Science Plan 2010-2014

Publication date: 30.11.2010

List of main authors by chapter / section

1	M. Arpagaus (MeteoSwiss)
2	M. Arpagaus (MeteoSwiss), H.-J. Koppert (DWD), D. Majewski (DWD)
3	M. Arpagaus (MeteoSwiss), H.-J. Koppert (DWD), M.W. Rotach (MeteoSwiss)
4	M. Arpagaus (MeteoSwiss), H.-J. Koppert (DWD), M.W. Rotach (MeteoSwiss), U. Blahak (DWD)
5	M. Baldauf (DWD)
6.1	D. Mironov (DWD), M. Raschendorfer (DWD)
6.2	F. Grazzini (ARPA-SIMC)
6.3	A. Seifert (DWD)
6.4	J. Helmert (DWD), J.-M. Bettems (MeteoSwiss)
6.5	B. Ritter (DWD)
6.6	D. Mironov (DWD)
6.7	D. Mironov (DWD)
6.8	H. Asensio (DWD)
7	C. Schraff (DWD), R. Potthast (DWD)
8	C. Marsigli (ARPA-SIMC), S. Theis (DWD), P. Eckert (MeteoSwiss)
9	A. Raspanti (USAM), F. Schubiger (MeteoSwiss)
10	U. Schättler (DWD)
11	M. Arpagaus (MeteoSwiss), H.-J. Koppert (DWD)
12	M. Arpagaus (MeteoSwiss), D. Majewski (DWD)
A1	M. Arpagaus (MeteoSwiss), H.-J. Koppert (DWD)

Table of Contents

1 Management Summary

This document describes the COSMO goal and the strategy to attain the goal for the 5-year period 2010-2014, and details the subsequent actions for the future development of the COSMO model.

The COSMO goal is to develop a model-system for the short to very short range with a convective-scale resolution to be used for operational forecasting of mesoscale weather, especially high impact weather. The strategic elements to achieve this goal are:

- an ensemble prediction system for the convective scale;
- an ensemble-based data assimilation system for the convective scale;
- extension of the environmental prediction capabilities of the model;
- a verification and validation tool for the convective scale;
- an intermediate resolution COSMO version for the provision of boundary conditions;
- use of massively parallel computer platforms;
- intensified collaboration within and beyond COSMO.

For each scientific area (dynamics and numerics, physics, data assimilation, predictability and EPS, validation and diagnostics, and computational aspects) a number of actions responding to the goal and strategy are identified (selection of currently ongoing and resource-intensive actions only):

- development of a conserving dynamical core (Priority Project CDC);
- progression towards a unified turbulence-shallow convection scheme (Priority Project UTCS);
- consolidation of the lower boundary conditions, including a revised soil, a newly available fresh-lake, and an urban module, as well as improved external parameters (Priority Project COLOBOC);
- design of an ensemble-based data assimilation system employing a Local Ensemble Transform Kalman Filter (LETKF; Priority Project KENDA);
- development of a convective-scale Ensemble Prediction System (COSMO-DE-EPS project);
- consolidation of the convection parameterisation employing short-range COSMO-SREPS and unification with COSMO-LEPS to form a single operational EPS for the short to medium range (Priority Project CONSENS);
- development of a common verification and validation tool that allows for the quality assessment of all the different deterministic as well as probabilistic COSMO implementations (Priority Project VERSUS 2);
- preparation of the model code for future computers and refactoring of selected model components for emerging architectures.

2 Introduction

COSMO (**"Consortium for Small Scale Modelling"**, http://www.cosmo-model.org) is a consortium among the national meteorological services of Germany (DWD), Greece (HNMS), Italy (USAM), Poland (IMGW), Romania (NMA), Russia (ROSHYDROMET) and Switzerland (MeteoSwiss). Through their national meteorological services, a number of additional institutions are participating in COSMO: The Office for Geo Information of the German armed forces (Germany), ARPA-SIMC (regional hydro-meteorological service, Emilia-Romagna, Italy), ARPA-Piemonte (regional hydro-meteorological service, Piedmont, Italy), and CIRA (Italian Aerospace Research Centre).

In addition, COSMO interacts very closely with academia, especially in the field of regional climate modelling (**COSMO-CLM**; http://www.clm-community.eu) and environmental prediction (**COSMO-ART**; http://www.imk-tro.kit.edu). These academic cooperations provide indispensable input to the further development of the COSMO modelling system and its applications.

COSMO is led by a **Steering Committee (STC)**, with a representative from each full member. The Chairman of the STC is, among other things, responsible for the relationship with third parties. The **Scientific Project Manager (SPM)** coordinates the scientific collaboration between the members and is the focal point for the exchange with other consortia as ex-officio member of the SRNWP Advisory Committee.

COSMO is organised along **Working Groups (WGs)**, which are concerned with, respectively

WG 1: Data assimilation

WG 2: Numerical aspects

WG 3: Physical aspects

WG 4: Interpretation and applications

WG 5: Verification and case studies

WG 6: Reference version and implementation

WG 7: Predictability and ensemble methods

Each of the member countries has agreed to dedicate staff resources equivalent to at least two full-time scientists (so-called FTEs, full time equivalents) to COSMO and its tasks. In order to streamline COSMO's activities, the STC has decided in 2006 to introduce so-called **Priority Projects (PPs)**. Since then, members are required to deliver their yearly 2 FTEs within the tasks as specified in the Priority Projects.

The WG and PP leaders together with the SPM, the chairperson of the STC, the coordinators of the CLM and ART communities, and the DWD COSMO Coordinator form the **Scientific Management Committee (SMC)**.

The present **COSMO Science Plan** defines the **goal** of COSMO, **identifies the strategy to achieve the goal**, summarizes related research issues and scientific developments as well as the status and expertise of COSMO, and outlines **proposed actions**.

The **scope of the Science Plan** is the **5-year period 2010-2014** with an **outlook to 10 years ahead**, and encompasses the COSMO model, the verification and validation tool needed to assess the quality of the COSMO model, the computational aspects related to the COSMO model as well as the COSMO consortium, if needed.

Explicitly **out of scope** of this document are therefore:

- **Pre- and post-processing tools** such as INT2LM, ODB, fieldextra, NinJo, etc. – However note that both INT2LM and fieldextra are important tools not only within COSMO, where the limited human resources ask for a full exploitation of the synergies available from employing common pre- and post-processing tools, but also in the context of the SRNWP Interoperability Programme.
- **Standalone application models** for, e.g., air quality, chemistry, dispersion modelling, hydrology, ocean waves, etc.

The strategic goals and further development of COSMO-CLM and COSMO-ART are formulated by the academia in close cooperation with COSMO, but only briefly mentioned in this COSMO Science Plan.

Chapter 3 highlights the most important general developments in Numerical Weather Prediction (NWP) and related areas which are relevant for the COSMO Science Plan. Chapter 4 depicts the COSMO goal, the strategy to achieve the goal, and the corresponding research issues. Chapters 5 to 10 discuss the scientific developments as well as the status and expertise of COSMO and detail the proposed actions pertinent to both goal and strategy for each scientific area. Finally, chapter 11 documents the most important external collaborations for the COSMO model development, chapter 12 acknowledges the very helpful review of the COSMO Science Plan by colleagues outside COSMO, chapter 13 contains a list of references, and appendix A1 provides a SWOT analysis of both the COSMO model as well as the COSMO consortium.

3 General developments

This chapter briefly reviews the most important general developments relevant for COSMO and its Science Plan. It hence does explicitly not intend to give an overview of all the related developments, not in Europe and definitely not in the U.S. or elsewhere, which is well beyond the scope of this document.

3.1 Global NWP models

The number-one global medium-range weather forecast centre is undoubtedly the **ECMWF**. Its declared strategy (ECMWF, 2005) is a reduction in their **deterministic** model's horizontal resolution to **10 km by 2015**, and a resolution of **20 km** for their **ensemble prediction system** (EPS).

DWD, in collaboration with the Max Planck Institute for Meteorology in Hamburg, is developing the **ICON** GCM (ICOsahedral Non-hydrostatic General Circulation Model, http://icon.enes.org), which will include the option of a refined grid in areas of interest, and will be run in deterministic as well as ensemble mode. Apart from being used for global weather forecasts, the ICON will also be an optional driving model providing initial and boundary conditions for high-resolution limited-area (deterministic as well as ensemble) COSMO applications. – Plans at **DWD** are to start using ICON in **deterministic** mode operationally by **2012** with a **horizontal mesh-size of 5 km over Europe** and 20 km elsewhere, and in **ensemble** mode **a year later** with **10 km / 40 km mesh-size,** respectively (note that the lead-time for the ensemble, which will primarily be used to provide the boundary conditions for the convective-scale ensemble, will be shorter than for the deterministic run).

3.2 Limited-area NWP models

In **Europe** there are currently **four (five) consortia** in the area of regional NWP. These are, in alphabetical order:

– **ALADIN** (Bubnova et al., 1995; http://www.cnrm.meteo.fr/aladin)

– **COSMO** (Steppeler et al., 2003; http://www.cosmo-model.org)

– **HIRLAM** (Unden et al., 2002; http://hirlam.org)

– **Unified Model** (Swinbank et al., 1998)

Note that a subset of the ALADIN group, namely meteorological institutes in Central Europe, constitutes the LACE Consortium. Recently, a rather close collaboration has started between ALADIN and HIRLAM, which is called HARMONIE.

Worldwide there are many limited-area meteorological models available. Some of them are freely available, like ARPS (Xue et al., 2003), others can be obtained for a fee, like RAMS (Pielke et al., 1992). One of the major projects in the community is certainly the development of the community model **WRF** in the USA (Skamarock and Klemp, 2008), which is designed to serve operational NWP as well as research needs.

3.3 Nowcasting

With the development of limited-area models with higher and higher resolution, targeted towards shorter and shorter lead-times (and employing data assimilation systems that are capable of producing high resolution analyses with an hourly or even higher updating frequency), **limited-area NWP model output becomes an increasingly attractive input for any dedicated nowcasting system**.

Consequently, limited-area NWP models will also become more and more important concerning the **(probabilistic) forecasting of high impact weather**, since most decision makers are reluctant to take any actions before the probability of occurrence reaches almost certainty[1], which, if at all, is most often only achieved in the nowcasting time-frame (i.e., up to +6 hrs ahead). On the other hand, the move of the limited-area NWP models towards very high resolution will help to improve the simulation of physical processes that can indeed produce high impact weather, such as, e.g., convective storms.

3.4 Climate simulations

Global NWP models have a long tradition of forming the basis of climate simulation models. For limited-area NWP models, this is a relatively new but important development. In case of **COSMO**, a **climate version** has been devised by a number of university groups (Will et al., 2006), which is called '**COSMO-CLM**' ('CLimate Mode of the COSMO model', http://www.clm-community.eu), and a number of regional climate studies have already been performed (e.g., Déqué et al., 2006).

3.5 Environmental prediction

The objective of the European **GMES** initiative (Global Monitoring for Environment and Security) is to develop an operational capability to **monitor the environment**. ECMWF therefore plans to extend its (re-) analysis and forecast capabilities from purely atmospheric as well as land-surface, ocean, sea-ice, aerosol and atmospheric chemistry aspects to other components of the environmental system (ECMWF, 2005). Hence the ECMWF Integrated Forecasting System (IFS) will eventually become an **environmental prediction** (and monitoring) system.

Limited-area NWP models are following this development, at least to some extent, for the following reasons: to benefit from the improved initial and boundary conditions (e.g., use of atmospheric constituents in radiation parameterisations), to directly improve the forecasts (e.g., visibility forecast based on aerosol concentration, improved radiation parameterisation), and to respond to the increasing demand for environmental predictions on the regional scale (e.g., air quality, pollen). For some of the above mentioned environmental forecasts, additional prognostic variables and indeed prognostic equations (e.g., aerosols and other atmospheric constituents, pollen) will have to be included into the limited-area models, for others one will need to add fully

[1] Most decision makers are therefore not (yet) very interested in the forecast of high impact weather a few days ahead, when probabilities are still fairly low.

coupled or standalone (i.e., external) application models (e.g., air quality, dispersion, hydrology, ocean waves).

COSMO-ART (see also section 11.2), which has been developed by the Karlsruhe Institute of Technology (Vogel et al., 2009), is an extension of the COSMO model, which includes full chemistry and aerosol modules and allows the dispersion of, e.g., pollen, dust, and volcanic ash.

4 Goal, strategy, and research issues

4.1 Goal: Operational forecasting of mesoscale weather

The focus of the COSMO model-system development within the Consortium for Small Scale Modelling is the **operational forecasting of mesoscale weather**, especially **high impact weather**.

The current state of mesoscale modelling in conjunction with the available computing capacity allows tackling the direct simulation of convective systems as well as the consideration of the effects of small-scale topography. With the real-time availability of advanced remote sensing data it becomes possible to complement sparse in-situ observations with spatially highly resolved data sets. Only with these high resolution observations data assimilation systems will be able to provide the correct mesoscale environment to the forecast model. **From the scale of the targeted processes it becomes clear that the mesh-size of the model-system has to be of the order of 1-3 km.**

Based on these considerations the COSMO Steering Committee decided **to focus on the development of a model-system for the short to very short range and with very high convective-scale resolution**.

It is important to mention here that the goal of a broader community encompassing COSMO-CLM (climate) and COSMO-ART (aerosols and reactive trace gases) is to enhance the COSMO model capabilities towards a regional climate and environmental prediction system, respectively. Activities towards these goals are mainly pursued in the COSMO-CLM and COSMO-ART communities (see also chapter 11), which, together with the Consortium for Small Scale Modelling, constitute the three main communities working on the development of the COSMO model and its applications. The Science Plan at hand however focuses on operational forecasting of mesoscale weather, which is tied to the COSMO consortium.

4.2 Strategy

The strategy to achieve the goal of COSMO encompasses the following elements:

4.2.1 Ensemble prediction system for the convective scale

Traditionally, COSMO has been run in deterministic mode at the highest possible resolution, and as a limited-area ensemble prediction system (LEPS) at somewhat lower resolution[2].

At the **convective scale** it is however advisable **to run an ensemble prediction system** (rather than 'only' a deterministic model) **at the highest possible resolution**[3] for the following two reasons[4]:

---

[2] Note that the operational COSMO applications employing a convection parameterisation scheme currently all run at a mesh-size of 7 km, including the COSMO-LEPS.

- Convection as well as many other **physical processes at the convective scale cannot be deterministically forecast** with today's numerical forecasting systems, due to lack of physical knowledge and/or scale adequate physics parameterisations, the problems of non-resolved processes and of imperfect initial and boundary conditions, and possibly other reasons;
- An ensemble prediction system provides a tool to **objectively assess the uncertainty of the forecasts** on the one hand, and allows generating **probabilistic forecasts and indeed probabilistic warnings** at the regional and local scale on the other hand.

4.2.2 Data assimilation system for the convective scale

Given the aforementioned need for an ensemble prediction system, the strategy for the data assimilation system is:

- to develop an **ensemble-based** data assimilation system **for the convective scale** that provides initial conditions for the convective-scale ensemble prediction system;
- to develop a **computationally efficient** data assimilation system that is **fast enough to allow for a frequent updating** of the analysis and that **makes best use of the locally available dense (in space and time) observational data**, especially remote sensing data such as radar and satellite data.

4.2.3 Extension of environmental prediction capabilities

To further improve the limited-area NWP forecasts in general and considering the developments for the driving global models (cf. section 3.5) in particular, the strategy concerning the **extension of the environmental assimilation and modelling capabilities** of COSMO is:

- to include the necessary **additional prognostic variables and equations** to improve the model formulation (e.g., number density for microphysics scheme, turbulent potential energy for turbulence scheme, aerosols for radiation scheme) and/or to facilitate the prediction of new parameters (e.g., aerosols for visibility forecasts, pollen);
- to establish or extend appropriate high-resolution **assimilation algorithms** or derive **suitable initial fields** for the **new prognostic variables** in the atmosphere (e.g., aerosols and other atmospheric constituents) and at the surface (e.g., snow height, snow density, and liquid water content within a snow deck for different layers of the snow scheme);
- to provide the necessary deterministic and probabilistic **output for standalone application models** (e.g., air quality, dispersion, hydrology, ocean waves).

---

[3] For specific applications, one may – if sufficient computational resources are available – still opt for a deterministic run at yet higher resolution (i.e., sub-kilometer mesh-size), but this is out of scope of the present Science Plan.

[4] Similar arguments of course also hold for O(5-10) km mesh-size COSMO runs.

The extension of the environmental prediction capabilities of the COSMO model is closely related to the primary goal of the COSMO-ART community (cf. section 11.2). Development work in this field is therefore done in very close collaboration with COSMO-ART.

4.2.4 Verification and validation tool for the convective scale

The verification and validation tool needs to be adapted for the convective scale. This results in the following strategy:

- to develop a **verification tool** suitable for operational verification of **convective-scale deterministic as well as probabilistic forecasts** against all kinds of observational data, especially remote sensing data such as radar and satellite data. In particular, this tool needs to overcome the **double penalty problem** associated with very high resolution forecasts;
- to enhance the verification and validation tool to allow for **conditional verification** (e.g., verify 2m temperature in conjunction with stable (neutral) boundary layer conditions and specific cloud cover, stratify precipitation verification according to weather type, verify under the condition of a clear sky in the upstream region or early morning temperatures below T_{thr}, etc.) for diagnostic as well as operational purposes (e.g., for the compilation of guidelines for the users);
- to extend the verification and validation tool to also work on **analysis data** as well as on output from the **single column version of COSMO** or of any **standalone module of COSMO** (e.g., the soil model).

4.2.5 Intermediate resolution COSMO version for BCs

The (limited-area) convective-scale COSMO applications need lateral boundary conditions (BCs) from coarser models. In case of the deterministic systems[5], these are currently taken from O(5-10) km mesh-size COSMO runs, which themselves are driven by the ECMWF IFS or the DWD GME global models. In case of the 7 km mesh-size COSMO-LEPS, the initial as well as the boundary conditions (ICs and BCs) are taken from the ECMWF EPS.

To be able to (continue to) provide the best possible boundary conditions for the convective-scale deterministic as well as probabilistic COSMO applications it is mandatory to **continue to maintain and further develop the intermediate resolution COSMO version[6] for both the O(5-10) km deterministic as well as the ensemble COSMO applications** for the time being. – Eventually, the O(5-10) km COSMO applications may be replaced by the DWD ICON (cf. section 3.1) or a sufficiently high-resolution ECMWF deterministic run or EPS, respectively.

---

[5] No COSMO member is yet running an EPS at the convective scale operationally.

[6] In case of the deterministic applications, this includes the nudging data assimilation system.

4.2.6 Use of massively parallel computer platforms

The available computational power has been and will be increasing steadily in the future. Meanwhile, the underlying hardware architectures to achieve this increase are changing quite dramatically. It is quite certain that the clock frequency of individual processing units will not increase substantially in the future, but that the speedup will be achieved by more processing units (multi-core architectures) of different type (heterogeneous architectures). Due to the nonparallelised nature of many applications performing time integrations, the increase in *sustained* computing power is not straightforward to achieve. **The COSMO code needs to be adapted for efficient use of these new architectures.**

4.2.7 Intensified collaboration

- **Intensify the collaboration within COSMO.**
- Increase **visibility** through peer-reviewed publications, conference contributions, and representation in international projects and committees.
- Commonly apply for extra external **funding at the European level**.
- Actively invite **external review** by establishing a Scientific Advisory Committee of external experts.
- Strengthen the collaboration with **COSMO-CLM** and **COSMO-ART** as well as the exchange with **academia**.
- Cooperate more closely with the other consortia in the framework of the EUMETNET **SRNWP** programme.

4.3 Research issues

Besides the strategic elements to achieve the goal of COSMO discussed in the previous section, there are **many research issues related to the development of a model-system for the short to very short range and with very high convective-scale resolution**.

Some of the challenges and open questions for the different scientific areas are the following, and they will be discussed, amongst others, in detail in the following chapters:

- Dynamics and numerics
  - Terrain-influenced coordinates will pose problems as the model terrain gets steeper and steeper at higher and higher horizontal resolution.
  - Vertical derivatives on slanted surfaces need to be treated correctly (in general: numerical procedures for the vertical coordinate in steep terrain).
  - Are unstructured grids (as in computational fluid dynamics) an alternative for NWP?

- Physics
  - The schemes need to be adapted to higher resolution and slanted surfaces, which may imply a complete reformulation in case the assumptions made are no longer valid at very high resolution.
  - A more unified description of various sub-grid scale processes is desirable to avoid artificial separation of processes and scales, e.g., a more unified description of turbulence and shallow convection.
  - Parameterisation schemes are currently one-dimensional (vertical) and might need to become three-dimensional at very high resolution (e.g., radiation, turbulence); implementation of at least the most relevant 3D effects should be considered, balancing costs and benefits.
- Data assimilation
  - 4D-Var works well if the dynamics are only weakly non-linear, which may however not be the case at the convective scale. Ensemble filter techniques are a fairly cheap (in terms of necessary resources for the development) and promising alternative, but not yet mature for the convective scale.
  - New sources of high resolution atmospheric data (e.g., radar, lidar, GPS tomography) are now at hand for use in km-scale data assimilation schemes. Although generally very attractive, those data might pose new problems.
- Predictability and EPS
  - What is the relative importance of perturbations to BCs, ICs, and model physics?
  - What is the best way of generating perturbations for a limited-area ensemble prediction system at the convective scale?
  - What is the predictability at the convective scale?
  - Translation of EPS output into new useful probabilistic products.
- Validation and diagnostics
  - Standard verification statistics can deteriorate when applied to higher resolution output (e.g., double penalty problem). Therefore, high-resolution verification approaches (like neighbourhood verification) need to be introduced, tested, and agreed upon.
- Computational aspects
  - Instead of faster processors, new massively parallel and shared memory computer architectures are on the horizon, and programming- and parallelization strategies have to be adapted in order to run the models efficiently on such machines.

The overall challenge for COSMO is to **translate the strategic elements** (see section 4.2) defined to reach the COSMO goal (see section 4.1) as well as the **research issues** connected to the development of a model-system at the convective-scale (see above) into specific short, medium, and long-term **actions for each of the scientific areas**. This will be done in the remaining chapters of this Science Plan.

5 Dynamics and numerics

Author: Michael Baldauf (DWD)

5.1 State of the art, scientific developments

To solve the adiabatic Euler equations, i.e., the balance equations for mass, momentum, and energy, a so-called dynamical core is needed. This dynamical core should have the following properties:

- accuracy of the resolved processes;
- higher order of convergence (at least higher than first order);
- robustness, i.e., stability in a wide range of parameters and topography;
- some conservation properties;
- efficiency.

To achieve this goal a number of decisions have to be made. Some of them are:

- What is an adequate level of approximations for the dynamical core? – The most popular answer for the mesoscale is to use the non-hydrostatic, compressible equations, but this answer is not shared by all the scientists working in the field.
- What are the prognostic variables and what is the set of equations?
- On which grid should these equations be solved? (structured, unstructured, terrain-following, z-coordinate, …)
- Which discretisations (spatial and temporal) should be chosen?
- What are the adequate boundary conditions?

Up to now the answer to these questions to achieve the above mentioned properties has led to a variety of model formulations. On the global scale the shift from spectral models to grid point models, which are considered more effective at higher resolution, has not yet been done at all the global forecasting centres. At the mesoscale, in most cases grid point models are used. Many of them use finite difference (FD) formulations, which are relatively easy to develop but are limited to structured grids. Orography can be included by a terrain-following coordinate-system and appropriate transformations. Finite element (FE) methods, originally developed for structural mechanics in engineering applications possess more freedom in using also unstructured grids but were not often used for meteorological models. One reason for that is that they inherently need implicit solvers. Currently discontinuous Galerkin (DG) methods promise a good combination of properties for accuracy and conservation and can also be applied on unstructured grids, but their application in meteorological models has just started. Finite volume (FV) methods have a long tradition in fluid mechanics especially in capturing shocks and other discontinuities by explicitly profiting from the conservative form of the equations. In principle FV-methods can be applied also to unstructured grids.

The COSMO model as it is applied in the COSMO consortium covers spatial resolutions with grid lengths from 14 km to currently 2.2 km and in the future (around the year 2015) down to about 1 km for operational weather forecasts. At these high resolutions, at least two problems arise:

First, the explicit simulation of deep moist convection by the high resolution model applications (grid length below 3 km) requires a closer coupling between the dynamical core and the parameterisations. This means that the dynamical core no longer has to describe the adiabatic equations but has to involve the diabatic terms, in particular latent heat release. Generally, this will lead to a closer collaboration between physical parameterisation and dynamics development. In the WRF model for example, the tendencies of the cloud microphysics scheme from the old time step are treated together with other physical tendencies from the current time step and in common are delivered to the dynamical core. This was up to now not possible in the COSMO model due to unstable 2 Δz patterns arising in the TKE field. Also, turbulence is a quite fast process, which therefore should closely interact with the dynamics.

Second, the transition to finer resolutions has the consequence of steeper slopes as well as more complex mountain and valley structures. This makes a terrain-following coordinate formulation more and more difficult, in particular for the COSMO model. One of the reasons for that is the current dynamical core, where the metric terms for the terrain following coordinates are treated explicitly and can therefore suffer from numerical instability. Furthermore, the metric terms must fulfil numerical constraints (metric tensor identities, Smolarkiewicz and Prusa, 2005) which are probably violated by the current model version. A possible alternative to the terrain-following coordinate would be the z-coordinate. To adequately resolve mountainous regions with large height differences between the mountain peaks and the deepest valleys, a formulation with a 3D-unstructured grid seems to be necessary if one wants to follow this approach. This is clearly beyond the scope of model development in the next few years. – In contrast, implicit (or semi-implicit) solvers are able to handle metric terms in an implicit and therefore stable manner.

In addition, direction-splitted tracer advection induces stability problems in the model. In strongly deformational flow situations a grid cell can be emptied by an advection step in one direction and therefore the *specific* tracer mass explodes during the compensating advection step in the other direction. This is both a problem of mass conservation and mass consistency. Such deformational flow fields occur more and more often when the complexity of the terrain increases with higher resolution. Consequently, new methods to transport additional variables will need to be developed to achieve the desired conservation properties. Traditionally, variables like moisture fields or turbulent variables (e.g., TKE) are essentially treated outside of the dynamical core. The tracer advection schemes are subdivided into two groups. Semi-Lagrange schemes (Staniforth and Côté, 1991) utilize the fact that physical quantities are transported together with the fluid parcel. They have the advantage that they can be easily formulated as full 3D schemes (which prevents from splitting errors) and have no Courant number restriction. The disadvantage of traditional semi-Lagrange schemes is the lack of conservation of the transported field. On the other hand, Eulerian methods, mainly finite volume schemes, can be easily formulated to conserve the quantity (e.g., Bott, 1989), but usually have Courant number restrictions and are harder to formulate in 3D. One exception concerning the latter point is MPDATA (Smolarkiewicz and Clark, 1986) which uses simple multidimensional upwinding and corrects the high diffusion term by the same upwinding with an artificial antidiffusive velocity. Semi-Lagrange methods formulated for volume transport can be conservative at least for 2D (horizontal) transport by the remapping procedure (Nair and Machenhauer, 2002). Finite volume schemes on the other hand can be formulated fully 3D by an appropriate flux reconstruction (Miura, 2007). Such schemes suffer less from the above mentioned splitting instability and inaccuracy.

In principle, the above mentioned limitations of the dynamical core for smaller model resolutions in complex orography can be cured by a stronger filtering of the orography. This 'dodge' is already used in the Alpine region for the convective-scale model applications (like COSMO-DE or COSMO-2). With an again stronger orography filtering model runs with dx=1 km over middle Europe are still possible, though this approach is unsatisfying. However, further testing is necessary to assess the true limitations in complex terrain.

Finally, the traditional distinction between tracer advection and the dynamical core has to be abandoned to get a satisfactory advection of specific masses. The advection scheme has to be consistent with the advection of total air density (Skamarock, 2006).

A transport process closely tied to advection is sedimentation of rain, snow, or graupel, with the difference that this transport does not follow the fluid parcel. Here often implicit schemes are used due to the quite high Courant numbers, particularly in the lower levels of the model.

Other transport processes like turbulent transport expressed by the divergence of diffusion fluxes falls in the area of 'numerics and dynamics', too (Baldauf, 2005 and 2006).

Boundary conditions (BC) for the open boundaries of a limited area model are a notoriously difficult problem. At the upper boundary at least mechanisms for damping gravity waves (whose direction of energy transport can be detrimental to the direction of the phase velocity) are necessary. Radiation conditions up to now were mainly developed for anelastic models. In compressible models the occurrence of sound waves (with a quite different dispersion relation) disturb this kind of artificial BC. In COSMO a Rayleigh damping layer is used. A new formulation (Klemp et al., 2008), which only relaxes the vertical velocity, produced reasonable results, too.

The lateral BCs of COSMO use a damping layer, too. At higher resolutions, much higher BC update frequencies than the currently used 1h (e.g. 5 min) will be needed. Though in principle not difficult, some technical adaptations to the code will be necessary.

5.2 Status and expertise of COSMO

Initiated with the LMK-project at DWD and continued in the COSMO Priority Project 'Runge-Kutta', a new dynamical core for the COSMO-model was developed. Based on the work of Wicker and Skamarock (1998, 2002) a two-timelevel time-integration scheme which uses a 3rd order Runge-Kutta (RK) method was implemented to replace the leapfrog scheme. The main advantage of this new scheme is the application of horizontal advection schemes with a higher accuracy. This means that the representation of a certain structure can be achieved with less grid points.

During these projects, expertise has been built up for the implementation of finite difference methods in the framework of RK-integration. These implementations were accompanied on the one hand by more theoretical insight into these methods and a better understanding of their limitations (e.g., Baldauf, 2008) and by detailed investigations of model sensitivities (e.g., Torrisi, 2006) on the other hand. Also experience with the application of FV-methods for the advection problem was gained (Förstner, Baldauf, and Seifert, 2006).

The COSMO model will also be used by climate research working groups (COSMO-CLM). The collaboration with these groups is recommended to test model properties in long climate runs. From the viewpoint of dynamical core development in particular, conservation properties of special variables are of importance. The current model version does not possess any conservation property. How far conservation is violated in practice, is currently being investigated (e.g., at the MPI Hamburg). Similar conservation requirements hold for air chemistry and air pollution modellers which in the last years have contributed to the COSMO model (e.g., COSMO-ART).

5.3 Strategy of COSMO and actions proposed

5.3.1 Development of a Conserving Dynamical Core

The current COSMO model does not have any explicit conservation property concerning the dynamical variables mass, momentum or energy, neither with the Leapfrog nor with the Runge-Kutta based integration scheme. Conservation of these variables is one of the fundamental guiding principles in the development of dynamical cores in all branches of fluid dynamics. It is well known that the correct expansion of shocks (or 'weak solutions' in general) can only be described in models where both the underlying equations are formulated in conservative form as also the numerical scheme is conserving. This shortcoming of the current COSMO model has led to the initiation of the Priority Project "Conservative Dynamical Core" (CDC) The project started in 2009 and should be completed by the end of 2011.

A large family of discretisation schemes to achieve this goal of conservation are finite volume (FV) discretisations applied to flux form equations. These methods are well established in the Computational Fluid Dynamics community (e.g., LeVeque, 2002) and are applied more and more in global and also in regional atmospheric modelling. The WRF model is partly formulated in flux form to conserve at least mass (Klemp, Skamarock and Dudhia, 2008; Skamarock and Klemp, 2008). Also the OMEGA-model uses finite volume methods for application in operational weather forecasting and atmospheric dispersion modelling (Bacon et al., 2000). Ideas developed there can be used for the COSMO-development. The EULAG model (Grabowski and Smolarkiewicz, 2002) solves an anelastic set of conservation equations by a FV solver. A numerical advantage is the use of implicit solvers which are well established for these types of equations. First comparisons between COSMO and EULAG in real case applications show that the numerical costs are comparable. Prusa et al. (2008) inspected scalability on massively parallel architectures and found good performance for the parallelisation and also for the implicit solver, but a strong dependency of the domain decomposition due to cache effects. Experiences won in other fields of fluid dynamics can also be transferred to meteorological applications. Jameson (1991) developed an implicit FV-solver for aerodynamic applications, which is worth to extend to more buoyancy driven flows, too.

The main focus concerning conservation properties lies on mass conservation, because this is the most robust conserved quantity (Thuburn, 2006). Next important seems energy conservation. Instead of local energy conservation a Lagrange conservation of potential temperature could be an intermediate second step. Conservation of momentum seems not as important but could possibly be achieved during this project, too; nevertheless it is this variable (or simply velocity) which is used in the standard formulation of the Euler- or Navier-Stokes equations. Of bigger importance are some rotational variables like the potential vorticity, whose conservation is not easy to achieve.

The goal of the project is to deliver a dynamical core based on finite volume discretisations with the above mentioned conservation properties. The accuracy should be at least as good as the current Runge-Kutta dynamics, whereas the efficiency should not be worse. Additionally, the use in complex terrain with steep slopes should be possible.

During the course of the project, testing tools have to be developed to assess the quality of the implemented methods or to detect implementation errors:

– idealised test cases, for which the solution is well known, e.g., flow over mountains, convection, gravity currents, pure advection, and pure sound expansion;
– diagnostic tools to assess special properties like integral budgets and convergence.
– Real cases are defined, which cover interesting meteorological situations (e.g. winter storm cases, summer convective cases, …). Furthermore cases were selected, for which the current COSMO-model either performed well or bad.

For more details on this Priority Project, refer to the **CDC project plan**.

5.3.2 Developments outside of COSMO

In the framework of the ‚Deutsche Forschungsgemeinschaft'-program ‚Metström' a new dynamical core will be developed which bases on the Discontinuous Galerkin-discretisation (e.g., Cockburn, 2003). This method provides local conservation and a high convergence order and bases on a 3D-unstructured mesh. This development is basic research. A useable version is not to be expected before 2011.

In the framework of the ‘Extramurale Forschung' at DWD high order compact schemes currently are under development (TU Cottbus). The aim is to improve mainly the fast wave solver to get a higher convergence order of the overall dynamical core. The compactness of the operators promises to better describe poorly resolved waves. This also can help in strongly structured orography.

6 Physics

The principal goal of COSMO is to focus on short to very short range forecasts and with very high convective-scale resolution providing final users with skilful operational products at the top end of NWP model (vertical and horizontal) resolution.

Model physics represent a major challenge in achieving this ambitious goal. Current parameterisations seem in fact to be partly inadequate and unsatisfactory for many reasons, not last because they have been developed when the model resolution was considerably lower (often taken from earlier version of global models), in addition our understanding of atmospheric processes and their uncertainties is still limited. The quantification of uncertainties related to physical processes is a particularly important aspect to consider if we wish to move towards probabilistic forecast at the local scale.

To achieve our goal, we should consolidate and further develop specific ***diagnostic*** tools able to point to the main weakness and shortcomings of the current physical parameterisations modules of COSMO. We should also foster and coordinate ***research activities,*** in cooperation with research institutes and universities, with the aim to increase our knowledge on physical processes at the local scale, leading eventually to new schemes specifically developed for small scale resolution.

Also, we should develop an option to share some physics packages with the ICON model, e.g., schemes for radiation, moist convection or the soil model with a tile approach, because of easier evaluation of physics packages in a global model.

Key physical parameterisation issues in the COSMO model

6.1 Parameterisation of turbulence and of PBL processes

Authors: Dimitrii Mironov (DWD) and Matthias Raschendorfer (DWD)

6.1.1 State of the art, scientific developments

Parameterisation of sub-grid scale (SGS) turbulence and of planetary boundary layer (PBL) processes represents one of the major challenges in atmospheric modelling. All turbulence parameterisation schemes currently used for NWP and related applications have serious shortcomings. These include their inability to maintain turbulence in strongly stable stratification, poor interaction with other physical parameterisation schemes (e.g., the cumulus convection and the microphysics schemes) as well as with the resolved-scale thermodynamics, and an insufficient account for the non-local transport properties of quasi-organised SGS motions (e.g., the PBL convective plumes and rolls), to mention a few. Turbulence in NWP models is parameterised on the basis of transport equations for the second-order statistical moments of fluctuating fields. One-equation turbulence schemes are widely used for short-range weather forecasting where only the turbulence kinetic energy (TKE) equation is considered. All other second-moment equations, i.e. the equations for the Reynolds stress components and for the fluxes and variances of scalar quantities, are reduced (truncated) to algebraic expressions by neglecting the time-rate-of-change, the advection and the turbulent diffusion terms. The resulting system of equations is closed through the use of highly simplified formulations for the dissipation rates, for the pressure-scalar and pressure-velocity covariances, for the third-order transport term in the TKE equation, and for the turbulence length (or time) scale. A comprehensive discussion of turbulence closure schemes for NWP and related applications is given in Mironov (2008a). Well-calibrated algebraic and one-equation turbulence closure schemes show a good performance in turbulent flows where the static stability is close to neutral. However, they are known to have serious problems in stratified flows, both stable and convective.

Most current turbulence schemes tend to extinguish turbulence in case of strong static stability, when the gradient Richardson number exceeds its critical value (of order 0.2). The schemes are then tuned in an ad hoc way to prevent turbulence from dying out entirely as the static stability increases, e.g. by introducing a “minimum diffusion coefficient”. Such a tuning device may have a detrimental effect on the NWP model performance in some important situations. For example, it may destroy a delicate balance of physical processes near the top of the stable or neutral PBL capped by stratocumulus clouds.

Difficulties of current turbulence schemes in convective conditions are associated with their inability to adequately account for non-local transport properties of convective turbulence. Usually the third-order terms, that describe the transport of variances and fluxes by the fluctuating velocity, are either entirely neglected or parameterised very crudely. As these terms are vital for maintaining the second-moment budgets in the well-mixed core of convective PBL, one-equation turbulence schemes are unable to reproduce the well-mixed character of the convective boundary layer.

An important aspect of any turbulence parameterisation scheme is the way it interacts with the resolved-scale thermodynamics and with the other physical parameterisation schemes, most notably, with a cumulus convection scheme. Recall that it is customary for NWP models to split the effects of various SGS motions into the contributions due to “turbulence”, that is thought to represent quasi-random small-scale motions, and due to “convection”, that is thought to represent quasi-organised motions of larger scales.

Many current limited-area NWP models operate with the horizontal mesh size of 10 to 5 km. These models use a separate scheme to parameterise deep precipitating cumulus convection. However, the interaction between the cumulus convection scheme and the turbulence scheme is largely unclear. It is not guaranteed that the sum of the two contributions actually represents the total effect of the SGS motions. If it is not the case, serious problems may be encountered, for example, double-counting of some energetically relevant modes of SGS motions, or their loss.

It is thought that cumulus convection scheme can simply be switched off in high-resolution NWP models using the horizontal mesh size from 3 to 1 km (see a discussion in Mironov and Jones 2005). It is unclear, however, at which resolution exactly that should occur. A parameterisation of shallow non-precipitating convection is still necessary. The question then arises whether regime-dependent parameterisation schemes should be used to describe various types of fluctuating motions, or some unification of different parameterisation frameworks could be achieved. Although a definitive answer to this question does not seem to exist at present, there is a growing interest in unifying various parameterisation ideas. Some attempts have already been made to achieve a more unified description of several types of SGS motions, of shallow convection and turbulence in particular. They can be classified, rather loosely, into three groups (see Mironov 2008a, for their more comprehensive description):

- *Extended mass-flux schemes* are built around the top-hat updraught-downdraught representation of fluctuating quantities. Lappen and Randall (2001a, 2001b, 2001c) developed an extended mass-flux scheme ADHOC (Assumed-Distribution Higher-Order Closure) that parameterises boundary-layer turbulence and shallow convection in a unified framework. Missing components, namely, parameterisations of the sub-plume scale fluxes, of the pressure terms, and, to some extent, of the dissipation terms, are borrowed from the ensemble-mean second-order modelling framework. An updated version of ADHOC, ADHOC2 (Lappen and Randall 2005, 2006) includes parameterisations of pressure terms and of momentum fluxes consistent with the mass-flux framework.

- In *hybrid schemes* the mass-flux approach and the ensemble-mean second-order closure approach have roughly equal standing . These schemes are exemplified by the EDMF (Eddy-Diffusivity/Mass-Flux) scheme proposed by Soares et al. (2004) based on earlier work of Siebesma and Teixeira (2000). In the framework of the EDMF scheme, the vertical flux of a fluctuating quantity is represented as a sum of two contributions, one is assumed to stem from the small-scale chaotic eddies and is described with the eddy-diffusivity down-gradient formulation, and the other is assumed to stem from the convective-layer-scale quasi-organised plumes and is described with the mass-flux formulation.

- *Non-local second-order closure schemes* represent one more alternative to describe boundary-layer turbulence and shallow convection in a unified framework. In pursuing this aim, a number of schemes have been developed, ranging from low-order turbulence closures, where the only prognostic equation is the TKE equation, to high-order closures, where transport equations are carried for all second-order and third-order moments involved.

Parameterisations of the surface layer deserve some attention since it is this layer where the interaction between the atmosphere and the underlying surface takes place. The Monin-Obukhov similarity theory have been commonly used for more than half a century to describe the vertical structure of the atmospheric surface layer and to compute the surface fluxes of momentum, heat, water vapour, and if necessary, of other scalar quantities. Since the surface-layer flux-profile relationships are consistent with the second-moment budgets they suffer from the same shortcoming as the (truncated) second-order closures, namely, the inability to properly predict surface layer fluxes in strongly stable flows or in conditions of free convection. In strongly convective conditions, the concept of “minimum friction velocity” (see e.g. Zilitinkevich et al., 2006) was introduced to improve the situation. As to the stably stratified surface layer, a pragmatic approach is usually taken. The flux–profile relationships are adjusted in a somewhat ad hoc manner to enable the fluxes to be nonzero at sufficiently strong static stability. Such “tuned” flux-profile relationships do not perform satisfactorily in many important situations. The development of more physically plausible parameterisations require better understanding of the structure and transport properties of strongly stable boundary-layer turbulence.

6.1.2 Status of development and expertise within COSMO

A one-equation turbulence closure scheme is developed and implemented into the COSMO model (Raschendorfer 1999, 2001, see also Mironov and Raschendorfer 2001, and Raschendorfer and Mironov 2002). The scheme is formulated in terms of variables that are approximately conserved for phase changes in the absence of precipitation. These are the total water specific humidity and the liquid water potential temperature. No account of cloud ice is made at present. The SGS statistical cloud scheme developed by Sommeria and Deardorff (1977) is used to diagnose the horizontal fractional cloud cover of a given model grid box and of the amount of cloud condensate it contains. Notice, however, that in the present operational configuration the statistical cloud scheme is only used in turbulence calculations. The radiation calculations make use of a different diagnosis of the fractional cloud cover based on the relative-humidity scheme.

A distinguishing feature of the COSMO turbulence scheme is that it accounts for the effect of the SGS horizontal inhomogeneity of the underlying surface on the turbulence structure in the stably stratified PBL. The extension of the traditional one-equation closure scheme developed by Raschendorfer (1999, 2001) is meant to guard the scheme against sharp turbulence cut-off at a critical Richardson number (Raschendorfer 1999, 2001, Mironov 2008a).

The current COSMO turbulence parameterisation scheme suffers from a number of deficiencies in the representation of PBL processes, leading, among other things, to a large bias of 2m temperature and 2m dew point and, in some situations, to a large bias of 10m wind speed over flat terrain. These deficiencies include the inability to produce strong inversions in the lowest levels and an underestimation of stable stratification in general (the scheme is too diffusive). The trouble is most likely due to a too large minimum diffusion coefficient (Buzzi et al., 2008). Further problems caused by excessive vertical diffusion are related to the representation of boundary-layer clouds. For convective scale forecasting, these are severe problems as realistic simulation of the PBL structures is vitally important.

In the medium term perspective, further development of the COSMO turbulence scheme is undertaken within the framework of the Priority Project “Towards Unified Turbulence-Shallow Convection Scheme” (UTCS). The project is aimed at improving the representation of shallow convection, turbulence and related processes in the COSMO model through the incorporation of transport equations for the SGS variance of scalar quantities, such as (total water) potential temperature and (total water) specific humidity. The SGS scalar variance actually represents potential energy of sub-grid scale motions. The use of scalar-variance transport equations along with the TKE transport equation is very advantageous, if not indispensable, to overcome a number of difficulties. These include representation of non-local transport in the PBL, triggering of cumulus convection, and prediction of partial cloud cover. An improved description of shallow convection and PBL turbulence is expected to lead to an improved forecast of several key quantities, including the rate and timing of precipitation and the 2m temperature.

6.1.3 Strategy of COSMO and actions proposed

Short to medium term (5 years)

In the near future, efforts should be mounted to improve the performance of the current one-equation COSMO turbulence scheme. These include

– a systematic analysis (diagnostics) of the turbulence scheme and of its individual components using conditional verification methods and numerical experiments with the single column model COSMO-SCM,
– verification of results from numerical experiments against data from high-resolution micrometeorological measurements (e.g., vertical profiles) at different measurement sites representative of different environment conditions (e.g., Lindenberg, Germany; Payerne, Switzerland; Capofiume, Italy; Cabauw, Netherlands),
– consolidation of the current turbulence parameterisation scheme, including the reduction of minimum diffusion coefficients and the increase of vertical resolution,
– introduction of the cloud water-cloud ice mixed phase into the sub-grid scale cloud scheme,
– modification of the surface-layer transfer parameterisations, including the reformulation and tuning of the laminar-layer resistance (with the primary aim to improve the scheme performance in stable stratification),
– investigation of numerical stability issues,
– optimisation of the turbulence routines in order to improve their performance in terms of the CPU time,
– re-working, testing and tuning of the extension of one-equation closure scheme that accounts for the effect of horizontal inhomogeneity of the underlying surface on the turbulence structure in the stably stratified PBL.

In the medium-term perspective, efforts should go into

– the implementation of the UTCS project.

A detailed description of the work to be performed is given in the **UTCS Project Plan**.

Long term (10 years)

The key issues to be addressed in the long-term perspective include

– the choice of prognostic variables (PDF moments or/and fractional cloud cover) for the SGS cloud parameterisation scheme, consistent coupling of an improved SGS cloud scheme with the other SGS parameterisation schemes and with the resolved-scale thermodynamics,
– adjustment, and further development as needed, of the turbulence parameterisation schemes to a high spatial resolution, where three-dimensional aspects of turbulence may be important and some physical processes are partially resolved.

Attention should also be given to

– the quality of external-parameter data at (very) high spatial resolution.

Resources required

Apart from the UTCS project for which resources have already been allocated (although they are still far from being sufficient), roughly three man-years (3 FTE) are required to address the short to medium term issues. Resources required to address the long term issues are difficult to estimate at the moment. In any case, the work on turbulence parameterisation involves a great deal of research and necessitates a solid scientific background. Given limited resources within COSMO, collaboration with universities and research institutes as well as with other NWP and climate modelling groups is required.

Expected Outcome

As the turbulence scheme is tightly coupled with virtually all other components of an NWP model, there is always a risk of having compensating errors when tuning a modified/new turbulence scheme. Still the proposed efforts is believed (hoped) to result in an improved representation of a number of processes. This in turn is expected to lead to an improved forecast of several key quantities, such as the cloud cover, the near-surface wind, temperature and humidity, and the rate and timing of precipitation.

Risk Assessment

There is no appreciable risk of not achieving the short to medium term goals (except, perhaps, that re-working of the parameterisation of the horizontal inhomogeneity effects is not trivial and requires some research effort). Further development of the COSMO turbulence scheme invites considerable research efforts. The quality and the timely delivery of results strongly depends on the availability of well-trained personnel with a solid scientific background.

6.2 Parameterisation of moist convection

Author: Frederico Grazzini (ARPA-SIMC)

6.2.1 State of the art, scientific developments

Numerical weather prediction models are required to adequately simulate the important effects of cumulus convection on the redistribution of temperature, humidity and stability of the atmosphere. In a typical numerical model with horizontal grid size of the order of tens of kilometre or greater the cumulus convection could not be resolved explicitly so it must be parameterised. This is one of the most challenging tasks since the parameterisation of this physical process involves turbulent mixing, mesoscale organization of updrafts and downdrafts, complex cloud microphysics, and a tight coupling with the atmospheric boundary layer and underlying surface. Conventionally, cumulus convection parameterisations could be divided in two main groups: moist convective adjustment in which moist convective instability is diagnosed and adjusted towards specified temperature and relative humidity profiles and mass-flux schemes where a model of the mass flow through a cumulus ensemble is used to predict all cumulus tendencies. Current mass flux schemes were developed for NWP models with large grid sizes, at least containing the whole circulation associated with a convective cell, assuming a substantial equilibrium between updraft, downdraft and large-scale subsidence. As NWP proceeds toward higher resolution, order of few kilometres, this local equilibrium assumption might not be true any more. A number of problems is therefore currently affecting these schemes that are highly resolution dependent. In addition they assume a stationarity of clouds in time and space. New hybrid scheme are emerging (3MT and Hymacs for example, see respectively Gerard and Geleyn 2005 and Kuell and Bott 2008) in which only the small scale convective updraft/downdraft are parameterised while the large scale subsidence is left to grid scale equations.

To coordinate and bundle research activities in the field of convection parameterization in Europe, recently a new COST action ES0905 (http://convection.zmaw.de) has been launched.

6.2.2 Status of development and expertise within COSMO

The current convection scheme of the COSMO model is based on the mass-flux Tiedtke scheme developed in the 80's for the global ECMWF model (Tiedke 1989). During the years ECMWF has introduced significant modifications and refinements that have not been incorporated in the COSMO scheme. There are still many open questions to be addressed concerning which scheme should be used in the future for the 7 km runs. It is not clear how much effort we should invest to improve and maintain the current Tiedtke COSMO-version that has proved to have serious deficiencies, underestimating the convective events and at the same time producing excessive localized precipitation on individual cases (a first modification to reduce this has been successfully introduced in COSMO version 4.4).

Most member states are already running, or have plans to do it shortly, a high resolution version of COSMO with the explicit representation of deep convection, though many applications like regional scale EPS or regional climate modelling are based on a version of the COSMO model which includes a convection parameterisation scheme.

Recent analysis from verification and case studies have shown that the QPF of the convection-permitting configuration is clearly better than the O(7 km) implementation in conditions where precipitation (convective and stratiform) is largely driven by large-scale forcing. For weakly forced convection or non-equilibrium convection, where O(2Km) should be more useful, instead it still suffers from some lack of triggering and organization (although the overall diurnal cycle of convection is clearly improved). Highlighting and solving these conditional errors is very important if we want go more and more towards a probabilistic prediction. We should check in fact that regime dependent errors are not altering the probabilities of certain states as it is shown to occur for weakly forced convection.

6.2.3 Strategy of COSMO and actions proposed

Short to medium term (5 years), in order of priority

– Incorporate the current ECMWF scheme (Bechtold, 2001), into the COSMO model.

– To design and run a convection oriented diagnostic, making also use of conditional verification tools and case studies.

– To continue with tests and modifications of the current Tiedtke COSMO scheme. Preliminary results show improvements on the double-counting problem and with precipitation in presence of orography.

Resources required

0.5 FTE for the implementation of the ECMWF scheme into the COSMO-model

0.25 FTE for the reanalysis and convection diagnostic of the QPF experiments

The third point is difficult to evaluate, may be another 0.25 FTE

Expected Outcome

The implementation of the ECMWF scheme and consolidation of diagnostic should give us more elements to judge about the real quality of the current scheme and at the same time provide some indication on how to reduce the "double counting problem". Improvements on this issue will have a clear benefit not only on regional and local quantitative precipitation forecast but also on the large scale dynamics.

Risk Assessment

No big risks are involved in the realisation of these plans, at most delays may arise form the lack of qualified resources.

6.3 Cloud microphysics

Author: Axel Seifert (DWD)

6.3.1 State of the art, scientific developments

In operational NWP models fully prognostic one-moment microphysics schemes with two or three ice species are still state-of-the-art (e.g., Thompson et al., 2004, and others), most operational models run much simpler schemes than that (e.g., Wilson and Ballard, 1999). In research models the complexity and sophistication of microphysical parameterisation has considerably increased over the last decade.

For example, two- and three-moment microphysics schemes are becoming more common for cloud-resolving modelling (Ferrier, 1994; Reisner et al., 1998; Seifert and Beheng, 2006a; van den Heever et al., 2006; Milbrandt and Yau, 2005b, 2006; Morrison and Grabowski, 2007, and others). A few research groups use even more expensive and complicated schemes, like mixed-phase spectral bin microphysics with several hundred prognostic variables (Lynn et al., 2005a,b), or bulk schemes with tens of even hundreds of different ice species (Straka and Mansell 2005, Gilmore and Straka, 2007). Many of the studies that use the more sophisticated schemes investigate aerosol effects on clouds and precipitation.

6.3.2 Status of development and expertise within COSMO

The COSMO model provides several microphysical parameterisations that have different levels of complexity. This ranges from a simple one-ice diagnostic scheme to a one-moment three-ice fully prognostic parameterisation (Doms and Schättler, 2004; Reinhardt and Seifert, 2006). A two-moment four-ice-classes scheme that includes a full treatment of hail microphysics is available for research applications (Seifert and Beheng, 2006a; Blahak, 2008), e.g., aerosol-cloud-precipitation studies (Seifert and Beheng, 2006b; Mühlbauer and Lohmann 2008), and will be implemented in the official code during 2010 (SB2006-scheme).

6.3.3 Strategy of COSMO and actions proposed

Several improvements of the cloud microphysical parameterisation are possible or even necessary for operational NWP in the future. In general, these improvements will often require additional particle classes or the prediction of additional moments of the particle size distributions, e.g., the number concentration of raindrops. Using a multi-moment approach seems especially promising for the problem of summertime deep convection as different particle sizes play a crucial role in these clouds.

- A1 - Improvement of the parameterisations of evaporation and sedimentation of raindrops by introducing the raindrops number concentration as prognostic variable in addition to the rainwater mixing ratio (Fovell and Seifert, 2005; Milbrandt and Yau, 2005a; Seifert, 2008). The evaporation of raindrops is crucial in convective systems as this process provides the main contribution to the formation of the cold pool and therefore the triggering of secondary convection.
- A2 - The parameterisation of ice nucleation and, subsequently, the size distributions of ice needs to be improved, e.g., for cirrus clouds (Karcher and Lohmann, 2002; Lohmann and Karcher, 2002). This provides an important link to the radiation scheme and a consistent treatment of clouds is an important topic to improve the overall model performance (Arakawa, 2004).
- A3 - Introduction of a prognostic shape or habit of snow is a promising way to improve the precipitation forecasts during winter (Woods et al., 2007). By predicting the particle habit which provides a better estimate about the correct fall speeds, this approach might be able to achieve improved precipitation forecasts in different temperature and orographic regimes.
- A4 - A prognostic melted water fraction within snow and/or graupel particles can be introduced to improve the prediction of precipitation phase, i.e., frozen vs. liquid precipitation (Walko et al., 1995; Meyers et al., 1997; Phillips et al., 2003, 2007).
- A5 - Further development of the SB2006 two-moment scheme. Investigation of aerosol effects on precipitation formation. Coupling with chemistry and aerosol models (in particular: online two-way coupling with COSMO-ART).

<u>Resources required:</u>

All developments in this field require well-trained scientists with a good background in cloud microphysics and mesoscale modelling. A1 is currently being worked on at DWD. Some research can be done in cooperation with universities, e.g., there are several proposals from universities that aim at proposed actions A2, A4 and A5. The topic A3, snow habit prediction, is maybe a more long term idea, but first feasibility and impact studies in that direction would be possible with 0.25 FTE.

Expected Outcome:

Improved forecasts of summertime deep convection, especially organized convection (A1, A5). Improved forecasts of cloud cover, ice supersaturation and maybe 2m-temperature (A2). Improved forecasts of wintertime precipitation patterns, orographic precipitation and maybe the 2m-temperature (A3, A5). Improved forecasts of precipitation phase (A4, A5).

Risk Assessment:

Based on the experience with the full two-moment scheme A1 is rather straightforward, but whether a significant improvement of the operational forecasts can be achieved is unclear. A2 is somewhat more difficult and a benefit for NWP could probably only be achieved if the radiation scheme is improved as well. A3 would be much more challenging and the necessary observations for validation are only available from a few field experiments, mostly in the United States. Whether A4 is possible with a bulk scheme is actually somewhat questionable, but there exists one example of such a scheme in the literature. The main risk with A5 is that the scheme might be computationally too expensive to become operational (currently an increase of about 50-70 % total model runtime).

6.4 Soil modules and surface properties

Authors: Jürgen Helmert (DWD) and Jean-Marie Bettems (MeteoSwiss)

6.4.1 State of the art, scientific developments

The soil vegetation atmosphere transfer (SVAT) scheme provides the lower boundary condition for the atmospheric circulation model based on the exchange of heat, moisture, and momentum between the surface and atmosphere. This results in a large impact of the SVAT model on the evolution of near surface weather parameters as well as in possible feedback mechanisms on atmospheric processes (e.g., boundary layer development, low level cloudiness, intensity of convection).

Subgrid land surface heterogeneity may also be important for the energy budget of the atmospheric boundary layer and for the atmospheric branch of the hydrological cycle (Heinemann and Kerschgens, 2005). SVAT models of higher complexity consider in fact heterogeneity effects for the exchange processes between land surfaces and the atmosphere using the so-called ‘‘tile’’ approach (e.g., Avissar and Pielke 1989, Mengelkamp et al., 2006). In this approach surface prognostic variables are defined for a set of specific surface types within each grid-cell. The soil scheme is applied for each of these types and grid mean values (e.g., fluxes of sensible and latent heat) are computed as weighted means over the fractional area of each type. Especially in case of a stably stratified PBL, the application of a tile approach might still be necessary even for a mesh size of 1 km or less. Here, as opposed to a convective PBL, most features of the (stably stratified) PBL will remain at subgrid scale, and then the use of a tile approach to aggregate the fluxes may be (vitally) important to realistically describe the PBL structure (Mironov and Sullivan, 2010).

For particular surface types (e.g., lakes, forests, towns, snow on sea ice, deserts) with potential large impact on atmospheric processes more sophisticated models are under development.

Even more than the atmospheric model, the simulation of the evolution of the soil is hampered by inadequate knowledge about the initial state. Despite the important role of soil moisture, most mesoscale NWP models use very simplified ways for initialising the land surface, ranging from nudging to climatology to optimal interpolation of proxy data. Improvements could be expected from the use of near real-time observation based forcing data (e.g., from LandSAF). Here, retrievals of surface albedo, leaf area index, and lake temperature are most important for an improvement of the initial state.

Due to unrealistic drifts in soil moisture that are ubiquitous in most NWP models (Scipal and Drusch, 2007), in recent years considerable effort has been devoted to the implementation of advanced assimilation techniques. Data assimilation is necessary to constrain model drift, bringing the model state closer to observations. This is particularly important given the large sensitivity of model integrations to the initial conditions of surface variables, e.g., root zone soil moisture. These activities have additionally been stimulated by the availability of new satellite based soil moisture observations from active and passive microwave sensors. However, one should bear in mind that soil moisture exhibits an extremely large spatial variability on small scales and is therefore difficult to analyse on the basis of coarse resolution data. The activities in assimilation of remote sensing soil moisture observations at the European Centre of Medium Range Weather Forecast (ECMWF) should be considered in respect to methods used at present in COSMO (e.g., soil moisture analysis, latent-heat nudging).

6.4.2 Status of development and expertise within COSMO

Similar to most of mesoscale NWP models, COSMO uses a multilayer SVAT model (TERRA) with direct solution of the heat conduction equation and considers moisture transport due to hydraulic processes within the soil and the effects of transpiration by plants. Phase change processes of soil water (freezing/thawing of soil water/ice) are incorporated in the scheme both for their thermodynamic effect and for their impact on the hydraulic properties of the soil. COSMO employs a single layer snow module considering melting of a snow pack with prognostic snow density and time dependent snow albedo. COSMO with TERRA in single-column mode was validated in a model intercomparison study (GABLS3) against observations at Cabauw showing results that are within the uncertainty range of different models.

The CLM-Community implemented the National Center for Atmospheric Research (NCAR) Community Land Model (NCCLM) in addition to TERRA as a SVAT scheme for climate simulations. For this application, the extensions of NCCLM, e.g. vegetation temperature and vegetation dynamics become important.

With the development of a new software for generation of external parameters within COSMO, additional invariant fields can be used in the COSMO model for new parameterisations, e.g. the freshwater lake-model Flake or the orographic radiation correction scheme. The operational availability of high-resolution global land cover data (GlobCover) and elevation data (ASTER GDEM) allow for future COSMO applications in cloud resolving resolution. An adaptation and extension of the hydraulic and thermal soil properties and assumptions used in the SVAT model is feasible with the advent of high-resolution global and regional soil data bases (e.g., the harmonized world soil data base, BÜK1000 of the Bundesanstalt für Geowissenschaften und Rohstoffe).

Even though it may be assumed that horizontal heterogeneity should be less of a problem for mesoscale models than for larger scale NWP models, it seems reasonable to assume that COSMO forecasts of near surface variables and boundary layer processes would benefit from an implementation of a tile approach in the SVAT model TERRA. In particular, the distinction between snow covered and snow-free conditions and the handling of partial water points should benefit from the tile approach.

As for the snow model itself, a single layer scheme as employed currently in the COSMO model, is definitely not able to simulate realistically many important aspects related to snow metamorphosis. This is particularly true for situations of snow melt, where the COSMO model frequently fails to provide a realistic simulation of the evolution of near surface temperatures.

6.4.3 Strategy of COSMO and actions proposed

Short to medium term (5 years)

The Priority Project COLOBOC (Consolidation of Lower Boundary Conditions) addresses the development of the soil model and the revision of land surface properties. It is the main goal of this project to incorporate all activities related to the lower boundary conditions which have already reached an advanced state, and to consolidate these developments into well tested and documented software packages readily usable by the COSMO community.

To achieve this goal the project includes several actions in seven tasks:

– Consolidate tools of general interest:
  externalized TERRA module (task 1),
  software for generation of external parameters (task 2),
– Facilitate verification tasks:
  facilitate access to and usage of soil/surface observations (tasks 0 & 1)
– Consolidate and extend external parameters database (task 3)
– Find and validate an optimal configuration of TERRA with its associated external parameters and look-up tables (task 4)
– Revision of snow analysis and snow model (task 5)
– Deployment of urban module developed at EPFL/Switzerland (task 6)
– Consolidate parameterisation of land surface heterogeneity: the implementation of a tile approach could improve the forecast of surface fluxes and should have a positive impact on near surface variables (task 7)

For more details on this Priority Project, refer to the **COLOBOC project plan**.

Long term (10 years)

– To improve the simplified treatment of infiltration, interception, and run-off from surface and ground, due to numerical problems a revised approach should be considered and extended to possible streamflow routing. This requires the implementation of soil water interflow, baseflow, and ground table.

– Assimilation of remote sensing soil moisture observations for SVAT model initialisation or other approaches improving the initial state of the model soil.

Expected Outcome

The proposed effort should result in an improved representation of surface fluxes of momentum, heat and moisture with an improved representation of the boundary layer. This is expected to lead to an improved forecast of several key quantities, such as the cloud cover, the rate and timing of precipitation, and the near-surface temperature and humidity.

Risk Assessment

There is no appreciable risk of not achieving the short to mid term goals. Further development of the tile approach, streamflow routing, and assimilation of remote sensing soil moisture requires considerable research efforts. In view of limited human resources within COSMO, the quality and the timely delivery of research results depends on the availability of well-trained COSMO member staff.

6.5 Radiation scheme and aerosol impact

Author: Bodo Ritter (DWD)

6.5.1 State of the art, scientific developments

Radiation provides the ultimate source and sink of energy in the earth-atmosphere and interacts strongly with other components of the NWP model, in particular those affecting the evolution of the cloud field. In particular the evolution and forecast of near surface properties like e.g., the 2m-temperature are heavily dependent on a successful simulation of the transfer of radiation through the atmosphere and the associated surface energy budget. In addition to its relevance for NWP applications, radiative transfer modelling becomes even more important in the context of the increased use of the COSMO model in the climate community. However, the vital role of radiative transfer stands in a certain contrast to a lack of resources and also scientific knowledge with regard to some of the challenges that exist partly as a consequence of high-resolution NWP and partly due to a lack of suitable observational data.

6.5.2 Status of development and expertise within COSMO

For mesoscale models some of the basic assumptions underlying the radiative transfer scheme currently employed in the COSMO model (cf. Ritter and Geleyn, 1992) are no longer valid. In particular for high resolution implementations of the COSMO model with grid sizes of the order of 2-3 km, a 1-dimensional solution of the radiative transfer problem, assuming plane-parallel, horizontally homogenous conditions, is at best a 0-order approach and neglects several important aspects like the impact of sloping surfaces, orographic and cloud shadowing effects, etc. At MeteoSwiss a method has been developed to include some orography effects by means of a correction of radiative surface fluxes computed from the standard method (Buzzi, 2008). A further step in the 3D-direction could be the first order approximation of cloud shadowing effects across grid columns via the so called 'tilted independent column approach' (cf. Wapler and Mayer, 2008). However, no suitable solution is available for the full 3-dimensional problem.

Another field of research is the specification of optical properties of atmospheric constituents. In conjunction with the distribution of the respective constituents (e.g., clouds, gases) these properties control the overall atmospheric opacity and also have a strong impact on the vertical structure of radiative heating and cooling rates. As optical properties of ice clouds carry a particularly large uncertainty, efforts by A. Bozzo (University of Bologna in collaboration with ARPA-SIMC) to improve their specification provide a chance for an overall improvement of the radiative transfer scheme.

As indicated by comparisons to reference radiative transfer simulations optical properties of gases might also benefit from a general revision, bringing them up-to-date to state-of-the-art spectroscopic data bases.

As an alternative to a revision of spectroscopic data, a complete replacement of the currently employed RT scheme of (Ritter and Geleyn, 1992) by a more recent scheme that has been shown to comply with the requirements of an NWP framework such as the so-called RRTM (Mlawer at al., 1997) may be envisaged.

However, even though this approach will implicitly contain an update of the spectroscopic data for gaseous constituents of the atmosphere, the problem that for some other constituents (e.g. ice clouds) the specification of optical properties is far from being solved remains.

The specification of the spatial distribution of aerosols, which also has a significant impact on the distribution of radiative fluxes and heating rates, so far is based on a climatological approach. The original rather coarse climatology is currently replaced by a more recent data set. However, in the long term it may be desirable to let the RT scheme interact with the aerosol distribution that is predicted in the framework of the COSMO-ART version of the COSMO model.

Due to lack of computational resources, the temporal resolution of radiative transfer calculations is much lower than that of other physical or dynamical processes simulated by the COSMO model. Efforts should be undertaken to study the impact of this approximation in detail. As an alternative to a reduced calling frequency other approaches like the so-called 'Monte Carlo Spectral Integration' (cf. Pincus and Stevens, 2009) or an adaptive sampling of model points for which computationally costly RT calculations are to be performed (cf. Venema et al., 2007) may be considered.

6.5.3 Strategy of COSMO and actions proposed

Short to medium term (5 years)

– The impact of revised ice cloud optical properties on the overall model performance should be evaluated thoroughly in the near future. Due to the mutual interaction with the cloud scheme this work and any further studies in this field should be done in close collaboration with work on the cloud micro-physics scheme.

- The revision of the aerosol climatology should be completed and introduced in the operational version of the COSMO.
- Optical properties of gases and possibly also of water clouds should be re-evaluated on the basis of available reference data.
- The impact of the temporal resolution of radiative transfer calculations on model performance should be evaluated in detail and alternative strategies should be investigated. The extramural research program of DWD will contribute to this effort as it supports a study of the feasibility of the ‘adaptive technique’ of Venema et al. (2007) for NWP modelling.
- (very short term) Adaptation of the software for the COSMO external parameters in order to include also the topographical parameters needed for the topographic radiation correction (the topographical parameters should be stored in a laf grib file used by the model).
- The use of an external satellite derived time dependent surface albedo should be implemented, but care must be taken to ensure that this data is consistent with other external parameters of the model.

Long term (10 years)

- The relevance and feasibility of 3D-radiative transfer calculations or at least 1st-order approximations of 3D-effects for NWP applications at very high resolution should be studied. The potential of the tilted independent column approach as a means to overcome some of the limitations of the 1D-apporach partially will be investigated in the framework of the extramural research program of DWD.

Expected Outcome

The proposed efforts should result in an improved simulation of radiative fluxes and heating rates and an associated impact on the overall energy budget and forecast quality o the model.

Risk Assessment

Short and mid term goals are realistic and carry little risk apart from a potential lack of qualified resources. The long term development of fully 3-dimensional radiative transfer schemes for high-resolution operational NWP models may be beyond the scientific capabilities available within the COSMO community and therefore require strong support and commitment by the academic community.

6.6 Parameterisation of sea ice

Author: Dimitrii Mironov (DWD)

6.6.1 State of the art, scientific developments

A large number of dynamic-thermodynamic sea-ice models for various applications have been developed to date (see e.g., http://stommel.tamu.edu/~baum/ocean_models.html). Most sea-ice models (parameterisation schemes) currently used for NWP purposes account for thermodynamic processes only. That is, no ice rheology is considered and the horizontal distribution of the ice cover is governed by the data assimilation scheme. These sea-ice schemes compute the ice surface temperature from the heat transfer equation that is solved on a finite difference grid where the number of grid points and the grid spacing differ with the application. The ice thickness is either computed from an evolution equation or is simply set to a fixed value (see, e.g., the ECMWF IFS Documentation, 2008).

6.6.2 Status of development and expertise within COSMO

At present, no sea-ice parameterisation scheme is implemented into the COSMO model. The ice surface temperature is either taken from the analysis of the driving (global) model or is set to a certain “climatological mean” value.

The expertise in sea-ice modelling is however available within COSMO. A sea-ice parameterisation scheme for the global NWP model GME of DWD was developed and favourably tested (Mironov and Ritter 2003, 2004a, 2004b). Since April 2004 the GME sea-ice scheme is used operationally and the results are monitored.

Unlike most currently used sea-ice schemes which solve the heat transfer equation on a finite difference grid, the GME scheme uses the integral, or bulk, approach. It is based on a parametric representation (assumed shape) of the evolving temperature profile within the ice and on the integral heat budget of the ice slab. In this way, the problem is reduced to solving two ordinary differential equations for the two time-dependent quantities, the ice surface temperature and the ice thickness. In the current operational GME configuration of the sea-ice parameterisation scheme, the heat flux from water to ice is neglected, the volumetric character of the solar radiation heating is ignored, and the snow layer over sea ice is not considered explicitly. The effect of snow is accounted for parametrically through the dependence of the surface albedo with respect to solar radiation on the ice surface temperature (provision is made to explicitly account for the snow layer using the bulk model framework). As regards the horizontal distribution of the ice cover, the sea-ice scheme is subordinate to the GME data assimilation scheme (see Mironov and Ritter 2003, 2004a, 2004b, for details). At present, no fractional ice cover is considered. The GME grid box is treated as ice-covered once the assimilation scheme has detected an ice fraction greater than 0.5.

6.6.3 Strategy of COSMO and actions proposed

Short to medium term (5 years)

In the near future,

– the GME sea-ice parameterisation scheme should be implemented into the COSMO model (the work is underway at DWD),

– the scheme should be brought into the operational use by the COSMO members, and

– operational results should be monitored.

An attempt should be made to develop a refined formulation for the ice albedo with respect to solar radiation. As far as the sea-ice physics is concerned, further development of the sea-ice parameterisation scheme does not seem to be necessary in the short to medium term prospect, at least until some experience with the present scheme is accumulated.

Long term (10 years)

In the long term prospect, efforts should go into

– the consideration of the fractional ice cover, and

– the explicit treatment of snow over sea ice.

The way to account for the snow layer above the ice using the bulk model framework is outlined in Mironov and Ritter (2004a) and Mironov (2008b). However, the necessary empirical information is lacking at present. In particular, the dependence of the snow density and of the snow temperature conductivity on the snow depth and temperature, on the snow age, and, perhaps, on other parameters is largely unclear.

Resources required

Roughly one half of man-year (0.5 FTE) is required to implement the GME sea-ice scheme into the COSMO model and to test it. The long term work involves a great deal of research and the effort required is difficult to estimate *a priori*. Collaboration with universities and research institutes and with the other NWP and climate modelling groups is essential.

Expected Outcome

The proposed effort should result in an improved representation of surface fluxes of momentum, heat and moisture, leading, among other things, to an improved representation of the boundary layer.

Risk Assessment

There is no appreciable risk of not achieving the short to medium term goals. Further development of the sea-ice scheme in terms of physics invites considerable research efforts. In view of limited human resources within COSMO, the quality and the timely delivery of research results depends on the availability of well-trained personnel.

6.7 Parameterisation of lakes

Author: Dimitrii Mironov (DWD)

6.7.1 State of the art, scientific developments

In most numerical weather prediction (NWP) models, the effect of lakes is either entirely ignored or is parameterised very crudely. A large number of small-to-medium size lakes become resolved scale features as the horizontal resolution of NWP models is increased. In models with coarse resolution, many small-to-medium size lakes remain sub-grid scale features. However, the presence of these lakes cannot be ignored due to their aggregate effect on the grid-scale surface fluxes. This also holds for climate modelling systems concerned with the time scales ranging from many days to many years. Then, a physically sound model (parameterisation scheme) is required to predict the lake surface temperature and the effect of lakes on the structure and transport properties of the atmospheric surface layer. Apart from being physically sound, a lake model must meet stringent requirements of computational economy. A brief summary of lake models (parameterisation schemes) developed to date for use in NWP and climate modelling studies is given in Mironov (2008b).

6.7.2 Status of development and expertise within COSMO

A lake parameterisation scheme, termed FLake, has been developed, favourably tested against observational data through single-column numerical experiments, and implemented into the COSMO model (Mironov 2008b, Mironov et al. 2007, 2010; see the FLake web page http://lakemodel.net for further information). FLake is based on a two-layer parametric representation (assumed shape) of the evolving temperature profile and on the integral budgets of heat and kinetic energy for the layers in question. The same concept is used to describe the temperature structure of the ice cover. Using the integral approach, the problem of solving partial differential equations (in depth and time) for the temperature and turbulence quantities is reduced to solving ordinary differential equations for the time-dependent quantities that specify the temperature profile. A detailed description of FLake is given in Mironov (2008b).

In order to be used within COSMO (or within any other NWP or climate model), FLake requires a number of two-dimensional external-parameter fields. These are, first of all, the fields of lake fraction (area fraction of a given numerical-model grid box covered by lake water that must be compatible with the land-sea mask used) and of lake depth. Other external parameters, e.g., optical characteristics of the lake water, are assigned their default values offered by FLake. No tile approach is currently used in the COSMO model, i.e. each model grid box is characterised by a single land-cover type. Then, only the grid boxes with the lake fraction in excess of 0.5 are treated as lakes. Each lake is characterised by its mean depth. Deep lakes are currently treated with the “false bottom”. That is, an artificial lake bottom is set at a depth of 50 m. A Global Land Cover Characterization (GLCC) data set (http://edcdaac.usgs.gov/glcc) with 30 arc sec resolution, that is ca. 1 km at the equator, is used to generate the lake-fraction field. The field of lake depth is generated on the basis of a new data set that contains mean depths of a number of European lakes and of major lakes of the other parts of the world (further development of that data set is underway at Météo-France).

Although this section is about lakes, sea surfaces should be mentioned briefly, because they might constitute a substantial part of most model domains in Europe. In the present COSMO-model configuration, the surface temperature of the ocean/sea grid boxes (not lake grid boxes) is determined through the sea surface temperature (SST) analysis and is kept constant over the entire forecast period. This seems to be adequate for NWP-applications but is certainly not applicable for climate applications (COSMO-CLM). Consequently, within COSMO-CLM work started to couple regional ocean models with the COSMO-model in climate mode for the Northern plus Baltic Sea (GKSS) and for the Mediterranean plus Black Sea (Uni Frankfurt, FU Berlin, BTU Cottbus), whereas no such plans exist in the consortium up to now for NWP applications (some other interaction aspects are however taken into account through a wind speed dependence of the aerodynamic roughness length of the water surface; the actual roughness length formulations currently used within the COSMO-model might well be oversimplified, but that raises other issues, e.g. coupling with a wave model).

6.7.3 Strategy of COSMO and actions proposed

Short to medium term (5 years)

- FLake should be brought into the operational use by the COSMO members, and
- operational results should be monitored and the effect of lake parameterisation scheme on the overall NWP model performance should be assessed.

Further issues that should be addressed in the short to medium term prospect include

- the inclusion of new programmes to generate two-dimensional fields of lake fraction and lake depth for an arbitrary numerical domain (using the data set developed by Ekaterina Kourzeneva at Météo-France) into the standard COSMO software package for the generation of external-parameter fields.

Apart from NWP and climate modelling, a wide use of FLake for operation, research and education should also be encouraged. As far as the model physics is concerned, further development of FLake does not seem to be necessary in the immediate future.

Long term (10 years)

The key issues are

- the explicit treatment of snow over the lake ice, and
- the extension of the temperature profile parameterisation to include the abyssal layer below the seasonal thermocline, i.e. the development of a three-layer version of FLake.

As to the external-parameter data set, it is advantageous

- to collect data on the optical properties of the lake water.

In case the COSMO model is to be used for seasonal forecasting, a two-way interactive coupling of the atmosphere with the upper ocean may be necessary. FLake can be utilised as the upper-ocean parameterisation scheme that offers a very good compromise between physical realism and computational economy. With this aim in view,

- FLake should be extended to incorporate the effect of salinity.

Resources required

Roughly one half of man-year (0.5 FTE) is required to make FLake operational at each COSMO NWP centre. The effort required to develop and harmonise a software package for the generation of lake-depth and lake-fraction external-parameter fields is tentatively estimated at 0.5 man-years (0.5 FTE). The long term efforts outlined above involve a great deal of research. Given limited resources within COSMO, collaboration with universities, research institutes and NWP and climate modelling groups is required.

Expected Outcome

The proposed efforts are expected to result in an improved representation of surface fluxes of momentum and of scalar quantities and hence in an improved representation of the boundary layer. Considering the growing popularity of FLake as a lake parameterisation scheme (see http://lakemodel.net, menu item “FLake users”), COSMO should assume a leading role within the European NWP and climate modelling community as regards the lake-parameterisation aspect of the atmospheric model development and application.

Risk Assessment

There is no appreciable risk of not achieving the short to medium term goals. Further development of FLake in terms of the model physics invites considerable research efforts. In view of limited human resources within COSMO, collaboration with universities and research institutes is required. The quality and the timely delivery of research results depend on the availability of well-trained personnel.

6.8 External parameters

Author: Hermann Asensio (DWD)

6.8.1 State of the art, scientific developments

Numerical weather prediction (NWP) and climate models require geographical localized datasets, the so-called external parameter fields. They provide input data for physical parameterizations. The development of new parameterizations or the revision and extension of existing parameterisations often require new external parameters. An example is the parameterisation of lakes, which requires external parameter fields of lake fraction and lake depth (see section 6.7). The revision and extension of the radiation scheme and of the soil model also require new additional external parameters (see sections 6.4 and 6.5).

The external parameter fields for the atmospheric models are generated on the basis of raw data sets with varying resolution and geographical projection. The mapping of categorical information to physical quantities (e.g. land use classification to the roughness length) is accomplished with the help of look-up tables (Doms and Schättler, 2004; Masson et al., 2003).

6.8.2 Status of development and expertise within COSMO

The currently used raw data sets to generate external parameter fields for the operational configurations of the COSMO model are GLOBE, a digital elevation model with the resolution of 30 arc seconds (ca. 1 km at the equator), the Digital Soil Map of the World (5 arc minutes), and the Global Land Cover 2000 Database GLC2000 (30 arc seconds). For experimental COSMO-model configurations, a climatology of the monthly-mean normalized differential vegetation index NDVI and a climatology of monthly-mean aerosol optical thickness are available. With the development of a new software “EXTPAR” for the generation of external parameters for COSMO, additional invariant fields can be used, e.g. fields needed for the freshwater lake-model FLake. Furthermore, a number of external parameter fields required by a revised version of the soil model TERRA and by an urban parameterisation scheme (field of urban fraction) can be generated with the new software. A consistency check on the target grid is performed in order to avoid possible inconsistencies between various parameters. These inconsistencies are difficult to avoid a priori since different external parameter fields are typically generated on the basis of different independent raw data sets. The option of a manual revision should be avoided, or at least reduced to a minimum, since an excessively large number of manual corrections may be required at high horizontal resolution of the target grid and it would be almost impossible to ensure reproducibility of external parameter fields.

The consolidation of the software for the generation of external parameter fields and the extension of raw databases are tasks of the priority project COLOBOC (COnsolidation of LOwer BOundary Conditions).

6.8.3 Strategy of COSMO and actions proposed

In the last years, new high resolution raw data sets have become available, e.g. the Harmonized World Soil Database (30 arc seconds), the GlobCover land use data (10 arc seconds), and the ASTER global digital elevation model (1 arc seconds). However, in order to use these data within NWP models some artefacts should be removed (by providers and/or by users). In 2010, a new global raw dataset on a 30 arc second grid with lake-depth data has been developed by Ekaterina Kourzeneva at Météo-France.

Short to medium term (5 years)

- Consolidate external parameters for the lake model FLake based on 2010 data set
- Consolidate new MODIS-based background surface albedo
- Consolidate alternative data sets of soil types (Harmonized World Soil Database, European Soil Data Base)
- Add parameters for orographic radiation correction
- Provide alternative vegetation characteristics using MODIS-based phenology model
- Provide for a more correct representation of scale separation for SSO/resolved scales (option for orography smoothing in EXTPAR instead of INT2LM)

Long term (10 years)

- Add vertically dependent soil information where available (e.g. depth of water reservoir or inactive layer and soil texture)
- Provide orography at higher resolution than GLOBE (e.g. SRTM or ASTER GDEM)
- Provide land use data at higher resolution than GLC200 (e.g. GlobCover)
- Address the uncertainties associated with the look-up tables, especially for the SVAT model. The determination of the roughness length should be revised. A new formulation of the surface-layer transfer scheme may require an additional external parameter field for the displacement height.

7 Data assimilation

Authors: Christoph Schraff (DWD) and Roland Potthast (DWD)

7.1 State of the art, scientific developments

Data assimilation in NWP is the process of adjusting a background state, typically a very-short range model forecast, to the real evolution of the atmosphere as indicated by the current observations. A rigorous basis for this process is given by estimation theory which requires as input the statistical error covariances of the observations and the background forecast. Within this framework, two classes of assimilation schemes are in the focus of current research and development efforts worldwide, that is the variational methods (3D- and 4D-Var) and (variants of) the Ensemble Kalman Filter (EnKF) approach (see Evensen, 2006). Recently, also hybrid variational – ensemble assimilation methods have started to attract considerable attention.

In **global** operational **NWP**, 4D-Var is applied very successfully at several centres and seen there as a major factor contributing to model forecast improvements in the past few years. Also for regional NWP at resolutions which do not allow for explicit simulation of deep convection, variational schemes are most commonly applied or being developed. In particular, the other major European consortia for NWP (Met Office, HIRLAM/ALADIN group) already apply operationally or develop 4D-Var for these scales. For global and regional applications, however, EnKF type methods have obtained strongly increased attention in recent years.

In the **convective scale**, i.e., for models which simulate deep convection explicitly, 4D-Var is being developed at HIRLAM/ALADIN. However, the special characteristics of the convective scale pose additional challenges to successfully implement 4D-Var, but also other methods, for this purpose. These characteristics include:

- non-Gaussian probability densities and errors
- unknown and very flow-dependent balance
- model errors
- highly non-linear physical processes (for which the tangent linear approximation need not be valid)
- limited predictability (of convective systems)
- direct and indirect observations with highly non-linear and complex observation operators and norms

It is noted that these properties are not absent in the larger scales, but in the convective scale, at least the first five issues are much more pre-dominant and play a larger role. The last issue is also important since in-situ observations are usually not dense enough to describe the small-scale meteorological situation accurately enough. Hence, it is crucial to be able to use remote-sensing data which typically are **indirect observations** (i.e., observations of quantities which are not prognostic model variables) and have **non-linear observation operators**.

The forecasting of convection is a primary goal of convective-scale NWP. Accurate estimation of both convective cells and their environment are important. Within precipitating areas, Doppler radial wind and reflectivity from radar must be used. The environment has a large influence on the initiation and further evolution of convection. However, in the absence of hydrometeor scatterers, the environment is poorly observed by remote sensing. It is therefore crucial to make optimal use of all available observations, including surface meso-nets, wind profilers, GPS-derived water vapour data, Meteosat (and other high-resolution satellite) data, clear-air wind and, if available, low-level refractivity from radars.

Most of these data come at asynoptic times when the data density is typically very variable and remains poor for some model variables (notably in comparison to the scales resolved by the model). The assimilation system should be capable of retrieving information also on those model variables that are not (well) observed. However, static (mass-wind) balances that are often a fair approximation at larger scales are weak or absent on the convective scale, and the flow is often truly three-dimensional and driven by latent heating. Therefore, **flow-dependent background error covariances and the coupling with the forecast model** are essential. In other words, the assimilation technique should be able to project the limited observational information onto the dynamically relevant structures which can be resolved by the model. EnKF can potentially do this, and the same applies to 4D-Var provided that the assimilation window can be chosen large enough. On the other hand, this renders these techniques particularly susceptible to analysis errors as a result of **model errors**. In particular, this applies to errors in the parameterisation of microphysics, turbulence, and surface fluxes since these **highly non-linear physical processes** have a great influence on convection. Those parameterisations therefore need to be more accurate at high resolution not only for the pure forecast, but also for the data assimilation. Even though methods exist to account for some model errors in data assimilation systems, model error is a critical issue. Furthermore, explicit modelling of (at least unorganised) convective cells over one or a few hours should already be seen as long-range forecasting, with very **limited predictability** for the individual cells. Probabilistic (ensemble) forecasting can provide a representation of the probability densities, and perturbed initial conditions can be delivered naturally by ensemble data assimilation.

Another basic topic which is of considerable interest for meteorological centres is the combination of convective-scale NWP systems with **nowcasting**, i.e. with real-time observations combined with simple forecast techniques employed in weather warning strategies and systems. Here, probabilistic approaches are used which are usually purely stochastic in nature and incorporate meteorological knowledge by rule-based systems. Real-time data assimilation strategies for various probabilistic distributions of weather systems and classifications generate the need to combine ensemble based NWP systems with real-time data. There are various open questions from the algorithmic setup to updating strategies and the use of nowcasting assimilation results for the full data assimilation problems of the physical state variables.

With continuing refinement of convective models and the integration of real-time data of high resolution the question how to optimally combine information on **different** (temporal and spatial) **scales** leads to further demands in research and development.

Neither 4D-Var nor EnKF is yet mature for convective scale NWP, and it is an open question which technique will turn out to be more successful in the future. Overall, comparative studies appear to show similar performance, e.g., for assimilation of Doppler radar data (Caya et al., 2005). Differences tend to come from practical details of the implementations rather than from fundamental differences in the two methods. With regard to the assimilation method, the **plans and research efforts** of the other European consortia are towards 3D-Var (AROME; Met Office in 2009) and 4D-Var (Met Office, for the longer term). The Japan Met Agency and at NCAR are investigating both 4D-Var and EnKF for the convective scale, and a lot of work on Ensemble Kalman filtering is being done at various universities and research institutions in the USA. It should also be mentioned that a centre for ensemble assimilation is being built up at Bergen with involvement of weather services of HIRLAM, and this will possibly also take up activities related to convective-scale assimilation.

With respect to the observations, research efforts at European consortia are focused on the variational assimilation of radar Doppler radial wind, reflectivity, radar-derived precipitation, cloud information, cloudy and rainy satellite radiances (mainly microwave), and surface meso-net data. It may be mentioned that for the assimilation of precipitation, doubts exist (e.g., at the Met Office) whether 4D-Var will be able to beat the far simpler approach of Latent Heat Nudging (LHN).

All the methods eluded so far have their shortcomings with respect to one or another of the above-mentioned characteristics of the convective scale. EnKF, for instance, is based on Gaussian statistics, and 4D-Var requires linearization of the forecast model (physics). Particle filters such as Sequential Importance Resampling (**SIR**) can in principle cope with these issues. However, they have been applied successively only to much lower-dimensional systems than NWP, e.g., SIR in an oceanographic study. The localisation approach adopted for this method so far in order to reduce the required large ensemble size is not feasible for NWP due to its demands on balance. Hence, significant research on this method will be needed before any practical application in NWP.

7.2 Status and expertise of COSMO

Observation nudging is the standard data assimilation algorithm for the COSMO model. It is currently used in all convective-scale (1-3 km grid spacing) and larger-scale implementations of the COSMO model, except for those implementations in which the forecasts start from interpolated coarser-scale analyses. Direct observations from radiosondes, aircrafts, wind profilers, synoptic surface stations, ships, and buoys are used operationally, and radar VAD wind, scatterometer wind, satellite-derived wind vectors, RASS virtual temperature profiles, and GPS-derived integrated water vapour data can be used optionally. For the assimilation radar-derived precipitation rates, a **latent heat nudging** (LHN) scheme has been developed and is applied operationally at the convective scale at DWD and MeteoSwiss.

These nudging-type schemes can cope with highly non-linear physical processes in the model and with non-Gaussian distributions, and they are able to continuously assimilate asynoptic and high-frequency data. However, there are two main shortcomings. Firstly, the formulation of explicit error covariances is strongly limited in the current implementation, and although implicitly, the effective influence of observations becomes weakly flow-dependent due to the coupling with the forecast model, this flow-dependency does not reflect the situation-dependent errors of the model background fields well. Secondly, indirect observations have to be expressed in terms of model variables by inverting them into retrievals which can then be digested by the nudging scheme. This inversion is usually subject to assumptions and approximations and prone to errors.

As a result, there is considerable work and experience in COSMO on **retrieval techniques**. LHN may be seen as an example. A 1D-Var module has been developed and is being refined and tested for temperature and humidity retrievals from SEVIRI, ATOVS, AIRS, and IASI satellite radiances. Work is underway to test the adoption of the 1D-Var approach to refine the LHN method. A simple adjoint technique is investigated to retrieve wind vector fields from successive scans of radar Doppler velocity and reflectivity. GPS tomography (developed at cooperating institutes) produces refractivity profiles from ground-based GPS networks. Work to derive and use a cloud analysis has been planned but has not yet started.

In some of the weather services participating in COSMO, further expertise on data assimilation methods is available though the work for model systems other than COSMO. Rather extensive experience exists on **3D-Var** at DWD (operational for the global GME model), USAM (operational for the regional hydrostatic model HRM), and RosHydromet. Furthermore, prototypes of the **LETKF** (Local Ensemble Transform Kalman Filter) have been developed at DWD (for GME) and at USAM (for HRM). At DWD scientists have worked with 4D-Var and Particle Filters on various smaller-scale applications.

A variational (2D-Var) approach is also adopted in a soil moisture initialisation scheme developed and operationally used at DWD. Work is underway to replace the additional model forecast runs by parameterised regressions which are used to determine the required gradient of predicted 2m-temperature with initial soil moisture content. Finally, an elaborate snow cover mask based on SEVIRI data has been developed and incorporated in the snow depth analysis at MeteoSwiss where this new scheme is running operationally.

7.3 Strategy of COSMO and actions proposed

For convective-scale modelling (and in the presence of moist convection), the fastest error growth is at the smallest scales, and a forecast of convective cells over a few hours should already be seen as a long-range forecast. Probabilistic forecasting should therefore be pursued even for very short lead times and will be part of the strategy. Due to the special challenges in the convective scale and the shortcomings of the present nudging approach (see above), it is appropriate on the one hand to use a common approach for a generalised system for global and regional modelling, and necessary on the other hand to develop a novel separate advanced data assimilation scheme for the convective scale which is also able to provide perturbed initial conditions. This is a main reason why the approach for this scheme should be **ensemble-based data assimilation**. Devising such a scheme is also preferred over 4D-Var due to its flexibility and scalability. Moreover, extensive research and development has a far longer history on 4D-Var (about 15 years) than for Ensemble Kalman filtering (very few years), and this gives reason to believe that the scope for further improvement may be greater for the latter method. Further, ensemble Kalman filtering has a high potential to be combined with variational elements into tailored hybrid schemes with well-designed purpose driven properties. By embarking on ensemble data assimilation, COSMO can attain a unique position within Europe with a chance for leadership in this area.

A generalised system for global and regional modelling is being developed in the project ICON (DWD and MPI Hamburg), including a 3D-Var – (L)ETKF data assimilation component, and this system can provide perturbed lateral boundary conditions for the convective-scale system.

Apart from developing an ensemble-based data assimilation which will have a strong focus on the use of radar (radial wind and reflectivity) data, the strategy must also include to improve the use of satellite data, in particular for deriving and using cloud information over land. Ongoing development activities related to the current nudging scheme shall be continued if improvements of the performance of that scheme can be expected with spending only limited (human) resources, or if these developments can also be applied to the ensemble-based assimilation. The **actions proposed** (**next 5 years**) are the following:

7.3.1 Km-Scale Ensemble-based Data Assimilation

A **Priority Project** "Km-Scale Ensemble-based Data Assimilation" (KENDA) is set up in order to develop a novel ensemble-based data assimilation system for the convective scale (i.e., 1-3 km model mesh-size) which can make better use of the wealth of the locally available observations than the current nudging scheme, and which is capable of providing perturbed initial conditions for convective-scale ensemble forecasting. In particular, the scheme must be able to assimilate, besides conventional observations, both radar radial velocity and radar reflectivity successfully, and in turn, the use of these data is an integral part of this development.

Two approaches are envisaged, that is the (Local) Ensemble (Transform) Kalman Filter (EnKF / LETKF) and the Sequential Importance Resampling (SIR) filter (van Leeuwen, 2003). For the EnKF / LETKF, successful meteorological data assimilation applications already exist, and less practical problems are expected than for the SIR approach. As preliminary statistical investigations do not anticipate a failure without explicitly taking into account non-Gaussianity, the main resources from the weather services in COSMO will be devoted to the EnKF / LETKF approach. To start with, the Local Ensemble Transform Kalman Filter (LETKF) as proposed by Hunt et al. (2007) will be implemented, but (an)other variant(s) of the EnKF / LETKF or hybrid EnKF-3DVAR family, if expected more suitable during the course of the development, may be investigated too. The more basic research required for SIR should rely mainly on resources from cooperating institutes in academia.

For more details on this Priority Project, see (a summary of) the **KENDA project plan** on www.cosmo-model.org.

7.3.2 Use of humidity and cloud related data

In addition to the use of radar data, emphasis should also lie on assimilating high-resolution humidity and cloud related observational data for convection-resolving NWP. The ensemble-based (EnKF / LETKF) framework offers the potential of deriving suitable analysis increments also in the dynamical fields from these humidity-related data, and this should help the model to retain the observation information in the forecast. The focus lies on two data types:

- Slant path delay data from the continuously enhanced and relatively cheap network of ground-based GPS stations.
- SEVIRI brightness temperature (over land and sea) indicating the presence or absence of cloud and measuring approximately its top temperature (height). These data can be assimilated either directly or combined with conventional (radiosonde, surface synoptic, ceilometer) and other satellite data (IASI, AIRS, CRIS, …) for increased vertical resolution to an (incomplete) cloud analysis which can then be fed as cloud or humidity data into the LETKF algorithm. The algorithms used to derive the cloud cover and cloud top temperature and height can be similar to the ones applied for the NWC-SAF products, but they can combine the data from several instruments and also include the current model fields.

Note that the use of cloud information is important to improve the specification of convective cells which are not yet precipitating and seen by the radars. Moreover, cloud is generally an important weather parameter to forecast, e.g., in low stratus conditions.

Developing the use of these two data types is included in (later stages of) the KENDA project. Not mentioning further observation types does not imply that there is no interest to assimilate them but that the priority to develop their use is not equally high.

7.3.3 Other activities

- Activities that have already started should be continued if they require limited resources to lead to forecast improvements using the nudging scheme. However, the amount of resources which is spent for modules, in particular retrieval techniques, which are only relevant for the nudging scheme, but not for KENDA, should be decreasing continuously. In turn, some work done in the context of retrieval schemes can also be used for KENDA even if the retrievals themselves are not used there. In particular, this applies to issues such as data pre-processing, quality control, data selection and thinning, and some of these issues can be integrated in the KENDA priority project. Work should continue on:
  - Further optimisation of LHN, including a 1D-Var approach
  - Nudging of the radial wind component of Doppler radar velocities
  - GPS tomography, use of GPS-derived integrated water vapour
  - (mainly data selection and screening of) screen-level data
  - Scatterometer wind
  - Radar VAD profiles

- Initialisation of (sub-)surface fields:
  - In the 2D-Var soil moisture initialisation, the additional model forecast runs should be replaced by parameterised regressions which are used to determine the required gradient of predicted 2m-temperature with initial soil moisture content.
  - The snow depth analysis, which includes the newly developed elaborate snow cover mask based on SEVIRI data should be further refined and more widely used operationally in order to take better benefit of the work already done.
- Nowcasting on COSMO Ensembles
  - The integration of nowcasting systems with COSMO ensembles has large potential to provide large innovation for weather warning systems and short-term prediction.

7.3.4 Long-term (10 years)

The longer-term plans will depend on research results in the meantime. An eye should be kept particularly on non-linear assimilation methods such as particle filters which can cope with strong non-Gaussianity. Research efforts in this field should be supported.

Furthermore, the assimilation of satellite data over land should be enhanced. For instance, microwave radiance channels which are both sensitive to the atmosphere and the surface could be used over land after retrieving the surface emissivity and subtracting the effect of the surface. Such type of data can help to improve e.g., the (cloud-free and cloudy) non-precipitating convective environment.

7.3.5 External collaboration

Since the basic assimilation methods developed and used in COSMO, nudging and ensemble-based data assimilation (LETKF, SIR), are different from the 3D- and 4D-Var approach adopted in the other European consortia, the collaboration within SRNWP has not yet reached its full potential.

Opportunities for bilateral collaboration should be screened for issues such as data exchange, data pre-processing, quality control, observation (forward) operators.

Once a basic convective-scale LETKF is running and major scientific issues are being tackled, communication and possibly collaboration should be set up with NCAR and / or institutes involved in convective-scale EnKF in the US.

Similar links may also be set up with the research centre on ensemble data assimilation that is being set up at Bergen (G. Evensen, Nansen Res. Centre; Met.no; Norsk Hydro; SMHI …).

We will continue to develop strong links and collaborations with universities and research institutes.

8 Predictability and EPS

Authors: Chiara Marsigli (ARPA-SIMC), Susanne Theis (DWD), and Pierre Eckert (MeteoSwiss)

8.1 State of the art, scientific developments

The atmosphere behaves in a chaotic way (Lorenz, 1963). This means that predicted states are extremely sensitive to small changes in the initial state and eventually to phenomena which are not described explicitly in the models. Uncertainty is intrinsic to the evolution of the atmosphere, so that **numerical weather prediction must necessarily be addressed in a probabilistic framework**.

Within the last 15 years, **ensemble prediction systems (EPS) have advanced to a standard method** for inferring probabilistic properties of the future atmospheric state (Lewis, 2005, and references within). When the EPS development started, the focus was set on global models.

Global EPSs mainly have as primary objective to capture the forecast spread generated by the uncertainty of the initial state due to operational constraints in the collection of observational data and to weaknesses in the analysis process. A global EPS is presently mainly designed to capture possible synoptic evolutions, the translation into weather parameters being subject to deficiencies, especially for high impact weather. The necessity to describe the uncertainty in the small scale physical processes and to better quantify parameters like rainfall amounts or wind speed led to the development of limited area EPSs which are described in the following.

In limited-area models (LAMs) with smaller grid spacing**, intrinsic forecast uncertainty continues to play an important role.** For example, in terms of precipitation forecasts, the decreased grid spacing is not necessarily expected to increase the quality of single model simulations as measured by “grid-based” metrics (Mass, 2002). The smaller grid spacing is rather expected to allow an improved spatial and temporal representation of statistical properties. In order to convey this benefit to the applications, a **probabilistic framework is indispensable** (Fritsch and Carbone, 2004). The possible benefit of mesoscale EPS has been described by Brooks et al. (1995), and now mesoscale ensemble forecasting (grid spacing O(10) km) is on the agenda of most weather forecasting centres. Several mesoscale EPS are running operationally and benefits have been demonstrated (e.g., Marsigli et al., 2008).

However, **the optimal design of a limited-area EPS is still a challenge.** Error growth in limited-area models is not a straightforward extension of error growth in global models. The presence of lateral boundary conditions introduces an added complexity. Large scales that are provided as nesting information at the lateral boundary are generally well reproduced in the short-range, whereas shorter scales behave chaotically and diverge as in an autonomous global model (de Elía at al., 2002). On the other hand, depending on the weather situation, LAM ensemble dispersion may be inhibited by the nesting information at the lateral boundaries (Nutter, 2003). In addition, physics and surface forcing play a different role in models with smaller grid spacing.

When developing an ensemble perturbation strategy, this also requires special attention.

A first attempt at introducing the idea of EPS in limited-area modelling is the **“dynamical downscaling of global EPS”** (Marsigli et al., 2001; Frogner and Iversen, 2002). In this approach, the limited-area model produces an ensemble of simulations which are nested into different members of the global EPS, respectively. Thus, the dynamical downscaling simply combines the benefit of the limited-area model (i.e., the improved representation of processes due to smaller grid spacing) with the benefit of the global EPS (i.e., the probabilistic framework, realized on the synoptic scales).

Obviously, the methodology of “dynamical downscaling” is closely tied to a global EPS. However, the scope of many global EPSs is medium-range forecasting (days 3-10) whereas most limited-area prediction systems focus on days 0-3. This discrepancy can lead to a severe underestimation of forecast uncertainties within the short range. Improvements within the “downscaling EPS” are expected, if the **short-range spread** within the driving global ensemble members can be improved. Various strategies have already been followed up, such as the multi-model approach (e.g., Tracton et al., 1998, García-Moya et al., 2009).

Further improvements (not only in the short range) of the “downscaling” EPS are expected, if perturbations also **explicitly represent the error growth associated with small-scale processes** which are resolved by the smaller grid spacing of the limited-area model. There are attempts to introduce additional perturbations directly within the limited-area ensemble system, for example perturbations of the model (e.g., Bright and Mullen, 2002) and also perturbations of the initial state (e.g., Wang and Kann, 2006).

In terms of **model perturbations**, current developments for global models and limited-area models are quite similar. Generally, dealing with model error in EPS is thought to be very important and very challenging. There is a multitude of different approaches: stochastic and non-stochastic perturbation of model parameters, stochastic perturbation of tendencies, stochastic parameterisation schemes, stochastic kinetic energy backscattering scheme, applying different parameterisation schemes (multi-scheme), applying different NWP models (multi-model), etc.

Currently, most limited-area EPS simply obtain their **initial condition perturbations** from the larger scale forecasting system, but there is growing interest in generating initial condition perturbations directly for the small scales. One motivation is the possibility to explicitly include the smaller scales in the perturbation strategy. Another motivation is the different focus on lead time. In a limited-area EPS, the perturbations need to be effective immediately from the initial time, because the EPS focuses on the short-range forecast. Therefore, the initial condition perturbations should reflect the uncertainties in the analysis (Bowler et al., 2008) and the approach is naturally tied to the way how the analysis is derived within the limited-area model. A problem which should be dealt with when following this approach, is that the effectiveness of the initial condition perturbations in a LAM ensemble may be limited by the dominating effect of the boundary conditions provided by the driving global model.

Another challenge is the allocation of computing time within the design of the EPS. The limited computing time leads to a **trade-off** between the minimum **grid spacing,** the maximum **domain size** and the maximum **number of ensemble members**. A small grid spacing benefits the realism of the process description, a large domain size benefits the self-organization of small-scale error propagation, and a large number of members benefits the statistical inference of probabilistic properties.

Probabilistic verification assesses the quality of EPS through a comparison between forecasts and observations, measured by certain metrics. Current results show that most limited-area EPS are still **underdispersive**, i.e., the ensemble does not sufficiently reflect the observed uncertainty of the forecast, especially for surface weather parameters.

The importance of **calibrating** ensemble forecasts has been widely recognised in recent years (Toth et al., 2006; Hamill et al., 2006), because it can improve ensemble "reliability" considerably. The calibration is based on a statistical relation between forecasted and observed state which is derived from a training data set. There is a multitude of different techniques: regression methods, Bayesian approaches, analogue matching, mapping of the cumulative distribution function, and also the Kalman filter. In addition, there are also **post-processing** methods that account for a small ensemble size, such as the inclusion of a lagged-average ensemble or the addition of a spatial/temporal neighbourhood (Theis et al., 2005; Schwartz et al., 2010).

In order to reflect the current status of limited-area EPS more specifically, the **status in the other European consortia** is briefly summarized:

Within HIRLAM, AEMET is running operationally the SREPS system, with 25 km horizontal grid spacing. The system nests five different limited-area models (including the COSMO model) on five different operational global models. In other words, it relies on a multi-model, multi-boundary approach for a description of all the sources of uncertainties. The Norwegian Meteorological Institute (met.no) has instead implemented the LAMEPS system, operational since 2005. It is a mesoscale downscaling ensemble based on HIRLAM, taking initial and boundary conditions from the TEPS global ensemble (a version of the ECMWF EPS targeted for Northern Europe), running with a horizontal mesh-size of 12 km. Beside this, NORLAMEPS has been created, a hybrid multi-model ensemble system which combines LAMEPS and TEPS.

Within the ALADIN Consortium, Météo-France has developed the PEARP short-range global ensemble prediction system. The perturbations are generated by the singular vectors technique, optimized over a limited area including Western Europe and the northern part of the Atlantic Ocean. By this way, perturbations are mainly efficient in the area of interest for the short range forecast over France. It has 11 members and it is based on the operational version of the ARPEGE model, with a variable grid mesh where the highest resolution is about 23 km over France.

In the LACE Consortium, ZAMG has put operational the LAEF system, a downscaling ensemble based on the ALADIN model, run with a horizontal mesh-size of 18 km. The ensemble members are a downscaling of the ECMWF EPS ones. Work in the consortium is ongoing to explore many perturbation techniques, both in the analysis and in the model.

In December 2008 the ALADIN LAMEPS system has been put into operations by the Hungarian Meteorological Service (OMSZ). This is a downscaling ensemble, where initial and lateral boundary conditions are provided by the PEARP system of Météo-France. The integration of the 10 + 1 ensemble members is performed every day at 18 UTC with the ALADIN model at a 12 km horizontal mesh-size, up to 60 hours.

The collaboration between HIRLAM and ALADIN-LACE has lead to the start of the GLAMEPS Project, aiming at creating a distributed multi-centre operational ensemble system. The Grand ensemble should cover a pan-European domain and at present is configured as an array of HIRLAM and ALADIN LAM-EPS models coupled to ECMWF EuroTEPS.

All these systems are, at present, essentially downscaling of either existing global ensembles or multi-model ensembles. A different approach was chosen by the UK Met Office, which is running operationally the MOGREPS system, a global and regional ensemble system based on the UM, where the boundary conditions for the regional ensemble are provided by the global one. The regional component resolution is 24 km. The initial condition perturbations are generated with an ETKF approach for the global components only, while the regional ones simply downscale the global analyses. In order to describe also the uncertainty due to the model formulation, model perturbations are also applied. The possibility of having a global and regional system running based on the same perturbation strategy prevents from having mismatching problems between the perturbations of the regional models and those ingested through the boundaries, which affect the other regional systems.

Also **outside Europe**, high-resolution ensemble activities are being carried out in many countries:

In the United States, the SREF system of NCEP is running operationally. Besides that, a multi-analysis, multi-model and multi-physics ensemble is running at a somewhat lower horizontal resolution (32 km), and many other institutions are developing mesoscale ensembles, too.

The U.S. Air Force Weather Agency is developing a mesoscale ensemble, focussing on the forecast on surface weather elements at a fine scale. It is a multi-physics ensemble, where different techniques for the inclusion of the initial condition uncertainty are being tested. The horizontal resolution is up to 10 km.

At Environment Canada, a regional ensemble prediction system is used, downscaling the GEM global ensemble at 33 km of horizontal resolution and perturbing the physics in the limited-area model integrations.

At the Japan Meteorological Agency (JMA), a mesoscale ensemble prediction system with a horizontal mesh-size of 15 km using the JMA non-hydrostatic mesoscale model has been tested, applying different methodologies for perturbation of the initial conditions, which have proven to be effective as compared to simple downscaling.

Finally, the China Meteorological Administration (CMA) has tested a mesoscale ensemble with 15 km horizontal mesh-size, where breeding is explored as a technique for initial condition perturbations and physics perturbations have also been applied.

With the advent of convection-permitting models (grid spacing 1-3 km), there is also need for **convection-permitting ensembles**, i.e., a method to account for uncertainties within convection-permitting simulations. The motivation, methodology and challenges are principally the same as in mesoscale “convection-parameterisation” ensembles (see above), with some minor differences and some added complexities.

Accounting for forecast uncertainties appears even more important when applying convection-permitting models. Physical processes leading to convection are **highly non-linear**, so that the explicit modelling of convective cells over a few hours should already be seen as long-range forecasting, with very limited deterministic predictability for the individual cells. Thus, convection-permitting ensembles focus on the **shortest-range (0-24 hours)**, as opposed to the short-range (0-3 days). Furthermore, error growth in convection-permitting models does not necessarily behave in a similar way as in convection-parameterisation models. **Different error growth** may arise from the strong non-linearities and the different role of physical processes. Together with the new focus on the shortest-range, this may require a **revision of the perturbation strategy**.

Concerning model perturbations, there is also a technical restriction. The **multi-scheme approach** may be **less feasible**, because there is less experience with exchanging different parameterisation schemes within the same model, due to the fairly recent development of convection-permitting models. Furthermore, there is obviously no possibility to vary the type of deep-convection parameterisation anymore, because this parameterisation scheme is switched off.

Another technical issue arises when looking at the **“dynamical downscaling”** approach. The convection-permitting ensemble cannot be directly nested into a global EPS, because the gap between the small and the large grid spacing is too large. Therefore, the “downscaling” amounts at least to a **2-step procedure**, going from the global EPS to a convection-parameterisation EPS, and from the convection-parameterisation EPS to the convection-permitting EPS.

Last but not least, a convection-permitting ensemble requires much **more computer resources** than a convection-parameterisation ensemble. This is already due to the computational cost of the convection-permitting model itself. As a consequence, the trade-off between grid spacing, ensemble size and model domain becomes tighter. The small grid spacing is definitely needed to allow for an explicit simulation of convection. A fairly large ensemble size is supposedly needed to account for non-linear error growth and also to allow for statistical inference of risks for extreme precipitation. And the model domain should allow for independent error propagation within the model, and should at least cover the region of interest (e.g., the nation).

Compared to the convection-parameterisation EPS, the **international status of convection-permitting EPS** is much less advanced.

There are increasing research activities dealing with convection-permitting EPS (e.g., Leoncini et al., 2010), but nearly all of them are still restricted to case studies. This might be due to the fact that convection-permitting ensembles are still difficult to afford because they demand a very large amount of computer resources.

Outside Europe, there is only one research project which runs convection-permitting ensembles for time periods of several weeks. The University of Oklahoma has been carrying out several real-time experiments with an ensemble of up to 20 members, based on the convection-permitting model WRF, with a grid spacing of 4 km, 2 km and

1 km (e.g., Kong et al, 2008; Schwartz et al., 2010). In terms of convection-permitting ensemble simulations, the domain size is impressively large, covering nearly the whole central United States.

Within Europe, DWD is also carrying out experiments covering several weeks. This is done in the framework of the project COSMO-DE-EPS which aims at an operational system. The project COSMO-DE-EPS is described in the following sections.

8.2 Status and expertise of COSMO

Ensembles with parameterised convection

With a mesh-size of 7 km, the COSMO-LEPS system operationally run by the COSMO consortium is one of the few operationally running ensembles with a mesh-size smaller than 10 km. A clustering is undertaken on the members of the ECMWF EPS so as to choose 16 representative members, which are then used as initial and boundary conditions for 16 COSMO runs with 7 km mesh-size. Although some perturbations on physics (convection and turbulence) have been recently introduced, this system can be seen essentially as a dynamical downscaling of the ECMWF EPS. This approach has the advantage of taking benefit from the description of the uncertainty affecting the forecast at the synoptic scale by a skilful global ensemble, leaving to the mesoscale model only the duty to downscale the information with a physical (not statistical) approach. Its skill has been shown superior to the skill of the EPS in terms of precipitation for high rainfall thresholds (Marsigli et al., 2008), where the importance of high-resolution modelling, with a better representation of orography and a better description of the phenomena leading to precipitation formation at the regional scale exerts its maximum influence. The system is widely used for operational purposes as well as research projects in several European countries. An especially important field of application has recently turned out to be hydrological ensemble forecasting. Thanks also to the MAP D-PHASE project (Rotach et al., 2009; Arpagaus et al., 2009), several centres have implemented meteo-hydrological probabilistic chains based on COSMO-LEPS, where the detail in precipitation forecasting has proven to be useful, especially for severe events.

From 2006 to 2008, a COSMO Priority Project led to the development of COSMO-SREPS, a mesoscale ensemble system for the short-range. It benefited from initial and boundary conditions provided by the multi-model SREPS ensemble of AEMET, treating the problem of the synoptic predictability within a mesoscale ensemble by following a multi-model approach instead of the single-ensemble downscaling used for COSMO-LEPS. Furthermore, the perturbation of the model physics is an essential ingredient of this ensemble, in order to guarantee a representation of the error of the model itself. The COSMO-SREPS Priority Project, in fact, has focussed mainly on studying the effect of parameter perturbations in short-range ensemble predictions and in analysing which parameters of the COSMO model are worth perturbing for this purpose and to which extent. In 2007, the perturbations which turned out to be most promising in a previous testing phase have been introduced in the pre-operational set-up of the COSMO-SREPS system, which ran during the MAP D-PHASE Operations Period (DOP). On the basis of this experimentation, the COSMO-SREPS suite has been updated with the inclusion of perturbations of a wider set of parameters, belonging to several schemes (Marsigli, 2009). These results have also lead to the introduction of two parameter perturbations in the COSMO-LEPS ensemble, allowing a description of a fraction of the turbulent uncertainty in the operational COSMO ensemble, where its effects will be evaluated also for the medium range (up to 5.5 days). Finally, COSMO-SREPS has permitted to establish a link with the data assimilation system, since at ARPA-SIMC a version of the 1D-Var assimilation of satellite data (already mentioned in chapter 7) is being tested where the COSMO-SREPS ensemble is used to compute a flow-dependent error covariance matrix to be used in the data assimilation (Di Giuseppe et al., 2010).

In order to carry on the mesoscale ensemble developments within an organic framework, COSMO has recently initiated the Priority Project CONSENS (see below), which, among other tasks, aims at merging these two limited-area ensembles into a unique COSMO ensemble in the next years, applying for the different forecast ranges (from day 1 to 5.5) the most appropriate perturbations.

Convection-permitting ensembles

Explicit representation of convection within models is already operationally adopted within the consortium, since several COSMO members run an operational chain with a high-resolution model of 2-3 km grid spacing, where the parameterisation of deep convection is switched off. Since the use of convection-permitting models is already established, there is need to build a probabilistic framework also for the convective scale, realized by a convection-permitting ensemble.

Up to now within COSMO, the development of a convection-permitting ensemble is tackled by the project COSMO-DE-EPS which is embedded within the so-called Innovation Programme at DWD. The project COSMO-DE-EPS started in 2007 and is developing a convection-permitting ensemble, the COSMO-DE-EPS. The declared aim is an operational system, which makes the project internationally unique.

For the COSMO-DE-EPS project, the DWD has allocated the necessary resources in staff and supercomputer facilities and has established a project outline, comprising the following tasks: ensemble generation (including the scientific perturbation strategy and also the preparation of the technical environment for ensemble forecasting within DWD), ensemble verification, ensemble post-processing, and ensemble visualization. According to the project plan, the COSMO-DE-EPS will run in pre-operational mode in 2010 (autumn) with 20 members differing in physics parameters, lateral boundary conditions, and initial conditions. Operational implementation with 40 members is envisaged to start in 2012.

The ensemble members are generated by the convection-permitting model COSMO-DE. The model COSMO-DE is operational at DWD since 2007. It is running with a grid spacing of 2.8 km and a domain covering the area of Germany. In ensemble mode, the choice of grid spacing and domain remains unchanged. Concerning the ensemble perturbations, the focus is on three sources of uncertainty: the lateral boundary conditions, the model physics and the initial conditions.

To quantify the uncertainty due to boundary conditions, the COSMO-DE-EPS is embedded in a chain of ensembles which propagates forecast uncertainty from large scales down to the convective scale. At the small-scale end of this chain, the COSMO-

DE is nested into selected members of COSMO-SREPS. This direct link to COSMO-SREPS is maintained during the experimental phase of COSMO-DE-EPS. In preparation of the (pre-) operational phase of the COSMO-DE-EPS, the provision of boundary conditions will be based on an ensemble chain managed by DWD. The COSMO-DE will be nested in 4 or 5 different COSMO simulations of 7 km grid size which differ by their driving global model. Depending on availability, global forecasts of UKMO, NCEP, JMA, DWD, and the ECMWF will be used. The scientific concept of this chain is very similar to COSMO-SREPS. The new set-up of the DWD ensemble chain is in line with a simultaneous redesign of the COSMO-SREPS suite. Once the DWD ensemble chain is running, it will also contribute some members to COSMO-SREPS.

The uncertainty in the physics is represented by varying distinct parameters of the parameterisation schemes that are expected to have a significant impact on forecast results spanning the parameterisations of the soil and the vegetation, boundary layer processes, as well as microphysics. In 2007 and 2008, a preliminary choice of parameters and their respective perturbations has been made. It is based on communication with model experts, on verification results, and on sensitivity analyses. At this point it should be mentioned that this particular choice is not necessarily also suited for physics perturbations within convection-parameterisation EPS, such as the COSMO-SREPS and COSMO-LEPS. This is due to the different role of physical processes, depending on the model grid spacing.

Ensemble experiments have been carried out for case studies and for a time series of several weeks (Gebhardt et al., 2008; Gebhardt et al., 2010). Probabilistic verification has been carried out with the verification package PACprove, software also developed within the project COSMO-DE-EPS. The results show that the ensemble is still underdispersive, i.e., the ensemble spread underestimates the forecast error.

The perturbation of initial conditions is a future task and will be carried out in close collaboration with data assimilation experts. As an intermediate solution, the perturbations will affect the nudging assimilation scheme which is part of the operational COSMO-DE routine at DWD. Later, when the development of the ensemble data assimilation has advanced (see chapter 7), the generation of perturbations will be closely linked with the LETKF.

8.3 Strategy of COSMO and actions proposed

At present, the ensemble activity within COSMO is well positioned at an international state-of-the-art level, with some advanced developments, namely the mesoscale ensemble COSMO-LEPS with a horizontal mesh-size of 7 km and the pioneering work carried out at DWD with the convection-permitting ensemble COSMO-DE-EPS.

Hence, COSMO aims at maintaining, in the next 5-10 years, its ensemble activities at the same high level as it is now.

In order to pursue this aim, it is necessary to develop systems which permit to have a good probabilistic assistance at the spatio-temporal scale at which the operational activity in the consortium is carried on.

The mesoscale ensemble system, hence, should be able to show (all) possible small scale weather elements (like precipitation, cloudiness, radiation, etc.) which are possible for a given synoptic evolution, leaving the representation of the uncertainty in the synoptic evolution to the driving global ensemble system. This implies that the system should be able to produce enough spread in these elements, even at small lead-times, taking care of the fact that the correct solution should be present among the ensemble members. Special care has thus to be given to the verification of the spread (i.e., curing the tendency for under-dispersion) and the amount of outliers.

Since it is reasonable to think that, within the next 5 years, global ensemble systems will be able to represent the mesoscale, for a LAM Consortium it is crucial to invest in the development of ensembles which represent the convection-permitting and convection-resolving scales. These systems will be necessary to represent the uncertainties playing a major role at the scales resolved by the future NWP operational models. Hence, resources should be invested in research to develop ensemble systems suitable for this purpose, continuing and extending the work already carried on at DWD and in close connection with the model development.

Actions

The main priorities can be identified as follows:

1. **Advective large scale orographic precipitation.** There is no need for a sophisticated model to predict the rainfall amounts on the wind side slope, but the transport to the lee side is often very difficult to capture. The model should thus be able to reproduce without bias the local structures present in reality. Actually, the deterministic model steadily improves in this respect.

   The mesoscale ensemble should therefore stick as closely as possible to the most performing version of the COSMO deterministic model. When computer performance will allow, an increase of the resolution can also help in this direction. This action is a sort of permanent action, to be carried out during the whole planning period.

2. **Convective precipitation in weak flow.** The correct representation of this type of precipitation is much dependent on the correct description of the lower boundary (vegetation, snow, soil moisture, roughness, albedo, etc.) and of soil-surface exchanges.

   Hence, three actions can be identified to improve ensemble forecasting:

   a. *The inclusion of perturbations of the lower boundary forcing in the mesoscale ensemble.*

   b. *The improvement of the representation of the uncertainties affecting the parameterised physical processes in the mesoscale ensemble. In particular, it would be beneficial to have perturbations in the convection and microphysics scheme as well.*

   c. *The development of convection-permitting and convection-resolving ensembles.*

   The first two actions are being carried out within the CONSENS Priority Project, as they are included in the development of the COSMO-SREPS system (see below). It has been planned to end up, in a two year time, with an ensemble system capable of taking into account a large fraction of the uncertainties in the *formulation of the operational forecasting model. The resources required and the risks foreseen are specified in the Priority Project subsection below.*

The project COSMO-DE-EPS (see previous section) represents an important step towards a more adequate forecasting of the convective precipitation. The way in which this task is accomplished in detail can be found in the previous section 8.2. Currently, special emphasis is put on the technical stabilization of the ensemble suite and on the advancement of initial condition perturbations. Also post-processing will be followed up (see below).

3. As explained in section 8.1, it is believed that **calibration** of ensemble forecasts will be very useful for improving the probabilistic information which is provided to forecasters. A deficiency in the COSMO-LEPS system from this perspective has been recently pointed out (Marsigli et al., 2008). Furthermore, a calibration based on climatology permits to remove the systematic errors which affect the forecast. While for precipitation forecasted by a low resolution model, the calibration problem has been successfully addressed by the already mentioned activities, for high resolution models the problem is still open. To design a strategy to calibrate a high-resolution ensemble is, therefore, a research issue.

   Therefore, within the CONSENS Priority Project, a post-processing activity is also being carried on, aiming at calibrating the mesoscale ensemble probabilities on the basis of climatological data, thereby removing the bias. The interest is focused on the prediction of the precipitation, as it is one of the surface parameters most important and difficult to predict. Within the consortium, some work on this topic has already been done at MeteoSwiss where a 30-year reforecast of COSMO-LEPS is permanently being re-calculated and a calibration technique has been developed and applied to precipitation forecast over Switzerland (Fundel et al., 2010). Following this work, the usefulness of other calibration techniques (Hagedorn et al., 2008, Hamill et al., 2008) is currently being explored, aiming at an application of calibration as an operational ensemble post-processing product. Due to the statistical nature of this work, cooperation with academia is desirable. Some cooperation on the subject has already started with the Statistics Department of the University of Bologna. The resources required and the risks foreseen are specified in the Priority Project subsection below.

   Also the project COSMO-DE-EPS includes post-processing activities. As a short-term goal, calibration will focus on exceedance probabilities of precipitation, since this is a high priority ensemble product. The calibration method will be logistic regression. The logistic regression is now being implemented and then its benefit will be investigated. Depending on the result, the post-processing procedure is envisaged to become operational. As a long-term goal, Bayesian approaches will be explored in cooperation with two German Universities. Since the end of 2009 DWD provides funding for a PhD thesis at University of Bonn which covers post-processing methods geared to extreme weather using quantile regression. A second research project, also funded by DWD, will start in autumn 2010 at University of Heidelberg following a proposal by Prof. Gneiting. The basic idea is a spatially adaptive Bayesian approach to estimating the BMA parameters. In such an approach, the way the post-processing is done will vary spatially, as *opposed to the traditional approach, which does not take geographical constraints into account and uses a single, spatially constant BMA model. The aim is to ensure physically realistic spatial dependence structures in the post-processed precipitation field.*

4. The importance of the **link between ensemble forecasting and data assimilation** (Kalnay et al., 2006, Hamill, 2006) has already been underlined in chapter 7.

   The recent development within COSMO of an ensemble developed for the short-range, where errors affecting the forecast already in the first hours are represented, and in particular of a convection-resolving ensemble system are clearly steps towards this aim. How the link between the convection-resolving ensemble system and the new data assimilation scheme for the convection-resolving scale will be pursued within COSMO is addressed in chapter 7.

5. Finally, the COSMO consortium recognises the importance of maintaining a strong **link with the international ensemble project TIGGE** (THORPEX Interactive Grand Global Ensemble), part of the THORPEX WMO Programme, and in particular with **TIGGE-LAM**, the Limited Area Model expert panel.

   Hence, in the framework of TIGGE, the extension of the cluster-selection technique of COSMO-LEPS to other global ensembles is being pursued (priority to MOGREPS, for the moment): the ensemble members would be nested on selected elements of either global ensemble. This would enable to explore a wider-fraction of phase space also for longer time ranges. This work is carried out in COSMO within the framework of the CONSENS PP.

   Furthermore, the COSMO-SREPS system, due to its multi-boundary nature, fosters a strong cooperation with other consortia within SRNWP and within the TIGGE-LAM framework as well. A COSMO implementation of the whole multi-model COSMO-SREPS chain at ECMWF is presently on-going, which will benefit of the possibility of nesting the COSMO model into some of the major global models (ECMWF, GME, GFS, JMA, UKMO), developed within the SRNWP Interoperability Programme.

8.3.1 CONSolidation of the O(10) km ENSemble

As already specified, part of the proposed actions are being carried out during 2009-2010 within the framework of the Priority Project "CONSolidation of the O(10)-km ENSemble" (CONSENS).

The actions proposed in the project are:

– the COSMO-SREPS system will be used to allow the experimentation on parameter and soil perturbations. This task can be accomplished in a 2-year period during which COSMO-SREPS will continue to provide initial and boundary conditions for the convection-resolving ensemble. After this testing period, the perturbations which have proven to be useful for the short range thanks to the COSMO-SREPS experimentation can be implemented into the unique mesoscale COSMO ensemble, which can be thought of as a "multi-perturbation-strategy" ensemble system. This unique ensemble could benefit of the new parameter and soil perturbations for the whole forecast range, permitting to overcome at least partially the under-dispersion problem already present in COSMO-LEPS.

– a unique mesoscale ensemble system will therefore be built, merging COSMO-LEPS and COSMO-SREPS. This “multi-perturbation-strategy” ensemble system, will benefit of perturbations more adapt for the short range in the beginning (e.g., since day 2), and of perturbations more adapt for the medium range after.
– a calibration strategy for the mesoscale ensemble will be developed and tested. This will be based on the reforecasts already made by MeteoSwiss for the COSMO-LEPS system and benefiting also of the work already done by MeteoSwiss on ensemble calibration

For more details on this **Priority Project**, refer to the **CONSENS project plan**.

9 Validation and diagnostics

Authors: Adriano Raspanti (USAM) and Francis Schubiger (MeteoSwiss)

9.1 State of the art, scientific developments

The systematic evaluation of numerical forecasts is crucial for the development, refinement and even interpretation of any modelling system. Normally a comparison between model predictions and observations can provide useful information on quality or accuracy of the modelling system. Of course the results of this comparison will depend on the methods and metrics used to verify. Different and contrasting results can also be obtained through different aggregation of both forecasts and/or observations, as well as with increasing the resolution of numerical models.

The resulting numbers, tables, and plots show measures of the overall performance of the model with regard to the product considered. The interpretation of these classical verification results, with regard to systematic deficiencies in the model simulation of specific processes, is far from trivial. And even though obvious failures of the model may be established, finding the reasons behind these drawbacks is not straightforward, without consideration of specific details of the atmospheric and/or surface situation. From a more general point of view, when performing standard verifications, potential interdependencies between various weather parameters and state variables are a priori ignored (e.g., cloud cover & near surface temperature). It is thus helpful to consider a process or a situation dependent verification, e.g., the evaluation of the model forecast quality with regard to the diurnal cycle of near surface temperatures in the absence/or presence of clouds. Formulating the verification of forecast products in conjunction with the existence of additional criteria, which are to be met, can be considered as “Conditional Verification” (CV).

As stated before and as reflected by the principal goal for COSMO, the focus is on very-short range forecasts and with very high resolution. The increasing resolution can have as an impact that the traditional objective scores for weather parameters can be worse for high resolution models than for low resolution models. Increased resolution, in fact, generally produces better defined mesoscale structures, greater amplitude features and larger gradients and as a consequence potentially larger errors in space and time. This leads, for example, to a larger RMSE than the smoother forecasts of a low resolution model. This is known as the “double penalty” problem. Nevertheless such a model can provide very useful information. The need for verification techniques that allow for some tolerance to reasonably small space and time errors is hence obvious. One possible approach is to average the output of the high-resolution model to a lower resolution and then applying the deterministic scores. This could reveal the superiority of high-resolution models over low-resolution models, opposite to a direct comparison of model outputs interpolated to a station point. This can be one simple option, but it is clear that, in this new framework, traditional “point-wise” verification measures can no longer reflect the real quality of forecasts information provided by such a model. Thus new techniques have to be found, capable to test the real quality of information provided by high-resolution models and the possible connections between forecasts deficiencies and specific weaknesses in model formulation.

These techniques are already widely studied and used, even if rarely in an operational mode, in some of most important meteorological centres in the world.

Also operational verification activities on ensemble implementation, COSMO-LEPS and COSMO -SREPS, are carried out by some of the COSMO countries through different verification tools. These tools will be soon reorganized and made available within the common verification tool (VERSUS see below) of COSMO.

9.2 Status and expertise of COSMO

Operational verification is done by all COSMO members. SYNOP (2m-temperature and dew point, 10m-wind speed and direction, precipitation, total cloud cover and mean sea level pressure) and TEMPs are verified. Some members verify also regularly parameters such as global radiation and gusts or the wind with windprofilers. Traditionally, main metrics like mean error (ME), root mean squared error (RMSE), standard deviation of error (STDE), their skill scores for continuous parameters, and contingency table scores for dichotomous events are used. To extract forecast data information to be compared with observation, different methods have to be used, depending on the physical parameters: for precipitation a mean of all gridpoints within a radius of 15 km is used, for cloudiness (with SYNOP) all gridpoints within a radius of 30 km and for the other variables we use the algorithm defined inside COSMO (Kaufmann, 2008): the algorithm searches gridpoints in the vicinity of the surface station, optimizing horizontal distance and vertical height differences. To perform this kind of common verification, a software package, named Common Verification Suite, has been developed by the COSMO consortium, along with a common graphics package for creation and visualization of scores plots. Results of these standard verifications are published periodically on COSMO web-site.

Then, a number of additional activities are routinely carried out in different countries, among them:

- High density verification of precipitation (with raingauges and/or radars);
- Verification or near-surface boundary layer processes (fluxes verified at Lindenberg and Payerne)
- Exchange of common data set of non-GTS data (currently only raingauge data).

Other than this, and following the current state of development, some experience has been carrying out inside COSMO about high-resolution verification, tackling especially precipitation. In fact this is probably one of the most important outputs of NWP and at the same time the most critical one to be assessed in terms of quality (again the problem of double penalty, e.g.), mainly at the convective scales.

For this purpose, during the last two years, different experiments using neighbourhood verification software (by B. Ebert) have been carried out inside COSMO, especially by MeteoSwiss and DWD, and the results are encouraging. With the conclusion of a dedicated special project on this matter, results and general and specific recommendations on scores to be used has been published (Eckert, 2009).

Verification of ensemble forecasts (from COSMO-LEPS), i.e., probabilistic verification, is done on a pre-operational basis at some centres (DWD; MeteoSwiss, ARPA-SIMC).

9.3 Strategy of COSMO and actions proposed

In line with the goals for COSMO the main priorities can be listed as follows. All these actions are intended in the *short and medium term (up to 5 years)*.

Development of a common verification and validation tool including Conditional Verification (CV)

The main purpose of CV is the systematic evaluation of the model performance for the need of the model developers. Once delivered and applied routinely, it should provide useful information to the developers that allow identifying the causes of observed model deficiencies.

The typical approach to CV could consist of the selection of one or several forecast products and one or several mask variables or conditions, which would be used to define thresholds for the product verification (e.g., verification of T_{2M} only for grid points with zero cloud cover in model and/or observations). After the selection of the desired conditions, a classical statistical score index can be used. Generally several masks may be applied at once, for example simultaneous application of cloud cover, soil moisture and plant cover thresholds. Obviously the size of the ensemble will depend on the number of criteria applied. Even though this could be detrimental for the evaluation of a few case studies, in an operational environment this problem would be alleviated by the large number of forecasts generated.

The implemented software, called VERSUS, is the substitute of the previous Common Verification Suite in all its features and it is proposed to be the common verification tool of COSMO.

Development of object-based and neighbourhood verification methods

In general these techniques are designed to identify patterns (mostly in precipitation fields) in both model and observation space, to choose the correspondent pairs, and to develop statistics measuring the discrepancies or matching between the two. Different object-based methods have been already developed and partially tested and inter-compared. Among them: Contiguous Rain Area (Ebert and McBride, 2000), neighbourhood method (Theis et al., 2005), Fractions Skill Score (Roberts 2005), Intensity scale technique (Casati et al. 2004, Mittermaier 2006), Upscaling, and so on. The output of some of these methods can be used as input to a neighbourhood verification engine to perform spatial scale and thresholds depending verifications. Through the exploitation of new object-based techniques (Davis et al, 2006) statistical and geometrical attributes, like moments, area, axis angle, or aspect ratio can be defined to compare forecast and observation features. These attributes can also be used as input of a neighbourhood logic engine for merging and matching (see MODE tool User Manual, by NCAR).

Thus specific goals and deliverables of the COSMO Project INTERP ("Advanced interpretation and verification of very high resolution models) that ended in 2008 (Eckert, 2009) were:

– compare different methods to understand their behaviour (first with idealized cases);

- on the basis of previous point, define a limited number of statistical methods and scores; Fractions Skill Score, Upscaling and Intensity-Scale have been chosen for further investigations and pre-operational verification studies.;
- investigate the use of object oriented techniques to assess the real spatial and temporal quality of precipitation forecasts;

These methods and techniques will be included in VERSUS 2 (extension of VERSUS, the common verification tool of COSMO).

There are further methods that will be studied and tested, in particular the SAL method (Wernli et al., 2008). This method identifies objects in both observation and forecasts space, and gives them the attribute of Structure, Amplitude and Location (so the name of the method). These attributes at this point can be compared to asses the quality of the forecast. This method seems to be promising especially applied on predefined boxes (e.g., river catchments). Also, new scores for verification of precipitation and extreme events (like the EDS score) have to be investigated.

In the field of object-oriented verification possible collaborations could be with the Development Testbed Centre (NCAR) group who developed the MET software that already implement some of the features described here, and the Australian Bureau of Meteorology.

Development of probabilistic forecasts and ensemble verification

As COSMO model future plans are in the probabilistic and ensemble forecasts direction, suitable verification methods have to be applied.

In general there are three methods to evaluate this kind of forecasts:

- Verification of an ensemble distribution;
- Verification measures for pdfs of a generic probability forecast (from a local point of view);
- Verification of the probability of an event

In this framework a common choice of “probabilistic measures” has to be done and included, in the next future, in the common verification package.

The above three actions represent the main priorities and can be seen as the minimal developments, to be able to explore the real quality of NWP forecasts and to have and maintain a “state of the art” verification system, also for the next future.

The verification of ensemble forecasts requires the use of dedicated quality measures, due to the probabilistic character of the forecast. A well established set of score measures for the ensemble verification are:

- Brier Score, Brier Skill Score, and their Reliability and Resolution components
- Reliability Diagrams
- Relative Operating Characteristics
- value score based on a Cost-loss Analysis
- Rank Histogram and Percentage of Outliers

This set of measures permits to verify the forecasts issued in terms of probability. Most of them require selecting a number of thresholds for the definition of the events over which the ensemble forecasts are evaluated (BS-like scores, ROC area, Cost-loss Analysis, Reliability Diagrams). Instead, the Rank Histogram and the Percentage of Outliers permits to an evaluation of the ensemble pdf not based on event selection.

It is recommended to evaluate the confidence of the results with the usual tests, parametric or non parametric or by applying a test based on the bootstrapping method

Two main factors have to be considered when comparing different ensemble systems: the difference in the number of ensemble members, which is peculiar of the ensemble verification, and the difference in terms of horizontal resolution, which affects also a comparison of deterministic forecast systems.

The issue of the different ensemble sizes may be disregarded if the verification focuses on assessing which are strengths and weaknesses of the different ensemble as they are, from an operational point of view. Anyway, the ensemble size has an impact on the value of the scores and, to account for this effect, a version of the Brier-type scores de-biased for the effect of the population can be used

It is suggested to take into account the problem of the different resolutions of the systems only for the verification of the precipitation, by preferring the use of spatial verification methods (aggregate values over boxes, neighbourhood verification, object verification, etc; see for reference Casati et al., 2008). As for 2m temperature and the other smoothly varying parameters, a comparison of the observed value on a station point with the value forecast by the system on the nearest grid point is usually regarded as satisfactory.

The following items represent, again in falling priority, what should be done in order to have a more complete common verification system.

Development of a Common Global Score

To better explore the improvement of the different implementations of COSMO model (and also to compare them) a Global Score has to be developed. This score will be based on a mixing of continuous and categorical elements and will provide a yearly trend of the general behaviour of the model. This score has to be conceived to be useful from an administrative, as well as developer’s points of view.

In particular it will be based on total cloudiness, 2mT, 10m wind vector and precipitation and will be included in the common unified verification library.

Use of new observation types

Verification of very high resolution models needs to be done more and more with gridded observations. Experiences have been gained with precipitation (from radars and gridded datasets of raingauge and radar observations combined). Other types of observations that should be considered are:

– satellite data (CM-SAF) for radiation (shortwave, longwave), cloudiness, vertically integrated water vapour content;
– GPS humidity from E-GVAP (EUMETNET GPS water vapour programme);
– gridded analyses from surface observations (such as temperature, pressure, …).

User-oriented Verification

With the increasing model resolution (up to 1 km or less) it will be more and more important the kind of products the final users will ask and their objective performances. Of course different users might have needs for different verification information (e.g., meteorological service's administrative decisions can depend on model performances).

Different verification strategies have to be chosen. Model developers can find benefit from time series of scores, stratified by season, weather regimes, or spatial and temporal aggregation, as well as from scales-dependency analysis. Forecasters might need a tool based on the latest verification result (quasi real-time verification) to choose the best-performing model among even several of them or methods able to reproduce the typical ability of a forecaster to identify if the proposed solution is believable or not and to which extent (like object-oriented verification). The management of a Met Service may finally need information about overall forecasts performance and long-term trends.

It will be necessary to diversify verification methodologies to match the different needs and to this end, the scientific community will have to work more closely with the user community in the design of such verification strategies.

VERSUS Priority Project and its extension VERSUS 2

The development of a complete Conditional Verification Tool has been the first priority and outcome of the VERSUS (VERification System Unified Survey) project.

The VERSUS 2 Priority Project aims at complementing the common COSMO verification tool with all the features mentioned above.

For more details see the VERSUS 2 System Architecture Design document and the VERSUS 2 Priority Project plan.

10 Computational aspects

Author: Ulrich Schättler (DWD)

The computational requirements to run the COSMO model in an operational environment are rather high and can only be met by high performance computers. While the definition of high performance computers can always be given by "the fastest computers available", the underlying architecture has changed significantly in the last decade. Since the mid 90ies, parallel computers with distributed memory are used. In the beginning of parallel computing, most machines had one processor per memory, but in the last years, clustered systems are available, where several processors share a common memory. In this way, the clusters combine the main concepts of distributed-memory and shared-memory parallel computers.

Because the chip manufacturing is about to hit some physical limits, which inhibit further growth of clock frequencies, it is no more the clock rate, that is increased, but the number of processing units on a single chip. These processing units are called cores and the chips are called multi-core processors.

10.1 State of the art, scientific developments

Although clusters are widely used nowadays in high performance computing, there exists no single programming paradigm to exploit the hierarchical structure of these machines. Most applications parallelized in the last years only use the “Message Passing Interface” (MPI) for the implementation on distributed-memory systems. These parallel applications will also run on clustered systems by pretending that every processor has its own memory. The shared memory of all processors within a node is (at the most) accounted for only in special MPI implementations, which use a memory copy instead of a real data communication within a node.

It is most likely, that the new multi-core architectures cannot be utilized efficiently by such a pure parallelization. A hybrid parallelization, also using a shared-memory parallelization, as offered by data parallel languages or by OpenMP for example, offers a higher flexibility for an efficient and scalable implementation on the new architectures (e.g., Hamrud et al., 2003, Benkner et al., 2003).

10.2 Status and expertise of COSMO

The COSMO model only uses the pure parallelization paradigm. It is parallelized by domain decomposition and it only uses message passing with MPI (see Schättler et al., 2000). This implementation works efficiently on actual clustered systems, if the proportion between domain size and number of processors is well balanced. This means that there have to be enough grid points (computations) on every subtask. Otherwise, the time for communication would dominate the model run. With existing horizontal domain sizes (e.g. 665×657 grid points for COSMO-EU) the COSMO-Model scales well up to about 1000 subtasks on existing computers.

10.3 Strategy of COSMO and actions proposed

A prototype implementation of the COSMO-Model should then be developed to test the benefits of hybrid parallelization and investigate the problems related to that programming paradigm. There are several ways to design such a prototype:

- Parallelization on the loop level.
- Re-designing the memory layout of the COSMO model to get a better exploitation of the shared memory.
- Re-designing the parallelization strategy and the memory layout for a better exploitation of multi-core processors and for implementing possible load-balancing strategies.

Formally outside COSMO, a subproject of the Swiss national $(HP)^2C$-project (**H**igh **P**erformance **H**igh **P**roductivity **C**omputing), starting in 2010, deals with such issues regarding the COSMO model. As a link to COSMO, a new Priority Project POMPA (**P**erformance **O**n **M**assively **P**arallel **A**rchitectures) will be initiated in 2010, which focus is to coordinate with - and transfer of - the work done within HP2C to COSMO.

If this subject is not tackled within the next 3-4 years, the COSMO model will not be able to use new computer hardware efficiently in the future.

While investigating different parallelization strategies, it is necessary to watch new developments for the different components of the COSMO model, most important the dynamics and numerics, but also the physical parameterizations. Different algorithms might need different parallelization and implementation strategies.

11 External collaboration

Over the last 10 years, the COSMO model has very much evolved into a community model. The most important contributions come from the CLM-community (Rockel et al, 2008) and from COSMO-ART (Vogel et al., 2009) developments, thus complementing COSMO's limited resources in the respective fields. However, research directions and resource management are subject to the planning of these groups. Nevertheless there is an intense collaboration and exchange of information on ongoing developments. COSMO and the CLM-community have agreed to participate in each others scientific steering groups: The coordinator of the CLM-community is invited to participate in the COSMO Scientific Management Committee (SMC) meetings, while COSMO sends a member to the CLM-Community Science Board meetings. COSMO-CLM and COSMO-ART codes have been integrated into the COSMO model code, thus representing a unified regional weather, regional climate, and regional environmental prediction modelling system.

11.1 COSMO-CLM

Continuous collaboration between the COSMO and COSMO-CLM communities will help improving physical parameterisations and model inconsistencies, especially in the domain of land-atmosphere exchange (e.g., Seneviratne et al., 2006). Systematic problems (e.g., drifts) are more easily uncovered in climate simulations (even small systematic errors accumulate due to the integration over long periods). NWP applications, on the other hand, have a much higher potential for verification and process studies.

11.2 COSMO-ART

COSMO-ART extends the regional weather forecast model COSMO by integrating the simulation of processes related to the spatial and temporal distribution of reactive gaseous and particulate matter. COSMO-ART avoids inconsistencies by applying the identical advection schemes, physical parameterisation schemes, and numerical schemes as used in the weather forecast model. With COSMO-ART it becomes possible to provide specialised forecasts, such as pollen or air quality forecasts. As mentioned in section 3.5, future directions of research and development of the COSMO modelling system will most likely integrate environmental prediction capabilities to improve weather forecasting itself. COSMO-ART will clearly be a candidate to evaluate certain approaches and will allow verifying their impact on the quality of the model forecast.

12 Acknowledgements

We are indebted to many people for their support during the preparation of this document. In particular, a number of colleagues outside COSMO readily took over the tedious task of reviewing the manuscript: Pierre Benard, András Horányi, Jeanette Onvlee, Bruce Macpherson, Sander Tijm, Andreas Will, and Xiaohua Yang. Their invaluable comments and insightful criticism helped to improve the manuscript substantially, which will hopefully contribute to a more focussed and better coordinated future development of the COSMO model.

13 References

Angevine, W. M., 2005: An integrated turbulence scheme for boundary layers with shallow cumulus applied to pollutant transport. *J. Appl. Meteorol.*, **44**, 1436-1452.

Arakawa, A., 2004: The cumulus parameterisation problem: past, present, and future. *J. Climate*, **17**, 2493–2525.

Arpagaus, M., M. W. Rotach, P. Ambrosetti, F. Ament, C. Appenzeller, H.-S. Bauer, A. Behrendt, F. Bouttier, A. Buzzi, M. Corazza, S. Davolio, M. Denhard, M. Dorninger, L. Fontannaz, J. Frick, F. Fundel, U. Germann, T. Gorgas, G. Grossi, C. Hegg, A. Hering, S. Jaun, C. Keil, M. A. Liniger, C. Marsigli, R. McTaggart-Cowan, A. Montani, K. Mylne, L. Panziera, R. Ranzi, E. Richard, A. Rossa, D. Santos-Muñoz, C. Schär, Y. Seity, M. Staudinger, M. Stoll, S. Vogt, H. Volkert, A. Walser, Y. Wang, J. Werhahn, V. Wulfmeyer, C. Wunram, M. Zappa, 2009: MAP D-PHASE: Demonstrating forecast capabilities for flood events in the Alpine region, *Veröffentlichungen der MeteoSchweiz,* **78**, 75pp.

Bacon, D. P., N.N. Ahmad, Z. Boybeyi, T. J. Dunn, M. S. Hall, P C. S. Lee, R. Ananthakrishna, and M. D. Turner, 2000: A dynamically adapting weather and dispersion model: The operational multiscale environment model with grid adaptivity (OMEGA), *Mon. Wea. Rev.,* **128**, 2044-2076.

Baldauf, M., 2005: The coordinate transformations of the 3-dimensional turbulent diffusion in LMK. *COSMO-Newsletter*, **5**, 132-140.

Baldauf, M., 2006: Implementation of the 3D-Turbulence Metric Terms in LMK*.* *COSMO-Newsletter*, **6**, 44-50.

Baldauf, M, 2008: Stability analysis for linear discretisations of the advection equation with Runge-Kutta time integration, *J. Comput. Phys*., **227**, 6639-6659.

Bechtold, P., E. Bazile, F. Guichard, P. Mascart, and E. Richard, 2001: A mass-flux convection scheme for regional and global models. *Quart. J. Roy. Met. Soc.*, **127**, 869-886.

Beljaars, A. C. M., and A. A. M. Holtslag, 1991: Flux parameterisation over land surfaces for atmospheric models. *J. Appl. Meteorol.*, **30**, 327-341.

Benkner, S., and V. Sipkova, 2003: Exploiting Distributed-Memory and Shared-Memory Parallelization on Clusters of SMPs with Data Parallel Programs, *Int. J. Parallel Programming*, **31**, 3-19.

Blahak, U.: 2008, Towards a better representation of high density ice particles in a state-of-the-art two moment bulk microphysical scheme. *Proc. 15th Int. Conf. Clouds and Precip.*, Cancun, Mexico.

Bott, A., 1989: A positive definite advection scheme obtained by nonlinear renormalization of the advective fluxes. *Mon. Wea. Rev*., **117/5**, 1006-1015.

Bowler, N. E., A. Arribas, K. R. Mylne, K. B. Robertson, and S. E. Beare, 2008: The MOGREPS short-range ensemble prediction system, *Quart. J. Roy. Met. Soc.*, **134**, 703-722.

Bright, D. R. and S. L. Mullen, 2002: Short-range ensemble forecasts of precipitation during the Southwest Monsoon. *Wea. Forecasting*, **17**, 1080-1100.

Brooks, H. E., M. S. Tracton, D. J. Stensrud, G. DiMegok, and Z. Toth, 1995: Short-range ensemble forecasting: Report from a workshop, 25-27 July 1994. *Bull. Amer. Meteor. Soc*., **76**, 1617-1624.

Buzzi, M, 2008: Challenges in operational numerical weather prediction at high resolution in complex terrain, PhD thesis, Swiss Federal Inst. of Technology (ETHZ), 184pp.

Buzzi, M., M.W. Rotach, and M. Raschendorfer, 2010: Performance of the COSMO-SCM turbulence scheme for a stably stratified boundary layer*,* manuscript in preparation.

Bubnova, R., G. Hello, P. Bénard, and J.-F. Geleyn: 1995, Integration of the fully-elastic equations cast in the hydrostatic pressure terrain-following coordinate in the framework of the ARPEGE/ALADIN NWP system. *Mon. Wea. Rev*., **123**, 515-535.

Casati, B., G. Ross and D. B. Stephenson, 2004: A new intensity-scale approach for the verification of spatial precipitation forecasts. *Meteor. Appl*., **11**, 141-154.

Casati, B., L. J. Wilson, D. B. Stephenson, P. Nurmi, A. Ghelli, M. Pocernich, U. Damrath, E. E. Ebert, B. G. Brown, and S. Mason, 2008: Forecast verification: Current status and future directions. *Meteor. Appl*., **15**, 3-18.

Caya, A., J. Sun, and C. Snyder, 2005: A comparison between the 4D-Var and the ensemble Kalman filter techniques for radar data assimilation. *Mon. Wea. Rev*., **133**, 3081 – 3094.

Cockburn, B., 2003: Discontinuous Galerkin methods, *J. Appl. Math. Mech*., **83/11**, 731-754.

Davies, C., B. G. Brown, and R. Bulloks, 2006: Object-based verification of precipitation forecasts. Part I: Methodology and application to mesoscale rain areas. *Mon. Wea. Rev*., **134**, 1772-1784.

De Elía, R., R. Laprise, and B. Denis, 2002: Forecasting skill limits of nested, limited-area models: A perfect-model approach. *Mon. Wea. Rev*., **130**, 2006-2023.

Déqué, M., D. P. Rowell, D. Lüthi, F. Giorgi, J. H. Christensen, B. Rockel, D. Jacob, E. Kjellström, M. de Castro, and B. van den Hurk, 2007: An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections, *Climatic Change*, DOI: 10.1007/s10584-006-9228-x

Di Giuseppe, F., C. Marsigli, and T. Paccagnella, 2010: The relevance of background error covariance matrix localization: an application to the variational retrieval of vertical profiles from SEVIRI observations. *Quart. J. Roy. Met. Soc*., in revision.

Doms, G., and U. Schättler, 2004: A description of the nonhydrostatic regional model LM. Part II: Physical parameterisation. Technical report, Deutscher Wetterdienst, Offenbach, online available: http://www.cosmo-model.org/public/documentation.htm.

Drusch, M., 2007: Initializing numerical weather prediction models with satellite derived surface soil moisture: Data assimilation experiments with ECMWF's Integrated Forecast System, *J. Geophys. Res.,* **112***,* D03102, DOI:10.1029/2006JD007478

Ebert, E., and J. L. McBride, 2000: Verification of precipitation in weather systems: Determination of systematic errors. *J. Hydrol*., **239**, 179-202.

Eckert, P., 2009: Final report on priority project INTERP (Advanced Interpretation of COSMO outputs). *COSMO Technical Report No. 16*, online available: http://www.cosmo-model.org/content/ model/documentation/techReports/default.htm.

ECMWF, 2005: ECMWF 10 Year Strategy (2006-2015). Online available: http://www.ecmwf.int/about/strategy

ECMWF, 2006: IFS Documentation, Cycle 31r1. Online available: http://www.ecmwf.int/research.

Evensen, G.: Data assimilation: the ensemble Kalman filter. *Springer, 2006*.

Ferrier, B. S., 1994: A double-moment multiple-phase four-class bulk ice scheme. Part I: Description. *J. Atmos. Sci.*, **51**, 249–280.

Förstner, J., M. Baldauf, and A. Seifert, 2006: Courant number independent advection of the moisture quantities for the LMK, *COSMO-Newsletter*, **6**, 51-64.

Fovell, R. G. and A. Seifert: 2005: The 19 june 2002 'mantle echo' case: Sensitivity to microphysics and convection initiation. 6th WRF / 15th MM5 Users Workshop, Boulder.

Fritsch, J. M., and R. R. Carbone, 2004: Improving quantitative precipitation forecasts in the warm season: A USWRP research and development strategy. *Amer. Meteor. Soc.*, **85**, 955-965.

Frogner, I.-L., and Iversen, T., 2002: High-resolution limited-area ensemble predictions based on low-resolution targeted singular vectors. *Quart. J. Roy. Met. Soc*., **128**, 1321-1341.

Fundel, F., A. Walser, M. A. Liniger, C. Frei, and C. Appenzeller, 2010: Calibrated precipitation forecasts for a limited area ensemble forecast system using reforecasts. *Mon. Wea. Rev*., **138**, 176-189.

García-Moya, J. A., A. Callado, C. Santos, D. Santos-Muños, and J. Simarro, 2009: Predictability of short-range forecasting: A multi-model approach. Nota Téchnica 1 del Servicio de Predecibilidad y Predicciones Extendidas, Agencia Estatal de Meteorología, Spain.

Gebhardt C, S. Theis, P. Krahe, and V. Renner, 2008: Experimental ensemble forecasts of precipitation based on a convection-resolving model, *Atmos. Sci. Letters*, **9**, 67-72.

Gebhardt, C., S. Theis, M. Paulat, Z. Ben Bouallègue, 2010: Uncertainties in COSMO-DE precipitation forecasts introduced by model perturbations and variation of lateral boundaries. Submitted to Atmospheric Research.

Gerard L., and J.-F. Geleyn, 2005: Evolution of a subgrid deep convection parametrization in a limited - area model with increasing reolution. *Quart. J. Roy. Met. Soc.*, **131**, 2293-2312.

Grabowski, W. W., and P. K. Smolarkiewicz, 2002: A multiscale anelastic model for meteorological research. *Mon. Wea. Rev*., **130**, 939-956.

Hagedorn, R., T. M. Hamill, and J. S. Whitaker, 2008: Probabilistic forecast calibration using ECMWF and GFS ensemble reforecasts. Part I: 2-meter temperatures. *Mon. Wea. Rev.*, 136, 2608-2619.

Hamill, T. M.: Ensemble-based atmospheric data assimilation. In: Predictability of weather and climate. Eds. T. Palmer and R. Hagedorn, p. 124-156, Cambridge University Press, 2006.

Hamill, T. M., and J. S.Whitaker, 2006: Probabilistic quantitative precipitation forecasts based on reforecast analogs: theory and application, *Mon. Wea. Rev.*, **134**, 3209-3229.

Hamill, T. M., R. Hagedorn and J. S. Whitaker, 2008: Probabilistic forecast calibration Using ECMWF and GFS ensemble reforecasts. Part II: Precipitation, *Mon. Wea. Rev.*, **136**, 2620-2632.

Hamrud, M., S. Saarinen, and D. Salmond, 2003: Implementation of the IFS on a highly parallel scalar system. In: Realizing Teracomputing. *Proceedings of the 10th ECMWF Workshop on the Use of High Performance Computing in Meteorology*. Eds. W. Zwieflhofer and N. Kreitz, p. 74-87.

Heinemann, G., and M. Kerschgens, 2005: Comparison of methods for area-averaging surface energy fluxes over heterogeneous land surfaces using high-resolution non-hydrostatic simulations. *Int. J. Clim.*, **25**, 379–403.

Houtekamer, P. L., L. Lefaivre, J. Derome, H. Ritchie, and H. L. Mitchell, 1996: A system simulation approach to ensemble prediction. *Mon. Wea. Rev*., **124**, 1225–1242.

Houtekamer, P. L., and H. L. Mitchell, 2005: Ensemble Kalman filtering. *Quart. J. Roy. Met. Soc.*, **131**, 3269-3289.

Hunt, B. R., E. J. Kostelich, and I. Szunyogh, 2007: Efficient data assimilation for spatiotemporal chaos: a Local Ensemble Transform Kalman Filter. *Physica D*, **230**, 112–126.

Kalnay, E., B. Hunt, E. Ott, and I. Szunyogh: Ensemble forecasting and data assimilation: two problems with the same solution? In: Predictability of weather and climate. Eds. T. Palmer and R. Hagedorn, p. 157-180, Cambridge University Press, 2006.

Karcher, B., and U. Lohmann, 2002: A parameterisation of cirrus cloud formation: Homogeneous freezing including effects of aerosol size. *J. Geophys. Res*., **107**, 4698.

Kaufmann, P., 2008: Association of surface stations to NWP model grid points. *COSMO Newsletter*, **9**, 54-55.

Kenjereš, S., and K. Hanjalić, 2002: Combined effects of terrain orography and thermal stratification on pollutant dispersion in a town valley: a T-RANS simulation. *J. Turbulence*, **3**, 1-25.

Klemp, J. B., W. C. Skamarock, and J. Dhudia, 2008: Conservative split-explicit time integration methods for the compressible non-hydrostatic equations. *Mon. Wea. Rev*., **135**, 2897-2913.

Köhler, M., 2005: Improved prediction of boundary layer clouds. *ECMWF Newsletter,* **104**, 18-22.

Kong, F., and co-authors, 2008: Real-time storm-scale ensemble forecast experiment. 9th WRF User's Workshop, NCAR, Center Green Campus, 23-27 June 2008, Paper 7.3.

Kuell, V., and A. Bott, 2009: Application of the hybrid convection parameterisation scheme HYMACS to different meteorological situations. *Atmos. Res.*, **94**, 743-753.

Lappen, C.-L., and D. A. Randall, 2001a: Toward a unified parameterisation of the boundary layer and moist convection. Part I: A new type of mass-flux model. *J. Atmos. Sci.*, **58**, 2021-2036.

Lappen, C.-L., and D. A. Randall. 2001b: Toward a unified parameterisation of the boundary layer and moist convection. Part II: Lateral mass exchanges and subplume-scale fluxes. *J. Atmos. Sci.*, **58**, 2037-2051.

Lappen, C.-L., and D. A. Randall, 2001c: Toward a unified parameterisation of the boundary layer and moist convection. Part III: Simulations of clear and cloudy convection. *J. Atmos. Sci.*, **58**, 2052-2072.

Lappen, C.-L., and D. A. Randall, 2005: Using idealized coherent structures to parameterise momentum fluxes in a PBL mass-flux model. *J. Atmos. Sci.*, **62**, 2829-2846.

Lappen, C.-L., and D. A. Randall, 2006: Parameterisation of pressure perturbations in a PBL mass-flux model. *J. Atmos. Sci.*, **63**, 1726-1751.

Leoncini, G., R. S. Plant, S. L. Gray, and P. A. Clark, 2010: Perturbation growth at the convective scale for CSIP IOP18. *Quart. J. Roy. Met. Soc*., **136**, 653-670.

LeVeque, R.: Finite-Volume Methods for Hyperbolic Problems, Cambridge University Press, 2002.

Lewis, J. M., 2005: Roots of ensemble forecasting. *Mon. Wea. Rev*., **133**, 1865-1885.

Lohmann, U., and B. Karcher, 2002: First interactive simulations of cirrus clouds formed by homogeneous freezing in the ECHAM GCM. *J. Geophys. Res*., **107**, 4105.

Lorenz, E. N., 1963: Deterministic nonperiodic flow. *J. Atmos. Sci*., **20**, 409-418.

Lynn, B., A. Khain, J. Dudhia, D. Rosenfeld, A. Pokrovsky, and A. Seifert, 2005a: Spectral (bin) microphysics coupled with a mesoscale model (MM5). Part I: Model description and first results. *Mon. Wea. Rev.*, **133**, 44–58.

Lynn, B., A. Khain, J. Dudhia, D. Rosenfeld, A. Pokrovsky, and A. Seifert, 2005b: Spectral (bin) microphysics coupled with a mesoscale model (MM5). Part II: Simulation of a CAPE rain event with a squall line. *Mon. Wea. Rev.*, **133**, 59–71.

Marsigli, C., A. Montani, F. Nerozzi, T. Paccagnella, S. Tibaldi, F. Molteni, and R. Buizza, 2001: A strategy for high-resolution ensemble prediction. Part II: Limited-area experiments in four Alpine flood events. *Quart. J. Roy. Met. Soc.*, **127**, 2095-2115.

Marsigli, C., A. Montani, T. Paccagnella, D. Sacchetti, A. Walser, M. Arpagaus, and T. Schumann, 2005: Evaluation of the performances of the COSMO-LEPS system. *COSMO Techincal Report No. 8*, online available: http://www.cosmo-model.org.

Marsigli, C., A. Montani, and T. Paccagnella, 2008: A spatial verification method applied to the evaluation of high-resolution ensemble forecasts, *Meteor. Applications*, **15**, 125-143.

Marsigli, C., 2009: Final report on priority project SREPS (Short Range Ensemble Prediction System). *COSMO Technical Report No. 13*, online available: http://www.cosmo-model.org/content/ model/documentation/techReports/default.htm.

Mass, C. F., D. Ovens, K. Westrick, and B. A. Colle, 2002: Does increasing horizontal resolution produce better forecasts? *Bull. Amer. Meteor. Soc*., **79**, 253-263.

Masson, V, J.L. Champeaux, F. Chauvin, C. Meriguet, and R. Lacaze, 2003: A global database of land surface parameters at 1-km resolution in meteorological and climate models, *J.Climate*, **16**, 1261-1282.

Mellor, G. L., and T. Yamada, 1974: A hierarchy of turbulence closure models for planetary boundary layers. *J. Atmos. Sci.*, **31**, 1791-1806.

Meyers, M. P., R. L. Walko, J. Y. Harrington, and W. R. Cotton, 1997: New RAMS cloud microphysics parameterisation. Part II: The two-moment scheme. *Atmos. Res*., **45**, 3-39.

Mengelkamp, H. T., F. Beyrich, G. Heinemann, F. Ament, J. Bange, F. Berger, J. Bösenberg, T. Foken, B. Hennemuth, C. Heret, S. Huneke, K. P. Johnsen, M. Kerschgens, W. Kohsiek, J. P. Leps, C. Liebethal, H. Lohse, M. Mauder, W. Meijninger, S. Raasch, C. Simmer, T. Spieß, A. Tittebrand, J. Uhlenbrock, and P. Zittel, 2006: Evaporation over a heterogeneous land surface. *Bull. Amer. Meteor. Soc.*, **87**, 775–786.

Milbrandt, J. and M. Yau, 2005a: A multimoment bulk microphysics parameterisation. Part I: Analysis of the role of the spectral shape parameter. *J. Atmos. Sci*., **62**, 3051-3064.

Milbrandt, J. and M. Yau 2005b: A multimoment bulk microphysics parameterisation. Part II: A proposed three-moment closure and scheme description. *J. Atmos. Sci*., **62**, 3065–3081.

Milbrandt, J. and M. Yau 2006: A multimoment bulk microphysics parameterisation. Part IV: Sensitivity experiments. *J. Atmos.Sci.*, **63**, 3137–3159.

Mironov, D. V., and M. Raschendorfer, 2001: Evaluation of empirical parameters of the new LM surface-layer parameterisation scheme. Results from numerical experiments including the soil moisture analysis. *COSMO Technical Report No. 1,* online available: http://www.cosmo-model.org/ content/model/documentation/techReports/default.htm.

Mironov, D., and B. Ritter, 2003: A first version of the ice model for the global NWP system GME of the German Weather Service. In: Research activities in atmospheric and oceanic modelling. Ed. J. Cote, Report No. 33, WMO/TD, 4.13-4.14.

Mironov, D., and B. Ritter, 2004a: A new sea ice model for GME. Technical Note, Deutscher Wetterdienst, Offenbach am Main, Germany, 12 pp.

Mironov, D., and B. Ritter, 2004b: Testing the new ice model for the global NWP system GME of the German Weather Service. In: Research activities in atmospheric and oceanic modelling. Ed. J. Cote, Report No. 34, WMO/TD-No. 1220, 4.21-4.22.

Mironov, D. V., and C. Jones, 2005: Summary of the working group discussion on the representation of convection in high resolution numerical models. *Proc. of the HIRLAM/NetFAM Workshop on Convection and Clouds*, 24-26 January 2005, Tartu, Estonia, p 113-116, online available: http://hirlam.fmi.fi/CCWS/Tarturepo_v3.pdf.

Mironov, D. V., E. Heise, E. Kourzeneva, B. Ritter, and N. Schneider, 2007: Parameterisation of lakes in numerical weather prediction and climate models. *Proc. of the 11th Workshop on Physical Processes in Natural Waters*. Eds. L. Umlauf and G. Kirillin, Berichte des IGB, **25**, Berlin, Germany, 101-108.

Mironov, D. V., 2008a: Turbulence in the lower troposphere: second-order closure and mass-flux modelling frameworks. In: Interdisciplinary aspects of turbulence. Springer Lecture Notes in Physics, **756**, Eds. W. Hillebrandt and F. Kupka, Springer-Verlag, Berlin, DOI: 10.1007/978-3-540-78961-1_5.

Mironov, D. V., 2008b: Parameterisation of lakes in numerical weather prediction. Description of a lake model. *COSMO Technical Report No. 11*, online available: http://www.cosmo-model.org/ content/model/documentation/techReports/default.htm.

Mironov, D. V., E. Heise, E. Kourzeneva, B. Ritter, N. Schneider, and A. Terzhevik, 2010: Implementation of the lake parameterisation scheme FLake into numerical weather prediction model COSMO. *Boreal Env. Res.*, **15**, 218-230.

Mironov, D. V., and P. P. Sullivan, 2010: Effect of horizontal surface temperature heterogeneity on turbulent mixing in the stably stratified atmospheric boundary layer. *Proc. 19th Amer. Meteorol. Soc. Symp. on Boundary Layers and Turbulence*, Keystone, CO, USA, paper 6.3, 10 pp. Online available: http://ams.confex.com/ams/19Ag19BLT9Urban/techprogram/paper_172701.htm.

Mittermaier, M. P., 2006: Using an intensity-scale technique to assess the added benefit of high-resolution model precipitation forecasts. *Atmos. Sci. Lett.*, **7**, 36-42.

Miura, H., 2007: An upwind-biased conservative advection scheme for spherical hexagonal-pentagonal grids. *Mon. Wea. Rev.*, **135**, 4038-4044.

Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102**, D16663, DOI:10.1029/97JD00237.

Montani, A., M. Capaldo, D. Cesari, C. Marsigli, U. Modigliani, F. Nerozzi, T. Paccagnella, P. Patruno, and S. Tibaldi, 2003: Operational limited-area ensemble forecasts based on the Lokal Modell, *ECMWF Newsletter,* **98**, 2-7.

Morrison, H. and W. Grabowski, 2007: Comparison of bulk and bin warm rain microphysics models using a kinematic framework. *J. Atmos. Sci*., **64**, 2839–2861.

Mühlbauer, A., and U. Lohmann, 2008: Sensitivity studies of the role of aerosols in warm-phase orographic precipitation in different dynamical flow regimes. *J. Atmos. Sci*., **65**, 2522-2542.

Nair, R. D., and B. Machenhauer, 2002: The mass-conservative cell-Integrated semi-Lagrangian advection scheme on the sphere. *Mon. Wea. Rev*., **130**, 649-667.

Nakanishi, M., and H. Niino, 2004: An improved Mellor-Yamada level-3 model with condensation physics: its design and verification. *Boundary Layer Meteorol.*, **112**, 1-31.

Nutter, P. A., 2003: Effects of nesting frequency and lateral boundary perturbations on the dispersion of limited-area ensemble forecasts. PhD thesis, University of Oklahoma, School of Meteorology, Norman, OK.

Phillips, V. T. J., T. W. Choularton, A. J. Illingworth, R. J. Hogan, and P. R. Field, 2003: Simulations of the glaciation of a frontal mixed-phase cloud with the explicit microphysics model. *Quart. J. Roy. Met. Soc*., **129**, 1351–1371.

Phillips, V. T. J., A. Pokrovsky, and A. Khain, 2007: The influence of time-dependent melting on the dynamics and precipitation production in maritime and continental storm clouds. *J. Atmos. Sci*., **64**, 338–359.

Pielke, R. A., W. R. Cotton, R. L. Walko, C. J. Tremback, W. A. Lyons, L. D. Grasso, M. E. Nicholls, M. D. Moran, D. A. Wesley, T. J. Lee, and J. H. Copeland, 1992: A comprehensive meteorological modeling system – RAMS. *Meteorol. Atmos. Phys*., **49**, 69–91.

Piriou, J. M., J. L. Redelsperger, J.-F. Geleyn, J. P. Lafore, and F. Guichard, 2007: An approach for convective parameterisation with memory: separating microphysics and transport in grid-scale equations. *J. Atmos.Sci*., **64**, 4127–4139.

Raschendorfer, M., 1999: Special topic: The new turbulence parameterisation of LM. *Quarterly Report of the Operational NWP Models of the Deutscher Wetterdienst*, No. 19, 3-12.

Raschendorfer, M., 2001: The new turbulence parameterisation of LM. *COSMO Newsletter*, **1**, 89-97.

Raschendorfer, M., and D. Mironov, 2002: Operational implementation of the new turbulence parameterisation. In: Research activities in atmospheric and oceanic modelling. Ed. H. Ritchie, Report No. 32, WMO/TD, 04.23-04.24.

Reinhardt, T., and A. Seifert, 2006: A three-category ice scheme for LMK. *COSMO Newsletter*, **6**, 115-120.

Reisner, J., R. M. Rasmussen, and R. T. Bruintjes, 1998: Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. *Quart. J. Roy. Met. Soc*., **124**, 1071–1107.

Ritter, B., and J.-F.Geleyn, 1992: A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations. *Mon.Wea.Rev*., **120**, 303-325.

Rockel, B.; A. Will, and A. Hense, 2008: The regional Climate Model COSMO-CLM (CCLM), *Met. Z*., **17**, 347-348.

Rotach, M. W., P. Ambrosetti, F. Ament, C. Appenzeller, M. Arpagaus, H.-S. Bauer, A. Behrendt, F. Bouttier, A. Buzzi, M. Corazza, S. Davolio, M. Denhard, M. Dorninger, L. Fontannaz, J. Frick, F. Fundel, U. Germann, T. Gorgas, C. Hegg, A. Hering, C. Keil, M. A. Liniger, C. Marsigli, R. McTaggart-Cowan, A. Montani, K. Mylne, R. Ranzi, E. Richard, A. Rossa, D. Santos-Muñoz, C. Schär, Y. Seity, M. Staudinger, M. Stoll, H. Volkert, A. Walser, Y. Wang, J. Werhahn, V. Wulfmeyer, M. Zappa, 2009: MAP D-PHASE: Real-time demonstration of weather forecast quality in the Alpine region, *Bull. Amer. Meteor. Soc.*, **90**, 1321-1336.

Schättler, U., G. Doms, and J. Steppeler, 2000: Requirements and problems in parallel model development at DWD, *Scientific Programmin*g, **8**, 13-22.

Schwartz, C. S., J. S. Kain, S. J. Weiss, M. Xue, D. R. Bright, F. Kong, K. W. Thomas, J. J. Levit, M. C. Coniglio, and M. S. Wandishin, 2010: Toward improved convection-allowing ensembles: Model physics sensitivities and optimizing probabilistic guidance with small ensembles membership. *Weather and Forecasting*, **25**, 263-280.

Scipal, K., and M. Drusch, 2007: *Geophysical Research Abstracts*, **9**, 01822, SRef-ID: 1607-7962/gra/EGU2007-A-01822.

Seifert, A., 2008: On the parameterisation of evaporation of raindrops as simulated by a one-dimensional rainshaft model. *J. Atmos. Sci*., **65**, 3608-3619.

Seifert, A., and K. Beheng, 2006a: A two-moment cloud microphysics parameterisation for mixed-phase clouds. Part I: Model description. *Meteorol. Atmos. Phys*., **92**, 45–66.

Seifert, A., and K. Beheng, 2006b: A two-moment cloud microphysics parameterisation for mixed-phase clouds. Part II: Maritime vs. continental deep convective storms. *Meteorol. Atmos. Phys*., **92**, 67-88.

Seneviratne S. I., D. Lüthi, M. Litschi, and C. Schär, 2006: Land–atmosphere coupling and climate change in Europe, *Nature*, **443,** 205-209, DOI:10.1038/nature05095.

Siebesma, A. P., and J. Teixeira, 2000: An advection-diffusion scheme for the convective boundary layer: Description and 1D results. *Proc. of the 14th AMS Symposium on Boundary Layers and Turbulence*, Aspen, CO, American Meteorol. Soc, Boston, USA, p 133-136.

Skamarock, W. C., 2006: Positive-definite and monotonic limiters for unrestricted-time-step transport schemes. *Mon. Wea. Rev*., **134**, 2241-2250.

Skamarock, W. C., and J. B. Klemp, 2008: A time-split nonhydrostatic atmospheric model for weather research and forecasting applications, *J. Comput. Phys*., **227**, 3465-3485.

Smolarkiewicz, P. K., and T. L. Clark, 1986: The multidimensional positive definite advection tracer transport algorithm: Further development and applications. *J. Comput. Phys*., **67**, 396-438.

Smolarkiewicz, P. K., and J. M. Prusa, 2005: Towards mesh adaptivity for geophysical turbulence: continuous mapping approach, *Int. J. Num. Meth. Fluids*, **47**, 789-801.

Soares, P. M. M., P. M. A. Miranda, A. P. Siebesma, and J. Teixeira, 2004: An eddy-diffusivity/mass-flux parameterisation for dry and shallow cumulus convection. *Quart. J. Roy. Met. Soc.*, **130**, 3365-3383.

Sommeria, G., and J. W. Deardorff, 1977: Subgrid-scale condensation in models of nonprecipitating clouds. *J. Atmos. Sci.*, **34**, 344-355.

Staniforth A., and J. Côté, 1991: Semi-Lagrangian integration schemes for atmospheric models – a review. *Mon. Wea. Rev*., **119**, 2206-2223.

Steppeler, J., G. Doms, U. Schättler, H. W. Bitzer, A. Gassmann, U. Damrath, and G. Gregoric, 2003: Meso-gamma scale forecasts using the nonhydrostatic model LM. *Meteorol. Atmos Phys*, **82**, 75-96.

Straka, J. M., and E. R. Mansell, 2005: A bulk microphysics parameterisation with multiple ice precipitation categories. *J. Appl. Met*., **44**, 445–466.

Swinbank, R., W. A. Lahoz, A. O'Neill, C. S. Douglas, A. Heaps, and D. Podd, 1998: Middle atmosphere variability in the UK Meteorological Office Unified Model, *Quart J Roy Met Soc.*, **124**, 1485-1525.

Thompson, G., R. M. Rasmussen, and K. Manning, 2004: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis. *Mon. Wea. Rev*.,**132**, 519–542.

Thuburn, J., 2008: Some conservation issues for the dynamical cores of NWP and climate models, *J. Comput. Phys*. **227/7**, 3715-3730.

Theis, S. E., A. Hense, and U. Damrath, 2005: Probabilistic precipitation forecasts from a deterministic model: a pragmatic approach. *Meteorol. Appl.*, **12**, 257-268.

Tiedtke, M., 1989: A comprehensive mass flux scheme for cumulus parameterisation in large-scale models. *Mon. Wea. Rev*., **117**, 1779-1799.

Tiedtke, M., 1993: Representation of clouds in large-scale models. *Mon. Weather Rev.*, **121**, 3040-3061.

Tompkins, A. M., 2002: A prognostic parameterisation for the subgrid-scale variability of water vapor and clouds in large-scale models and its use to diagnose cloud cover. *J. Atmos. Sci.*, **59**, 1917-1942.

Tompkins, A. M., 2005: The parameterisation of cloud cover. Technical Memorandum, European Centre for Medium-Range Weather Forecasts, Reading, U.K., 23 pp.

Torrisi, L., 2006: Sensitivity experiments with the Runge-Kutta time integration scheme*, COSMO-Newsletter,* **6**, 65-73.

Toth, Z., O. Talagrand, and Y. Zhu: The attributes of forecast systems: a general framework for the evaluation and calibration of weather forecasts. In: Predictability of weather and climate. Eds. T. Palmer and R. Hagedorn, Cambridge University Press, 2006.

Tracton, M. S., and E. Kalnay, 1993: Operational ensemble prediction at the National Meteorological Centre: practical aspects. *Weather and Forecasting*, **8**: 379-398.

Tracton, M. S. , J. Du, Z. Toth, and H. Juang, 1998: Short range ensemble forecasting (SREF) at NCEP/EMC 12th Conf. on Numerical Weather Prediction, Phoenix, American Meteorological Society, 269-272.

Unden, P,. and co-authors, 2002: HIRLAM-5 scientific documentation. Online available: http://hirlam.org.

Van den Heever, S. C., G. G. Carrio, W. R. Cotton, P. J. DeMott, and A. J. Prenni, 2006: Impacts of nucleating aerosol on florida storms. Part I: Mesoscale simulations. *J. Atmos. Sci*., **63**, 1752-1775.

Van Leeuwen, P.J., 2003: A variance minimizing filter for large scale applications. *MWR*, **131**, 2071-2084.

Venema, V., A. Schomburg, F. Ament, and C. Simmer, 2007: Two adaptive radiative transfer schemes for numerical weather prediction models, *Atmos. Chem. Phys.,* **7**, *5659-5674.*

Vogel, B., H. Vogel, D. Bäumer, M. Bangert, K. Lundgren, R. Rinke, T. Stanelle, 2009: The comprehensive model system COSMO-ART - Radiative impact of aerosol on the state of the atmosphere on the regional scale, *Atmos. Chem. Phys*., **9**, 8661-8680.

Walko, R. L., W. R. Cotton, M. P. Meyers, and J. Y. Harrington, 1995: New RAMS cloud microphysics parameterisation. Part I: The single-moment scheme. *Atmos. Res*., **38**, 29–62.

Wang, Y., and A. Kann, 2006: Dealing with the uncertainties in the initial conditions in ALADIN-LAEF. 1st MAP D-PHASE scientific meeting, 6-8 November 2006, Vienna.

Wapler, K., and B. Mayer, 2008: A fast three-dimensional approximation for the calculation of surface irradiance in large-eddy simulation models. *Jour. Appl. Meteor. Clim*., **47**, 3061-3071.

Wernli, H., M. Paulat, M. Hagen, and C. Frei, 2008: SAL — a novel quality measure for the verification of quantitative precipitation forecasts. *Mon. Wea. Rev*., **136**, 4470-4487.

Will, A., K. Keuler, and A. Block: 2006: The Climate Local Model - evaluation results and recent developments, *TerraFLOPS Newsletter*, **8**, 2-3.

Wilson, D. R., and S. P. Ballard, 1999: A microphysically based precipitation scheme for the UK meteorological office unified model. *Quart. J. Roy. Met. Soc*., **125**, 1607–1636.

Woods, C. P., M. T. Stoelinga, and J. D. Locatelli, 2007: The IMPROVE-1 storm of 1-2 February 2001. Part III: Sensitivity of a mesoscale model simulation to the representation of snow particle types and testing of a bulk microphysical scheme with snow habit prediction. *J. Atmos. Sci*., **64**, 3927-3948

Xue, M., D. Wang, J. Gao, K. Brewster, and K. K. Droegemeier: 2003: The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation, *Meteor. Atmos. Phys.,* **82**, 139–170.

Zilitinkevich, S. S.; J. C. R. Hunt, I. N. Esau, A. A. Grachev, D. P. Lalas, E. Akylas, M. Tombrou, C. W. Fairall, H. J. S. Fernando, A. A. Baklanov, and S. M. Joffrer, 2006: The influence of large convective eddies on the surface-layer turbulence. *Quart. J. Roy. Met. Soc.*, **132**, 1423-1456.

Appendix

A1 SWOT analysis of COSMO

In the following, an analysis of the strength, weaknesses, opportunities, and threats (SWOT) of the COSMO model as well as the COSMO consortium is done. The result of the analysis is however not (yet) reflected in the preceding chapters of the Science Plan.

A1.1 Model

	helpful	harmful
internal	**Strength** – 10 yrs experience of successful operational non-hydrostatic modelling – 3 yrs experience of successful operational convection-permitting modelling – high resolution (deterministic and probabilistic) – easy world wide relocatability – fully portable, well maintained model code	**Weaknesses** – insufficient use of indirect observations – some parameterisation packages require revision – weak coupling between parameterisation schemes – incomplete documentation

external	**Opportunities**
	– increasing demand
	    – nowcasting
	    – EPS for decision making
	    – environmental modelling (air quality, hydrology, …)
	    – re-analysis data
	    – regional climate modelling
	– increased popularity in academic community
	– close link to ICON development (in particular shared physics)
	– SRNWP Interoperability Programme
	– SRNWP Verification Programme
	– model application in private sector
		Threats
		– risk of loosing focus because of high diversity of applications and requirements
		– strong competition from HARMONIE and Unified Model
		– potential inefficiency on massively parallel HPC platforms (i.e., O(10k) CPUs)

A1.2 Consortium

	helpful	harmful
internal	**Strength** – community of weather services running the same model in operational mode – joint operational applications (LEPS, SREPS) – creative environment for bottom-up initiatives – strong links to academia	**Weaknesses** – no budget – no dedicated development team – inhomogeneous resources between members (manpower, qualification, technical infrastructure, funding) – dispersion of resources to address too many issues
external	**Opportunities** – COSMO-CLM – COSMO-ART – SRNWP, especially Expert Teams – Licensing	**Threats** – strong competition from other consortia – pressure towards quick wins – national plans that interfere with COSMO plans, or even prevent their realisation