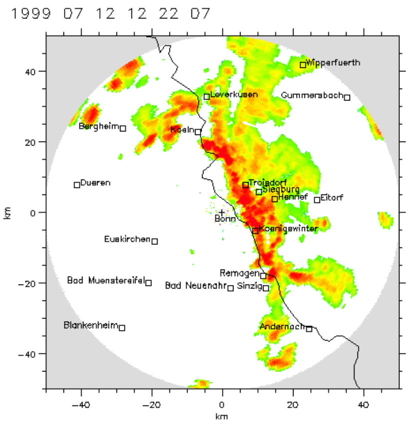
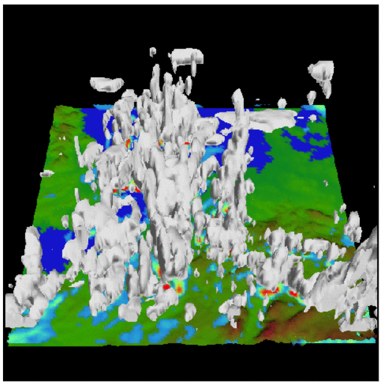
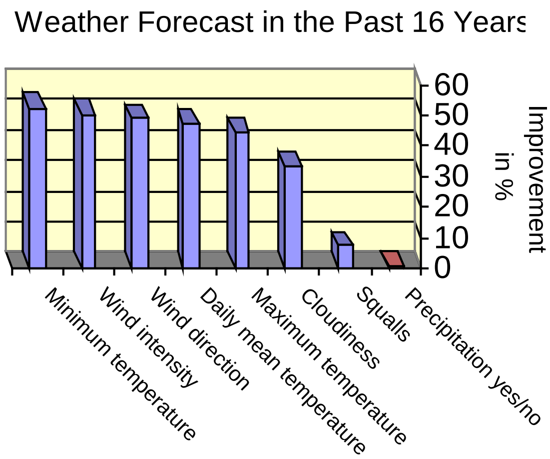
Priority Program of the German Research Foundation

Quantitative Precipitation Forecast







Submitted by

Andreas Hense (Speaker), Gerd Adrian, Christoph Kottmeier,
Clemens Simmer, and Volker Wulfmeyer

14 February 2003

Quantitative Precipitation Forecast:

Abstract

Water is the prerequisite for the major processes of life. The atmosphere regulates the availability of water above all through precipitation. Therefore, predictability of the atmosphere in general and of precipitation in particular is of extraordinary societal, economic, and social significance. In Europe, this became obvious in 2002 again. Further development of meteorological forecasting methods and observation systems has constantly improved the quality of short-term (up to 3 days) and medium-term (up to 10 days) weather forecast, e.g. for temperature and wind, in the past years. In contrast to this, precipitation forecast still is associated with the same deficiencies than 16 years ago. Quantitative precipitation forecast, for instance, still is of such poor quality that it can hardly be used for many applications, e.g. hydrology. Presently, deficiencies include (a) the incomplete modelings of the components of the water cycle, (b) gaps, non-resolved structures, and errors of the initial fields, (c) inadequate methods of optimally linking observations with forecast models (assimilation of data into models), but also (d) basic problems in the understanding and interpretation of deterministic weather forecast models. So far, this combination of problems has prevented the situation from being improved significantly by the efforts of individual groups of researchers and national weather services. The scope of tasks to be treated simultaneously is so wide that these challenges may only be mastered by a joint and coordinated effort of university institutes and other research institutions together with the Division of Research and Development of the German Weather Service within the framework of a priority program.

The priority program proposed here has the following superordinate scientific objectives:

- **I Identification of physical and chemical processes responsible for the deficiencies in quantitative precipitation forecast**
- **II Determination and use of the potentials of existing and new data and process descriptions to improve quantitative precipitation forecast**
- **III Determination of the prognosis capacity of weather forecast models by statistico-dynamic analyses with respect to quantitative precipitation forecast**

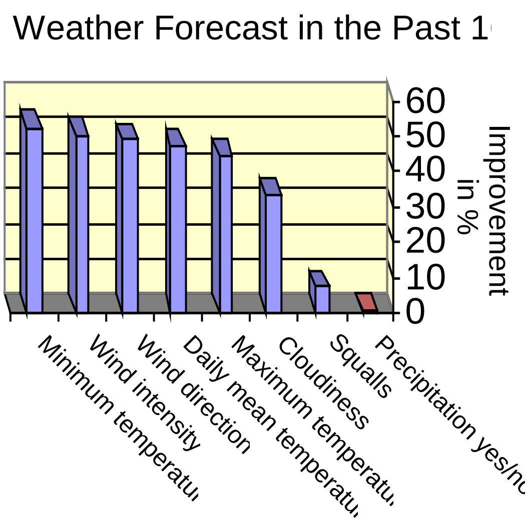
The German Weather Service will make available its operational forecast system and a supercomputer environment to universities and research institutes. This represents an excellent support of the priority program. By the retrieval and modeling of atmospheric flows with the current model system of the Weather Service, meteorology in Germany is given the unique chance of reaching the project objectives and contributing to current international research programs.

1. Introduction

Water is the prerequisite for the major processes of life. The atmosphere regulates the availability of water above all through precipitation. Therefore, predictability of the atmosphere in general and of precipitation in particular is of extraordinary societal, economic, and social significance. Its improvement represents a task of provident character for our future existence. Agriculture and water resources management, air and shipping traffic, road transport and energy economy directly depend on the state of the atmosphere. Damage caused by extreme precipitation events extremely burdens the budgets of industrial enterprises, the Federal Republic of Germany, and the federal states. People affected by extreme precipitation events often face economic ruin. Susceptibility to extreme events, e.g. strong precipitations, hailstorms or storms, will further increase in the industrialized nations due to the increasing accumulation of material assets and the optimization of economic processes. In Europe, this became clearly obvious in 2002 again. Quantitative forecast of non-extreme precipitation events is of comparable value at least, although the avoidable losses mostly do not appear to be so spectacular. Complemented by estimates of their potential uncertainties at least, such forecasts are of inestimable value as input variables for hydrological applications or for consulting in agriculture and the construction sector.

Further development of forecasting methods and observation systems has resulted in a constant increase in the quality of short-term (up to 3 days) and medium-term (up to 10 days) weather forecast, e.g. for temperature and wind, in the past years. In contrast to this, precipitation forecast still is associated with the same deficiencies than 16 years ago. These findings are supported by Fig. 1, where the improvements in forecast quality (RV: Reduction of variance) of the German Weather Service (DWD) are illustrated for various atmospheric variables. In the course of the past 16 years, it was not succeeded in improving the forecast as to whether precipitation will fall in a certain area or not (precipitation yes/no). The situation is even more dissatisfying for quantitative precipitation forecasts. It is shown by Fig. 2 that forecast quality becomes worse, the larger the precipitation volume observed is. This is no DWD-specific problem. Similar conclusions may also be drawn for other weather services. This uncertainty represents a general feature of deterministic models, on the basis of which today's operational weather forecast is made to a large extent. It results from the conceptual difficulty of predicting the occurrence of events of short lifetimes. Accordingly, the quality of forecasting precipitations in excess of 10 mm over 12 hours of 20% is not acceptable. Here, the quality of prognosis is described by the Heidke Skill Score (HSS). It does not only express how often the model has predicted correctly that no precipitation of a certain volume fell. It also takes into consideration whether the model has correctly predicted an actually occurring precipitation event, which is of even greater importance to most users. But just here, blatant deficiencies are encountered.

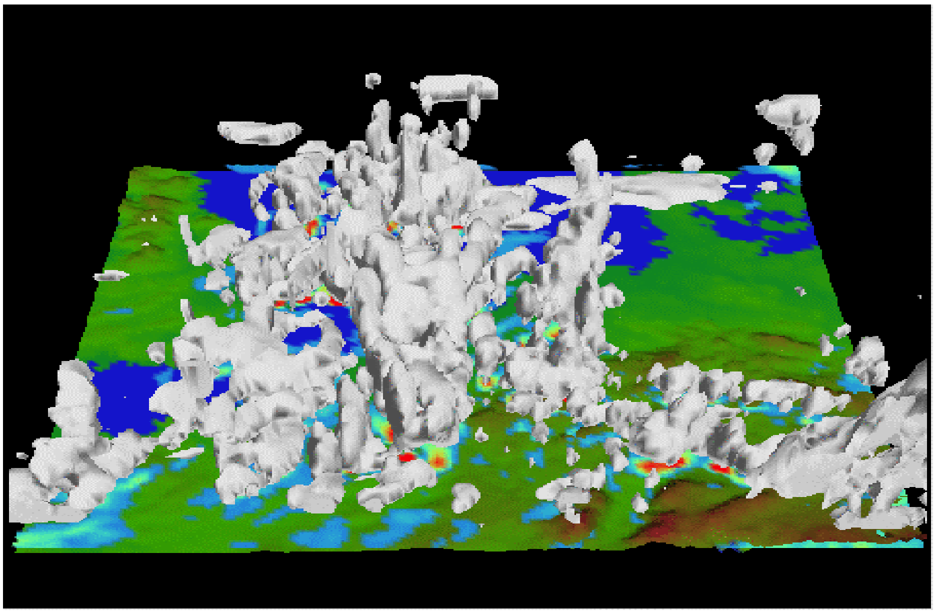
Hence, it must be noted that the improvement of quantitative precipitation forecast has not kept up with the society's requirements on our forecast systems. This is associated with a lacking acceptance of the prognosis results by the public. The population's trust in the reliability of precipitation forecast is so small that justified warnings are often ignored. The present, very dissatisfying situation in precipitation forecast is underlined by the fact that no adequate objective forecast methods exist for the time range between 1 and 6 hours, which is of importance to many users and might be used for issuing warnings of local extreme precipitations and the associated extreme events.



RV in 16 Jahren = Reduction of variance in 16 years

Extrapoliert = extrapolated

Fig. 1: *Increase in the forecast quality of the German Weather Service during the past 16 years for the model variables of daily minimum temperature (MIN), daily maximum temperature (MAX), average temperature (T), wind direction (dd), wind intensity (ff), cloudiness (B), wind peaks > 12 m/s (fx), and precipitation yes/no (N.0). In fact, no improvement was reached in precipitation forecast (RV = 0.5%) (according to an internal report of the German Weather Service).*



Vorhersagegüte HSS (%) = Forecast quality HSS (%)

Kritischer Schwellenwert (mm/12 Std.) = Critical threshold value (mm/12 h)

Fig. 2: *Quality of short-term precipitation forecast reached by the German Weather Service in 2000 and measured by the Heidke Skill Score (HSS) for four different types of forecast approaches. SYN: Final forecast by a meteorologist interpreting the numerical forecasts, GME and LM: Direct, dynamic model prognosis, GMOS: Model improvement by statistical post-treatment (model output statistics) of the numerical predictions GME (according to an internal report of the German Weather Service).*

Insufficient quality of precipitation forecast makes its use by potential users very difficult. A major group of users of quantitative precipitation forecast is hydrology. Precipitation is the decisive input variable of hydrological models. Without precise precipitation forecasts, hydrological models can only calculate outflow volumes and levels on the basis of already fallen precipitations. At the moment, the requirements made by hydrologists with respect to quantitative precipitation forecast cannot be fulfilled. Typically, 10% accuracy of quantitative precipitation forecast with spatial and temporal resolutions of 10 km and one hour, respectively, are needed (Arnaud et al. 2002, Zehe et al. 2001). Quantitative precipitation forecast is far from meeting these requirements. Improvements in the forecasts of hydrological models by taking into account precipitations to be expected would significantly profit from a more reliable precipitation forecast. Prognoses of floods and an early warning of the population require reliable quantitative precipitation forecasts, such that highest priority should be given to its improvement. Furthermore, the efficiency of water quality assurance measures – to give an example, the control of sewage treatment plants – would be improved considerably by a better quantitative precipitation forecast. This priority program among others will generate the basis for reducing economic damage due to extreme precipitations and floods by more accurate and longer-term warnings. In addition, water resources management will be provided with a basis for more efficient control mechanisms.

2. Objectives of the Priority Program

This research program meets the challenges put up by the user groups with respect to quantitative precipitation forecast. It has been initiated by atmosphere researchers at universities and research institutes, who excellently combine the knowledge required to improve quantitative precipitation forecast. Under this priority program, scientists and experts in the following fields will cooperate:

- Dynamics of the atmosphere
- Physics of cloud and precipitation formation
- Probabilistic treatment of atmospheric processes
- Methods of data assimilation
- Development and application of dynamic simulation models
- Remote sounding of the atmosphere

A priority program combining this expertise accounts for the fact that in view of the high development level of operational weather forecast systems, further improvement of quantitative precipitation forecast can no longer be achieved by isolated efforts of individual groups of researchers. The scope of tasks to be managed simultaneously is so wide that a joint and coordinated effort of university institutes and research institutions is envisaged, with the operational forecast system of the German Weather Service being integrated as a development, testing, and validation instrument. In the past two decades, meteorological research in Germany may have produced important fundamental knowledge on atmospheric processes, but this only partly resulted in an improvement of quantitative precipitation forecast. Specific implementation requires a focal point to meet the high international standard in this field. Within the framework of the present priority program, the offer by the German Weather Service to make available its operational forecast system, including a supercomputer environment, to universities and research institutes, is accepted. This is a unique chance for meteorology in Germany to study acute problems of the retrieval and modeling of atmospheric flows with the objective of decisively improving quantitative precipitation forecast.

Under the priority program, it is focused on reaching the following scientific objectives:

- **I** **Identification of physical and chemical processes responsible for the deficiencies in quantitative precipitation forecast**
- **II** **Determination and use of the potentials of existing and new data and process descriptions to improve quantitative precipitation forecast**
- **III** **Determination of the prognosis capacity of weather forecast models by statistico-dynamic analyses with respect to quantitative precipitation forecast**

Improvement of quantitative precipitation forecast may only be successful, if the causes of the latter's deficiencies are identified. Presently, these deficiencies are seen in errors of the initial fields, non-adequate modelings of components of the water cycle, inadequate methods for the simulation of data sets in the models, and in basic problems in the interpretation of deterministic models. To eliminate these deficiencies, coordinated research work has to be carried out in the following fields:

1. To identify the causes, a systematic evaluation of model simulations with comprehensive observation data is required. On this basis, the so far inadequate descriptions of cloud and precipitation processes as well as of the exchange processes of water vapor between land surfaces and the lowest atmospheric layers will have to be expressed by new or at least considerably improved concepts. Actually, the fundamentals required for this purpose are lacking. This is illustrated by the fact that today's methods are largely based on formalized plausibility assumptions rather than on confirmed effect mechanisms. The conclusion can be summarized as follows:

   Understanding of atmospheric processes relevant to precipitation formation has to be improved considerably. These processes have to be modeled in a more realistic manner.

2. Errors of the description of initial conditions, above all with respect to water vapor fields and atmospheric dynamics, are very large. By making use of all potentials, these errors have to be reduced considerably by means of modern observation and analysis methods. Spatial and temporal structures of the water field in all phases have to be represented adequately by the initial conditions of numerical simulation. The present errors of these fields alone are largely unknown. A great potential results from the data sources that have not been used at all or adequately in weather

forecast, e.g. the numerous high-resolution precipitation measurement networks of the water resources management associations, cloud observations, modern experimental satellite sensors, and data from radar networks. It may therefore be stated that:

Initial distribution of the atmospheric water content in the three phases of vapor, liquid, and ice has to be improved by data that have not been used so far and new data. Their potential for quantitative precipitation forecast has to be quantified.

3. The deficiencies in quantitative precipitation forecast are caused by lacking data as well as by the lack of data assimilation methods, by means of which the irregularly distributed and indirect observations of the atmospheric water content and other state variables (apart from precipitation measurements, these are e.g. cloud observations, measurements of the global satellite-supported navigation systems) are processed to a four-dimensional field that is consistent with the remaining dynamics of the atmosphere. Among others, this requires the simulation of the measurement process for the assimilation of observation data. For forecasts over six to twelve hours (short-term and shortest-term forecasts) adequate data assimilation methods are lacking in general. Hence, the following activities are needed for all potentials being made use of:

Methods of assimilating measurement data into atmospheric simulation models and application of these methods to data of any type for a statistico-dynamically consistent retrieval of the initial water distribution and, hence, optimum use of all data have to be improved.

4. So far, the stochastic character of precipitation forecasts and observations and the associated water vapor variations have hardly been taken into consideration. To determine the prognosis capacity, identification of the relevant scales in space and time has to be enhanced. This also applies to the determination of flow structures that allow for quantitative precipitation prognoses, including estimations of uncertainties. Innovative forecast strategies have to be developed for better taking into account these facts. They do not necessarily have to follow previously used deterministic strategies. The corresponding studies and developments are only possible, if evaluation is improved by integrating innovations in an atmospheric simulation model and validating the simulations with observations. This results in the last major field of work:

The stochastic character of precipitation has to be taken into account when using observation data, interpreting deterministic simulations, and developing alternative forecast strategies.

In general, more precise specification of spatial and temporal scales on which precipitation can be predicted quantitatively is essential to an improvement of quantitative precipitation forecast. Moreover, it is necessary to identify the dynamic processes and four-dimensional structures of atmospheric flows that contribute to predictability. However, real structures and processes may only be identified by combining modeling with the aggregation of observation data and only verified by validating realistic forecasts with observations. This yields the following four major areas of work under the planned priority program (Fig. 3). These four areas of work comprise the following tasks:

Area A) Studies of Atmospheric Processes Contributing to Precipitation Formation

It is the main objective to improve the understanding of precipitation-relevant processes for their adequate modeling in the range below the usual model mesh widths (sub-scale processes). New and efficient approaches are considered for the following processes: Convection, cloud and precipitation formation, radiation, turbulence, and vertical exchange in general as well as in the planetary boundary layer in particular. As pointed out under Area C) below, probabilistic approaches taking into account the inherent uncertainties of any sub-scale parameterization should be developed and verified.

Development and validation shall be based mainly on data from current and planned national and international large-scale experiments. For the validation and further development of sub-scale process simulation, a specific field experiment on precipitation processes shall be carried out in the fourth year of the project together with an at least state-wide, intensive observation phase over the entire year. For this purpose, it is planned to retrieve, in a four-dimensional manner, the small-scale to turbulent interactions between water vapor, clouds, and precipitation. During the first three years of the priority program, an appropriate measurement strategy and an experiment plan shall be developed on the basis of theoretical and conceptual studies and the experimental experience gained so far. This strategy and plan shall serve as a basis for an evaluation by experts and the bundling of proposals concerning the measurement technology for the planned experiment.

Area B) Database and Data Supply

Analysis of the water cycle in the atmosphere starts with the sources and sinks on the Earth's surface and extends over the spatial and temporal distribution of water vapor in the boundary layer and complex multi-phase processes in the troposphere. Here, new satellite sensors, novel ground-based, balloon-borne, and aircraft-borne techniques as well as methods of situation-adapted measurements shall be given priority when determining the water content of the atmosphere. Within the framework of the priority program, it is required to integrate the data in the existing forecast system, to extend the latter in terms of assimilation and quality control, these activities being closely connected with those of Area (C), and to verify and evaluate the influence of the new data on the quality of quantitative precipitation forecast.

Area C) Development of Data Assimilation Systems and Studies with Respect to Validation and Predictability

As it is closely linked with small-scale atmospheric processes (Area A), precipitation requires the respective assimilation methods to fulfill special requirements that have not been met so far. Development and use of 3d to 4d assimilation methods shall be supported for all water phases, including an extensive quality control of input data. Apart from the further development of already existing methods, this requires the development of the adjoint and tangent-linear model in the high-resolution atmosphere model that is to be used jointly. Furthermore, physically based forecast methods have to be developed for the short-term and shortest-term range of 0 to 12 hours, which may well extend or leave the previously pursued approach of deterministic model simulation.

Apart from the utilization of observations as input data (Area B), however, optimum data use also includes the interpretation of simulation results when validating and statistically processing numerical simulations. Validation (model assessment) and statistico-dynamic interpretation for optimum use of the model results (Model Output Statistics, MOS) shall contribute to identifying the spatial and temporal scales and processes (Area A) that contain relevant information for a quantitative precipitation forecast. In this respect, these activities link the areas A through D apart from the joint atmospheric simulation model. Progress in quantitative precipitation forecast in the probabilistic sense may be expected from e.g. Monte Carlo ensemble simulations as well as from their evaluation and assessment.

Area D) Linking of the Objectives by Integration, Testing, and Evaluation in an Operational Model System

A high-resolution, close-to-reality, and modern simulation system of atmospheric flows will be made available to all parties involved by the German Weather Service and further developed by the results obtained under (A) through (C).

Areas A through C cannot be separated from each other (see Fig. 3). New approaches to describing precipitation-relevant processes (A) may only be verified efficiently (C) with the help of an improved and extended database (B). Optimization of data use in models and reduction of uncertainties of initial and boundary conditions (C) – in particular of the water vapor field – also require an extended database (B). Quality control of input data (C) to be included in data assimilation will allow for a quantitative assessment of new data sources (B). Their influence on the forecast quality on different scales is studied by validation in the operational environment (D). Apart from the initial conditions of the forecast, data assimilation (C) always provides for a measure of the size and structure of uncertainty, which has to be considered by probabilistic quantitative precipitation forecast (D). Integration of novel developments in an existing quasi-operational system made available by the German Weather Service together with a computer environment will result in a high synergy of the results to be achieved under (A) through (C).

Large-area Observation Period and Precipitation Experiments:

The urgently required improvement of knowledge on the relevant processes as a basis of model optimization with respect to the currently blatant uncertainty of quantitative precipitation forecast can only be achieved when data are made available, which meet a far higher standard than the measurement values that are routinely recorded for weather forecast and climate investigation. Major key processes, such as the initiation of convection, are not recorded at all by the standard instruments presently used. It is therefore indispensable to extend the database by field experiments, where measurement instruments allow for the observation of decisive atmospheric variables. These include the atmospheric dynamics, the water vapor field as well as cloud and precipitation parameters. A new generation of measurement instruments shall be applied that allow for the three-dimensional determination of these variables with high temporal resolution.

The entire experiment (a detailed description is given in Section 3.5) shall comprise a large-area observation phase of one year (General Observation Period, GOP), one or several dedicated experiments regarding the precipitation process over several months (Intensive Observation Period, IOP), and high-resolution, four-dimensional measurements of atmospheric variables. Following the GOP, integration of operationally not recorded or stored data will result in the presently achievable optimum of information on the state of the atmosphere being supplied to a regional forecast system. Combination with the IOPs shall not only give rise to a far improved data set for assimilation and validation of models, but also to an improved in-depth understanding of the process. Evaluation of the data sets obtained under this priority program will lead to a better representation of relevant processes in models and, hence, to an improved quantitative precipitation forecast.

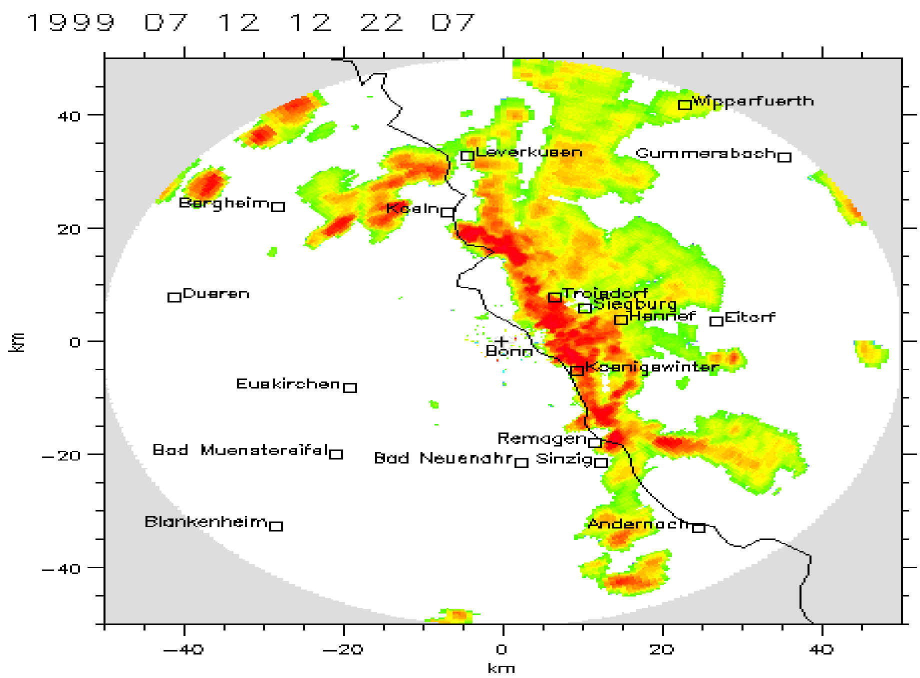


Fig. 3: *Structure of the planned priority program*

This priority program on the quantitative predictability of precipitation will be able to objectively document its successes. The quality of weather forecasts is controlled regularly with the help of observations made by the forecast centers. For this reason, the results may be applied for obtaining commercially usable statements. Improvements can be documented when the use of an existing operational simulation system under the priority program produces results that can be verified with observations. Hence, integration of a high-resolution atmosphere model made available by the German Weather Service in the activities is of crucial importance.

3. State of Research and Approach

3.1 Investigation and Improvement of the Modeling of Precipitation-relevant Atmospheric Processes (Area A)

Especially in the field of non-explicitly resolved physical processes, atmosphere is characterized by extremely intensive movement processes (small-scale turbulent vortices, convection structures, organized circulations in the boundary layer) and energy conversions (cloud formation, radiation divergences) that can only be accounted for in a parameterized form only by weather forecasts. State parameters on the surface of the Earth (surface temperature, soil humidity, terrain height and slope, natural cover, roughness) as well as at the upper limit of the boundary layer and the associated fluxes (shear stress, evapotranspiration, radiation balance, entrainment) usually are very heterogeneous and have to be modeled e.g. by effective values. The individual structures in a grid cell non-linearly enter the latter's effective mean value. This so-called "model physics" of an atmosphere model also includes the simplified and, hence, computation-efficient description of radiation transport and the formation of clouds and precipitation.

Selection of the "model physics" and of effective boundary values on the surface of the Earth has a considerable influence on prognosis quality. At the moment, a number of weather forecast models are still based on concepts that partly originate from measurement projects under very idealized conditions (extended, plain steppe areas) and partly simplify the processes in an impermissible manner. Conventional physics packages frequently exhibit inconsistencies between the different models. The planned measurement projects are therefore expected to have high a development potential. They will be far more complete than previous experiments due to novel instrumental methods with data being obtained under realistic boundary conditions. Dedicated field experiments for recording sub-scale precipitation processes are planned to serve as a nucleus for a larger European initiative (see 3.5). Within the framework of this priority program, projects shall be supported in this area. Experimental data, modeling, and data analysis shall be coupled such that (a) the basic understanding of hydrometeorological processes is improved, (b) the treatment of processes in models is verified and optimized using data from field measurement programs, and (c) concepts of improved model representations of this type, also in the form of process models, are tested in the environment of an operational weather forecast system (D).

State of the Art

Turbulence closure: Closure methods for turbulence processes in the boundary layer are required to describe the sources and sinks of energy, impulse, and water in all phases, which are due to divergences of turbulent fluxes. Conventional methods are those according to Smagorinsky/Lilly (Smagorinsky 1963, Lilly 1962) and closure of the order 1.5 (Klemp and Wilhelmson 1978, Mellor and Yamada 1974) or higher order (Moeng and Wyngaard 1989). Newer methods include the dynamic method according to Germano (Germano et al. 1991), the transilient method according to Stull (1984), and a number of non-local closure methods based on simulations of the coarse turbulence structure (Large Eddy Simulation, LES) (Moeng 1993). Boundary layer parameterization for an atmosphere model has to cover all processes smaller than the scale of model resolution. This parameterization of sub-scale processes is of decisive importance to boundary layers above homogeneous surfaces that represent most of the land surfaces (see below).

Boundary conditions for inhomogeneous, orographically structured terrain: In case of structured terrain, fluxes on the earth's surface considerably differ from those above homogeneous, plain areas, for which known relations exist (Businger et al. 1971). Land surfaces are characterized by fractal properties (Mandelbrot 1980). When the scale studied is reduced, variability of the structural features and local evaporation does not decrease, but increase under certain conditions, e.g. at the transitions from a forest area to individual trees to individual leaves with stomas. A not yet solved problem is the specification of effective boundary values of fluxes and scalar parameters at the earth's surface for prognosis models (aggregation effect, Avissar and Pielke 1989, Kalthoff et al. 1998, Schädler 1990). But also the scale interaction between the surface and the boundary layer is of significance. It causes complex sub-scale flow structures that considerably influence the exchange of water between the soil and the atmosphere (Chen and Avissar 1994, Avissar and Schmidt 1998). Although it is not yet accounted for by today's coupling of weather forecast models with extensive soil vegetation models (SVAT), the results obtained with current SVAT schemes already reveal differences in precipitation formation, which may be attributed to the treatment of vegetation and soil water (Seuffert et al. 2002).

Radiation processes: Clouds and precipitation couple the energy and water cycles in the atmosphere. Presently, radiation is hardly considered as a primary energy in the models. However, it is the clouded atmosphere with its extreme gradients that leads to local insolation, e.g. by shadow effects on the ground. Their relevance to convective precipitation formation must not be underestimated. Water vapor and cloudiness exhibit a high temporal and spatial variability on all scales. Due to the horizontal net radiation fluxes induced, radiation transfer has to be treated as a 3D problem in principle, contrary to the past practice (O'Hirok and Gautier 1998, Davies and Marshak 1998). This allows to correctly determine the mean backscattering capacity of could fields and, hence, the radiation energy available (Cahalan et al. 1994). Inhomogeneous insolation is of comparable importance to the exchange processes on the ground. It leads to small-scale circulations and, hence, affects the boundary layer, cloud formation (McNider et al. 1995, Lipton 1993, Segal et al. 1986, Mölders and Raabe 1996), and precipitation (e.g. Chen and Avissar 1994). Precipitation itself causes a massive change of the radiation properties of the earth's surface, which influences convection.

Deep convection: Modeling of the formation of deep convection is important, as it is accompanied by intensive precipitation and a high hazard potential due to hail, squalls, and lightning. In weather forecasting very different parameterization methods are applied, e.g. methods analyzing humidity convergence (Kuo 1965, Tiedtke 1989), wet-convective adjustment (Manabe et al. 1965, Betts and Miller 1986), or methods based on simple cloud models and statistical closures (Arakawa and Schubert 1974). A comprehensive survey of deep convection is given by Emanuel (1994). Experimental generation and verification of parameterizations of deep convection are difficult, as convection clouds develop in a large-scale environment and retroact on the latter, such that causes and effects can hardly be separated. The changes induced in the environment retroact on convection, but cannot be measured with sufficient accuracy. Moreover, feedback on the environment strongly limits natural variations, such that the range of fluctuation of large-scale stability conditions becomes very small and minimum differences may initiate deep convection already (Raymond 1993). For these reasons, weather forecast models have problems as far as the initiation and development of deep convection are concerned.

Cloud and precipitation formation: Central problem areas of the simulation of cloud and precipitation formation are the model physics representation, the associated computation time, and spatial resolution. In the case of a regional model, the area size, horizontal humidity advection across the boundaries, and humidity convergence in the model area have a strong influence on precipitation formation. This is confirmed by a number of case studies (e.g. Keil et al. 1999). Cloud physics representation comprises the specification of components and the corresponding number of balancing equations to describe hydrometeors. A minimum set includes water vapor, cloud water, and rainwater. This set may be extended by various classes of ice (graupel, ice crystals, snow) of various levels of detailing and the resolution into size classes (e.g. 100 classes for droplets, crystals, graupel, snow). Alternative methods focus on equations for the temporal change of momentums of size distributions (Wacker and Seifert, 2002). The balancing equations contain three terms that are difficult to treat in connection with precipitation forecast. (1) Advection: Here, the problem consists in e.g. ensuring the positive definiteness of the water contents. (2) Sub-scale transport by turbulence and gravity-induced falling. (3) Conversion of components in interaction with others (e.g. frost coating of graupel by the capture of cloud droplets). A central part of cloud microphysics modeling is the formulation of conversion rates (Seifert and Beheng 2001). Here, a wide variety of concepts exist, and there is considerable need for testing in an operational model environment (D). An open question is that of the rapid growth of particles observed in a convective shower cloud. Another open question covers the use of the precipitation process. For instance, it is revealed by observations with cloud radars that most boundary layer clouds drizzle in their lower range (Fox and Illingworth 1997). So far, this has hardly been verified quantitatively by models. Finally, it has to be taken into account that precipitation formation in warm clouds takes place via the coalescence process only and that at mid-latitudes also the ice phase is involved.

Work Plan

Research work in the field of modeling based on numerical simulations and field measurements under realistic conditions must be aimed at improving existing concepts or finding new concepts for studying precipitation-relevant processes. These concepts will then be implemented in the atmosphere model system and tested and evaluated in an operational environment. Superordinate accompanying activities to improve physical consistency of model physics also are expressly welcome. Novel measurements may contribute decisively in this area. For instance, novel methods of ground-based remote sounding provide fields of major atmospheric variables of high temporal and spatial resolution. In combination with other measurements (towers, aircraft), they promise to bring about new findings regarding the budget of atmospheric variables. In this respect, the recently developed lidar processes (Senff et al. 1994, Wulfmeyer 1999) and radar methods (Angevine et al. 1994, Lippmann et al. 1996) have to be mentioned.

As far as the heterogeneous land surface is concerned, it will be an important task to compare hydrologically consistent SVAT models area-wide taking into account remotely sounded aircraft and satellite data and to validate them under quasi-operational conditions. To better consider radiation effects, multi-dimensional radiation codes cannot be applied in the foreseeable future. Here, efficient approaches will be required to adequately simulating these effects on all relevant scales. Neural networks and perturbation theory have a considerable potential in this respect. *Independent column approximation* appears to be a usable approximation (Scheirer and Macke 2001). Statistical methods are under development, which take into account the sub-scale variability at large-scale radiation flux divergences. However, also the construction of sub-scale variability itself is of considerable importance, i.e. consistent coupling of radiation divergences in dynamics, convection parameterizations, and treatment of the background (cf. Area C, stochastic parameterizations). New concepts for deep convection to be implemented under this priority program result from the four-dimensional structure of the water vapor field to be acquired. Its inhomogeneities may have a decisive influence on the start of convection (Weckwerth et al. 1996, Weckwerth et al. 1999). A major possibility of concept verification does not only consist in a complex statistical analysis of measurement data, but also in the use of cloud-resolving models together with the operational forecast system.

Minimum mesh width of a forecast model determines the size of the smallest, still resolvable precipitation cells. It is known that precipitation often falls from individual cells (also in case of frontal precipitation) and is highly variable over time and small areas. These mostly sub-scale variations contain stochastic and deterministic fractions. Statistical methods allow to investigate sub-scale variability as a function of the orographic boundary conditions and the state variables resolved by the model. Using smaller-scaled nested models with an explicit initialization by precipitation data under certain circumstances (e.g. Haase et al. 2000), small-area precipitation distribution can be calculated explicitly. Statistico-dynamic modeling combines both approaches and provides major fundamental data for practical problems (dimensioning in water resources management, flood protection). Quality of precipitation modeling, however, is limited significantly by the quality of the water vapor field and realistic representation of dynamic processes. If a front shift is prognosticated incorrectly, frontal precipitation may be calculated correctly, but occurs at a wrong position. Improvement of precipitation forecast therefore requires parallel efforts in all four areas of the priority program. Additional verification of newly developed models of sub-scale processes shall be ensured by long-term simulations, e.g. to control annual variation.

3.2 Database and Data Supply (Area B)

State of Research

Initialization of atmosphere models is based on standard input parameters obtained from direct measurements with radiosondes, synoptic ground-based or ship-borne stations to determine meteorological variables near the ground, aircraft measurements during starting and landing, and satellite measurements above cloud-free areas. For validation purposes, climate and rain measurement stations are used. These data are of high significance to reach the research objectives of the priority program. Their temporal (6 to 12 hours) and spatial (50 to several 100 km) resolution, however, is not sufficient for a detailed description of precipitation processes. It is therefore aimed at using data sets that have not been used so far due to their status of data analysis or insufficient measurement devices.

To enhance the understanding of the process, very high requirements are made on the measurement devices, which could not be fulfilled until a few years ago. Key instruments for studying small-scale processes in precipitation development are ground-based scanners as well as aircraft-borne and satellite-based remote measurement systems, as they allow to determine spatial and temporal distributions of atmospheric variables on the relevant scales. To study the entire process, the latter have to be combined with standard measurements through assimilation and statistical analysis (Area C). As a whole, the database has to provide for a sufficient coverage and accuracy, such that it may also be used for the tasks under Area D.

In Germany, excellent expertise exists in the field of the development of *in situ* sensors and *in situ* measurements. These highly developed techniques, however, do not provide any insight into the 2-dimensional and 3-dimensional structure of atmospheric variables and their temporal variability. In passive remote sounding microwave devices are applied, which allow for the determination of many parameters of the clouded atmosphere (see Crewell et al. 2001, Czekala et al. 2001 for the latest ground-based systems). Passive devices are robust and characterized by a small power consumption which makes them predestined for long-term measurements and use on satellites. Active remote sounding is based on radar and lidar systems as well as on the GPS (global positioning system). Radar and lidar systems allow for distance-resolved measurements of atmospheric variables. Whereas several radar systems (e.g. rain radar) have already been operated routinely for a long time (Handwerker 2002), lidar systems have been employed for a few years only, after decisive breakthroughs were achieved in laser development and measurement methodology. As far as microwave, lidar (Wulfmeyer and Bösenberg 1998, Ehret et al. 1999, Müller et al. 1999), and radar methods (Lippmann et al. 1996, Danne et al. 1999) are concerned, Germany assumes a leading position worldwide in major research areas. The fact that novel systems are now available in Germany is one of the reasons why this research program has the potential of decisively improving the understanding of precipitation processes. While developing the database, the focus will be on the following variables:

Water vapor: The water vapor content plays a decisive role for the priority program as, among others, its spatial inhomogeneity may cause deep convection and precipitation (Crook 1996, Weckwerth 2000). In spite of its relevance, appropriate high-resolution devices only appeared recently (for the current status, see Weckwerth et al. 1999). In the past years, major progress was reached in the measurement of water vapor fields. Ground-based passive microwave radiometry and GPS technology meanwhile allow to measure all-weather fields of the vertically integrated water vapor content with the accuracy of radiosondes. Multi-spectral and scanning microwave radiometers can be used to determine water vapor profiles. The GPS radio-occultation technology allows for the retrieval of water vapor profiles (see Ware et al. 1996) from satellites. These methods shall be employed above all for process studies during the experiment phase of this project. In the near future, new passive systems will be applied on satellites, as a result of which global coverage will be reached. Such systems include sensors on ADEOS-II and ENVISAT, SEVIRI on MSG (METEOSAT Second Generation), and AIRS on the EOS PM/1 AQUA satellite. All these satellites were launched in 2002.

Lidar technology has the potential of retrieving water vapor variability on the scale of decameters up to 10 km. By means of the Raman lidar or differential absorption lidar (DIAL), water vapor profiles can be determined with high accuracy and resolution. Some of the best systems were developed in Germany. They are frequently applied in international measurement campaigns (Wulfmeyer and Bösenberg 1998, Ehret et al. 1999, Hoinka et al. 2003). Due to their high accuracy, lidar systems may well be employed as individual devices for studying the pre-convective water vapor field and in networks for routine field measurements.

Cloud parameters: Remote sounding plays a very important role in the determination of the spatial distribution of the cloud water and cloud ice content. Due to the extremely high spatial and temporal variability of clouds, measurement devices have to meet very high requirements. Vertically integrated liquid water contents can be measured by passive microwaves (Crewell et al. 2001). Cloud radars record the vertical structure and phase of clouds, but hardly allow any quantitative statements to be made. In the past years, progress was achieved in the determination of the profiles of these parameters by the synergy of passive and active systems. In the future, these systems will be available at the so-called atmospheric base stations (Löhnert et al. 2001). The microwave radiometers and cloud radar systems developed and used in Germany are unique in terms of resolution and scanning properties. Modern satellite systems will supply cloud parameters of global coverage. MSG and ENVISAT (since 2002) are of relevance to the priority program.

Precipitation: In situ precipitation measurement systems record the spatial and temporal structure of the precipitation field at certain points only. Adequate spatial-temporal interpolation methods are currently being developed (e.g. RADOLAN by the German Weather Service; EU Project MUSIC in Italy). The potential of such interpolation methods in combination with radar measurements has not yet been made use of completely. Scanning radar systems have already been applied for a long time in precipitation measurement, but suffer from the fact that general allocation of radar reflectivity and precipitation rate (Z-R relation) is limited. Nevertheless, the existing network of operational radar measurements of the German Weather Service (radar network) will represent an essential database for this priority program, as only these data will allow to determine the temporal and spatial structure of precipitation over large areas. Methods to improve quantitative precipitation retrieval by radar measurements associated with assimilation into atmosphere models (Haase and Crewell 2000, Haase et al. 2000) or for process studies on precipitation development will contribute considerably to reaching the objectives of this priority program.

Temperature: Temperature profiles are determined by in situ measurements as well as by passive and active remote sounding. In Europe, only a few measurements are made by ground-based passive systems (e.g. microwaves, see Crewell et al. 2001). In the USA, networks have already been established (Feltz et al. 1998). Temperature profiles in the boundary layer can also be measured by radar and sodar systems (tomography) and by means of the RASS (radioacoustic sounding system) technology. Vertical profiles are retrieved by several systems available in Germany. However, scannings have not yet been performed. New, improved global data sets are and will be obtained by the present and future passive satellite-based systems on MSG, NOAA, METOP-1, and PM/1 AQUA.

Wind: Although retrieval of the dynamics is of crucial importance to the understanding of precipitation processes, there is no doubt that wind measurements are subject to significant deficiencies. Passive measurements are limited to winds on water surfaces and cloud tracing. Wind and temperature measurements on board of commercial aircraft are transferred to meteorological use under international programs (AMDAR, ACARS), the data volume amounting to 50,000 data per day with the tendency increasing. Their use for improving the prognosis quality has already been documented (Mamrosh, 1997).

To measure wind profiles, only active systems with Doppler components may be used. New Doppler radars (Danne et al. 1999) and Doppler lidar systems are available in Germany (Reitebuch et al. 2001). Both systems allow to carry out highly accurate measurements with high resolution.

Microphysical properties of aerosol particles: Measurements of these parameters, which should take place under realistic conditions in the free atmosphere, provide important insight into cloud formation. However, it is difficult to determine their parameter range. By means of lidar systems, aerosol particle layers can be detected and their microphysical properties estimated (Müller et al. 1999). The potential of new systems in the measurement of these variables is far from being exhausted. In field experiments, use of these new systems shall be combined with conventional measurements (see Section 3.5).

Other variables: Other major variables that shall be measured above all in the intensive observation phases of this program include turbulent variables as well as the size distributions of cloud droplets and precipitation particles. These variables are not measured routinely. Their measurement, however, yields very important information on the role of small-scale processes in precipitation development, provided that measurement is combined with the determination of other parameters in field experiments. While in situ turbulence measurement devices have been applied for decades (Lenschow and Stankov 1986), active remote sounding systems reached the resolution required for turbulence measurements a few years ago only (Senff et al. 1994, Angevine et al. 1994, Lippmann et al. 1996). Active remote sounding allows to instantaneously measure atmospheric turbulence profiles, such that the divergences of flux profiles that are so important to the budget of atmospheric variables can be determined (Wulfmeyer 1999). Lightning localization systems supply useful information on the spatial distribution of deep convection.

Work Program

Under this priority program, data will become accessible and be made available to research within the framework of a distributed virtual data center, which have not yet been used for studying precipitation processes. On the one hand, these are already existing conventional data sets, e.g. precipitation measurement networks and lightning localization systems. On the other hand, data sets obtained with new measurement instruments will be used. All these data sources will have to be structured such that they may be used for the tasks under either (A) or (C) and (D), where they directly serve to improve the initial fields (supported by new assimilation techniques, Area (C)) and make influences on prognosis quality verifiable. Consistent use of these data in the operational test environment is expected to enhance the understanding of precipitation processes.

The work program is divided into three partial areas:

1. Generation of a database of relevant atmospheric variables that are measured routinely. The database will consist of a combination of ground-based, aircraft, and satellite measurements. Particular emphasis will be put on components of the water cycle and on extending the currently available data by access to other data sources. All data will have to be subjected to a quality control comparable to that of the Mesoscale Alpine Project MAP (DAQUAMAP; Groehn et al. 2000).

2. Based on a large-area general observation period (GOP), the database shall be extended to cover more than one year (see Section 3.5). Data shall be collected, which cannot be obtained under operational conditions or which may only be measured with a considerable expenditure, e.g. if there are no possibilities of *online* transmission.

3. Finally, the highest stage of extension of the database shall be reached by the execution of experiments with the latest generation of remote sounding systems being used. Synergy with other data sets shall be made use of to obtain 3-dimensional to 4-dimensional data of atmospheric variables for a limited period of time.

Under this part of Area (B), also data of other large-scale experiments can be analyzed, provided that they are of high value to this priority program. The scientists involved have access to national and international data sets that are collected under AFO2000 (4D-Wolken, VERTIKO, VERTIKATOR) as well as under DEKLIM/BALTEX funded by the BMBF (EVA_GRIPS, BALTIMOS), the planned experiment TRACKS, European experiments (e.g. BBC-1/2, August/September 2001 and May 2003), and the US experiment IHOP (spring/summer 2002) to meet other research objectives. Furthermore, data of the planned THORPEX project, a global atmospheric research program of the WWRP, will be applied.

3.3 Assimilation, Optimization of Data Use, Validation and Predictability Studies (Area C)

State of Research

Improvement of precipitation forecast requires to considerably reduce the errors of the initial conditions of water distribution in space, time, and state of phase by the use of modern analysis methods. 4-dimensional variation methods are increasingly and successfully applied for this purpose by the weather services (e.g. Rabier et al. 2000, Zupanski et al. 2002). Such methods, however, hardly integrate measurements with respect to sub-scale processes that may be of relevance to precipitation forecasts. For short-term and shortest-term forecast of precipitation in particular, assimilation methods have to integrate data sources that have not been used at all or adequately so far. These sources range from precipitation measurements made by the associations for the use of water resources to latest experimental satellite sensors. In general, precipitation measurements and close-to-ground air temperatures are applied for data assimilation in operational forecast models to a very limited extent only. Experimental studies with respect to the assimilation of precipitation are reported by e.g. Krishnamurti et al. (1991) and Haase et al. (2000). The American Weather Service is currently testing an experimental version of precipitation data assimilation for the regional model Eta (see NMC 2001). Ament et al. (2001) present experimental assimilation runs for the local model of the German Weather Service regarding cloudiness and cloud water.

Use of not yet applied data from measurement networks that are not subordinate to the state’s weather services requires a complex quality control with the plausibility and representativeness of raw data being tested automatically based on their dynamics. Various methods are described in literature, e.g. the method according to Gandin (1993) that was applied for NCEP reanalysis, generalized cross validation according to Wahba and Wendelberger (1980) or the DAQUAMAP process (Groehn et al. 2000).

For forecasts in the range of 0 to 12 hours, methods of short-term or shortest-term forecasting are applied, as complex forecast models have problems in this time window, due to the always occurring initialization errors. For this reason, strongly observation-based forecast methods in the time range of up to 2 hours are applied, which often represent a simple stastico-dynamic extrapolation of the situation observed. On the European level, significant preliminary work was carried out under the COST78 Action “Improvement of Nowcasting Techniques“. Nowcasting is used in thunderstorm warnings, aviation, road weather forecast, agro-meteorological consulting, energy industry, and the construction sector. Torrential rain events, hail and the probability of lightning in case of thunderstorms, strong snowfall, freezing rain or undercooled cloud water are meteorological phenomena that concern quantitative precipitation forecast in the range of less than 6 hours. Any actual nowcasting method is based on data from forecast models, satellites, radar, lightning localization or conventional ground-based or aircraft-borne methods.

Calculation of an atmospheric flow as a function of time from an initial condition derived from observations yields a prognosis, the quality of which can be estimated by additional simulations. For these additional simulations, initial and boundary conditions are selected, which are generated by random variations in the range of uncertainty of the undisturbed initial and boundary conditions. Instabilities of atmospheric flow enhance these initial and boundary variations. This technique is referred to as Monte Carlo ensemble simulation. On the global scale, such simulations are carried out by the ECMW and the American Weather Service NMC. Using this technique, weather forecasts are converted into scenario descriptions of the future state of the atmosphere, which sketch a most probable scenario and possible extreme deviations under certain circumstances. By validating the simulations with observations, the spatial and temporal scales can be identified, on which the model results produce predictable information.

The ECMW (Buizza, 1997) has been using an ensemble prognosis system for global weather forecasts since 1992. This system takes into account spatially and temporally variable uncertainties of the initial state and, for a short time now, also uncertainties of the parameterizations in a pragmatic form (Buizza et al. 2000). The American Weather Service has also made ensemble prognoses for medium-term forecasts since 1992 (Toth et al. 1997). Operational ensemble forecasts, however, are not available for regional weather forecast models in Europe. Various weather services in Europe and the USA are conducting experimental work on this issue. Idealized statements of ensemble forecasts have been studied theoretically among others by Fraedrich and Ziehmann (1994) and by Smith et al. (1999).

Apart from the uncertainties of the initial state, also fluctuation ranges of boundary values in case of a strong horizontal inhomogeneity of roughness, plant growth or orography have to be taken into account by statistical approaches to forecasting. Theis et al. (2000) have shown, for instance, that random variations of the roughness length of 10% in amplitude only may lead to massive random variations of the LM convective precipitation forecast. Uncertainties of the formulation of parameterizations are accounted for by the ECMW changing the tendencies of prognostic variables by sub-scale processes using random amplitudes that vary horizontally and temporally. Approaches to randomized parameter variations are employed in automotive industry, where ensembles of crash simulations are carried out with the system parameters being varied randomly within the production error range (see SGI 2001).

Validation of weather forecasts is carried out operationally and published by the German Weather Service. This refers to both the close-to-ground parameters, e.g. temperature and precipitation, and the parameters describing synoptic flow in the free atmosphere. Statistical fundamentals of validation are dealt with extensively in literature. For instance, they are summarized in the monography of von Storch and Zwiers (1998). It was demonstrated by the validation studies that the statistical relationship between model forecast and observations can be optimized *a-posteriori* by regression methods based on a common data set of forecasts and observations. These regression methods are known under the term of *Model Output Statistics* (MOS, Glahn and Lowry, 1972). By optimization, the impacts of unavoidable model errors of systematic and random nature on the weather forecast of local events are minimized. MOS systems are employed by all weather services worldwide, as they (1) may even further improve any forecast system and (2) automate pointwise weather forecast (Knüpfer 1996; Schölzel et al. 2000). Moreover, they are suited to identify systematic model errors. A large potential of future MOS systems lies in modern methods of mathematical statistics. The problem of the automatic generation of thunderstorm warnings, for instance, is comparable with the monitoring of patients in intensive medicine. Additionally, measurements by modern remote sounding systems (Area B), such as lidar, radar, satellite measurements or the localization of lightning, can be integrated increasingly in the shortest-term weather forecast so as to better cover the forecast period of 0 to 6 hours or to identify deviations from the most probable scenario in ensemble forecasts (Keil et al. 2003). The corresponding approaches to empirico-stochastic description are presented by Raible et al. (1999) with the focus lying on the short-term prognosis of temperature and precipitation probability. In statistical literature, statistical methods for the correction of the forecasts of complex systems were presented in the past two years. Here, a few simulations only with an extensive computer code are available (Craig et al. 2001).

Work Program

Apart from lacking data availability and model errors, deficiencies in quantitative precipitation forecast are caused by lacking data assimilation methods, by means of which the irregularly distributed and indirect observations of the atmospheric water content and other state variables are processed to a 4-dimensional field that is consistent with the remaining dynamics of the atmosphere. This does not only require an optimized use of modern observation methods (see Area (B)), but first of all the simulation of the measurement process for the assimilation of the observation data. Furthermore, development of data assimilation methods suited for the simulation system of the German Weather Service has to be promoted. For this purpose, various assimilation techniques (nudging, Kalman filter, variational analysis) are available in theory. Variational analysis and partly also the Kalman filter technique require the development of an adjoint or tangent-linear model for the high-resolution atmosphere model and its partial models used. As this is associated with a high expenditure, further development of less resource-intensive nudging techniques should be pursued.

Assimilation of humidity parameters with their (due to phase transitions) discontinuous dynamics, however, may be very difficult. With increasing model resolution, this also is to be expected for modern methods, e.g. the 4D-var method, which are based on the assumption of a continuous development. More general probabilistic methods with discrete optimization capacities should be developed for data assimilation.

Typical work objectives in the development of a nowcasting method range from the understanding of the phenomenon to be modeled to the development of the actual short-term forecasting technique to appropriate visualization methods to the user interface. As all data sources mentioned above are available, Germany possesses a good basis for the development of nowcasting methods that meet with considerable interest in traffic guiding planning or by mobile phone suppliers for the transmission of location-specific information or warnings.

A physically reasonable possibility of considering the uncertainties of parameters selected for process descriptions consists in disturbing the free parameters (in the parameterizations fit by comparison with observations (calibration)) within the range of uncertainty and, thus, in developing randomized parameterizations. In the future, this will be one of the major tasks of fundamental research on weather forecast, which will also be in the focus on the international level. Development of randomized parameterizations is closely linked with Area (A). First approaches to a stochastic convection parameterization are found in e.g. Yano et al. 2001.

As larger ensemble random sampling requires considerable computing times and storage capacity, methods for the statistical interpretation of small random samples or even individual quasi-deterministic prognoses are needed to separate random variabilities of precipitation forecast (using the validation results) from the predictable fractions. Thus, both a quantitative precipitation forecast as well as its uncertainty are obtained. As an alternative, a probabilistic precipitation forecast could be applied to quantify probabilities of occurrence of certain precipitation events. To optimally use numerical precipitation forecasts, a MOS system should be developed for the *a-posteriori* correction of errors of the forecast system by integrating available observations. For this purpose, modern methods of time series analysis can be used. Recursive methods (e.g. ensemble Kalman filtering or as described by Craig et al. 2001) have a high potential in this respect.

3.4 Linking of the Objectives by Integration, Testing, and Evaluation in a Complex Model System (Area D)

The objectives of this priority program with respect to weather forecast as outlined under Areas (A) through (C) are directed towards a better understanding of the physical processes, innovations related to the database and data supply, and an enhanced consideration of stochastic elements. Activities under Area (D) shall ensure that the results are used for improvements of quantitative precipitation forecast in a verifiable manner. Furthermore, a model environment meeting the international standard is made available, which can be maintained by none of the institutions involved alone. For university institutes availability of this model environment represents a unique opportunity of training. Moreover, it will enforce cooperation under this priority program. For this purpose, the German Weather Service will grant rapid access to its experimental forecast system (Doms and Schättler, 1999; Majewski et al. 2002) for new observation data and parameterization concepts to be integrated. In addition, the program tools of the German Weather Service will be applied to assess the prognosis quality on the basis of objective criteria. These criteria should be further developed, in particular with respect to the variable of precipitation. In this way, improvement in the modeling of precipitation processes will be documented.

This system is modeled after an operational forecast system that can be modified by the user e.g. introducing additional observation data, observation operators, and model components. From the simulation results obtained with the experimental forecast system over a sufficiently long period of time, influence of the changed database and model can be determined quantitatively by comparison with the reference operational numerical weather forecast made by the German Weather Service.

Supply of the test environment under this priority program represents a highly innovative and integrating element. In this way, numerical weather forecast with its already high development level is developed to a new tool of research. Thus, developments that have already been made in other fields (e.g. for the reconstruction of temporal development of the state of the atmosphere over 40 years, EU project ERA-40, or for the assessment of new observation methods by the *observation system simulation experiments* (OSSE) as a decision basis for the construction of new observation satellites) are complemented.

Within the framework of the forecast process, the partial process of data assimilation links all current observation data available for weather forecast with the information on the past temporal development of the state of the atmosphere, the result being an optimum estimate of the current state of the atmosphere with a temporal resolution of a few hours. This estimate represents the best, complete, and consistent description of the state of the atmosphere. Together with the forecast model, data assimilation allows for the validation of new (improved) observation systems and new (improved) descriptions of relevant physical processes. To describe and predict the state of the atmosphere, the additional information obtained under objective conditions, including all available observations, is important. Integration of longer periods of time and larger areas up to the coverage of the entire atmosphere ensures the reproducibility of the results. This always is a requirement to be fulfilled by natural scientific laboratory experiments, but cannot be met in principle by episodic and local observations and the stochastic properties of the atmosphere.

A numerical weather forecast system as a whole cannot be portable, as the necessary databases and pertinent communication systems represent major and technically very complex components that are available in weather forecast centers only. Users of the forecast system to be supplied will have to familiarize with this system so as to make use of its advantages "as a laboratory". Thus,

- the improvement reached in the description and prognosis of the atmospheric process studied can be determined objectively,
- consideration of the spatial and temporal variability of the atmosphere can be verified directly,
- sufficient supply of information, e.g. on error characteristics of data and processes, can be checked by the developers, and
- the sensitivity of the atmosphere with respect to uncertainties and errors of data and process descriptions can be determined.

All activities under this priority program, which will directly use the operational test environment, will require an efficient organization structure. It will be established jointly with the German Weather Service and the European Center. The working group to be formed will conceive the test scenarios, develop the computer network, and act as an interface between the scientific institutes and the German Weather Service.

3.5.1Experiment

The test and validation strategy outlined in Section 3.4 for the planned new developments is tailored mainly to the needs and requirements of operational weather forecast. The actually achieved process understanding can be assessed in a limited and indirect manner only. But it is here, where – as was mentioned above – major gaps exist. Consideration of data that have not yet been used for assimilation into models is another aspect that will have to be covered by this priority program. The influence of new data sets on quantitative precipitation forecast and the quality of parameterization of sub-scale processes may only be assessed by a dedicated field experiment that covers the atmospheric variables over several mesh widths on the physically relevant scales.

The high complexity of the planned field experiment as determined by the target variable of precipitation requires a preparation phase of several years, during which measurement instruments are further developed for use under field conditions, adequate convection and cloud models are prepared for the experiment, and a detailed experiment plan as well as an adequate and efficient coordination structure are set up. The experiment therefore is planned to be carried out in the fourth year of the program.

Traditionally, field experiments are crucial to the progress of meteorological research, as they bring together developers and operators of novel measurement techniques with the old hands of operational weather monitoring and, to an increasing extent, the users of numerical simulations for research purposes with operational numerical weather forecast. We expect that the planned experiment will bring together a number of research groups, as it addresses an interdisciplinary and challenging issue of atmosphere research. Thus, cooperation between university institutes and atmosphere research institutes will be enhanced. The experiment will serve as a nucleus for increasing the number of participants on both the national and international level.

Measurement of the processes causing precipitation is one of the greatest challenges of atmosphere physics. Knowledge of the relevant processes can only be improved, if data of so far unreached quality are produced. Key processes, such as the initiation of deep convection, are not recorded at all by the standard instruments used today. It is therefore indispensable to extend the database (Area (B)) by experiments, during which measurement instruments determine the atmospheric dynamics, water vapor field, and cloud and precipitation parameters in three dimensions and with high temporal resolution. Due to the necessary size of the area and the limitations that are imposed on all measurement methods by the clouded and turbulent atmosphere, retrieval always remains incomplete when the expenditure is realistic. These gaps have to be closed by the assimilation of data into simulation models that resolve these scales.

Planning of the experiment is a major partial objective of the first three program years. While preparing this priority program, preliminary work along this line was carried out at several meetings already. The basic decisions taken result from the scientific objective as well as from the selected structure of the priority program. The most important decision concerned the problem of the investigations of precipitation processes requiring both long time series of routine measurements as well as very-high-resolution observations of the key processes (among others, turbulence, convection). This problem is now solved by the combination of a general large-area observation phase (general observation period, GOP) with an embedded, dedicated experiment (intensive observation period, IOP). The GOP will be aimed at collecting and archiving data which cannot or only hardly be collected online under operational weather forecast conditions. During the IOP, key processes, such as turbulence and convection, which are not covered by conventional observation systems and models, shall be recorded in three dimensions and with high resolution and accuracy.

Another major decision concerned the place of the IOP and the atmospheric processes to be studied. Here, it has to be kept in mind that a number of atmospheric processes over a large range of scales are relevant to precipitation formation. It is therefore very important to specify clear objectives and define key processes to be studied with the present and future measurement systems. As the largest errors typically occur in terrains of complex orography, such as the German low mountain ranges, the IOP will concentrate on orographically influenced precipitation events in a low-mountain area. As the data of the IOP shall enhance the understanding of precipitation processes and, hence, improve quantitative precipitation forecast, observation will take place in an area, where this improvement will be of particular relevance to the users.

Novel measurement instruments have the potential of reaching the objectives specified for the IOP. At one measurement point at least, a combination of a Doppler precipitation radar, a Doppler cloud radar, a water vapor lidar, and a Doppler lidar shall be used to make use of the synergy of multiple-wavelength measurement. All systems will have to possess scanning properties. A close network of ground stations (precipitation, soil humidity, wind vector, temperature, humidity, pressure, turbulence measurement) and additional measurements with radiosondes and captive balloons shall condense the operational measurement network in the area investigated. Research aircraft shall be used to optimally condense the field distributions with *in situ* measurements (Vihma and Kottmeier 2000) and remote sounding systems (Ehret et al. 1999).

4. Program Committee

Prof. Dr. A. Hense (*Meteorological Institute of the University of Bonn*), Speaker of the Program Committee

Priv.-Doz. Dr. G. Adrian (*Head of the Research and Development Division of the German Weather Service, Offenbach*)

Prof. Dr. Ch. Kottmeier (*Institute of Meteorology and Climate Research, University of Karlsruhe/Forschungszentrum Karlsruhe)*

Prof. Dr. C. Simmer (*Meteorological Institute of the University of Bonn*)

Prof. Dr. V. Wulfmeyer (*Institute for Physics and Meteorology, University of Hohenheim*)

5. References

Ament F., G. Haase, and C. Simmer (2001) Initialisierung von Wolken im Lokalmodell mit Meteosatdaten, Deutsch-Österr.-Schweizerische Meteorolog.Tag., *Österr. Beitr. Meteorol. und Geophysik*, Heft Nr. 27.

Angevine, W.M., R.J. Doviak, and Z. Sorbjan (1994) Remote sensing of vertical velocity variance and surface heat flux in a convective boundary layer. *J. Appl. Meteor.,* **33**, 977-983.

Arakawa, A., and W. H. Schubert (1974) Interaction of a cumulus cloud ensemble with the large-scale environment: Part I., *J. Atmos. Sci*., **31**, 674-701.

Arnaud, P., C. Bouvier, L. Cisneros, and R. Dominguez (2002) Influence of rainfall spatial variability on flood prediction. *J. Hydrol.* **260**, 216 230.

Avissar, R. and R. A. Pielke (1989) A parameterization of heterogeneous land surface for atmospheric numerical models and its impact on regional meteorology. *Mon. Wea. Rev.,* **117**, 2113-2136.

Avissar, R. and T. Schmidt, (1998) An evaluation of the scale at which ground-surface heat flux patchiness affects the convective boundary layer using a large-eddy simulation model. *J. Atmos. Sci.,* **55**, 2666-2689.

Betts, A.K. and M.J. Miller (1986) A new convective adjustment scheme. Part II: Single column tests using GATE wave, BOMEX, ATEX, and Arctic air-mass data sets. *Quart. J. Roy. Meteor. Soc.*, **112**, 693-709.

Buizza, R., J. Barkmeijer, T. N. Palmer, and D. S. Richardson (2000) Current status and future developments of the ECMWF Ensemble Prediction System. *Meteor. Appl*., **163**

Buizza, R., (1997) Potential Forecast Skill of Ensemble Prediction and Spread and Skill Distributions of the ECMWF Ensemble Prediction System. *Mon. Wea. Rev*., **125**, 99-119.

Businger, J. A., J. C. Wyngaard, Y. Izumi, and E. F. Bradley, (1971) Flux profile relationship in the atmospheric surface layer. *J. Atmos. Sci*., **28**, 181-189.

Cahalan, R. F., W. Ridgway, W. J. Wiscombe, T. L. Bell, and J. B. Snider (1994) The albedo of fractal stratocumulus clouds, *J. Atmos. Sci*., **51**, 2434-2455.

Chen, F. and R. Avissar (1994) The impact of land-surface moisture variability on local shallow convective cumulus and precipitation in large-scale models. *J. Appl. Meteorol*., **33**, 1382-1401.

Craig, P. S., M. Goldstein, J. C. Rougier, and A. H. Seheult, (2001): Bayesian forecasting for complex systems using computer simulators. *J. American Statistical Association*, **96**, 717-729.
Crewell, S., H. Czekala, U. Löhnert, C. Simmer, Th. Rose, R. Zimmermann, and R. Zimmermann (2001) MICCY – a microwave radiometer for cloud cartography: a 22-channel ground-based microwave radiometer for atmospheric research. *Radio Science*, **36**, 621-638.
Crook, N. A., (1996) Sensitivity of moist convection forced by boundary layer processes to low-level thermodynamic fields. *Mon. Wea. Rev*., **124**, 1767-1785.
Czekala, H., S. Crewell, C. Simmer, and A. Thiele (2001) Discrimination of cloud and rain liquid water path by ground-based polarized microwave radiometry. *Geophys. Res. Lett.*, **28,** 267-270.
Danne, O., M. Quante, D. Milferstädt, H. Lemke, and E. Raschke (1999) Relationships between Doppler spectral moments within large-scale cirro- and altostratus cloud fields observed by a ground-based 95 GHz cloud radar. *J. Appl. Meteorol.*, **38**, 175-189.
Davies, A. and A. Marshak (1998) Levy kinetics in slab geometry: Scaling of transmission probability. In *Fractal Frontiers*, edited by M.M. Novak and T.G. Dewey, pp.63.72, World Scientific, Singapore.
Doms G. und U. Schättler (1999) The nonhydrostatic limited area model LM (Lokal-Modell) of DWD, Part I: Scientifc documentation. Technical Report, German Weather Service (DWD), Research Department, PO 100465,D-63004 Offenbach
Ehret, G., K.P. Hoinka, J. Stein, A. Fix, C. Kiemle, und G. Poberaj (1999) Low stratospheric water vapor measured by an airborne DIAL. *J. Geophys. Res*., **104**, 31,351-31,359.
Emanuel K. (1994) Atmospheric convection. Oxford University Press, 580pp.
Feltz, W. F., W. L. Smith, R. O. Knuteson, H. E. Revercomb, H. M. Woolf, and H. B. Howell (1998) Meteorological applications of temperature and water vapor retrievals from the ground-based Atmospheric Emitted Radiance Interferometer (AERI). *J. Appl. Meteor.*, **37**, 857-875.
Fox, N. and A.J. Illingworth (1997) The retrieval of stratocumulus cloud properties by ground-based cloud radar. *J. Apply. Meteorol.,* **36**, 485-492.
Fraedrich, K. and C. Ziehmann, (1994) Predictability experiments with persistence forecasts in a red noise atmosphere. *Quart. J. Roy. Meteor. Soc.*, **120**, 387-428.
Gandin L. (1993) Two Years of Operational Comprehensive Hydrostatic Quality Control at the National Meteorological Center. *Weath.Forecast.*, **8**, 57-72.
Germano, M., U. Piomelli, P. Moin, and W. H. Cabot (1991) A dynamic subgrid-scale eddy viscosity model. *Phys. Fluids*, **A 3**, 1760-1765.
Glahn H.R. und D. A. Lowry (1972) The use of model output statistics (MOS) in objective weather forecasting, *J. Appl. Meteorol*., **11**, 1203-1211.
Groehn, I., R. Steinacker, Ch. Häberli, W. Pöttschacher, M. Dorninger (2000) Data Quality Control of MAP DAQUAMAP). *MAP Newsletter*, **13**, 6-8.
Haase, G., S. Crewell, C. Simmer und W. Wergen (2000) Assimilation of radar data in mesoscale models: Physical Initialization and latent heat nudging. Phys. *Chem. Earth (B),* **25**, 1237-1242.
Haase, G. and S. Crewell, (2000) Simulation of radar reflectivities using a mesoscale weather forecast model. *Water Res. Res.*, **36**, 2221-2230.
Handwerker, J. (2002) Cell tracking with TRACE3D – A new algorithm., *Atmos. Res.*, **61**, 15-34.
Hoinka, K.-P., E. Richard, G. Poberaj, R. Busen, J.-L. Caccia, A. Fix and H. Mannstein (2003) Analysis of a potential vorticity streamer crossing the Alps during MAP IOP 15 on 6 November 1999. *Quart. J. Roy. Meteorol. Soc.*, **129**, 24 pp., in print
Kalthoff, N., H. J. Binder, M. Kossmann, R.Vögtlin, U. Corsmeier, F. Fiedler, and H. Schlager (1998) Temporal Evolution and Spatial Variation of the Boundary Layer over Complex Terrain, *Atmos. Environ*., **32**, 7, 1179-1194.
Keil, C., H. Volkert and D. Majewski (1999) The Oder flood in July 1997: Transport routes of precipitable water diagnosed with an operational forecast model. *Geophys. Res. Lett.*, **26**, 235-238.
Keil, C, A. Tafferner, H. Mannstein, and U. Schättler (2003) Evaluating High-Resolution Model Forecasts of European Winter Storms by Use of Satellite and Radar Observations. Accepted in *Weather Forecast*.
Klemp, J. B. and R. B. Wilhelmson (1978) The simulation of three-dimensional convective storm dynamics. *J. Atmos. Sci.*, **35**, 1070-1096.
Knüpfer K. (1996) Methodical and predictability aspects of MOS systems, *13th Conference on Probability and Statistics in Atmospheric Sciences,* p. 190-197, San Francisco, Ca., USA.
Kottmeier, Ch. and H. Höller (Herausg.) (2001) Transporte und chemische Umsetzungen in konvektiven Systemen (TRACKS). Ein Konzept für ein mehrstufiges Grossexperiment der Helmholtzzentren.
Krishnamurti T.M. (1991) Physical initialization for numerical weather prediction over the tropics, *Tellus,* **43A-B**, 53ff.
Kuo H.-L. (1965) On formation and intensification of tropical cyclones through latent heat release by cumulus convection, *J. Atmos. Sci*., **22**, 40-63.
Lenschow, D. H. and B.B. Stankov (1986) Length-scales in the convective atmospheric boundary layer. *J. Atmos. Sci*., **43**, 1198-1209.

Lilly, D. K. (1962) On the Numerical Simulation of Buoyant Convection. *Tellus*, **14**, 168-172.
Lippmann, J., Bauer, and G. Peters (1996) Methods of virtual heat flux determination from boundary layer wind profilers/RASS measurements. *Contrib. Atmos. Phys.*, **69**, 119-128.
Lipton, A.E., (1993) Cloud shading retrieval and assimilation in a satellite-model coupled mesoscale analysis system. *Mon. Wea. Rev*., **121**, 3062-3081.
Löhnert, U., S. Crewell, A. Macke, and C. Simmer (2001) Profiling cloud liquid water by combining active and passive microwave measurements with cloud model statistics. *J. Atmos. Ocean. Tech.*, **18**, 1354-1366.
Majewski, D. , D. Liermann, P. Prohl, B. Ritter, M. Buchhold, T. Hanisch, G. Paul, W. Wergen, J. Baumgardner, (2002) The Operational Global Icosahedral–Hexagonal Gridpoint Model GME: Description and High-Resolution Tests. *Monthly Weather Review*, 130, 319–338.
Mandelbrot B. (1980) The fractal geometry of Nature, WH Freeman , 468p.
Manabe, S., J. Smagorinsky, and R.F. Strickler (1965) Simulated climatology of a general circulation model with a hydrologic cycle. *Mon. Wea. Rev*., **93**, 769-798.
Mamrosh, R. D. (1997) The Use of high-frequency acars soundings in forecasting convective storms. *AMS Weather and Forecasting Conference*, January 12-16, 1997, Phoenix,
AZ.McNider, R.T., J.A. Song, and S.Q. Kidder (1995) Assimilation of GOES-derived solar insolation into a mesoscale model for studies of cloud shading effects. *Int. J. of Remote Sensing*, **16**, 2207-2231.
Mellor, G. L., Yamada, T. (1974) A hierarchy of turbulence closure models for planetary boundary layers. *J. Atmos. Sci.*, **31**, 1791-1806.
NMC 2001, siehe http://www.emc.ncep.noaa.gov/experiments.html.
Mölders, N., and A. Raabe (1996) Numerical investigations on the influence of subgrid-scale surface heterogeneity on evapotranspiration and cloud processes. *J. Appl. Meteorol.*, **35**, 782-795.
Moeng, C.-H. and J. Wyngaard (1989) Evaluation of turbulent transport and dissipation closures in second-order modeling. *J. Atmos. Sci*., **46**, 2311-2330.
Moeng, C.-H. (1993) Large eddy simulation of boundary layer turbulence. WCRP Workshop on "*Parameterization of subgrid-scale tracer transport''*. Virginia Beach, VA.
Müller, D., U. Wandinger, and A. Ansmann (1999) Microphysical particle parameters from extinction and backscatter lidar data by inversion via regularization. *Theor. Appl. Opt.*, **38**, 2346-2357.
O'Hirok, W., and C. Gautier (1998) A three-dimensional radiative transfer model to investigate the solar radiation within a cloudy atmosphere. Part I: Spatial effects. *J. Atmos. Sci*., **55**, 2162-2179.
Rabier, F., H. Jarvinen, E. Klinker, J.-F. Mahfouf, and A. Simmons (2000) The ECMWF operational implementation of four-dimensional assimilation.I: Experimental results with simplified physics. *Quart. J. Roy. Meteor. Soc.*, **126A**, 1143-1170.
Raible C. C., G. Bischof, K. Fraedrich, and E. Kirk, (1999) Statistical single station short-term forecasting of temperature and probability of precipitation: Area interpolation and NWP – combination. *Weather and Forecasting*, **14**, 203-214.
Raymond, D.J. (1993) Observational Constraints on Cumulus Parametrizations. Chapter 2 in ``*The representation of cumulus convection in numerical models of the atmosphere*''. Americ.Meteor.Soc., Meteor.Monogr., 24, No. 46, 17-28.
Reitebuch, O., C. Werner, I. Leike, P. Delville, P. H. Flamant, A. Cress, and D. Engelbart (2001) Experimental Validation of Wind Profiling Performed by the Airborne 10-μm Heterodyne Doppler Lidar WIND. *J. Atmos. Ocean. Tech*., **18**, 1331-1344.
Schädler, G. (1990) Triggering of atmospheric circulations by moisture inhomogenities of the earth's surface. *Bound.-Layer Meteor*., **51**, 1-29.
Scheirer, R and A. Macke (2001) On the accuracy of the independent pixel approximation in calculating the downward fluxes in the UV-A, UV-B and PAR spectral ranges. *J. Geophys. Res*., **106**, 14301-14312.
Schölzel C.A., A. Hense, and J. Klaßen (2000): AVN guided MOS system for Europe based on regression screening and cross validation, *15th Conf. Probability and Stat. in Atm. Sci.*, p. 34-35, Ashville, NC, USA.
Segal, M., J.F.W. Purdom, J.L. Song, R.A. Pielke, and Y. Mahrer (1986) Evaluation of cloud shading effects on the generation and modification of mesoscale circulations. *Mon. Wea. Rev*., **114**, 1201-1212.
Seifert, A. and K.D. Beheng (2001) A double-moment parameterization for simulating autoconversion, accretion and selfcollection. *Atmos. Res.*, **59-60**, 265-281.
Senff, C., J. Bösenberg and G. Peters (1994) Measurement of water vapor flux profiles in the convective boundary layer with lidar and radar-RASS. *J. Atmos. Ocean. Tech*., **11**, 85-93.
Seuffert, G., P. Gross, C. Simmer, and E.F. Wood (2002) The influence of hydrologic modeling on the predicted local weather: Two-way coupling of a mesoscale weather prediction model and a land surface hydrologic model. *J. Hydrometeorol.,* **3**, 505-523.
SGI 2001: siehe http://www.sgi.com/manufacturing/success/bmw.html.
Smagorinsky, J. (1963) General circulation experiments with the primitive equations, I. The basic experiment. *Mon. Wea. Rev.*, **9**1,99-164.

Smith, L.A., C. Ziehmann, and K. Fraedrich (1999) Uncertainty dynamics and predictability in chaotic systems. *Quart. J. Roy. Meteor. Soc.*, **125**, 2855-2886.
Storch H. von and F. Zwiers (1999) Statistical analysis in climate research, Cambridge University Press.
Stull R.B. (1984) Transilient turbulence theory part I: the concept of eddy mixing across finite distances, *J. Atmos. Sci.*, 41, 3351-3367
Theis, S., U. Damrath, A. Hense, and V. Renner (2000) Statistical postprocessing of weather parameters for the DWD high resolution model LM, *1st SRNWP Workshop on statistical adaptation*, SWSA2000, Wien.
Tiedtke, M. (1989) A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Mon. Wea. Rev.*, **117,** 1779-1800.
Toth, Z., E. Kalnay, S. M. Tracton, R. Wobus and J. Irwin, (1997) A synoptic evaluation of the NCEP ensemble. *Weather and Forecasting*, **12**, 140-153.
Vihma, T. and C. Kottmeier (2000) A modelling approach for optimizing flight patterns in airborne meteorological measurements. *Boundary-Layer Meteorology*, **95**, S.211-30.
Wacker, U. and A. Seifert (2001) Evolution of rain water profiles resulting from pure sedimentation: Spectral vs. parameterized description. *Atmos. Res*., **58**, 19-39.
Wahba G. and J. Wendelberger (1980) Some new mathematical methods for variational objective analysis using splines and cross-validation. *Mon. Wea. Rev.,* **108,** 36-57.
Ware, R., M. Exner, D. Feng, M. Gorbunov, H. Hardy, B. Herman, Y. Kuo, T. Meehan, W. Melbourne, C. Rocken, W. Schreiner, S. Sokolovskiy, F. Solheim, X. Zou, R. Anthes, S. Businger, and K. Trenberth (1996) GPS sounding of the atmosphere from low earth orbit: Preliminary results. *Bull. Amer. Meteor. Soc*., **77**, 19-40.
Weckwerth, T.M., V. Wulfmeyer, R.M. Wakimoto, R.M. Hardesty, J.W. Wilson, and R.M. Banta (1999) NCAR-NOAA lower tropospheric water vapor workshop. *Bull. Amer. Meteor. Soc*., **80**, 2339-2357.
Weckwerth, T.M., J.W. Wilson, and R.M. Wakimoto (1996) Thermodynamic variability within the convective boundary layer due to horizontal convective rolls. *Mon. Wea. Rev*., **124**, 769-784.
Weckwerth, T.M. (2000) The effect of small-scale moisture variability on thunderstorm initiation. *Mon. Wea. Rev.,* **128**, 12, 4017–4030.
Wulfmeyer, V. and J. Bösenberg (1998) Ground-based differential absorption lidar for water-vapor profiling: Assessment of accuracy, resolution, and meteorological applications. *Appl. Opt.*, **37**, 3825-3844.
Wulfmeyer, V. (1999) Investigation of turbulent processes in the lower troposphere with water-vapor DIAL and Radar-RASS. *J. Atmos. Sci*., **56**, 1055-1076.
Yano, J.-I., K. Fraedrich, and R. Blender (2001) Tropical convective variability as 1/f noise, *J. Climate*, **14**, 3608-3616.
Zehe, E., R. Becker, and A. Bardossy (2001) The influence of spatial variability of soil moisture and precipitation on runoff production. Presentation at the International Workshop on Catchment scale Hydrologic Modelling and Data Assimilation, Sept. 3-5 2001, Wageningen, Book of Abstracts: 57-58.
Zupanski, M., D. Zupanski, D. F. Parrish, E. Rodgers, and G. DiMego (2002) Four-dimensional variational data assimilation for the Blizzard of 2000. *Mon. Wea. Rev.,* **130**, 1967-1988.