U.S. DEPARTMENT OF ENERGY | Office of Science

Convective and Orographically Induced Precipitation Study Science Plan

V Wulfmeyer A Behrendt
C Kottmeier U Corsmeier

November 2005

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Convective and Orographically-induced Precipitation Study

Science Overview Document

November 9, 2005

An observation program within the

Priority Program "Quantitative Precipitation Forecast (PQP)"

funded by the German Research Foundation

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Editors:

Volker Wulfmeyer[1], Andreas Behrendt[1],

Christoph Kottmeier[2], Ulrich Corsmeier[2]

1. Institut für Physik und Meteorologie, Universität Hohenheim

2. Institut für Meteorologie und Klimaforschung,

Forschungszentrum Karlsruhe/Universität Karlsruhe

Authors:

Gerhard Adrian, Hans-Stefan Bauer, Andreas Behrendt, Alan Blyth,

Edward V. Browell, Ulrich Corsmeier, George Craig, Susanne Crewell,

Kenneth J. Davis, Richard Dirks, Hartmut Graßl, Martin Hagen,

R. Michael Hardesty, Jost Heintzenberg, Luis Kornblueh, Christoph Kottmeier,

Jos Lelieveld, Evelyne Richard, Mathias Rotach, Herman Russchenberg,

Ulrich Schumann, Reinhold Steinacker, Hans Volkert,

Tammy Weckwerth, Heini Wernli, James W. Wilson, Volker Wulfmeyer

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1 The Research Desiderate

1.1 Introduction

Water is the prerequisite for the existence of life on Earth. The atmosphere mainly regulates the availability of water 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 industry, national governments and international organizations. 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 (Pielke and Klein, 2001). In Europe, this became obvious in 2002 again during the catastrophic flash flood event in Saxonia, which caused an economic loss of 10B US$ (Munich Re Group 2002). The devastating hurricane season 2005 demonstrated that even the most developed countries such as the US can hardly handle these events.

Quantitative forecast of non-extreme precipitation events is of comparable importance, although the avoidable losses mostly do not appear to be that spectacular. Complemented by estimates of their potential uncertainties, such forecasts are of inestimable value as input for hydrological applications or for consulting in agriculture and the construction sector.

As precipitation is one of the most important meteorological variables not only for every day life but also for agriculture, there is an urgent need to improve forecasting of precipitation from the short-range to the long-range as well as to improve predictions of precipitation anomalies on monthly, seasonal to inter-annual time scales and projections of precipitation changes as a consequence of global climate change. Particularly, an intensification of the global water cycle is expected, which may lead to an increase of extreme weather events in certain regions (e.g. Schär et al.

2004). As in the future, climate and weather models will be based on the same parameterizations and model physics, any science program leading to an improvement of quantitative precipitation forecast (QPF) will also have a significant positive impact on the performance of regional and global climate models.

1.2 User Requirements

The QPF user community is huge and it is still a subject of research to investigate their respective needs (see, e.g., Hense et al. 2004, Fritsch and Carbone 2004). For example, the demands of the hydrologists for using QPF to extend the lead time for flash flood forecasting are summarized in Fig.1.1.

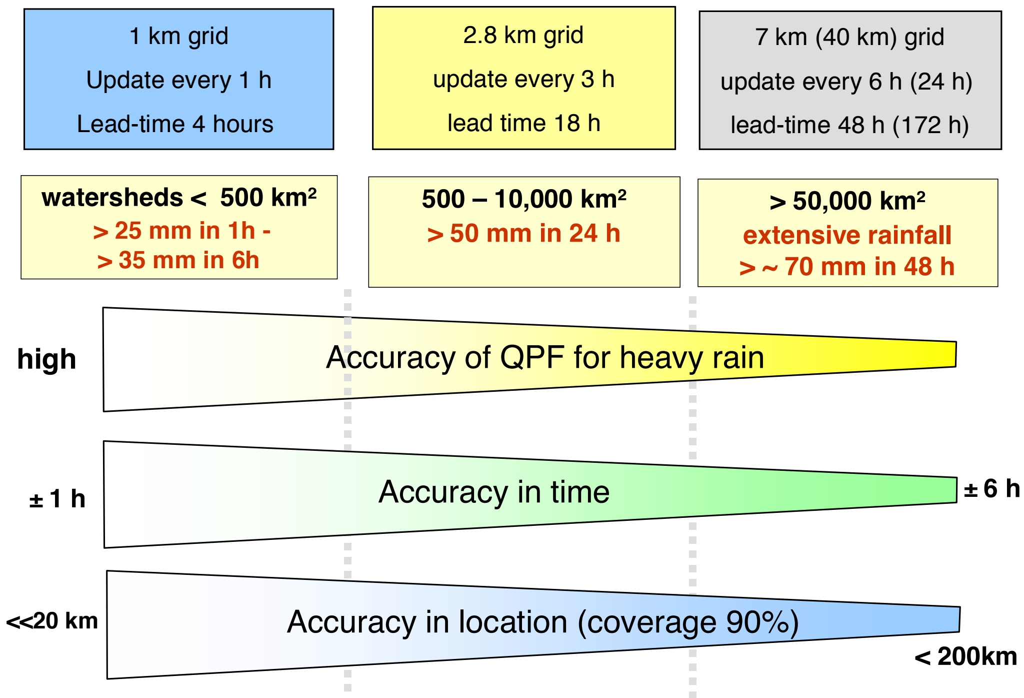


Fig.1.1. *Requirements set to QPF for extending the lead-time of flash-flood forecasting (Courtesy of Werner Schulz, Landesamt für Umweltschutz, Baden-Württemberg, Germany).*

It turns out that these requirements cannot be compressed in a few numbers but depend on the size of the catchment area. For instance, in watersheds with a size of up 500 km^2 the requested accuracy of QPF at rain rates of the order of 30 mm/h is typically 10 %.

The requirements are rising with the complexity of the terrain, as it is becoming more and more essential to predict accurately the spatial/temporal distribution and development of precipitation. Prediction of QPF in complex terrain is obviously most important for many users, as the amount of precipitation is enhanced by orography.

1.3 Performance of Current Weather Forecast Models

Weather forecasting and climate models, initialized by basic atmospheric or surface variables like temperature, pressure and wind are able to forecast or calculate precipitation rate and distribution, however, with comparably low skill, especially for convective conditions.

The ability of numerical weather prediction (NWP) models to correctly forecast the amount of precipitation with a certain spatial and temporal resolution has been subject of several studies (Ebert et al. 2003, Hense et al. 2004). In this proposal we are not discussing difficulties of model validation, as this is another large area of research.

Advances in forecasting methods and observation systems resulted in a constant increase in the quality of short-range (up to 3 days) and medium-range (up to 10 days) weather prediction, e.g. for temperature and wind, in the past years. In contrast, precipitation forecast still has similar deficiencies known for some 15 years (Ebert et al., 2003). These findings are supported by Fig.1.1, where the improvements in forecast quality (RV: Reduction of variance) of the German Meteorological Service (DWD) are illustrated for various atmospheric variables. In the course of the past 16 years, it was not accomplished to improve the forecast as to whether precipitation will fall in a certain area or not (precipitation yes/no).

Ebert et al. (2003) as well as Fritsch and Carbone (2004) confirm that persistent deficiencies in QPF are a problem for all weather services. Figure 1.3 presents threat and bias scores for global NWP models of six forecast centers (Ebert et al. 2003). The figure illustrates several common properties of QPF performance. The left panel shows that all models overpredict light rain. The right panel demonstrates that the skill is strongly decreasing with increasing rain rate. Already at modest rain rates of 8 mm d^{-1}, the skill of the prediction is not much better than a random forecast or persistence. It is obvious that this performance is not sufficient for many users (see above).

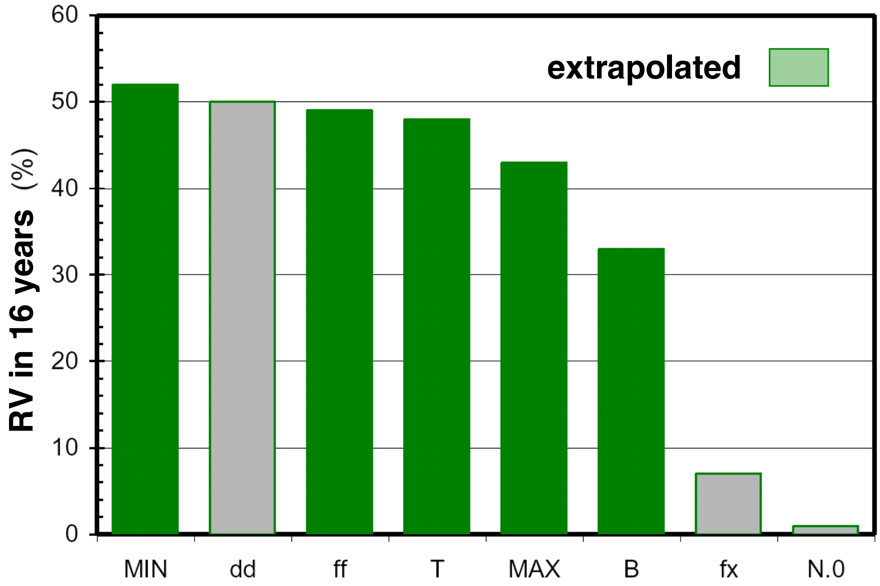


Fig.1.2. *Reduction of variance (RV) of the German Meteorological Service (DWD) forecasts during the past 16 years for the model variables of daily minimum temperature (MIN), daily maximum temperature (MAX), average temperature (T), wind direction (dd), wind intensity (ff), cloudiness (B), wind peaks > 12 m/s (fx), and precipitation yes/no (N.0). In fact, no improvement was reached in precipitation forecast (RV = 0.5%) (internal report DWD, Hense et al. 2004).*

Additional fundamental problems are indicated in Fig.1.4. The time series of the equitable threat score does not show an improvement from 1997 to 2000 but even a slight degradation for some models. A reduction of the threat scores in summer is always visible. This is likely due to a larger contribution of convective precipitation, which is more difficult to predict (e.g., Weckwerth and Parsons 2005).

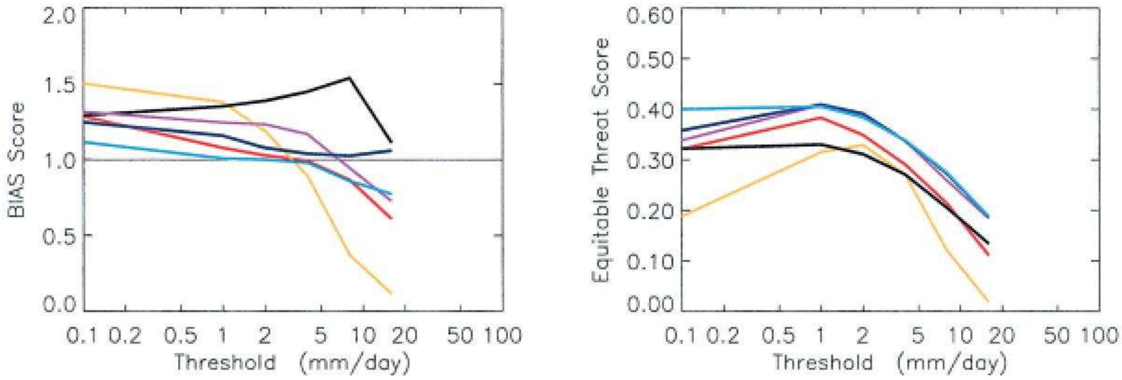


Fig.1.3. *Bias score (left panel) and equitable threat score (right panel) as a function of rain threshold for 24-h accumulated precipitation valid 42 h into the forecast (ECMWF, red line) or 30 h (other models) for Jan-Dec 2002 over Germany. The thresholds were 0.1, 1, 2, 4, 8, and 16 mm d^{-1}. Adapted from Ebert et al. 2003.*

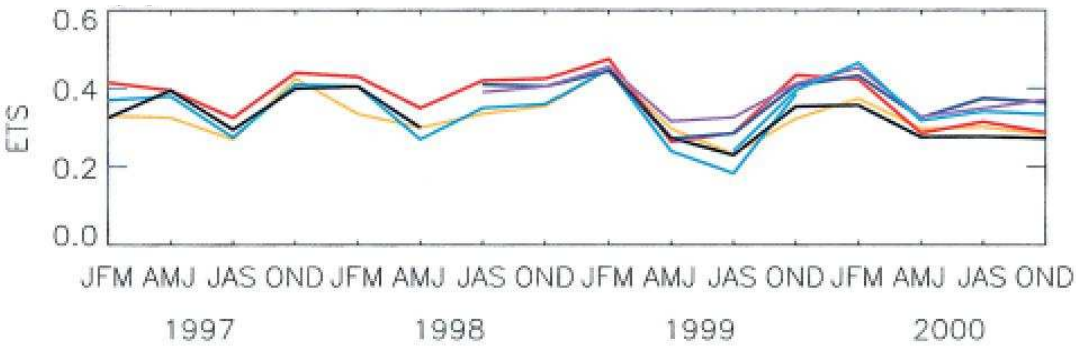


Fig.1.4. *Time evolution of the equitable threat score over Germany between Jan. 1997 and Dec. 2000 for a rain threshold of 2 mm d^{-1}. The forecast valid times are 42 h (ECMWF, red line) and 30 h (other models).*

Comparable comprehensive studies for mesoscale models have been lacking until recently. Preliminary studies indicated that the skill of mesoscale models for short- and medium-range QPF is not better or even degrades in comparison with global models using conventional verification parameters (e.g. Davis and Carr 2000, Colle et al. 1999). This has been confirmed by several studies, which have been initiated within the German Priority Program introduced in chapter 2. A first draft summarizing the results of several verification projects of the DWD mesoscale model Lokalmodell (LM) is available (van Lipzig et al. 2005). These studies show a degradation of skill scores in summer due to more convective precipitation. The results indicate major problems of QPF in orographic terrain. Furthermore, the diurnal cycle of precipitation is not well reproduced and shows that the initiation of convection is triggered too early in the mesoscale model.

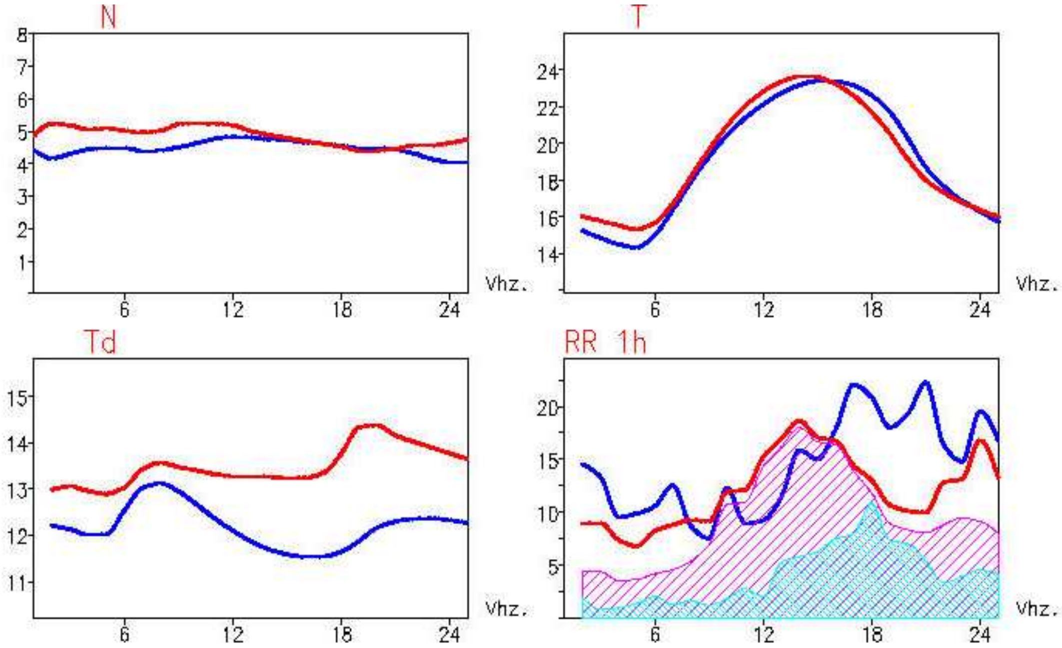


Fig.1.5. *Validation of LM forecast of cloud coverage (N), temperature (T), dew point (Td), and rain rate (RR) in dependence of forecast lead time in the region 6.5-15E, 47.3-54N between 03.-27. July 2003. Blue line: Observations; red line: forecast; shaded area: contribution of convective precipitation. Courtesy of Ulrich Damrath, DWD, Germany.*

This finding is substantiated in Fig.1.5, where the forecasts of different variables are compared with observations between July 3 – July 29, 2003. Obviously, in the course of the day, precipitation is predicted too early. This is related to incorrect modeling of the diurnal cycle of boundary layer variables such as temperature and dew point. This study indicates a general problem with the parameterization of land-surface exchange processes and/or turbulence closure. For a long time this issue has been a significant problem in precipitation forecast but no success in the removal of this deficiency has been reported yet. It is likely that this problem is due to interwoven inadequate representations of land-surface processes as well as of parameterizations of turbulence and convection (Guichard et al. 2004, Chaboureau et al. 2004).

Another fundamental systematic error, which has been revealed in the COPS region, is the windward/lee problem (see Fig.1.6). Statistical analyses of QPF errors of the Lokalmodell (LM) of the DWD show a clear overestimation of precipitation on the windward site whereas precipitation is strongly under-predicted on the lee side. As the major part of precipitation is due to convection, it is reasonable to assume that this problem is due to an inadequate convection parameterization. The strength of this error also depends on model resolution; however, it has been shown by Meißner et al. (2005) that increasing model resolution alone is clearly not sufficient to improve forecast skill.

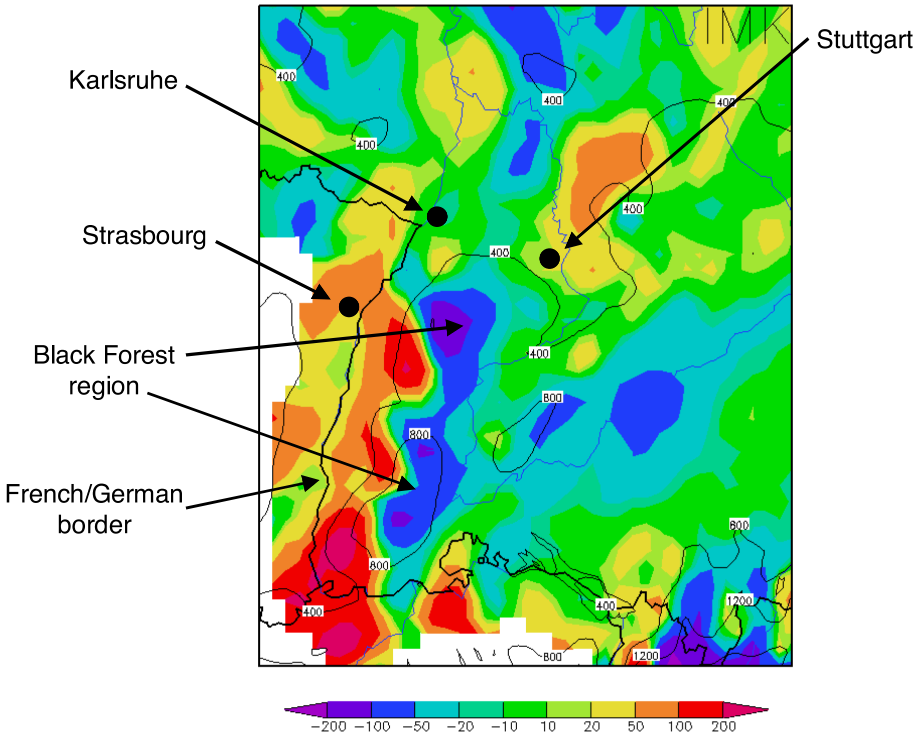


Fig.1.6. *Difference in mm between predicted and observed precipitation in the Black Forest Area for August 2004 using the Lokal-Modell (LM) of the DWD confirming the windward/LEE problem. The thin black lines indicate the topography. The locations of major cities and the French/German border are also shown. Courtesy of L. Gantner, IMK, Karlsruhe, Germany.*

Further information about deficiencies of mesoscale models has been gathered by case studies, e.g., using the LM of the DWD. We present a comparison of the prediction of convective rainfall in the Black Forest region on June 15, 2003. In this case, the lower troposphere over whole southern Germany was governed by severe potential instability from the surface up to 600 hPa in the LM (15 K) and up to 550 hPa measured in Stuttgart (18 K) at 12 UTC. Large scale lifting combined with a front moving slowly southward caused the initiation of convection and subsequent precipitation. Figure 1.7 shows accumulated measured and model calculated precipitation over 24 hours. In both cases precipitation is found nearly in the whole area. The mean measured rain fall is 11.6 mm with high spatial variability (0 – 40 mm), while the models calculates a mean precipitation of only 3.7 mm ranging from 0 to 20 mm. In the model there are about 75 % of the grid points with precipitation less than 4 mm while in reality 75 % had more than 4 mm rain fall with maxima of 10 - 15 mm at 20 % of the grid points.

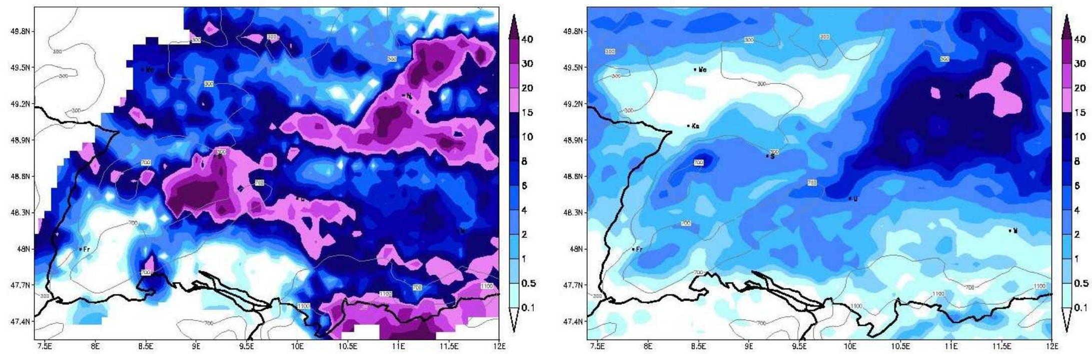


Fig.1.7. *Comparison of measured precipitation accumulated over 24 hours (left) and corresponding model calculated 24 h precipitation sum (right) for the area of southwest Germany from June 14, 2003, 06 UTC to June 15, 2003, 06 UTC. Measurements were made at 895 stations in the area (Eisenmann, 2004). For precipitation forecasts, the LM of the German Weather Service (DWD) has been used with 7 km grid spacing and convection parameterization.*

It may be argued that the main problem in model performance is its coarse resolution in combination with the necessity of the parameterization of convection. However, recent results demonstrate that increasing the model resolution and shutdown of convection parameterization alone do not lead necessarily to an improvement of model performance. This is indicated in Fig.1.8. Here, the Lokal-Modell (LM) of the DWD was run using three different resolutions (7km with convection parameterization, 2.8km und 1km without convection parameterization). It seems so that the increase to 2.8km leads to a significant improvement of precipitation in comparison with radar reflectivity measurements. However, a further increase to 1km results in a severe degradation of model performance.

Detailed analyses of the DWD revealed that model deficiencies are particularly large over low mountains and concern the following aspects

- too frequent forecasts of weak precipitation,
- large errors for strong precipitation /flood forecast,
- wrong positioning and onset of convective precipitation,
- incorrect flow dynamics over mountains,
- enhanced windward/lee precipitation differences,
- deficiencies of soil moisture and water vapor data in the planetary boundary layer (PBL).

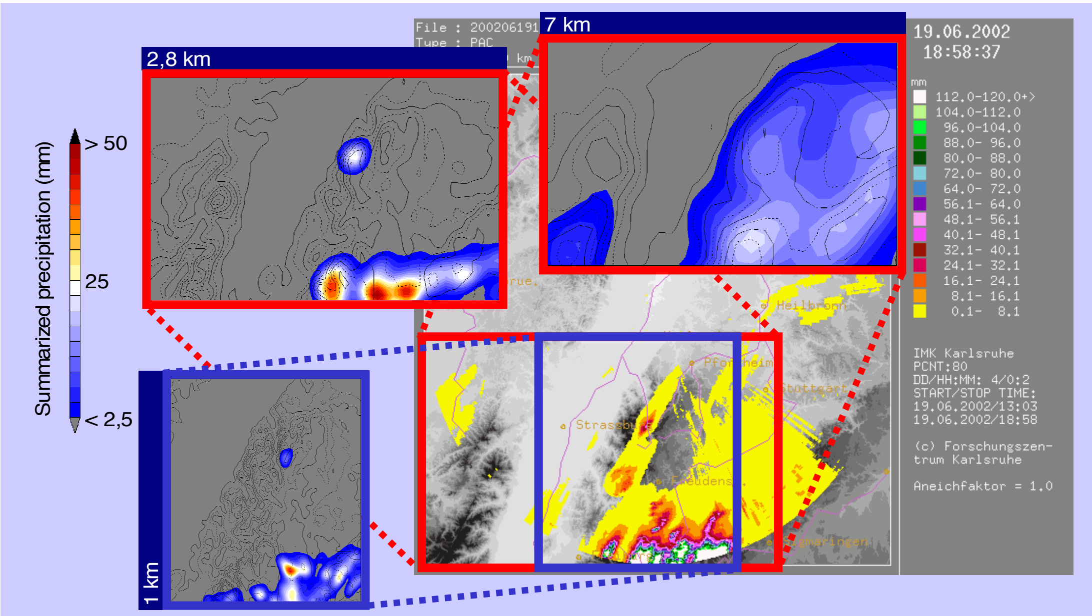


Fig.1.8. *LM-precipitation simulation for June 19, 2002, using different grid sizes and precipitation estimate from Karlsruhe C-band Radar (Meißner et al., 2005, Barthlott et al. 2005).*

Another uncertainty, which is not considered in detail in NWP models, is the interaction of aerosol and cloud microphysics. In a modeling study employing a new cloud microphysics parameterization scheme it was demonstrated that clouds forming either on maritime or continental cloud condensation nuclei (CCNs) do not only develop differently with respect to their microphysical properties but also the dynamics as well as the resulting rain rates are different (Seifert and Beheng 2005). Figure 1.9 shows a comparison of two precipitating clouds developing in maritime and continental CCNs, respectively, after 48 min modeling time. Relationships between aerosol particles and intensity of precipitation have also been explored in numerous other studies such as Rosenfeld, 2000, Andrea et al. 2004, Segal et al. 2004, Khain and Pokrovsky 2004.

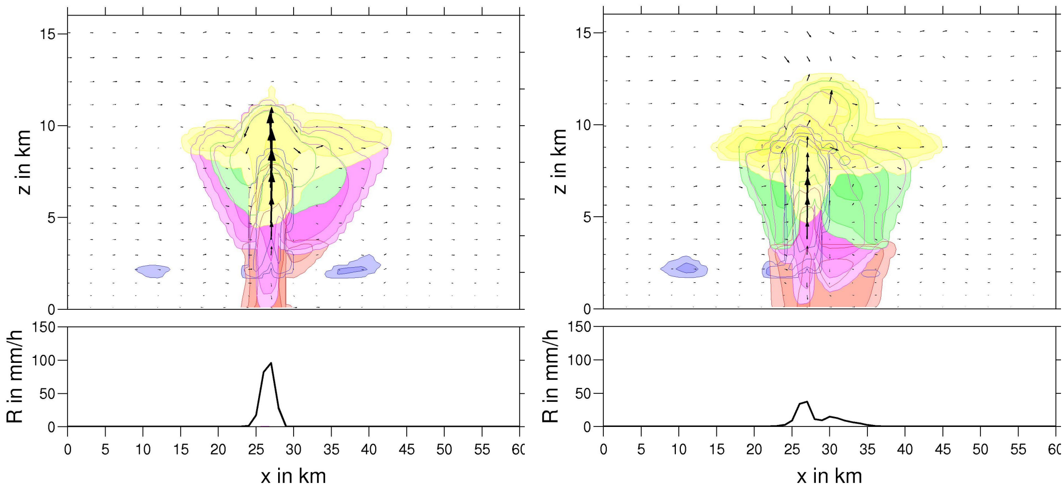


Fig.1.9. *Clouds modeled in environments with maritime or continental CCNs including wind vectors. Blue: cloud droplets, red: rain drops, magenta: graupel, yellow: cloud ice, green: snow Courtesy of Klaus-Dieter Beheng, IMK, Karlsruhe, Germany, Seifert and Beheng 2005).*

We note that both, global and mesoscale models, are far away from fulfilling the needs of the hydrologists (see Fig.1.1). This is one of the challenges this research program is accepting.

1.4 Reasons for QPF failures

Figure 1.10 depicts the different components of NWP models and their relationships. This figure illustrates the complexity of the prediction of precipitation. Many reasons exist for deficiencies of QPF, which are coupled in a complicated way.

This coupling of different factors influencing the forecast quality causes problems in the identification of model deficits. And if a certain problem has been isolated, model improvements on physically based grounds provide a similar challenge. Shown in this figure are the paths how the results of field campaigns (e.g., an Intensive Observations Period – IOP as proposed in this document) could be used to lead to a long-term positive impact of the quality of NWP models.

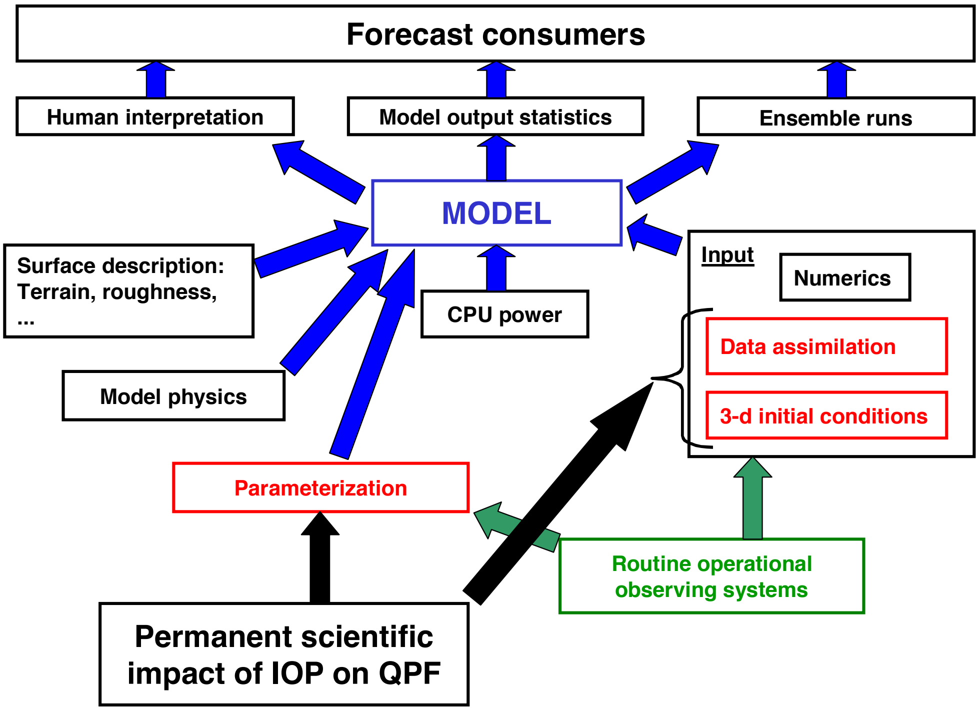


Fig.1.10. *Set up of an NWP model. Also shown are the paths for a permanent scientific impact of a field campaign (Intensive Observations Period or IOP) on QPF.*

1.4.1 Model Resolution and Numerics

One reason for model deficiencies can be numerics and model resolution. In two recent studies by Zängl (2004a, 2004b) it was demonstrated that for the Saxony flash flood case an improvement of model resolution alone led to a significantly better QPF. However, in regions with complex terrain, it was found that the horizontal diffusion of atmospheric variables had to be properly taken into account, too. Also the studies of Corsmeier et al. 2005, Bartlott et al. 2005 demonstrated that an increase of model resolution did not lead necessarily to an improvement of model performance.

Therefore, the performance of different mesoscale models with varying horizontal and vertical resolution must be studied. This requires a strong link between instrument

PIs, the modeling community and weather forecast centers. This has been realized right from the beginning of this research project (see chapter 2).

1.4.2 Errors in Parameterizations

Processes which cannot be resolved in mesoscale models must be parameterized. These processes include radiation, cloud microphysics, turbulence, and convection. It is an important subject of this research program to investigate parameterizations and suggest their improvements.

Numerous sensitivity studies analyzing the relation between parameterizations and QPF are available. Similar studies were dedicated to the quality of parameterizations in regional climate models (e.g., Hagemann at al. 2004, Mölders and Olson 2004. Richard et al. 2003, Schlünzen, and Katzfey 2003, Walser et al. 2004, Zängl 2004a). The results can be summarized as follows:

- Deficiencies in model performance are not related to one special problem in parameterization. In contrast, each model showed special deficiencies, which also showed a strong dependence on regional and meteorological conditions, respectively.
- Forecast errors due to parameterizations are of the same order of magnitude as errors due to model initialization and resolution.
- There is no particularly critical parameterization of a physical process.

Therefore, it does not make sense to focus just on the improvement of a special parameterization. Errors of parameterizations have to be separated and to be investigated simultaneously. Furthermore, representations of physical processes, which are currently missing, have to be improved such as the interaction of CCN and cloud droplet size distribution. If priorities are set for improving specific parameterizations or for concentrating on certain processes, these should take into account the capabilities of observing systems to deliver appropriate data sets (see chapter 7).

1.4.3 Sub-optimal use of Data Assimilation

Data sets are particularly beneficial for NWP models if prognostic variables are measured, which can be used for direct model evaluations and data assimilation. Currently, this is accomplished using radiosonde and aircraft in-situ data as well as various space-borne observations such as radiances from TOVS, SSM/I, and recently AIRS.

A large amount of additional data is available, however, often either suitable operators are lacking for data assimilation or the set up of the data assimilation system does not permit their inclusion. A prominent example is the assimilation of aerosol microphysical properties. Different data assimilation techniques are available such as four dimensional data assimilation (FDDA), 3D variational analysis (3DVAR), 4D variational analysis (4dVAR) and Kalman filtering (Bouttier and Courtier 1999, Kalnay 2003). The best compromise between complexity of the data assimilation system, required computer power, and improvement of QPF is often unclear.

Data assimilation is a rapidly developing research area and, within this project, the recent advances shall be applied. We are considering different data assimilation techniques and the application of different advanced, high-resolution observing systems on different platforms in combination with high-resolution modeling (see section 6.4).

There is an urgent need to study the impacts of different measurement techniques in dependence of spatial and temporal resolution as well as coverage. In any case, several studies demonstrate that there is large potential for improvements of the initial conditions. This is indicated by large background errors of the initial states. If special data sets (e.g. collected during field campaigns) were assimilated, often considerable improvements of the forecast quality have been observed (Kamineni et al. 2003, Kamineni et al. 2004, Wulfmeyer et al. 2005). The impact of high-quality observations is manifold. Improved forecasts with stronger constrained initial fields will lead to a better characterization of the background error covariance matrix. Observations with low errors merged with this background field will yield an improved and more accurate analysis including a better specified error covariance matrix.

1.4.4 Incomplete Coverage of Observations

Numerical models are only as good as the data sets used for their validation and initialization. Consequently any improvement of QPF, anomaly predictions and projections needs new 4D data sets with higher spatial and temporal resolution as well as higher accuracy for more variables than hitherto.

We distinguish between three levels of observations. *Routine* observations can be used for data assimilation in operational weather forecasts (see Fig. 1.9). However, these data sets are of limited use for identifying model deficits and for separating errors due to parameterizations and initial conditions.

Advanced observations are routine measurements from different platforms, which are not used in operational weather forecasts, but employ well-defined retrieval algorithms and error analyses. These observations include time series of the fundamental meteorological parameters solar radiation flux density and precipitation, which were largely unknown over the entire oceans and large continental areas until recently. Therefore, we can only now establish first short climatologies of precipitation (GPCP, 2004) and surface solar radiation flux density (SRB, 2004) on global scale. These climatologies still suffer from inadequate error estimates, as algorithms using satellite data are not validated for all climatic zones and "in situ truth" data themselves or ground based remote sensing methods sometimes contain large errors depending on the meteorological conditions encountered.

Similar climatologies are available for water vapor but with low vertical and time resolution and limited accuracy. New data sets are currently being collected with considerable potential for model validation. Suitable observations are discussed in chapter 7 where their properties and applications within this research program are highlighted. Particularly poor is the observation of atmospheric dynamics. New space borne sensors are under development for closing this delicate data gap (e.g. Atmospheric Dynamics Mission (ADM) at ESA).

These measurements are very valuable for producing long-term data sets for improving our understanding of the Earth's weather and climate system. Long-term observations with new data sets using operational systems can be used for model evaluation and for identifying model deficits. The CloudNet project (see http://www.met.rdg.ac.uk/radar/cloudnet) is a prominent example of the application of a synergy of remote sensing systems for this purpose. Corresponding data sets are collected within this project (see section 2.2). However, we are convinced that an *improvement* of models on physically-based grounds can only be achieved with the addition of *research* data sets which are collected during field campaigns.

This is due to the fact that even combining all existing operational and advanced sensors, huge data gaps are left hindering the complete separation of errors due to different parameterizations and errors due to initial conditions. Key processes controlling the initiation and development of convection and precipitation are not observed. Particularly important is the characterization of the 4D thermodynamic state of the atmosphere from the pre-convective environment, to the initiation of convection, to the formation of clouds, to the formation and decay of precipitation. It is obvious that it is always impossible to achieve this ideally in practice. However, if today's most-advanced state-of-the-art *research* data were available, for the first time not only specific model deficits could be identified more in detail, but also improvements could be suggested and tested.

The following example shall clarify this statement. Consider the routine long-term observation of clouds parameters with radars and passive remote sensing systems. It is beyond all questions that this data set is very valuable to validate the prediction of cloud parameters using mesoscale models. However, if model deficiencies are found, it is still extremely challenging to identify whether these deviations are due to incorrect parameterization of turbulence, convection, cloud microphysics or even due to a remaining bias in the initial conditions. This detailed error separation is only possible by combining the cloud observations with high-resolution 4D clear-air measurements.

1.4.5 The limits of predictability

It is well known that certain weather situations exist where even a nearly perfect knowledge of the initial conditions and physics does not allow an accurate forecast with the desired lead time. The current understanding of the factors causing such a critical situation to arise in the near future is inadequate. Particularly, this is of concern if an extreme event may develop. Due to the high degree of freedoms of state-of-the-art weather forecast systems, it is neither possible to analyze these cases mathematically nor the whole phase space of the possible solutions can be scanned, e.g., by varying the initial conditions at each grid point using Monte Carlo simulations (Leigh, 1974).

To circumvent this problem, several techniques have been developed to select ensembles of forecasts (see e.g., Kalnay 2003, Monteni et al. 2001, Walser et al. 2004), which are supposed to simulate the most critical forecast error spreads. As the weather system is chaotic, small-scale errors may grown to the large scale setting a final limit of predictability. However, not very much is known to date, when and how small-scale errors limit the forecast quality and how these interact with the large scales. Some general conclusions have been made (Buizza et al., 2005). On the global scale, in the mid-latitude, predictability is mainly limited by inaccurate knowledge of baroclinic instabilities (Buizza et al, 2005). On the mesoscale, convection initiates nonlinear processes so that error growth becomes important down to the scale of single convective elements. The corresponding error growth is unknown and sets a significance hindrance to the development and application of mesoscale ensemble prediction systems (Molteni et al., 2001).

Consequently, studies of the limits of predictability need to be improved by better knowledge of small-scale conditions such as dynamics and the water vapor field and by detailed modeling studies investigating small-scale/large-scale error growth. The development of sophisticated ensemble forecast systems is also considered and will be applied within this research program.

1.5 Conclusion: The Role of Field Campaigns

Based on the analyses above, we conclude that the improvement of quantitative precipitation forecast has not kept up with the society's requirements on our forecast systems. Particularly beneficial for the user community is the improvement of QPF in terrain with significant orography.

In general, more precise specification of spatial and temporal scales, on which precipitation can be predicted quantitatively, is essential to an improvement of QPF. Moreover, it is necessary to identify the dynamic processes and space-time structures of atmospheric flows that contribute to predictability. However, real structures and processes can only be identified by combining modeling with the aggregation of observation data and only be verified by validating realistic forecasts with high quality observations. These demands with respect to the desired data bases lead to the theory-based requirements for a comprehensive atmospheric experiment aiming at the improvement of QPF.

When planning a field experiment with this ambitious goal, one has to know the most important factors influencing precipitation events. Ideally, this would require observing system simulation experiments with models already containing all the processes influencing precipitation formation. This is not the case, even for most non-hydrostatic mesoscale models. From long-term meteorological and atmospheric research we know at least five major factors which are determining the location and amount of precipitation:

- large scale atmospheric dynamics,
- three dimensional observations of water in all its phases,
- surface fluxes of momentum, heat, and moisture over inhomogeneous terrain,
- orography, and
- three-dimensional size distribution and chemical composition of tropospheric aerosol.

Two of these factors are strongly influenced by human activities, namely surface fluxes by land use and aerosol content by direct emissions and/or precursor gases.

Under special circumstances, one of these four factors can be the dominating one, but very often all will play a considerable role, for example over moderately complex terrain in an industrialized country, like in most parts of Central Europe, during the summer half year.

This has major consequences for the planning of observations during the field experiments, which are the subject of this Science Overview Document (SOD), and for model development. The following “Gedankenexperiment” may show the difficulties. The situation: Large-scale atmospheric flow across two chains of hills in combination with moderate convective activity, leading to cloud top temperatures of about –12 °C along the first hills. Whether showers develop here, depends on the tiny insoluble portion of the aerosol particles, acting as freezing nuclei already at –12 °C.

If they are absent, the second large chain of hills could generate more and more intense showers.

Thus the research tasks ahead for an “ideal” field experiment are:

- Establishment of four-dimensional time series of atmospheric variables in the entire troposphere including as many aerosol, cloud, and precipitation variables as possible.
- Development of assimilation techniques that allow for incorporating water cycle and aerosol parameters like water vapor, cloud water, and aerosol size distribution profiles into mesoscale and cloud resolving models.
- Time series of high spatial and temporal resolution surface flux estimates in a large region, covering at least several hundred by several hundred square kilometers, to be used as lower boundary for the atmospheric models.
- Derivation of new parameterizations for mesoscale weather forecasting models and regional climate models and subsequent test of the skill of these models.

The first three of these tasks can only be accomplished if remote sensing with satellites as well as with ground-based active and passive instruments are the foci of the experiment.

As the full implementation of the above objectives is beyond the scope of the project PQP, the planning has to include support from interested institutions and other third-party funding, e.g. special research foci of the German Research Foundation (DFG). But the organizers will also focus on specific science questions using the knowledge about facilities and their instrumentation available to national and international members of the consortium. The known potential of the consortium and the new sensors under construction will be part of the next sections.

The timing for performing this campaign is excellent, as base funding from DFG has been requested. The campaign is imbedded in a large German QPF program and strongly coupled with the activities of weather forecast centers. Therefore, this program will provide a unique focal point for international collaboration and the application of the data set collected during the campaign.

We are proposing a field campaign, which provides a data set for identifying the reasons of deficiencies in QPF and for improving the skill of mesoscale model forecasts with respect to precipitation.

Furthermore the limits of predictability of short-range QPF shall be investigated.

We are focusing on a region with a large amount of rainfall, as this will have the optimum benefit for the user communities.

In Germany, these critical regions are the alpine frontal range and low-mountain ranges (see chapter 4). QPF research in regions with significant orography is also essential in many other countries. As this experiment is performed in terrain with significant orography, the name of the experiment is

Convective and Orographically-induced Precipitation Study (COPS).

2 The Priority Program "Quantitative Precipitation Forecast"

2.1 Objectives and Set up of the Priority Program

The deficiencies of QPF summarized in chapter 1 led to the initiation of the Priority Program (PP) 1167 "Quantitative Precipitation Forecast PQP" by the German Research Foundation (DFG) in 2003 (PQP stands for Praecipitationis Quantitativae Praedictio). This research program addresses the challenges identified by the user groups with respect to QPF. The program gathers atmospheric scientists at German and Swiss universities and research institutes to combine their knowledge for improving QPF. In close cooperation with the German Meteorological Service (DWD) their operational forecast systems are used and refined as a basic backbone for model development, testing, and validation. The structure of PQP is depicted in Fig. 2.1.

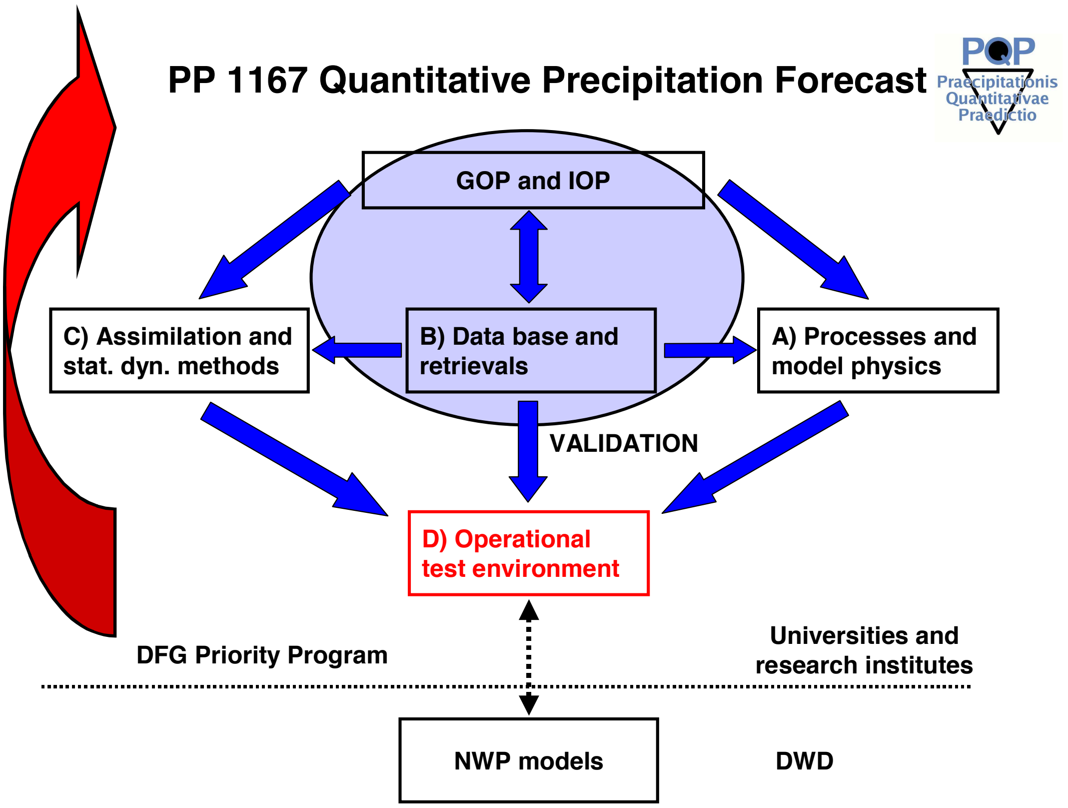


Fig. 2.1. Structure of Priority Program 1167 Quantitative Precipitation Forecast - Praecipitationis Quantitativae Praedictio (PQP). GOP: General Observations Period, IOP: Intensive Observations Period = COPS

The priority program focuses on reaching the following scientific objectives:

I. Identification of processes responsible for deficiencies in QPF.

II. Determination and use of the potentials of existing and new data as well as new process descriptions to improve QPF.

III. Determination of the predictability of weather forecast models by combined statistical and dynamical analyses with respect to QPF.

Presently, the main deficiencies of QPF are considered to be due to errors of the initial fields, suboptimal methods for the assimilation of observations, inadequate modeling of components of the water cycle, and fundamental problems in the interpretation of deterministic models.

The schedule of PQP is shown in Fig. 2.2. The program has been accepted in May 2003 and started in April 2004. The duration will be 6 years. The program is divided in three 2-year funding periods. More details are found on the PQP webpage (www.meteo.uni-bonn.de/projekte/SPPMeteo/).

	April 2004-2005	April 2005-2006	April 2006-2007	April 2007-2008	April 2008-2009	April 2009-2010
Year	1	2	3	4	5	6
	Period 1		Period 2		Period 3	
GOP				One year		
IOP	Phase 1: Preparation			Phase 2: Performance: Summer 2007	Phase 3: Data analysis	

Fig. 2.2. *Funding and timing of PQP. Exp: Experiment. GOP: General Observations Period, IOP: Intensive Observations Period (= COPS)*

23 research projects have been funded by the DFG after a review process, which took place in winter 2003/2004. These projects are related to surface-atmosphere exchange, convection, aerosol and cloud microphysics, data assimilation, remote sensing, numerics, and verification. More details are presented on the PQP web page. Strong collaboration between PQP PIs is fostered by the performance of joint workshops.

International collaboration is strongly supported. The field campaign, which is subject of this proposal, is an example.

Separately, funding has been requested for experiments, which shall be performed within the scope of the PQP. These experiments are imbedded in the center of the PQP program so that these activities can be coordinated with all PQP research projects. Furthermore, this permits to perform IOP projects and the corresponding data analysis within the duration of the PQP.

2.2 Experiments Within the Scope of PP 1167

The urgently required improvement of knowledge on the relevant processes as a basis of model optimization with respect to the currently blatant uncertainty of QPF 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. It is therefore indispensable to extend the database by field experiments, where advanced sensors allow for the observation of decisive atmospheric variables. These include the atmospheric dynamics, the water vapor field, as well as cloud and precipitation parameters.

The experimental set up takes into account the huge temporal and spatial distribution of precipitation making the analysis of its statistics very difficult. The entire experiment shall comprise a large-area observation phase of one year **(General Observations Period, GOP)**, and a dedicated experiment regarding the precipitation process over several months **(Intensive Observations Period, IOP = COPS)**, providing high-resolution, four-dimensional measurements of atmospheric variables. This field campaign is the subject of this Science Overview Document (SOD).

During the GOP, all available observations routinely performed will be gathered (e.g., rain gauges, three-dimensional radar observations, satellite observations) in the GOP area covering the major part of Europe. Research institutes shall be supported for operating their "standard" instruments. Available instruments shall be redistributed within the GOP area to obtain information on the atmospheric state at certain sites as complete as possible. Strong cooperation with European Observatories (Cabauw, Chilbolton, Lindenberg, Palisieau) is planned. Additionally, at least one special long-term observation site shall be operated within the COPS area a critical location, which has been identified in the experiment preparation phase. The Atmospheric Radiation Measurement Program (ARM) Mobile Facility (AMF) has been requested for this purpose. This integration of operationally not employed data will result in the presently achievable optimum of information on the state of the atmosphere being supplied to a regional forecast system.

COPS shall be performed in summer 2007 in southwestern Germany and eastern France for 3 months. Precipitation processes will be observed in 4D by means of a synergy of a new generation of research remote sensing systems operated on ground, aircrafts and satellites. The whole life cycle of convective precipitation from the initiation of convection, to the formation and development of clouds, to the formation and development and decay of precipitation shall be observed in detail.

The combination of the GOP with COPS shall not only give rise to a far improved data set for assimilation and validation of models, but also to an improved in-depth process understanding. Evaluation of the data sets obtained under this priority program will lead to a better representation of relevant processes in models and, hence, to improved QPF.

3 COPS Science Goals and Hypotheses

It is the overarching objective of COPS to identify the physical and chemical processes responsible for the deficiencies in QPF over low-mountain regions with the target to improve their model representation. Correspondingly, the overarching goal of COPS is to

Advance the quality of forecasts of orographically-induced convective precipitation by 4D observations and modeling of its life cycle

The determination and use of the potentials of existing and new data sets and of better process descriptions are central issues to improve QPF in this context.

The COPS community developed the following fundamental hypotheses:

- Upper tropospheric features play a significant but not decisive role for convective-scale QPF in moderate orographic terrain.
- Accurate modeling of the orographic controls of convection is essential and only possible with advanced mesoscale models having a resolution of the order of a few kilometers.
- Location and timing of the initiation of convection depends critically on the structure of the humidity field in the planetary boundary layer.
- Continental and maritime aerosol type clouds develop differently over mountainous terrain leading to different intensities and distributions of precipitation.
- Novel instrumentation during COPS can be designed so that parameterizations of sub-grid scale processes in complex terrain can be improved.
- Real-time data assimilation of key prognostic variables such as water vapor and dynamics is routinely possible and leads to a significant better short-range QPF.

These hypotheses are the consequence of the gaps in our knowledge concerning QPF, which have been identified in chapter 1. Testing these hypotheses requires a combination of the most powerful remote sensing instruments with proven ground-based and airborne measurement techniques within COPS. Measurements must be arranged to obtain unachieved accuracy and resolution. Intensive collaboration with modelers and forecast centers providing deterministic and probabilistic forecasts is essential for model evaluation and testing these hypotheses. This requires a sophisticated scientific preparation and a careful coordination between the efforts of the institutions involved.

4 The COPS Region

4.1 Orography

The area envisaged to conduct COPS in summer 2007 is located in central Europe at the border between Germany and France. The area covers about 250 km in west-east direction and 170 km from south to north. The center of the domain is located 150 to 200 km south of Frankfurt and north of the Swiss Alps. This is between 6.0 and 10.0 °E and between 47.7 and 49.2 ° N. The climate of the region is a typical mid-latitude moderate climate, characterized by a westerly flow in winter with rainfall associated with frontal systems and more convective precipitation in summer combined with thunderstorms caused by local instability of the atmosphere.

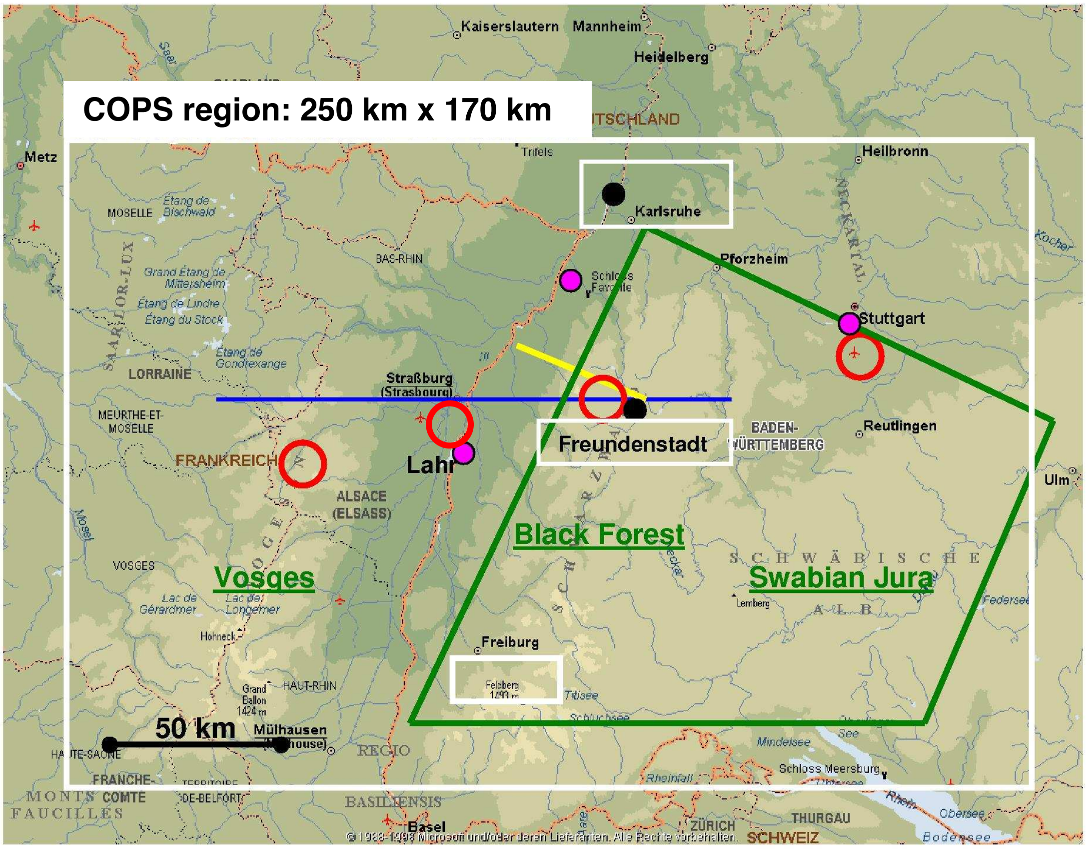


Fig. 4.1 The most pronounced orographic feature in the COPS (= IOP) region is the Rhine valley between the Vosges and the Black Forest mountains. The red circles indicate the proposed supersites for the COPS field campaign. The thunderstorm climatology (Fig. 4.6) is valid for the green box including Black Forest and Swabian Jura. The blue line marks the model cross section in Fig. 4.13. The aircraft measurements in Fig. 4.14 were made along the yellow line from the Rhine valley (150 m) to the Black Forest (Hornisgrinde, 1163 m). Pink dots indicate the locations of airports suitable for COPS aircraft operations.

In the east of the Rhine valley the hills of the Black Forest rise rapidly. Just opposite of the Voges peak Grand Balon, Feldberg is located as the highest mountain of the Black Forrest (1493 m) at the southern border of the COPS region. The mean terrain height in this region is 1000 m. The height of the Black Forest in its central and northern part (near Freudenstadt) is between 500 and 800 m. The highest peak in the northern part of the low mountain range is Hornisgrinde (1163 m) located northwest of Freudenstadt. This area is dominated by high convective precipitation in summer, including severe thunderstorms. Therefore, it is planned to place one of the COPS supersites in the region. Eastward, the Black Forest is descending slowly to the Neckar valley.

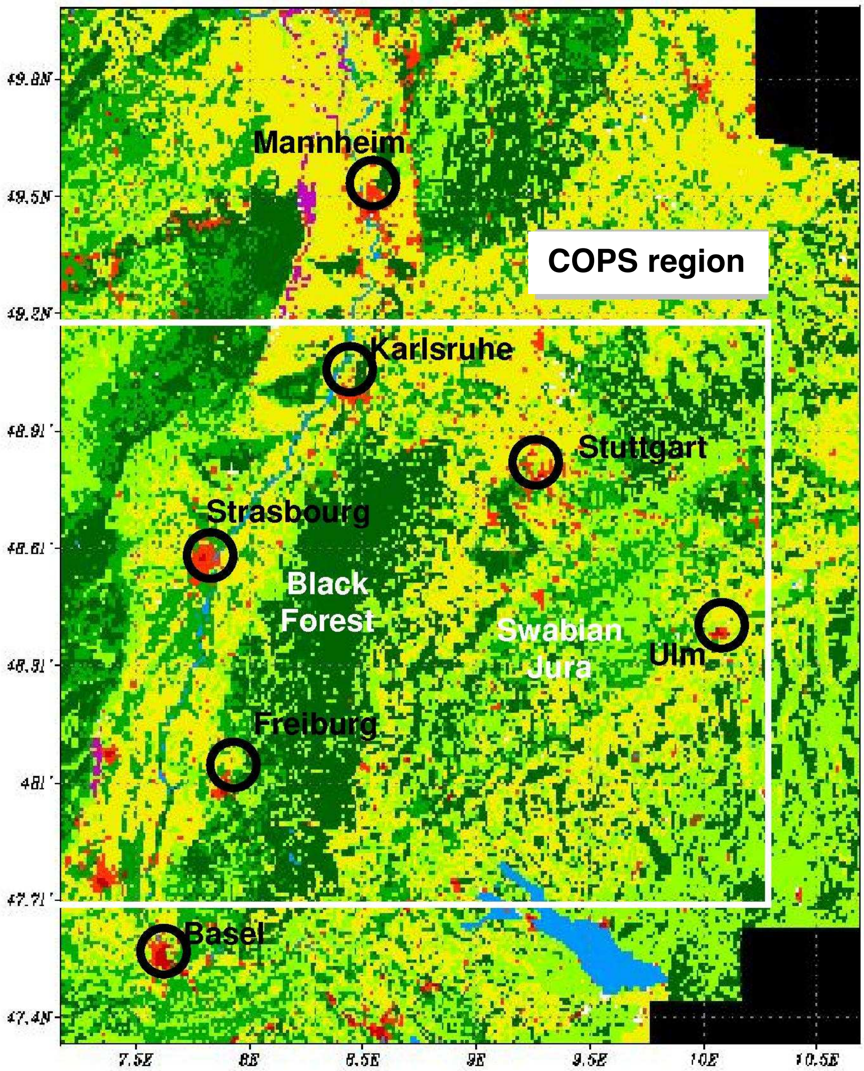


Fig.4.2. *Landsat-TM image indicating the land use in south-western Germany in the COPS region. Horizontal resolution is 1 km and the main land use classes are agricultural areas (48 %, yellow, light green), woodlands (37 %, green, dark*

green), water (1 %, blue), and urban areas (red). The low-mountain ranges Black Forest and Vosges are mainly covered with coniferous woodlands.

The whole Black Forest is dominated by coniferous woods and only little agricultural use. North of Pforzheim, around Stuttgart and to the eastern border of the COPS region, the height of the hills is less than 500 m. The Swabian Jura is a low-mountain range with peaks up to 1000 m located in the south-eastern part of the COPS area. It stretches from southwest to northeast. The north-western slope of the Swabian Jura is quite steep, the mountain ridges are often plain and free from woodlands.

The land-use classification of the German section of the COPS region derived from Landsat-TM satellite images is shown in Fig. 4.2. The main land-use classes are agricultural areas (48 %), woodlands (37 %), and water (1 %). The other 14 % are urban areas (red), vineyards (violet), sand, fens, moor (brown) and unclassified areas (white). As can be seen easily, the land use is dominated by deciduous and coniferous woodlands in the higher altitudes of the Voges and the Black Forest. Here the landscape is often cliffy and due to its altitude not useable for agricultural purposes. Contrary to that, the hills of the Swabian Jura are more flat and rounded. Here less woodlands are found but greenland dominates in large parts of this low mountain range. The areas of Stuttgart (600 000 citizens) and Karlsruhe (270 000 citizens) are clearly dominated by urbanized and industrialized areas and areas for public and private transportation. Besides these two major cities, there is a dense population as well in the Rhine valley and in the Neckar valley south of Stuttgart. Except for the settlements in the valleys and in the area southwest of Ulm, agricultural land use dominates in the region.

4.2 Climatology

Climate diagrams of three different locations within the COPS region are given in Fig. 4.3. The yearly cycles of temperature, water vapor pressure, and relative humidity are given for Karlsruhe (112 m), located in the Rhine valley, for Freudenstadt (797 m), a possible supersite location in the central Black Forest, and for the Feldberg summit (1486 m), the highest peak of the Black Forest.

The summer climate in Karlsruhe is characterized by high mean temperature (18 to 20 °C) and high humidity (14 to 15 hPa water vapor pressure), south-westerly surface winds on average caused by channeling of the flow in the Rhine valley, and a mean precipitation of 60 mm in June, 70 mm in July, and 50 mm in August. The mean temperature in the low-mountain-range station Freudenstadt, located on a plateau downstream of the western summits of the Black Forest, is 14 to 15.5 °C in summer, and specific humidity is less than in Karlsruhe while relative humidity is higher. The mean wind is more moderate (1.5 to 5 m s^{-1}) coming from west-southwest. Mean precipitation in Freudenstadt calculated from 1961 to 1990 is 150 mm in June and 120 mm in July and August. Most of the rainfall, which is about twice as high as in Karlsruhe, is of convective origin. The temperature at the "Feldberg" is 8 to 11.5 °C in summer and the relative humidity is between 80% and 85% most of the year. The mean wind speed in summer is 5 up to more than 8 m s^{-1} from southwest. The mean precipitation at the Feldberg is 160 mm in June, 140 mm in July, and 150mm in August.

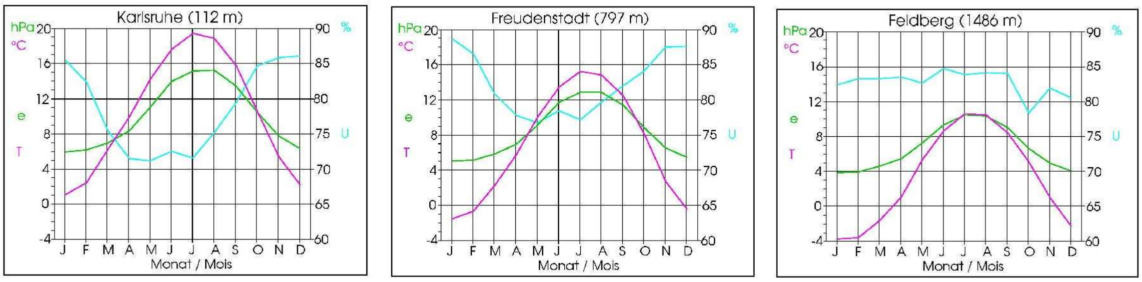


Fig.4.3. *Climate of the COPS region for the period 1951-1980. Yearly circle of temperature (pink), water vapor pressure (green) and relative humidity (cyan) for Karlsruhe (Rhine valley), Freudenstadt (Black Forest, presumably supersite location), and Feldberg (highest mountain of the Black Forest). Potential locations of the sites are given in Fig.4.1. (Fiedler, 1998).*

In central Europe, precipitation patterns are influenced by orography to a large extent, especially in summer in cases of convective rainfall. This causes a strong temporal and spatial variability of precipitation. The maximum amounts of precipitation are found in the low-mountain ranges as well as the Alpine front-range (see Fig. 4.4).

This finding resulted in separating PQP experimental periods in the GOP and COPS. As large deficiencies in QPF are found in regions with complex orography (see chapter 1) and users would benefit strongly from an improvement of QPF, COPS will be performed in the region indicated in Fig. 4.1. Furthermore the campaign shall be performed in summer, as during this period, the forecast skills are poorest.

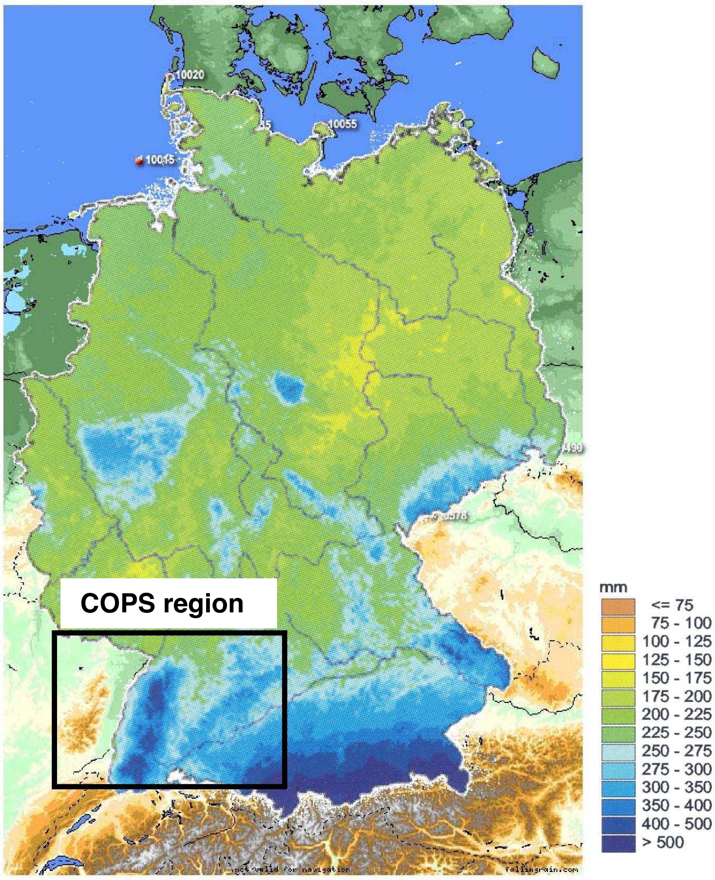


Fig.4.4. *Precipitation climatology in Germany for summer 1901-2000 (DWD Klimastatusbericht 2001). The COPS domain (= IOP region) is located in the southwestern part of Germany and eastern France approx. 200 km south of Frankfurt am Main. The area is dominated by the low mountain ranges of the Vosges in France as well as the Black Forest and the Swabian Jura in Germany.*

In Fig. 4.5, a closer look on precipitation statistics in the COPS region is given. The precipitation in June (mean of the years 1961 to 1990) is shown in the left diagram. There is more the 150 mm rainfall (max. 200 mm) in the northern Black Forest (Freudenstadt). The same amount is measured in the southern Black Forest, while in the Swabian Jura 100 to 130 mm are observed on average. In the Rhine and Neckar valleys and the surrounding plains, a mean rainfall of 80 mm or less is measured. The right diagram gives the mean number of precipitation events with more than 10 mm/day in the months of April to September. There are 20 -30 of these events in the northern and southern Black Forest, respectively, 16 – 20 in the Swabian Jura and 12-16 in the valleys of Rhine and Neckar. This clearly demonstrates that the mountains are preferred regions of summer rainfall and that the precipitation is mainly of convective character in summer. For this reasons a field campaign from June to August in the low mountain ranges of southwest Germany will cover severe storms and therefore support the goals of COPS.

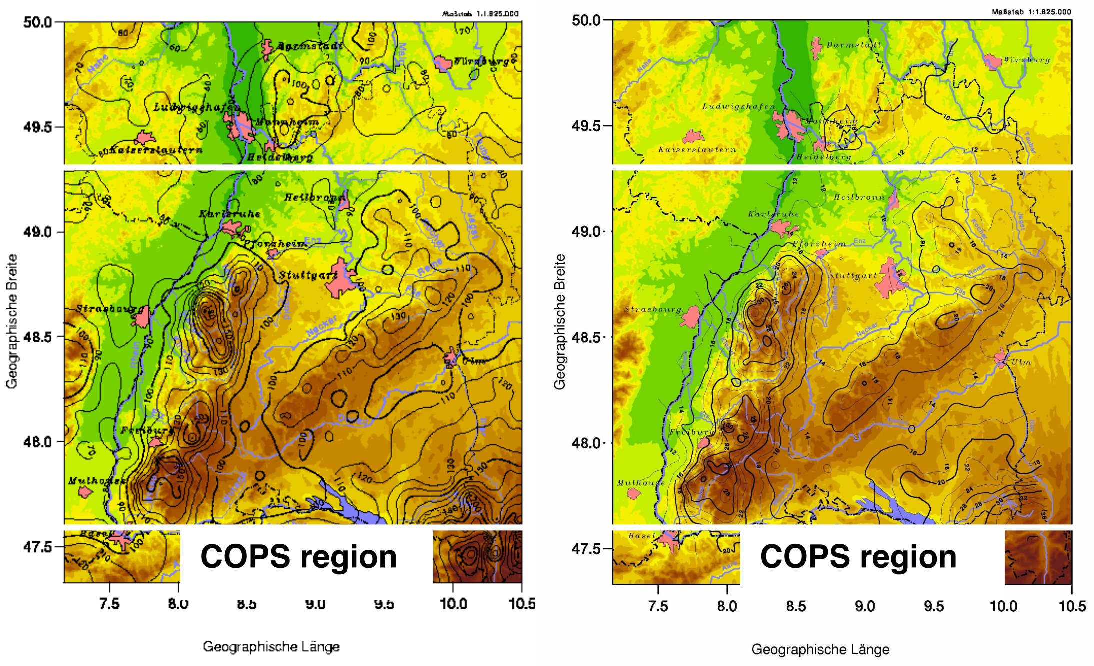


Fig.4.5. *Precipitation in the COPS-region. Left diagram: 30-years mean precipitation (mm) in June calculated from data between 1961 and 1990. Data of 749 stations are used, resulting in a mean density of 1 station each 75 km^2. Right diagram: mean number of precipitation events per year of more than 10 mm per day from April to September of the period from 1951 to 1995. Calculated from data of 459 stations (Courtesy of G. Mühr, IMK).*

The mean temporal and spatial distributions of thunderstorms in the COPS region are given in Fig. 4.6. SYNOP-observations between 1995 and 1998 gathered within the area marked with a green box in Fig. 4.1 are taken to calculate the distribution of thunderstorms in the circle of the year (left) and day (right). From May to August the probability of thunderstorms is significantly higher than during the rest of the year. As in the second half of August the thunderstorm activity is reduced (not shown), a three-month campaign should take place from June to August. The daily thunderstorm cycle is characterized by the minimum at 09:00 and the maximum at 16:00 local time. In summer, sunrise is at 04:00 and sunset at 22:00 local time in the area of interest. Thus it is possible to operate aircrafts between sunrise and sunset and to measure the pre-convective atmospheric environment as well as during the most pronounced thunderstorm activity.

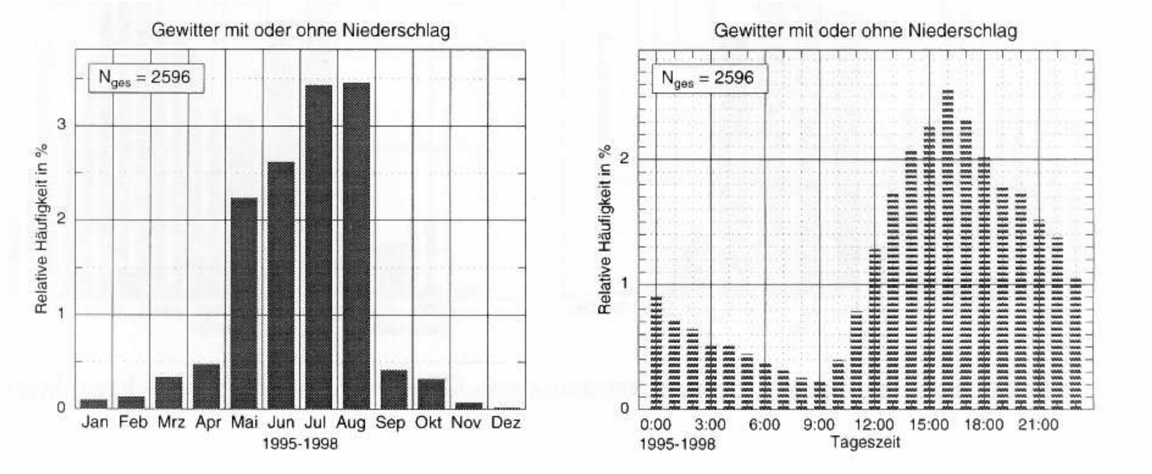


Fig.4.6. *Frequency distribution of thunderstorms with and without precipitation on the basis of 2596 DWD-synop-data between 1995 and 1998 for the area of the Black Forest and the Swabian Jura (area marked with a green box in Fig. 4.1). Yearly circle (left) and diurnal circle (right), (Hofherr, 1999).*

The spatial distribution of lightning is shown in Fig. 4.7 as an example for the year 1994, which can be seen as typical for the region. Mainly in case of non-frontal thunderstorms forced by regional destabilization of the atmosphere due to large-scale lifting and surface near moisture convergence triggered by secondary circulation systems, the lightning density in the COPS region is highest in southern Germany and the northern parts of the Alps. As seen from other observations (see Fig. 4.5) in average most of this thunderstorms (92 %) happen in summer between April and September, and 74 % in the 4-month period May to August.

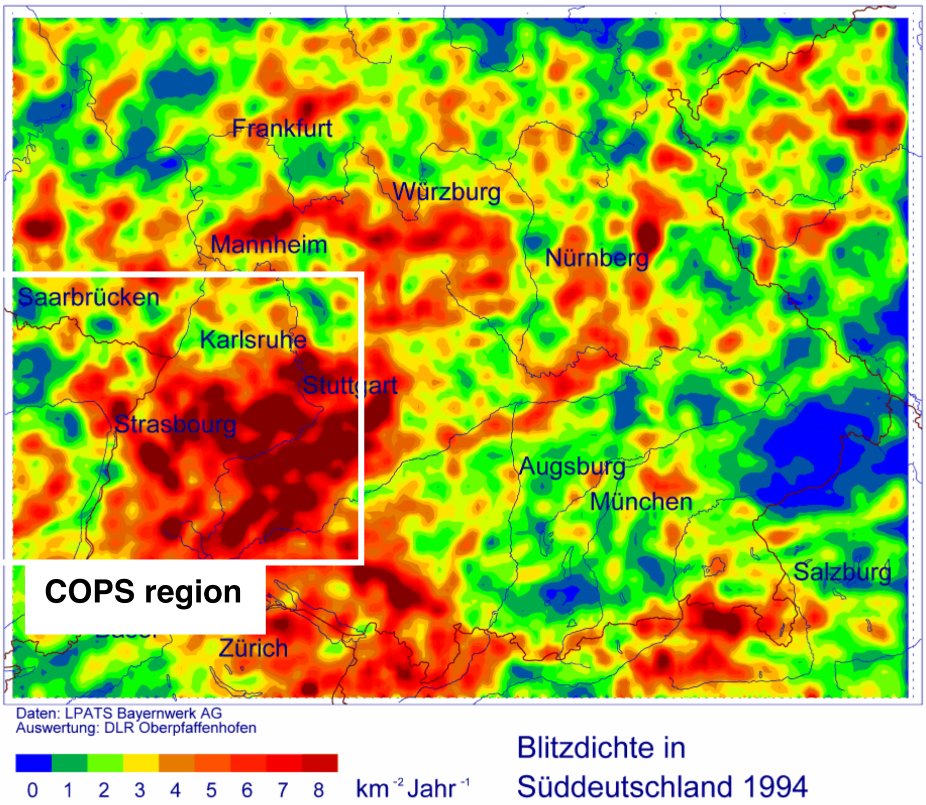


Fig.4.7. *Lightning density in the southern part of Germany in 1994. The maximum of 8 lightnings per km^2 and year is found in the COPS area between Strasbourg, Karlsruhe, Stuttgart and Zürich. (Finke and Hauf 1996).*

4.3 Large-scale Processes: Synoptic Environment for Intensive Precipitation in the COPS Region in Summer

In order to get an idea of the large-scale weather situations that are associated with strong precipitation in the COPS regions, a number of events has been examined, based on a simple climatological analysis. Five stations were selected, Freiburg, Freudenstadt, Klippeneck, Lahr and Feldberg (see Fig. 4.1 for locations), and a list was compiled of all days in June, July and August during the period 1996-2003 when at least 25 mm of precipitation occurred. To identify characteristic weather patterns these days were then classified according to the 16 categories of the DWD Grosswetterlage (GWA; Bisolli, 2001), which attempts to categorize the synoptic flow over Germany. The implications of this classification for convection in the COPS region were then explored by looking at weather charts for 20 individual events. In particular, the top ten days in terms of rainfall amount, with and without reported lightning, were considered. This was done to identify whether there was a significant chance of severe precipitation not associated with convection, although in the events examined, the precipitation always appeared on satellite imagery to be mainly convective, even when embedded in frontal lines.

Based on the examination of individual events, it appears that the GWA categories fall into two main groups with regard to their importance for convection in the COPS region. The first is where there is a low pressure area or trough over or to the west of the region, with a diffluent flow at 500mb, suggesting the presence of synoptic-scale ascent and forcing of convection. The second major category included days where the COPS region was in an area of high pressure, or a high pressure bridge (ridge connecting two high pressure centers). Some of the patterns, particularly those with Easterly flow, possibly associated with a region of high pressure to the north, were more difficult to classify, with different events having different flow configurations over the COPS region. Table 1 below lists the GWA categories, and the following Fig. 4.8 shows their frequencies of occurrence. It is immediately apparent that more than half of the cases have evidence of large-scale forcing in westerly flow. A substantial fraction, one quarter to one third, occur in high pressure areas.

A second important result of the examination of individual events was that many of the cases were clearly associated with a surface front, typically with a line of convection embedded, while others featured more pre- or post-frontal convection, or no front in the region at all. The frequency of occurrence of low-level frontal forcing for the 20 cases is shown in the table below (figures in brackets denote days with lightning observed).

Table 1. *Categorization of large-scale weather conditions according to GWAs.*

Synoptic forcing	WZ	Westerly cyclonic
	SWZ	South-westerly cyclonic
	NWZ	North-westerly cyclonic
	TRW	Trough west-Europe
	TM	Low mid-Europe
	TRM	Trough mid-Europe
	TB	Low pressure bridge
High pressure	HM	High mid-Europe
	BM	High pressure bridge
Other	WA	Westerly anticyclonic
	SWA	South-westerly anticyclonic
	NZ	Northerly cyclonic
	HNA	High North Sea anticyclonic
	NEZ	North-easterly cyclonic
	HNFZ	High North Sea cyclonic
	SEZ	South-easterly cyclonic

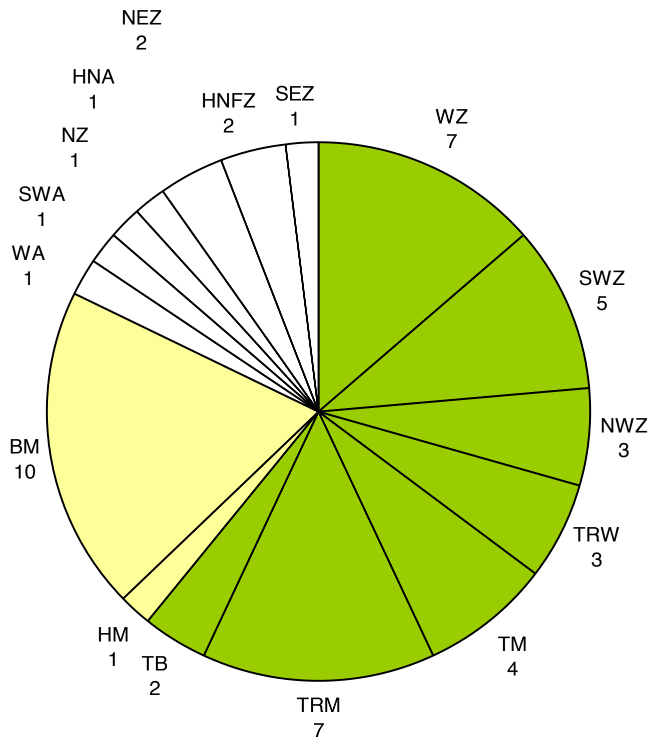


Fig.4.8. *Statistics of synoptic weather conditions leading to significant precipitation in the COPS region.*

Table 2. Most typical large-scale conditions for intense precipitation in the COPS region.

	Synoptic forcing	High Pressure
Surface front	6 (3)	0 (0)
Non-frontal	11 (5)	3 (2)

The final conclusion of this analysis is that there are three characteristic patterns of large-scale flow associated with heavy precipitation in the COPS region. Some examples have been identified, which have been or will be analyzed within the preparation of COPS:

1. Forced/frontal: typically a frontal line with embedded convection in a region of large-scale ascent. The precipitation appears to be initiated by the forcing, with orographic modification of the flow and surface fluxes playing a secondary role.

   Example: 5 June 2002 (or 10 June 2004)

2. Forced/non-frontal: synoptic-scale ascent, but no surface front, so that convection is breaking out over a wider area. There is significant low-level flow, so orographic forcing is likely to be important, and surface fluxes may also play a role.

   Example: 19 June, 2002. Analyses of this case are also shown in the DFG proposal for COPS.

3. Air mass convection (non-forced/non-frontal): occurring in a region of high pressure with no evidence of large-scale forcing in upper or lower levels. Since the low-level flow is also weak, surface fluxes may be dominant in initiating convection.

   Example: 27 July 2002 (or 20 May 2004)

From this limited analysis it is difficult to draw conclusions on the frequencies of the events. In the present sample, the most common type is upper-level forcing without a synoptic low-level front (type 2), second is frontal (typically embedded convection, but stratiform cannot be ruled out, type 1), and third is air-mass convection in a high pressure area (type 3).

In the COPS DFG Proposal, this analysis is used to derive a suitable design of observing systems.

4.4 Small-scale Processes: The COPS Natural Convection Laboratory

4.4.1 Precipitation initiation statistics in the COPS region

European composite radar reflectivity datasets have been used to assess the summertime climatology of precipitation initiation (PrI) in the COPS region (Wilson and Weckwerth, unpublished). Precipitation is seen in the Black Forrest region on more than 50 % of all days in summer (see Fig.4.9). There may be a slight bimodal distribution with maxima at the beginnings of June and August. This finding is consistent with the 30-year monthly-mean precipitation climatology which shows also less precipitation in July than in June and August in the COPS region. Figure 4.10 shows the initiation of precipitation in this area. The data also indicate a bi-modal distribution of summertime PrI with maxima of PrI events in early June and early August, and a minimum at early July. The fraction of days with PrI events is about 45 % for the maxima and 10 % for the minimum. The diurnal cycle of PrI shows a broad distribution at daytime with a maximum in the early local afternoon.

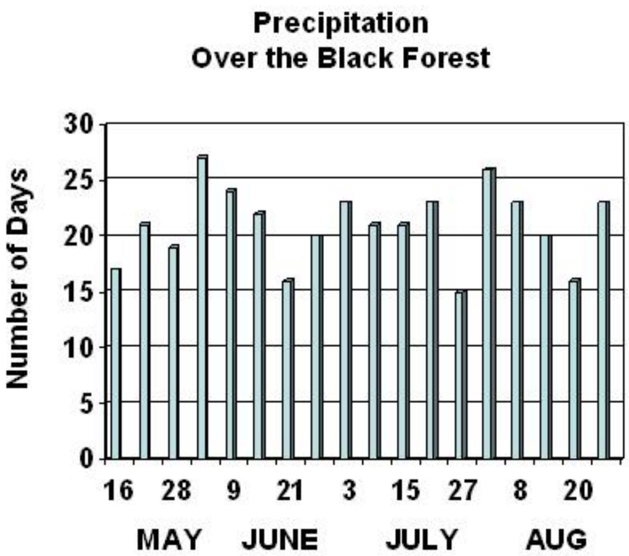


Fig.4.9. *Precipitation climatology in the Black Forrest region using radar composites of the five years of 2000 to 2004 (Wilson and Weckwerth, unpublished). Number of days in the period of 16 May to 31 August with initiation of precipitation in the Black Forest region. Each column is for a 6-day period starting at the date indicated. The total number of days investigated for each column is 30.*

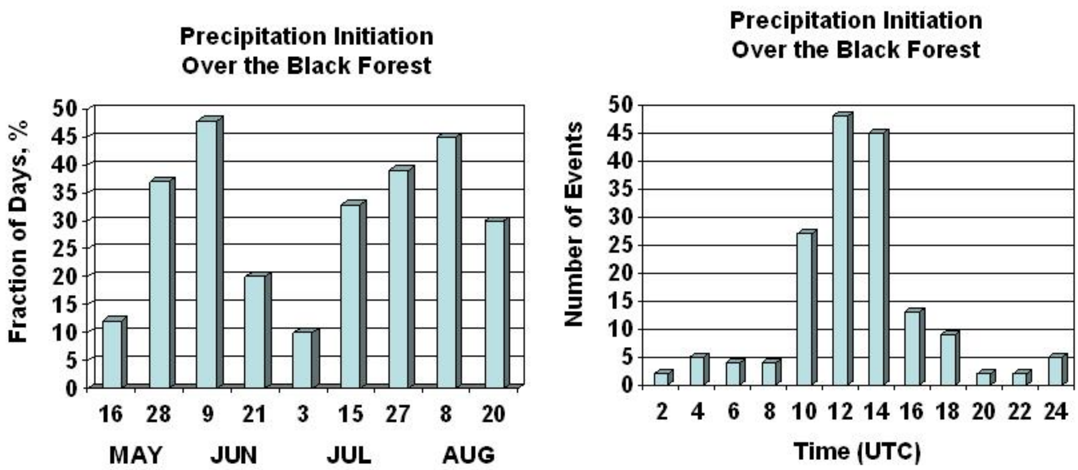


Fig.4.10. *Precipitation initiation (PrI) climatology in the Black Forrest region using radar composites of the five years of 2000 to 2004 (Wilson and Weckwerth, unpublished). Left panel: Fraction of days in the period of 16 May to 31 August with initiation of precipitation in the Black Forrest region. Each column is for a 12-day period starting at the date indicated. Right panel: Diurnal variation of precipitation initiation. Each column is for a 2-hour period staring at the time indicated. Local noon is at ~12:35 UTC. The total number of days investigated in this study is 540.*

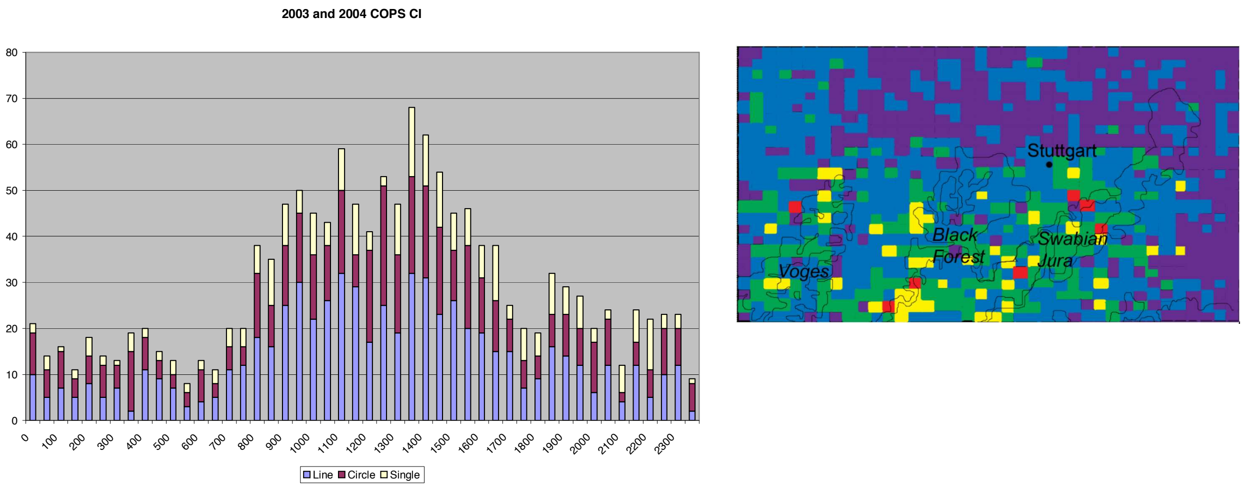


Fig.4.11. *Convection initiation (CI) climatology in the COPS domain using radar composites of June to August of the years 2003 and 2004 (Wilson and Weckwerth, unpublished). Left panel: Diurnal variation. Blue indicates linearly-organized convection; maroon is cluster form organization and yellow is single-cell initiation. Local noon is at ~12:35 UTC. Right panel: Initiation distribution. Purple is 0-3; blue is 4-7; green is 8-11; yellow is 12-15 and red is 16-20 CI events. The black lines indicate topography.*

For the full COPS region, data of the years 2003 and 2004 have been used to investigate the diurnal cycle of different types of convective precipitation and the locations of the initiation of convection (see Fig. 4.11). The analyses identified a daytime peak in rainfall development from 0800-1700 UTC. This initiation was mostly in the form of a line of new cells popping up. About 33 % of the time, however, the new convection formed in the same area with no apparent organization to the structure. About 19% of the time solitary cells formed.

4.4.2 Regional Circulation Patterns and Orographically-Induced Initiation of Convection

The boundary layer structure in the COPS region has been studied previously within several field campaigns (e.g., VERTIKATOR see section 5.1.3). An example of the flow structure in the COPS area is given in Fig. 4.12., which shows the near-surface wind field for the VERTIKATOR day June 19, 2002, simulated by the mesoscale model KAMM. Medium-high mountains like the Vosges and the Black Forest produce strong inhomogeneities in the flow structure by dynamics and thermal effects. Slope winds carry energy, mass, and moisture along the slopes leading to zones of confluence over the mountain ridges. The formation of valley winds through the stronger warming of air above the mountains compared to air at the same height over flat terrain is also contributing to this effect. A significant amount of moisture is thus reaching the valley end, where it can be included into the convective processes above the ridges. By condensation, the energy for maintaining the convection can be supplied. These high-resolution studies performed with non-operational models indicate that these models start to reproduce in a more realistic manner flow and humidity structures leading to the initiation of convection. However, only by means of a field campaign it can be investigated whether these models are accurate enough for improving QPF in these regions. Furthermore, it is important to study the performance or even the necessity of parameterizations such as for convection. These data sets are not available yet.

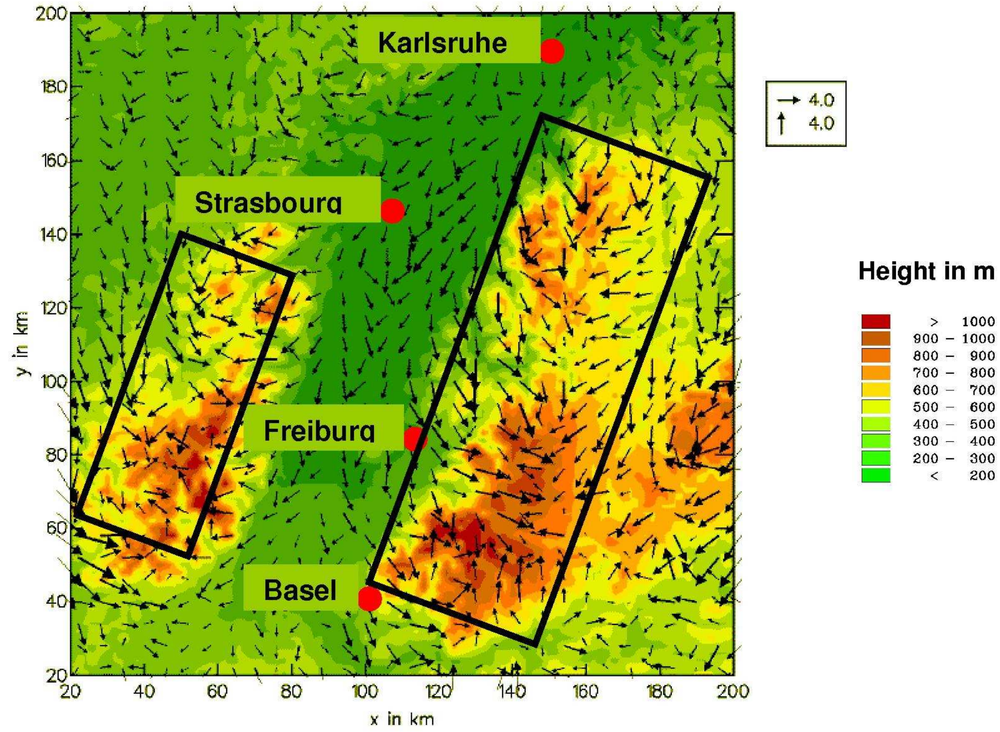


Fig.4.12. *Simulation of the near-surface wind field in the COPS area with the mesoscale model KAMM (KArlsruher Mesoscale Model). A north-easterly flow, channeling in the Rhine valley and convergence over the mountain ridges is seen at 14 UTC on June 19, 2002, a VERTIKATOR observation period (Courtesy of H. Noppel, IMK).*

Two main processes are needed for the evolution of atmospheric convection: a small-scale triggering process at the ground by heating of the land surface and/or larger scale lifting of the air with a sufficient amount of moisture so that the cumulus condensation level can be reached. For this case study, the convergence above the mountain ridges was identified as triggering process for the onset of convection. As a sufficient amount of moisture was present, the formation of clouds above the mountain ranges was observed and simulated with KAMM. The cross section as indicated in Fig. 4.1 with wind vectors and cloud water content is given in Fig. 4.13. Strong vertical movements and the formation of clouds are simulated above the Vosges and the Black Forest. However, again a detailed data set is lacking to verify model performance covering the whole life cycle of convective systems including the pre-convective environment.

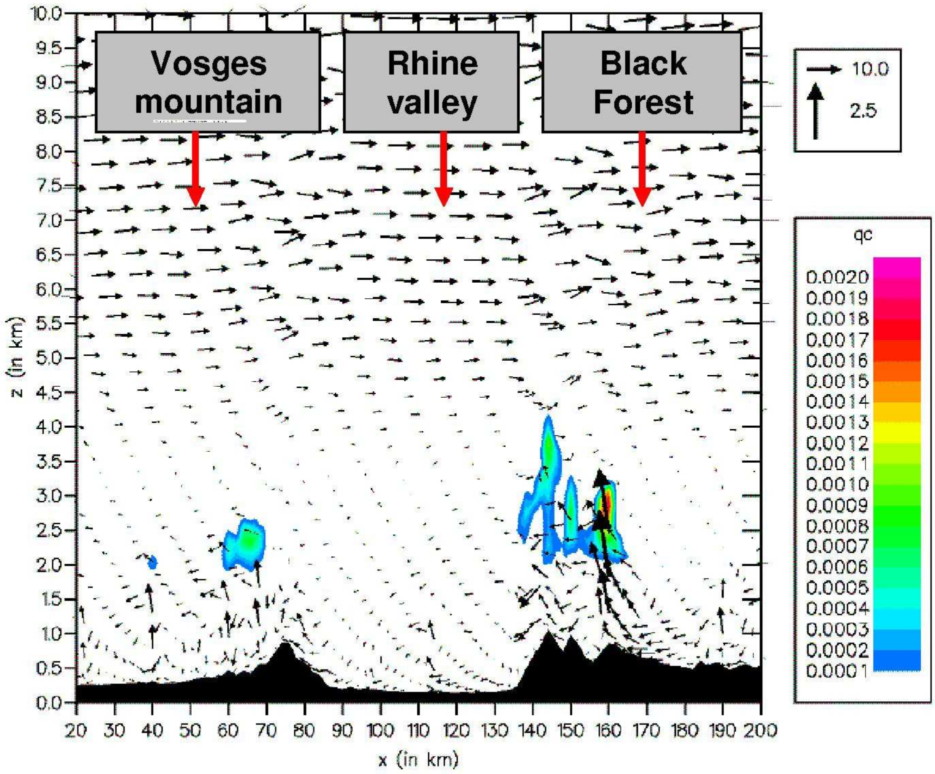


Fig.4.13. *West-east component of the horizontal wind, vertical wind (arrows), and cloud water content (color code) along the cross section marked blue in Fig.4.1. at 14 UTC on June 19, 2002 (Courtesy of H. Noppel, IMK).*

Transport processes of water vapor and trace gases from the boundary layer to the free atmosphere governed by convective cells locally and temporally breaking the boundary layer inversion over complex terrain have been investigated in the TRACT project 1992: Transport of Air Pollutants over Complex Terrain. One of these events (see Fig. 4.14) took place over the upper Murg valley near Freudenstadt, which is a typical location for the initiation of convection. One of the COPS supersites is planned in this area. During the measurement flight of the research aircraft Do 128, a convective cell penetrated the boundary layer capping inversion at 8.43°E. In the center of the cell updrafts of up to 3 m s^{-1} occurred. The updrafts were combined with specific humidity values of about 8 g kg^{-1}, which are 2-3 g kg^{-1} higher than east and west of the cell and higher values than below the cell in the boundary layer. The lifetime of the cell was about 1 hour and the horizontal cross section was estimated to be at least 1 km^2. The cinematic turbulent moisture flux w'q' was calculated along the cross section, which gave values with highest positive values in the center of the cell and negative sign in the downdrafts around. The dimensions of this relatively small cell with a short lifetime and the fluxes calculated, resulted in a transport of water from the boundary layer to the free atmosphere of about $6x10^7$ kg h^{-1} km^{-2}. Neglecting humidity advection and calculating the evaporation in this case to be 2.5 mm water per day, an area of about 25 km^{-2} can replace the humidity in the boundary removed by the small cell. This is done by moisture convergence over the mountain ridges due to secondary circulations (Kossmann et al. 1999).

This study indicated the various science questions and the measurement needs in connection with the initiation of convection in orographic terrain. On the one hand, these measurements need to be verified by high-resolution mesoscale models, which are just becoming available. On the other hand, 3D simultaneous measurements of thermodynamics before the development of convection as well as in and around convective systems are essential to improve our process understanding as well as to evaluate and to improve models. The model studies should be performed with different resolutions, with and without convection parameterization in order to validate different parameterization schemes.

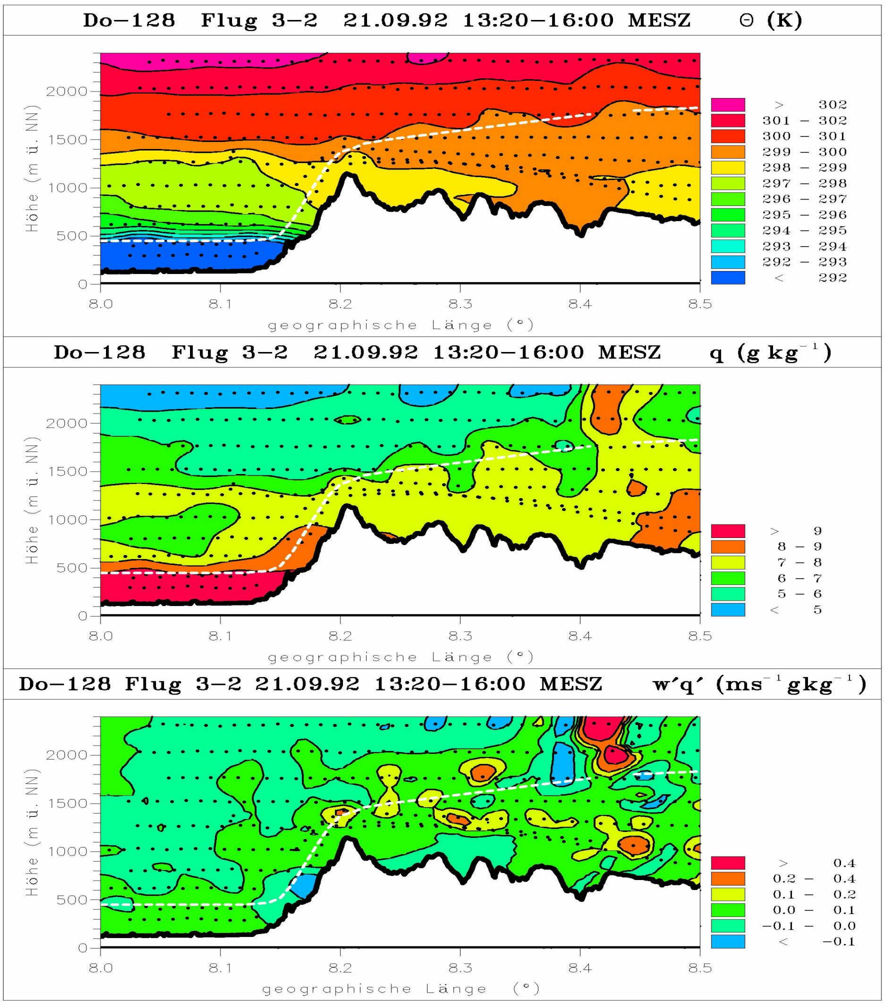


Fig.4.14. *Vertical cross section of potential temperature (upper diagram), specific humidity (middle diagram) and turbulent latent heat flux, indicated by w'q' covariance (lower diagram). Measurements were made by the research aircraft Do 128 on 10 horizontal flight legs (dotted lines) during TRACT in 1992. A convective cell was breaking through the PBL inversion (white line) at 8.43° E. This is a location over the upper Murg valley where convective development is often observed and a COPS supersite is planned. The horizontal range of the cross section is about 36 km. The location of the measurements is shown in Fig. 4.1 with a yellow line.*

5 Experience from previous campaigns and coordination with other international activities

5.1 Previous campaigns

The formation and the microphysical and dynamic processes along frontal systems have been studied in detail by Hobbs (Hobbs, 1978) and Browning (Browning, 1990) in the 1980s. The interaction of frontal systems with orography was the topic of research during the DFG PP "Fronts and Orography" (1987; Hoinka and Volkert, 1987) in Southern Germany.

More recently, the MAP field campaign in 1999 (Bougeault et al. 2001) investigated, among other topics, orographic effects on precipitation in and around the Alps. During the IMPROVE 1 and 2 campaigns in 2001 (Stoelinga et al. 2003), the role of cloud microphysics in orographic enhancement of stratiform precipitation along the Cascade mountains in the Western USA was investigated.

Previous field campaigns in Southern Germany focused on convection. In 1992 in Southern Germany, the CLEOPATRA field campaign investigated convection and convective precipitation in the Alpine Foreland (Meischner et al. 1993). Several field campaigns followed later on to study deep convection, transport and production of NO_x by lightning in the Alpine Foreland (SETEX 1994, LINOX 1996, EULINOX 1998). Finally in 2002 convective processes and their initiation or modification by orography were investigated in the Black Forest and the Alps plus the Alpine Foothills during the VERTIKATOR field campaign (Lugauer et al. 2003). However, neither of these campaigns considered the whole life cycle of convection. Aerosol-cloud interaction was neglected. Data assimilation as a key tool for combining observations and forecasts did not play a role. Furthermore, none of these campaigns was related to an improvement of QPF.

Particularly, we are benefiting from field campaigns, which were focusing on improvements of QPF. These were IHOP_2002, MAP, and CSIP.

5.1.1 IHOP_2002

A recent related project was the International H_2O Project (IHOP_2002) conducted in the U.S. Southern Great Plains (SGP) in the summer of 2002 (Weckwerth et al. 2004). The overarching hypothesis of IHOP_2002 was that improved measurements of water vapor will lead to a corresponding improvement in our ability to predict convective rainfall amounts. To address this hypothesis, four complementary research components were established: i) the QPF research component to determine the degree of improvement in forecast skill that occurs through improved characterization of the water vapor field, ii) the convection initiation component to better understand and predict the processes that determine where and when convection first forms, iii) the atmospheric boundary layer processes research component to improve understanding of the relationship between atmospheric water vapor and surface and boundary layer processes and their impact on convection initiation and subsequent QPF and iv) the instrumentation research component to determine the future optimal mix of operational water vapor measurement strategies to better predict warm-season rainfall. This group is also working toward better quantification of measurement accuracy, precision and performance limitations.

The regional variations in thermodynamics and dynamic characteristics over the Southern Great Planes (SPG) in the US and how these variations relate to the storm environment have been known for some time (e.g., Miller 1959, Newton 1963, Carlson and Ludlam 1968, Carlson et al. 1983). For example the characteristics of the IHOP_2002 region of study are known to vary significantly with longitude. There is high soil moisture content in the east and south but the air mass is often capped with a strong inversion creating a situation where the triggering of storms becomes critical. Due to substantial amounts of convective available potential energy (CAPE), once the cap is broken, the ensuing thunderstorms may be severe. The region has large mesoscale variations in water vapor with the dryline, a sharp gradient in moisture, occurring quite frequently. Prior to IHOP_2002, this was believed to be the primary surface forcing mechanism in the region but IHOP_2002 analyses have since shown that cold fronts and outflow boundaries were the dominant surface forcing mechanisms. Elevated convection with no associated surface features was also often observed (Wilson and Roberts 2005). The local orographic variations are small and generally not critical to the triggering convection although the Texas Caprock area does exhibit an increased frequency of convection. The precipitation maximum is nocturnal. Recently a continental-scale organization has been noted in terms of the propagation of convection (Carbone et al. 2002).

While IHOP_2002 and COPS have some overarching goals in common, the meteorological situation, topography and measurement strategies are clearly different. It is expected that the expansion of these IHOP_2002-type of convection-related studies to more complex terrain found in the COPS domain will have general application in numerous regions world-wide. COPS provides a gradual transition to complex terrain with the low-mountain regions within the COPS domain. As the terrain is more pronounced in COPS, certain physical effects, such as the role of differential onset of solar heating due to the slope of the terrain become more important. Dynamic effects such as blocking are also likely to play a larger role. The environment will be more marine than IHOP_2002 and CAPE will not be as high. The diurnal cycle is also different in that the precipitation maximum is in the afternoon rather than nocturnal for IHOP_2002. This suggests different primary forcing mechanisms than were observed in IHOP_2002. It is possible that synoptic forcing will play a larger role in COPS than in IHOP_2002.

Together these experiments will greatly improve our understanding of convection initiation and QPF over a broad flow regime. These combined programs provide a unique opportunity to test and refine numerical models over various regions. With different countries taking the lead on providing facilities, the programs are more cost effective than if the US or EU performed separate programs aiming at the understanding of different flow regimes. Obviously, there will be a progression in the degree to which data assimilation will be utilized in real-time as, for example, forward model and error covariances for certain new water vapor techniques are under development using data of IHOP_2002 and thus will be available for implementation during COPS.

5.1.2 MAP

The Mesoscale Alpine Programme (MAP) concentrated on *mesoscale* flow systems (space scales from 2 to 2000 km; time scale between 2 hours and 2 days), which were regarded in 1995 as central for the understanding of weather and climate details in mountains areas:

Mountains, and in particular ***Alpine****-type orography, instigate or influence a rich range of* ***mesoscale*** *phenomena. These phenomena and their associated processes are intricate in character, interact with larger and smaller scale flow, and are responsible for much of the day-to-day mountain weather and for many of the extreme weather events. Moreover their composite effect contributes significantly to determining the climatic features of mountainous regions* (from the Design Proposal, 1995).

During the Special Observing Period (SOP) from 7 Sep. to 15. Nov. 1999 seventeen Intensive Observation Periods (IOP) were declared by the Scientific Director who was advised by an internationally staffed Mission Selection Team. The IOPs covered 41 of the 70 SOP days. This enabled a fair and adequate partitioning of the experimental resources (e.g. aircraft, experimental radars and lidars, additional radiosonde ascents) to the eight different MAP projects, the entire Alpine region and the three target regions in particular (see Bougeault et al. 2001 for details).

Orographic precipitation was investigated during 15 of the IOPs in different regions of the Alpine range. It was systematically analyzed in numerous detailed modeling studies. One major conclusion is that the simulated precipitation amounts depend as much on the larger-scale specification of initial field as on the microphysical parameterizations. This calls for true mesoscale data assimilation in the future. Orographically modified initiation of convection tends to increase the predictability of precipitation details in space and time.

During the ongoing *harvest activity* of the MAP results it becomes evident that progress is only possible when the experimentalists in the field co-operate closely with the academic modelers, who can afford to scrutinize the measured cases in great detail, and these in turn with the developers of operational numerical weather prediction models for the mesoscale with grid sizes smaller than 3 kilometers. It is anticipated that such co-operations within European countries and between Europe and America, which became well established during MAP, will be most useful during the planning and conduct of COPS.

5.1.3 VERTIKATOR

Results from previous projects carried out in the COPS region such as REKLIP, TRACT and VERTIKATOR gave insight in the local daily cycle of boundary layer development and convection initiation in the area. The results from the VERTIKATOR experiment show, that the trigger effect of mountains on vertical exchange is the reason that convective development starts earlier and is more intense compared to flat terrain conditions. Through a synergy of several airborne measurements with 2-hourly radiosonde launches, the evolution of boundary-layer height was investigated. It was found, that great differences up to 1800 m between the boundary-layer heights over the Black Forest and the Rhine valley occur, showing the great distinctions in turbulent mixing above the two regions. Surface related CI over the Vosges, Black Forest, and Swabian Jura ridges were found to be influenced by boundary-layer and low-level processes. Evidence was found for the important role of mesoscale wind systems on CI over the mountain crests (Kottmeier et al. 2003, Lugauer et al. 2003).

These studies provided insight in the complex dynamics and boundary layer structure in orographic terrain. However, these were mainly based on modeling studies, as high-resolution observations of dynamics and moisture were not available. COPS goes far beyond this, as corresponding instrumentation will be available extended by cloud and precipitation microphysics observing systems. Data assimilation will play a very important role within COPS. Furthermore, the organization of convection and precipitation was not subject of previous studies in this area but will be an essential part of COPS.

5.1.4 CSIP

The Convective Storm Initiation Project (CSIP) was a joint project between a consortium of universities in the UK funded by the Natural Environment Research Council, the Forschungszentrum Karlsruhe/University of Karlsruhe, and the UK Met Office. It was designed to understand precisely where and how convective clouds form and develop into showers in the maritime environment and rather flat terrain of the UK. A major aim of CSIP was to compare the results of the fine-resolution Met Office weather forecasting model with detailed observations of the early stages of convective clouds and to use the newly gained understanding to improve the predictions of the model.

A large array of ground-based instruments, from the NCAS Universities' Facility for Atmospheric Measurement (UFAM) and the Institute for Meteorology and Climate Research (IMK), Karlsruhe, were deployed in southern England, over an area centred on the Chilbolton radars, during an observational period covering June, July and August 2005. The deployment of the instrumentation was influenced by experience gained during the CSIP Pilot project held in July 2004. In addition to a variety of ground-based remote-sensing instruments, numerous radiosondes were released at up to hourly intervals from 6 different sites. In addition, two aircraft complemented the ground-based instruments. The Met Office weather radar network and Meteosat satellite imagery were also used to provide context for the observations made by the instruments deployed during CSIP.

The field campaign succeeded very well and produced a legacy of outstanding data, with which to address most of the key scientific issues. It was found in the 2004 pilot project and the main CSIP project in 2005 that processes influencing convective initiation in the UK included: upper-level forcing; multiple lids; density currents (sea-breeze, Cb outflows); low-level forcing (convergence lines and areas of deeper convection) by topography (hills and coastlines) and land-use; longitudinal and transverse convective lines; differential heating due to cloud shadowing; and cold pools with attributes (gust fronts, bow echo, and subsidence).

5.2 Coordination with Ongoing Programs

5.2.1 THORPEX

THORPEX, a World Weather Research Programme, is a ten-year international research program under the auspices of the WMO Commission for Atmospheric Sciences to accelerate improvements in the accuracy of 1-day to 2-week high impact weather forecasts (Shapiro and Thorpe 2004). Research objectives are developed under four Sub-programs: Predictability and Dynamical Processes; Observing Systems; Data Assimilation and Observing Strategies; Societal and Economic Applications. THORPEX will address weather research and forecast challenges through international cooperation between academic institutions, operational forecast centers, and users of forecast products. A core research objective of THORPEX is to contribute to the design and demonstration of *interactive forecast systems* that allow information to flow interactively among forecast users, numerical forecast models, data-assimilation systems and observations to maximize forecast skill. Observation system test and targeting experiments are performed within so-called THORPEX Regional Campaigns (TreCs).

Research in connection with THORPEX is very interesting for COPS, as unique tools are developed and applied for QPF such as multi-ensemble prediction systems and targeting. In this connection, ECMWF is taking the lead to establish the THORPEX Interactive Grand Global Ensemble (TIGGE). Various research on ensemble prediction systems is performed such as studies of the role of observation and model errors on ensemble spread. The role COPS can play in connection with THORPEX goals includes the use of COPS observations as a validation network of targeted observations, performance tests of new in-situ and remote sensing systems, develop strategies for investigating predictability of convective precipitation, improvement of parameterizations, particularly of convection. **Therefore, it has been proposed to coordinate COPS with the first summertime European THORPEX Regional Campaign in 2007 (ETReC 2007). On the 2nd THORPEX ERC Meeting, Vienna, Austria, April 2005, this proposal was accepted by the THORPEX European Regional Committee.**

5.2.2 MAP D-PHASE

As the first Research and Development Project of the World Weather Research Program (WWRP) of WMO, MAP has seen three phases so far: a *Development Phase* when the plans were made and the project was designed, the *Field Phase* with the SOP in fall 1999 and the *Analysis Phase* that is still ongoing and has brought a wealth of interesting results and insight in alpine meteorology (see Volkert 2004, Bougeault et al. 2001). Still, WWRP has encouraged the leading MAP scientists to consider a fourth or *Demonstration Phase*, namely the planning and organization of a Forecast Demonstration Project (FDP). FDPs form an essential part of the WWRP programs and are intended to confirm, by objective measures, the '*enhanced prediction capabilities* gained through improved understanding and/or the utilization of enabling technologies'.

The MAP Steering Committee has decided in early 2004 to establish a Working Group with the goal to explore the possibilities for, and define the details of a MAP FDP. In this working group, the national meteorological services of the Alpine (and some other) countries are represented as well as a number of university groups from atmospheric and hydrological sciences. The WWRP Science Steering Committee (SSC) just accepted the MAP FDP proposal.

The most relevant, high-impact, and best-studied aspect of weather with an international component in the Alps and during MAP is certainly heavy (orographic) precipitation and associated flooding. The main achievements of MAP in this respect can be summarized as follows:

- **Modeling**: The *operational use* of a high-resolution numerical model (i.e., the Canadian MC2) for decision-making purposes during the Special Observation Period, SOP (Benoit et al. 2002). Development of a new terrain-following coordinate for steep orography (Schär et al. 2002). Progress in hydrological modeling (Bacchi et al. 2003 and associated near-surface exchange processes (Rotach et al. 2004). Exploration of *ensemble prediction* of precipitation events in the Alps (e.g., Walser et al. 2004).
- **Observations**: The set-up of an alpine radar composite (e.g., Chong et al. 2000) and many related studies. High-quality Doppler lidar data and airborne data (e.g., Durran et al 2003). Small-scale soil moisture and near-surface hydrological observations (Zappa and Gurtz 2002).
- **Theory**: New insight in mechanisms of orographic precipitation (e.g., Medina and Houze 2003), PV banners and streamers (e.g., Schär et al. 2003).

Based on these achievements, *operationally forecasting flood events in the Alps* using high-resolution numerical modeling in connection with hydrological modeling has been decided to become the focus of the MAP FDP. Due to the foreseen emphasis on ensemble prediction techniques, the corresponding project is called **D-PHASE**: **D**emonstration of **P**robabilistic **H**ydrological and **A**tmospheric **S**imulation of flood **E**vents in the Alps. It will include the elements high-resolution atmospheric modeling (km-scale), ensemble prediction, data assimilation (e.g., radar composits), small-scale processes and hydrological modeling. The ultimate goal is to provide improved forecasts to the end users (civil protection authorities, water managers etc.).

Previously, a *demonstration phase* was foreseen for fall 2006, i.e. the season of the MAP SOP (September to November). **However, due to the unique opportunity to coordinate MAP FDP with COPS, this phase has been moved to the period of summer 2007 to winter 2008.** In connection with the modeling efforts, possibilities are being explored to make available some additional data during the very demonstration phase, to some extent thus mirroring the additional value of radar composites during the actual SOP. This might be achieved, for example, through collaborative efforts with EUCOS (EUMETNET Composite Observing System).

The relations of D-PHASE to COPS are apparent in as both projects deal with (heavy) precipitation, its observation and forecast, and both are tied to (more or less) complex terrain. The most pronounced difference between the two projects is the fact that D-PHASE is by definition a *forecast* demonstration project and hence heavily relies on modeling. COPS, on the other hand, has its focus on observations.

Clearly, the participants in COPS will be able to profit from the experience and outcomes of D-PHASE. The MAP experience with using high-resolution numerical modeling in the day-to-day mission planning during the SOP was indeed very fruitful and significantly contributed to the success of MAP.

The expected outcome of D-PHASE will consist of a strategy to forecast heavy precipitation events (a mixture between mid-range EPS forecast and short-range deterministic forecast combined with observations), demonstration of coupling capabilities between atmospheric and hydrological models and evaluation protocols and strategies in order to assess the value of all these forecasts to end users. Clearly, all these products will be available to the COPS community.

5.2.3 TRACKS

TRACKS "Transport and Chemical Conversion in Convective Systems (TRACKS)" has been planned by six Helmholtz-Centers to merge their expertise in initiating and organizing ambitious large-scale international experiments in atmospheric sciences, which are out of reach for university groups and smaller research institutes. Within the TRACKS project, the Helmholtz-Centers plan to study convective processes, which are of crucial importance to climate and environmental research. The present concept foresees three experimental regions (Tropics, Mid-Europe, Northern Europe), where measurement campaigns will be initiated and supported. The scientific focus of TRACKS is on (i) transport processes and precipitation formation in convective systems, (ii) influence of convection on the trace gas balance of the atmospheric boundary layer, and (iii) influence of deep convection on the budget of climatically active constituents in the upper troposphere. The paper describing TRACKS can be downloaded from the websites of participating Helmholtz-Centers, such as *http://www.imk.uni-karlsruhe.de/fi/fzk/imk/seite_417.php*.

Perfectly matching the objectives of the COPS, it is planned to measure in great detail transport processes of energy, momentum, and humidity as well as of cloud microphysical processes in various types of convection. These processes shall be investigated on the scales ranging from individual convection cells to convective systems like fronts and organized convection. Accordingly, measurements shall be performed in convective systems during various states of development. It is therefore timely and of mutual benefit for both PQP and TRACKS to focus the experimental efforts in Mid-Europe on COPS in 2007. Accordingly, **COPS has formally been accepted as a TRACKS experiment by both the TRACKS steering board and the COPS ISSC.**

Other TRACKS objectives regard the influence of convection on the trace gas balance of the Atmospheric Boundary Layer and of the upper troposphere. The atmospheric boundary layer is that part of the atmosphere, where most natural and anthropogenic emissions and the most intensive chemical conversion takes place. As habitat of man, fauna, and flora, the boundary layer and its air quality are of significant importance. Transport, transformations within the boundary layer, and exchange processes between the boundary layer and the free atmosphere determine the spatial distribution of trace gases and the hand-over of primary trace gases or secondary products to the free troposphere. Both shallow and deep convection are supposed to play a decisive role in these transport and exchange processes, in particular as far as the distribution of short-living substances is concerned.

It is planned to experimentally determine the effective convection-induced trace gas fluxes from the ground up into the free troposphere under various boundary conditions. Measurements will be sufficiently detailed to allow an improved model of vertical transport by convection to be derived. Convection provides rapid pathways for short-living primary substances, which couple short time scales to large space scales. The contributions from shallow convection and the frequency of redistribution by deep convection will be assessed. These interacting biological, air chemical, and meteorological processes are far from being understood or quantified completely. This especially applies to the feedback of turbulent transport processes of trace gases to HO_x chemistry, the associated conversion rates in the boundary layer, and further transport into the free troposphere.

Foreseeable contributions to the COPS-related experiment of TRACKS would be from Research Center Jülich (FZJ, ICG; gas phase chemical measurements from ground and from an instrumented air ship (ZNT)), Forschungszentrum Karlsruhe (FZK, IMK-TRO; air chemical and meteorological measurements from Do128 aircraft), Geoforschungszentrum Potsdam (GPS water vapor network from ground stations) and Deutsches Zentrum für Luft- und Raumfahrt (DLR, IPA; own contributions to Polarisation Radar, Falcon aircraft, lightning location network).

5.3 Summary

During COPS, a large community will come together benefiting from previous collaboration within field campaigns and projects in atmospheric sciences. COPS is focusing on one of the most challenging but also on the most important topics in atmospheric sciences, QPF. Tools for advancing QPF shall be developed which can also be applied in other critical regions of the globe.

An ambitious experiment like COPS can only be successful, if it is linked with other international activities. Figure 8.1 demonstrates that this effort has already resulted in COPS being coordinated with the most important projects in meteorological sciences. The infrastructure of different leading research institutes will be combined and funding of different programs will be put together. This leads to a win-win situation not only for all participants but also for the funding agencies, as the output of this program will have a significantly higher impact on progress in atmospheric sciences. Due to the large international collaboration, which has been initiated in connection with COPS, it was reasonable to propose this experiment as WWRP RDP. **At the 8th Session of the WWRP SSC, this proposal was endorsed so that COPS became the first WWRP RDP initiated by German scientists.** Details of the ongoing collaboration are subject of COPS DFG Proposal such as coordination of D-PHASE model runs and ETReC07 activities with COPS. Furthermore, a very important topic is the organization of data archiving and data structure. It has been proposed that the group Models & Data at the Max Planck Institute for Meteorology (MPI) in Hamburg, Germany, will be the main data center using the same infrastructure for model data storage as TIGGE at ECMWF. Also all field data shall be stored at MPI with extensive quality control. Further details are discussed in section 10 of the SOD and sections 3.2 and 4 of the DFG proposal.

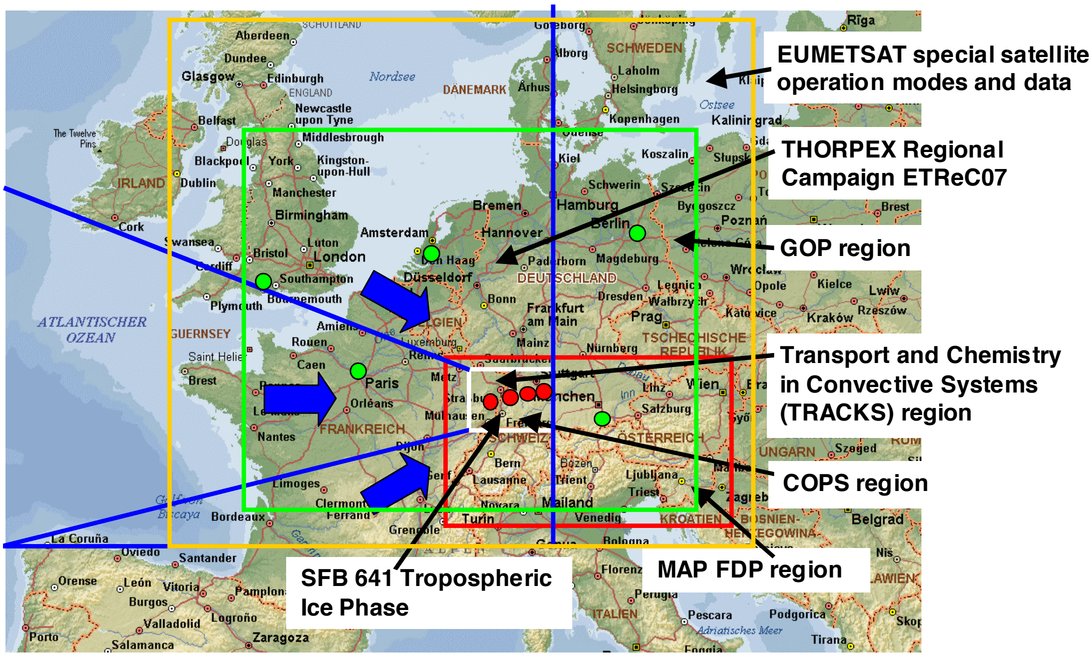


***Fig. 8.1:** Coordination of COPS measurements with other international activities.*

6 Key Research Components

The COPS science questions are addressed by four working groups (WGs), which have been established during the two recent COPS Workshop:

The **WG Initiation of Convection (CI)** is focusing on high-resolution, 4D observations and modeling of convection in orographic terrain. Dynamical and thermodynamic theories shall be developed to understand the complex flow and the related moisture variability in order to understand the timing and location of the initiation of convection. For this purpose, a unique combination of instruments will be applied to study the pre-convective environment in 3D including the upper tropospheric forcing and secondary forcing due to orography.

The **WG Aerosol and Cloud Microphysics (ACM**) is exploring the relationship between aerosol properties and cloud microphysics in a low-mountain region. For instance, they will study whether sub-cloud aerosol variability affect convective precipitation. The relation between cloud turbulence and condensation, coalescence, aggregation and thus precipitation is also addressed. Furthermore, the correlation between measurable aerosol properties and ice formation will be determined.

The **WG Precipitation Processes and its Life Cycle (PPL)** is investigating the role of orography for the development and organization of convective cells. A critical point is also the distribution of the condensed water into the different hydrometeor categories (cloud water and ice, graupel, snow, rain water) where large differences between mesoscale models have been noted. To study the development of graupel, hail and the drop size distribution of precipitation a combination of polarimetric radars, satellite observations, micro rain radars disdrometers will be used as well as observations supersites to study the onset of full precipitation from drizzle conditions.

The **WG Data Assimilation and Predictability (DAP)** is studying the impact of current and new observations for improving QPF. Data assimilation is the key to separate errors due to initial fields and parameterization, as the model can be forced to reduce forecast uncertainties due to initial fields by means of assimilation of the whole COPS and GOP data set. Therefore, data assimilation is an essential tool for process studies. Furthermore, using a variety of mesoscale models in combination with ensemble forecasting, studies on the predictability of convective precipitation shall be performed. A preliminary list of models to be applied within COPS is given in Appendix II.

Detailed investigations will focus on the processes at different stages in the life cycle of convection and convectively induced precipitation. These are complemented by intense data assimilation efforts, all of them being decisive for matching the goals of the COPS research topics.

6.1 Initiation of Convection

6.1.1 Relevant processes

Studies of convective initiation focused on specific initiation processes, such as thermally forced anabatic flow (e.g., Braham and Draginis 1960) due to differential heating depending on land use and orography, to orographic lifting of a high-Froude number current over a barrier (e.g., Banta and Schaaf 1987) and to leeside convergence (Chien and Mass 1997). Studies on the preferred locations for convection have shown various results ranging from on top of the ridge (e.g., Raymond and Wilkening 1982) to the sloped terrain to the surrounding lowlands (e.g., Kaltenböck 2004) and to spatial variations affected by low-level shear, prevailing flow, moisture and instability (e.g., Banta and Schaaf 1987; Calas et al. 2000).

Three conditions are needed for the initiation of convection: sufficient moisture at low levels, potential instability of the air mass, and vertical motion being forced thermally at the ground or dynamically by synoptic scale ascent and/or orographic effects. Basically three different initiations may be distinguished.

Convection over complex terrain ("COPS small scale target")

Land surface and boundary layer processes play a key role in differential heating of the Earth's surface and in moisture uptake by the lowest layers. In low-mountain regions, in particular orography triggers convection. The relevant scale of this type of convection is up to about 20 km in the horizontal and 0.5 to 2 hours in time. The process to be investigated is the development of convection over low-mountain ranges. This is a QPF-related process because rapidly growing deep convection is often accompanied by sudden heavy rainfall in a small area, which can result in flash floods and may cause severe damages.

Secondary-circulation systems, which develop during daytime in the larger valley systems are believed to be responsible for triggering of convection and subsequent precipitation. The 7-km LM version that uses the Tiedke scheme for convection parameterization does not correctly resolve the convection initiation forced by valley winds and consequently fails to predict precipitation correctly in time, amount, and location. This has been demonstrated in the northern Black Forest, e.g., with the data of the VERTIKATOR project.

Embedded convection at convergence lines and frontal zones ("COPS mesoscale target")

Another process responsible for the low forecast quality of precipitation especially in summer is embedded convection within convergence lines and frontal zones. Prior to a trough, direct thermal circulation systems develop, sharpening convergence lines and frontal zones. Enhanced instability gives rise to the formation of embedded convection, forming thunderstorms and squall lines with the risk of severe weather.

The scale of this process is between 20 km and 100 km. The numerical simulation of such a development with operational models is at date still challenging because of the limited scale of the process, the relatively fast development within a few hours and the coarse observation network. Therefore QPF is often very unsatisfactory in these cases. Figure 5.1 shows the conceptual model of the process. While under the cloud layer of a cold front associated with rainfall the daily temperature amplitude is quite weak, there is a prefrontal zone with clear sky and high incoming radiation resulting in high air temperatures. This causes the horizontal temperature gradient to increase significantly during the day. A thermal circulation develops while the wind, humidity and temperature fields are modified by soil variables. This gives reason for the triggering of embedded convection at the convergence line which can lead to the forming of squall lines. The precipitation and gusts accompanied with these features are heavy and, in most cases, so far unforeseen because even if the prediction of the convergence or front is correct, the smaller scale inhomogeneities in the fields of the relevant meteorological variables which are responsible for the convection generation are not recorded by the present operational network and are consequently not predicted by the models.

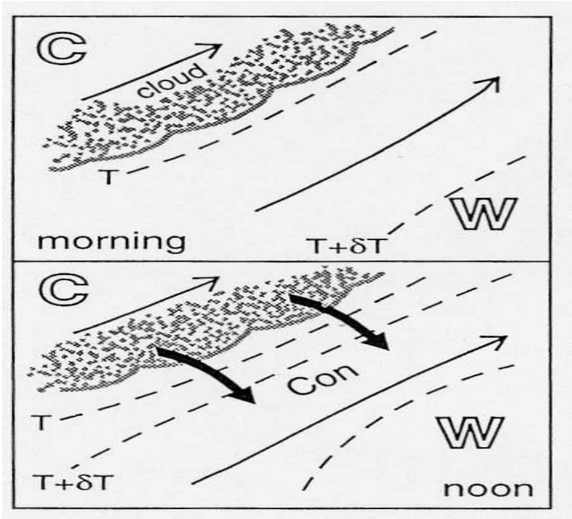


Fig. 6.1. *Conceptual model of the development of a thermally direct circulation pattern on the fringes of cloud and precipitation zones.*

Fronts in the temperature and moisture fields may initiate convection by baroclinically driven secondary circulations and vertical motion. Similarly, differences in the wind or flow field such as gust fronts and convergence lines cause mesoscale uplift. Besides single convection cells, such clouds also develop in special large-scale situations like on convergence lines or fronts. In those cases an ensemble of convective clouds like squall lines occurs. The evolution typically is more complicated, in particular transient, since cloud effects may interact with the environment letting new clouds appear or cease (e.g., triggering by gust fronts). Also larger cloud systems can develop which show a more or less organized structure as mesoscale convective systems lasting for hours and covering large areas (see also next subsection). In addition, all these phenomena are strongly influenced by orography.

Convection triggered by lifting within areas of potential instability ("COPS large scale target")

On a larger scale, at the transition zone between a ridge and a trough, lifting can be triggered by upper tropospheric divergence. If the lifted air mass is potentially instable, convection can be triggered very rapidly over a wide area. In this case, a large number of precipitation events with high amounts of rainfall of limited extent is typical. The scale of the area affected may be up to several hundreds of kilometers. LM simulations show that in such cases the rainfall starts too early on the day and again is too much area averaged. The process of triggered potential instability on the large scale often coincides with the very local scale of convection triggered by secondary circulations over mountain ranges (see above). Upper tropospheric forcing may arise from scale advection of vorticity, from approaching upper level troughs and Rossby gravity waves. Height dependent cold advection is a most relevant factor for an increase of CAPE and deep convection.

In either case, it turns out that an interaction between thermodynamic, hydrodynamic, and cloud-microphysical processes determines the temporal and spatial structure of convection entities. Thus, sophisticated measurements have to be made comprising the parameters, which are crucial to the evolution of first convective cells and their possible transformations. Some of these measurements can be made localized whereas advanced observations should be done following the tracks of convective clouds and precipitation patterns. Clearly, ambient as well as cloud-internal parameters should ideally be measured.

It is important to point out that these different CI mechanisms are closely related to the synoptic conditions (see section 4.3). Therefore, it is not necessary to develop different strategies to observe simultaneously large-scale conditions and the corresponding mechanisms of CI but they can easily be coordinated.

6.1.2 Scientific questions

The pre-convective conditions, the appearance and the development of convective systems shall be observed in all stages during their lifetime with ground-based and airborne instruments. These measurements can at-date only be carried out within a large field experiment like COPS. Based on surface, in-situ and remote sensing data, 4D data sets of all meteorological key variables such as water vapor, temperature and wind need to be acquired for testing the hypotheses of convection initiation, to validate models, and to identify deficiencies in mesoscale models. The CI component of COPS is dedicated to answer the following key science questions and to test related hypotheses:

- What is most relevant for the heterogeneity of the boundary layer fields of key prognostic variables (differences in soil moisture, surface parameters, vegetation, orography, etc.)?
- How are small-scale inhomogeneities of atmospheric humidity, temperature, and wind in complex terrain related to CI?
- How is the diurnal cycle of CI related to processes at the surface and in the boundary layer and why is the diurnal cycle of convection not represented adequately in the models?
- To which extent do gravity waves and mountain waves initiate or inhibit convection?
- Do aerosol particles influence convection initiation?

The latter question demonstrates the relationship between the WGs CI and ACM and the importance of the coordination of their measurements.

6.1.3 Required instruments and operation strategy

To match any of the objectives research instrumentation is essential in addition to data of existing operational instruments and networks (radars, radiosondes, rain gauges, lightning detection, synoptic weather stations). The data of the existing networks of DWD, Meteo France, MeteoSwiss, Flood Prediction Center Baden-Württemberg, and private weather consulting companies etc. shall be collected.

Supersites with continuous observations are needed to derive synergetic parameters from the combined set of data and to ensure the quality of the data by intercomparisons. They have to be set up near locations of highest probability for CI, which are known for the COPS low-mountain region where the locations of initiation of convection are rather confined. Scanning multi-wavelength remote sensing instruments for water vapor, wind, temperature, clouds, and aerosols need to be operated combined with energy balance stations, and at least one near-by upwind radiosonde station.

Domain scale measurements (200 km x 300 km) can be obtained at high resolution by airborne measurements with in-situ and with remote sensing instruments. Several types of aircrafts with ranges covering the different convective scales should focus on specific parameters as well on different altitude regions.

The operational weather radar network needs to be complemented with additional radars to achieve dual/triple Doppler radar capability. Additional radiosonde stations and dropsonde launches provide means of sensing the clouds interior and their environment. A network of mesonet stations accomplishes information on spatial inhomogeneity of near surface temperature and humidity.

Satellite remote sensing (in special observing modes for COPS) should allow for spatial extension of land-surface properties from in-situ measurements. High-resolution land use maps from satellites help to specify the lower boundary conditions.

The strategy for observations ideally comprises also flexible components for targeted observations. In addition to fixed sites also mobile observations could be made on the mesoscale, in cases for which model simulations show critical gaps in the data of the observational network. This can be achieved with mobile teams in the field which launch radiosondes and install met-masts within 30 minutes at locations of special interest.

6.2 Aerosol and Cloud Microphysics

6.2.1 Relevant processes and current representation of aerosol and cloud microphysics in weather forecast models

The formation of clouds and ensuing precipitation in the troposphere requires condensation nuclei in the form of aerosol particles. In the atmospheric range of water vapor supersaturations, the size and chemical composition of the particles strongly control the process of initial drop formation. As a third parameter the number of cloud-forming aerosol particles is crucial because of the competition amongst the growing cloud drops for the available water vapor. The initial phase of cloud formation may also be affected by soluble gases such as nitric acid, which can enhance the condensational growth (Kulmala et al., 1993).

Condensational droplet growth models predict a droplet size distribution, which is narrower than observed in warm atmospheric clouds. On the one hand, the numerical representation of the droplet size distribution and the treatment of the condensational growth process in the cloud models as well as instrumental effects may contribute to this discrepancy. On the other hand, besides numerical and instrumental effects, several secondary processes have been suggested to cause broad drop size distributions, e.g., very large hygroscopic aerosol particles (Woodcock and Mordy, 1955; Yin et al., 2000), entrainment of dry air into the cloud (Baker et al., 1980), varying updrafts (Warner, 1969) or turbulent processes (Almeida, 1976). The resulting broadened drop size distribution facilitates coalescence of drops of different fall speeds that may subsequently generate precipitation-size hydrometeors.

The formation of precipitation in mid-latitude clouds can be critically dependent on the formation of the ice phase (Bergeron, 1935). Aerosol particles with specific ice nucleating properties have been implicated for many years (Pruppacher and Klett, 1997). However, as opposed to condensational drop formation a host of nucleating processes leading to droplet freezing or new ice particle production is possible in atmospheric ice formation. After the initiation of the ice phase additional ice particle multiplication may occur through the so-called Mossop-Hallet process (Hallett and Mossop, 1974).

To date neither aerosol nor cloud microphysical processes are explicitly incorporated in operational weather models. In parameterized form, integral cloud parameters such as cloud liquid water (Pudykiewicz et al., 1992), solid hydrometeors, rain and aerosol cloud interactions are included in high resolution meteorological and climate models for research purposes (e.g., Beheng, 1994; Benoit et al., 2002; Lohmann, 2002; Jacobson, 2003).

All these processes are currently hardly represented in NWP models. However, first steps have been taken at ECMWF to develop the capability to improve the parameterization of aerosol-cloud interaction and to assimilate aerosol data. A similar approach is pursuit in the US in connection with the development of the WRF model (Skamarock et al., 2005), particularly the WRF-Chem module (Grell et al., 2005). Therefore, incorporation of aerosol measurements within COPS will make important contributions towards the development of NWP models, which consider more in detail the role of aerosols in cloud and precipitation development and evolution.

6.2.2 Sensitivity of QPF on cloud microphysics

There are a number of model studies about the possible aerosol influence on precipitation processes (Levin et al., 1996; Yin et al., 2002; Segal et al., 2004). In stratiform marine clouds, the effect of high inputs of aerosol particles on cloud evolution has been studied for a long time (Coakley Jr. et al., 1987). Radke et al. (1989) and Noone et al. (2000) presented results from aircraft and satellite measurements of ship tracks that showed a good correlation between the presence of high particle concentrations in ship plumes and increased cloud droplet concentrations. They also found that the Liquid Water Content (LWC) in ship tracks was often higher than in the ambient cloud, which they speculated was due to the suppression of drizzle formation. The issue of drizzle suppression has also been the subject of model studies (e.g., Baker and Charlson, 1990). Similar effects have been found for clouds forming in biomass burning situations. Owing to the high particle concentrations supplied by the fires, warm precipitation formation is believed to be suppressed in many cases and that precipitation, if at all, is formed by the ice phase. Several satellite-based investigations indicate a possible link between input aerosol particles, microphysical evolution of convective clouds and ensuing precipitation (Rosenfeld, 1999; Rosenfeld, 2000; Ramanathan et al., 2001; Rudich et al., 2003; Andreae et al., 2004).

6.2.3 Scientific Questions

For want of mechanistic and in situ studies the influence of the atmospheric aerosol on the initiation and evolution of convective precipitation is unclear. Critical gaps in our knowledge are due to instrumental limitations, e.g., the lack of in-cloud data on water vapor saturation or lack of process-specific instrumentation related to ice formation. Turbulent cloud processes are poorly understood (Vaillancourt and Yau, 2000). Furthermore a new generation of size distribution measurement techniques covering the full hydrometeor size range from initial droplets to ice particles and precipitation-sized cloud particles is missing.

The first and foremost questions in this section of COPS are very simple: **What is the role of aerosol particles in changing cloud microphysical properties and the initialization of convection? Does sub-cloud aerosol variability affect convective precipitation?** If it does not or only marginally, future weather forecast systems could be designed with much less microphysical efforts than presently foreseen.

The second question concerns the issue of ice formation. **Can we relate any of the measurable aerosol parameters to the occurrence and characteristics of the ice phase in the studied systems?** If we cannot, we would need to direct much more of future research towards ice forming properties of aerosol particles and towards ice forming processes in clouds in general.

A third question that is discussed in cloud physics concerns the possible effects of turbulent motions in clouds on the evolution of hydrometeors: **Does cloud turbulence promote condensation, coalescence and aggregation and thus precipitation?** To investigate this question very fine resolution observations of clouds (size and spatial distributions of droplets and ice particles, energy dissipation rates, temperatures, humidity fields etc.) are required (Vaillancourt and Yau, 2000).

Furthermore, attempts will be made to study the interaction of aerosol properties and the ice phase. We are asking: **Is there a correlation between measurable aerosol properties (e.g., depolarization) and ice formation? What statistical information about ice formation in COPS can we derive from present satellite sensors?**

6.2.4 Required instruments and operation strategy

COPS offers a unique chance to test hypotheses and model predictions concerning mechanistic connections between sub-cloud aerosol particles, cloud microphysical processes and precipitation processes. For that purpose a complete physical and chemical characterization including soluble and insoluble compounds of the input aerosol particles at cloud base (level 1) would be desirable. The same request would hold for the aerosol surrounding the investigated cloud systems (level 2) in order to understand the effects of entrained aerosols. Additionally, and of great benefit for atmospheric aerosol research would also be a full characterization of cloud-processed aerosol particles remaining after cloud dissolution (level 2) and aerosol particles vented from the tops of deep convective systems (level 3).

The full width and depth of aerosol instrumentation is neither available nor affordable at all three levels. Instead, it is suggested to set up at least one ground station (level 0) in that area of COPS where most likely orographically-induced convective systems develop. This site should be equipped with the complete range of state-of-the-art aerosol instrumentation (number size distribution dry and humidified; chemical composition; state of mixture of aerosol particles). Near that site state-of-the-art ground-based remote aerosol measurements should extend the surface aerosol data to level 1, and wherever not blocked by clouds, to level 3. These remote measurements should be complemented with Doppler-based remote aerosol flux measurements up to level 1. The Doppler measurements should be extended in terms of vertical wind as high up as possible outside clouds. Additional surface aerosol stations with less sophisticated instrumentation would be useful for estimating regional aerosol inputs in the COPS area.

Only a subset of the ground-based aerosol instrumentation can be deployed on airborne platforms reaching the upper levels 1 to 3. However, the airborne platforms need to include the full range of in-situ cloud instrumentation for interstitial size distribution, hydrometeor size distribution, in-cloud thermodynamic and dynamic parameters, including turbulence and phase distribution of the cloud water. At level 1, the size-dependent quantification of insoluble material in the input aerosol is important.

The collection of cloud water, ice, and precipitation samples with subsequent analysis should be made to search for connections between the characteristics of the input aerosol and subsequent formation of ice and precipitation.

6.3 Precipitation and its Life Cycle

6.3.1 Relevant processes

Convection starts when the stratification of the boundary layer is unstable or potentially unstable and there is a triggering mechanism like converging winds, elevated heating surfaces, up-sloping winds, or like gravity waves (Hauf and Clark, 1989). Cumulus clouds will form when the rising air parcel is reaching the condensation level and with the release of latent heat additional energy is provided for accelerated rising of the air parcel. Precipitation initiation in mid-latitudes normally requires the presence of ice particles, therefore the air parcel has to rise well above the 0 °C isotherm until ice particles can form.

Figure 6.2 shows the life cycle of a single thunderstorm cell (Höller, 1994). A typical time frame for such a cell is about 30 minutes to 1 hour. Single cells are observed if there are weak winds and if there is no or only weak vertical wind shear and the air of the cooler downdraft is falling into the region supporting the warm updraft air reservoir.

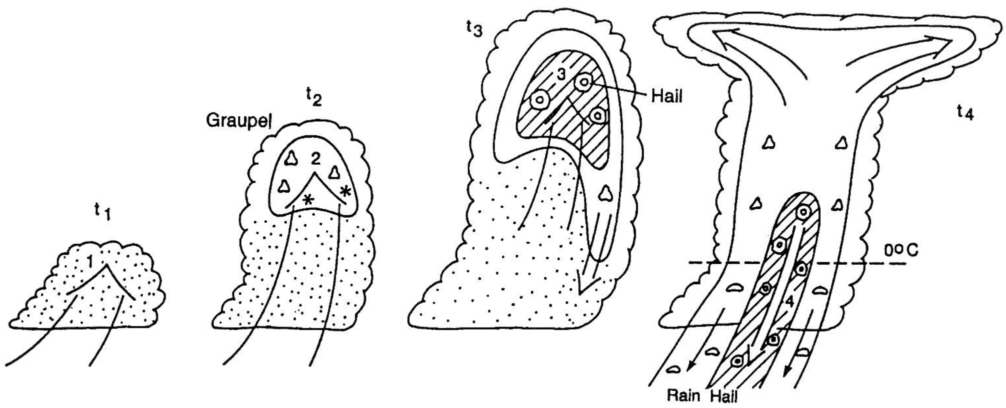


Fig.6.2. *Life cycle of a single cell (Höller 1994).*

Temporally short rain showers occur if there is an inversion layer at heights below about the -15 °C isotherm (t_2, graupel phase, see Fig. 6.2), which suppresses updrafts, or if the updraft energy is not sufficient to reach time step t_3 or t_4, in this case the precipitation observed at ground is melted graupel.

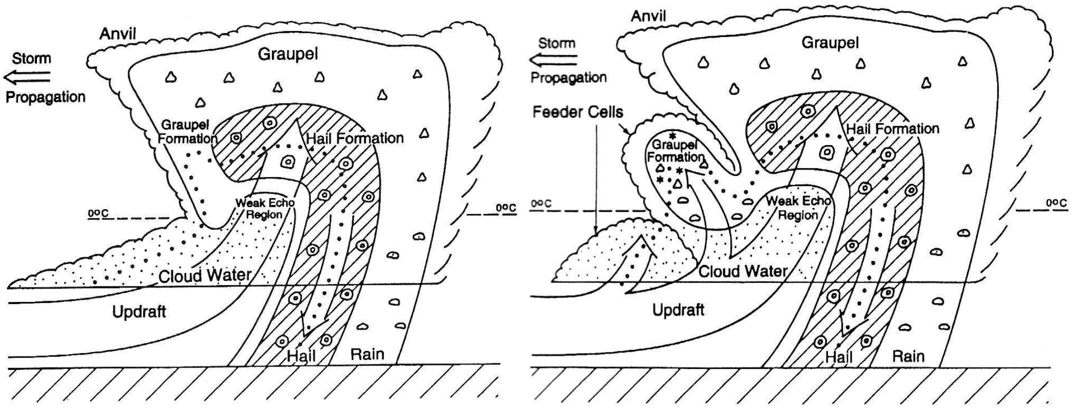


Fig.6.3. *Schematic structure of a multi-cell (left) and a super-cell (right) thunderstorm (Höller, 1994).*

If wind shear is present, multi-cell or super-cell structures can organize. Both kinds of systems can live for several hours. The systems move with the wind speed and direction of mid-troposphere height levels (app. 5 km) towards new warm air reservoirs, which are also advected with the low-level winds.

Figure 6.3 shows the schematic structures of a multi-cell and a super-cell. While a multi-cell consists of several connected cells at different stages of their life cycle, a super-cell is one single cell, which has a continuous updraft and downdraft region.

Convective cells are not only observed as isolated cells as described above, frequently mesoscale organizations or clusters are observed. Houze et al. (1993) listed several structures, which were observed in the Swiss radar composite and can also be observed in southern Germany. The authors state that environmental wind and thermodynamic stratification are interfered to be the primary factors, which determine the storm structure. However, the environment supports multiple storm structures, and those storm modes selected by nature at a specific time and location may be determined by very subtle local effects like the perturbation of the low-level hodograph. Such local variability of the winds is likely related, directly or indirectly, to orography (Houze et al., 1993).

Observations in Southern Germany (e.g. Hagen et al., 1999; Hagen et al., 2000) show that such mesoscale convective systems, as well as super- or multi-cells, can live for several hours and can propagate during that time for several hundreds of kilometers. This holds especially for large systems like squall lines. They are normally related to cold fronts, but develop well ahead of the front (50 -200 km). It is the prefrontal south-westerly flow with warm and humid air at low levels and prevailing cold air in upper levels, which destabilizes the prefrontal air mass and favors the development of organized deep convection (e.g. Meischner et al., 1991, Haase et al., 1997).

6.3.2 Microphysics of convective precipitation

In convective precipitation, hydrometeors exist in the form of rain, graupel, or hail. Additionally, in the stratiform region of mesoscale convective precipitation systems, also hydrometeors like dendrites and aggregates are observed. Normally in mid-latitudes the initiation of precipitation is through the ice phase. Graupel forms from super-cooled cloud droplets freezing on to an ice nucleus in a convective environment (i.e., high updraft winds) and later melts to raindrops. The growth of hail is more complex and requires the presence of super-cooled water droplets, which accumulate around graupel (see Figs. 5.1 and 5.2). This requires high updraft velocities exceeding the fall velocity of graupel. For the further growth of hail, a re-circulation through melting of the particle and freezing again is necessary. Associated with this re-circulation is the further accumulation of water by the particle.

6.3.3 Dynamics of convective precipitation

While single cells occur in an environment with weak winds and low wind shear, other organization of convection can only exist in an environment with wind shear. As mentioned above, wind shear is responsible to support long-living systems. Due to tilting of the vertical wind shear in the updraft region, rotation within the convection is created. Severe rotation is most visible within a tornado, but rotation is also responsible for the propagation of the storm relative to the environment (e.g. Houze et al., 1993). Rotation leads to cell-splitting and cell-merging. Understanding these processes is essential for successful nowcasting of thunderstorms by extrapolating radar observations. Besides rotation, strong winds are observed in the downdraft region of storm cells. The downdraft is enhanced by cooling, by melting, and especially by evaporative cooling. When hitting the ground, divergent outflow is observed, leading to damages, but also to the triggering of new convection at the leading edges of the gust fronts. These out-flow gust-fronts are observed up to 100 km from the storm.

6.3.4 Scientific questions

Most observations of deep convection have been performed in relatively flat terrain. It is today still open to which degree orography influences the evolution of convective cells. It has been observed that orography can trigger the development of cells, however, it is open whether convection is suppressed in the subsiding flow in the lee of hills. It is assumed that the life cycle of single cells can be modulated by orography, but it is open whether medium-high mountains like the Vosges Mountains or the Black Forest have a significant influence on the formation and propagation of multi- or super-cells or even mesoscale organizations. How significant is this influence if the cells have been already formed before they interact with orography? Another open question is the role of embedded convection triggered by topography. Formerly stably stratified precipitation clouds may be destabilized by the forced uplift through mountains. Finally, it is strived for detailed understanding of the distribution of precipitation in low-mountain regions in order to address and to remove the windward/lee problem.

6.3.5 Required instrumentation

Various field campaigns have been performed to understand microphysics and dynamics of deep convection. But only with advanced radar techniques like polarization diversity and multiple-Doppler radar it was possible to retrieve a 4-dimensional image of the hydrometeor distribution and the flow within a thunderstorm cell. The development of hydrometeor classification schemes for polarimetric radars (Höller et al. 1994, Vivekanandan et al. 1999) gave new insights into the microphysical processes of graupel and hail formation. The classification also allows for the separation of snow particles from small graupel, and hence the separation of regions where convective or stratiform precipitation initiation processes dominate. The retrieval of raindrop-size distribution from polarimetric radar observations (e.g. Seliga and Bringi, 1976; Zang et al., 2001) can provide additional information on the underlying microphysics governing the initiation of precipitation. Additionally, polarization diversity allows for a more accurate estimation of the rain rate. The high variability of the relation between rainfall rate (R) and reflectivity (Z) (termed as Z-R relation) as it is observed with conventional radars is considerable reduced when polarimetric radar parameters are used additionally (e.g. Seliga and Bringi, 1976, Vivekanandan et al., 2004).

From the radar systems operated by meteorological services in the COPS region, only the radar at Montancy will be polarized in 2007. Thus, it is highly beneficial to increase the number of polarimetric radars during COPS to observe the prevailing hydrometeors and to be able to monitor the formation of rain, graupel, or hail in the updraft region of the convective cell. Additionally observations with a 3D lightning detection system would enable a confirmation of the assumptions associated with the electrification of the cell, which is according to the current understanding only possible with the co-existence of graupel and water droplets.

Weather radars cannot only detect precipitation, there are numerous examples where the radars observe signals from the precipitation-free atmosphere. These signals are termed “clear-air echoes” and have their origin in insects and Bragg-scatter due to turbulent gradients of the temperature and humidity field. The signal is normally strong enough to be observed in the boundary layer during daytime in summer. By clear-air echoes it is possible to retrieve dynamic features of the boundary layer, like convergence zones in the pre-storm environment.

For observations of convective precipitation weather radars are best suited. No other instrument is able to cover the complete 4D life cycle with high temporal (some minutes) and spatial (some kilometers) resolution. National and international networks of radars allow now to cover the huge area of large mesoscale precipitation systems with dimensions of several hundreds of kilometers. Since meanwhile almost all radars in Europe are Dopplerized, the dynamics of convective cells can be observed directly. If more than one radar observes the same area a multiple-Doppler analysis can be performed to retrieve the 3D flow within the precipitation. The resolution and the accuracy of the retrieval can be enhanced if additional radar systems like mobile radars or bistatic radar networks are deployed.

However, as pointed out above, for advancing significantly the understanding of convective systems, additional observations of the environmental conditions are indispensable. Therefore, 4D observations of the clear-air environment of these systems are essential, e.g., the temperature, humidity and wind fields. Additionally, an extension of these measurements in the non-precipitating regions of clouds is required. To complete the observations, measurements from remote sensing systems can be used to observe the profile of humidity and the liquid-water path in the environment of convective precipitation systems. Therefore, the measurements of the WG PPL have to be strongly coordinated with WGs CI and ACM.

Another exciting capability of radars is the possibility to retrieve the humidity fluctuation field close to the surface with a technique proposed by Fabry et al. (1997). However, up to now the required precision of phase measurements of backscattered radar signal can only achieved with a phase-stable klystron transmitter. Those radars are not available in Central Europe. Therefore, the deployment of the S-Pol radar operated by UCAR will be very beneficial for COPS. Impressive observations were shown in Weckwerth et al. (2005) during the IHOP_2002 campaign. A proposal for the deployment of the NCAR S-Pol radar during COPS is in preparation and will be submitted to NSF in autumn this year. Furthermore, it is essential to extend the radar coverage in complex terrain with mobile systems. Therefore, also two Doppler-on-Wheels (DOWs) will be requested via another NSF proposal. Also this type of mobile radar is only available in the US.

Besides weather radars additional instrumentation is necessary to study precipitation processes and the life cycle of convective systems. First of all a dense network of rain gauges will help to adapt the rain estimates by radar to the amount of precipitation observed at ground. Of considerable interest is the observation of the raindrop size distribution (RDSD) at the surface and above. Surface measurements can be performed by different kind of disdrometers, while measurements above can be performed by vertical pointing Doppler radars. The use of polarimetry to improve rainfall rate estimation by radar or to classify the precipitation particles requires the knowledge of the shape and the falling behavior of the particles. This can be accomplished via the recording of holographic images of particles.

6.4 Data assimilation

6.4.1 Introduction

Data assimilation poses one of the most pressing challenges in the forecasting of severe weather and especially for QPF. Indeed in the case of cumulus convection "*data assimilation, in the overall process of forecasting convective precipitation, may be the most critical path through which the pace of forecast advances will be modulated*." (Fritsch and Carbone, BAMS 2004). While forecasting of convective precipitation shares the general difficulties of weather prediction in general, it has particular aspects that make data assimilation difficult. The most notable of these come from the rapid timescales of the precipitation formation processes, both microphysical and dynamical, which are often short compared to the forecast lead time. Within the forecast period, the evolution of the system becomes highly non-linear, and may pass well beyond the limits of deterministic predictability. The (tangent) linearity assumption that forms the basis of variational methods, the current state of the art, are less easy to justify here than for medium-range forecasting of mid-latitude cyclones. The relative roles of fast and slow processes in the atmosphere in determining the predictability of convective precipitation thus determine, which data assimilation algorithms are appropriate, as well as what data is most relevant.

The use of high-resolution remote sensing data, including radar, lidar, and satellite observations, particularly of water vapor, clouds, and precipitation, provides a major opportunity for improvement in the analysis of the atmospheric state. At the same time it raises difficulties, since the forecast may depend very strongly on parameterized processes, including cloud microphysics or convection (depending on model resolution), which are not well modeled and may be accounted for in the data assimilation scheme in a very simplified manner. Model error becomes an essential part of the problem, and error characteristics for the new observation operators and control variables must be determined.

A major change in numerical weather prediction is currently underway, with the introduction of models with resolutions of a few kilometers down to 1 km, which explicitly resolve deep convection. The removal of a very problematic parameterization is attractive, but the need for high resolution on large model domains makes data assimilation expensive. This combined with the probabilistic nature of the prediction problem makes ensemble-based methods attractive but there is currently little experience and a need for new methods to be explored.

It will not be possible to conduct a rigorous evaluation of all data assimilation techniques in the context of a short observational campaign, but the ability to directly compare an unusually wide variety of operational and experimental methods with existing and new data sources will provide strong indications of the most promising approaches for extensive, long-term trials.

6.4.2 Scientific questions

The COPS planning workshops identified the following principle scientific questions to be addressed by data assimilation experiments:

1. Is there an obvious impact of COPS measurements on model forecasts?
2. If reasons for lack of positive impact can be identified, can a better measurement strategy be devised?
3. Which assimilation systems handle the data best, and which may be practical for real-time use (nudging, 3DVAR, 4DVAR, ensemble-based)?
4. Is such a system a valuable tool to support mission planning?

6.4.3 PQP data assimilation projects and methodology

PQP includes three projects aimed at developing new data assimilation capabilities, and a fourth exploring new forecast validation methods. All of these are participating in the planning of the field experiment and intend to conduct trials using the data.

a) SRQPF: The goal of this project is to demonstrate the impact of new observations on the quality of short-range forecasts. Particularly, water vapor, temperature, and wind lidar as well as GPS slant path measurements will be assimilated. Different assimilation schemes will be compared including nudging, 3DVAR, and 4DVAR. This capability is currently only available in the MM5 model (Grell et al., 1995). Of course, other routine data sets from in-situ sensors and radar observations will also be assimilated simultaneously. It will be tested what improvement of mesoscale initial fields with this approach can be achieved. In the final phase of PQP, a unique ensemble forecast system where the most advanced clear-air thermodynamic measurements are assimilated shall be developed for the research and user community focusing on short-range and nearly medium-range forecasting.

b) DAQUA

Methods for short-range quantitative precipitation forecasting using a regional high-resolution weather forecast ensemble. Improved regional ensemble modeling will be combined with best member selection based on the most recent remote sensing information, with further broadening and narrowing of the distribution by a new evolutionary approach, followed by improved data assimilation and further forecast integration. A key part of this process is the introduction of a Monte Carlo technique to invert the highly nonlinear and critically discontinuous microphysical problem in a novel way in cloud and rain assimilation. Physical initialization techniques, nudging techniques and variational approaches with the timeliest available information from remote sensing including radar reflectivities, cloud parameters, and water vapor content will be employed.

With this stacked procedure we expect to substantially reduce the influence of phase errors in the background field, which currently impede the successful assimilation of observations for short-range precipitation forecasting by regional numerical weather forecast models. The project will establish an advanced capability for ensemble forecasting in the German research community. Validation efforts will explore and quantify the sources of uncertainty in forecasts especially under convective conditions. The differing requirements for the forecasting system under different meteorological conditions will be explored in the first instance by examining a set of case studies of convective storms in environments with orography of varying degrees of steepness. The case studies will be orientated around the likely location of the field experiment, to aid in planning of the operations and to prepare for real-time forecasting.

c) PROB-QPF

This project will set up an ensemble forecast system for 3-5 day QPF, based on the global model GME using the breeding technique. With an ensemble forecasting system available, the covariance matrix of the first guess can be estimated from the spread of the individual realizations, using Ensemble Kalman filtering which will be implemented together with the 3DVAR analysis of DWD currently under development. The complete system will be validated first by using standard scores from the literature on single observations and averages for catchments. Standard scores will be extended through a new method from geostatistics to account for the spatial representativeness error. Having set up this system, new ideas in validation and Ensemble Kalman filtering arising from a Bayesian view of the statistical problems will be applied.

The participation of the meteorological services of several neighboring countries has been confirmed, including France and the participants in the forecast demonstration project (FDP) of the Mesoscale Alpine Programme (MAP) D-PHASE (see section 5.2.2).

7 Measurement Strategy

7.1 Ground-based Systems

7.1.1 Overview

This section describes the possible strategy of ground-based instruments to measure the relevant atmospheric and surface parameters. In many cases the instruments have to be combined in order to allow new understanding. This *sensor synergy* is described in section 7.4. Table 3 gives an overview of the required ground-based instruments, categorized over the four key scientific areas that are described in chapter 6: CI, ACM, PPL, and DAP.

Apart from the instruments, Table 3 also shows the required spatial coverage needed: areal coverage and/or vertical profiles, which will result in requirements for the scanning mode of the instruments.

7.1.2 Observation strategies

Rainfall is a time-varying, spatially distributed phenomenon, influenced by local land-atmosphere interaction and terrain heterogeneities, entailing physical processes over a large span of scales: temporally as well spatially. The observation strategy has to aim at capturing the development of these physical processes on all relevant scales. This leads to the following considerations regarding the ground-based observations strategy.

- Scanning systems like a weather radar, or networks thereof, are needed to cover large areas for the observation of trajectory and evolution of rain cells. The scanning modes should not only aim at the horizontal distribution of rainfall, but also at its vertical structure. Hydrometeor identification is very important to understand the microphysical processes. This can only be achieved with polarimetric radar systems.
- Cloud microphysical processes at small scales cannot be observed with scanning weather radars. To capture the processes, continuous vertical profiling is needed. For this a combination of co-located, ground-based sensors is crucial to obtain vertical profiles of the (microphysical) cloud

structures, be it water, ice or mixed-phase clouds. The prime instruments to achieve this are cloud radar, lidar, and multi-channel microwave radiometers. To study local terrain influences on cloud formation, several sites should be installed with the minimum set of instruments: cloud radar, lidar, and radiometer.

- Initiation of convection is closely related to surface properties, like vegetation and soil moisture as well as to inhomogeneities in the field of key atmospheric variables such as wind and water vapor. The spatial variability of land surface properties dictates the need for observations with sufficient spatial coverage. Scanning weather radars are able to observe horizontal patterns of convection in the boundary layer, however, they provide no direct observations of prognostic variables in NWP models. Details of horizontal and vertical structures can be obtained with a combination of sensors like water vapor, Doppler, and temperature lidar, FM-CW profilers, RASS, and GPS. This setup is also needed for the observation of aerosol activation.
- The ground observations should be carefully matched with experiments that are done from the aircrafts. This is a difficult but crucial task, in order to avoid the situation of incompatibility of data due to non co-located observed areas. During aircraft flights, ground-based equipment may be setup in different modes than during the 'operational' periods during the campaign.
- In several cases, retrieval algorithms require additional input. This can come from ancillary instruments or NWP models (see also Table 3).

Radiosondes are very important to capture profiles of temperature, humidity, and wind beyond the heights were remote sensing instruments can require accurate data. Besides the regular routines, additional intensive radiosonde launches need to be requested.

Table 3: *Overview of required ground-based instruments; although each key area has its own specific requirements, an efficient setup of the instruments will be designed to avoid unnecessary overlap of instruments.*

Initiation of convection		
Spatial information needed: areal coverage; vertical profile: scanning instruments, networks, pointing instruments		
Physical quantity	**Instruments/Data source**	
Water vapor field	DIAL, Raman lidar, GPS network, microwave radiometer	NWP
Synoptics	Radiosondes	NWP
3D wind profiles	Doppler lidar, wind profiler	
Temperature profiles/fields	Rotational Raman lidar, RASS, radiosondes, microwave radiometer, FTIR	NWP
Surface energy fluxes	Scintillometer, in-situ instrumentation, (FM-CW) wind profiler	
Soil moisture	TDR	
Spatial distribution PBL convection	Weather radar, FM-CW radar	

Aerosol and cloud microphysics		
Spatial information needed: detailed vertical profiling at several sites; co-located pointing instruments		
Physical quantity	**Instruments/Data source**	
Aerosol properties	Lidar, especially Raman lidar; Sun photometer	
Cloud properties	Cloud radar, lidar, microwave radiometer	
Cloud dynamics	Cloud radar, wind profiler, weather radar	
Water vapor field	DIAL, Raman lidar, GPS network, microwave radiometer	NWP
Temperature profiles/fields	Rotational Raman lidar RASS, radiosondes, microwave radiometer	NWP
Aerosol size distribution and hygroscopic properties	DMPS, SMPS, HTDMA, ground-based aerosol container, Partenavia, ACTOS, Cessna	
Cloud drop size distribution, Liquid water, Cloud temperature, cloud turbulence spectrum	Drop spectrometer, CVI, Particle Volume Meter, Cloud thermometer, Sonic, Partenavia, ACTOS	

Precipitation and its life cycle		
Spatial information needed: areal coverage; vertical profile: scanning instruments, networks		
Physical quantity	**Instruments/Data source**	
Rain geometry	Weather radar	
Hydrometeor classification	Polarimetric weather radar	
Rainfall rate	(Doppler)(Polarimetric) weather radar, rain gauges, disdrometers	
Dynamics	Doppler weather radar	
Non-precipitating clouds	Cloud radar, lidar	
Vertical structure of rain	Cloud radar, micro rain radar, (Doppler)(Polarimetric) weather radar	

7.2 Airborne Systems

It is very clear that COPS would benefit greatly from the participation of a number of airborne instruments that could provide measurements of water vapor, aerosols, clouds, winds, and precipitation over the spatial domain of this field experiment.

Furthermore, an airborne cloud radar would be very beneficial for tracking a developing convective system. To best accomplish the COPS objectives, it would be most optimum to have three different aircraft flying at different altitudes and covering different horizontal scales of sampling to obtain the pre- and post-convection meteorological fields across the COPS domain. A low altitude aircraft (<1 km) could be used to obtain the boundary layer moisture distribution with a horizontally pointing lidar. A medium-altitude aircraft (~4 km) could obtain the moisture and wind fields, respectively, and a high-altitude aircraft (>6 km) could obtain the moisture and wind fields over the largest area of the COPS domain. Since the funding for the participation of any of these instruments and aircraft will have to come from sources external to COPS, the actual measurement strategy employed during COPS will depend on which instruments and aircraft get funded to participate. Several aircrafts have been requested and are subject of the DFG PP1167 COPS proposal. These include aircrafts and helicopters for remote sensing of water vapor and wind, measurements of atmospheric turbulence and of aerosol microphysical properties.

7.3 Satellite Systems

7.3.1 Overview of satellite remote sensing systems

Recently launched satellite systems allow observations of the earth at significantly increased spatial and temporal resolution which, e.g., enables the observation of the diurnal cycle of the atmospheric system and resolves small scale features like convective cells.

Currently, three satellite systems allow operational remote sensing of the atmosphere: the SEVIRI instrument onboard Meteosat-8 (MSG), the Moderate Resolution Imaging Spectroradiometer MODIS onboard TERRA and AQUA, and the Medium Resolution Imaging Spectrometer MERIS onboard Envisat. Meteosat-8 is a geostationary satellite positioned at 0° longitude and latitude. It provides a full disk image of the earth every

15 minutes with a nadir resolution of ~3 km. The resolution over Europe is about 5 km. SEVIRI provides radiance measurements at 11 spectral channels covering the solar and infrared range (0.6 – 13.4 μm). SEVIRI is well suited for atmospheric studies with its high temporal and moderate spatial resolution and coverage. TERRA and AQUA (MODIS) are polar orbiting satellites with a descending and ascending mode, respectively. The duration of a full orbit is approximately 90 minutes, which results in a complete coverage of the earth every 1-2 days. The spatial resolution depends on wavelength and varies between 0.25 and 1 km. MODIS conducts measurements in 36 channels between 0.4 and 14.3 μm. Envisat (MERIS) is also a polar orbiting satellite in an ascending mode. The 15 spectral channels of MERIS, which are located in the visible and near infrared, are programmable and measure with a spatial resolution of 0.3 km. Global coverage is reached every 2-3 days.

For the 2007 COPS field campaign, satellite support will come by way of four main components:

1) Measurements of atmospheric variables such as integrated water vapor, land-surface properties and cloud properties.
2) Satellite-derived soundings that assess regional atmospheric stability (e.g., lifted index, convective available potential energy, CAPE).
3) A geostationary satellite-based algorithm that provides 0-1 hour forecasts of convective initiation 24 hours a day.
4) Probability indices that combine various satellite, land-surface and numerical weather prediction (NWP) model fields to assess convective initiation in the 1-6 hour timeframe. A fourth component provided via satellite information for COPS is a capability of satellite-based lightning prediction. The following sections describe in detail this satellite support for COPS.

7.3.2 Land surface, water vapor, and cloud measurements

The setup of the three satellite-borne instruments SEVIRI, MERIS, and MODIS allows for remote sensing of various atmospheric parameters. Besides cloud optical thickness, MERIS and MODIS provide measurements of the integrated columnar water vapor (IWV) from backscattered solar radiation measurements (Bennartz and

Fischer, 2001 and Albert et al., 2001), both over clouds and land surfaces. In case of MERIS, the retrieval of IWV is also possible over ocean due to surface wind speed measurements. Utilizing the oxygen A-band absorption, cloud top pressure is derived from MERIS observations (Preusker et al., 2004). These products are well documented and validated and used in several ongoing studies. In particular, efforts had been undertaken in using IWV from MODIS for data assimilation in a numerical weather prediction model. Using a window channel and a channel affected by liquid water absorption, droplet number concentration N, geometric cloud thickness H, liquid water path LWP, and effective radius r_{eff} are retrieved from MODIS measurements (Brenguier et al., 2000 and Schüller et al., 2003). These products are reliable only if retrieved over warm boundary layer clouds. The MERIS products are provided with a spatial resolution of 1.0 km, for selected case studies with a spatial resolution of 0.3 km, while MODIS products have generally a spatial resolution of 1 km. A cloud mask and near true color images (tci) are generated for SEVIRI, MODIS, and MERIS. All products are processed on a near real time basis and accessible via internet at http://wew.met.fu-berlin.de/nrt/. The products are summarized in table 4.

SEVIRI is equipped with channels in the NIR and IR which are sensitive to cloud properties and atmospheric water vapor. The IWV retrieval from SEVIRI and its validation is currently under progress. The retrieval utilizes several IR channels affected by various degrees of water vapor absorption. The product will be available for cloud free pixels during day and night and current validation efforts are carried out. Utilizing CO_2 absorption at 13-14 μm, cloud top pressure and cloud top temperature will be derived. Brightness temperature differences at thermal emission wavelengths will form the basis for the determination of cloud top phase. A combination with cloud top temperature can help identifying super-cooled water clouds. The MODIS retrieval scheme for N, LWP, H, and r_{eff} will change to be applicable to SEVIRI observations. It will be extended to allow a retrieval over land surfaces. The surface albedo information will be taken from regular MODIS products. Using the cloud phase determination, one of two algorithms will be activated to estimate cloud optical thickness, N, H, LWP, and r_{eff} in case of water clouds and effective ice diameter in case of ice clouds. The potential of retrieving properties of mixed phase clouds will be studied. A day and night time retrieval of LWP and r_{eff} will be realised, however, during night only for small LWP, because of saturation effects in the thermal infrared. The potential of estimating precipitation will be investigated and will be based on the cloud top phase, temperature and pressure, LWP as well as r_{eff} retrievals.

The products of the three satellites provide a well-validated, reliable long-term data set of IWV and cloud products. The near real processing allows a fast access to the products and makes it highly valuable for observation periods and assimilation in numerical weather prediction models. The high spatial resolution of MERIS in combination with the high temporal resolution of SEVIRI is perfectly suited to investigate the dynamic evolution of water vapor and cloud fields. The analysis leads to a better understanding of underlying physical processes and helps identifying problems related to numerical weather prediction.

Table 4: *Atmospheric variables retrieved with space-borne sensors*

Instrument	**Product**	**Details**
SEVIRI / Meteosat-8	1) tci, cloud mask 2) cloud top pressure 3) r_{eff}, LWP 4) IWV	*http://wew.met.fu-berlin.de/nrt* 3) only for clear sky
MODIS / TERRA	1) tci, cloud mask 2) cloud optical thickness 3) N, H 4) r_{eff}, LWP 5) IWV	3) over oceans and warm boundary layer clouds 4) for all clouds 5) over land and cloud *http://wew.met.fu-berlin.de/nrt*
MODIS / AQUA	similar to MODIS / TERRA	
MERIS / Envisat	1) tci, cloudmask 2) cloud optical thickness 3) cloud top pressure 4) IWV	4) over land, ocean, and cloud

7.3.3 Measurements of atmospheric stability

Geostationary satellite sounders are able to provide regional calculations of convective stability parameters (lifted index and convective available potential energy (CAPE)) at hourly temporal resolution (Menzel et al, 1998). Meteosat Second Generation (MSG) can provide satellite-derived soundings that access this regional atmospheric stability, which should play an important role in nowcasting the convective potential in the orographic area of interest for COPS.

In addition to geostationary satellite capabilities, MODIS instruments are available to provide higher spatial resolution stability indices but at less temporal resolution. Polar orbiting hyperspectral resolution satellite (IASI, CrIS, AIRS, etc.) information will be routine by 2007 providing much higher vertical resolution profiling capabilities in clear sky environments (when maximum destabilization is occurring). The new infrared sounding capabilities will provide better estimates of cloud top altitude, inversion intensity, and vertical water vapor distributions.

7.3.4 Very Short-term Convective and Lightning Initiation Predictions

The convective initiation (CI) nowcasting algorithm of Mecikalski and Bedka (2005) identifies the precursor signals of new thunderstorm development in sequences of 5- and 15-min time resolution 1 km visible (VIS) and infrared (IR) imagery from geostationary satellites. This method has been developed and tested with GOES data, and by 2007, will be developed for the Meteosat Second Generation (MSG) instruments (in particular, MSG-2 and MSG-3), as well as to take advantage of periodic MODIS imagery from AQUA and TERRA. Using this algorithm, CI may be forecasted up to 45 minutes in advance through the Lagrangian tracking (see Bedka and Mecikalski 2004) and monitoring of key IR temperatures/trends for convective clouds, and up to 60-minute lead times in certain convective regimes. Predictability limitations of this algorithm are ~1 hour, as cumulus clouds evolving for longer periods often do not grow to initiate rainfall.

Very short-term CI forecasting is made possible by first interpolating all IR data to the VIS resolution and projection, second by locating only the clouds capable of initiating rainfall within GOES/MSG data through using the cumulus cloud mask at 1 km resolution, third by performing several multi-spectral IR channel differencing techniques to identify cumulus in a pre-CI state, and finally by utilizing combined VIS and IR satellite-derived atmospheric motion vectors (Bedka and Mecikalski 2004) as a means of tracking individual cumulus clouds in sequential imagery to estimate cloud-top trends. In effect, the nowcasting techniques isolate only the cumulus convection in satellite imagery, track moving cumulus convection, and monitor their IR cloud properties in time. CI is predicted through the accumulation of information within a satellite pixel that is attributed to the first occurrence of a ≥35 dBZ radar echo as obtained from WSR-88D mosaic data. These data are currently being demonstrated within the AutoNowcaster system at the National Center for Atmospheric Research (Mueller et al. 2003) as value-added "interest field" information for CI prediction.

MSG will provide the Mecikalski and Bedka (2005) algorithm opportunities to demonstrate the use of 3 km resolution channels 1.6 μm, 3.9 μm, 7.3 μm, 8.7 μm, 9.7 μm, channels not currently available on GOES, for assessing cloud growth and microphysical changes. Use of 1 km, high-resolution visible (channel 12) data will help develop for MSG a "convective cloud mask" (Nair et al. 1998; 1999). This mask is formed from the Nair et al. technique is an pseudo-unsupervised statistical clustering methodology that isolates only convective clouds in various stages of development (i.e. "fair weather" cumulus, towering cumulus, cumulus with new and old anvils), as well as provides statistics of the cloud field (e.g., size distributions on regional scales), to allow the CI algorithm to subsequently operate only on those pixels. This in effect speeds processing for 0-1 hour CI forecasting as only the 10-30% of cumulus pixels within MSG infrared images are in turn processed, leading to real-time processing over large domains (15 minutes over a region the size of Europe).

In addition to GOES (GOES-10 and –12), MODIS data is being developed within this methodology as a means of providing enhanced convective cloud information to that already provided by the GOES convective cloud mask. The methods already developed for MODIS will be immediately transferable to MSG given that the ~1.6 μm and 8.55 μm MODIS spectral bands, found useful for assessing cloud-top glaciation and microphysics, are also available on MSG.

For COPS, this CI forecasting capability could help provide critical lead time, ahead of that available from ground-based Doppler radar systems. This forecast information would therefore help tune surface instruments deployments, guide mobile mesonets, and focus attention on likely (versus unlikely) regions for CI as daytime heating progresses. Once convection has developed in a location, the CI forecasting will provide COPS scientists information on where new convection is forming in relation to existing thunderstorms, and on the vigor of the convection. The Mecikalski and Bedka (2005) algorithm effectively and optimally isolates cumulus with strong, wide updrafts, which may be used to ascertain upscale growth, lightning and rainfall potentials.

7.3.5 1-to-6 hour CI Probability Indices

A CI Index can be designed to consolidate valuable information in satellite, land-surface (vegetation, soil moisture, topography), and NWP fields that describes the likely locations of CI as daytime heating progresses. The CI Index therefore has been developed in regions similar to those of the COPS field campaign in Germany by researcher at the University of Alabama and EUMETSAT.

The CI Index is designed to assess via probabilities for the occurrence of deep convection based on the understood conditions for convection based on environmental conditions on a given day. It is expected that the Index will provide valuable probability forecasts at lead times beyond the 0-1 hour forecasts. As the CI Index is designed to assess the effects of topography on CI, is should complement COPS program objectives.

7.4 Sensor synergy

The previous sections have shown the capabilities of current sensors for observing a multitude of atmospheric parameters. However, it is even possible to extract more parameters by exploiting the complementary information of different sensors as the interaction of atmospheric constituents with atmospheric radiation changes with wavelength (e.g. microwave, infrared and solar range). For this reason efforts have been made to combine measurements from different instruments as well for ground-based observation as for satellite missions or even the combination of both. To exploit the sensor synergy it is crucial to align the instruments with each other and sample the atmosphere in a synchronized way, as the observation target is highly variable in time and space. This is best realized by ground-based systems with vertical pointing direction or by simultaneous scanning systems. The potential of sensor synergy is depicted in Fig. 7.1.

7.4.1 Ground-based sensor synergy

In order to observe the atmospheric state as completely as possible ground-based atmospheric observatories compile a large number of advanced remote sensing and in situ sensors. Examples are the Cloud and Radiation Test beds (CART) of the Atmospheric Radiation Measurement (ARM) program in the Southern Great Plains, the Tropical Western Pacific, and the North Slope of Alaska as well as the Coordinated Enhanced Observing Period (CEOP) reference sites like Cabauw or Lindenberg. Major efforts to develop and apply synergetic algorithms for European observatories have been made in the EU projects Cloudnet (http://www.met.rdg.ac.uk/radar/cloudnet/) and CLIWA-NET (Crewell et al., 2002; Crewell et al., 2004). The application of synergetic algorithms to observations from these stations has provided only glimpse at the enormous potential of sensor synergy which will be outlined below.

Due to their fine vertical and horizontal resolution, **active remote sensing instruments**, in particular radar and lidar, can be well matched and are uniquely able to provide essential information on the vertical profile. It has already been mentioned that both can provide complementary information about cloud base height as the lidar is not affected by drizzle. On the other hand attenuation of the lidar signal is strong and the cloud can be penetrated. Therefore cloud top height derived from cloud radar is more reliable. The complementary nature of lidar and radar does not only provide a more complete description of cloud boundaries than either instrument alone, additionally, simultaneous lidar and radar retrievals for profiling mean particle size, water content, and number density in cirrus clouds are currently developed (Donovan and van Lammeren, 2001). Another interesting approach is the use of dual wavelength radar (Hogan et al., 1999; Gaussiat et al., 2003 and 2004) to derive cloud water content and cloud particle characteristics.

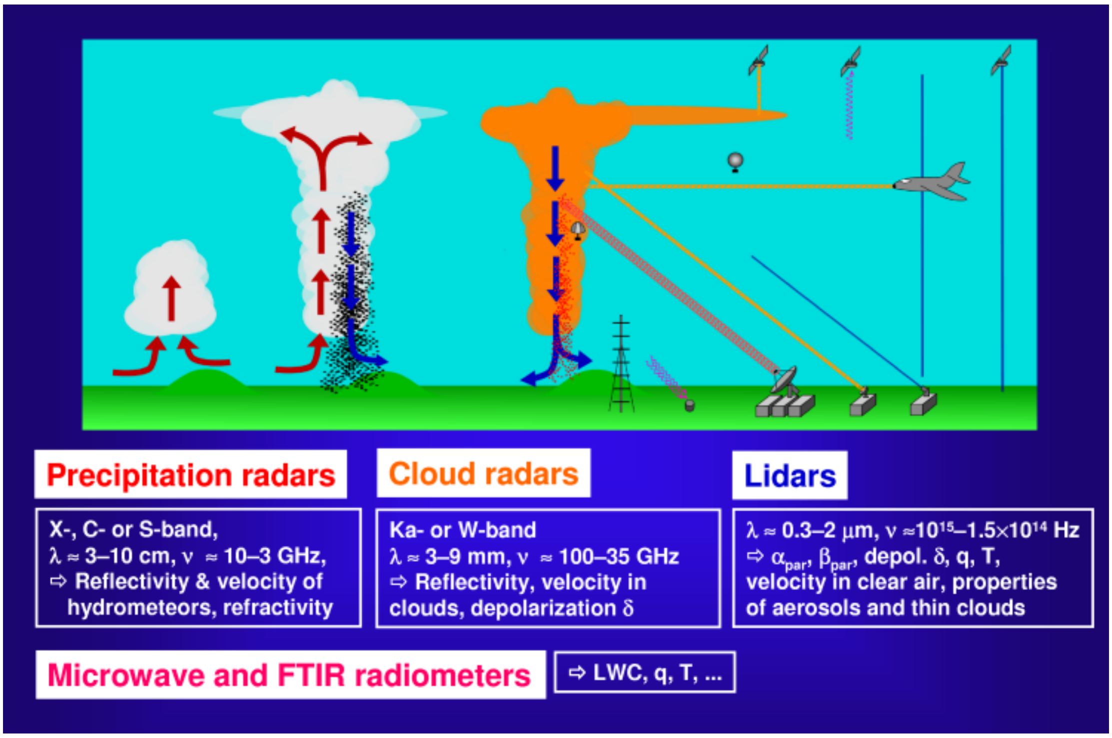


Fig.7.1. *Proposed sensor synergy for COPS for observing the life cycle of convective precipitation. Schematic of instrumentation at the three Supersites, whose locations are shown in Fig.4.1. The Supersites will consist of a synergy of in-situ sensors as well as passive and active remote sensing systems such as radiometers, precipitation radars, cloud radars, and different types of lidars. These instruments will be operated from mobile, ground-based, airborne and space-borne platforms. This way, convective processes will be studied in high spatial and temporal resolution and in both clear air and within clouds.*

During COPS, we are striving for an intensification of the use of sensor synergy by the combination of sensors at different sites, which have not been available before. There are two ways of making use of sensor synergy. Firstly, a combination of different instruments can be used to enhance measurements of atmospheric processes. For instance, adding lidar vertical profiling to radar measurements permits the measurement of key variables in the pre-convective environment before the cloud development is initiated as well as in the environment of clouds. These data are crucial to understand the conditions in which clouds are maintained and modified. Only by simultaneous multi-wavelength active remote sensing the whole life cycle of a convective system can be investigated. This multi-wavelength sensors synergy enhances the spatial coverage of the measurement of key variables. This is one novel approach applied during COPS (see Fig. 7.1).

Secondly, in the same range cells, the information of different sensors can be used simultaneously. These sensor synergies are not necessarily limited to remote sensing observations but can also include in-situ measurements as noted by Westwater (1997). Such measurements are needed, e.g., when using Raman lidar to obtain humidity profiles (Han et al. 1994). An integrated technique to obtain tropospheric water vapor and cloud liquid water is presented by Han and Westwater (1995). Here, ground-level measurements of temperature, humidity and pressure are combined with a lidar ceilometer, RASS and microwave radiometer measurements within a retrieval based on radiosonde statistics. Statistics are useful in retrieval algorithm development, especially when complex relationships with a large number of degrees of freedom are being studied. However, if physical knowledge of the radiation-atmospheric parameter interaction is given, retrieval algorithms can be made physically consistent, i.e. the retrieved parameters are forced to reproduce the measurements by means of a so-called forward model, and are thus more realistic. This is a constraint which statistical algorithms are not required to meet.

Instead of combining retrieval products derived from single instruments the direct observables can be integrated in one retrieval system. Within the so-called **optimal estimation theory** (e.g. Rodgers 2000) – a special notation of Bayesian probability theory – it is principally possible to incorporate a multiple number of measurements into the desired retrieval. The problem to be solved is an ill-posed inverse problem, which means that the forward model relating retrievable parameters to measurement is well known, but retrieving the parameters from the measurement is ambiguous. Given a set of measurements, the optimal estimation inversion procedure finds a solution which satisfies the measurements after the forward model has been applied to the retrieved parameters. As a condition, the error characteristics of each measurement and of the forward model must be accurately described by covariance matrices. The "degree of satisfaction" for each measurement depends on the measurement error and the corresponding forward model error. This means that measurements with low error and an accurate description of the relation between measurement and parameter will have a higher weight in the solution than measurements with high error and an inaccurate description of the relationship between measurement and parameter.

Many synergetic algorithms have been developed to retrieve **microphysical properties of clouds.** Here, both active and passive microwave remote sensing provide information valuable information as clouds are semitransparent in this frequency range. While the radar provides vertical structure information microwave radiometers can accurately determine the vertically integrated liquid water content. In the past methods have been developed to combine co-located microwave radiometer and cloud radar measurements to infer the liquid water content (LWC) and effective radius profiles (Frisch et al. 1998). In principal, such methods use the microwave-derived liquid water path (LWP) to scale the LWC derived from the cloud radar reflectivity measurements at each height. The work by Frisch et al. (1998) involves assumptions about the DSD and the vertical profile of cloud droplet concentration. To avoid assumptions on the DSD an optimal estimation framework for combining LWP and radar reflectivity profiles was used by Löhnert et al. (2001). He also incorporated an *a priori* profile (and its error covariance), which was derived from a single column microphysical model.

Multi-spectral microwave measurements contain additional information on the vertical profiles of temperature, humidity, and to a very limited degree, LWC. Using an Integrated Profiling Technique (IPT) (Löhnert et al., 2004), which applies optimal estimation theory, profiles of temperature, humidity and LWC from six different types of measurements can be simultaneously retrieved. In contrast to the other methods mentioned above, IPT directly combines 19 microwave brightness temperatures with cloud radar reflectivity profiles, lidar ceilometer cloud base, ground-level measurements of temperature, humidity, and pressure, nearest-by radiosonde profiles, and a LWC a priori profile obtained from a microphysical cloud model. The advantage of this technique is that the retrieved profiles are "physically consistent". This is accomplished by the fact that the retrieved profiles constrained to the ground-level measurements, fulfill the condition of saturation within the detected cloud boundaries from ceilometer (base) and cloud radar (top), and their forward-modeled brightness temperatures are constrained to the measured values. The Bayesian framework also provides an error estimate for each retrieved profile, which is important when the data are used to validate atmospheric models. The IPT is, however, limited to cases of single layer water clouds with neglible precipitation. Currently, efforts in the framework of COST 720 "Integrated Ground-Based Remote

Sensing Stations for Atmospheric Profiling" are ongoing to improve its applicability and retrieve more microphysical parameters in co-operation with the Cloudnet community.

7.4.2 Sensor synergy on space borne platforms

On satellites complementary instruments are operated simultaneously in order to overcome the limitations of single systems. For example, infrared humidity profilers are supplemented by microwave profilers, which have a coarse resolution but provide all-weather information. Because measurements of solar radiation have a superior spatial resolution they can be used to provide sub-pixel variability of the highly variable cloud field for the other methods. The AIRS sounding suite on NASA's Earth Observing System (EOS) Aqua spacecraft is intended to be used to create global three-dimensional maps of temperature, humidity and clouds in the Earth's atmosphere with unprecedented accuracy. For that purpose AIRS interferometer itself is complemented with a 4-channel visible/near-infrared imaging module, a 15-channel microwave temperature sounder and a 4-channel microwave humidity sounder. Combing such measurements yields much more accurate information than using a single instrument alone.

7.4.3 Synergy between ground-based, airborne, and spaceborne sensors

In addition to the combination of instruments operated on one platform the **synergy between space and ground-based** instruments is pursued. While satellite instruments mostly have good observing capabilities in the middle and upper troposphere, ground-based systems have better resolution in the planetary boundary layer (PBL). Processes in the PBL can change the thermodynamic structure rapidly which can be well observed in the time series from the ground. Satellite revisit times are less frequent and may be sufficient to detect the development in the upper atmosphere over a larger area. Clouds block infrared and solar radiation effectively, and the synergy of ground-based and space-borne sensors can provide information above and below the cloud as well as the properties of the cloud boundaries. However, in the simultaneous presence of high and low clouds information about the mid troposphere can be only gained employing microwave techniques.

A sophisticated attempt to combine ground-based and satellite observations was made by Stankov (1998) who combined lidar ceilometer, wind profiler/radio acoustic sounding system (RASS), and satellite data to obtain temperature, humidity and wind profiles of the troposphere. Another example for this kind of synergy is the blending of ground-based AERI Raman lidar measurements at the ARM CART site with GOES hourly temperature and water vapour retrievals to give high resolution water vapour profiles (Turner et al., 2000).

It is clear that also airborne and ground-based measurements are to a large extent complementary. Whereas ground-based remote sensing systems have a limited range but high resolution, airborne measurements cover a larger area but with lower resolution in a certain horizontal grid box. Tools to combine these measurements have already been mentioned in this document: this is data assimilation.

7.5 Validation Efforts

Thorough control of the data quality is the fundamental basis of the success of any measurement. This is especially true for large campaigns in atmospheric science where the latest generation of state-of-the-art instruments and novel measurement techniques are employed in the field. In addition to internal quality control and standard calibration, the measurement data of the same quantity must also be compared with each other in order to ensure a consistent data set. Consequently, part of the operation time of the instrumentation will be allocated repeatedly during COPS for intercomparisons.

It is obvious that intercomparisons have to be as close in space and time as possible to minimize the effects of atmospheric variability. Thus stacked formation flights of the aircrafts carrying remote sensing instrumentation will be performed. These intercomparison flights need not be at the cost of employing the same instruments for the other meteorological aims of the campaign, e.g., they can be made on the ways to and from the central region of interest. In addition to such stacked formation flights also frequent overpasses over the ground-based supersites will be organized when the flight patterns are planned. Frequent overpasses are necessary to identify potential instrumental biases with good accuracy as the data of the remote sensing instruments are averaged in space and time and different air masses are sampled during these airborne/ground-based intercomparisons (Behrendt et al. 2005a,b). In extension to what was done in previous campaigns, all performed intercomparion cases will be listed in real-time to assure that there will be enough cases for statistical analysis of the data. Software tools for recording airplane-airplane meetings/stacked formation flights and supersite overpasses will be developed well in advance with information like instruments in operation at the same time, flags for good data quality, e.g., without thick clouds for lidar intercomparisons, day/night condition and different atmospheric conditions (clear air/cloudy, moist/dry, hot/cold, different aerosol content, different wind directions/velocities etc.).

Previous to the data comparison during COPS in the field, the potential instrumentation of COPS shall be validated as good as possible. In summer, 2005 there was one of such rare opportunities for intercomparisons during LAUNCH2005. A second campaign where some of the proposed German instruments are involved in, will be the field experiment within the virtual HGF institute COSI-TRACKS in summer 2006. In addition to data comparisons, also algorithm comparisons by the use of synthetic data are planned in advance of the COPS field phase for instruments using the same techniques.

7.6 Resulting Overall Measurement Strategy

According to the scientific considerations made in chapter 6 and to the analysis of existing instrumentation, we distinguish between four observation phases (see Fig.7.1) in order to observe the whole process chain from convective initiation over cloud microphysics to precipitation. Furthermore, we perform the measurements in three adaptive target areas as defined in section 6.1. Instruments will be deployed in several supersites in order to take advantage of sensor synergy as described in section 7.4.

Phase 1 is defined by the presence of a pre-convective situation. During this time, mainly three activities will take place. Within the ETReC07 (see Fig. 8.1), targeting will be performed for improving large-scale forecasts a few days ahead before CI is taking place. Mesoscale targeting for better characterization of the inflow in the COPS area will take place at suitable located surface stations as well as by airborne and satellite observations. Meanwhile, boundary layer processes will be characterized in great detail in the COPS domain.

During **Phase 2**, CI takes place. The operation mode of scanning remote sensing systems will be adapted to 3D observations of atmospheric key variables. Aerosol in-situ, scanning microwave radar and radiometer measurements will be added for extending the range of 3D observations into clouds and for investigation aerosol-cloud interaction.

During **Phase 3**, CI is continuing and precipitation is forming. Clear-air and cloud measurements will be continued to study the organization of convection, and precipitation radars will be added. Tracking of the convective system will be performed with ground-based mobile instrumentation, aircrafts, radar systems with large range, as well as satellite observations.

Phase 4 is defined by the maintenance and decay of the convective system, which will also be observed as continuous and detailed as possible. These observations will be surrounded by a preparatory phase based on mesoscale forecasts and an important accompanying activity, the real-time data assimilation of COPS and GOP observations.

Details of this strategy are worked out in the PP1167 COPS DFG proposal, as this depends on the type of instruments, which have been requested.

8 Methods for Reaching the Science Goals

Based on these observations, the COPS science questions will be addressed. Unique model evaluation and process studies will be possible by the 4D observation of the life cycle of precipitation. The data will be compared with the recent generation of high-resolution mesoscale models as well as of global NWP models. Data assimilation studies permit refined investigations of processes by means of reanalysis or studies on predictability of convective precipitation. The highlights of COPS and the interaction of its components are depicted in Fig. 8.1.

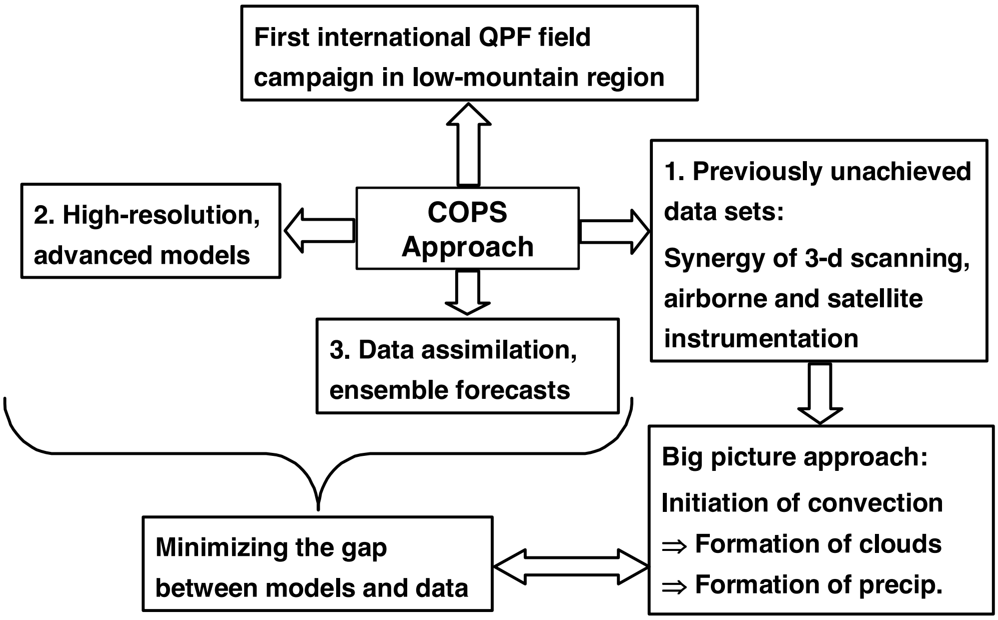


Fig.8.1: *COPS approach to reach the science goals*

8.1 Model evaluation

Research using the COPS data set can be performed in different steps. First of all, it is reasonable to perform statistical comparisons between observations and model forecasts. These results can be used for identifying model deficits, which gives indications concerning the major problems of the model (see sections 1.3 and 1.4).

In order to optimally exploit the diverse multi-dimensional remote sensing observations, two different approaches can be pursued. On one hand, the synergy of multi-wavelength (active/passive) observations can be combined to derive the atmospheric variables using existing or newly developed algorithms (observation-to-model approach). For evaluation of model forecasts these variables will be the prognostic model parameters; for development of parameterizations an even more complete set of variables will be necessary to formulate and test parametric assumptions. On the other hand, it can be helpful to convert the model output to the direct observables (model-to-observation approach) and perform comparison in terms of observables. This approach avoids uncertainties due to the retrieval process because the so-called "forward" model (operator) can be described much more accurately than the inversion process, which always involves certain assumptions to compensate for the ambiguities of the problem. The development of operators, which convert model output to observation space, is also an important step towards assimilation since these operators are a prerequisite for modern assimilation techniques, including variational methods. The application of a polarimetric radar operator (Pfeifer et al. 2004) developed as part of PQP has been found very valuable in investigating cloud microphysical parameterizations.

For the observation-to-model approach, data from in situ sensors, cloud radars, lidars, and microwave radiometers will be combined, e.g., using the synergetic algorithms developed as part of the EU Project CloudNET (http://www.met.rdg.ac.uk/radar/cloudnet) and of BALTEX (Crewell et al. 2004). This includes a cloud classification, ice water content, cloud fraction, turbulence levels, and liquid water path with a strict quality control and error estimates. Furthermore, the optimal estimation technique developed by Löhnert et al. (2004) and extended within the COST720 initiative "Integrated Profiling" will continuously provide profiles of temperature, humidity, cloud liquid water content, drizzle water content, cloud effective radius, and the corresponding error estimates.

8.2 Process Studies

Model evaluation alone often suffers from remaining data gaps so that a clear identification of the key process leading to QPF deficits may not be possible. Particularly, if errors due to initial conditions and model physics are coupled, it is very difficult to separate their respective contributions. In order to achieve this, more comprehensive 4D data sets are essential. These can only be obtained during field campaigns.

Particularly in orographic terrain, the limited representativeness of passive remote sensing systems due to their low range resolution and limited scanning capability has to be extended by various scanning lidar systems, which are considered as key components of COPS (Wulfmeyer et al. 2003). These systems will deliver 3-d fields of humidity (Wulfmeyer and Walther 2001a, 2001b), wind components (Henderson et al. 1993, Grund et al. 2001), and temperature (Behrendt 2005; Arshinov et al., 2005) in the pre-convective environment or the environment around convective systems. These measurements are considered essential to *understand* the properties of clouds and precipitation, as well as their development and evolution.

Therefore, an extended data set, which can be used for precipitation process studies, should encompass the whole chain of events leading to the onset and organization of convective precipitation. Particularly, it is important to obtain data in 2D or even 3D, as in complex terrain, small-scale processes have a high spatial variability. If this data set contains the major part of atmospheric key variables such as dynamics and water in all its phase then it can be expected that detailed **process studies** can be performed.

The COPS data set will allow for investigating a variety of key processes in a low-mountain region. These include land-surface exchange processes, boundary layer processes, and aerosol-cloud interaction.

Long-term measurements of the diurnal cycle of boundary layer variables on the windward and the lee side of the mountains can reveal systematic errors in models, e.g., due to an inadequate representation of the complex flow and of land-surface exchanges processes.

3D simultaneous observations of dynamics, humidity, and temperature will contribute to detect inhomogeneities in the fields of boundary layer variables leading to the initiation of convection. In this connection, an example shall be discussed. During COPS, simultaneous scanning water vapor, wind, and temperature lidar systems shall be operated. Their measurements permit for the first time, the measurement of humidity advection (by combination water vapor and wind lidar measurements), and convective available potential energy (CAPE) (by combining water vapor and rotational Raman temperature lidar). These data can be used to study closure assumptions in convection parameterizations. Furthermore, the relationship between initiation of convection and strength of CAPE can be explored. These are just a few examples of the new capabilities of these instruments. These studies of initiation and organization of convection can be related to small-scale and large-scale conditions in the COPS domain.

Furthermore, the relationship between aerosol and cloud microphysics can be explored by combining aerosol in-situ and remote sensing measurements with simultaneous cloud-microphysics measurements, either by in-situ or by remote sensing. In this connection, we expect that observations in orographic terrain have the advantage that initiation of convection is often localized leading to several interesting cases and better statistics of the observations. Only if the gaps in our understanding of complex processes can be closed, it will be possible to represent these processes adequately in the models of the next generation.

8.3 Data assimilation studies

8.3.1 Real-time data assimilation

Real-time data assimilation studies have been incorporated in the design of COPS in order to demonstrate a potential impact of new observing systems. For this exercise, only systems, which either provide prognostic variables or which provide observations with suitable forward operators will be considered. In both cases, a detailed error analysis of the measurements is important. Different data assimilation schemes such as nudging, 3DVAR, and 4DVAR will be compared as well as different state-of-the-art mesoscale models.

The new observations collected in COPS mesoscale and/or large-scale target regions shall be assimilated. This option will also be open for D-PHASE and ETReC 2007 participants and weather services, as the data will be ingested in the GTS. The suitable instrumentation includes:

- Water vapor, wind, and temperature lidar
- GPS
- In-situ sensors (drop sondes, radiosondes)
- Radars, e.g., Doppler radial velocity
- Passive remote sensing systems such as ground-based FTIR

- Satellites remote sensing data.

For this purpose all data must be delivered in BUFR format. A working group focusing on this effort has been initiated led by MPIfM and the COPS WG Data Assimilation and Predictability. Fast transmission of airborne data to a ground station is also under consideration, maybe using UTMS links.

Real-time data assimilation would be an exciting demonstration of the impact of new observing systems. This effort is strongly related to one of the THORPEX goals (see section 5.2.1).

8.3.2 Reanalyses

Comprehensive reanalyses of the measurement period shall be performed. All available observations shall be assimilated using the most sophisticated data assimilation schemes. The result will be a consistent, gridded data set to be used for forecast validation and investigation of physical processes. Particurlarly, it will be investigated whether the relative impact of the improvement of initial fields can be separated from model physics. This will be possible by studying and comparing the impacts of different types of observation systems. If data assimilation of a certain observation systems lead to a significant improvement of the forecast, it is very likely that the forecast quality is mainly limited by errors in initial conditions. It will also be interesting to study the relative impact of small-scale/large-scale conditions on forecast quality. This should be possible by the collaboration of COPS with ETReC 2007 scientists.

In combination with testing different parameterizations, the relative impact of initial conditions and model physics on QPF skill can be studied. By means of these activities, optimized initial fields for research on predictability and parameterizations can be provided.

8.3.3 Data assimilation experiments

After the assimilation of the data of a certain window, the forecast quality will be explored by verification of the free running models. Again, various impact studies of additional data sources on QPF skills of different models can be performed. The relative importance of different data will be explored. In a final step, the role of initial and model errors on forecast quality and their separation can be investigated by assimilating the whole COPS data set in combination with ensemble prediction systems. The limits of predictability of convective precipitation can be studied (see Fig. 8.1). In summary, COPS addresses simultaneously all PQP science goals (see section 2.1).

8.4 Recommendations

Improvements of QPF, which are most promising for early introduction to operational practice, taking into account cost, computational requirements, and ease of deployment, as well as raw performance shall be suggested. Recommendation on future strategies for advancing operational weather forecast will be made. This includes the

a) Investigation of errors due to initial fields.

b) Impact studies of new observation systems:

   - Ground based networks
   - Satellite measurements
   - Targeted observations

c) Optimal use of future data assimilation systems. What system shall be used for what kind of forecasts?

d) Characterization of errors due to parameterizations.

e) Development and test of new parameterizations (turbulence closure; convection, and cloud microphysics).

f) Investigation of the limits of predictability.

As outlined in this SOD, COPS is designed to be an important milestone on the way to an improved QPF, which will combine the full potential of models and observing systems of the next generation.

9 List of candidate instruments

9.1 Proposed German instruments

Proposed instruments for COPS listed according to type. ***TBD****: to be determined.* ***WG IC****: COPS Working group "Initiation of convection",* ***WG ACM****: "Aerosol and cloud microphysics",* ***WG PPL****: "Precipitation processes and their life cycle";* ***WG DAP****: "Data assimilation and predictability";* ***GOP****: "General observations period". x: Red crosses mark main contributions to WGs and GOP, respectively.*

Instrument	Type	PI	Institution	WG CI	WG ACM	WG PPL	WG DAP	GOP
Airborne								
DLR Falcon	Aircraft + H2O Lidar + Doppler Lidar + Dropsondes	Ehret	DLR	x	x		x	
DO 128	Aircraft	Corsmeier	FZK	x		x		
ACTOS	Helicopter + payload	Siebert	IfT		x			
CVI+INT	Aircraft + payload	Mertes	IfT		x			
CASI+POLIS	Cessna aircraft + payload	Fischer, Wiegner	FUB, LMU		x			
HELIPOD	Helicopter + payload	Bange	U. Braunschweig	x				

Ground-based Lidars								
UHOH WV DIAL	Lidar, H2O DIAL, IR, scanning	Wulfmeyer	U. Hohenheim + IfT + U. Potsdam + DLR	x	x		x	
UHOH RRL	Lidar, Rotational Raman, UV, temperature & aerosols, scanning	Behrendt	U. Hohenheim/ COSI-TRACKS	x	x		x	
WindTracer	Doppler lidar, scanning	Wieser	FZK	x	x		x	
MWL & WiLi	Multi-wavelength Raman lidar (vertical) + Doppler lidar (vertical)+ radiosondes	Althausen	IfT	x	x			
Radiometers								
HATPRO	MW radiometer	Crewell	U. Munich	x	x			
MICCY	MW + IR radiometer,	Simmer	U. Bonn	x	x			
Radars								

POLDIRAD	Polarization Radar, C-band, scanning	Hagen	DLR			x		
Karlruhe Radar	Weather Radar, C-band, scanning	Beheng	FZK			x		x
UHOH X-Band	Precip radar	Schaberl	U.Hohenheim			x		
IMK Cloud Radar	Cloud Radar	Beheng	FZK		x			
UHH Cloud Radar	Cloud radar	Peters	U. Hamburg		x			
MRRs	Micro Rain Radars	Peters	U. Hamburg			x		x
Hydrometeor Imager								
HODAR	Holograhic Hydrometeor Imager	Vössing	U. Mainz			x		
GPS								
GPS Network	GPS, 5 additional stations for COPS	Gendt	GFZ	x			X	x

WTR + Sodar + RASS								
WTR	Mobile wind temperature radar	Vogt	FZK	x				
2 Sodars	Sodar	Kalthoff	FZK	x				
Sodar-RASS	Sodar, RASS	Foken	U. Bayreuth	x				
Flat array sodar	Sodar	Mayer	U. Freiburg	x				
Surface in-situ								
2 Energy balance stations		Kalthoff	FZK	x			TBD	
5 Turb. Towers		Kalthoff	FZK	x				
SISOMOP	Soil Moisture sensors	Hauck	FZK	x			TBD	
Rad.-Tur. Cluster	3 Energy balance stations + Bowen ratio system + Scintillometer	Foken	U. Bayreuth	x				
12 Automatic Weather Stations		Smith	U. München	x		x	TBD	
Aerosol container	Aerosol analysis	Wiedensohler	IfT		x			

Masts + tethered balloons								
4 MMM	Micro-Meteorology-masts, comb. w. Drop-up sondes	Kalthoff	FZK	x				
12-m Mast		Foken	U. Bayreuth	x				
Hartheim site		Mayer	U. Freiburg	x	x	x	TBD	x
Tuttlingen site		Mayer	U. Freiburg	x	x	x	TBD	x
Tethered Ballon		Mayer	U. Freiburg	x				
Radiosonde stations								
2 Mobile RS Stations		Kalthoff	FZK	x			x	
Drop-up sondes	Advanced radiosondes (30 sondes, 5 kits)	Corsmeier	FZK	x			TBD	

9.2 Proposed US instruments

Institution or Facility	**Instrument**	**Principal Investigator**	**Anticipated Sponsor**
DOE ARM program	ARM Mobile Facility (microwave radiometers, radiosondes, broadband radiometers, surface pressure/temperature/humidity, millimeter cloud radar, micropulse lidar, infrared interferometer)	Mark Miller	US DOE
NASA	Lidar Atmospheric Sensing Experiment (LASE) on the NASA'DC-8	Ed Browell	NASA
NASA	Raman Airborne Spectroscopic Lidar (RASL) on P-3, DC-8 or Dash-7	Dave Whiteman, Belay Demoz	NASA
NASA	Scanning Raman Lidar (SRL)	Dave Whiteman, Belay Demoz	NASA
NCAR	S-POL	Jim Wilson	NSF/ Deployment pool & DFG
NCAR	3 DOWs	Tammy Weckwerth	NSF & DFG
NOAA	High-Resolution Doppler Lidar (HRDL)	Michael Hardesty, Sara Tucker	NSF & NOAA
NOAA	Mini-MOPA CO_2 Doppler lidar	Alan Brewer, Christoph Senff	NSF & NOAA
U. of Colorado/NOAA	CODI water vapor DIAL	Janet Machol	NOAA

9.3 Proposed UK instruments

Letter of Intent for UK Participation in COPS
Alan Blyth, Stephen Mobbs, Chris Collier and many others

The UK community propose to participate in COPS in an integrated project with the following objectives:

- Characterise thermally driven flows in complex terrain and their role in (a) convective initiation and (b) fluxes and transport. Significant modelling effort in parallel.
- Understand the microphysics, dynamics and thermodynamics of convective clouds over complex terrain and the interactions that play important roles in the development of CuCg clouds into major thunderstorms.
- Determine the role of aerosols in the development of orographic convective clouds and in the intensity of precipitation.
- Determine the vertical fluxes of chemical species from the forest canopy during convective events and their importance (a) in the behaviour of orographic convective clouds and (b) in regional transport.
- Determine how convective clouds process aerosols and what effect the processing has on initiation and development of clouds that form as a result of outflows.

In order to achieve this, the following instruments or facilities will be requested as part of the NERC proposal:

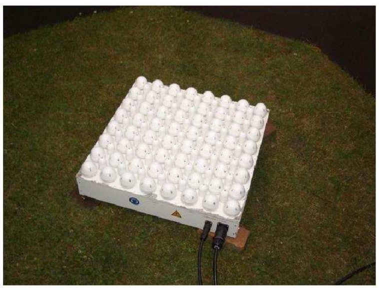
- The BAe 146 operated jointly by FAAM and the Met Office will be equipped with the aerosol mass spectrometer, CCN probe, chemical tracer probes, and standard cloud microphysics instruments (PCASP, Cloudscope, Fast FSSP, 2DC, 2DP, Cloud Particle Imager and Small Ice Detector). Long legs will be made in the boundary layer in order to measure the aerosols and cloud base conditions. Penetrations will be made in developing clouds (reflectivity less than about 35 dBZ) to measure the properties of the cloud.


- The Cessna aircraft will be used to map out the temperature and humidity structure, wind fields and aerosol sizes and concentrations within the boundary layer. It has a cruise speed of 55 m s^{-1}, a range of 1000 km, an endurance of about 3 - 4 hrs and a ceiling of about 4 km.
- The UFAM ozone DIAL and aerosol backscatter lidar operated by the University of Manchester (below left) will be used to measure aerosol distributions and ozone in the BL as well as venting from the BL.
- The UFAM mobile wind profiler (below right) also operated by the University of Manchester is a "clear-air" three panel 1290 MHz UHF Doppler radar system designed by Degreane Horizon. It consists of three panels to emit and receive three

separate beams; one vertical from the central panel and the other two at an elevation of 73°to enable full wind vectors to be calculated. It will be used to measure Bragg scattering signals from humidity fluctuations near lids and at the edges of thermals and cumulus clouds and to determine the 3D wind field. The maximum vertical range depends on atmospheric conditions, but is typically between 3 and 5 km.

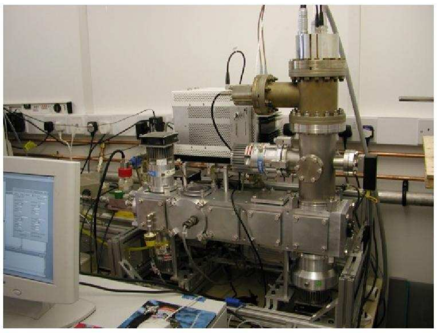
- The UFAM Doppler lidar system (below left) operated by University of Salford will be used to observe the detailed wind and turbulence structure of boundary-layer features, such as convergence lines, thermals and small cumulus clouds. It has a CO_2 laser with a wavelength of 10.6 μm; the pulse energy is 70 mJ and a pulse repetition rate of 9 Hz. The minimum and maximum range are 800 m and 9 km respectively, and the range resolution is 112 m. Further details are discussed in Pearson and Collier (1999). The lidar system is housed within a mobile unit which is equipped with a scanner capable of performing scans at rates of up to 6 deg per second. The scanner is capable of scanning from 0 - 42 deg in elevation and 0 - 295 deg in azimuth.

- Three UFAM Scintec sodars (below right) operated by the University of Leeds will be used to provide a time-height record of the 3D wind in the boundary layer. They have a maximum range of between 500 and 1000 m depending on atmospheric conditions. A typical averaging time required to produce meaningful profiles is about 10 min. The lowest measurement height is 20 m, the maximum number of layers is 100 and the thickness of the measurement layers varies between 10 to 250 m.

- The tether sonde comprises a Gill 3-axis mini sonic anemometer running at 10 Hz. The sonic is mounted on an aerodynamic pod containing digital RH, T and P sensors as well as, pitch, roll and yaw sensors, and 3-axis accelerometers all running at 10 Hz. Auxiliary A/D channels are also available allowing additional sensors to be added and again these are logged at 10 Hz. The GPS unit provides accurate location and time. Communications with the base station use a bi-directional radio link in the 2.4 GHz band with a transmitter power of 100 mW. The balloon is a Sky-Doc with the following features: 15 ft diameter prolate spheroid (major axis horizontal); 25 lb static lift; 1000 lb lift at 90 mph; capable of flying in 110 mph winds; 708 cu ft of He required; 1.5 miles of tether; and 24 V winch.

- The UFAM Aerodyne Aerosol Mass Spectrometer operated by the University of Manchester provides submicron mass loadings of non refractory aerosol chemical components as a function of particle size. The particles are entrained into a vacuum through an aerodynamic lens, forming a particle beam that strikes a heated surface and is thermally vaporised and subsequently ionised in an electron cloud. The ground-based instrument uses a time of flight mass spectrometer to analyse the ions and so can obtain size resolved mass spectra and, if the signals are large enough to detect, mass spectra of single particles. It will likely be located at a supersite perhaps downwind of convective clouds to investiage cloud processing of aerosols.



- Two (possibly three) Vaisala sounding systems.

9.4 Proposed French instruments

Letter of Intent for French Participation in COPS

Cyrille Flamant, Evelyne Richard, Joël Van Baelen, Véronique Ducrocq, François Bouttier, Martial Haeffelin, Wolfram Wobrock, and many others

The French community propose to participate in COPS in an integrated project with the following objectives:

- Understand the microphysics, dynamics and thermodynamics of convective clouds over complex terrain and the interactions that play important roles in the development of CuCg clouds into major thunderstorms,
- Determine the role of aerosols in the development of orographic convective clouds and in the intensity of precipitation,
- Determine how water vapor variability in the PBL and surface conditions impact the initiation and development of clouds.

In order to achieve this, the following instruments or facilities will be requested as part of proposals submitted to the INSU/PATOM and CNES/TOSCA programs:

- the SAFIRE F20 equipped with the airborne water vapor differential absorption lidar LEANDRE 2 for investigating the pre-convective water vapor field and its relation to the initiation of convection. Some very challenging aspects associated with the deployment of LEANDRE 2 are the real time assimilation of lidar-derived water vapor mixing ratio profiles in operational nowcasting models,
- the SAFIRE ATR-42 will be used to map out the temperature and humidity structure, wind fields and possibly the aerosol sizes and concentrations (provided that it is equipped with the aerosol package HYGRO) within the boundary layer,
- the SIRTA Observatory (http://sirta.ipsl.polytechnique.fr) for long-term monitoring of physical, radiative and dynamical processes in Palaiseau, France. Routine measurements will be made available to the COPS participants. Provided that adequate funding is alloted, enhanced profiling capabilities (e.g. backscatter and wind lidars) will be activated during the COPS Special Observing Period.
- the ground-based remote sensing plateform TReSS operated by IPSL, to be deployed upstream of the COPS operation region. TReSS is an autonomous and high-performance system designed to observe radiative and structural properties of clouds and aerosol layers, as well as atmospheric boudary layer (ABL) dynamics. The standard payload is made of the following instruments: (1) a multi-wavelength elastic and Raman channels backscatter Mini-Lidar operating at 532, 1064 and 607 nm (with diverse polarization capability at 532 nm), (2) a sun-photometer, (3) an IR radiometer and (4) a full sky visible channel web-type camera,
- the ground-based Raman lidar developped jointly by IGN and IPSL/CNRS and operated by IPSL and IGN, to be deployed upstream of the COPS operation region,
- a suite of X-band radar (precipitation rate estimation and horizontal distribution), a vertically pointing K-band radar (characterisation of des hydrometeores) and possibly a multiple antenna wind profiler currently under development, operated by LaMP, to be deployed upstream of the COPS operation region,
- a network of approximately 10-15 GPS stations loaned by INSU/CNRS and operated by LaMP and IPSL, to be deployed upstream of the COPS operation region.

In parallel, signifcant modelling and assimilation efforts will be conducted, lead by the Centre National de Recherches Météorologiques (CNRM), the Laboratoire d'Aérologie, and the Laboratoire de Météorologie Physique. These wil include:

- developing of GPS and radar observables,
- testing assimilation tools developed for the operational model AROME,
- high resolution simulations of historical cases to refine the experimental strategy,
- high resolution simulations of COPS case studies.

9.5 Proposed Austrian contributions

Universität Wien
Institut für Meteorologie und Geophysik
Head: O. Univ.-Prof. Dr. Reinhold Steinacker

Contribution to COPS

Manfred Dorninger
Institut für Meteorologie und Geophysik
Universität Wien
Althanstr. 14, A-1090 Wien
Tel.: +43-(0)1-4277-53731
Email: manfred.dorninger@univie.ac.at

The Department of Meteorology and Geophysics is interested in supporting two key research components of COPS. These are Initiation of Convection (IC) and Precipitation Processes and Life Cycle (PPL). For exploring the pre-convective as well as the convective boundary layer several ground based measurement systems are available and if funding can be raised, will be set up for the field campaign.

These include:

3 automatic met. stations
4 3D-Sonic anemometers
1 energy balance system
1 mobile radiosonde system
1 disdrometer
1 micro rain radar
10-15 temperature sensors
1 RASS (probably)

The systems should be included in the overall COPS Management Document which will be elaborated in a later stage.

To our opinion in the documents there seems to be too little emphasis put to data management, (real time) quality control and model validation questions. It is our feeling that data assimilation on very high resolution might not be too easy with data not having being undergone complex quality control. May be you could profit from the “bad” experiences from ALPEX and MAP (see e.g. Häberli, C., et al, 2004, Met Z 13, 109-121.

In the field of real time model validation we could eventually contribute to COPS (via MAP-FDP), depending on funding.

Vienna, 27 September 2005

9.6 Proposed instruments from Italy, Switzerland, and The Netherlands

Facility	Instrument	Principal Investiga-tor	Anticipated Sponsor
Basilicata University	Università della Basilicata Lidar (BASIL), aerosols, water vapor, temperature Raman lidar	Paolo Di Girolamo	tbd
Institute of Applied Physics (IAP) of the University of Bern	TROWARA, ASMUWARA radiometers	Christian Mätzler	tbd
Istituto di Metodologie per l'Analisi Ambientale (IMAA)	Aerosol Lidar	Gelsomina Pappalardo	tbd
Istituto di Metodologie per l'Analisi Ambientale (IMAA)	Aerosol, water vapor, temperature Raman Lidar	Gelsomina Pappalardo	tbd
Istituto di Metodologie per l'Analisi Ambientale (IMAA)	Microwave radiometer	Gelsomina Pappalardo	tbd
NICT	Airborne Doppler Lidar	Kohei Mizutani	tbd
RISH	Water vapor and aerosol Raman lidar	Takuji Nakamura	MEXT Japan
TU Delft	TARA Cloud Radar	Herman Russchen-berg	tbd
Meteo-Swiss	Radar network, radiosonde network, surface network	NN	Meteo-Swiss

10 Logistics, Campaign Management, and Data Management

10.1 Logistics

The German part of the proposed IOP-Region is characterized by several independent networks measuring meteorological data and in particular precipitation. The density of stations and the different networks are presented in Figure II.1. Networks of the German federal states Baden-Württemberg, Hessen, and Rheinland-Pfalz are measuring precipitation with a time resolution of up to 10 minutes. The 50 SYNOP stations of the German Weather Service (DWD) give hourly values of the standard SYNOP-dataset, while the 34 DWD-MIRIAM stations measure precipitation and other meteorological data automatically in 10-minute intervals. At the approx. 500 DWD-RR24 stations, precipitation measurements are available every 24 hours. Radiosoundings are made by DWD in Stuttgart on four times a day at 00, 06, 12, and 18 UTC. There are several aerological stations performing radiosonde launches around the COPS region at Munich, Payerne (Switzerland), Nancy (France) and others.

Additionally the ranges of four precipitation radar systems are indicated in Fig.II.1. The IMK radar located at the Forschungszentrum Karlsruhe approx. 12 km north of Karlsruhe (red circle), and three radars of the DWD-radar network located at Frankfurt, the summit of the Feldberg (1483 m) in the southern Black Forest and at Türkheim near Ulm (blue circles). The ranges of the radar systems are approx. 120 km. Two French radar systems are also overlapping with the COPS domain. A dense lightning network is operated by the Siemens AG in Germany. The data are open to the public and can be used in COPS.

For research aircraft operations there are several airports in the area, which can be used as COPS airbase, e.g., Freiburg/Lahr, Karlsruhe/Baden-Baden, Stuttgart, and several German military air bases. The former Canadian military airbases Freiburg/Lahr and Karlsruhe/Baden-Baden are good choices for aircraft operations. Lahr, located 50 km north of Freiburg in the Rhine valley, is open for freight flights only and a special permit is necessary for others than cargo aircraft.

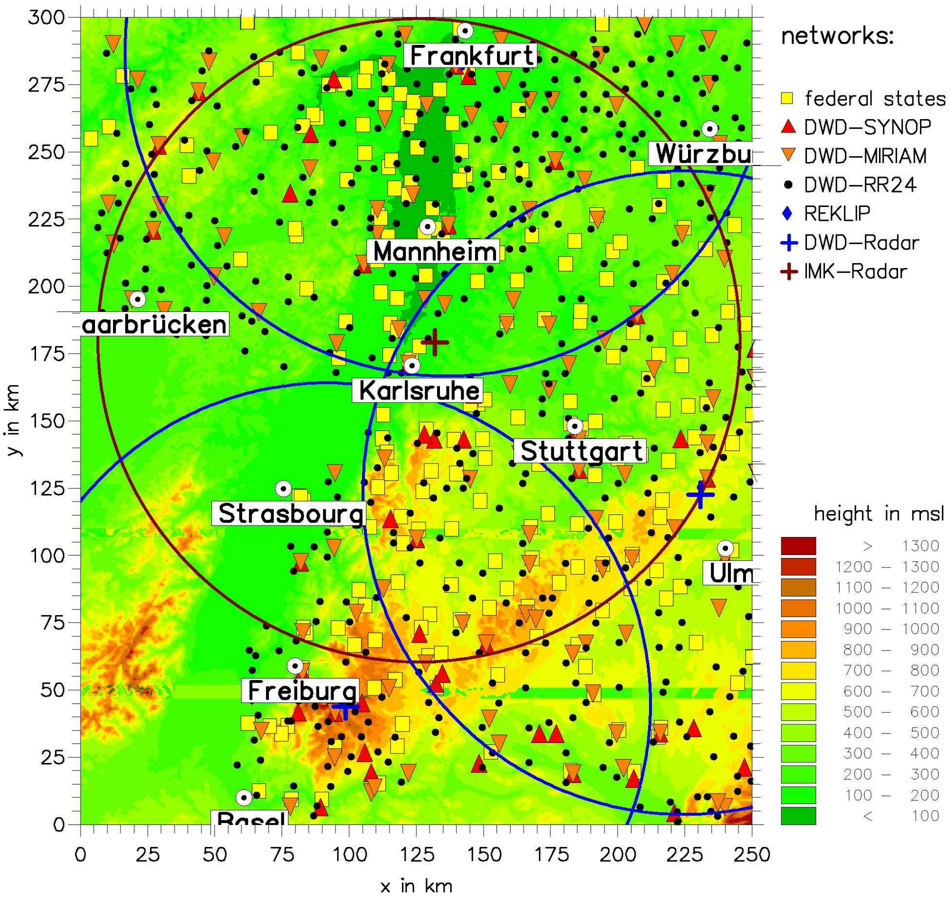


Fig.10.1. *Networks for precipitation measurements operated by DWD and environmental protection agencies. Radius of view (120 km) of the IMK precipitation radar located at the Forschungszentrum Karlsruhe (red circle) and radii of DWD radars at Frankfurt (north), Türkheim (east), and Feldberg (south), (Kunz, 2004). The networks in the French part of the IOP region, operated by Meteo France and others will be included.*

Karlsruhe/Baden-Baden, as well a former Canadian military airbase is located 30 km south of Karlsruhe in the Rhine valley. It's now a regional airport with international traffic, open 24 h a day (if necessary), hangar space and offices are available, it is within the area of operation (no ferry), full landing equipment is available, no restrictions due to weather are to expect in summer. The traffic is quite low at Karlsruhe/Baden-Baden. In former campaigns there was a very good cooperation between the scientists and the crews on the one hand and the airport administration and the tower on the other hand.

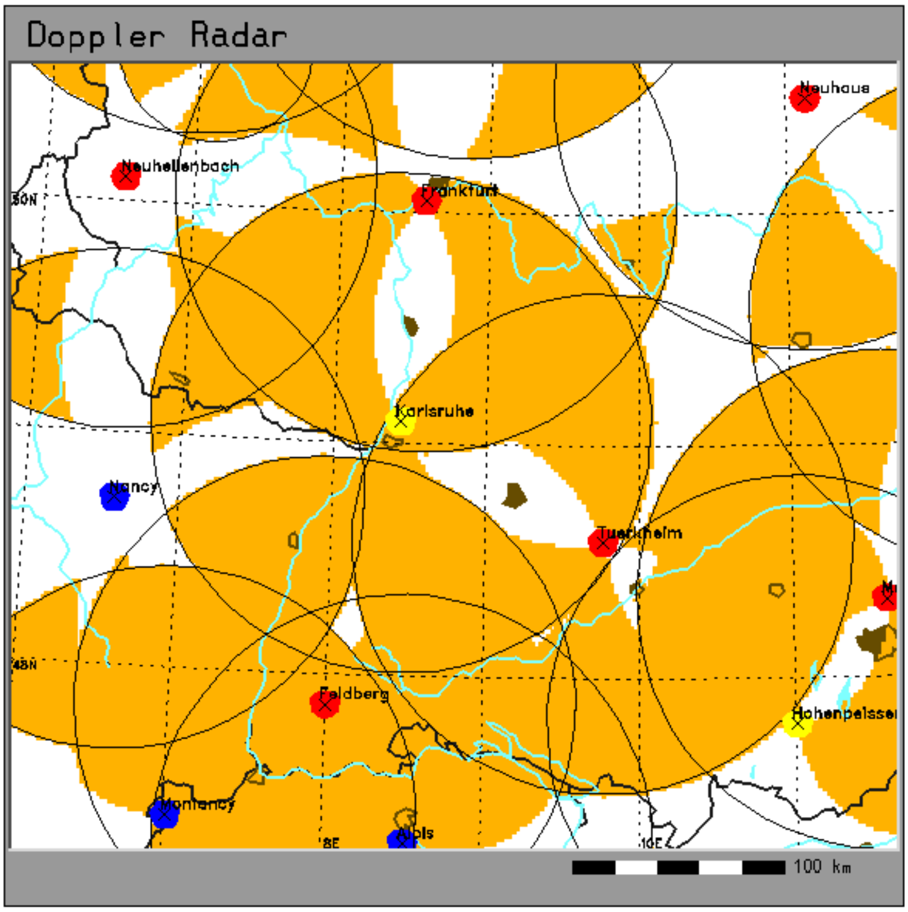


Fig.10.2. *Operational C-band Doppler weather radars in the COPS region. Circles indicate the 125 km range. Only the radar at Montancy will be polarized. The shaded areas indicate areas where dual-Doppler wind field retrieval would be possible. Shielding by orography is not considered here, but reduces the area with of dual-Doppler coverage considerably at lower altitudes.*

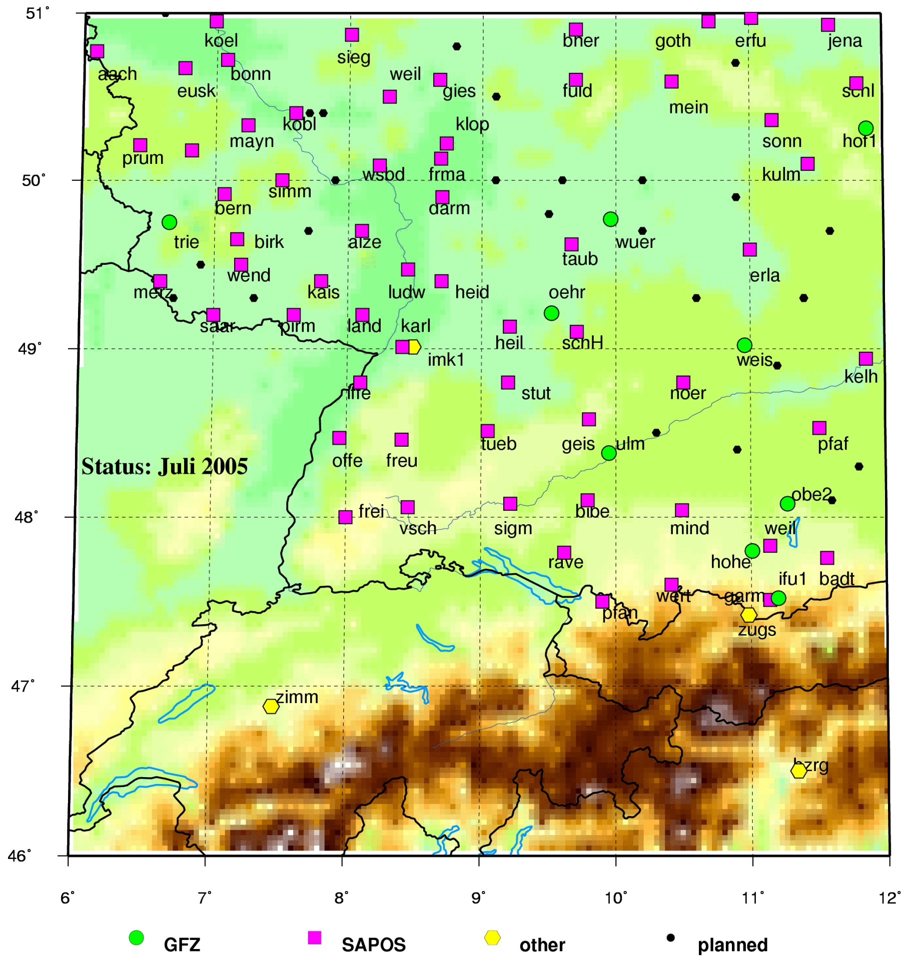


Fig.10.3. *Location of standard GPS observations within the COPS area and its surroundings. Five additional stations will be installed as part of the GOP in the COPS region.*

In the COPS region several radars are operated by DWD, FZ Karlsruhe, Meteo France and Meteo Swiss. All radars are C-band and Dopplerized, but only the radar at Montancy will be polarized by 2007. Of further interest are data form further French radars to have a good representation of the upstream inflow.

With a Doppler radar the dynamics of convective cells can be observed directly. If more than one radar observe the same area a multiple-Doppler analysis can be performed to retrieve the 3-dimensional flow within the precipitation. The resolution and the accuracy of the retrieval can be enhanced if additional radar systems like mobile radars or bistatic radar networks are deployed (e.g. Friedrich and Hagen, 2004). The Doppler radar network shown in Fig. 10.2 is quite dense. However, if one considers shielding of the radar beams by orography leads to a considerably reduced coverage from to the surface up to a few kilometres above ground. Also the flow and dynamics of cells developing in larger valleys (Murg, near the city of Rastatt; Kinzig near the city of Lahr) can only be monitored if there are radars within the valleys. It is therefore to necessary to increase the areal coverage and avoid shielding by orography by the installation of additional Doppler radars in the COPS region. In addition the use of airborne Doppler radars, as shown by Bousquet et al.(2003), is of great benefit. The deployment of this instrument will be requested for funding in France.

10.2 Campaign Management

The scientific and logistic management of the COPS campaign, including pre and post campaign activities is subject of the COPS Operations Plan (OP), which will be elaborated at the beginning of 2006. An important subject of this document will be the preparation of a large variety of model forecasts to be used for mission planning. For this purpose, access to the results of MAP FDP forecasts has to be ensured. Currently, it is discussed to store these results at ECMWF. Other model forecasts such as the European PEPS shall also be used. At the COPS Operations Center (OC), the major information of these forecasts will be visualized. The COPS OC will be most likely located at the airport Karlsruhe/Baden-Baden where several aircrafts can be operated.

Furthermore, the COPS OP will include the location of each instrument and its operations modes during each mission. A key part will be the joint set up of different observation systems at the supersites. Each mission will be explained and labeled in a playbook, which will provide the basis for the combination and performance of different missions. A special section will deal with aircraft operations.

The COPS OP will contain detailed plans for mission design, preparation, and performance including the set up of briefings and debriefings including corresponding times, agendas, and members. During each briefing, one or more forecasters will provide a detailed introduction in the weather situation for all scientists based on the huge amount of information provided by operational forecasts including MAP FDP and ETReC07 results. The NINJO operation system of the DWD will be used for visualization of most forecast results overlaid on additional observations from different platforms.

A clear path for the decision process will be proposed announcing the involved scientists and their responsibilities. A communications plan will be derived in order to include all COPS scientists even at remote locations in the decision process. After a discussion between COPS Lead Scientists in the OC, missions of the day will be selected. For each mission, a PI will be announced who will be responsible for ground and aircraft operations. The information content of real-time satellite data will be used for last minute detailed mission planning. This includes strong communication with air traffic control. An alert system for field teams will be available in order to optimize the operation of mobile instrumentation during all missions.

Finally, the results will be uploaded in form of quicklooks and in well-specified raw data formats to the COPS field catalogue. Two categories of data will be provided. One set of data will be available for real-time data assimilation (see II.3), which sets high demands to data quality and documentation. The other data will be used after the performance of COPS for research on QPF. The COPS field catalogue shall be designed similar as during IHOP_2002 in the US (see www.joss.ucar.edu/ihop/catalog/). After the performance of the campaign, all data will be delivered to the COPS archive in a previously specified format containing all critical information about the data including an extended error analysis.

10.3 Data management

The Model and Data group of the Max Planck Institute will organize the data archive for COPS and GOP data for Meteorology who is also hosting the World Data Center for Climate (WDCC, http://www.mad.zmaw.de/wdcc/). After syntax quality checks, the observation data acquired within COPS and GOP will be archived with quicklooks and together with related model outputs (forecasts and analyses of models of weather services and research models) and satellite data. Access to the data will be provided by a data bank structure, which allows to extract data by a range of selection criteria. The latter is especially useful for model data in order to select data of interest.

Measuring atmospheric parameters by a set of new and advanced research instruments like it is planned for COPS, will cause challenges for data-assimilation systems if the data format is not suited for the preprocessing and processing in that system. To allow flexible, simple, and efficient access, all data, which are to be assimilated in real-time during COPS, will be encoded in BUFR (Binary Universal Form for the Representation) (Dragosavac, 2004), the standard format for observation data handling as defined by

WMO. The use of BUFR will probably not be possible for all instruments and all platforms used during COPS and the GOP, but actions have been taken to allow this even for instruments where BUFR tables are yet to be defined. For almost all instrument types, which are planned for COPS and GOP, the required BUFR tables are already defined or will soon be available by WMO. Exceptions are lidar systems. COPS participants have started to work on the definition of the missing BUFR tables. For introducing BUFR software interfaces and data handling routines, the COPS participants will come together on a programming & implementing workshop in early 2006. For real-time data assimilation, the timely delivery of the observation data needs to be prepared thoroughly; this includes the definition of error characteristics. Initial testing, monitoring and data-assimilation system tuning will to be performed well before the field phase of COPS in summer 2007.

10.4 COPS Data Policy

The following is a draft summary of the COPS/GOP Data Policy that all participants of COPS and the GOP are requested to abide by. Further details shall be provided in the COPS Operations Plan.

1. All investigators participating in COPS or the GOP must agree to promptly submit their data to the joint COPS/GOP Data Archive to facilitate the intercomparison of results, quality control checks and inter-calibrations, as well as an integrated interpretation of the combined data set (up to end of phase 2 of PQP, i.e., up to March 2008, the latest).
2. All data shall be promptly provided to other COPS or GOP investigators upon request. A list of investigators will be maintained by the COPS Project Office and will include the principle investigators directly participating in the field experiment as well as collaborating scientists who have provided guidance in the planning of COPS/GOP activities.
3. During the initial data analysis period (up to end of phase 2 of PQP, i.e., up to March 2008), no data may be provided to a third party (journal articles, presentations, research proposals, other investigators) without the consent of the investigator who collected the data. This initial analysis period is designed to provide an opportunity to quality-control the

combined data set as well as to provide the investigators time to publish their results.

4. All data will be considered community domain for all COPS/GOP investigators after March 2008 and any use of the data will offer co-authorship at the discretion of the investigator who collected the data.
5. After the end of phase 3 of PQP, i.e., March 2010, all data will be considered public domain. In this phase, any use of the data will include either acknowledgment (i.e., citation) or offer co-authorship at the discretion of the investigator who collected the data.

11 References

Albert, P., R. Bennartz, and J. Fischer, 2001: Remote sensing of atmosperic water vapour from backscattered sinlight in cloudy atmospheres. *J. Atmos. Oceanic Technol.*, **18 (6)**, 865-874.

Almeida, F.C., 1976: The collisional problem of cloud droplets moving in a turbulent environment. Part I: A method of solution. *J. Atmos. Sci.*, **33**, 1571-1578.

Andreae, M.O., D. Rosenfeld, P. Artaxo, A.A. Costa, G.P. Frank, K.M. Longo, and M.A.F. Silva-Dias, 2004 : Smoking Rain Clouds over the Amazon. *Science*, **303**, 1337-1342.

Arshinov, Y.F., Bobrovnikov, S.M., Serikov, I.B., Ansmann, A., Wandinger, U., Althausen, D., Mattis, I. and Müller, D., 2005. Daytime Operation of a Pure Rotational Raman Lidar by Use of a Fabry-Perot Interferometer. *Appl. Optics*, **44**(17): 3593-3603.

Bacchi, B., R. Ranzi, and E. Richard (Eds.), 2003: Hydrometeorological processes and floods in the Alps. *Hydrology and Earth Systems Sciences,* issue 6, **7**, 783-948.

Baker, M.B. and R.J. Charlson, 1990: Bistability of CCN concentrations and thermodynamics in the cloud-topped boundary layer. *Nature*, **345(6271)**, 142-145.

Banta, R.M., and C.B. Schaaf, 1987: Thunderstorm genesis zones in the Colorado Rocky Mountains as determined by traceback of geosynchronous satellite images. *Mon. Wea. Rev.*, **115**, 463-277.

Baker, M.B., J. Latham, and R.G. Corbin, 1980: The influence of entrainment on the evolution of cloud droplet spectra: I: A model of inhomogeneous mixing. *Quart. J. Roy. Meteorol. Soc.*, **106**, 581-598.

Bedka, K. M., and J. R. Mecikalski, 2005: Application of atmospheric motion vectors for estimating mesoscale flows. Submitted. *J. Appl. Meteor.*

Beheng, K.D., 1994. A parameterization of warm cloud microphysical conversion processes in a general circulation model. *Atmos. Res.*, **33**, 193-206.

Behrendt, A., V. Wulfmeyer, P. Di Girolamo, H.-S. Bauer, T. Schaberl, D. Summa, D.N. Whiteman, B.B. Demoz , E.V. Browell, S. Ismail, R. Ferrare, C. Kiemle, G. Ehret, J. Wang, 2005: Intercomparison of water vapor data measured with lidar during IHOP_2002, Part 1: Airborne to ground-based lidar systems and comparisons with chilled-mirror radiosondes. Submitted to *J. Atmos. Oceanic. Technol.*.

Behrendt, A., V. Wulfmeyer, C. Kiemle, G. Ehret, T. Schaberl, H.-S. Bauer, E.V. Browell, S. Ismail, R. Ferrare, C. Flamant, 2005: Intercomparison of water vapor data measured with lidar during IHOP_2002, Part 2: Airborne to airborne systems. Submitted to *J. Atmos Oceanic. Technol.*.

Behrendt, A.: Temperature Measurements with Lidar. In: C. Weitkamp (Ed.), Lidar: Range-Resolved Optical Remote Sensing of the Atmosphere, Springer Series in Optical Sciences, Vol. 102, ISBN: 0-387-40075-3, Springer, New York, 273-305, 2005.

Bennartz, R., and J. Fischer, 2001: Retrieval of columnar water vapour over land from backscattered solar radiation using the Medium Resolution Imaging Spectrometer. *Rem. Sens. Environ.*, **78**, 274-283.

Benoit, R., C. Schär, P. Binder, S. Chamberland, H.C. Davies, M. Desgagne, C. Girard, C. Keil, D. Lüthi, K. Müller, P. Pellerin, J. Schmidli, F. Schubiger, C. Schwierz, M. Sprenger, A. Walser, S. Willemse, W. Yu, and E. Zala, 2002: The real-time ultrafinescale forecast support during the special observing period of the MAP. *Bull. Amer. Meteor. Soc.*, **83**, 85-109.

Bergeron, T., 1935: On the physics of cloud and precipitation, Proceedings of the 5th Assembly of the U.G.G.I. Paul Dupont, Paris, Lisbon, Portugal, pp. 156-178.

Bisolli, P., 2001: Wetterlagen und Großwetterlagen im 20. Jahrhundert. In: Klimastatusbericht 2001, DWD, Offenbach, Germany.

Bougeault, P., P. Binder, A. Buzzi, R. Dirks, J. Kuettner, R.B. Smith, R. Steinacker, and H. Volkert, 2001: The MAP specia observing period. *Bull. Amer. Meteorol. Soc.*, **82**, 433-462.

Bousquet, O., and B.F. Smull, 2003: Observations and impacts of upstream blocking during a widespread orographic precipitation event. *Quart. J. Roy. Meteorol. Soc.*, **129**, 392-409.

Bouttier, F., and P. Courtier, 1999: Data assimilation concepts and methods. Meteorological Training Course Lecture Series, ECMWF, available online on: http://www.ecmwf.int/newsevents/training/rcourse_notes/DATA_ASSIMILATION/index.html.

Braham, R.R., and M. Draginis, 1960: Roots of orographic cumuli. *J. Meteor.*, **17**, 214-226.

Brenguier, J.-L., H. Pawlowska, L. Schüller, R. Preusker, J. Fischer, and Y. Fouquart, 2000: Radiative properties of boundary layer clouds: Droplet effective radius versus number concentration. *J. Atmos. Sci.*, **57**, 803-821.

Browning, K.A., 1990: Organisation and internal structure of synoptic and mesoscale precipitation systems in mid-latitudes. In *Battan Memorial Volume on Radar Meteorology*, Ed.: D. Atlas, Amer. Meteor. Soc., Boston, 433-460.

Buizza, R., P.L. Houtekamer, Z. Toth, G. Pellerin, M.Wei, and Y. Zhu, 2005: A Comparison of the ECMWF, MSC and NCEP Global Ensemble Prediction Systems. *Mon. Wea. Rev.*, **133**, 1076–1097.

Calas C., V. Ducrocq, S. Sénési, 2000: Mesoscale analyses and diagnostic parameters for deep convection nowcasting. *Meteorol. Appl.*, **7**, 145-161.

Carbone, R.E., J.D. Tuttle, D.A. Ahijevych, and S.B. Trier, 2002: Inferences of predict-ability associated with warm season precipitation episodes. *J. Atmos. Sci.*, **59**, 2033-2056.

Carlson, T.N., and F.H. Ludlam, 1968: Conditions for the formation of severe local storms. *Tellus*, **20**, 203–226.

Carlson, T.N., S.G. Benjamin, G.S. Forbes, and Y.-F. Li, 1983: Elevated mixed layer in the severe-storm environment – Conceptual model and case studies. *Mon. Wea. Rev.*, **111**, 1453–1473.

Chaboureau, J.-P., F. Guichard, J.-L. Redelsperger, and J.-L. Lafore, 2004: The role of stability and moisture in the diurnal cycle of convection over land. *Quart. J. Roy. Meteorol. Soc.,* **130**, 3105-3117.

Chien, F.C. and C.F. Mass, 1997: A numerical study of the interaction between a warm-season frontal system and the coastal mountains of the western U.S., Part II: Evolution of a Puget Sound Convergence Zone. *Mon. Wea. Rev.*, **125**, 1730-1752.

Chong, M., J.F. Georgis, O. Bousquet, S.R. Brodzik, C. Burghart, S. Cosma, U. Germann, V. Gouget, R.A. Houze Jr., and James 2000: Real-time Wind Synthesis from Doppler Radar Observations during the Mesoscale Alpine Programme. *Bull. Amer. Meteorol. Soc.*, **81**, 2953-2962.

Coakley Jr., J.A., R.L. Bernstein, and P.A. Durkee, 1987: Effect of ship-stack effluents on cloud reflectivity. *Science,* **237**, 1020-1022.

Colle, B.A., K.J. Westrick, and C.F. Mass, 1999: Evaluation of the MM5 and Eta-10 precipitation forecasts over the Pacific Northwest during the cool season. *Wea. Forecasting*, **14**, 137-154.

Crewell, S., M. Drusch, E. Van Meijgaard, and A. Van Lammeren, 2002: Cloud Observations and Modelling within the European BALTEX Cloud Liquid Water Network, *Boreal Environment Research*, **7**, 235-245.

Crewell, S., C. Simmer, H. Bloemink, A. Feijt, S. García, D. Jolivet, O. Krasnov, A. van Lammeren, U. Löhnert, E. van Meijgaard, J. Meywerk, K. Pfeilsticker, M. Quante, S. Schmidt, M. Schröder, T. Scholl, T. Trautmann, V. Venema, M. Wendisch, U. Willén, 2004: The BALTEX Bridge Campaign: An integrated approach for a better understanding of clouds, *Bull. Amer. Meteor. Soc.*, **85(10)**, 1565-1584, doi: 10.1175/BAMS-85-10-1565.

Davis, C., and F. Carr, 2000: Summary of the 1998 workshop on mesoscale model verification. *Bull. Amer. Meteorol. Soc.*, **81(4)**, 809-819.

Donovan, D. P., and A. Van Lammeren, 2001: Cloud effective particle size and water content profile retrievals using combined lidar and radar observations. 1. Theory and examples, *J. of Geophys. Res.*, **106**, 27425-27448.

Dragosavac, M., 2004: BUFR User's Guide. Internal report from ECMWF.

Durran, D.R.; T. Maric, R.M. Banta, L.S. Darby, and R.M. Hardesty: 2003, A comparison of ground-based Doppler lidar and airborne in situ wind observations above complex terrain, *Quart. J. Roy. Meteorol. Soc.*, **129,** 693-713.

Ebert, E.E., U. Dammrath, W. Wergen, and M.E. Baldwin, 2003: The WGNE Assessment of Short-term Quantitative Precipitation Forecasts. *Bull. Amer. Meteorol. Soc.,* **84(4)**, 481–492.

Eisenmann, M., 2004: Güte quantitativer Niederschlagsvorhersagen mit dem Lokal-Modell unter konvektiven Bedingungen (Performance of the Lokal-Modell in convective cases), Diplomarbeit im Fach Meteorologie, September 2004, Institut für Meteorologie und Klimaforschung, Universität Karlsruhe (TH)/Forschungszentrum Karlsruhe

Fabry, F., C. Frush, I. Zawadzki, and A. Kilambi., 1997: On the extraction of near-surface index of refraction using radar phase measurements from ground targets. *J. Atmos. Ocean. Technol.*, **14**, 978–987.

Finke, U., and T. Hauf, 1996: The characteristics of lightning occurrence in southern Germany. Contrib. Atmos. Phys., 69, 361-374.

Friedrich, K., M. Hagen, 2004: On the use of advanced Doppler radar techniques to determine horizontal wind fields for operational weather surveillance. *Meteorol. Appl.*, **11**, 155-171.

Frisch, A. S., G. Feingold, C.W. Fairall, T. Uttal, and J.B. Snider, 1998: On cloud radar and microwave measurements of stratus cloud liquid water profiles, *J. Geophys. Res.*, **103**, 23195-23197.

Fritsch, J.M., and R.E. Carbone, 2004: Improving Quantitative Precipitation Forecasts in the Warm Season: A USWRP Research and Development Strategy. *Bull. Amer. Meteorol. Soc.,* **85(7)**, 955–965.

Gaussiat, N., H. Sauvageot, A.J. Illingworth, 2003: Cloud liquid water and ice content retrieval by multi-wavelength radar. *J. Atmos. Oceanic Tech,* **20**, *1264-1275.*

Gaussiat N., R.J. Hogan, and A.J. Illingworth, 2004: Cloud water content and cloud particle characteristics revealed by dual wavelength cloud radar observations, *Proc. 14th Int. Conf. on Clouds and Precipitation, Bologna, Italy.*

Giuchard, F., J.C. Petch, J.-L. Redelsperger, P. Bechthold, J.-P. Chaboureau, S. Cheinet, W. Grabowski, H. Grenier, C.G. Jones, M. Köhler, J.-M. Piriou, R. Tailleux, and M. Tomasini, 2004: Modelling the diurnal cycle of deep precipitating convection over land with cloud-resolving and single-column models. *Quart. J. Roy. Meteorol. Soc.* **130**, 3139-3172.

Grell, G.A., J. Dudhia, and R.R. Stauffer, 1995: A description of the fith-generation Penn State/NCAR mesoscale model (MM5). *NCAR Technical Note* **TN-398+STR**, 122pp.

Grell, G.A., S.E. Peckham, R.Schmitz, and S.A.McKeen, 2005: Fully coupled online chemistry within the WRF model. *Atmos. Environ.*, accepted.

Grund, C.J., R.M. Banta, J.L. George, J.N. Howell, M.J. Post, R.A. Richter, and A.M. Weickmann, 2001: High-resolution Doppler lidar for boundary layer and cloud research. *J. Oceanic Atmos. Technol.*, **18**, 376-393.

Haase-Straub, S.P., M. Hagen, T. Hauf, D. Heimann, M. Peristeri, and R.K. Smith, 1997: The squall line of 21 July 1992 in Southern Germany: An observational case study. *Beitr. Phys. Atmos.*, **70**, 147-165.

Hagemann, S., B. Machenhauer, R. Jones, O.B. Christensen, M. Déqué, D. Jacob, and P.L. Vidale, 2004: Evaluation of water and energy budgets in regional climate models applied over Europe. *Clim. Dyn.*, **23**, 547-567.

Hagen, M., B. Bartenschlager, and U. Finke, 1999: Motion characteristics of thunderstorms in southern Germany. *Meteorol. Appl.*, **6**, 227-239.

Hagen, M., H.-H. Schiesser, and M. Dorninger, 2000: Monitoring of mesoscale precipitation systems in the Alps and the northern Alpine foreland by radar and rain gauges. *Meteorol. Atmos. Phys.*, **72**, 87-100.

Hallett, J. and S.C. Mossop, 1974: Production of secondary ice particles during the riming process. *Nature*, **249**, 26-28.

Han, Y., and E.R. Westwater, 1995: Remote sensing of tropospheric water vapor and cloud liquid water by integrated ground-based sensors. *J. Atmos. Oceanic Technol.*, **12**, 1050–1059.

Hauf, T., and T.L. Clark, 1989: Three-dimensional numerical experiments on convectively forced internal gravity waves. *Quart. J. Roy. Meteorol. Soc.*, **115**, 309-333.

Henderson, S.W., P.J.M. Suni, C.P. Hale, S.M. Hannon, J.R. Magee, D.L. Bruns, and E.H. Yuen, 1993: Coherent Laser Radar at 2mm Using Solid-State Lasers. IEEE Trans. *Geosci. Remote Sens.*, **31**, 4-15.

Hense, A., G. Adrian, C. Kottmeier, C. Simmer, und V. Wulfmeyer, 2004: Das Schwerpunktprogramm SPP 1167 der Deutschen Forschungsgemeinschaft „Quantitative

Niederschlagsvorhersage“. *Mitteilungen DMG*, 02/2004, 2-5.

Hobbs, P.V., 1978: Organization and structure of clouds and precipitation on the mesoscale and microscale in cyclonic storms. *Rev. Geophys. Space Phys.*, **16**, 741-755.

Hofherr, T., 1999: Gewitterhäufigkeit, Starkniederschlags- und Starkwindereignisse in Deutschland. Diplomarbeit, Institut Meteorologie und Klimaforschung, Universität Karlsruhe.

Hogan, R.J., A.J. Illingworth and H. Sauvageot, 1999: Cloud characteristics from dual wavelength millimeter-wave radar, *Proc. 29th Int. Conf. on Radar Meteorol.*, Montreal, Kanada, 457-459.

Hoinka, K.-P., and H. Volkert, 1987: The German Front Experiment. *Bull. Amer. Meteor. Soc.*, **68**, 1414-1427.

Höller, H., 1994: Mesoscale organization and hailfall characteristics of deep convection in Southern Germany. *Beitr. Phys. Atmos.*, **67**, 219-234.

Höller, H., V. N. Bringi, J. Hubbert, M. Hagen, and P. F. Meischner, 1994: Life cycle and precipitation formation in a hybrid-type hailstorm revealed by polarimetric and Doppler radar measurements. *J. Atmos. Sci.*, **51**, 2500–2522.

Houze, R.A. Jr., W. Schmid, R.G. Fovell, and H.-H. Schiesser, 1993: Hailstorms in Switzerland: left movers, right movers, and false hooks. *Mon. Wea. Rev.*, **121**, 3345-3370.

Jacobson, M.Z., 2003 : Development of mixed-phase clouds from multiple aerosol size distributions and the effect of the clouds on aerosol removal. *J. Geophys. Res.*, **108(D8)**, doi:10.1029/2002/JD002691,2003.

Kalnay, E., 2003: Atmospheric Modeling, Data Assimilation and Predictability, Cambridge University Press.

Kaltenböck, R., 2004: The outbreak of severe storms along convergence lines northeast of the Alps. Case study of the 3 August 2001 mesoscale convective system with a pronounced bow echo. *Atmos. Res.*, **70**, 55-75.

Kamineni, R., T.N. Krishnamurti, R.A. Ferrare, S. Ismail, and E.V. Browell, 2003 : Impact of high resolution water vapor cross sectional data on hurricane forecasting. *Geophys. Res. Lett.*, **30**, 1234-1237.

Kamineni, R., T.N. Krishnamurti, S. Pattnaik, E.V.Browell, S. Ismail, and R.A. Ferrare, 2004 : Impact of CAMEX-4 data sets for hurricane forecasts using a global model. *J. Atmos. Sci.*, submitted.

Khain A. and A. Pokrovsky, 2004: Effects of atmospheric aerosols on deep convective clouds as seen from simulations using a spectral microphysics mixed-phase cumulus cloud model Part 2: Sensitivity study. *J. Atmos. Sci.*, **61**, 2983-3001.

Kossmann, M., U. Corsmeier, S.F.J. de Wekker, F. Fiedler, R. Voegtlin, N. Kalthoff, H. Guesten and B Neininger, 1999: Observations of handover processes between the atmospheric boundary layer and the free troposphere over mountainous terrain. *Contr. Atmos. Phys.*, **72**, 329–50.

Kulmala, M., A. Laaksonen, P. Korhonen, T. Vesala, T. Ahonen, and J.C. Barrett, 1993 : The effect of atmospheric nitric acid vapor on cloud condensation nucleus activation. *J. Geophys. Res.*, **98(D12)**, 22949-22958.

Leigh, C.E., 1974: Theoretical Skill of Monte Carlo Forecasts. *Mon. Wea. Rev.*, **102(6)**, 409–418.

Levin, Z., E. Ganor, and V. Gladstein, 1996: The effects of desert particles coated with Sulfate on rain formation in the Eastern Mediterranean. *J. Appl. Meteorol.*, **35(9)**, 1511-1523.

Lohmann, U., 2002: Possibile aerosol effects on ice clouds via contact nucleation. *J. Atmos. Sci.*, **59**, 647-657.

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. Oceanic Technol.,* **18(8)**, 1354-1366.

Löhnert, U., S. Crewell, C. Simmer, 2004: An integrated approach towards retrieving physically consistent profiles of temperature, humidity, and cloud liquid water, *J. Appl. Meteorol.*, **43(9)**, 1295–1307.

Lugauer, M., H. Berresheim, U. Corsmeier, A. Dabas, W. Dyck, S. Emeis, J. Egger, T. Fehr, F. Fiedler, C. Freuer, L. Gantner, S. Gilge, B. Heese, M. Hornsteiner, H. Höller, G. Jakobi, W. Junkermann, N. Kalthoff, U. Kaminski, M. Kirchner, H. Kraemer, P. Koehler, C. Kottmeier, B. Luksch, C. Plass-Duelmer, O. Reitebuch, M. Tagliazucca, T.Trickl, S. Vogt, and P. Winkler, 2003: An overview of the VERTIKATOR Project and results of alpine pumping. In *Preprints Int. Conf. on Alpine Meteorology, May 2003, Brigg*, 129-132.

Mecikalski, J.R., and K.M. Bedka, 2005: Forecasting convective initiation by monitoring the evolution of moving cumulus in daytime GOES imagery. *Mon. Wea. Rev.* in press.

Medina , S. and R.A. Houze Jr., 2003: Air motions and precipitation growth in alpine storms, *Quart. J. Roy. Meteorol. Soc.*, **129,** 345-372.

Meischner, P., V.N. Bringi, D. Heimann, and H. Höller, 1991: A squall line in Southern Germany: Kinematics and precipitation formation as deduced by advanced polarimetric and Doppler radar measurements. *Mon. Wea. Rev.*, **119**, 678-701.

Meischner, P.F., M. Hagen, T. Hauf, D. Heimann, H. Höller, U. Schumann, W. Jaeschke, W. Mauser, and H.R. Pruppacher, 1993: The field project CLEOPATRA, May-July 1992 in Southern Germany. *Bull. Amer. Meteorol. Soc.*, **74**, 401-412.

Meißner, C., N. Kalthoff, M. Kunz, U. Corsmeier and G. Adrian, 2005: Initialisation of deep convection over low mountain ranges, *Meteorol. Atmos. Phys.*, submitted.

Menzel, W. P., F. C. Holt, T. J. Schmit, R. M. Aune, A. J. Schreiner, and D. G. Gray, 1998: Application of GOES-8/9 soundings to weather forecasting and nowcasting. Bull. *Amer. Meteorol. Soc.*, **79**, 2059–2077.

Mölders, N., and M.A. Olson, 2004: Impact of Urban Effects on Precipitation in High Latitudes. *J. Hydrometeorology*, **5 (3)**, 409-429.

Molteni, F., R. Buizza, C. Marsigli, A. Montani, F. Nerozzi, and T. Paccagnella, 2001: A strategy for high-resolution ensemble prediction. Part I: Definition of representative members and global-model experiments. *Quart. J. Roy. Meteor. Soc.*, **127**, 2069-2094.

Mueller, C., T. Saxen, R. Roberts, J. Wilson, T. Betancourt, S. Dettling, N. Oien, and J. Yee, 2003: NCAR Auto-Nowcast system. *Wea. Forecasting*, **18**, 545-561.

Nair, U.S., R.C. Weger, K.S. Kuo, and R.M. Welch, 1998: Clustering, randomness, and regularity in cloud fields 5. The nature of regular cumulus cloud fields. *J. Geophys. Res.*, **103**, 11363-11380.

Nair, U.S., J.A. Rushing, R. Ramachandran, K.S. Kuo, R.M. Welch, and S.J. Graves, 1999: Detection of cumulus cloud fields in satellite imagery. *SPIE Conf. on Earth Observing Systems IV*, Denver, Colorado, 345-355.

Newton, C.W., 1963: Dynamics of severe convective storms. *Meteor. Monogr.*, **5**, No. 27 (D. Atlas, Ed.), Amer. Meteor. Soc., Boston, 33-58.

Noone, K.J., D.W. Johnson, J.P. Taylor, R.J. Ferek, T. Garrett, P.V. Hobbs, P.A. Durkee, K. Nielsen, E. Öström, C. O'Dowd, M.H. Smith, L.M. Russell, R.C. Flagan, J.H. Seinfeld, L. de Bock, R.E. Van Grieken, J.G. Hudson, I. Brooks, R.F. Gasparovic, and R.A. Pockalny, 2000. A case study of ship track formation in a polluted marine boundary layer. *J. Atmos. Sci.*, **57(16)**, 2748-2764.

Pielke , Jr. R.A. and R.A. Klein, 2001: Extreme Weather Sourcebook 2001 Edition, Environmental and Societal Impacts Group, National Center For Atmospheric Research, and the American Meteorological Society, January. (http://sciencepolicy.colorado.edu)

Preusker, R., J. Fischer, P. Albert, and R. Bennartz, 2004: Cloud top pressure retrieval using the oxygen A-band in the IRS-3 MOS instrument. *Int. J. Rem. Sens.*, accepted.

Pruppacher, H.R. and J.D. Klett, 1997: Microphysics of Clouds and Precipitation. Kluwer Academic Publishers, Dordrecht/Boston/London, 945 pp.

Pudykiewicz, J., R. Benoit, and J. Mailhot, 1992: Inclusion and Verification of a Predictive Cloud-Water Scheme in a Regional Numerical Weather Prediction Model. *Mon. Wea. Rev.*, **120**, 612-626.

Radke, L.F., J.A. Coakley Jr., and M.D. King, 1989: Direct and remote sensing observations of the effects of ships on clouds. *Science*, **246**, 1146-1149.

Ramanathan, V., P.J. Crutzen, J.T. Kiehl, and D. Rosenfeld, 2001: Aerosols, climate, and the hydrological cycle. *Science*, **294**, 2119-2124.

Raymond, D.J., and M.H. Wilkening, 1982: Flow and mixing in New Mexico mountain cumuli. *J. Atmos. Sci.*, **39**, 2211-2228.

Richard, E.., S. Cosma, P. Tabary, and M. Hagen, 2003: High-resolution numerical simulations of the convective system observed in the Lago Maggiore aera on 17 September 1999 (MAP IOP 2a). *Quart. J. Roy. Meteorol. Soc.*, **129**, 543-564.

Rodgers, C.D., 2000: Inverse Methods for Atmospheres: Theory and Practice, World Sci.; Singapore, 238 pp.

Rosenfeld, D., 1999: TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophys. Res. Lett.*, **26**, 3105-3108.

Rosenfeld, D., 2000: Suppression of rain and snow by urban and industrial air pollution. *Science*, **287**, 1793-1796.

Rotach, M.W., P. Calanca, G. Graziani, J. Gurtz, D.G. Steyn, R. Vogt, M. Andretta, A. Christen, S. Cieslik, R. Connolly, S.F.J. De Wekker, S. Galmarini, E.N. Kadygrov, V. Kadygrov, E. Miller, B. Neininger, M. Rucker, E. Van Gorsel, H. Weber, A. Weiss, and M. Zappa, 2004: 'Turbulence structure and exchange processes in an Alpine Valley: The Riviera project', *Bull. Amer. Meteorol. Soc.*, **85(9)**, 1367-1385.

Rudich, Y., A. Sagi, and D. Rosenfeld, 2003: Influence of the Kuwait oil fires plume (1991) on the microphysical development of clouds. *J. Geophys. Res.*, **108(D15)**, AAC 14-1 - AAC 14-8.

Schär, C.; D. Leuenberger, O. Fuhrer, D. Luethi, and C. Girard, 2002: A new Terrain-Following Vertical Coordinate Formulation for Atmospheric Prediction Models, *Mon. Wea. Rev.*, **130**, 2459-2480.

Schär, C., M. Sprenger, D. Lüthi, Q. Jiang, R.B. Smith, and R. Benoit, 2003: Structure and dynamics of n alpine potential vorticty banner, *Quart. J. Roy. Meteorol. Soc.*, **129,** 825-856.

Schär, C., P.L. Vidale, D. Lüthi, C. Frei, C. Häberli, M.A. Liniger and C. Appenzeller, 2004: The role of increasing temperature variability in European summer heatwaves. *Nature* **427**, 332-336.

Schlünzen, K.H., and J.J. Katzfey, 2003: Relevance of sub-grid-scale land-use effects for mesoscale models. *Tellus A*, **55 (3)**, 232-246.

Schüller, L., J.-L. Brenguier, and H. Pawlowska, 2003: Retrieval of microphysical, geometrical and radiative properties of marine stratocumulus from remote sensing. *J. Geophys. Res.*, **108**, 8631, doi: 10.1029/2002JD002680.

Shapiro, M.A., and A.J. Thorpe, 2004: THORPEX: A global atmospheric research programme for the beginning of the 21st century. *WMO Bulletin,* **54(3)**, July 2004.

Segal, Y., A. Khain, M. Pinsky, and A. Sterkin, 2004: Sensitivity of raindrop formation in ascending cloud parcels to cloud condensation nuclei and thermodynamic conditions. *Quart. J. Roy. Meteorol. Soc.*, **130**, 561-581.

Seliga, T.A., and V.N. Bringi, 1976: Potential use of radar differential reflectivity measurements at orthogonal polarizations for measuring precipitation. J. *Appl. Meteorol.*, **15**, 69-76.

Seifert, A., and K.D. Beheng, 2005a: A two-moment cloud microphysics parameterization for mixed-phase clouds. Part I: Model description. *Meteorol. Atmos. Phys.*, DOI 10.1007/s00703-005-0112-4.

Seifert, A., and K.D. Beheng, 2005b: A two-moment cloud microphysics parameterization for mixed-phase clouds. Part II: Deep convective storms. *Meteorol. Atmos. Phys.*, DOI 10.1007/s00703-005-113-3.

Skamarock, W.C., J.B. Klemp, J. Dudhia, D.O. Gill, D.M. Barker, W. Wang, and J.G. Powers, 2005: A Descrip-tion of the Advanced Research WRF Version 2. *NCAR Technical Note* **TN-468+STR**, 88pp.

Stankov, B.B., 1998: Multisensor retrieval of atmospheric properties. *Bull. Amer. Meteor. Soc.*, **79**, 1835 - 1854.

Stoelinga, M.T., P.V. Hobbs, C.F. Mass, J.D. Locatelli, N.A. Bond, B.A. Colle, R.A. Jr. Houze, and A. Rangno, 2003: Improvement of Microphysical Prameterization through Observational Verification Experiment (IMPROVE). *Bull. Amer. Meteorol. Soc.*, **17,** 1807-1826.

Turner, D.D., W.F. Feltz, and R.A. Ferrare, 2000: Continuous water vapor profiles from operational ground-based active and passive remote sensors, *Bull. Amer. Meteorol. Soc.*, **81**, 1301-1317.

Van Lipzig, N.P.M., H. Wernli, S. Crewell, L. Gantner, and A. Behrendt, 2005: Synthesis of preliminary results of SPP verification projects. Newsletter PP1167 'Quantitative Niederschlagsvorhersage' , 25 pages, 26.08.2005,- Nr. 1/2005b.

Vaillancourt, P.A., and M.K. Yau, 2000. Review of particle-turbulence interactions and consequences for cloud physics. *Bull. Amer. Meteorol. Soc.*, **81(2)**, 285-298.

Vivekanandan, J., D.S. Zrnic, S.M. Ellis, R. Oye, A.V. Ryzhkov, and J. Straka, 1999: Cloud microphysics retrieval using S-band dual-polarization radar measurements. *Bull. Amer. Meteorol. Soc.*, **80**, 381–388.

Vivekanandan, J., G. Zhang, and E. Brandes, 2004: Polarimetric radar estimators based on a constrained gamma drop size distribution model. *J. Appl. Meteorol.*, **43**, 217–230.

Volkert, H., 2004: Progress in the Atmospheric Sciences during the past ten years: What did MAP contribute?, *Preprints 11th AMS Conference on Mountain meteorology*, 21-25 June 2004, Bartlett, NH, paper 12.1 (pdf on conference web page).

Walser A; D. Lüthi, and C. Schär: 2004: Predictability of precipitation in a cloud-resolving model. *Mon. Wea. Rev.*, **132**, 2, 560-577.

Warner, J., 1969: The microstructure of cumulus clouds. Part II. The effect of droplet size distribution, of the cloud nucleus spectrum, and updraft velocity. *J. Atmos. Sci.*, **26**, 1272-1282.

Weckwerth, T.B., D.B. Parsons, S.E. Koch, J.A. Moore, M.A. LeMone, B.B. Demoz, C. Flamant, B. Geerts, J. Wang and W.F. Feltz, 2004: An Overview of the International H_2O Project (IHOP_2002) and Some Preliminary Highlights. *Bull. Amer. Meteorol. Soc.,* **85**, 253–277.

Weckwerth, T., and D. Parsons, 2005: Outstanding issues in convection initiation: Motivation for IHOP_2002. Mon. *Wea. Rev.*, in press.

Weckwerth, T. M., C. R. Pettet, F. Fabry, S. Park, M. A. LeMone, and J. W. Wilson, 2005: Radar refractivity retrieval: Validation and application to short-term forecasting. *J. Appl. Meteorol.*, **44**, 285–300.

Westwater, E.R., 1997: Remote sensing of tropospheric temperature and water vapor by integrated observing systems. Bull. *Amer. Meteorol. Soc.*, **78**, 1991-2006.

Wilson, J. W., R. D. Roberts, and C. K. Mueller, 2005: Summary of convective storm initiation during IHOP: Observational and modeling perspective. *Mon. Wea. Rev.*, in press.

Woodcock, A.H. and W.A. Mordy, 1955: Salt nuclei, wind and daily rainfall in Hawaii. *Tellus*, **7(3)**, 291-300.

Wulfmeyer, V., and C. Walther, 2001a: Future performance of ground-based and airborne water vapor differential absorption lidar. I: Overview and theory. *Appl. Opt.,* **40**, 5304-5320.

Wulfmeyer, V., and C. Walther, 2001b: Future performance of ground-based and airborne water vapor differential absorption lidar. II: Simulations of the precision of a near-infrared, high-power system. *Appl. Opt.*, **40**, 5321-5336.

Wulfmeyer, V., H.-S. Bauer, S. Crewell, G. Ehret, O. Reitebuch, C. Werner, M. Wirth, D. Engelbart, A. Rhodin, W. Wergen, A. Giesen, H. Grassl, G. Huber, H. Klingenberg, P. Mahnke, U. Kummer, C. Wührer, P. Ritter, R. Wallenstein, and U. Wandinger, 2003: Lidar Research Network Water Vapor and Wind. *Meteorol. Zeitschrift*, **12**, 5-24.

Wulfmeyer, V., H.-S. Bauer, M. Grzeschik, A. Behrendt, F. Vandenberghe, E.V. Browell, S. Ismael, and R. Ferrare, 2005: 4-dimensional variational assimilation of water vapor differential absorption lidar data: The first case study within IHOP_2002. *Mon. Wea. Rev*. 2005, in press.

Yin, Y., Z. Levin, T.G. Reisin, and S. Tzivion, 2000: The effects of giant cloud condensation nuclei on the development of precipitation in convective clouds - a numerical study. *Atmos. Res.*, **53**, 91-116.

Yin, Y., S. Wurzler, Z. Levin, and T.G. Reisin, 2002: Interactions of mineral dust particles and clouds: effects on precipitation and cloud optical properties. *J. Geophys. Res.,* **107(D23)**, AAC 19 pp.

Zängl, G., 2004a: The sensitivity of simulated orographic precipitation to model components other than cloud microphysics. *Quart. J. Roy. Meteorol. Soc.*, **130**, 1857-1875.

Zängl, G., 2004b: Numerical simulations of the 12-13 August 2002 flooding event in eastern Germany. *Quart. J. Roy. Meteorol. Soc.*, **130**, 1921-1940.

Zappa, M. and J Gurtz, 2003: Simulation of soil moisture and evapotranspiration in a soil profile during the 1999 MAP-Riviera Campaign. *Hydrology and Earth Systems Sciences,* issue 6, **7**, 903 – 919.

Zhang, G., J. Vivekandan, and E. Brandes, 2001: A method for estimationg rain rate and drop size distribution from polarimetric radar measurements. *IEEE Trans. Geosci. Rem. Sens.*, **39**, 830-841.

Appendix I: Interested Parties

a) Universities

German PQP community

Germany:

Universities of Bayreuth, Berlin, Bonn, Braunschweig, Cologne, Freiburg, Hamburg, Hannover, Hohenheim, Karlsruhe, Leipzig, Mainz, Munich, Stuttgart

International:

ETH Zurich, Pennsylvania State University (USA), University of Basilicata (Italy), University of Clermont-Ferrand (France), University of Kyoto (Japan), University of Leeds (UK), University of Vienna (Austria), Technical University of Delft (The Netherlands)

b) Research Centers

Germany:

DKRZ, DLR, FZJ, FZK, GFZ, IfT, MPIfC, MPIfM

International:

FSL, IMAA (I), NASA (USA), NCAR (USA), NOAA (USA), RISH (J)

c) Weather Forecast Centers

DWD, Meteo-France, Meteo-Swiss, ECMWF, UK Met Office

d) Organizations

ESA, EUMETSAT, EUCOS, NASA, WWRP

Appendix II: Atmospheric Models and Data Assimilation Systems to be Used Within COPS

	Provider	**Configuration**		**Nest ing**	**Data assimilation**	**Boundary forcing**
		operational	**research**			
IFS (global)	ECMWF	T511 (40 km) resolution 60 vertical levels	same	no	4DVAR with 12 hour assimilation window	no
ECMWF EPS (global)	ECMWF	Ensemble prediction system with 51 members, ca 80km (T256)	same	no		
Unified Model Global (UM-G)	UK Met Office	- 40 km horizontal resolution in mid latitudes - 432x325 grid points - 38 vertical levels - 48 hr forecasts every 6 hr - 144 hr forecast every 12 hr	same	no	6 hourly 3DVAR data assimilation cycle (planned to be 4DVAR by 2005)	no
UM-ELA (European limited Area)	UK Met Office	- 20 km horizontal resolution, covers whole North Atlantic and Europe - 48 hr forecasts every 6 hr (currently under testing)	same		3 hourly 3DVAR data assimilation cycle	UM (global)
UM-M (mesoscale)	UK Met Office	- 11 km horizontal resolution (this will improve to 4 km by 2005) - 146x182 grid points centered over the UK - 38 vertical levels - 48 hr forecasts every 6 hr	same		3 hourly 3DVAR data assimilation cycle plus cloud and rainfall assimilation using nudging	UM (global, limited area)
GME (global)	DWD	- 60 km resolution - 31 vertical levels - 200 s time step - 00Z forecast for 78 hours - 12 Z forecast for 174 hours	same	no	OI soon 3DVAR	no
LME under develop-ment	DWD	- 7 km resolution - 665x657 grid points - 40 s time step - 40 vertical levels	Simulations with variable horizontal and vertical resolution from real and artificial initial conditions are possible	no	Nudging	GME ECMWF
LMK under develop-ment	DWD, FZK	- 2.8 km resolution - 421x461 grid points - 30 s time step - 50 vertical levels - 18h forecasts every 3 hours		no	Nudging Latent heat nudging of radar data	GME ECMWF

LM	DWD, FZK	- 7 km resolution - 325x325 grid points - 40 s time step - 35 vertical levels - 00Z,12Z,18Z forecast for 48 hours		no	Nudging	GME ECMWF
aLMo	Meteo Swiss	7 km resolution 385 x 325 grid points 40s time step 45 vertical levels 00Z, 12Z forecast	same	no	nudging	ECMWF
aLMo2.2	Meteo Swiss	2.2km resolution 480x350 grid points, 10-40 s approx. 60-80 vertical levels forecast every 3 hrs. over 18 hrs	same	no	nudging	ECMWF, aLMo(7)
MM5 (global version available)	NCAR/ PennState	Used for real time numerical weather prediction in various configurations	- global to 1 km resolution - arbitrary domain & time step - idealised simulations	1-way, 2-way, moving	Nudging (obs+ana) 3DVAR, 4DVAR	ECMWF NCEP
WRF **under development**	NCAR/…	Real-time tests in different configurations	- global to 1 km resolution - arbitrary domain & time step - idealized simulations	1-way, 2-way, moving	3DVAR, Nudging (?) 4DVAR under development	ECMWF NCEP
MC2	MSC	Various high-resolution real-time applications (e.g. McGill, MAP, …) - 3 km horizontal resolution - 400x490 grid points - 35-60 vertical levels - 12-18 hour forecasts	Various idealized applications using different model configs.			
Arôme	Meteo-France	Under development, pre-operational tests with 2.5 km resolution starting in 2006, operational usage planned for 2008	same			
Meso-NH	Meteo-France	6 – 50 km horizontal resolution	Usable with resolutions from mesoscale to microscale	yes		

COSMO-LEPS quasi operational	ARPA-SIM	- Based on LM version 3.9 resolution 10 km - 306x258 grid boxes - 60 s time step - 32 vertical levels - forecast range 120 h	idem	no		ECMWF
ARPS	CAPS Oklahoma University		Many – down to 150m horizontal resolution	1-way	3DVAR	ECMWF, NCEP (others?)
METRAS with an aerosol/ cloud model (MITRAS)	MI Hamburg	No	Idealized simulations with resolution 50 m – 2 km		Nudging	
RAMS	Colo State Univ	operational upon request	Many	2-way	?	various

Appendix III: COPS Organizational Structure and International Science Steering Committee (ISSC)

Project Office: Institute of Physics and Meteorology, University of Hohenheim
COPS Coordinator: Andreas Behrendt, Dr.

Volker Wulfmeyer,	Prof. Dr.; Institute of Physics and Meteorology (IPM), Hohenheim University (UHOH), Stuttgart, Germany, Chair
Christoph Kottmeier,	Prof. Dr.; Institute of Meteorology and Climate Research (IMK), University of Karlsruhe/Forschungszentrum Karlsruhe, Germany, Co-Chair
Gerhard Adrian,	Prof. Dr.; German Meteorological Service (DWD), Offenbach, Germany
Alan Blyth,	Prof. Dr.; School of Environment, University of Leeds, UK
Ed Browell,	Dr.; NASA Langley Research Center, Hampton, Virginia, USA
George Craig,	Dr., Institute of Atmospheric Physics (IPA), Head Department of Cloud Physics and Traffic Meteorology, DLR Oberpfaffenhofen, Germany
Susanne Crewell,	Prof. Dr.; Institute of Meteorology, TU Munich, Munich, Germany
Kenneth J. Davis,	Prof. Dr.; Pennsylvania State University, University Park, Pennsylvania, USA
Hartmut Graßl,	Prof. Dr.; Max-Planck-Institute of Meteorology (MPIfM), Hamburg, Germany
R. Michael Hardesty,	Dr.; Environmental Techology Laboratory, NOAA, Boulder, CO, USA
Jost Heintzenberg,	Prof. Dr.; Institute for Tropospheric Research, Leipzig, Germany
Jos Lelieveld,	Prof. Dr.; Max-Planck-Institute for Chemistry, Mainz, Germany

Dave Parsons, Dr.; NCAR MMM, Boulder, Colorado, USA

Evelyne Richard, Dr.; Laboratoire d'Aerologie, University of Toulouse, Toulouse, France

Mathias Rotach, Prof. Dr.; Meteo Swiss, Zurich, Switzerland

Herman Russchenberg, Dr.; International Research Centre for Telecommunications-Transmission and Radar (IRCTR), Delft University of Technology, Delft, The Netherlands

Peter Schlüssel, Dr.; EUMETSAT, Darmstadt, Germany

Ulrich Schumann, Prof. Dr.; Head Institute of Atmospheric Physics (IPA), DLR Oberpfaffenhofen, Germany

Reinhold Steinacker, Prof. Dr.; Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria

Tammy Weckwerth, Dr.; NCAR ATD, Boulder, Colorado, USA

COPS Working Groups and Chairs

1. **Initiation of convection (CI),**
   Chair: Christoph Kottmeier,
   Prof. Dr.; Institute of Meteorology and Climate Research (IMK), University of Karlsruhe/Forschungszentrum Karlsruhe, Germany
2. **Aerosol and cloud microphysics (ACM),**
   Chair: Jost Heintzenberg
   Prof. Dr.; Institute for Tropospheric Research, Leipzig, Germany
3. **Precipitation processes and life cycle (PPL),**
   Chair: Martin Hagen,
   Dr.; Institute of Atmospheric Physics (IPA),
   DLR Oberpfaffenhofen, Germany
4. **Data assimilation and predictability (DAP),**
   Chair: George Craig,
   Dr.; Institute of Atmospheric Physics (IPA),
   DLR Oberpfaffenhofen, Germany

Appendix IV: Abbreviations

1D, 2D, 3D, 4D 1-Dimensional, 2-Dimensional, 3-Dimensional, 4-Dimensional

3DVAR ....3 Dimensional Variational Assimilation

4DVAR ....4 Dimensional Variational Assimilation

ACM ....Aerosol and Cloud Microphysics, working group of COPS

ACTOS ....Airborne Cloud Turbulence Observation System

AERI ....Atmospheric Emitted Radiance Interferometer

AIRS ....Atmospheric Infrared Sounder

aLMo..........................Alpine Model (based on LM)

AMF...........................ARM Mobile Facility

AQUA ....Advances in Quantitative Areal Precipitation Estimation by Radar, DFG project

ARM ....Atmospheric Radiation Measurement

Arôme ....New French mesoscale forecast model

ARPA-SIM ....Agenzia Regionale Prevenzione e Ambiente Dell'Emilla-Romagna – Servizio Idro Meteo

ARPS..........................Advanced Regional Prediction System

ATR 42.......................Avions de Transport Regional 42 (aircraft)

ATReC ....Atlantic-THORPEX Regional Campaign

BAe 146 ....British Aerospace 146 (aircraft)

BALTEX....................Baltic Sea Experiment

BUFR ....Binary Universal Form for the Representation

CAPE ....Convective Available Potential Energy

CAPS..........................Coupled Atmosphere–Plant–Soil (global model)

CART.........................Cloud and Radiation Testbed

CCN ....Cloud Condensation Nuclei

CEOP ....Coordinated Enhanced Observing Period

CI ....Convection Initiation

CLEOPATRA ....Cloud Experiment Oberpfaffenhofen And Transport (campaign 1991)

CLIWA-NET ....Cloud Liquid Water Network

CloudNET ....Research project supported by the European Comission

CLOUDSAT ....NASA Earth System Pathfinder Satellite mission

CNRS ....Centre Nationale de la Recherche Scientific

CODI..........................Compact DIAL

COPS..........................Convective and Orographically-induced Precipitation Study (= intensive observations period (IOP) of PQP)

COSI-TRACKS ....Convective Storm Institute within TRACKS

COSMO-LEPS...........Consortium On Small Scale MOdelling-Local Ensemble Prediction System

COST-720 ....European Cooperation in the Field of Science and Technology, Action 720: Integrated Ground-Based Remote Sensing Stations for Atmospheric Profiling

CrIS ....Cross-Track Infrared Sounder

CSIP ....Convective Storm Initiation Project (UK, summer 2005)

CVI.............................Counterflow Virtual Impactor

D-PHASE...................Demonstration of Probabilistic Hydrological and Atmospheric Simulation of flood Events in the Alpine region; MAP Forecast Demonstration Project

DAP............................Data Assimilation and Predictability, working group of COPS

DAQUA ....Combined Data Assimilation with Radar and Satellite Retrievals and Ensemble Modelling fort he Improvement of Short Range Quantitative Precipitation, project within PQP

DFG............................German Research Foundation, Deutsche Forschungsgemeinschaft

DIAL ....Differential Absorption Lidar

DLR............................Deutsches Zentrum für Luft- und Raumfahrt

DOE ....Department of Energy

DOW ....“Doppler-on-Wheels”, mobile radar system

DSD............................Drop Size Distribution

DWD ....Deutscher Wetterdienst, German Meteorological Service

EC ....European Comission

ECHAM5 ....ECMWF model HAMburg version, release 5

ECMWF.....................European Centre for Medium-Range Weather Forecasts

EMETNET ....The Network of European Meteorological Services

Envisat........................Environmental Satellite

EOS ....Earth Observing System

EPS.............................The Canadian ensemble prediction system

ESA ....European Space Agency

ETReC07....................European THORPEX Regional Campaign 2007

EU ....European Union

EUCOS ....EUMETNET Composite Observing System

EULINOX..................European Lightning Nitrogen Oxides Project

EUMETSAT ....European Organization for the Exploitation of Meteorological Satellites

FDDA.........................Four Dimensional Data Assimilation

FDP ....Forecast Demonstration Project

FM-CW ....Frequency Modulated Continuous Wave

FSL............................Forecast Systems Laboratory

FTIR ....Fourier Transformed Infrared

FZJ ....Research Center Jülich

FZK/UKa ....Forschungszentrum Karlsruhe, Universität Karlsruhe

GFZ ....GeoForschungsZentrum Potsdam, Research Centre for Geosciences Potsdam

GME...........................Global Model of the DWD

GOES ....Geostationary Satellite Server

GOP............................General Observations Period of PQP

GPCP..........................Global Precipitation Climatology Project

GPS ....Global Positioning System

GTS ....Global Telecommunication System

GWA ....Ground Water Atlas

HATPRO....................Humidity and Temperature Profiler

HELIPOD ....Helicopter-borne Turbulence Probe, University of Braunschweig

HGF............................Helmholtz-Gemeinschaft Deutscher Forschungszentren

HODAR ....Holographic Particle Recorder, University of Mainz

HRDL.........................High-Resolution Doppler Lidar

HTDMA.....................Humidified Tandem Differential Mobility Analyzer

IASI ....Infrared Atmospheric Sounding Interferometer

ICG.............................Institut für Chemie der Geosphäre

IFS..............................Integrated Forecast System of ECMWF

IfT ....Institute for Tropospheric Research

IHOP_2002 ....International Water Vapor Project 2002 (USA, 2002)

IMAA ....Istituto di Metodologie per l'Analisi Ambientale

IMK ....Institut für Meteorologie und Klimaforschung, Karlsruhe

IMPROVE..................Improvement of Microphysical Prameterization through Observational Verification Experiment

INSU .... Institut National des Sciences de l'Univers

INT ....Interstitial Inlet

IOP ....Intensive Observations Period = COPS

IPA ....Institute of Atmospheric Physics

IPM ....Institute of Physics and Meteorology, University of Hohenheim

IPT ....Integrated Profiling Technique

IR ....infrared

IRCTR........................International Research Centre for Telecommunications-Transmission and Radar

ISSC ....International Science Steering Committee

IWV ....Integrated columnar Water Vapour

KAMM ....Karlsruher Mesoscale Model

LaMMA ....Laboratory for Meteorology and Environmental Modelling

LAUNCH2005 ....International Lindenberg campaign for assessment of humidity and cloud profiling systems and its impact on high-resolution modelling, Field experiment (Germany & Italy, 2005)

LINOX ....Lightning produced NO_X (1996)

LM ....Lokalmodell of DWD

LME ....LM Europe

LMK ....Lokal Modell Kürzestfrist

LWC ....Liquid Water Content

LWP ....Liquid Water Path

MAP ....Mesoscale Alpine Programme

MC2 ....Modèle Mésoéchelle Compressibile Communautaire (Canada)

MERIS ....Medium Resolution Imaging Spectrometer

Méso-NH ....french mesoscale model

Met Office UK ....British Weather Service

Meteo France ....French Weather Service

MeteoSwiss ....swiss Weather Service

METRAS ....Mesoscale Transport and Fluid Model

MICCY ....Microwave Radiometer for Cloud Cartography

MITRAS ....Microscale Transport and Fluid Model

MM5 ....Mesoscale Model Release 5

MMM ....Micro Meteorological Masts

MODIS ....Moderate Resolution Imaging Spectroradiometer

MPI ....Max-Planck-Institute

MPIfC ....MPI for Chemistry

MPIfM ....MPI for Meteorology

MRR ....Micro rain radar

MSC ....Meteorological Service of Canada

MSG ....Meteosat Second Generation

MWL ....Multi-Wavelength Raman Lidar of IfT

NASA ....National Aeronautics and Space Administration

NCAR ....National Center for Atmospheric Research

NCAR ATD ....NCAR Atmospheric Technology Division

NCAR MMM ....NCAR Mesoscale & Microscale Meteorology Division

NCAS ....NERC Centres for Atmospheric Science

NCEP ....National Centers for Environmental Prediction

NERC..........................Natural Environment Research Council

NINJO ....Meteorological workstation of DWD

NIR.............................near infrared

NOAA ....National Oceanic & Atmospheric Administration

NSF ....National Science Foundation (USA)

NVaP..........................NASA Water Vapor Project

NWP...........................Numerical Weather Prediction

OC ....Operations Center

OP ....Operations Plan

PBL ....Planetary Boundary Layer

PEPS ....Poor Man's EPS

PI ....Principal Investigator

POLDIRAD ....Polarization Diversity Doppler Radar, DLR Oberpfaffenhofen

PP ....priority program (= SPP1167, Schwerpunktprogramm1167 = PQP)

PPL.............................Precipitation Processes and its Life Cycle, working group of COPS

PQP ....Praecipitationis Quantitativae Praedictio (Latin for "quantitative precipitation forecast"), Priority Program 1167 of DFG

PrI...............................Precipitation Initiation

QPF ....Quantitative Precipitation Forecast

RAMS ....Regional Atmospheric Modeling System

RASL ....Raman Airborne Spectroscopic Lidar

RASS..........................Radio Acoustic Sounding System

RDSD.........................Rain Drop Size Distribution

REAL ....Raman-shifted Eye-save Aerosol Lidar

REKLIP......................Regionales Klimaprojekt

RISH ....Research Center for a Sustainable Humanosphere

RR ....Rain Rate

RR ....Rotational Raman

RS...............................Radiosonde

RV ....Reduction of variance

S-POL ....S-band Dual Polarization Doppler Radar

S-POL ....S-Pol radar of NCAR

SAFIRE......................Surveillance et Alerte Foudre par Interférometrie Radioélectrique; Blitz-Ortungssystem des Instituts für Meteorologie und Klimatologie, Universität Hannover

SETEX ....Severe Thunderstorms Experiment

SEVIRI........................Spinning Enhanced Visible and Infra-Red Imager

SFB ....Sonderforschungsbereich

SGP ....Southern Great Plains

SISOMOP ....Simple Soil Moisture Probe

SMPS ....Scanning Mobility Particle Spectrometer

SOD............................Science Overview Documentation of COPS

Sodar ....Sonic Detecting and Ranging

SOP ....Special Observing Period

SRB ....Surface Radiation Budget

SRL ....Scanning Raman Lidar

SRQPF ....Short-Range QPF, project within PQP

SSC ....Science Steering Committee

SSM/I ....Special Sensor Microwave Imager

SYNOP ....Surface Synoptic Observations

TDR............................Temperature Data Record

THORPEX ....The ObservingSystem Research and Predictability Experiment

TIGGE........................THORPEX Interactive Grand Global Ensemble

TIROS ....Television Infrared Observation Satellite

TOVS ....TIROS Operational Vertical Sounder

TRACKS....................Transport and Chemical Conversion in Convective Systems; HGF project

TRACT ....TRansport of Air pollutants over Complex Terrain

TreCs..........................THORPEX Regional Campaigns

UCAR ....University Corporation for Atmospheric Research

UFAM ....Universities' Facility for Atmospheric Measurement

UHF............................Ultra High Frequency

UHOH ....Universität Hohenheim, University of Hohenheim

UK..............................United Kingdom

UM-ELA ....Unified Model – European Limited Area

UM-G ....Unified Model - Global

UM-M ....Unified Model - Mesoscale

US ....United States

UTC............................Coordinated Universal Time

UTMS ....Urban Transportation Modeling System

UV..............................ultraviolet

UWKA ....University of Wyoming King Air

VERTIKATOR ....Vertikaler Transport und Orographie, Field experiment, see http://www.vertikator-afo2000.de/ (Germany, 2002)

VIS ....visible

WCRP ....World Climate Research Programme

WDCC........................World Data Center for Climate

WG ....Working Group of COPS

WiLi ....Wind Lidar of IfT

WindTracer ....Scanning Doppler Wind Lidar from IMK/FZK

WMO ....World Meteorological Organization

WRF...........................Weather Research & Forecasting Model, mesoscale model

WRF-Chem ....WRF with a chemistry module

WSR-88D...................Weather Surveillance Radar 88 Doppler

WTR...........................Wind-Temperature Radar

WV ....Water Vapour

WWRP ....World Weather Research Programme

WWRP RDP ....WWRP Research and Development Project