1. Better Understanding of the Energy and Water Cycles

Better understanding of the energy and water cycles – this first objective indicates that, despite significant progress made so far towards meeting the prime objectives of BALTEX Phase I, gaps still exist which require continuation of BALTEX research. In view of the extended objectives of Phase II, the research components related to this objective aims at providing a solid framework for enhanced environmental investigations and more realistic climate studies. Based on the achievements of BALTEX Phase I, models and data sets will have to be upgraded and extended in order to properly meet the objectives defined for Phase II. New data sources and model concepts must be exploited to achieve the much more demanding requirements and special goals of BALTEX Phase II detailed in Chapters 2, 3 and 4.

1.1. Major Goals

- To evaluate in increasing detail regional models used for climate and environmental studies, and to develop strategies for climate and environmental impact assessments.
- To obtain better and more comprehensive observations from the entire Baltic Sea basin, including new satellite data, in particular to cope with regional resolution requirements.
- To develop further the numerical regional models for the atmosphere, the land surface including rivers and lakes, and the Baltic Sea including sea ice.
- To lower the uncertainty when closing the energy and water budgets from measurements.

1.2. How to achieve these Goals

1.2.1. Evaluation of Regional Models

- *To evaluate in increasing detail regional models used for climate and environmental studies, and to develop strategies for climate and environmental impact assessments*

Regional models are indispensable to better understand the feedback mechanism between atmosphere, land and ocean at the regional scale. Only regional model experiments will satisfy the needs for a better understanding of the current climate of the Baltic Sea basin, its past and its future. Such experiments have, however, no meaning without proper validation of the models for this purpose. A systematic approach for the evaluation of the models needs to be further developed. In addition to standard parameters, this approach needs to include also the fluxes, the budgets and processes in order to ensure that models give "the right answers for the right reasons". Especially in view of the extended objectives of BALTEX Phase II detailed in Chapters 3 and 4 of this document, uncertainties and limitations of models and their results must be clearly defined and convincingly communicated for the education of both users and decision makers.

Strategies for climate and environmental impact assessments must be developed based on using regional models. This includes coupling and forcing of regional models with results from global models, as well as other aspects of the design of model investigations. Account must be made of the role of natural variability, inherent uncertainties of future forcing scenarios, as well as of known shortcomings of global and regional models, *e.g.* concerning some aspects of precipitation, land surface evolution and ecological feedback mechanisms not yet included in many models. In parallel, regional climate models as well as their input and validation data sets still need considerable improvement. The accuracy and availability of such data is of crucial importance.

In view of the above, BALTEX Phase II research will focus on the following three main issues outlined in sections 1.2.2 to 1.2.4.

Fig. 1.4 Strong rain shower near a lake in northern Sweden. Precipitation intensity may change drastically at small spatial scales requiring high-resolution data sets such as combinations of radar, *in-situ* and satellite data for a quantitative estimation of precipitation at low uncertainty. (Photo: Holger Nitsche)

1.2.2. Better and more Comprehensive Observations from the Baltic Sea Basin

- *To obtain better and more comprehensive observations from the entire Baltic Sea basin, including new satellite data*

Of utmost importance are longer-term and more detailed area-covering quantitative precipitation estimates based on measurements for:

a) better constraining estimates of the energy and water cycle based on observations alone,
b) better documenting and understanding the development and causes of extreme events,
c) quantitative input to hydrological models of various scales,
d) the extension of BALTEX to water quality and more general environmental issues, and finally
e) a more comprehensive and quantitative model evaluation.

Of special importance for the Baltic Sea basin is the quantification of solid precipitation, which dominates precipitation during the cold seasons in many regions of the Baltic Sea basin. Of equal importance are observations of snow accumulation and melting at ground.

The impact of water vapour, clouds and aerosols on the regional radiation balance components – including its variability - needs to be estimated from both surface and satellite observations. Better estimates of the radiation budget from independent measurements will lead to more stringent quantitative measures to evaluate regional model performance due to its strong impact on the total energy balance of atmosphere, ocean and soil.

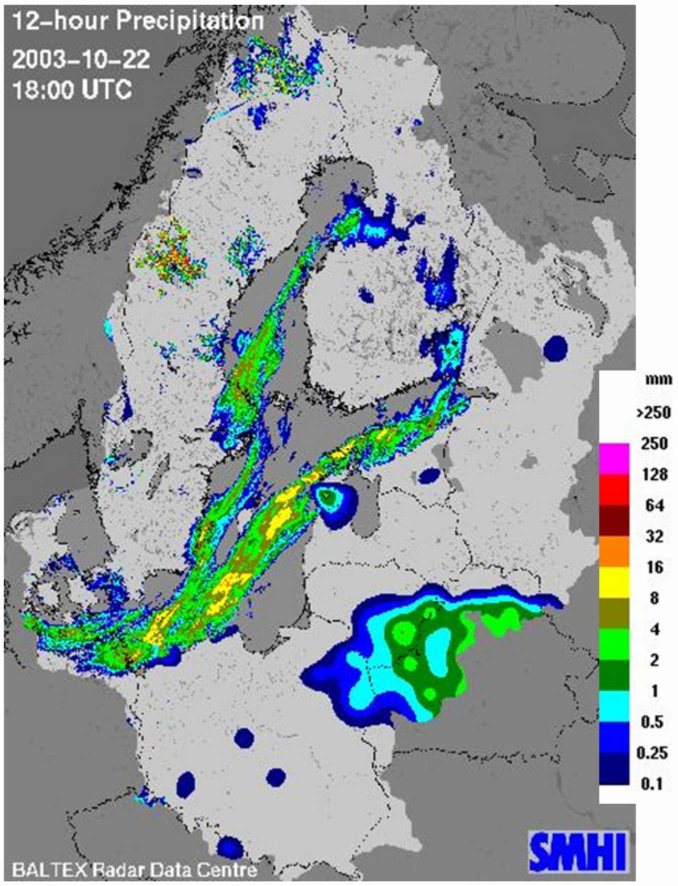

Fig. 1.5 12-hour accumulated, gauge-adjusted precipitation based on BALTRAD composites on 22 October 2003, 6 to 18 UTC. The horizontal resolution in most of the basin is 2x2 km. Note the lower resolution in the south-eastern part where no weather radar coverage was available at that time and only in-situ gauge observations are used. (by courtesy of Jarmo Koistinen, FMI, and Daniel Michelson, SMHI.

Due to the stronger focus on water management issues in BALTEX Phase II (see Chapter 3), better estimates of soil water, its phase (frozen or liquid) and its spatial and temporal distribution including information on the behaviour of aquifers need much more attention. Besides existing and upcoming powerful monitoring systems based on passive and active microwave sensors for estimating the upper layer soil moisture, also river runoff estimates using satellite techniques (*e.g.* by combining digital elevation maps with conventional altimetry, or by high resolution altimetry using higher frequency sensors including Lidar techniques) need to be further developed or exploited. Variations of the gravity field of the Earth due to changes in the soil water column could be applied for this issue. Despite its currently very low resolution (at least several hundreds of kilometres) this information might provide valuable integral measures to validate model derived fluctuations in the catchment water table. A forward modelling approach based on the output of coupled regional hydro-meteorological models would be a first step to better understanding and later use of this information. The potential of the techniques mentioned above for the initialisation of and assimilation in adequately extended hydro-meteorological models needs to be exploited together with the use of river discharge data for an improved constraint of distributed hydrological models. Combining all data sources in a variational-type assimilation approach is expected to lead to a better description of soil characteristics in the basin and quantitative modelling of the energy and water cycle.

To close the energy and water balance at the catchment level with reduced uncertainties, reliable error estimates of available runoff data, and continuous measurements of in- and outflow through the Danish straits are indispensable. Attention should also be paid to measurements of dense bottom currents in the Baltic Sea in order to better model or parameterize their important influence on water mass circulation and mixing. Baltic Sea ice is a very sensitive component of the Baltic Sea basin climate system; it requires more detailed investigation of its variability under current climate conditions. New satellite sensors with all weather capability (*e.g.* passive and active microwaves, SSMIS, AMSR, ERS, later SMOS, HYDROS; see Chapter 8.3 for details) are available nowadays for this purpose and need to be exploited. Similar data with lower quality do exist (SMMR and SSM/I), which could be used to extend such data sets back to the late 1970s.

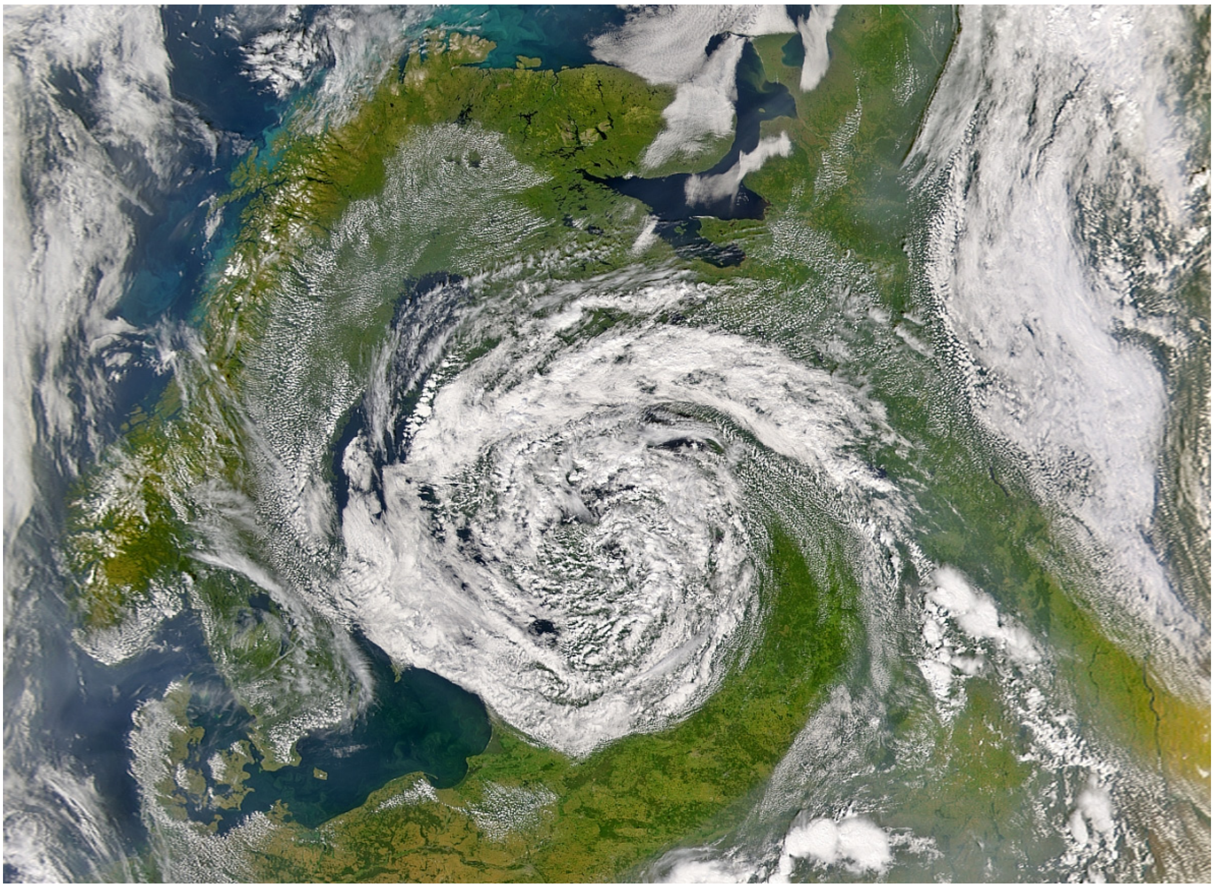

Fig. 1.6 A well-developed cyclone over the eastern Baltic Sea basin, as seen by the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) on July 30, 2004. (SeaWiFS, NASA/Goddard Space Flight Center, GeoEye).

The new objectives of BALTEX Phase II require much more detailed, quality improved regional re-analysis data sets composed from the available data sets based on appropriate models. These data sets should quantify the state and the variability - as well as their uncertainties - of the regional climate system including all relevant climate system components. Besides for the climate system change studies described in Chapter 2, such data sets will serve for a more detailed process-based model evaluation (see below), provide important input for the solution of various water management issues put forward in Chapter 3, and support a variety of environmental studies as suggested in Chapter 4.

Finally, the continuation and extension of super observation sites for the atmosphere and the land surface at e.g. Sodankylä, Lindenberg, and Cabauw and their integration in the Coordinated Enhanced Observing Period (CEOP, see Chapter 10.3) is a pillar in the BALTEX Phase II observational programme. They have in common high quality observations of the tropospheric column, including clouds and aerosol, and the soil down to generally 2 meter depth. Besides the basic meteorological parameters these observation sites are able to provide higher level products, like local budget estimates of energy and water. These measurements are therefore of prime importance for regional model evaluation, for inclusion and/or evaluation of regional re-analysis data sets, and for the development and improvements of parameterisations related to atmospheric boundary layer structure and clouds. Monitoring of atmospheric composition should be extended in a coordinated manner (in terms of *e.g.* type of substances to be monitored, and method of measurement) in order to allow for model validation studies with regional aspects.

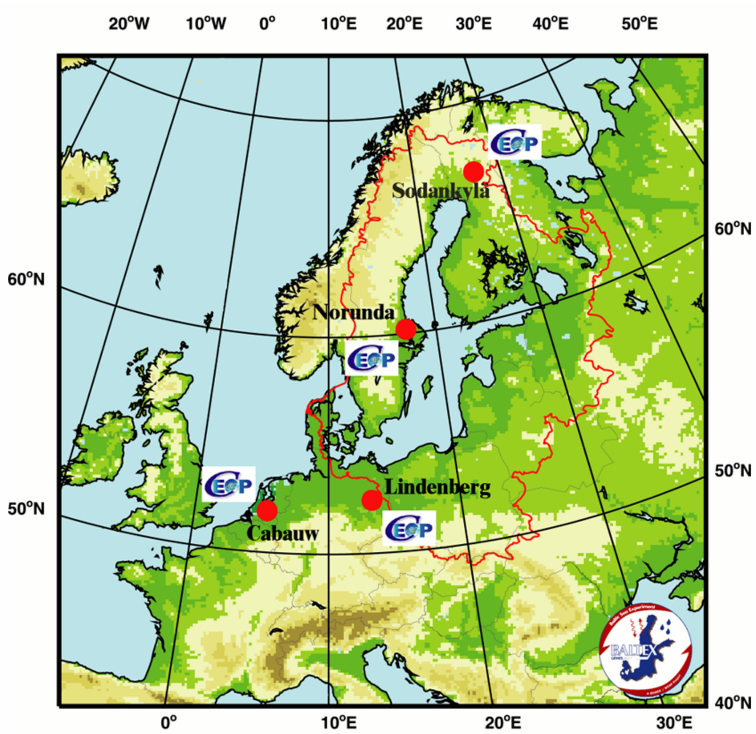

Fig. 1.7 Location of major observational sites which provided reference site data for CEOP (Coordinated Enhanced Observing Period) Phase I during 2002 to 2004.

1.2.3. Development of a Complete Numerical Regional Climate Model System

- *To develop further the numerical regional models for the atmosphere, the land surface including rivers and lakes, and the Baltic Sea including sea ice*

A major achievement of BALTEX Phase I is the establishment of two regional coupled climate models. The objectives of BALTEX Phase II need, however, a higher stage of operability, versatility and reliability of these models. These requirements necessitate upgrades concerning the quality of the model components, the coupling strategies, and extensions leading towards a regional Earth system model. For this, improved modelling of the soil water table and the inclusion of aquifers should be considered. Of utmost importance are improved physical parameterisations for the all-important exchange processes between surface water bodies, the land surfaces including ground water and aquifers and the atmosphere. The inclusion of biological components of the climate system in regional climate models needs stronger efforts, including the factors or substances influencing vegetation growth and development. The representation of the physical exchange processes still suffers from inadequately resolved scale discrepancies between the different components, which also accounts for large differences between model results and measurements. Improved and physically based modelling of soil water should be pursued along the same lines, especially for the objectives laid down in Chapter 3, because these approaches enlarge considerably the potential to use independent measurements for assimilation and validation. Estimates of soil moisture expected from new sensor types, for example, can be used much more efficiently, if soil moisture means the same in both model and real world.

Of similar importance is precipitation initiation and development, in particular in the context of coupling atmospheric with hydrological models on smaller scales. Improved parameterisation schemes and the potential for increased spatial resolution down to the kilometre scale need to be considered. The influence of aerosol variability especially during cloud and precipitation initialisation should be considered in atmospheric model components. In the ocean component, bottom boundary currents need to be better described, because of their importance for water mass circulation and mixing. Concerning sea ice models, more sophisticated simulations of sea ice characteristics such as different ice classes should be included to allow for a better physical description and comparability with observations.

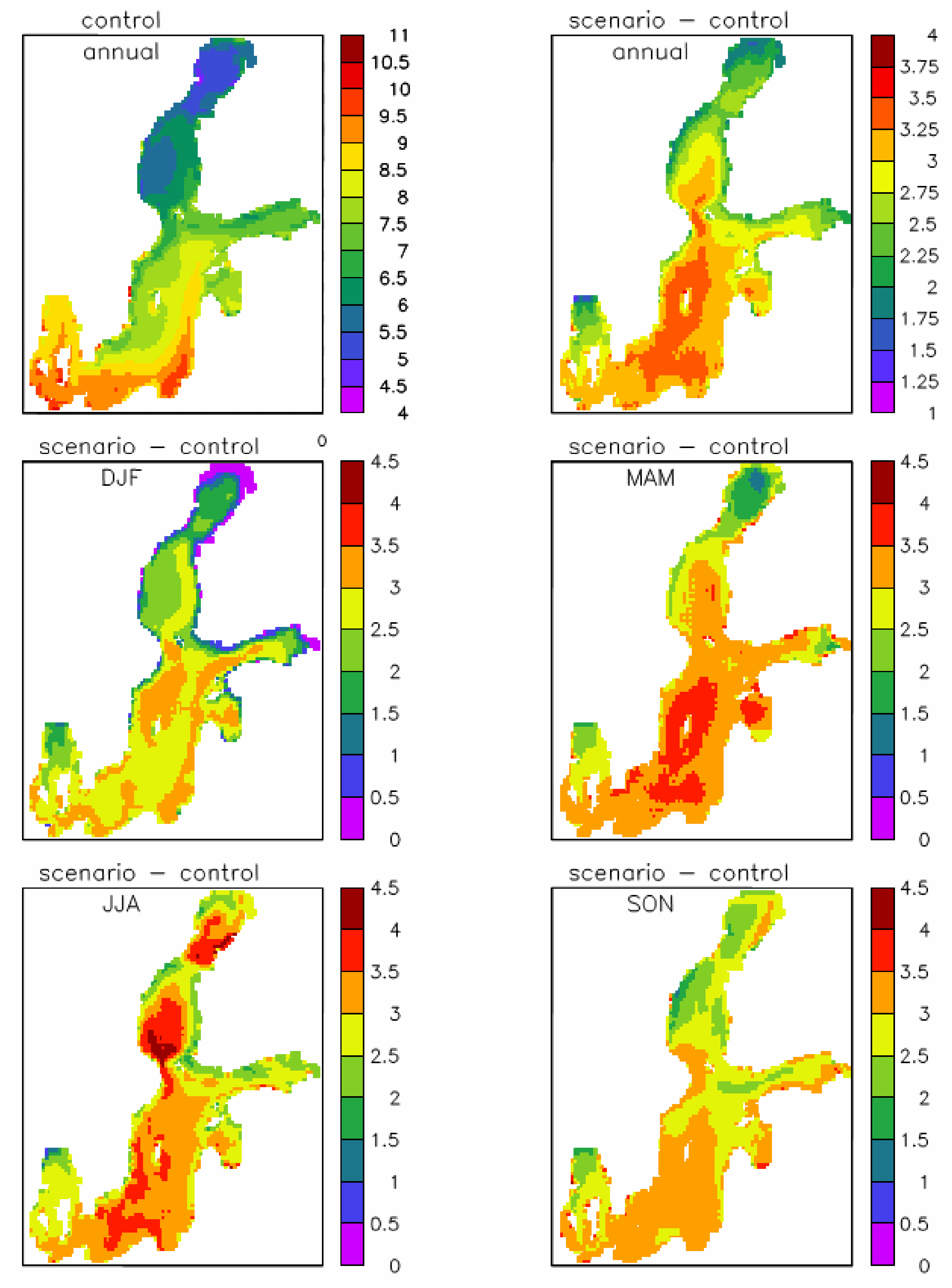

Fig. 1.8 Sea surface temperature in the Baltic Sea, simulated for the time period 2071-2100 by the coupled model system RCAO of the Rossby Centre, SMHI, Norrköping, Sweden. RCAO is one of the two major coupled regional modelling systems developed during recent years in the frame of BALTEX. Upper left panel shows annual mean temperature (°C) averaged for the period 1961-1990 (the control run). All other panels show differences of a scenario ensemble mean minus the control run (°C). Upper right panel shows annual mean differences, others show winter (DJF), spring (MAM), summer (JJA) and autumn changes (SON) (by courtesy of Ralf Döscher, SMHI).

1.2.4. Closing the Energy and Water Budgets

- *To close the energy and water budgets from measurements at lower uncertainty*

Water and energy budget estimates based on improved measurements *e.g.* of precipitation and turbulent and radiation fluxes must be established for much longer periods than available to date in order to better understand both storage in and exchange between regional climate system components. Such estimates will serve as integral measures for assessing the reliability of regional climate models, and therefore the investigated periods need to span years to decades instead of only months to a few years, as has been possible in the past. Precipitation fields of improved quality for longer time periods and better temporal and spatial resolution are urgently needed for this task. It will have to be explored whether gravity variations detectable from current and future satellite missions (GOCE, CHAMP, GRACE - see Chapter 8.3 for details) can provide sufficiently accurate integral measures of the variability of water stored in the ground and aquifers; our current knowledge of these parameters is considered poor at best. Astonishingly enough, the radiation budget of the atmosphere and the surface are still known to an insufficient degree to serve as a real constraint for other components of the energy budget. Radiation provides the sole energy input to the Earth climate system as a whole; on the regional scale lateral influx considerably complicates the situation putting an even stronger requirement on the quality of the estimation of the radiation budget components. As regional climate models approach reality, a basis will exist for improved regional re-analysis data sets, to be useful *e.g.* for closing the energy and water budget at lower uncertainty.

1.3. Involvement of Stakeholders

The involvement of stakeholders also for the basic science issues portrayed in this section is of extreme importance for its success. Environmental agencies, at both national and international level, as well as national hydrological and meteorological services are responsible for establishing most of the observational data sources and - at least in part - for the development of regional climate models, both of which form the basis of the research efforts in BALTEX. Communication with these stakeholders will have to be intensified with the view that their active contribution to BALTEX is a major prerequisite for obtaining dependable results – not only with regard to a better physical understanding and modelling of the energy and water cycles, but also with regard to the extended objectives put forward in Chapters 2 to 4.

Frequent exchange of information between the agencies and the BALTEX research community about, for example, documented model and data deficiencies and BALTEX achievements in model and data improvements will foster active cooperation and stronger involvement of agencies, and stakeholders in general. An open and unrestricted access to data sources is still of prime importance for this first objective of BALTEX Phase II. BALTEX is presently revising its data exchange policy in close cooperation with relevant data providers (see Chapter 8.4), and a dedicated BALTEX Working Group on Data Management was recently re-established. Since the new objectives of BALTEX Phase II relate much more directly to both the interests and the responsibilities of these stakeholders, an information strategy hinting to the applicability of BALTEX achievements is expected to improve the willingness of the stakeholders to cooperate. Capable research groups working on model components also relevant for regional climate modelling can be found at many national services. Thus, model improvement efforts will benefit from a closer interaction by involvement of these groups in BALTEX.

1.4. Potential Activities

Potential activities, contributing to a better understanding of the energy and water cycles of the BALTEX region, can be grouped in the following areas of research.

1.4.1. Regional Analysis and Re-analyses of Different Variables for Specific Purposes

Global re-analysis data sets like ERA-40 (the 40 years re-analysis of the European Centre for Medium-Range Weather Forecasts, ECMWF, see www.ecmwf.int/research/era/) and the NCEP

(National Centre for Environmental Prediction, USA) products (www.cdc.noaa.gov/cdc/reanalysis/) have a number of shortcomings, which need to be improved or extended for BALTEX Phase II. Observations of clouds and precipitation need to be included in a regional re-analysis which should be performed on finer spatial scales. Especially precipitation fields should be made available over land areas with resolutions down to a few kilometres on at least a daily base for use *e.g.* in hydrological studies and analysis of extreme events. This requires the merging of Radar data with surface observations and possibly with satellite data. Also wind fields over the Baltic Sea are required in higher resolution in order to remove the influence of land effects. New radiation parameterisation schemes should be implemented to better estimate the components of the surface radiation budget *e.g.* from satellite observations. Error estimates should be an integral part of the derived fields. Addressing the last 40 years is also very relevant for the analysis of climate variability and change (Chapter 2), see section 2.4.1 in particular.

Generally, there is not one regional analysis data set available serving all purposes in BALTEX Phase II. In this broad view, at least five types are envisioned and should be established:

1. Re-analysis data sets for a better understanding of the current climate: This re-analysis will include all available measurements of the past 10 to 20 years assimilated in a regional dynamic model system.
2. A full re-analysis, which exploits all local data, is sensitive to changes in the observational coverage. A less sensitive approach is to assimilate large-scale features instead, provided by a global re-analysis. Obviously, such an approach returns less skilful reconstructions but, with its likely lower sensitivity to data inhomogeneity, it thus allows a better estimation of long-term trends and low-frequency variability. Such efforts have already been implemented, and the results are used for assessing changing climate conditions; however, further improvements, in particular with better spatial resolution, shall be pursued, in particular for the Baltic Sea basin.
3. Re-analysis data sets in climate change and variability studies: The spatial and temporal homogeneity of measurements is of highest importance in order to suppress spurious trends and variability caused by temporal changes of data availability (see also Chapter 2.4.1).
4. Re-analysis data sets with reduced model influence. These data sets should be based on as few model assumptions as possible (intelligent interpolation) in order to be used as independent data sources for regional climate model evaluation.
5. Re-analysis data sets using models run in climate mode, without data assimilation. This serves the purpose of the development and evaluation of models applied for future projections (see Chapter 2.4.1).

1.4.2. Further Development of Models and Model Improvement

All important exchange processes between ocean, atmosphere and the land surface are acting on scales not well resolved in the current models. Model improvements should be directed to explicitly taking into account the appropriate scales by either adapting the model resolution to the process, or by developing adequate parameterisations. Examples are in- and outflows and dense bottom currents within the Baltic Sea, sea ice diversity, air-sea interactions in coastal regions, precipitation generation and development, effects of land surface heterogeneity on fluxes of energy and matter, ground-water and runoff generation.

Components of regional climate modelling systems, which still need to be developed further, are more detailed treatments of aerosol effects on cloud and precipitation development, inclusion of dynamic vegetation and substances influencing vegetation growth and development (*e.g.* CO_2, N_2), as well as improved treatment of lakes and aquifers.

Further improvement of the increasingly complex regional climate models needs the involvement of an increasing number of researchers often situated in different groups. An adequate organisational structure needs to be set up, which allows for an efficient communication between model developers to better exploit existing knowledge and resources and to shape and implement standards for code development and module coupling. The high quality monitoring of the tropospheric column and the land surface at the three super sites Lindenberg, Cabauw and Sodankylä provides the most complete data sets currently available for these tasks. These sites should therefore be integrated in the model development network, thus also taking advantage of their experienced scientific staff.

1.4.3. Closing the Energy and Water Budget on a High Level of Confidence

Closure of the energy and water budget of the Baltic Sea basin means to independently estimate the different exchange fluxes between the reservoirs (ocean, atmosphere, land) with sufficient accuracy. This potential activity will carefully evaluate existing data sets, *e.g.* the re-analysis data sets to be developed as described in section 1.4.1, with respect to the fluxes between major reservoirs including error characteristics. Eventually emerging inconsistencies in the energy and water balance will be used to trace down deficient data characterisations or assumptions used when computing the fluxes, thus successively narrowing down uncertainties and better understanding the different energy and water flows in the regional climate system. The results will also provide benchmarks for a system approach to the evaluation of regional climate models.

1.4.4. Improvement of Quantitative Precipitation Forecast

The quality of Quantitative Precipitation Forecast (QPF) is an essential limiting factor of our ability to understand and model the energy and water cycle. Several national initiatives are planned or already exist, aiming to improve QPF in specific regions by further developing model performance and data assimilation, and by conducting dedicated field experiments. An effort shall be made to connect BALTEX to these initiatives in order to participate in the new developments. BALTEX will also draw attention to the specific problems of QPF in the Baltic Sea basin caused for example by the interaction of the Baltic Sea with the atmosphere and the increasingly important role of solid precipitation and the specifics of land surface-atmosphere interactions in a Nordic environment. Quality advances of the QPF have a direct influence on the quality of flood forecasts (see Chapter 3 for details).

1.4.5. Evaluation of Models and Data Sets for their Use in Climate Impact Analysis and Environmental Issues

Regional climate model and data comparisons should be performed at different scales. Regional-scale flux estimates such as those resulting from activity 1.4.3 shall be used for evaluation of coupled climate models. For an improved evaluation of coupled models, the communication structure put forward in activity 1.4.2 includes scientists and groups which are conducting and exploring field measurements. This will allow for a more efficient, timely and intelligent use of available measurements and resources. In turn, it will lead to the setup and execution of more focussed monitoring programs, instrument development, and field experiments necessary for improved evaluation of different model components and the models as a whole.

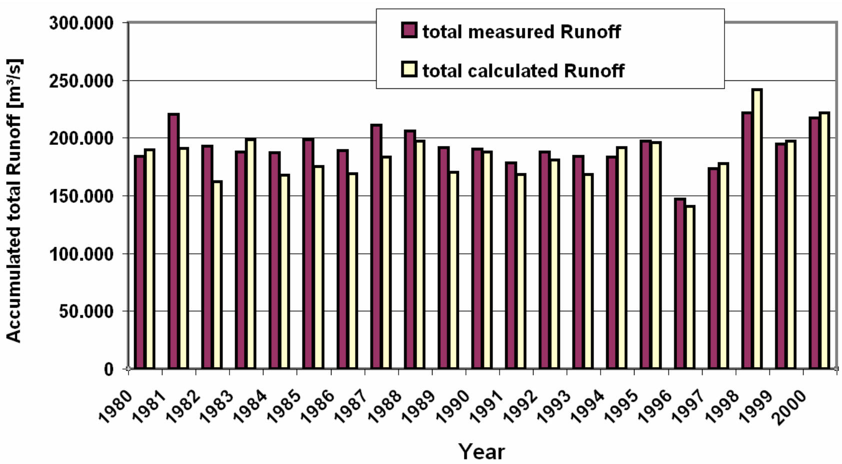

Fig. 1.9 Accumulated total runoff into the Baltic Sea from 1980 - 2000. Comparison of measured meteorological data and simulated runoff calculated by the coupled model system BALTIMOS (by courtesy of Daniela Jacob, MPI for Meteorology, Hamburg)

1.5. Specific Data Needs

A wide spectrum of observational data is required to properly address this objective. One prerequisite is the continuous further build-up of the archives of the existing BALTEX Data Centres (see Chapter 8.1). The presently archived data types need to be continuously extended to cover the future time period until the end of the BALTEX research period. Extensions of the already archived data types – and periods presently covered - are key for a better understanding of the energy and water cycles, and the specific additional requirements are formulated as a major goal of this objective in section 1.2.2. A further specific requirement is the access and exploration of new and existing satellite data, as detailed in sections 1.2.2 and 8.3.