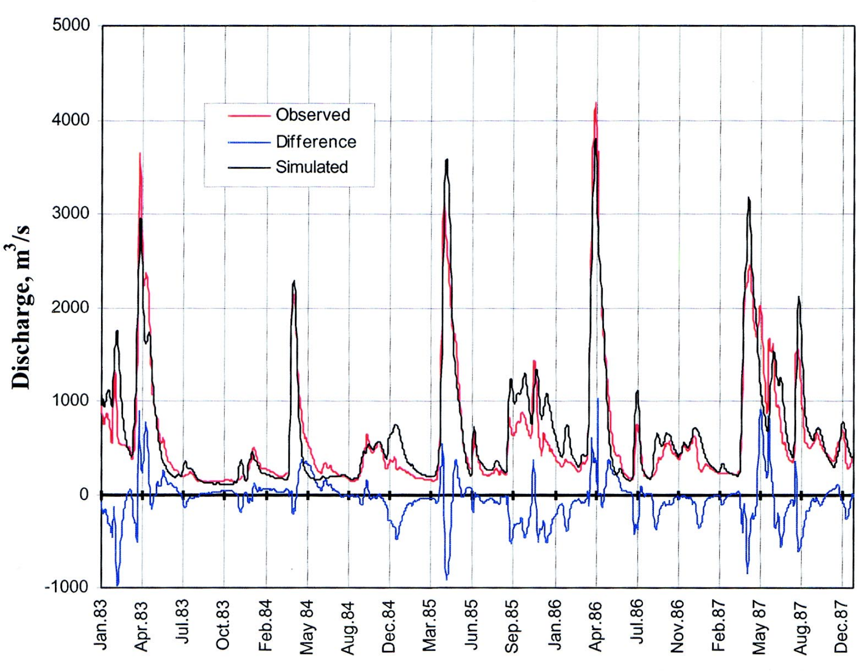

FIG. 14. Runoff of the Daugava measured at station Plavinas (Latvia) and simulated for the same position with the METQ98 model on the basis of meteorological input data.

f. Coupled atmosphere–ocean–ice modeling

The transient nature and the seasonal cycle of the atmosphere force highly variable currents and changes in the temperature and salinity distribution of the Baltic Sea on spatial scales ranging from 5–20 km to the entire basin size. Timescales range from hours (currents) over days (volume changes, inflows, heat and salt fluxes, up- and downwelling) to seasons and years. There is also a well-pronounced interannual variability (sea ice extent, volume, heat and salt storage), and a typical freshwater residence time of about 34 yr (Winsor et al. 2001). The circulation of the Baltic Sea and the water mass exchange with the North Sea are influenced by ice coverage during the winter season. Ice occurs annually in the Baltic Sea. On average the annual maximum sea ice extent is 45% and the duration of the ice season is 6 months in the northern parts. Therefore one major task in BALTEX is the coupling of atmosphere–ocean–ice models as described in this section.

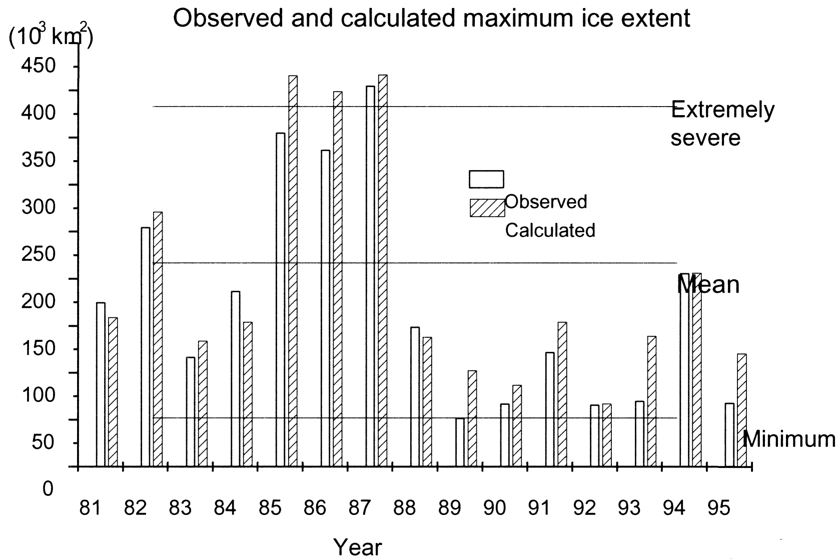

FIG. 15. Observed and calculated (PROBE-Baltic) maximum ice extent in the Baltic Sea (from Omstedt and Nyberg 1996).

1) ATMOSPHERE–OCEAN MODELING WITH REMO

A three-dimensional coupled high-resolution atmosphere–ocean model for the BALTEX region has been developed by Hagedorn et al. (2000) combining the REMO (see section 4a) and the Kiel Baltic Sea Ice Ocean Model (Lehmann 1995). The coupling is made directly via the corresponding fluxes across the atmosphere–ocean interface. The quality of simulated sea surface temperatures is comparable to the quality of observed sea surface temperature fields (see Fig. 16). Differences occur preferably during stationary atmospheric situations with low pressure gradients and meridional flow (high index composite, strong coupling effects). At zonal flow and strong westerly winds (low index composite, minor coupling effects) only small coupling effects are detected. The lateral boundary conditions strongly impact the solution in the inner model domain, especially under strong advective conditions. In these cases the response of the atmosphere to change in the SSTs is transported downstream, to the borders of the model domain, and absorbed by the lateral boundary conditions (Hagedorn et al. 2000). Simulations of the atmosphere–ocean model have focused so far on the ice-free seasons. Long-term coupled modeling requires the implementation of a dynamic and thermodynamic sea ice module into the coupled atmosphere–ocean system.

2) ATMOSPHERE–OCEAN–ICE MODELING WITH HIRLAM

Ice plays a major role at the air–sea interface and largely modifies the momentum transfer and the exchange of heat, freshwater, and other materials between the atmosphere and ocean. Freezing and melting of ice have also notable effects on the stratification of the Baltic Sea water masses. In recent years, several ice models and coupled ice–ocean models of the Baltic Sea have been developed (Omstedt and Nyberg 1996; Haapala and Leppäranta 1996; Kleine and Skylar 1995).

At SMHI, HIRLAM (see section 4a) has been coupled to a 2.5-dimensional ice–ocean model. The ice–ocean model includes two-dimensional, horizontally resolved ice and storm surge models and a one-

TABLE 2. A comparison among some model estimates of the long-term mean water budget of the Baltic Sea (not including the Kattegat and the Belt Sea), where Q_r is the river runoff, $A_S(P–E)$ the net precipitation, P the precipitation rate, and E the evaporation rate.

Source	Q_r (m³ s⁻¹)	$A_S(P–E)$ (m³ s⁻¹)	P (mm yr⁻¹)	E (mm yr⁻¹)
Omstedt and Rutgersson (2000)	15 141	1 868	599	443
Jacob et al. (1997), run 1	15 316	3 773	827	505
Control run RCA 9806	18 761	3 407	646	361

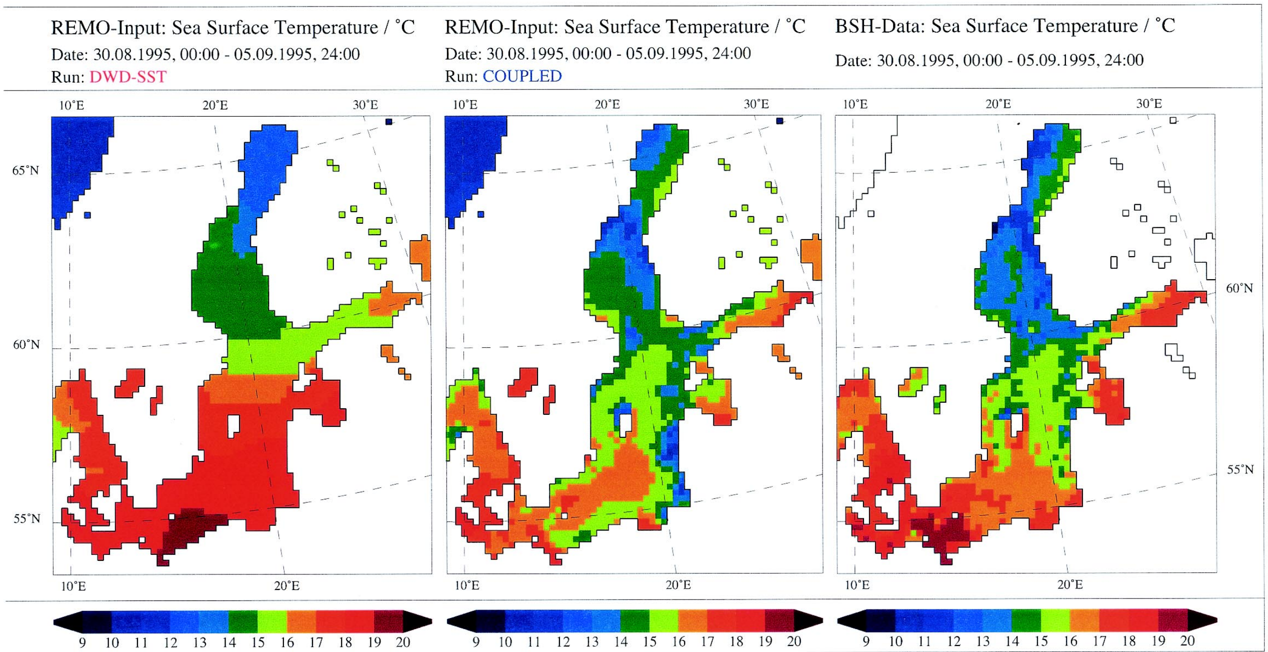

FIG. 16. Mean SSTs of the Baltic Sea during the period 30 Aug–5 Sep 1995: (left) operational values of DWD, used here for the simulations; (middle) simulated with the coupled model; (right) derived from satellite measurements. From Hagedorn et al. (2000).

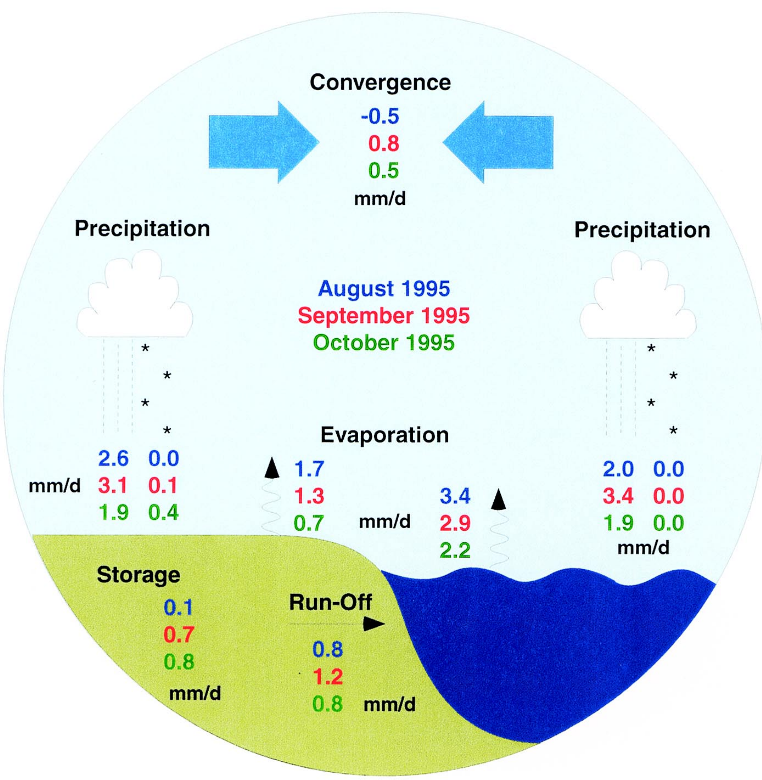

FIG. 17. A first water budget estimate for the BALTEX area, based on observational data collected during the PIDCAP period (1 Aug–31 Oct 1995) and modeled with REMO (from U. Karstens 2001, personal communication).

dimensional, vertically resolved ocean model applied to 31 Baltic Sea regions. Case studies demonstrate that improvements in short-range weather forecasting in the area of the Baltic Sea require an accurate description of the lower boundary condition over the sea, due to the local impact of the surface fluxes of sensible and latent heat. The convective snowbands during winters with cold airmass outbreaks over the open water of the Baltic Sea are extreme examples of the influence of sea state variables on the regional scale (Gustafsson et al. 1998).

5. A first study of the water and energy budget

Of all branches of the water cycle over continental surfaces and also over the open sea, the evapotranspiration and evaporation is possibly the most difficult measure as a representative quantity over a larger area. Similarly the horizontal convergence or divergence of water fluxes in the atmosphere are also difficult to extract from analyses. Therefore models need to be used to determine the spatial and temporal variability of all branches of the water cycle. Their results for the runoff and the precipitation can be validated with direct observations relatively easy. The same holds also for the radiation budget at the surface and at the top of the atmosphere.

Heise (1996) provided a first multiyear budget on the basis of operational analyses and forecasts. Karstens et al. (1996) simulated the water budget for June 1993 with REMO-GKSS. They found a total precipitation of 59.1 mm for the Baltic Sea drainage basin (including the Baltic Sea), an evaporation of 44.3 mm, a convergence of 8.1 mm, and a storage decrease of 0.55 mm. The simulated precipitation of 40.2 mm over the Baltic Sea only is close to the climatological value of 40.8 mm. Another study was made with all data of the PIDCAP period (Aug–Oct 1995). Figure 17 (U. Karstens 2000, personal communication) summarizes the monthly averages of all water fluxes as calculated with REMO-GKSS on the basis of daily analyses of the DWD, where budgets over the continents and the Baltic Sea are given separately. The precipitation values are in close agreement with those given by Heise (1996). The runoff calculated with the runoff model by Graham (1999) is for August, 0.33 mm day^{-1}; for September, 0.49 mm day^{-1}; and for October, 0.54 mm day^{-1}.

6. Odra flood event 1997

The Odra flood event in 1997 serves as a special test case for some hydrological models being developed in BALTEX. This event had the highest water levels of the twentieth century and was caused by extremely high rainfall in the upper and middle catchment up to 600 mm within 5 days or, in other words, 5 times the monthly average. A second period of almost as intense precipitation followed 2 weeks later. The flood inundated several cities and industrial areas in Poland.

A combination of the land surface scheme SEWAB (Mengelkamp et al. 1999) with the routing scheme of Lohmann et al. (1996) has been applied to model this flood. This model reproduced the measured runoff in the upper Odra, but it failed for the total catchment. In a second simulation, linear storage, which represents lumped reservoirs and floodplains, have been introduced and calibrated to match the observed hydrograph. The result (Fig. 18) shows that SEWAB is capable to simulate flood events and that only the routing scheme needs further development, such as the inclusion of floodplains and dam brakes; that is, this simulation encourages further developments toward operational warning systems on the basis of weather forecasts.

On the other hand, countries like Poland need large amounts of water for agricultural irrigation and for its population. In years of low precipitation and runoff, critical situations are likely to occur. Increased water deficits may develop if water demand is not reduced with appropriate economical and political means (Kaczmarek et al. 1997). Several adaption options must be considered. A sophisticated water management is necessary in such regions. BALTEX will help develop appropriate tools.

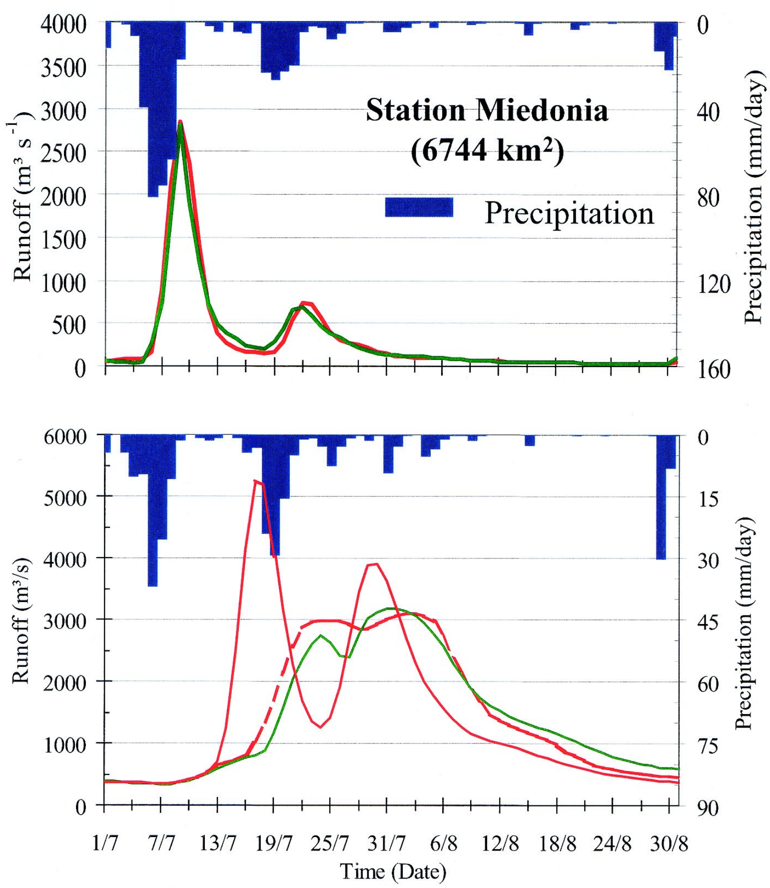

FIG. 18. Measured and modeled hydrograph at stations Miedonia (upper panel) and Gozdowice (lower panel) during the Odra flood in July 1997.

7. Conclusions and outlook

Research, as in BALTEX, with the aim of providing highly accurate simulations of the energy and water cycle in numerical models for weather forecasting, climate anomaly predictions, and climate change projections requires long-term observations. BALTEX, and the other CSEs of GEWEX, have already provided early encouraging results and new more comprehensive datasets, thus favoring continuation until the goals have been reached. These datasets must cover several seasonal cycles to reach these goals. All participating organizations, therefore, agreed to actively support with high priority the second phase of BALTEX, named BRIDGE. BRIDGE has been scheduled for the period from October 1999 to October 2000 (Fig. 2) and is operated at the same time as similar enhanced observation periods of other GEWEX CSEs.

The major purpose of BRIDGE is to aid access to all observations made in the study area, enhance the use of new experimental data, and improve the coupling of atmospheric, hydrological, and oceanographic processes in models. Important parameters at the interfaces of the model domains include soil moisture, snow cover, sea surface temperature, sea ice, surface fluxes of heat, radiation and momentum, precipitation, and river runoff. These models must be transferable to other regions on our globe. First model exchanges were exercised with modelers from Canada. Observational networks are encouraged to perform at their maximum capacity, which requires additional resources from participating institutions. All data must be accessible also to related research in the other CSEs. Therefore BRIDGE is a contribution to the coordinated enhanced observing period of GEWEX.

The first of five planned EOPs (see Fig. 2) of BRIDGE has already been completed. It has been dominated by the major phase of a Europe-wide experiment (CLIWA-NET; see also http://www.knmi.nl/samenw/cliwa-net) to measure micro- and macrophysical cloud field properties by coordinating existing, ground-based passive microwave radiometers and profiling instruments. This network has also been operated during the second EOP (April–May 2001). Further details and plans for BRIDGE are available online (w3.gkss.de/baltex).

The BALTEX results, models, and data are also of eminent importance to other scientific investigations: that is, for studies of the carbon cycle, transport of matter through rivers, eutrophication of lakes and the Baltic Sea, pollutant transports, and forecasts of weather and floods, among other topics.

Acknowledgments. The work so far performed within BALTEX would have never been possible without the additional financial support, which was obtained from ministries and science foundations particularly in Germany, Sweden, Denmark, and Finland. In addition these countries also provided additional support to Poland and the new states of the former Soviet Union. The weather services in all countries of the BALTEX area made large efforts to provide all available additional data, which are not reported routinely via GTS. Several special projects, like NEWBALTIC, have obtained financial support from the European Union over several years. The WCRP and the GEWEX officials supported from the outset the establishment of this European effort within the framework of the WCRP.

Particular thanks are due to the former chairman, L. Bengtsson, and to early members of the BALTEX Science Steering Group and founders of BALTEX (J. Dera, Sopot, Poland; E. Holopainen, Helsinki, Finland; Z. Kaczmarek, Warsaw, Poland; W. Krauß, Kiel, Germany; L. Laursen, Copenhagen, Denmark; P. Mällki, Helsinki; H. Sundqvist, Stockholm, Sweden). Their advice and active contributions accelerated considerably our work during the buildup phase. We also acknowledge the excellent worldwide cooperation with all members of the other GEWEX continental-scale experiments, which led to first steps toward the intercontinental transfer of models and knowledge to other watersheds. Two NATO-sponsored summer schools, supported also by the WCRP, BALTEX, and others, were held in 1993 and 1996 and were attended by about 70 young scientists each.

Three anonymous reviewers and Dr. Rick Lawson (NOAA, Washington DC) contributed very constructively to the final shape of this manuscript.

Appendix: List of organizations contributing to BALTEX

Map	Institute	Acronym
1	Finnish Meteorological Institute, Helsinki, Finland	FMI
	University of Helsinki, Helsinki, Finland	UHEL
	Finnish Environmental Institute, Helsinki, Finland	FEI
	Finnish Institute of Marine Research, Helsinki, Finland	FIMR

Map	Institute	Acronym
2	Department of Earth Sciences, Uppsala University, Uppsala, Sweden Meteorological Institute, Uppsala University, Uppsala, Sweden	UUpp MIUU
3	Russian State Hydrometeorological University, St. Petersburg, Russia A. I. Voeikov Main Geophysical Observatory, St. Petersburg, Russia Russian State Hydrological Institute, St. Peterburg, Russia Institute of Oceanology, St. Petersburg, Russia	RSHU MGO RSHI IOSI
4	Estonian Meteorological and Hydrological Institute, Tallinn, Estonia Estonian Marine Institute, Tallinn, Estonia	EMHI EMI
5	Department of Meteorology, Stockholm University, Stockholm, Sweden Stockholm Marine Research Center, Stockholm University, Stockholm, Sweden	SUM SMRC
6	Swedish Meteorological and Hydrological Institute, Norrköping, Sweden	SMHI
7	Tartu Observatory, Estonian Academy of Sciences, Toravere, Tartumaa, Estonia	TO
8	Department of Oceanography, Gothenburg University, Gothenburg, Sweden	UGot
9	Onsala Space Observatory, Chalmers University of Technology, Onsala, Sweden	Chalmers
10	Latvian Hydrometeorological Agency, Riga, Latvia	LHA
11	Department of Environmental and Water Resources Management, University of Agriculture, Jelgava, Latvia	LLU
12	Royal Danish Administration of Navigation and Hydrography, Copenhagen, Denmark Water Resources Division, Danish Hydraulic Institute, Copenhagen, Denmark Research and Development Division, Danish Meteorological Institute, Copenhagen, Denmark Risø National Laboratory, Risø, Denmark	RDANH DHI DMI Risø
13	Institute for Marine Research, University Kiel, Kiel, Germany	IfMK
14	Institute for Baltic Sea Research Warnemünde, Warnemünde, Germany	IOW
15	Institute of Marine Sciences, University of Szczecin, Szczecin, Poland	IMS
16	Department of Operational Oceanography, Maritime Institute, Gdansk, Poland Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland Institute of Hydroengineering, Polish Academy of Sciences, Gdansk, Poland	MIG IOPAS IHPAS
17	Atlantic Branch of Shirshov Institute of Oceanology, Russian Academy of Science, Kaliningrad, Russia	ABIO-RAS

Map	Institute	Acronym
18	Lithuanian Hydrometeorology Service, Vilnius, Lithuania	LHMS
19	State Committee for Hydrometeorology of the Republic of Belarus, Minsk, Belarus	CHB
20	Max Planck Institute for Meteorology, Hamburg, Germany	MPIfM
21	Institute for Atmospheric Physics, GKSS Research center, Geesthacht, Germany	GKSS
22	Meteorological Observatory, German Weather Service, Lindenberg, Germany	MOL
23	Interdisciplinary Center, ICM Warsaw University, Warsaw, Poland Polish Academy of Sciences, Warsaw, Poland Institute of Meteorology and Water Management, Warsaw, Poland Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland	ICM PAS IMGW IGW
24	Royal Netherlands Meteorological Institute, De Bilt, the Netherlands	KNMI
25	Institute of Meteorology and Climatology, University of Hanover, Hanover, Germany	UHan
26	Institute for Hydrology and Meteorology, Technical University, Dresden, Germany	TUD
27	Institute of Meteorology and Water Management, Wroclaw Branch, Wroclaw, Poland	IMGW
28	Meteorological Institute, Rheinische Friedrich-Wilhelms-University, Bonn, Germany	UBon
29	Global Runoff Data Centre, Bundesanstalt für Gewässerkunde, Koblenz, Germany	GRDC
30	GB Forschung und Entwicklung, Deutscher Wetterdienst, Offenbach, Germany	DWD
31	Department for Micrometeorology, University of Bayreuth, Bayreuth, Germany	UBay
32	Research Center Karlsruhe, Institute for Meteorology and Climate Research, Karlsruhe, Germany Dr.-Ing. Karl Ludwig, Wasserwirtschaft-Wasserbau, Karlsruhe, Germany	FZK LCE
33	Institute for Meteorology and Geophysics, University of Wien, Vienna, Austria Department for Biometeorology, Veterinary-Medical University Wien, Vienna, Austria	UVie VUW

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