CONSORTIUM FOR SMALL SCALE MODELING

COSMO

Science Plan 2015-2020

Publication date: 21. 04. 2015

List of main authors by chapter / section

1	M. Ziemiański (IMGW-PIB), D. Majewski (DWD)
2	M. Ziemiański (IMGW-PIB), D. Majewski (DWD), P. Steiner (MeteoSwis)
3	M. Ziemiański (IMGW-PIB), D. Majewski (DWD), C. Marsigli (ARPA-SIMC), P. Steiner (MeteoSwis)
4	M. Ziemiański (IMGW-PIB), M. Baldauf (DWD), F. Gofa (HNMS), D. Majewski (DWD), C. Marsigli (ARPA-SIMC), B. Ritter (DWD), C. Schraff (DWD), P. Steiner (MeteoSwis), M. Raschendorfer (DWD)
5	M. Baldauf (DWD)
6.1-6.2.1	M. Raschendorfer (DWD)
6.2.2	M. Raschendorfer (DWD), A. Seifert (DWD), U. Blahak (DWD)
6.2.3	M. Raschendorfer (DWD), B. Ritter (DWD), U. Blahak (DWD)
6.2.4	M. Raschendorfer (DWD)
6.3.1	J. Helmert (DWD), E. Machulskaya (DWD), G. Vogel (DWD), J-P. Schulz (Uni Frankfurt), J-M. Bettems (MeteoSwiss)
6.3.2	D. Mironov (DWD)
6.3.3	D. Mironov (DWD)
6.3.4-6.3.5	J. Helmert (DWD), J-M. Bettems (MeteoSwiss)
7	C. Schraff (DWD), R. Potthast (DWD)
8	C. Marsigli (ARPA-SIMC), M. Arpagaus (MeteoSwiss), R. Bonanno (ARPA-Piemonte), N. Loglisci (ARPA-Piemonte), A. Mazur (IMGW-PIB), A. Montani (ARPA-SIMC), S. Theis (DWD), A. Walser (MeteoSwiss)
9	F. Gofa (HNMS), A. Raspanti (USAM), F. Schubiger (MeteoSwiss)
10	M. Milelli (ARPA Piemonte), U. Schättler (DWD), O. Fuhrer (MeteoSwiss)
11	M. Baldauf (DWD), P. Eckert (MeteoSwiss), F. Gofa (HNMS), C. Marsigli (ARPA-SIMC), M. Raschendorfer (DWD), B. Ritter (DWD), C. Schraff (DWD)
12	M. Ziemiański (IMGW-PIB)
13	M. Ziemiański (IMGW-PIB), M. Arpagaus (MeteoSwiss)
A1	D. Majewski (DWD), P. Steiner (MeteoSwis), A. Raspanti (USAM)

Revision history

Revision	Date	Author(s)	Remarks
2.0	26.08.2013	Baldauf, Bettems, Eckert, Gofa, Marsigli, Milelli, Raschendorfer, Schraff	outlines of chapters 5 to 10 and proposition on additional subchapter on postprocessing/user aspects with initial feedback of the SPM
2.1	03.09.2013	As above	feedback to outlines of chapters 5 to 10 and cross-cutting issues during STC meeting on 2/3.09.2013
2.2	06.09.2013	As above	feedback to outlines of chapters 5 to 10 and cross-cutting issues during SMC meeting on 5/6.09.2013
2.3	10.12.2013	Baldauf, Bettems et al., Eckert, Gofa et al., Marsigli et al., Milelli et al, Raschendorfer et al., Schraff et al.	draft chapters 5 to 10 and on postprocessing isssues with feedback of the SPM
2.4	11.12.2013	As above	feedback to draft chapters 5 to 10 and on postprocessing issues during SMC meeting on 11.12.2013
2.5	23.12.2013	Baldauf et al., Marsigli et.al., Raschendorfer et.al.,	draft chapters on cross-cutting issues with feedback of SPM
2.6	15.01.2014	Baldauf et al.	chapter on cross-cutting issues concerning dynamics/physics/code structure
2.7	16.01.2014	Baldauf, Bettems et al., Eckert, Gofa et al., Marsigli et al., Milelli et al, Raschendorfer et al., Schraff et al.	chapters 5 to 10 for inclusion to consolidated draft of the Science Plan
2.8	20.01.2014	Ziemiański	update of draft chapters 1 to 4 and 12
2.9	22.01.2014	Ziemiański et al.	consolidated draft of the Science Plan: v1.0
2.10	28.01.2014	Raschendorfer et al.	chapter on cross-cutting issues concerning verification feedback on model development
2.11	31.01.2014	Marsigli et al.	chapter on cross-cutting issues concerning stochastic physics
2.12	03.02.2014	Ziemiański et al.	consolidated draft of the Science Plan with complete chapter on cross-cutting issues: v1.1
2.13	14.03.2014	Ziemiański et al.	updated draft of the Science Plan after the first STC review: v1.2
2.14	8.04.2014	Ziemiański et al.	updated draft of the Science Plan after the STC discussion on 20.03.2014: v1.3
2.15	29.07.2014	Ziemiański et al.	revised Science Plan draft integrating feedback from the external reviewers: v1.4
2.16	23.01.2015	Ziemiański et al.	revision of Science Plan draft integrating feedback from STC and additional external reviewers: v1.5
2.17	16.02.2015	Ziemiański et al.	corrections after SMC discussion: v1.6
2.18	21.04.2015	Ziemiański et al.	final version approved by the COSMO STC

Table of Contents

1 Management Summary

This document describes the COSMO goal and the strategy to attain the goal for the 6-year period 2015-2020, and details the subsequent actions for the future development of the COSMO model.

Chapter 4 provides a concise overview of the COSMO goal and scientific strategy, while chapters 5 to 11 provide a comprehensive discussion of the strategy and of actions required for its implementation.

The document is intended mainly for COSMO scientific community and its managing groups. It will be published on COSMO web page and available for scientific community outside the consortium.

The COSMO goal is to develop further an operational and research mesoscale model-system for the short to very short range, aimed especially at high-impact weather forecast and having ensemble prediction methodology at its core. 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;
- conservative robust dynamical core;
- atmospheric and surface physics for convective scale;
- extension of the environmental prediction capabilities of the model;
- a verification and validation tool for the convective scale;
- use of massively parallel computer platforms and emerging new (heterogeneous) architectures;
- intensified collaboration within and beyond COSMO, especially with academia.

The new COSMO Agreement which was signed in 2014 enables the chance to broaden the scientific expertise by accepting a small number of highly qualified National Meteorological Services as new COSMO members.

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-PIB), Romania (NMA), Russia (ROSHYDROMET) and Switzerland (MeteoSwiss). Through their national meteorological services, a number of additional institutions are participating in COSMO: The Centre 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. It concerns practically all areas of the model development, but especially the field of regional climate modelling (**COSMO-CLM**; http://www.clm-community.eu) and environmental prediction (**COSMO-ART**; http://www.imk-tro.kit.edu). Close cooperation of COSMO with the communities allows for COSMO model applications within these important areas. There is also a strategic cooperation with Max-Planck Institute in Hamburg on development of ICON (ICOsahedral Nonhydrostatic general circulation model; http://icon.enes.org).

Other type of cooperation with academia concerns basic and exploratory research within areas of strategic importance for COSMO. It is mainly organised on national levels and includes, for instance HErZ (Hans Ertel Centres for Weather Research; for data assimilation research see LMU, Munich, http://www. cosmo-model.org/content/consortium/generalMeetings/general2012/wg1-kenda/weissmann_HErZ_DA.pdf) or ETH Zurich. Such academic cooperation provides indispensable input to further development of the COSMO modelling system and its applications. However, COSMO takes on responsibility for development of operational code and its maintenance. COSMO also usually takes on responsibility for final application research.

While the use of COSMO model is free for all for research applications, it is also open for operational use by Governmental Meteorological Services from outside the consortium under licence conditions. There exists a world-wide group of such users.

COSMO organization

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 Expert Team.

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

WG 1: Data assimilation

WG 2: Numerical aspects

WG 3a: Physical aspects: upper air

WG3b: Physical aspects: soil and surface

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) and Priority Tasks (PTs)** (the latter smaller in terms of resources and duration). They are dedicated to activities of special importance for the consortium and usually aim at development of COSMO tools. Since then, members are required to deliver their yearly 2 FTEs within the tasks as specified in the Priority Projects/Priority Tasks, accepted by the STC. Current PP/PTs are described within chapters 5 to 10 of the current document.

The WG coordinators together with the SPM, the chairperson of the STC, and the coordinators of the CLM and ART communities form the **Scientific Management Committee (SMC)**. The SMC is, in between, a platform for coordination between the consortium and CLM and ART communities with a special aim to maintain a common code utilised within all COSMO communities.

The Source Code Management document governs the rules of development of the code of COSMO software, including the COSMO model. The official COSMO software includes also pre-processing tool INT2LM, post-processing tool fieldextra, tool for geospatial data preparation EXTPAR, and verification tool VERSUS. The Source Code Administrators (SCAs) of the COSMO software together with the WG6 Coordinator and SPM form the **Technical Advisory Group (TAG)**.

Recently, a renewed COSMO Strategy was formulated aiming at harmonization of COSMO and ICON (see chapter 3.1) developments which will lead to the unification of the modelling system involving physical parameterisations and possibly the dynamical core. The strategy calls also for the exploitation of the new heterogeneous high performance computing (HPC) architectures like graphics processing units (GPU) and hybrid GPU/CPU. The strategy was endorsed by the COSMO Directors in September 2013. It foresees the unification of the modelling system up to 2020, that is within the time frame of this document, with COSMO taking up the responsibility for the regional mode of ICON.

COSMO Science Plan

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 **6-year period 2015-2020** and encompasses the COSMO model, the data assimilation components, the verification and validation tools 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.

The Source Code Management rules are defined in a separate document (http://cosmo-model.org/content/model/documentation/standards/default.htm), however their development based on scientific principles is also covered by the current document.

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

– **Pre- and post-processing tools** such as INT2LM, fieldextra, NinJo, etc.

– **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.

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. Chapter 11 discusses selected important cross-cutting aspects of the scientific developments. Chapter 12 documents the most important external collaborations for the COSMO model development, chapter 13 acknowledges the very helpful review of the COSMO Science Plan by colleagues outside COSMO, chapter 14 contains a list of references, and appendix A1 provides a SWOT analysis of both the COSMO model as well as the COSMO consortium. Finally, appendix A2 provides a list of acronyms.

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**. It is likely to introduce a horizontal resolution upgrade to either **10 or 8 km** for **deterministic** forecast, and to a resolution of about **20 km** for their **ensemble prediction system** (EPS) **by 2020**.

DWD, in collaboration with the Max Planck Institute for Meteorology in Hamburg, developed the **ICON** GCM (ICOsahedral Non-hydrostatic General Circulation Model, http://icon.enes.org), which includes the option of a refined grid in areas of interest, to be run in deterministic as well as ensemble mode. Apart from being used for global weather forecasts, the ICON became an optional driving model providing initial and boundary conditions for high-resolution limited-area (deterministic as well as ensemble) COSMO applications. The model was implemented operationally at **DWD** on 20 January 2015 in **deterministic** mode with a **horizontal mesh-size of 13 km and 90 vertical layers,** about six months later the higher resolution nest with a **mesh-size of 6.5 km over Europe** will be activated, and the **ensemble forecast** mode **in 2017** with **20 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). Following the success of global ICON, measured by its verification scores and computational efficiency well above the previous GME, a limited-area mode is being developed to be available for testing within 2017 in the framework of the German scientific project HD(CP)^2. That allows defining the COSMO Strategy aimed at unification of the COSMO-ICON system by 2020. The practical details of the strategy will be decided shortly after implementation of the current document.

Currently, many interesting activities aimed at development of high resolution global models, also in a context of Earth system modelling, take place. In Europe, apart of ICON, it concerns especially Gung-Ho project at the Met Office and PantaRhei at ECMWF. In America it concerns development of MPAS (the Model for Prediction Across Scales) by NCAR and Los Alamos National Laboratory, Next Generation System for GFS (Global Forecast System) in NCEP and GEM (the Global Environmental Multiscale Model) by Environment Canada, while in Japan the enhancement of GSM (Global Spectral Model) by Japan Meteorological Agency.

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, classified here as the fifth one. Close collaboration is taking place between ALADIN and HIRLAM, which is called HARMONIE. There is also a close exchange of information between the consortia especially within the EUMETNET C-SRNWP project.

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 Convective-scale EPS modelling

In May 2012, DWD introduced the operational convective-scale ensemble forecast system COSMO-DE-EPS, the first such forecasting tool in Europe. It comprises of an ensemble of 20 members calculated by the COSMO model with horizontal resolution of 2.8 km, employing the initial and boundary conditions of four global models as well as perturbed parameters of model physics. Similar systems are developed by MeteoSwiss (COSMO-E with 21 members and 2.2 km horizontal resolution) by ARPA-SIMC/CNMCA/ARPA-Piemonte (COSMO-IT-EPS, with 10 members and 2.8km horizontal resolution), and by ROSHYDROMET (COSMO-RU2-EPS with 2.2 km resolution and 10 members).

Convection-scale EPS systems are also currently developed by other European consortia: MOGREPS-UK (12 members ensemble with 2.2 km horizontal resolution) is operationally run by the UK Met Office, while ALADIN and HIRLAM are developing HarmonEPS (20 members ensemble with 2.5 km horizontal resolution, based on AROME and ALARO multi-model approach), Meteo France is developing AROME-EPS (12 members, 2.5 km horizontal resolution) and an AROME-EPS is being developed also by LACE (11 members, 2.5 km horizontal resolution).

3.4 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 convection permitting resolution, linked with implementation of appropriate data assimilation and parameterisation schemes, will help to improve the simulation of physical processes that can indeed produce valuable information on high impact weather, such as, e.g., convective storms but also fog/stratus areas characteristic for stable atmospheric conditions.

The activities aimed at development of NWP based nowcasting capabilities take place in many countries. In Europe they are coordinated within EUMETNET Nowcasting Activity, aimed at developments of short-range NWP models for a better capability in nowcasting in the horizon of 2017.

3.5 Climate simulations

Global NWP models have a long tradition of forming the basis of climate simulation models. Their newly developed very-high resolution global reanalysis products based on off-line surface models will provide high-resolution climate trends in near future. For limited-area NWP models, their climate applications became a well established practice allowing to add value to the global climate simulations (see e.g. the IPCC 4th and 5th Assessment Reports). All operational limited-area NWP models described in section 3.2 have their climate branches. In case of **COSMO**, a **climate version** has been devised by a number of research groups (Will et al. 2006, Rockel et al. 2008, Böhm 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 (for recent publications see the CLM web page http://www.clm-community.eu/index.php?menuid=26).

3.6 Environmental prediction

The objective of the European Copernicus Programme (www.copernicus.eu), formerly known as **GMES** initiative (Global Monitoring for Environment and Security) is to develop an operational capability to **monitor the environment**. ECMWF therefore extends 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 so that from 2015 it will operate Copernicus Atmosphere service (ECMWF, 2011). Hence the ECMWF Integrated Forecasting System (IFS) will be used for **environmental prediction** and monitoring.

Limited-area NWP models also became environmental prediction systems, and COSMO-ART takes a leading role in the process. The main reasons are: 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

---

[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.

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) are already included into the limited-area models, for others one will need to add fully coupled or standalone (i.e., external) application models (e.g. air quality, dispersion, hydrology, ocean waves).

COSMO-ART (see also chapter 12.2), 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. Strong link between COSMO and ART allows for a practical incorporation of recent ART developments into the state-of-the-art COSMO operational framework which constitutes a unique strength of the COSMO system. Its current operational implementations involve pollen and volcanic ash transport (DWD, MeteoSwiss) and air quality assessment (ROSHYDROMET).

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 explicit 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. **The scale of the targeted processes and expected HPC capabilities require that the mesh-size of the model-system has to be of the order of 0.5-2 km.**

Currently, the reliable deterministic numerical forecasting of convective processes using such resolutions is not possible due the chaotic character of these processes with rapid error growth on the smallest spatial scales. It is necessary, therefore, to implement ensemble forecast methods to reflect the uncertainties involved and to allow for reliable probabilistic forecasts, especially of high-impact weather.

The still unknown factors, related e.g. to small scales of the flow and their interactions, prompt for enhanced research on convective-scale aspects of atmospheric processes and especially of high-impact weather. The model itself should provide for such opportunities and become a bridge between academic and operational communities.

Based on these considerations the COSMO Steering Committee decided **to define the main COSMO goal as the development of an operational and research mesoscale model-system for the short to very short range and with very high convective-scale resolution, aimed especially at high-impact weather forecast and with ensemble prediction methodology at its core**.

The results of the modelling system are used operationally for provision of vital information for many users. It concerns whole societies especially in terms of life and property saving information, but also such demanding groups of users like energy providers (including renewable energy sources) and transport (including aviation). The high quality of the model results stands therefore as one of the main concerns of the consortium. With that, the development of very-high resolution deterministic mode is also foreseen with the aim to work on reduction of the model errors, but also to provide additional products e.g. for high-orography areas. Due to the uncertainties still present in the modelling system at these scales, the reduction of the model errors should be also accompanied by their assessment (following an ensemble approach) for both (probabilistic) forecasting and data assimilation purposes.

Within the time frame of this Science Plan the targeted horizontal resolution of the deterministic mode is 1 to 0.5 km while for the ensemble mode it is 2 to 1 km, depending of course on the computer power available, the size of the model domain and the production times required.

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, combined further within a framework of Earth system modelling. Activities towards these goals are mainly pursued in the COSMO-CLM and COSMO-ART communities (see also chapters 12.1 and 12.2), which, together with the Consortium for Small Scale Modelling and ICON, constitute the four 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

At the **convective scale** it is advisable **to run an ensemble prediction system** (rather than 'only' a deterministic model) **at the highest possible resolution**[2] for the following two reasons:

- convection as well as many other **physical processes at the convective scale cannot be deterministically predicted** with today’s numerical forecasting systems, due to lack of physical knowledge, to lack of scale adequate physics parameterisations and/or the representation of their interaction with the resolved processed (often referred to as “grey zone” problem), the problems of non-resolved processes and of imperfect initial and boundary conditions, and possibly other reasons; in particular, the chaotic character of convective-scale systems with rapid error growth of small scale structures is an important reason for very limited predictability, and entail with it the need for more attention to improve small-scale analysis and the representation of its uncertainty
- an ensemble prediction system provides a tool to **quantify 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.

That should be linked, however, with general model enhancement including reduction of its errors and especially biases (resulting e.g. from the ‘grey zone’ effects) as well as improved analyses.

The COSMO strategy is, therefore:

---

[2] For convection permitting ensemble systems the highest possible resolution would still need to take into account available computer resources; with this a deterministic run at yet higher resolution (for sub-kilometre mesh-size) can be used, as is anticipated within chapter 4.1 of the current Science Plan.

- to develop an **ensemble** prediction system **for the convective scale** allowing for **probabilistic forecasts and warnings**, especially for the high impact weather.

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 both for deterministic forecasts and the convective-scale ensemble prediction systems at the convective scale
- to develop the data assimilation system such that it is **computationally efficient 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, data related to humidity and weather parameters, and to the surface.

4.2.3 Robust dynamical core for the convective scale

There is a need for a dynamical core allowing for the robust representation of vigorous convective processes as well as of the influence of complicated (steep) orography which with O(1km) horizontal grid size well reflects the natural high steepness of mountain slopes. Following COSMO and ICON experiences the strategy is:

- to develop and implement a dynamical core of high accuracy and stability which exhibits **basic conservative properties**, at least of mass conservation
- to focus on the ICON dynamical core meeting such requirements and assess its practical capabilities against COSMO-supported benchmarks (COSMO models employing Runge-Kutta and EULAG dynamical cores).

4.2.4 Subgrid-scale physical parameterisations for the convective scale

The convective-scale resolutions pose a challenge for physical parameterisations of sub-scale processes, as most of currently available parameterisation schemes were developed for models with parameterised deep convective processes. The current strategy is:

- to develop and implement the physical parameterisations of atmospheric processes for subscales within so called ‘grey zones’ of convective and turbulence processes with the aim of a single, **scale-adaptive** convection scheme interacting with turbulence
- to reflect, where possible, the 3-dimensional nature of subgrid-scale atmospheric processes
- to develop further surface/soil model allowing for sufficient representation of surface properties and their variability within O(1km) horizontal scales and sub-scales to allow for adequate representation of interactions between surface and atmosphere,

with focus on water budget, surface energy budget, snow properties, application of stochastic approach within TERRA model

- to unify the COSMO and ICON physics packages to create synergies and facilitate realization of COSMO strategy to harmonize with ICON.

4.2.5 Extension of environmental prediction capabilities

The **extension of the environmental assimilation and modelling capabilities** allows for further improvement of meteorological forecast and for environmental information important or crucial for increasing number of users. The COSMO strategy is:

- to more widely use and develop further **additional prognostic variables and equations** (e.g. number density for microphysics scheme, turbulent potential energy for turbulence scheme, trace gases and aerosols for chemistry and radiation schemes), e.g. to facilitate the prediction of new parameters (e.g. aerosols for visibility forecasts)
- 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).

The extension of the environmental prediction capabilities of the COSMO model is closely related to the primary goal of the COSMO-ART community which provides prognostic tools for atmospheric chemistry and aerosols (see chapter 12.2). Development work in this field is therefore done in very close collaboration with COSMO-ART.

4.2.6 Verification and validation system for the convective scale

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

- to develop further the **verification tool** suitable for the validation and 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, it needs to provide the necessary methods to identify the relevant skill of convection-permitting and near convection-resolving model configurations as well to assess the performance for high-impact weather through suitable metrics
- to develop further the tool for diagnostics and scientific verification in order to develop further and improve the model; in particular to enhance collaboration between key stakeholders to arrive at a common understanding of how to address model deficiencies

- 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, LES mode** or of any **standalone module of COSMO** (e.g. the soil model).

4.2.7 Use of massively parallel and heterogeneous computer architectures

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, GPU) of different type (heterogeneous architectures). Due to the non-parallelised nature of many applications performing time integrations, the increase in *sustained* computing power is not straightforward to achieve. **The already started adaptation of the COSMO code for efficient use of these new architectures needs to be continued.** The COSMO strategy is:

- to continue adapting the COSMO and adapt the ICON models for emerging and future high-performance computing architectures
- to provide for an appropriate coding paradigm allowing for flexible use of high performance computing (HPC) computer architectures while retaining a high level of transparency of the code for current and future productive developments by the domain scientists**.**

4.2.8 Intermediate resolution COSMO version

While the consortium strategy explicitly focuses on the model developments for convection-permitting resolutions, there is still a need to support a deep convection parameterisation for COSMO runs with larger (intermediate) resolutions. This will still be used in deterministic mode by at least some of the COSMO partners (e.g. Russian Federation), strategic partners like COSMO-CLM and at least some licences. Of course, parameterisation of deep convection is indispensable for the ICON model and hence in the common COSMO/ICON physics package. Thus for a longer term, we try to proceed towards a scale adaptive convection scheme valid for all the possible model resolutions. Also the EPS mode of the intermediate COSMO will be supported for the time being to serve as the benchmark for the developed convective-scale EPS systems as well as the test bed for the research on their perturbation strategies.

4.2.9 Intensified collaboration

The intensified scientific collaboration within the consortium and between the consortium and outside world is considered vital to attain the COSMO goal. The COSMO experiences show that especially intensive collaboration between COSMO partners and academic/research institutions within their countries results in fruitful developments which otherwise would not be possible. With this the strategy is:

- **intensify the collaboration within COSMO**

- **intensify the collaboration with academic/research institutions, especially on national levels**
- increase **visibility** through peer-reviewed publications, conference contributions, and representation in international projects and committees
- joint application for external **funding at the European level**
- actively invite **external reviews**
- strengthen the collaboration with **COSMO-CLM, COSMO-ART** and **ICON** developers as well as the exchange with **academia**
- cooperate more closely with the other consortia in the framework of the EUMETNET **C-SRNWP** programme
- cooperate more closely with ECMWF, e.g. on application of new computer architectures, data structures and model setups.

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 fundamental assumptions underlying currently used schemes are no longer valid at very high resolution
- a consistent description of various subgrid scale processes is desirable to target appropriate processes and scales, e.g. description of turbulence and shallow convection for convection-permitting scales
- 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:

- strongly flow-dependent and unknown balance, non-linear processes and non-Gaussianity of probability densities, and limited predictability of the small scales and their interaction with larger scales pose problems for data assimilation which are particularly prominent at the convective scale. This calls e.g. for a strong use of ensembles in the data assimilation system. Also, model errors may be more pre-dominant at small scales and have to be accounted for
- several relatively new sources of high resolution atmospheric data (e.g. radar, GNSS (Global Navigation Satellite System) slant path delay, aircraft Mode-S, cloudy radiances) are particularly attractive for data assimilation at the convective scale. However, the use of those data might pose new problems as they often have correlated errors and nonlinear observation operators, are non-local, and/or are related to model variables and processes with significant model error. The resulting observation increments often have non-Gaussian distributions.

Predictability and EPS:

- what is the best way of generating perturbations for a limited-area ensemble prediction system at the convective scale?
- how high should be the resolution of the convection-permitting ensembles, on the basis of our understanding of the predictability limits?
- what is the relative importance of perturbations to BCs, ICs, model physics, lower boundary?
- Translation of EPS output into new useful probabilistic products (in particular, more reliable forecast for high impact weather).

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 spatial, neighbourhood and object-based verification) need to be introduced, tested, and agreed upon.

Computational aspects:

- with massively parallel and shared memory computers of increasing capacities and of architectures evolving toward GPU and hybrid ones, the programming strategy is needed to ensure flexibility of the model code for varying architectures and its clarity for efficient development by domain scientists.

The overall challenge for COSMO is to **translate the strategic elements** (see chapter 4.2) defined to reach the COSMO goal (see chapter 4.1) as well as the **research issues** connected to the development of a model-system at the convective-scale into specific short-term, long-term and perspective **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
- (local) conservation properties
- fulfil so called mimetic properties
- efficiency.

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

- what is an adequate level of approximations for the dynamical core?
- 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. One popular answer for the first question is to use the non-hydrostatic, compressible Euler equations. However, at least for the mesoscale, this answer is not shared by all the scientists working in the field. On the global scale the shift from spectral models to grid point models, which are considered more efficient 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.

A large family of discretisation schemes to achieve the 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), mainly because they are able to correctly treat shocks and other discontinuities by explicitly profiting from the local conservation form of the equations. In principle, FV-methods can also be applied to unstructured grids, however, higher order methods are difficult to achieve and computationally expensive. They are increasingly applied in global and also in regional atmospheric modelling, too. 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 with a FV solver.

Currently discontinuous Galerkin (DG) methods are a synthesis of FV- and FE-methods and promise a good combination of accuracy and conservation properties and can also be applied on unstructured grids. However, their application in meteorological models has just started.

Further properties of the dynamical core like well-balancing, i.e. no or at least reduced spurious artificial vorticity generation by imbalanced pressure terms or Coriolis terms, or kinetic energy conservation in the appropriate part of the momentum equations are also of importance. These ‘mimetic properties’ (see e.g. Thuburn and Cotter 2012) are a valuable wish list for the development of dynamical cores and are broadly investigated in the ‘Gung-Ho’ project initiated by the UK MetOffice. They should be investigated in all future dynamical core developments for COSMO, too.

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 down to about 1 km (around the year 2015) or even to 500 m (around 2020) for operational weather forecasts. At these high resolutions, at least two problems arise:

First, the explicit (but still insufficiently accurate) simulation of deep moist convection by the high resolution model applications (grid length below 3 km) probably 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 quite a 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 lies in the current dynamical core, in which 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-split tracer advection can induce 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-Lagrangian 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-Lagrangian 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 (see 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-Lagrangian methods formulated for volume transport can be conservative at least for 2D (horizontal) transport by using an appropriate 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, which are implemented in the ICON model, suffer less from the above mentioned splitting instability and inaccuracy.

Finally, the traditional distinction between tracer advection and the dynamical core would need to be abandoned for the present dynamical core 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) (see also interdisciplinary chapter 11.1 about 3D turbulence).

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 inverse 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) disturbs 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 not difficult in principle, some technical adaptations of the code will be necessary.

5.2 Strategy of COSMO and actions proposed

5.2.1 Further maintenance of the RK dynamical core

Status and expertise within COSMO

The current dynamical core of COSMO is based on time-splitting using a 3rd order Runge-Kutta scheme (Wicker and Skamarock 2002). During the recent years, a thorough revision of the fast-waves solver has been done, resulting in its complete redesign (Baldauf 2013). The new development contains:

- the proper weightings due to the vertical grid stretching in all (explicit and implicit) vertical discretisations
- the use of the divergence operator in so called ‘strong conservation form’
- the option to use the 3-dimensional isotropic divergence damping instead of the current quasi-2D form
- the option to use the Mahrer (1984) discretisation for the horizontal pressure gradient
- several smaller changes concerning the lower boundary condition, stability improvements of the divergence damping, etc.

This new fast waves solver is in operational use since January 2013 at DWD and currently under inspection by MeteoSwiss for their planned 1 km version.

Additionally, higher order schemes (4th order centred) in the horizontal discretisations of the fast waves terms on the one hand and a kinetic energy conserving discretisation of the advection terms based on Morinishi et al. (1998) on the other hand is under development at the University of Cottbus. First test runs in a climate setup have been done successfully.

Actions proposed

The ability to use the COSMO dynamical core in steep terrain should be further improved. Therefore, the ‘Mahrer-option’ in the new fast waves solver shall be further investigated and improved. Whereas the main implementation of the vertical pressure interpolation is done and works stable in real case simulations, there are some deficiencies concerning the lower boundary treatment. As pointed out in Zängl (2012) the not completely satisfying treatment of the lower boundary in Mahrer (1984) is the main reason why this method is less frequently used than expected. Unfortunately, due to the use of the divergence damping, the method proposed in Zängl (2012) can not be used directly in COSMO and another approach should be found.

The 3D divergence damping has definitely better dispersion properties (Baldauf et al. 2013, chapter 7) compared to the current version, but is more time consuming. The pros and cons of the 3D version should be further investigated.

The Morinishi et al. (1998)-approach will be further investigated. Since for the advection scheme of the dynamic variables, no longer a 5th order upwind scheme but a centred difference scheme is proposed, another Runge-Kutta time integration scheme might be advantageous (Baldauf 2008). Furthermore, it should be clarified if this concept is consistent with an improvement done recently in the temperature advection to prevent the model from generating ‘hot chimneys’ over mountains.

Further measurements for the current version are a general efficiency increase for cache based architectures and the implementation of additional vertical weightings outside of the fast waves solver.

The possibility of variable time steps will also increase the efficiency of the whole model. Finally the option for a horizontal grid stretching (separately for x- and y-direction as in the ‘Unified Model’ of the UK Met Office) allows a more flexible nesting of small scale models into larger scale driving models (e.g. IFS).

A code rewrite of the new fast waves solver with the stencil library STELLA (developed in WG6) must be written to allow the model to also run on graphical processor units (GPU’s).

The maintenance of the RK core (i.e. the first three paragraphs above) has high priority, since it will probably still be used during the next few years. The same holds for the code rewrite with the stencil library because some weather services might change their computer architecture in the next few years.

Resources required

Total amount of resources required is about 2 FTE including 1 FTE for the Morinishi et al. (1998) approach (done at Univ. Cottbus).

Expected outcome

A further stability improvement in steep terrain is expected. Higher order discretisations have potential benefits on the accuracy of the dynamical core. The code more efficient and usable on different computer architectures.

Risk Assessment

The current version of the new fast waves solver seems to be sufficiently stable for the COSMO 1km runs at MeteoSwiss, i.e. even in the steep Alpine region. Therefore, a further improvement of the Mahrer (1984) approach is welcome but not absolutely necessary.

5.2.2 COSMO-EULAG operationalisation

Status and expertise within COSMO

The current COSMO model does not have any explicit conservation properties concerning the dynamical variables mass, momentum or energy, neither with the old Leapfrog nor with the current Runge-Kutta based integration scheme. Local conservation of these variables is one of the fundamental guiding principles in the development of dynamical cores in many 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 and also the numerical scheme is locally conserving. In meteorology, shocks play a minor role, and the answer, which variables should be conserved is less obvious. Thuburn (2008) argues that mass conservation (total and all tracers) are very important, probably also energy. On the global scale momentum conservation plays only a minor role, but it surely has increasing importance when going to smaller scales. By the way, this latter fact could be an argument to develop different flavours of dynamical cores for global and limited area models (which contradicts of course the goal of developing 'unified models')

The lack of conservation of all the dynamic variables (total mass, energy, momentum) in the current COSMO model has led to the initiation of the Priority Project "Conservative Dynamical Core" (CDC) during the years 2009-2012 (Baldauf et al. 2013, Kurowski et al. 2011, Rosa et al. 2011, Ziemianski et al. 2011); see also http://www.cosmo-model.org/content/tasks/pastProjects/cdc/default.htm). During this project, the dynamical core of the EULAG model (see e.g. Grabowski and Smolarkiewicz 2002) was implemented into COSMO and it was concluded that with the available staff resources, it is most promising to further develop this branch of the project. This has led to the definition of a follow-up Priority Project "COSMO-EULAG Operationalization" (CELO) (see PP CELO project plan by Z. Piotrowski http://www.cosmo-model.org/content/tasks/priorityProjects/celo/default.htm).

The EULAG model solves an anelastic set of conservation equations. For the prognostic equations and the associated divergence operations a finite-volume solver mainly based on the MPDATA scheme is used. A further numerical advantage is the use of implicit solvers which are well established for these types of equations. In particular, this allows a stable integration of all metric terms of the terrain-following coordinate system. Consequently, the EULAG model is stable also in very steep terrain.

Actions proposed

Essentially, a consolidation of the EULAG dynamical core formulation for NWP applications is necessary. An optimal way of adjusting the flow at the boundaries to satisfy the integrability condition (divergence free flow) must be found. The hybrid coordinate of COSMO should be possible to use, while retaining the important tensor identities of EULAG. Full pressure recovery is needed, which is not an easy task in an anelastic model. Furthermore, an increase of efficiency of the elliptic solver is needed, mainly by improving the preconditioner and by a possible reduction of global communications.

Apart from that, more technical improvements on the coding side are necessary to better adapt to the possibilities/requirements of COSMO applications as e.g. a more flexible domain decomposition and the possibility of using restart files. A code rewrite by the stencil library should be done to be able to run COSMO-EULAG on GPU's, too.

All of these actions have high priority because it is planned to introduce COSMO-EULAG operationally around the second half of the decade.

For the future, a collaboration with the PantaRhei project at ECMWF could be of interest: one goal of this project is to further develop the compressible version of EULAG. This could be a candidate for a follow up priority project.

Resources required

In total about 10 FTE according to the CELO project plan, possibly 1 FTE by the Poznan Supercomputing centre.

Expected outcome

An anelastic, finite volume semi-implicit dynamical core (EULAG) is available in COSMO and all necessary parameterisations are tuned for NWP and climate applications.

Risk Assessment

This relatively large project depends on the availability of the well trained people at IMGW-PIB. Some of the above mentioned tasks (e.g. pressure recovery) are not straightforward, nevertheless the current results are very encouraging.

5.2.3 Investigation in new Euler solvers based on Finite volume schemes

Status and expertise within COSMO

As mentioned in section 5.2.2, locally conserving, finite-volume based discretisation schemes are attractive candidates for future dynamical cores. Apart from the EULAG solver, a solver based on a fully implicit dual time-stepping scheme proposed by Jameson (1991) was investigated in the PP CDC (see chapter 8 in Baldauf et al. 2013). This solver is still in the state of a toy model, but several idealized standard test cases have been simulated successfully.

In the framework of the Deutsche Forschungsgemeinschaft'-program 'Metström' a new dynamical core in COSMO is under development which is based on the Discontinuous Galerkin discretisation (see e.g. Cockburn 2003). This method both provides local conservation and a higher convergence order. Further advantages are the possibility to use it relatively easily on unstructured meshes and, due to the compact stencil, on massively parallel computer architectures. Currently a version based on the local DG (LDG) scheme is implemented in COSMO and coupling with the physics parameterisations is undertaken. Nevertheless, still a purely explicit solver is used and therefore it is far from being competitive regarding efficiency. Therefore, at least a vertically implicit scheme is needed. Furthermore, if these methods are applied to tracer advection, monotonic and positive definite schemes are needed, i.e. appropriate flux limiters must be found. The easy use of unstructured grids makes DG an interesting candidate to collaborate with European groups developing grid generation frameworks like the Atlas project at ECMWF.

This development is basic research. A useable version is not to be expected in the next few years.

Due to the more exploratory character of these actions, their priority is lower than for the previously described tasks/projects.

Actions proposed

The work on both solvers should be continued.

Resources required

At least 3 FTE to implement the fully implicit solver in COSMO (partially done at CIRA/Italy). At least 3 FTE to continue physics coupling and to enhance efficiency of the DG/LDG scheme by using a vertically implicit time integration scheme.

Expected outcome

Alternative locally conserving solvers will be available based on the compressible, non-hydrostatic equations. The fully implicit solver promises to be stable in very steep terrain, too. The DG solver might be an interesting alternative in the future unstructured grid model ICON.

Risk Assessment

Both schemes have been at first developed in other fluid dynamic communities and therefore for other purposes than NWP. It is not yet clear, if the current drawbacks in efficiency (in comparison with our current solvers) can be solved.

Additionally, a problem concerns staff resources (e.g. the Metström project ended at Q3/2014).

5.2.4 Tracer advection schemes

Status and expertise within COSMO

Currently there exist two tracer advection schemes in COSMO. The Bott (1989) finite-volume scheme is the preferred advection scheme because it is (nearly) mass conserving. The 3rd order classical Semi-Lagrangian scheme is not mass-conserving and occasionally produces strong peaks in precipitation, which do not occur with the Bott-scheme. Otherwise, the Semi-Lagrangian scheme as a fully (non-split) 3D-scheme turns out to be quite stable in steep terrain, whereas the Bott-scheme (formulated as a direction split scheme) has slight stability problems in complex terrain. The latter drawback could be improved by using Strang splitting, however, this enhances the computation time of the advection scheme alone by about 60%. Semi-Lagrangian schemes might be computationally advantageous in the case of many tracers because the calculation of the backward trajectory must be done only once.

Actions proposed

Recently new ideas to improve the splitting in the Bott-scheme arose (Bott 2010) and have been implemented into COSMO at the University of Bonn. This new approach does not seem to need the Strang splitting and therefore reduces the computation time. Further investigation of its stability in steeper and complex terrain is needed.

Furthermore, an improvement of its efficiency on other computers (e.g. vector computers) might be necessary.

In Kaas (2008) a method to generate local conservation for a given classical (i.e. non-conserving) Semi-Lagrangian scheme is proposed. Regarding the robustness and the positive efficiency aspects in aerosol/chemistry simulations this path should also be followed. However, a problem could be to additionally fulfil tracer consistency with this scheme.

Up to now an unofficial 2D-version of MPDATA in COSMO as a third advection scheme might be improved to act as a full 3D scheme.

Of course, these new implementations must properly interact with the new tracer module used in the COSMO model (Roches and Fuhrer 2012).

<u>Resources required</u>

In total about 1.2 FTE are required including involvement of academia for the Bott (2010) approach (probably done at University Bonn) and the Kaas (2008) approach (possibly done at EMPA/CH).

<u>Expected outcome</u>

More stable and more computationally efficient tracer advection schemes.

<u>Risk assessment</u>

Since on the one hand the development effort is rather small and on the other hand our current schemes are satisfyingly working, the risks are relatively low.

5.2.5 Other tasks

Status and expertise within COSMO

For the application of COSMO in the 1 km or sub-km range, 3D turbulence seems to be necessary (see an interdisciplinary chapter 11.1 about 3D turbulence, too). It has been found that the current formulation of the metric terms in terrain-following coordinates suffers from stability problems in very steep terrain (Baldauf 2005 and 2006). Therefore, a z-coordinate discretisation of these terms has been developed at MeteoSwiss.

One cause of such stability problems in complex terrain is a too narrow level spacing near the bottom. Beyond, the vertical resolution and level distribution have an important impact on the model accuracy. Currently ongoing work in COSMO to increase horizontal and vertical resolution should be better coordinated in this respect. E.g. the influence of the boundary layer level spacing influence on convection initiation or boundary layer top heights should be investigated.

The upper boundary condition (rigid lid) causes problems under some circumstances and should be replaced by a better condition. Alternatively, one might simply increase the model top height. It is not yet clear if this can be done easily.

Actions proposed

Further development of the ‘z-diffusion’. It is not entirely clear how to treat this z-diffusion at the lower boundary.

Testing of COSMO with higher model top. Possible problems may arise from parameterisations.

To assess as objectively as possible the different above mentioned dynamical core developments, a dynamical core test suite should be installed. A starting point is the ‘decision tree’ developed during the PP CDC.

Resources required

About 1.5 FTE are required including support of academia for the installation of a dynamical core test suite (done at University Cottbus).

Expected outcome

The numerical requirements to run 3D diffusion in steep terrain are fulfilled. A model version for the use until H_top ~ 60 km is available. A dynamical core test suite is available and delivered together with the official COSMO code.

Risk Assessment

If the current ideas for a 3D turbulence scheme do not work, there is a remedy to simply limit horizontal diffusion coefficients. However, this is not a physically satisfying approach.

5.2.6 Transition to the new model ICON

Status and expertise within COSMO

The ICOsahedral Non-hydrostatic global model (ICON) is a joint development between DWD and the Max-Planck-institute for Meteorology in Hamburg. It went into operational usage (and therefore replaced GME) at DWD in January 2015. The limited-area mode of ICON will become available in the course of the year 2017 thanks to efforts in the German HD(CP)² project. It is planned to use the regional mode of ICON also for the convective-scale applications around 2020.

Actions proposed

After the availability of the regional mode of ICON, an extensive testing of the dynamical core of ICON and a comparison with the COSMO version should be done regarding accuracy, stability and efficiency according to the methodology developed in the COSMO dynamical core test suite (see chapter 5.2.5). This will probably be organised within a Priority Task. Such a PT might be reasonably installed after the finishing of PP CELO (at 03/2016) and starting with a kick off meeting. The main deliverable of such a PT is the recommendation (or not) to replace COSMO by ICON or if serious improvements of ICON are necessary for the regional mode. One important issue could be to closer inspect the boundary treatment in ICON regional mode. ICON uses an unstructured grid with triangles as base elements. Perhaps a version using a quadrilateral grid (but still using the unstructured grid framework) is better suited for a LAM. For such further developments of the ICON core it could be beneficial to use common grid generating and grid optimization libraries. An example for this is the ATLAS library under development at ECMWF for their future global model which promises to offer high flexibility and a relatively easy to use interface. This testing and the adaptation of ICON is also a longer term action and its priority will increase around

2018-2020. The overall evaluation (i.e. not only of the dynamical core) will be the subject of a larger Priority Project.

Resources required

5 FTE for extensive testing preferably distributed over several institutions to collect experience with the new model. 1 FTE for a quadrilateral version (possibly by HD(CP)² project).

Expected outcome

A unified model from global scale down to mesoscale and even for LES applications is available.

Risk Assessment

The risks are relatively low for the COSMO community because the existing COSMO could be used for a longer time.

5.2.7 Summary of expected FTEs

FTEs for main priority actions for period 2015-2017		FTEs for secondary priority actions for period 2015-2017	
To be provided by COSMO partners - Already secured: - Potentially available: - Missing:	16 1 0	To be provided by COSMO partners - Already secured: - Potentially available: - Missing	0 0 3
To be provided by academia - Already secured: - Potentially available: - Missing:	0.5 3 0	To be provided by academia - Already secured: - Potentially available: - Missing:	0 4.2 0
All secured and potentially available	20.5	All secured and potentially available	4.2
All missing	0	All missing	3
Total required	20.5	Total required	7.2

6 Physics

Author: Matthias Raschendorfer (DWD)

General aspects

Model physics represent a major challenge in achieving the principal goal of COSMO to provide final users with skilful operational products at the top end of NWP model (vertical and horizontal) resolution by focusing on short to very short range forecasts with very high **convective-scale resolution**. This is true, since many of so far applied assumptions in this field are only valid for much coarser horizontal resolution. Hence some familiar concepts need to be changed or at least extended. The new concepts should on the one hand serve the universal goal to end up with more general valid and self-consistent formulations that are valid for arbitrary model resolutions. In that sense we want to set up a common physical package for COSMO and ICON. To be prepared for **special applications** (e.g. such as COSMO-ART or COSMO-CLM) and in order to provide working tools or reference versions for further development in that package, it might also be necessary to maintain schemes of different complexity for the same process. Finally we are trying to adapt our model in order to better provide **important key sectors of customers** (like aviation, renewable energy exploitation and water management) with specific and further improved products. This includes also the task to **remove well known and persistent systematic errors** that have become evident, e.g. within the Boundary Layer (BL), in particular the Stable BL (SBL).

The functionality of model physics is **closing the set of discretised model equations** in terms of considered model variables by means of some additional equations, which are beyond those being solved in the dynamical core (see chapter 5.1 about dynamics) and which always involve the introduction of (physical) parameters. Since the new challenges for that task are rather manifold and come along with a revision of some basic concepts, we try to find an ordering strategy along this general functionality. For that purpose we first of all discriminate the closing procedure into “local” and “grid scale” (GS) **Parameterisations** (PMs) respectively:

Local PMs represent all contributions that in principle are also present for arbitrary high (local) model resolution. These are (apart from molecular diffusion) expressions of various diabatic source terms due to “**Cloud Microphysics**” (CM) or “**Radiation Transfer**” (RT). Since the corresponding equations can be based on general valid physical principles, the involved parameters should be general valid natural constants, unless simplifications have been introduced. However, the reduction of complexity can’t be avoided, not at least due limited computer power.

In contrast, **GS PMs** are the consequence of finite model resolution in combination with the non-linearity of the so far closed model equations, since numerical operations can only be applied to model equations that have been appropriately **filtered with respect to space**, in order to avoid significant “**discretisation errors**”. The various “**statistical moments of model variables**”, which appear in the resulting (so called) “**1st order equations**”, represent the impact of **“sub grid scale” (SGS) processes** on GS variables and can only be described by the introduction of **additional constraints** that are beyond the first principles. Thus GS PMs can only be valid (that means the involved parameters can only be constant) under **certain conditions**. The more the properties of SGS processes differ, the more distinct (and very likely even incompatible) might be the necessary **Closure Assumptions** (CAs). Hence we traditionally discriminate at least two SGS classes: “**turbulence**” and “**convection**”.

Finally, also the SGS topographic structure of the non-atmospheric (lower) model boundary, usually called “**roughness of the (natural) surface**”, influences the evolution of GS model variables. The impact of these structures is restricted to the **Roughness Layer** (RL), which is the lower part of the BL, where spatial differentiation and the filter operator (associated to the numerical discretisation) are no longer commutable. This causes additional **RL-terms** in the discretised model equations, which are present in the higher order equations as well. Moreover close to the lower boundary, discretisation errors arise due to strong curvature of (vertical) near-surface profiles and restricted **vertical** resolution. Their treatment is the field of **Surface-to-Atmosphere Transfer** (SAT), which contains the effect of the vertically **not** resolved lowest part of the RL as well. Although these kinds of PMs belong to GS PMs as well, they employ special **external parameters** (somehow related to characteristics of the SGS surface structure and thus dependent on the location within the model domain). In contrast, all the other parameters are **internal parameters**, which are globally defined.

A special class of parameterisations are those providing the values of model variables at the atmospheric boundary by including some physical simulation of the **non-atmospheric body** close to the atmosphere (soil, plants, buildings, water, snow or ice), which again needs to be expressed by means of proper external and internal parameters.

Future challenges

For the scope of this science plan we are aware of the following general challenges:

i) Better consideration of **SGS contributions to non-linear local PMs** and of **source term contributions to GS PMs**, which both express interactions between the two regimes of PMs.

ii) Better representation of interdependencies between local PMs (**cloud-radiation feedback**).

iii) Expression of missing **interactions** between GS PMs representing different scales of SGS variability.

iv) Removal of **various types of inconsistency** and **some hidden numerical artefacts**.

Although the aimed (partly) convection permitting model resolution offers the neglect of some GS PMs (above all that for deep convection), the following special challenges (apart from serious **numerical problems with steep orography**) arise just as a consequence:

v) Formulation of **scale adaptive PM schemes** that can contribute only for the actually SGS part of a process, since there exists no general scale separation at the aimed horizontal grid scales. This applies in particular to the PM of convection in order to avoid “**double counting**” of the already resolved part of convection or convection-like turbulence.

vi) Introduction of **3D-aspects**, because smaller horizontal grid scales do not tolerate for the application of the **Horizontal BL Approximation** (HBLA) any longer, which implies the neglect of horizontal gradients and vertical wind speed, and has led to simple Single (vertical) Column (SC) schemes for turbulence or RT, as well as to the currently used mass flux schemes for convection.

vii) An increased horizontal resolution calls also for an increased vertical resolution close to the lower boundary, and the RL formed by larger scale land use patterns is no longer restricted to a small part of the lowest model layer. Rather we have to deal with a **Vertically Resolved RL** (VRRL) causing RL-terms in a couple of the lowest model layers, which may represent the vertical structure within a city (urban layers) or within a plant population like a forest (canopy layers).

Some further aspects of atmospheric physics are connected with **cross-cutting issues** (see also the related chapters 11.1 to 11.3):

viii) Setting up a **common physical package** that can be used in both, the current COSMO model and the **new ICON model** in the framework of the aimed “COSMO-to-ICON migration”. Since the latter will be used as a global model with a sequence of higher resolved nests, the contained PM schemes need to be prepared for **multi-resolution applications**. This however emphasizes the requirement of rather generally valid, scale adaptive PMs even more. For lack of perfect schemes and in order to facilitate different levels of sophistication (and computational expense), the common package may absolutely form “multi-scheme ensembles” of single PMs, which can also be used for ensemble forecasts.

ix) **Improving model diagnostics** and developing methods of an **objective determination of optimal parameter values**. In the long run we’re thinking also about a kind of **statistical hyper-PM**, in order to remove the remaining dependency of model parameters on the model state, what always is a characteristic of incomplete physical PM schemes (see chapter 11.2 about ”Processing verification feedback on model development”).

x) Since very likely, there always will remain some uncertainty in the PMs at the very end, **stochastic model extensions** are being developed, which try to treat model uncertainty with respect to PMs as a stochastic process by running parts of the model for a number of realizations (see also the cross-cutting chapter 11.3 about ”Stochastic Physics”).

xi) Optimization of the code with respect to computational expense to enable the operation of more complex schemes.

Extramural collaboration

Collaboration with universities and research institutes as well as with other NWP and climate modelling groups is required and mostly already initiated for almost all fields of PMs: e.g. with subject area “Clouds and Convection” at Hans-Ertel-Zentrum: HERZ-CC and university of Hamburg [CM, RT, turbulence]; universities of Bologna [turbulence and SAT], Bonn and Munich [convection, radiation], Frankfurt [still open], Hannover [turbulence], Zurich [turbulence, convection] or Leuven [urbanisation]; Karlsruhe Institute of Technology: KIT [CM, radiation].

Explanation of abbreviations

The following abbreviations are used as (or related with) attributes of planned activities:

application: application research (assessing the impact of a scheme including parameter optimization)

exploratory: exploratory research (deep investigation, reformulation or new setup of a scheme)

basic: basic research (fundamental research and design of a new scheme)

consistency: increasing consistency

scale_adaptivity: enables scale adaptivity

convection_initiation: affects initiation of convection

roughness_surface: improves roughness and surface layer simulation

precipitation: contributes to simulated amount of precipitation

cloud_radiation_coupling: improving the cloud radiation coupling

P1: main priority (high benefit expected or precondition for further important tasks

P2: secondary priority (important but not time critical)

Crude estimates of necessary human resources are given for each of the two action categories “short-term” and “long-term”. The third category “perspective” denotes activities, which always require some basic research, so that their duration typically can’t be estimated yet, although they should also start as soon as possible.

6.1 Parameterisations of SGS processes (GS parameterisations)

6.1.1 General remarks

In the following we discriminate between two truncation frameworks that can be applied in order to introduce the closure assumptions of GS PMs somehow systematically. Due to the truncation however, GS PMs necessarily can’t be general valid (closure dilemma):

One of these frameworks is “**Higher Order Closure (HOC)**”, based on the set of budget_equations for all additional statistical moments, which however always contain additional moments of the same order and higher order moments (expressing the closure dilemma) and needs to be truncated by approximations that usually are as better valid as smaller are the spatial scales of variability. They also allow for reducing the maximal considered order of statistical moments. As in other NWP models, we use HOC for turbulence closure and restrict to equations for the 2nd order moments (**2nd order closure**), since closure of even higher order is extremely more expensive. But also 1st order closure schemes with ad hoc PMs of statistical moments in the 1st order equations are still used in NWP.

Another framework may be called "**Conditional Domain Closure (CDC)**" and is based on budget equations for **conditional averages** (e.g. according to classes of vertical velocity) of model variables (and equations for the related volume fractions), which can be used to compose statistical moments of the resulting flow patterns. Truncation is mainly introduced by limitations of the internal variability of considered classes and by the adoption of some GS properties for each conditional class. The mass flux equations, employed in current convection schemes are along this line (**mass flux closure**).

The closure of RL-terms requires the application of idealized assumptions about the surface roughness and its interaction with the flow. Dependent on the definition of the vertical coordinate used to resolve the SGS RL there can be discriminated two concepts: One is based on model layers without SGS slopes that are intersected by the roughness elements (sometimes called the porous medium approach) and the other assumes model layers without intersections that follow an idealized SGS topography (including the land use roughness), resulting in a **Generalized BL Approximation** (GBLA).

The following chapter 6.1.2 is dedicated to describe some (so far missing) integrating concepts on a higher level and is related to all the subsequent chapters of this paragraph (and in some aspects even to 6.3.1 and 6.3.4).

6.1.2 Performing a consistent separation of GS parameterisations

State of the art, scientific developments

In general, SGS flow patterns cover a large range of scales (**multi scale problem**). Thus in any of the above mentioned frameworks, a way out of the closure dilemma can only be a procedure offering a "**separation**" of SGS variability into classes, such that each of them is in accordance with specific closure assumptions. As usual, also the current separation in COSMO is according to some idealized characteristics of scale ranges within one or the other of the above frameworks. Specific PMs for the following SGS regimes are either available or at least taken into account to some extent: These are **small scale quasi isotropic turbulence** (being dependent only on a single length scale parameter and matching quite well to HOC truncation conditions), **larger scale non turbulent arbitrary anisotropic "circulations"** (being dependent on several length scales and matching quite well to CDC truncation conditions) and **wave patterns**, which however do not contribute significantly (at least to SGS mixing), unless the waves are braking. Circulations can be divided into some more sub classes, like **"deep and shallow" convection**, **ana- and katabatic density currents** and eddies produced by various pressure forces (such as **wake eddies** due to form drag of obstacles, **breaking gravity wave patterns** and **separated horizontal shear eddies** (dependent on horizontal grid scale rather than isotropic turbulent length scale). Although all these patterns are already somehow considered in COSMO, their representations are far from being complete and consistent, particularly with respect to **SGS interactions** (s. challenge iii), to a proper **inclusion of source terms** (s. challenge i), to **scale** adaptivity (s. challenge v) and to their **individual effects on diffusion** including the horizontal directions (s. challenge iv).

These inconsistencies are very likely the reason for serious and well known deficiencies. So, non-physical or even singular solutions of current turbulence schemes (occurring in particular for stable stratification) force the introduction of artificial **security measures** (like minimal diffusion coefficients) with their corresponding **security limits**. These problems can easily be related to missing interaction terms in the turbulence scheme; as the action of circulations always is connected with an additional shear production of turbulence, being not represented without that interaction. These unphysical security measures (and the causative missing physics) however lead to difficulties with the **diurnal cycle of near surface variables**, particularly, if **low level clouds or fog** are involved (s. also chapter 6.1.3). Others are e.g. a non-realistic **turbulent triggering of deep convection** or the disability to simulate **Clear Air Turbulence (CAT)**. On the other hand the so far missing limitation of mass-flux convection towards turbulent scales (s. also chapter 6.1.4) inhibits the introduction of interaction terms in the convection schemes and affords some **double counting** of intermediate scales. Missing direct (also horizontal) mixing by so far not even represented SGS circulations may also hamper a realistic implementation of **SGS 3D-transport** (see also chapter 6.1.3 and the cross-cutting chapter 11.1 about 3D-turbulence).

The realizations of separation are ranging from a pure non-interactive set (consisting of a HOC turbulence scheme and mass flux schemes for shallow and deep convection) up to quite enmeshed combinations. A rather elaborated (but computational by far too expensive) combined approach is the **Assumed Distribution Higher Order Closure** (ADHOC) formulation (Lappen and Randel 2009) using HOC-equations also for describing higher order moments of the pure convective (top-hat) distribution functions. A rather loose combination is present in the **Eddy-Diffusivity/Mass-Flux scheme** (EDMF, see e.g. Soares et al. 2004) by solving the implicit flux-gradient diffusion from turbulence and explicit mass flux diffusion from shallow convection within a common numerical framework.

The multi-scale problem becomes apparent also in connection with an **overall estimate of cloud cover** and other cloud properties, for which the superposition of all SGS processes needs to be considered. Apart from direct cloud cover PMs based on **relative humidity**, statistical cloud schemes based on local saturation equilibrium can be used. However, such a **“local saturation adjustment**” is dependent on properties of the employing **Probability Density Functions** (PDFs) of local oversaturation. While the PDF for turbulent fluctuations can be estimated quite easily, the overall PDF is also affected from convection (Tompkins 2005). As an alternative, also prognostic equations for cloud cover are postulated (see e.g. Köhler 2005).

As the depth of the RL is increasing with decreasing horizontal model resolution, the RL can be divided along a decomposition of surface roughness into horizontal scales, and it depends on the individual structure of the surface, what scales belong to the VRRL (s. above and challenge vii). However, usually the arising RL-terms are only considered as far as they are caused by “**SGS Orography**” (SSO), and related schemes provide only PMs of the friction due to associated form drag or gravity wave drag (resulting from the discretised pressure gradient), which affect the 1st order momentum budget only. RL-terms in the other 1st or even 2nd order budgets are typically not considered, not even the related **wake production terms** in the budget of SGS kinetic energy. According to a GBLA (s. chapter 6.1.1) a **separation of the various surface structures** is performed implicitly and treats all **land use patterns** including the vertically not resolved part where only the latter is still a matter of SAT (s. chapter 6.1.5).

Of course, this field is also closely related to the land-surface scheme (chapter 6.3.1), which has somehow to describe the influence of physical properties related to the interior of the non-atmospheric bodies on the atmospheric budget variable right at the body surfaces. A special problem at this very place is the treatment of roughness elements in contrast to the compact soil- ice- or water-body and their (radiative) interaction, which really is a cross-cutting issue sometimes called the "treatment of a **non-atmospheric canopy- or cover-layer**" (s. chapter 6.1.5 and 6.3.1). However, this issue needs to be separated from overall canopy models, which try to describe the whole surface-atmosphere coupling of a surface covered by vegetation or buildings in a bulk 1st order approach, already incorporating all aspects of the RL including SAT and turbulence. This kind of models can't be used for the concept of a VRRL employing the prognostic atmospheric model equations. In this sense, 'urbanization', for instance, is the application of the VRRL for urban areas.

Problems related with a missing VRRL are **unrealistic simulations of the biosphere** and the roughness layer of strongly structured terrain, which are a serious shortcoming of a high resolution circulation model that shall be used e.g. for local climate or air pollution simulations.

Status of development and expertise within COSMO

Since in future COSMO configurations, precipitating (deep) convection is expected to be a pure GS process, it seems to be possible to treat turbulence and remaining (at least shallow) convection (together often called "non-local turbulence") within a **single** HOC framework. We have developed an extension like this by introducing **prognostic equations for the Scalar Variances** (TKESV) within a past Priority Project Towards an Unified Turbulence-Shallow Convection Scheme (UTCS, see http://www.cosmo-model.org/content/tasks/pastProjects/utcs/default.htm), which is feasible with moderate additional computational effort. The approach is being described by D. Mironov (DWD) and has the characteristic to include turbulent transport of scalar (co-)variances. However, as long as non-equilibrium phase change processes (like those associated with the ice phase or precipitation products) are present or pronounced multi-scale or strongly non-isotropic SGS processes are active, this kind of extension should not be sufficient, since it is still based on a single-scale formulation (see also the chapter 6.1.3).

Therefore we have also been aiming to set up a more consistent formal separation between the GS PMs for turbulence and non-turbulent circulations. This approach facilitates the restricted application of turbulence approximations only to those (small) scales being in accordance with them. In this context, 'turbulence' is clearly defined by the employed closure assumptions, and the introduced separation automatically

generates additional interaction terms between turbulent and circulation scales mainly describing additional shear production of prameterised turbulence by means of the SGS circulation flows. The theoretical concept of this kind of **"Separated Turbulence Interacting with Circulations"** (STIC) is based on a cascade of at least two filters applied to the governing budget equations and is being described by M. Raschendorfer (DWD). According to STIC, non-turbulent SGS circulations belong to a band-pass filtered part of the SGS length scale spectrum, and they need to be described by specific closure equations, either based again on HOC or formulated along CDC. It is a particular consequence that turbulence can't be treated as a completely SGS and stochastic process any longer. Hence the typically employed **ensemble average** needs to be substituted by a **scale dependent filter operator** (e.g. a "moving volume average").

We have already introduced some **scale interaction terms** into our separated TKE equation associated to the action (shear production) of non-turbulent SGS flow patterns. One part of them is related to already active PMs, such as form-drag wakes or eddies from braking gravity waves in correspondence with our **SSO scheme**. Vertical circulations related to the current **mass flux convection schemes** belong to that part as well. On the other hand, we introduced some special PMs only for the scale interaction TKE-production due to **near surface density currents** and **separated horizontal shear eddies**. These latter PMs are based on a simple equilibrium between production of kinetic energy related to the SGS circulations and the scale transfer of that energy towards TKE. Although being formulated rather rudimentary for the time being, just these interaction terms allowed us to provide e.g. a better turbulence forecast for aviation purpose (nearly doubling the TSS-value) or to reduce security measures for the SBL in the turbulence scheme (s. above in this chapter). A main remaining deficiency is that the current mass flux scheme for convection does not yet contain any corresponding interaction terms from turbulence and that **cloud processes are not consistently treated** with respect to GS and SGS processes. In particular we use a **GS saturation adjustment** at the end of each time step, which partly destroys cloud water previously produced by SGS processes (turbulence and convection). Finally, both of these treatments are in contrast to the **diagnosed cloud properties** that are used as an input for the radiation scheme. For the latter we employ a crude estimate of cloud water and cloud cover due to SGS convection and a modified and tuned cloud diagnostics based on **relative humidity** (according Sundquist 1978) for the remaining grid-box fraction. According to STIC however, all source terms in 1st order budget equations should be the sum of contributions for all convective subdomains, upon which turbulent fluctuations are acting. Thus estimates of the **updraft- and downdraft- fractions** are necessary, which can be calculated by employing an evolution equation for skewness of convective distributions according to the ADHOC-scheme. However they should also be expressible by appropriately **modified mass flux equations**.

Finally the representation of a VRRL so far includes only the impact of the **terrain modes** of the SGS surface structure as formulated in the **SSO scheme** (Lotts/Miller 1997), which only affects the budgets of momentum and (via a related scale interaction term) of TKE. For the time being, the whole land-use part of the RL is treated (according to the concept of a "**lowered natural surface**") as a transfer-resistance for scalars only, which is calculated in the SAT scheme (s. chapter 6.1.5). A prepared revised GBLA (by M. Raschendorfer) is based on a spectral composition of an equivalent topographic surface with specific RL-parameters (like roughness length, or displacement height) for each spectral mode interval. This particularly allows for a separation between the VRRL and a small-scale RL still to be treated by the SAT scheme and promises to treat also larger scale land use roughness (composed e.g. by buildings or trees) as a part of the VRRL which causes RL-terms in all budget equations. Finally, also the related separated SGS flow structures (such as wakes) can be considered according to STIC. On the other hand, the urbanization in terms of adapted external parameters for the schemes of land-surface and SAT (also in relation with a surface tiling) has already started in cooperation with H. Wouters (KU Leuven, Belgium).

Strategy of COSMO and actions proposed

As a leading concept we aim to proceed along the scale separation approach (STIC). For that purpose and as a **short term priority**, existing PMs of scale interaction TKE-production needs to be revised. In particular, the direct effect of the related circulations in the 1st order equations has to be implemented, e.g. horizontal diffusion by separated horizontal shear eddies. For a **medium term perspective**, in particular the PM of separated surface driven density currents should be improved. A **further important issue** is the implementation of a **consistent derivation of cloud properties** due to SGS processes via the application of a local (turbulent) saturation adjustment to each of the convective subdomains. This would in particular provide an estimate of the **overall cloud fraction and cloud water**, which can be used for radiation calculation as well. Although the needed convective volume fractions for the up- and down-draft can’t be derived naturally from current convection schemes, a first improved estimate should be tried. A comprehensive solution seems only to be possible within a **reformulated convection** scheme, which should also include the missing dependencies on turbulence in the PM of convection. On a **longer term perspective**, we also aim to separate the direct impact of vertically resolved land use structures from roughness length, in order to describe the associated RL-terms and related SGS flow structures explicitly for at least one land use mode (and two terrain modes), which utilizes to simulate the vertical structure of the VRRL by means of the prognostic model equations. For that purpose however, additional external parameters (s. chapter 6.3.4) need to be collected in order to characterize each of the resulting 4 surface modes: 1 small scale land use mode treated by SAT (for low vegetation etc.), 1 larger scale land use mode (for trees, buildings etc.), 1 quasi terrain mode (for patterns of trees or buildings) and at least one real terrain mode (for SSO). The atmospheric-dynamical part of the VRRL-treatment is part of the schemes for turbulence and other SGS circulations, as well as SAT, where the non-atmospheric part is dedicated to the land-surface scheme including the (non-atmospheric) canopy layer description.

<u>Short term activities (2015-2017):</u>

- Revision of the PM of separated horizontal shear eddies and introduction of their effect on horizontal diffusion. [exploratory, 3D-aspects, P1]
- Implementing diffusion by all separated SGS circulations, also applied to prognostic 2nd order moments built by turbulence and related to the horizontal directions. [exploratory, 3D-aspects, consistency, P2]

Longer term activities (2018-2020):

- Reformulation of (the so far very crude representation of) TKE-production by near surface density currents and of their vertical mixing, in terms of SSO-parameters (thermal SSO effect) and lower boundary values of scalar variances derived from surface tiles. [exploratory, SBL, P1]
- Application of turbulent saturation adjustment to convective subdomains after a plausible estimate of convective volume fractions (for up- and downdraft), used as the final substitute for GS saturation adjustment (at the end of a time step) and as the overall cloud diagnostics, being consistent with turbulent and convective fluctuations. [basic, consistency, convection_initiation, P2]

Perspective activities:

- Introducing turbulent properties into the convection scheme, e.g. related to initial plume conditions or lateral plume mixing (en- and detrainment). [basic, consistency, CBL, convection, P2]
- Introduction of a VRRL built by terrain (SSO) and land use modes, which provides related roughness terms in all model equations including radiation interaction by roughness elements and the separated treatment of related SGS wake-eddies. [basic, consitency, roughness_surface, P2]

Resources required:

In total, roughly 0.5 FTE for the short term issues and at least another FTE for the longer term activities are required. The work requires a general view on the overall closure problem of GS PMs in combination with microphysical processes and the SGS structures of the lower boundary. This ongoing process might mainly be carried over by DWD.

Expected outcome:

Substitution of artificial security measures for turbulence by physical content and thereby a better simulation of the SBL or the diurnal cycle of near surface variables as a whole; consistent and more realistic cloud diagnostics (also as an input for radiation); possibility of improved initiation of GS convection by considering the full latent heat release due to SGS condensation; horizontal diffusion by horizontal shear eddies might already represent a main 3D-impact of SGS transport; additional improvement of turbulence forecast for aviation; more realistic simulations of the near surface flow and of pressure systems over land by an improved representation of land use roughness via VRRL.

Risk Assessment:

Modifications in various parts of the model are required, bearing the risk of being a rather complex task. So the introduction of a local saturation adjustment may cause undesirable feedbacks or oscillations, unless not yet known adaptations are applied to the microphysics scheme. On the other hand, the necessary modifications can be introduced stepwise along the line of continuously improving the whole system.

6.1.3 Parameterisation of Turbulence based on HOC

State of the art, scientific developments

Today the majority of turbulence schemes in current NWP models is based on **2nd order closure** and the **HBLA**, resulting in **single column schemes**, in which the whole system of 2nd order equations reduces to a **flux-gradient representation** of the correlations between vertical wind and either horizontal wind components or scalar model variables, which are the only remaining statistical moments of relevance. This kind of solution however is associated with the well known closure of pressure correlation terms (according to Rotta) and dissipation (according to Kolmogorov), as well as the neglect of molecular transport and of any direct correlation containing diabatic source terms of 1st order model variables (Rotta 1951, Wyngaard 1983). Further, a pure source term equilibrium in the budget equations for all residual 2nd order moments (for which the velocity variances are substituted by the diagonal elements of the traceless turbulent stress tensor) is essential for the flux gradient solution, whereas a **prognostic equation** for the trace of the turbulent stress tensor, which means twice the **Turbulent Kinetic Energy** (TKE) is still compatible with this solution and belongs to the **level-2.5** according the classification of Mellor and Yamada (Mellor/Yamada 1974). As long as diabatic source terms can be approximated by local saturation equilibrium (as it is the case for condensation and evaporation of cloud water) their effect on turbulence can be considered indirectly by employing respective **conservation variables.** Then, related local saturation adjustment provides an estimate of the saturated volume fraction (cloud cover) and of cloud water produced by turbulent fluctuations, which usually are in accordance with **Gaussian PDFs** of the fluctuating variables. Hence, the related cloud variables are dependent only on the governing 2nd order moments of such a “moist turbulence scheme” (Mellor/Yamada 1982). Although the employed closure assumptions are fairly valid in the **rather neutral stratified BL well above the RL**, they are more or less violated in more general situations; and that as more as the model resolution is decreasing. Most problematic seems to be the **SBL**, since simulated turbulence is decaying to unrealistic small intensities or the turbulence schemes are even no longer realizable (running towards a singularity) without **artificial manipulations** (such as lower limits for diffusion coefficients see also chapter 6.1.2). These however very likely produce too much vertical mixing in very stable cases (strong ground inversions do not develop, low stratus resolves too early).

In order to cure such problems, more sophisticated **level-3 schemes** with prognostic equations also for scalar (co)variances have been tried (Nakanishi and Niino 2004), which are very similar to our TKESV-extension mentioned in chapter 6.1.2. Since they introduce **turbulent transport of turbulent scalar (co)variances**, the associated additional degree of freedom automatically generates **non-gradient contributions** of vertical turbulent flux densities, which may be even counter-gradient. As those transport terms are related to 3-rd order moments, the assumed PDFs of a local saturation adjustment scheme can hence be generalized by introducing **skewness** as an additional variable. In some of these schemes (just as in our current TKESV version), the turbulent length scale has been substituted for an estimate of a **length scale of vertical coherence** (Baugeault and Lacarrere 1989) in order to increase the non-local properties. However, this modification is in contradiction with already employed assumptions (isotropy of the length scale) and destroys the previous scale adaptivity of turbulence against SGS circulations or (for sufficient horizontal resolution) against resolved processes, and hence introduces a source for “double counting”. Further and for all its additional freedom, even a lelvel-3-scheme remains essentially restricted by the fundamental assumptions for turbulent flow patterns related to the driving pressure forces (only **return-to-isotropy forces** and buoyancy), which are expressed by means of a **single isotropic master length scale**. Thus it can’t be a substitute for PMs of non-turbulent circulations (in the sense of chapter 6.1.2), in particular for those associated with precipitation. On the other hand, the mentioned additional features of a level-3-scheme (like non-gradient flux contributions, SGS transport of scalar variances or skewness of distribution functions) are mainly related to the coherent circulation patterns anyway, and the latter can **develop independent on incompatible turbulence approximations** only if they are separated from a scale adaptive turbulent regime, which then is affected by the circulations only through additional **scale interaction terms** in the 2nd order equations. In this sense, it should be favourable to delegate all the additional potential aspects of a level-3-scheme completely to the PMs of that circulations and the related coupling to turbulence according to the STIC-concept of section 6.1.2. Nevertheless, also a TKESV-scheme can certainly be included into the STIC-concept (at least without the above length-scale modification). However, the additional computational effort, mainly associated with the prognostic treatment of further statistical moments, needs to be compared with its remaining physical gain.

Although most of the non-turbulent processes are already resolved, when proceeding towards LES, the emerging necessity of **3D-extensions** (Arnold et al. 2012) calls for other assumptions in order to make the set of closed 2nd order budget equations tractable. A common strategy is to postulate a 3D flux-gradient form comparable to molecular diffusion with diffusion coefficient similar to that of the SC solution, but considering 3D shear and sometimes also anisotropy due to the aspect ratio of vertical and horizontal grid spacing (see e.g. the textbook of Sagaut 2001). Possible double counting by already resolved parts of turbulence can be avoided by a grid scale dependent turbulent length scale, consistent with the **moving volume average** employed for discretisation.

Status of development and expertise within COSMO

The operational turbulence scheme (**TURBDIFF**) used in COSMO is a **moist single column** scheme based on Mellor/Yamada (1982) on **level-2.5** with a **prognostic TKE-equation** and a **local saturation adjustment** employing a Gaussian PDF of local cloud oversaturation according to Sommeria and Deardorff (1977), which contains also some special treatment in order to avoid singularities of the solution of the TKE-equation as well as of the remaining linear equations expressing the influence of static stability (**stability functions**). Although the scheme has not yet been described completely in a published paper, some aspects are contained in Raschendorfer (1999, 2001), Mironov and Raschendorfer (2001), Raschendorfer and Mironov (2002), Raschendorfer (2003), Wacker et al. (2005), Buzzi et al. (2010) or Baldauf et al. (2011).

Nevertheless, we kept the former, dry, level-2.0 scheme with a diagnostic TKE-equation (PARTURA) for comparison. A restructured version of TURBDIFF is the default turbulence scheme in ICON as well, where also an implementation of EDMF is available as an option. In the ICON-version of TURBDIFF a reformulation of numerical schemes has started, which allows for a better control of various **security limits** (see section "State of the art, scientific developments" in chapter 6.1.2) that hopefully can be reduced considerably while introducing more and more of the before mentioned missing effects. This includes a reformulation of the **combined solution** of the prognostic TKE-equation and the remaining diagnostic equations of other 2nd order moments (merging to the stability functions). Further, a **more general numerical scheme for vertical diffusion** has been prepared allowing for non-gradient flux corrections as well as for diffusion of half level variables and passive tracers.

For LES applications, **3D-turbulence** schemes are available as well, which all can be activated by NAMELIST-settings. One of them is based on a rudimentary TKE-balance between 3D shear production and dissipation according to **Smagorinsky** (Langhans 2012) and an ad-hoc stability correction of the diffusion coefficients dependent on Richardson-number, while the other one has been implemented years ago upon a prognostic TKE-equation (Herzog et al. 2002). Although these 3D-schemes proved to be successful for LES, they suffer from their rudimentary physics related to vertical stratification (when applying them for coarser resolution) and from a large uncertainty in the derivation of **anisotropic diffusion coefficients** (see also the cross-cutting chapter 11.1 about 3D-turbulence).

Furthermore, there has already been developed a test version of TURBDIFF according to the TKESV-extension with **prognostic equations also for the 3 (co)variances** from the 2 quasi conserved scalar variables (total water content and liquid water potential temperature). Right on the track of that approach, a fourth **prognostic equation for skewness** of local oversaturation is being included in order to use this property in a statistical cloud scheme that is based on a more general (**double-Gaussian**) **distribution function**. However, the consideration of cloud **ice** in the statistical estimate of cloud cover is a problem already for the Gaussian approach, since there doesn't exist a saturation equilibrium for cloud ice in general. We are trying to solve this problem by considering a **mixed water/ice-phase** with an ice-fraction that is in accordance with the CM of the homogeneous box model. Finally according to the revised GBLA, a RL-extension for the closed 2nd order equations for turbulence has been derived, which also goes along with an adapted formulation of turbulent length scale and of the stability functions (see again chapter 6.1.2). A prior (obsolete and so far deactivated) version of a RL-extension is going to be substituted by that revision.

Strategy of COSMO and actions proposed

Apart from consolidation of the implemented scale interaction terms according to STIC, we are further going to extend TURBDIFF by optional 3D-extensions, as well as by additional prognostic equations following the TKESV-approach. Thus, as it seems to be possible (in contrast to e.g. convection), we really try a switchable generalization in case of turbulence, rather than to leave a couple of schemes for special purposes. Finally we are also preparing RL-extensions according to a GBLA. For a **short term**

perspective we **prioritise** the “implementation, consolidation and testing of almost ready development into a common module for COSMO and ICON”. Further **prioritised key issues** are: “Activating and developing 3D-components in TURBDIFF”, “Improving the simulation of the SBL” and “Further development of the separated scale interactive turbulence scheme.

Short term activities (2015-2017)

- Inclusion of advanced already prepared development, such as TKESV and the mixed water/ice phase as selectable options in the common module for COSMO and ICON (including possible code optimization). [application to exploratory, SBL, CBL, P1]
- Activating 3D-components (advection and horizontal shear production of TKE and general horizontal diffusion) for TURBDIFF and including horizontal diffusion by separated horizontal shear eddies (promising to provide a physical explanation of anisotropic diffusion coefficients). [exploratory to basic, 3D-aspects, P1]
- Intensive testing of the various developments with major attention to the simulation of the SBL as well as to the initiation of convection while reducing artificial constraints by introduction of improved physical content, applying conditional verification, as well as component testing (using SC runs forced by measurements offered by the COSMO-SC test-bed (see chapter 11.2)). [application, urgent, SBL]

Longer term activities (2018-2020)

- Extending the turbulent saturation adjustment to more general distribution functions using the higher order moments of scalar variables being available in the TKESV-approach. [basic, CBL, with academia, P2]
- Revision and completion of the formulation of scale interaction terms. [exploratory, STIC, SBL, CBL, P2]
- Reformulations of roughness and laminar layer corrections in the turbulence scheme to be used for the VRRL according to GBLA [preparation, consistency, P2].

Perspective activities

- Introduction of turbulent statistics into the PMs of microphysical processes (including precipitation and icing) as well. [basic, consistency, CBL, with academia, P2].

Resources required

Roughly 1.5 FTE are required for the short to medium term issues. Resources required for the long term activities are difficult to estimate and may be of the same order. Some of the work involves a great deal of research and the ability to pursue scientific objectives in an efficient manner. There is some need to develop resources with respect to testing and tuning the upcoming versions.

Expected outcome

More realistic simulations at the km-scale or for LES model runs, in particular with respect to the simulation of (partly) resolved convection (e.g. intensity and timing of precipitation); improved simulation of the SBL (coverage of low stratus clouds and the daily cycle of near surface variables); related improvements already mentioned in the previous section about separation.

Risk Assessment

There is a risk of only partly removing compensating errors. Some of the proposed sophistications may be computationally rather expensive.

6.1.4 Parameterisation of Convection based on CDC

State of the art, scientific developments

Convection covers the coherent and **anisotropic SGS flow structures with rather large vertical extend**, for which the **full CM** can develop (including the generation of precipitation). Thus turbulence closure approximations (suitable for a 2nd order framework and mentioned above) are not valid for this kind of PM. In contrast (and apart from methods based on an adjustment of “moist convective instability” towards specified profiles of temperature and specific humidity), a CDC framework that is based on truncated budgets (mass-flux equations) for convective subdomains (like updraft, downdraft and environment) carries the most important properties of those structures inherently. In the prevalent Tiedke scheme (Tiedke 1989) the convective motion is forced by grid scale dynamics (moisture convergence) and many assumptions are necessary, mainly for the PM of lateral mixing between convective subdomains, fixing the initial values for vertical updraft- and downdraft-integration and for terminating that integration. For all their success, schemes like this show some serious deficiencies, as they tend to underestimate convective events on average, while producing excessive localized precipitation on individual cases. A further characteristic is a **wrong diurnal cycle of convective precipitation,** which systematically shows its maximum around noon and might be due to a **missing memory effect** (Piriou et al. 2007). This however appears to be significantly improved by the recent development of (Bechthold 2001, 2008b). Further, the tight coupling of convection with BL turbulence and the heterogeneity of the underlying surface is not yet visible in current convection PMs, reflecting the missing formulation of a **scale separation against turbulence**.

All prevailing closure strategies are founded on crucial approximations like the stationary single column equilibrium, negligible volume fractions for up- and downdraft and the neglect of mean vertical wind speed compared to convective vertical velocities (see e.g. Tiedke 1989). Although these assumptions are fairly well fulfilled for large horizontal grid cell areas that completely contain a statistical ensemble of convective cells, they do not longer hold for the aimed model resolutions, since in the critical range of horizontal scales between about one km and several decades of that distance (sometimes called “**grey zone**” or “terra incognita”) a varying amount of convection may be resolved for a given grid scale (Plant and Craig 2008). This partial resolution of convection apparently violates the above assumptions and reveals the missing **separation against GS convection** (that is the lack of a scale adaptive formulation).

Some attempts to adapt convection PM to higher horizontal model resolution have already been made in academia, such as the **Plant-Craig scheme** (Plant and Craig 2008), which differs from the Kain-Fritsch mass flux scheme mainly through the introduction of **stochastic variability** reflecting the uncertainty of a not scale adaptive scheme running in a model of the critical horizontal scales. Another example is the **Hybrid Mass Flux Convection Scheme HYMACS** (Küll 2009), in which the resulting convective mass flux (from up- and downdraft) is considered as an additional source term for grid scale density, since a compensating environmental mass flux might no longer be SGS (also Gerard and Geleyn 2005). European research activities in that field have also been investigated in the COST action ES0905 (http://convection.zmaw.de).

Status of development and expertise within COSMO

The current deep convection scheme of the COSMO model is based on the **Tiedtke mass-flux scheme** developed in the 80's for the global ECMWF model (Tiedtke 1989). During the last years ECMWF has introduced significant modifications and refinements that have not been incorporated in the COSMO scheme yet. However the update by Bechthold (2001, 2008b) is already the default scheme in the ICON-model and even the Plant-Craig scheme is being implemented there.

On the other hand, we have also a "**shallow convection scheme**" available in COSMO, which is more or less a truncated Tiedtke mass-flux scheme, as it is limited to rather shallow non-precipitating convective mixing. Although this scheme is an option for convection permitting model runs, we can also use the extended **EDMF-scheme** (Neggers 2009) in ICON, which contains (as one of it two parts) a particular shallow convection mass flux scheme. Further we are going to test, to what extend the **TKESV-extension** of our turbulence scheme can be used as an alternative to existing shallow convection schemes in the case of sufficient high horizontal resolution.

Strategy of COSMO and actions proposed

Although we can probably get rid of a deep convection scheme for the aimed truly convection permitting model resolution, COSMO is still going to be applied with coarser horizontal resolution, e.g. when running for large domains (COSMO-RU) or in case of climate applications (COSMO-CLM). Thus a deep convection PM will still be used in COSMO and in ICON even more. Since we are aiming to configure a common physics package for COSMO and ICON, a **prioritised key issue for short term** is the "preparation of common modules with regard to the available convections schemes" to be present in both models. In a **medium term perspective**, we want to "try out the available solutions also with regard to their scale adaptivity", which can also be used in a **multi-scheme ensemble approach** (see challenge no. viii, beginning of chapter 6). Since we won't get rid at least of some kind of a shallow convection PM very likely, a **medium term prioritised key issue** is the "investigation and improvement of available shallow convection formulations". On a **long term perspective** however, we aim to "prepare a single, **scale-adaptive** convection scheme interacting with turbulence according to STIC", which reduces to remaining not resolved (shallow) convection by itself. For that purpose at least a concept of accordingly modified mass flux equations is being prepared.

Short term activities (2015-2017)

- Testing the modified Tiedtke-scheme (according to Bechthold) and the Plant-Craig scheme after they are available for COSMO in the course of compiling the common physics modules. [application, promising, P1]

- Investigation of the HYMACS-approach and trying to integrate this into the available schemes if indicated. [application, grey-zone, P2]
- Investigating the mass flux part of EDMF as an alternative shallow convection scheme. [application to exploratory, P2]

Longer term activities (2018-2020)

- Introduction of further stochastic variations (e.g. to the initial state of individual plumes) if suitable. [exploratory to basic, P2]
- Developing a foundation of a scale adaptive convection mass flux scheme, valid for all grid scales, containing explicit dependencies on turbulence and surface inhomogeneity and providing an estimate of convective volume fractions needed for a consistent treatment of clouds. [basic, scale_adaptivity, P1]

Perspective activities

- Setting up and implementing a scale adaptive convection scheme, possibly by modification of a proper existing scheme. [basic to exploratory, scale_adaptivity, P2]

Resources required

Roughly 2 FTE are required for the short to medium term issues, but they seem not to be available so far! Resources required for the long term issues are difficult to estimate, since a scale adaptive convection scheme is really not yet feasible, aside from an initial concept. They may be in the order of 0.5 FTE. The work involves a great deal of research and necessitates a solid scientific background.

Expected outcome

Overall improvement of convective precipitation forecast, in particular related to its diurnal cycle, its maximal amount, its location and for runs in the “grey zone” of model resolution; general model improvement by using different convections schemes in a multi-PM ensemble; improvement of cloud diagnostics by providing convective volume fractions.

Risk Assessment

Available alternative schemes might not significantly contribute to the problems or might not be adaptable to the existing model system easily. The success of a new development is uncertain.

6.1.5 Parameterisation of Surface-to-Atmosphere Transfer (SAT)

State of the art, scientific developments

Due to the strong curvature of vertical profiles close to the natural surface, even the pure laminar lower boundary fluxes, called “surface fluxes”, can’t be estimated primitively (that is by linear interpolation of the profiles). Rather, these fluxes can only be expressed by considering a model of the vertical profiles through the “**Transfer Layer**” (TL) below the lowest full model level, which is usually based on a **constant flux approximation** for that vertical range, resulting in a final **resistance form** of the desired fluxes, in which the resistances are functions of friction velocity and Monin-Obuchov stability length. In order to include **laminar and RL-effects** in a preferably easy way, they usually are represented by virtual distances (**roughness length**

values) of a pure turbulent TL (which is free of these effects, but still shows the real resistance) from the natural surface. This typically requires assuming that the RL needs to be quite **shallow** compared to the TL, which may be called the "**Shallow-RL-Approximation**" (SRLA). Since an analytical solution of the resistances in terms of GS model variables is not feasible, approximated formulae, motivated by measurements, are widely used (Louis et al. 1982 or Beljaars/Holtslag 1991). It is a main shortcoming of traditional schemes that in particular the artificial **roughness length for the scalar fluxes** is treated like a pure function of geometric properties of the surface or even like a constant, although it dependents considerably on the model variables within the transfer layer as well. A further weakness is the derivation of the resistance functions, which is based on a rather simple model of homogeneous turbulence. Consequently these transfer schemes suffer from the same fundamental problems as traditional turbulence schemes. While for strongly convective conditions the consideration of a "**convective velocity scale**" (Beljaars 1994) or the concept of "**minimum friction velocity**" (see e.g. Zilitinkevich et al. 2006) may help, the problem for the very stable TL usually requires some artificial tuning, unless the before described scale interaction terms are already considered.

An additional aspect is the rather complex wind feedback on (vertically not resolved) **roughness in case of a water surface**, which commonly is parameterised by means of surface stress (**Charnock-relation**). However this description is rather rudimentary and seems to be problematic in strong wind situations as well as in convective situations with weak mean wind but strong SGS wind patterns. Finally roughness of free waves (independent on local wind forcing) can't be described with this approach at all.

Status of development and expertise within COSMO

The SAT scheme **TURBTRAN** used in COSMO and ICON is based on the application of the turbulence scheme (TURBDIFF) within the transfer layer and thus has the ability to include the extensions of the (separated) turbulence scheme as well. Instead of the SRLA (s. above), we use the concept of a **natural surface being lowered by the depth of the vertically not resolved part of the RL** (chapter 6.1.2), where the lower boundary of the atmospheric model is the top of that lowered part of the RL, which is treated as a pure mass-less resistance for scalars without any storage capacity. Although this concept formally allows for a lowered RL of arbitrary depth (in contrast to the SRLA), a simulation of air-properties of that RL is purely based on the derivation of vertical profiles associated to interpolated vertical resistance profiles. We want to improve this by the concept of the VRRL (see chapter 6.1.2). According to this, only the small scale part of the surface roughness forms a rather shallow lowered RL, while the other part (composed of land-use- and terrain-modes) is represented by additional RL-terms in the governing budget equations within some of the lowest model layers. The equations for the TL resistances are solved via iteration over the time loop by employing some vertical interpolation of turbulent properties (profile functions) throughout the TL. Moreover, instead of defining a scalar roughness length, the resistance contribution by the (lowered) RL (including the laminar layer) is derived explicitly using transfer-layer-variables and –parameters (such as the "roughness length" and the "surface enlargement by means of surface roughness"). Finally, the diagnostics of near surface variables (2m- values of temperature and dew point, 10m wind speed) is based on the mentioned vertical resistance profiles (and an interpolation between model layers, if the lowered RL is shallower than 2m or 10m). Another issue in TURBTRAN is the formulation of **sea surface roughness**, which has been extended by considering shear stress of SGS wind as well. Like TURBDIFF also TURBTRAN (both developed by M. Raschendorfer) has not yet been fully described in a reviewed publication.

Some deficiencies in the setup of the current scheme may be one reason for still remaining shortcomings in simulating a correct **diurnal cycle of near surface variables** in particular during the night time. A reason for that may be the same **numerical security limits** that are already under investigation related to turbulence. Further, some simplifications and inconsistencies related to the interpolated profile functions raise suspicion to make the scheme responding too weakly as a function of the transfer layer stratification. Another remaining problem is the separation of an **idealised laminar layer for scalars** instead of using a unified mixed laminar-turbulent flux representation for the resistance calculation. Finally the treatment of **RL-effects**, in particular related to the derivation of near surface variables (2m-temperature or 10m-wind), is not yet completely satisfying, and the **treatment of fog** is completely missing in the derivation of 2m-variables at all. A particular problem is a feed-back of diagnosed temperature and dew-point temperature at the 2m-level onto the model state, if the latter are used for **variational Soil Moisture Analysis** (SMA, as used at DWD). For that purpose the **2m-diagnostics** needs really to match with the **local** measurements, which could be improved when applied to a proper surface tile representing the lawn of a typical SYNOP-station.

Although an implicit treatment of surface fluxes was favourable with respect to numerical properties, we use an explicit **surface-to-atmosphere coupling** for the time being, since the soil model (TERRA) can’t be forced by water vapour fluxes so far. In addition, we avoid difficulties when using **surface tiles** (see chapter 6.3.1 about land-surface schemes) by this kind of coupling. Nevertheless, it would be an advantage to include even the surface temperature into a (semi-)implicit treatment. For such a treatment, surface temperature needs to be diagnosed by a linearised heat budget of a “surface layer”, and through this, a kind of **flux limiter applied in the soil model** (for reasons of numerical stability) should be dispensable, as well. This treatment however, would require the calculation of an effective “pore-resistance” for vapour transport not only for vegetation (stomata-resistance) but also for the soil, which can be used in the mentioned surface heat budget being solved for the surface temperature.

Although the revised GBLA (see again chapter 6.1.2) mainly is dealing with SGS topographic slopes, GS inclinations of the lower model boundary are included as well. They affect surface fluxes mainly due to an increase of the surface and an inclination of their direction. Therefore they can be denoted as a 3D-contribution by the SAT scheme.

Strategy of COSMO and actions proposed

For a **short term** perspective we are **prioritising** a “revised implementation of the existing SAT scheme as a part of the common module for COSMO and ICON” containing TURBDIFF and TRUBTRAN. A **medium term priority** is “implementation of further modifications and parameter tuning” aiming to improve the daily cycle of near surface variables, including very rough surfaces. For a longer term perspective, we are aiming to introduce a non-atmospheric surface layer covering the underlying, compact soil- (snow-, ice- or water-) body, which would represent the roughness elements (**canopy layer**) of the surface and would be coupled rather loosely to that body compared to the coupling of layers within the body. This would also facilitate an implicit calculation of surface temperature. However, this issue is also related to the chapter 6.3.1 and would also include aspects of the **snow cover** and **shadowing of the soil body by a plant canopy**. Finally we are interested in a more “complete and consistent representation of the VRRL” (see chapter 6.1.2).

Short term activities (2015-2017)

- Removing inconsistencies and unnecessary simplifications (mainly regarding the profile function and the treatment of laminar effects), including a first extension considering inclined surfaces. [exploratory, urgent, SBL, diurnal cycle, P1], related to dynamics
- Performing the near surface diagnostics of scalars based on conserved variables (being more consistent and offering a fog diagnostic at 2m level) and including RL-issues in the 10m wind diagnostic. [application to exploratory, consistency, roughness_surface, P1]
- Further investigating the PM of sea surface roughness and other special issues of SAT in case of water surfaces. [application to exploratory, precipitation, CBL, P2]

Longer term activities (2018-2020)

- Evaluation of optimized parameter values controlling SAT (including evapotranspiration and soil moisture issues) and near surface diagnostics preferably by component testing using COSMO-SC (to be extended by some parameter optimization facilities. [application, promising, P1], related to verification with feedback
- Introduction of a surface canopy layer covering the compact soil (including shadowing e.g. by plants) and possibly introducing an implicit formulation of surface temperature within the vertical diffusion framework (some reformulations in TERRA required). [exploratory, diurnal cycle, promising, P1], related to land-surface scheme

Perspective activities:

- Supporting the VRRL development by derivation of vertical profiles of RL-parameters and by adopting the formulation for the vertically not resolved part. [basic, roughness_surface, P2]

Resources required:

Roughly 1 FTE are required for short to medium term issues. The long term activities may require even more. The work requires a deep familiarity with the SAT scheme and its concepts. The canopy layer issue necessitates also knowledge of soil and vegetation modelling. Apart from desirable support for preparing component testing based on measurements and COSMO-SC, there is sufficient personal for the time being.

Expected outcome:

More realistic partitioning of solar radiation at the surface and improved simulation of evaporation; better diurnal and annual cycle of near surface variables in general and in particular for regions with rough topography or complex land use; positive impact on development of low pressure systems by improved SAT over sea surfaces.

Risk Assessment:

More degrees of freedom of more sophisticated formulations and feedbacks with SMA may be difficult to control (e.g. by adequate external or internal parameters).

6.2 Parameterisations of source terms (local parameterisations)

6.2.1 General remarks

In contrast to GS PMs, the challenge of local PMs is to find a reasonable **simplification of microphysical processes** that are intractable complicated with regard to a numerical treatment. This refers to the following processes:

i. Cloud microphysics (conversions of various water constituents) and related thermodynamics (CM)
ii. Radiation transfer and the related thermodynamics (RT).

Although pure local PMs should be independent on the model resolution, their practical extensions that enable tractable simplified formulations can absolutely make use of resolution dependent assumptions, as in the case of current single column schemes of RT. The **effects of SGS variability** on the source term formulations in the discretised model equations however, are a matter of the GS PMs, not at least because the related source term variations significantly influence the SGS flow patterns again. Anyway, these SGS effects still can be considered only rudimentary, and may also be regarded as a part of the source term PMs, if the feedback on the flow patterns can be neglected. Since all the additional species that needs to be considered for CM have a significant impact to RT as well, this **cloud-radiation interaction** is of major importance.

6.2.2 Parameterisation of Cloud Microphysics

Authors: Matthias Raschendorfer (DWD) based on previous Science Plan text by Axel Seifert (DWD/MPI-Hamburg) and input by Ulrich Blahak (DWD)

State of the art, scientific developments

Cloud microphysics (CM) deals with the PM of all conversion terms of water phases and interacting hydrometeors (and aerosols) that need to be considered in order to get a closed description of the atmospheric system. Although precipitation products are not a primary part of the atmospheric state, their simulation is of particular interest. The formulations are founded on micro-scale statistics that basically are determined by the values of characterising local macroscopic model variables, namely **moments of particle size distributions**. Nevertheless, all the interactions are not yet understood completely, even though they can be studied mainly in laboratory chambers. Moreover, even the relations of understood processes often can't directly be used in NWP models due to their complexity and thus need to be simplified considerably. The so called "**bulk schemes**" currently used are based on **assumed particle size distributions** of the considered water phases, and provide relations to predict at least one moment (i.e. **the mixing ratio**) of that distribution. In operational NWP models **fully prognostic one-moment microphysics schemes** with **two or three ice species** are still state-of-the-art (see e.g. Thompson et al. 2004 and others). Many operational models, however, run much simpler schemes (se e.g. Wilson and Ballard 1999). In research models the complexity and sophistication of microphysical PMs has considerably increased over the last decades. 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 or even hundreds of different ice species (Straka and Mansell 2005). Many of the studies with more sophisticated schemes investigate **aerosol effects** on clouds and precipitation. A particular problem arises from the influence of **(ice-) particle shape** (Woods et al. 2007) on the microphysical processes and in particular on **sedimentation velocity**. As, e.g., sedimentation of raindrops is strongly influencing their evaporation efficiency, and with it, the generation of cold pools, these processes can significantly affect the **triggering of secondary convection**.

Although the inclusion of **SGS (i.e. turbulent) variability** is already possible with respect to equilibrium processes (local saturation adjustment), many of the microphysical processes (e.g. related to cloud ice or auto-conversion) have rather large (restoring) time scales compared to the usual model time steps and thus are incompatible with such a source term equilibrium (Naumann et al. 2013). Since GS precipitation is strongly determined by **vertical velocity**, a consistent **dynamic coupling** is of importance as well, and particularly the missing of some diabatic heat sources due to turbulence might be of significance. Thus this field is becoming more and more a matter of recent research.

Status of development and expertise within COSMO

The COSMO model provides several microphysical PMs that have different levels of complexity. These range from a simple diagnostic scheme with only one ice class to a **one-moment three-ice fully prognostic PM** (Doms and Schättler 2004, Reinhardt and Seifert 2006). A **two-moment four-ice-classes scheme** (that includes a full treatment of hail microphysics and of particle number concentration as a second prognostic moment) is available for research applications (Seifert and Beheng 2006a, Blahak, 2008), such as aerosol-cloud-precipitation studies (Seifert and Beheng 2006b, Mühlbauer and Lohmann 2008, Seifert et al. 2012), and it can be used in connection with COMO-ART for special purposes.

For the **one-moment schemes**, some improvements are already at hand, such as the PM of ice nucleation and the size distributions of ice, e.g., for cirrus clouds (according to Karcher and Lohmann 2002, Lohmann and Karcher 2002, Köhler 2013), which provides an important link to the radiation scheme. Further, a prognostic treatment of snowflake water content has been developed (according to Walko et al. 1995, Meyers et al. 1997, Phillips et al. 2003, 2007, Frick et al. 2013), which improves the fractioning of frozen vs. liquid precipitation. Important particularly for the forecast of aircraft icing is an improved simulation of super-cooled water (done by F. Rieper at DWD) by considering a liquid water sub layer on top of ice cloud layers due to ice sedimentation. Finally the former exponential distribution function for particle size has already been substituted by a more general gamma-function successfully, and an improved sedimentation formulation for rain droplets and snow has been introduced as well.

The more sophisticated **two-moment schemes** have definite advantages, since for instance a prognostic treatment of rain-drop-number concentration can provide better options to parameterise evaporation and sedimentation of raindrops (Fovell and Seifert 2005, Milbrandt and Yau 2005a, Seifert 2008) and thus show improvements in convection permitting model runs with respect to the diurnal cycle of precipitation as well as related to the lifecycle and intensity of convective systems (Baldauf et al. 2011, Seifert 2012). Nevertheless, their overall benefit needs to be proved with special respect to **numerical expense**, including also questions of **data assimilation** and **explicit hail forecasting**. Notably convective-scale data assimilation and the assimilation of cloud information in general could benefit from the two-moment microphysics, and the latter may only show its full advantage, if consistent data assimilation is applied. Although hail is already treated in the two-moment scheme, an explicit hail forecasting is not yet possible. A step in that direction is the explicit PM of **snow- and ice melting** according to Frick et al. 2013. An important issue (in particular for two-moment schemes) is the (possibly prognostic) treatment of aerosols and their assimilation, which are included by means of COSMO-ART (Vogel et al. 2009).

A special topic is the treatment of **SGS variability**. Although convective tendencies due to CM are already part of the convection scheme, the used microphysical PM is only rudimentary compared to the standard scheme, which is assumed to produce the remaining tendencies valid for the whole grid box. On the other hand, related **turbulent tendencies remain still unconsidered**, even though at least a local saturation adjustment of cloud water (based on saturation equilibrium) is applied as a part of the turbulence scheme.

Strategy of COSMO and actions proposed

We are going to “implement and carefully test prepared development for the one-moment scheme” for a **short term priority** with a special focus on its “suitability for convection permitting model runs”. For the **medium term perspective**, we aim to “further develop and investigate the two-moment microphysics including the effects of prognostic properties of aerosols”. For a **longer term priority**, we aim to “approach a more consistent implementation of CM with respect to SGS variability (strongly related to turbulence and convection PM)” by including **non-equilibrium** processes as well. However, apart from technical solutions like the mixed water/ice-phase (see chapter 6.1.3 about turbulence), existing theoretical frameworks are not yet suitable for all these issues.

Short term activities (2015-2017)

- Implementing the improved treatment of ice nucleation and cirrus processes, as well as the new snow melting PM into the current one-moment scheme. [application, cloud_radiation_coupling, promising, P1]

- Carrying over the improvements for super-cooled liquid water in mixed-phase clouds into the 1-moment scheme(s) of the official COSMO version. [application, aircraft-icing, promising, P1]
- Investigating the benefit of further extensions of the one-moment scheme(s), such as introducing the raindrop number concentration as a prognostic variable. [exploratory, convection_initiation, P2]

Longer term activities (2018-2020)

- Tests/evaluations of two-moment vs. one-moment schemes and performing possible measures to decrease the computational expense of the 2-moment scheme and with particular view on data assimilation. [application to exploratory, P1]
- Adopting an improved simulation of melting/shedding of graupel and hail (work within the HD(CP)^2 project, following the work of C. Frick). [basic to exploratory, P2]

Perspective activities

- Explore possibilities of explicit hail forecasting with the 2-moment scheme. [basic, with academia, P2]
- Keeping an eye on the scientific developments regarding SGS processes (turbulence) in cloud microphysics (apart from local saturation adjustment), which is not always feasible yet within the existing theoretical frameworks (e.g. related to the auto-conversion process). [basic, with academia, P2]

Resources required

About 2 FTE of well trained scientists with a good background in CM might be sufficient for the short to medium term issues, including support by academia. The long term and perspective actions might primarily be addressed to academia anyway.

Expected outcome

Improved forecast of precipitation amounts and phases; more realistic cloud information as an input for RT with an indirect impact also on near surface temperature and humidity; positive impact on GS convection by a better representation of cooling due to evaporating precipitation or by the impact of conversion rates due to turbulent variability.

Risk Assessment

The well-tuned existing system might be hard to beat by improved cloud properties, as related modification in the radiation scheme could be necessary as well. It might remain problematical to increase the computational efficiency of the full two-moment scheme, which currently causes an increase of about 50-70 % total model runtime.

6.2.3 Parameterisation of Radiation Transfer

Authors: Matthias Raschendorfer (DWD) based on previous Science Plan text by Bodo Ritter (DWD) and input by Ulrich Blahak (DWD)

State of the art, scientific developments

Radiation provides the ultimate source- and sink-term of energy in the earth-atmosphere system and interacts strongly with other components of the NWP model, in particular with those affecting the evolution of the cloud variables. But also the forecast of near surface variables like the 2m-temperature are heavily dependent on a successful simulation of Radiation Transfer (RT) through the atmosphere and the associated surface energy budget.

Since numerical treatment of the full 3D RT-equation (with all its dependencies from wavenumber specific optical properties of gases, clouds and aerosols) is by far not feasible, **single column** schemes, which in addition discriminate only between very few spectral bands, are still state-of-the art in NWP models. Moreover, even under these simplifications, computer time needs to be saved by either calling these schemes with **reduced frequency** or on a **coarser horizontal grid**, which both is applied in COSMO and ICON. In order to run a radiation scheme in a better temporal and spatial resolution without ignoring further spectral information of radiation, some alternative strategies are being investigated now. One of these approaches, named "**Monte Carlo Spectral Integration**" (MCSI) (Pincus and Stevens, 2009), is based on high temporal frequency calculations of RT in conjunction with a quasi-random, bias free sampling of the spectral space instead of complete integrations over the full radiation spectrum. Another approach has some characteristics of a "**statistical hyper-PM**", since it is tried to reduce the numerical effort by calculating only **parameterised radiation tendencies** expressed by regression functions that are calibrated by rather few calls of the full radiation code, spread in time and location (Venema et al. 2007). This concept, called "**Adaptive Parameterisation Approach**" (APA), may also be applied to other (computational expensive) PMs.

Although SC schemes (assuming plane-parallel, horizontally homogenous conditions) have been applied successfully for meso-scale models, in case of very high horizontal resolution, **3D-effects** become increasingly important. Since complete 3D-schemes (e.g. Monte-Carlo methods that simulate RT by evaluating the PDF of a large set of photons, which are tracked as they pass though the atmosphere) remain much too expensive for operational model runs, only some important 3D-aspects can be taken into account so far. As slopes of topography cause **heterogeneity by shadowed and exposed surfaces**, they are related to the surface forcing of circulations like convection, and thus belong to these important issues. Some of these mechanisms can be considered by rather effective modifications using geometric pre-calculations (Buzzi 2008). A 1st -order approximation of the radiative interaction between optical constituents in adjacent grid columns can be introduced via the so-called "Tilted Independent Column Approach" TICA (Wapler and Mayer 2008). This approach has already been implemented in a test version of COSMO.

Besides this kind of problems, there remain also rather basic shortcomings in view of the derivation of optical properties dependent on the presence of **cloud particles or precipitation**. These properties control the overall atmospheric opacity and also have a strong impact on the vertical structure of radiative heating and cooling rates. But particularly the optical properties of **ice clouds** can only be determined with large uncertainties. A related problem is the specification of the **spatial distribution of aerosols and their corresponding optical properties**, which also has a significant impact on the distribution of radiative fluxes and heating rates, and commonly is based on climatological approaches. All this may bias current radiative heating rates, which is partly compensated by other errors or adaptive tuning of other model components, precluding further improvement of the whole system of PMs.

Moreover, the **SGS variability** of these hydrometeors (with respect to the characterising model variables) might also have a significant impact on the derivation of effective GS values of optical properties and seems to be an ambiguous source of uncertainty. First of all, the amount and distribution of hydrometeors that is present under consideration of SGS processes needs to be known. However, apart from some heuristic 1st order closure, only adjustment processes can be included to a statistical treatment of microphysics so far. On the other hand, inherent non-linearity in the representations of optical properties (in terms of the descriptors for the hydrometeors) may result in additional SGS corrections, which can not yet be specified. Hence they are considered by some "**effective factors**" at the most. Finally similar to CM, also the remaining relations of RT should produce SGS corrections in the discretised budget equations and in turn, the related radiative heating rates should influence the SGS flow patterns (mainly as a feedback with SGS cloud patterns) as well. However, neither known convection schemes nor present turbulent schemes contain any interaction with radiation so far. This common issue with GS PMs should be taken into account in a future design of model physics.

Status of development and expertise within COSMO

In the COSMO model we currently use a **SC δδ-two-stream RT scheme** (Ritter and Geleyn 1992) with **8 spectral intervals** (3 solar, 5 thermal). In this scheme, cloud optical properties depend only on cloud liquid water content and ice content so far, at which their dependence on the particle size distribution is considered only implicitly. The contributions by rain and snow are ignored completely. A first attempt to introduce the size distribution dependence of optical properties of hydrometeors in terms of **effective radii** (Nakajima 1990) has been introduced experimentally. The contribution of precipitating hydrometeors (i.e. rain and snow) is currently also under evaluation. Since cloud water is still diagnosed according to a **GS saturation adjustment**, cloud water due to SGS processes is diagnosed independently (see chapter 6.1.2 about separation). Further, the effect of SGS variability of cloud properties on optical properties is considered by a rather arbitrary "**effective factor**", which needs to be investigated and preferably be substituted by a more sophisticated approach dependent on SGS statistics. Although this inclusion of SGS variability is desirable for the same reasons as related to CM, it appears to be far from feasible for the time being. Nevertheless, if that is ever tried, all the interdependencies with GS PMs will be involved as well.

Apart from those problems, the calculation of **optical properties of gases** needs to be updated towards state-of-the-art spectroscopic data bases. However, those data are implicitly contained in the more recent **Rapid Radiation Transfer Model** (RRTM) (Mlawer et al. 1997), which is already the default scheme of ICON and IFS. Although the used **aerosol climatology** is based on a recent data set in COSMO, 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, at least on a longer term perspective (Vogel et al. 2009).

In order to enable the RT scheme to be called with the same temporal and spatial resolution like other physical schemes and with even more accuracy than before both, MCSI as well as APA are being investigated in test versions of COSMO at academia. Related to the more and more important **3D-extensions**, the work of M. Buzzi (introduction of heterogeneity by shadowed and exposed surfaces) is already available in COSMO; but it is used for operational NWP only at MeteoSwiss for the time being. Further, TICA is investigated in a test version of COSMO at academia.

Strategy of COSMO and actions proposed

On a **short term perspective** we aim for “implementation and further development of an improved cloud-radiation interaction” and for “merging this development with RRTM in a common module for COSMO and ICON” as a **priority**. On a **medium term perspective**, we **prioritise** the “incorporation of the extramural development” mentioned above (in particular 3D-extensions), in order to end up with an operational RT scheme really valid for model NWP runs at a sub-km scale. On a **long term perspective** we also keep an eye on “possible contributions to a proper representation of turbulent statistics in the framework of cloud- radiation interaction”.

Short term activities (2015-2017)

- Evaluation of the RRTM scheme (available via a common physics package for COSMO and ICON) and merging the developments of the current scheme and RRTM to be available in the future scheme that is probably based on RRTM. [application, urgent, P1]
- Implementing state-of-the-art formulations of optical properties of hydrometeors based on effective radii and improved corrections accounting for the effects of SGS variability of clouds. [exploratory, promising, cloud_radiation_coupling, P1]
- Implementing the consideration of snow, graupel and rain into the radiation scheme. [exploratory, consistency, cloud_radiation_coupling, P1]
- Careful tuning of the new cloud-radiation coupling (especially the SGS scale variability factor for hydrometeors and in connection with the substituted cloud diagnostics). [application, promising, cloud_radiation_coupling, P1]

Longer term activities (2018-2020)

- Implementation and testing of other already available contributions (e.g. in test versions of COSMO) making the radiation code more efficient (MCSI and APA) or in order to introduce slope effects of terrain and solar radiation (in particular TICA). [application to exploratory, 3D-aspects, promising, P1]

Perspective activities

- Implementation and testing new approaches or contributing to the current development, in order to obtain a radiation scheme containing the most important 3D-effects, neither loosing essential spatial resolution nor significant accuracy, though it is called more frequently. [basic to exploratory, 3D-aspects, P2]
- Contributing to a proper representation of turbulent statistics in the description of cloud radiation interaction. [basic, cloud_radiation_coupling, P2]

Resources required

About 1 to 2 FTE of well trained scientists with a good background in radiation modelling and CM might be sufficient for the short term issues, which seems to be available. There is a strong need to develop resources for implementing, consolidating and testing of more or less available methods and extensions (in particular for the longer term activities) and the engagement in new development, which altogether may require a similar amount of resources.

Expected outcome

Overall improvement of the model climate and for simulation of the diurnal and annual cycle of near surface variables, in particular related to the forecast of solar energy supply (mainly by improving the description of cloud optical properties); more accurate simulations and integration of more physical content like 3D-effects due to more efficient RT-calculations; better initiation of resolved convection due to a more realistic solar surface forcing in case of structured topography or shadowing by clouds.

Risk Assessment

Related to the cloud-radiation interaction, there is a risk not to improve a well tuned existing system. Further it might be difficult to merge RRTM, extramural development and the ongoing development on the current scheme. Considerable problems with computer time may arise after implementation of 3D-effects.

6.2.4 Summary of expected FTEs in Atmospheric Physics area

FTEs for main priority actions for period 2015-2017		FTEs for secondary priority actions for period 2015-2017	
To be provided by COSMO partners		To be provided by COSMO partners	
- Already secured:	3.9	- Already secured:	3.2
- Potentially available:	1.0	- Potentially available:	1.4
- Missing:	0.8	- Missing	1
To be provided by academia		To be provided by academia	
- Already secured:	0.9	- Already secured:	0.7
- Potentially available:	0.9	- Potentially available:	0.9
- Missing:	0.0	- Missing:	0.3
All secured and potentially available	6.7	All secured and potentially available	6.2
All missing	0.8	All missing	1.3
Total required	7.5	Total required	7.5

6.3 Parameterisation of processes within the adjoining non-atmospheric body

6.3.1 Parameterisation of land- and plant-processes

Authors: Jürgen Helmert (DWD), Ekaterina Machulskaya (DWD), Gerd Vogel (DWD), Jan-Peter Schulz (Uni. Frankfurt), Jean-Marie Bettems (MeteoSwiss)

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 leads to many dependencies between the SVAT scheme and other parts of the NWP system (incl. the data assimilation). Due to strong interaction with the surface to atmosphere transfer the SVAT model has a large impact on the evolution of near surface weather parameters as well as on atmospheric processes through possible feedback mechanisms (e.g., boundary layer development, low level cloudiness, intensity of convection), and a fast and efficient coupling between both model parts is required. Obviously, the evolution within the SVAT scheme depends also strongly on the atmospheric forcing, in particular on the global radiation and on the precipitation.

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). The effects of heterogeneity for the exchange processes between land surfaces and the atmosphere is often represented by the so-called ‘‘tile’’ approach (see 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 boundary layer (SBL), 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 boundary layer, most features will remain at subgrid scale, and effects of surface temperature heterogeneities may be (vitally) important to realistically describe the SBL structure (Mironov and Sullivan 2010).

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

For some regions, artificial irrigation may play an important role for the surface heat and moisture exchange at small scales. Apart from the issue of harvest related changes in the plant cover of agricultural areas, it is probably not necessary to consider the vegetation dynamics in a NWP context. In comparison to the influence of rather slowly varying vegetation properties, the consideration of the impact of a vegetation canopy on the surface radiative fluxes and on the associated ground heat flux is of high relevance for NWP time scales (see e.g. Viterbo and Beljaars 1995).

With the advent of very high resolution NWP forecasts at 100m-scale, parameterisation schemes and the corresponding external parameters required for them will probably become even more important as models try to simulate more and more details of atmospheric and surface processes. At some stage it may be necessary to overcome the limitations of a purely one-dimensional simulation approach and take lateral exchanges across grid boxes into account, even for soil processes.

Even more than for the atmospheric model, the simulation of the evolution of the soil is hampered by inadequate knowledge of the initial state. 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 data (e.g. from LandSAF). Here, retrievals of surface albedo, leaf area index, and lake temperature are of particular importance 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), considerable effort has been devoted to the implementation of advanced assimilation techniques in recent years. This is particularly important given the large sensitivity of model integrations to the initial conditions of surface variables, in particular to the 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. Although soil moisture exhibits an extremely large spatial variability on small scales, validation studies have shown a rather good agreement of satellite derived products with in-situ observations; however, root zone soil moisture, especially below vegetation, remains a challenge. The activities in assimilation of remote sensing soil moisture observations at the European Centre of Medium Range Weather Forecast (ECMWF) should be closely considered and compared with the methods currently used in COSMO (e.g. soil moisture analysis, latent-heat nudging).

Status of development and expertise within COSMO

Similar to most of the operational mesoscale NWP models, COSMO uses a fast and efficient coupled multilayer SVAT model (TERRA) with a direct solution of the heat conduction equation and considers moisture transport due to hydraulic processes within the soil and also the effects of transpiration by plants. Phase change processes of soil water are incorporated in the scheme both for their thermodynamic effect and for their impact on the hydraulic properties of the soil. Note however that the effect of the vegetation canopy is not considered. The focus on the core land-surface processes results in CPU efficient code; for example, the wall-clock time of the whole model is about 30% smaller than when using a more sophisticated SVAT scheme in a typical application (Akkermans et al. 2012).

Even though it may be assumed that horizontal heterogeneity is less of a problem at mesoscale than at larger scale, it is reasonable to assume that COSMO forecasts of near surface variables and boundary layer processes will benefit from an implementation of a tile approach. In particular, the distinction between snow covered and snow-free conditions and the handling of a subgrid scale water surface should be beneficial. A tile approach for TERRA is currently available in the ICON framework.

TERRA can be run with either a single layer or a multi-layer snow model considering melting of the snow pack with prognostic snow density and time dependent snow albedo. The single layer scheme, currently used in production, is definitely not able to realistically simulate many important aspects of the 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 the near surface temperature. This should be solved by combining the tile approach with the multi-layer snow model.

Using prescribed conditions, COSMO with TERRA in single-column mode (SCM) was validated in a model intercomparison study (GABLS3) against observations at Cabauw for a stable PBL case. In this study, the results of TERRA are within the uncertainty range of different other models (Bosveld et al. 2010).

With the development of a new software for the generation of external parameters, additional invariant fields can be used in the COSMO model for new parameterisations (e.g. the freshwater lake-model Flake, the orographic radiation correction scheme). The operational availability of high-resolution global land cover data (GlobCover) and elevation data (ASTER GDEM) should improve future COSMO applications at cloud resolving resolution. An adaptation and extension of the hydraulic and thermal soil properties 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). It was shown e.g. in Akkermans et al. (2012), that external parameters can have a significant impact on the quality of the SVAT model results. A demand for more realistic external parameters exists also from applications in environmental prediction, where recent studies (see e.g. Arnold et al. 2012) have shown that realistic surface properties improve high-resolution local forecasts and support improved model physics.

Strategy of COSMO and actions proposed

Due to the numerous dependencies between the overall NWP system and the SVAT model itself, a deep understanding of the capabilities and limitations of the SVAT model is required in the operational services. The TERRA model, which was developed at DWD, fulfils this condition; moreover, TERRA is running safely and efficiently since many years at all scales. For these reasons, although more advanced SVAT's are also coupled with COSMO and employed by the COSMO-CLM community (CLM, Veg3D), TERRA is chosen as the basis for further developments in the frame of NWP applications.

In terms of scientific goals, the further development of TERRA will focus on

- processes with expected large impact on the NWP forecast;
- improved coupling to the atmosphere (taking into consideration the work done for ICON; see also Polcher et al. 1998; Schulz et al. 2001, Best et al. 2004);
- stronger integration of data assimilation, also to update surface properties using near real time monitoring of continental surfaces from remote sensing;
- implementation of the stochastic physics approach, for the benefit of ensemble prediction and assimilation systems.

The further development of TERRA takes into account the results of the former COSMO Priority Project COLOBOC (see Bettems et al. 2015, also http://www.cosmo-model.org/content/tasks/pastProjects/coloboc/default.htm).
During COLOBOC extensive experiments with TERRA and the associated external parameter have been performed by various COSMO partners, which contributed to a better knowledge of the strengths and limitations of TERRA in different seasons and with different forcing.

With the advent of the ICON model, which employs a more advanced version of TERRA, the further development of the soil model TERRA is embedded in the shared ICON/COSMO physics library. In this way, features like the enhanced tile approach and the multi-layer snow scheme, which have been successfully implemented and tested in the ICON framework, will easily be transferred to the COSMO system.

Within this strategy, the more advanced SVAT models coupled with COSMO (CLM, Veg3D) will be used for regular inter-comparison and validation studies for supporting the further development of TERRA. These studies take into account international programs to characterise and compare land surface model behaviour e.g. the Global Land/Atmosphere System Study (GLASS) within the Global Energy and Water Cycle Exchanges Project (GEWEX) (see also Chen et al. 1997; Schulz et al. 1998).

The following proposed actions are divided into two categories: P1 for time critical and important tasks and P2 for important but not time critical tasks. An action is classified in P1 if it creates a high benefit for the SVAT model or if it is a precondition for further important tasks.

Short term actions (2015 – 2017)

- Revision of the surface energy budget: extracting a “pore-resistance” for evaporation of the soil and consideration of the role of vegetation in close cooperation with developments of the surface to atmosphere transfer scheme (shading effect, additional vegetation layer – the latter topic is coordinated by WG3a, see chapters 6.1.2 and 6.1.5) (P1),
- Revision of plant water uptake : impact of vegetation properties (P2),
- Implementation of advanced soil properties data sets: Harmonized World Soil Database, new formulation of soil water transport (P2),
- Identification of processes to be used in stochastic physics approach (P1), (in cooperation with WG7),
- Assimilation of soil moisture, and maybe soil temperature, (remote) observations, or other approaches improving the initial state of the soil taking into account developments of the data assimilation system (this work is coordinated by WG1, see chapter 7.3 for details) (P1),
- Model inter-comparison and validation studies (SRNWP data pool) to identify future fields of development activities (P1).

Long term actions (2018 – 2020)

- 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 stream flow routing. This requires the consideration of horizontal transports, implementation of soil water interflow, base flow, and ground water table (P2),
- Improve the multi-layer snow model, in particular in complex topography, and the related assimilation techniques (this latter task is coordinated by WG1) (P2).

The development of stochastic physics for the SVAT model belongs to exploratory research. All other items belong to application research.

Resources required

Approximately 1.5 FTE are required to achieve the short term goals, without the data assimilation aspects. For this latter task, at least 2 FTE are required (1 FTE in data assimilation, 1 FTE for the SVAT model experiments) and strong interaction and coordination with the data assimilation working group is a pre-requisite.

The first part of the long-term goals (water transport) includes research tasks, which require close collaboration with universities and experiments with the COSMO model.

In addition, at least 1 FTE is required for the implementation. This goal could be (part of) a well-defined COSMO Priority Project.

For the second part of the long term goals, much knowledge and expertise is available outside of the NWS, in particular in the institutions responsible for avalanche forecast. Collaboration should be developed with these institutions.

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. Development of the stream flow routing, and assimilation of remote sensing soil moisture require considerable research efforts (but this latter activity can use the experience of other NWP centres). 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.

6.3.2 Parameterisation of sea-ice processes

Author: Dimitrii Mironov (DWD)

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 for a long list or http://www.nemo-ocean.eu/ for the description of a sea-ice model already coupled with COSMO).

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 on the basis of 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).

Status of development and expertise within COSMO

The expertise in sea-ice modelling is 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. That scheme was implemented into the COSMO model (Schulz 2011). Since 2 February 2011, the sea-ice scheme is used operationally at DWD within the COSMO-EU configuration of the COSMO model.

Unlike most currently used sea-ice schemes which solve the heat transfer equation on a finite difference grid, the COSMO-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, namely the ice surface temperature and the ice thickness. In the current operational 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 COSMO (GME) data assimilation scheme (see Mironov and Ritter 2003, 2004a, 2004b, for details). At present, no fractional ice cover is considered. The COSMO (GME) grid box is treated as ice-covered once the assimilation scheme has detected an ice fraction greater than 0.5 (see the implementation of the sea ice scheme into the global model ICON, where fractional ice cover is considered). A detailed description of the sea-ice parameterisation scheme is given in Mironov et al. (2012).

Strategy of COSMO and actions proposed

Short to long term (5 years)

In the near future,

- results from the operational use of the sea-ice parameterisation scheme within COSMO should be monitored in order to make a comprehensive assessment of the quality of the scheme performance and to formulate recommendations as to the scheme improvement.

Further effort should go into

- the consideration of the fractional ice cover within a COSMO grid box.

An attempt should also be made to develop a refined formulation for the ice albedo with respect to solar radiation. As far as the sea-ice physics *per se* 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.

Perspective activities (10 years)

In the long term prospect, efforts should go into

- 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 et al. (2012). However, the necessary empirical information is lacking at present. In particular, the dependence of the snow density and of the snow thermal conductivity on the snow depth, on the snow temperature, on the snow age, and, perhaps, on other parameters is largely unclear.

Resources required

Consideration of the fractional ice cover and of the explicit treatment of snow over sea ice 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 (and related parameterisations, e.g. tile approach to compute the surface fluxes with due regard for the fractional sea-ice cover) 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.

6.3.3 Parameterisation of processes in lakes

Author: Dimitrii Mironov (DWD)

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 subgrid 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 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 parameterisation scheme must meet stringent requirements of computational economy. A brief summary of lake parameterisation schemes developed to date for use in NWP and climate modelling studies is given in Mironov (2008b).

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, 2012; 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. A global lake external-parameter data (Kourzeneva 2010, Kourzeneva et al. 2012) is used to generate the lake-fraction and the lake-depth field. 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. Since 15 December 2010 FLake is operational at DWD within COSMO-EU; since 18 April 2012 Flake is also used operationally within COSMO-DE.

Although this section is concerned with lakes, the ocean/sea surface should also be mentioned briefly as it may constitute a substantial part of the COSMO-model numerical domain. 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 the NWP applications but is not adequate for climate applications (COSMO-CLM). The work has been initiated within the COSMO-CLM community to couple regional ocean models with the COSMO model for the North plus Baltic Sea (GKSS) and for the Mediterranean plus Black Sea (Uni Frankfurt, FU Berlin). Currently, the work on coupling COSMO to a regional ocean model in the context of NWP is not planned within the Consortium. Notice, however, that some other aspects of the air-sea interaction are taken into account. For example, there is a wind speed dependence of the aerodynamic roughness length of the water surface, although the roughness length formulations currently used within the COSMO model are somewhat oversimplified (that raises other issues, e.g. coupling with a wave model).

Strategy of COSMO and actions proposed

Short to long term (5 years)

- results from the operational use of the lake parameterisation scheme FLake within COSMO should be monitored in order to make a comprehensive assessment of the scheme performance and the effect of lakes on the overall forecast quality, and to formulate recommendations as to the scheme improvement.

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.

Perspective activities (10 years)

The key issues are

- the explicit treatment of snow over 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.

If a two-way interactive coupling of the atmosphere with the upper ocean is necessary in the future, FLake can be utilised as the upper-ocean parameterisation scheme, offering 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

The perspective 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 and keep a leading role within the European NWP and climate modelling community as regards to the lake-parameterisation.

Risk Assessment

There is no appreciable risk of not achieving the short to long 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.

6.3.4 Preparation of external parameters

Author: Jürgen Helmert (DWD), Jean-Marie Bettems (MeteoSwiss)

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 parameterisations. The external parameter fields are generated on the basis of raw data sets, often from remote sensing, 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). The development of new parameterisations or the revision and extension of existing parameterisations e.g. environmental prediction require additional and realistic external parameter fields.

Status of development and expertise within COSMO

The consolidation of the software for the generation of external parameter fields and the extension of raw databases was part of the Priority Project COLOBOC (see Bettems et al. 2015). Consolidation of external parameters has the goal of operational implementation of the new physiographic fields in COSMO NWP centers and CLM simulations.

As one result of this project, the software EXTPAR for the generation of external parameters now fulfils the needs of several NWP (GME, COSMO, ICON) and climate models (COSMO-CLM). Depending on the model configuration a suitable set of external parameter fields is provided by EXTPAR. Multiple consistency checks on the target grid are performed in order to avoid potential 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.

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). 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. However, in order to use these data within NWP models, some artefacts should be removed (by providers and/or by users).

Short to long term (5 years)

- Consolidate land use data based on GlobCover;
- Consolidate orography data based on ASTER GDEM;
- Consolidate external parameters for the lake model FLake, discriminate between lake and river points;
- Consolidate MODIS-based background surface albedo (e.g. consideration of available spectral bands);
- Consolidate alternative data sets of soil types (Harmonized World Soil Database, European Soil Data Base, BGR BÜK);
- Add vertically dependent soil information where available (e.g. depth of water reservoir or inactive layer and soil texture);
- Provide alternative vegetation characteristics using MODIS-based phenology model;
- The determination of the roughness length will be revised (part of WG3a activities);
- Evaluate the need for comprehensive high resolution data sets on urban properties;
- Include a MPI parallelisation of EXTPAR for very high resolution grids (will be done in the framework of the German research project HD(CP)^2).

Perspective activities (10 years)

- Address the uncertainties associated with the look-up tables, especially for the SVAT model; possibility for objective calibration will be evaluated.

- The introduction of the Vertically Resolved Roughness Layer (VRRL) requires characterizing external parameter fields for each of the discriminated surface modes (see chapter 6.1.2).

Resources required

For the maintenance, development, and documentation of EXTPAR a minimum of 3 FTE is required, in total. An EXTPAR repository is hosted at CSCS that needs management work. The close collaboration with the CLM community is needed to avoid additional expenses in the development work.

Expected Outcome

With the proposed measures, improved input fields for physical parameterisations in COSMO will be provided. New datasets in EXTPAR support the developments of the physics in the NWP models.

Risk Assessment

EXTPAR is a well-established software, used for various models. However the proposed actions depend in parts on numerical experiments with the COSMO model, which requires additional resources.

6.3.5 Summary of expected FTEs in TERRA and EXTPAR

FTEs for main priority actions for period 2015-2017		FTEs for secondary priority actions for period 2015-2017	
To be provided by COSMO partners		To be provided by COSMO partners	
- Already secured:	4.5	- Already secured:	0.0
- Potentially available:	x.x	- Potentially available:	x.x
- Missing:	x.x	- Missing	x.x
To be provided by academia		To be provided by academia	
- Already secured:	1.2	- Already secured:	0.0
- Potentially available:	x.x	- Potentially available:	x.x
- Missing:	x.x	- Missing:	x.x
All secured and potentially available	x.x	All secured and potentially available	x.x
All missing	x.x	All missing	x.x
Total required	x.x	Total required	x.x

The resources provided by academia reflect contributions for preparation of external parameters and development of TERRA including improved coupling to the atmosphere, with implementation of representation of urban processes, and model inter-comparisons and validation studies.

7 Data assimilation

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

7.1 State of the art, scientific developments

Data assimilation (DA) in NWP is the process of adjusting an a priori (or background) estimation of the system 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 Bayesian estimation theory which combines a-priori probability densities with observation likelihoods. In case of Gaussian distributions, this process requires as input the statistical error covariances of the observations and the background forecast. Within this framework, two classes of assimilation methods and their combination are in the focus of interest for NWP worldwide, that is the variational methods (3D- and **4D-Var**) and (variants of) the Ensemble Kalman Filter (**EnKF**) approach (see Evensen, 2006).

For operational global deterministic forecasts, 4D-Var is applied very successfully at several centres and seen there as a major factor contributing to model forecast improvements in the past decade. 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. To provide initial conditions for global ensemble prediction systems (EPS), 4D-Var ensembles (e.g. Meteo-France, ECMWF) and EnKF (e.g. Environment Canada (EC), UK Met Office) are applied successfully at different centres. Coupling between deterministic and ensemble data assimilation systems has been introduced, e.g. by complementing the climatological forecast error covariances in 4D-Var with EnKF or 4D-Var ensemble estimates of the error variances (and more recently correlations), or by replacing the ensemble mean analysis of the EnKF by the deterministic 4D-Var analysis. The other major European consortia for NWP are developing or already running such **hybrid** approaches on the regional (HIRLAM/ALADIN) or from global down to convective scales (UK Met Office). Recently, a technique called **4D-EnVar** (Buehner et al. 2010, named En-4D-Var therein) has attracted great attention, which combines Var with EnKF by augmenting the (transformed model state) control vector by a transform vector of the ensemble members, and which can produce initial conditions both for deterministic and ensemble forecasts. It combines many of the advantages of 4D-Var and EnKF but (unlike the other mentioned 4D hybrid approaches) without the need for a tangent linear and adjoint of the forecast model, and it is computationally much more efficient and better scalable than 4D-Var. By implementing 4D-EnVar operationally in 2014, EC is the first NWP centre to replace a fully operational 4D-Var system by another technique which does not require an adjoint model any more. Similar steps are planned or considered by most other NWP centres (excluding ECMWF), e.g. by UK Met Office or Meteo-France, in particular in view of convective-scale DA.

The main purpose of convective-scale NWP, i.e. for models which simulate deep convection explicitly, is to provide more accurate (short-range) forecasts of local weather. This is often related to complex, short-lived small-scale atmospheric structures with rapid error growth, such as convective systems or fog and low stratus cloud. In the context of DA, the following properties, even though not absent in the larger scales, are considered more pre-dominant in the convective scale and therefore pose additional challenges for **convective-scale DA**:

- highly non-linear physical processes (for which the tangent linear approximation in 4D-Var is not valid for time windows exceeding a few minutes)
- observations with highly non-linear and complex observation operators and norms
- non-Gaussian probability densities and errors, notably with respect to observations related to intermittent weather phenomena such as clouds and precipitation
- unknown and very flow-dependent balance
- large model errors, often related to physical processes or insufficient resolution
- limited predictability (of convective systems)

Despite these characteristics, applying already existing larger-scale (variational) DA schemes for the convective scale with relatively small adaptations and without requiring fundamentally different algorithmic choices has proven fairly successful (e.g. 3D-Var for AROME, 3D-Var for UK-V and 4D-Var for NDP (Nowcasting Demonstration Project at UK Met Office). One reason might be that these systems run in data-dense areas, which ensures that a lot of useful information enters the DA system. In data-poor areas, this approach may be less successful.

For forecasting of convection, the accurate estimation of both convective cells and their environment is important. Within precipitating areas, Doppler radial wind and reflectivity from radar must be used. The environment, e.g. low-level temperature, humidity and wind, 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 ground-based weather radars. Therefore and also for non-convective significant weather forecasting, it is crucial to make an optimal use of all available **observations**, including screen-level humidity, temperature and wind from surface meso-nets, wind profilers, ground-based GNSS (Global Navigation Satellite System) delays related to water vapour, high-resolution (mainly geostationary) satellite data (particularly those providing information on cloud and humidity), aircraft ascent and descent data, and if available, low-level refractivity from weather radars. Optimal use of observations also requires appropriate quality control and correct description of the observation errors, including representativeness errors. Remote sensing data have correlated errors. While these are often addressed approximately by thinning, superobbing, and increase of specified error variances, explicit representation of correlated errors between channels has been found beneficial for the use of satellite radiances recently.

Even in data-rich areas, there is considerable scope for improvement by refining the DA algorithms. Most of the available 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 strongly influenced 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 does this inherently unless sampling errors become large, and the same applies to 4D-Var if the assimilation window can be chosen large enough (which is severely limited at small scales by the presence of strongly nonlinear processes) or if flow-dependent error structures can be prescribed explicitly. A lot of effort will therefore be needed in the 4D-Var framework to develop suitable background error structures that consider the cloud processes, the impact of the orography, the structure of convective cells or the stable boundary layers. And EnKF needs optimized **sampling**, e.g. by introducing suitable perturbations in the atmosphere and the surface. A suitable combination of the variational and EnKF approaches appears to offer the best perspective eventually.

Particle filter (PF) like algorithms which, in contrast to Var and EnKF, can in principle cope both with strong non-linearity and non-Gaussianity, suffer even more from sampling errors when applied to high-dimensional systems such as NWP models. They remain prohibitively expensive as long as their resampling step does not allow them to efficiently sample the short-range forecast error distributions. Using EnKF as a proposal density in a particle filter framework might point a way to mitigate this problem, but much more basic research (in academia) on PF will be needed to pave the way for operational use in NWP.

The strong inherent coupling of the forecast model with the DA renders all 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 and low-level clouds. Those parameterisations therefore need to be more accurate at high resolution not only for the pure forecast due to higher demands on forecast accuracy in small-scale NWP, but also for the sake of data assimilation. Even though methods exist to account for some model errors in data assimilation systems, model error is a critical issue.

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 ensemble DA is a natural approach to deliver an ensemble of analyses which, possibly complemented by additional perturbations, can be used as perturbed initial conditions.

In recent years, activities have increased towards the aim of using NWP for forecast lead times below 6 hours, including **nowcasting** (0 – 2 hrs). Studies have been made using very high-resolution model setups on small domain e.g. for airport forecasting. There are technical issues such as running very high frequency analysis and forecast updates with small latency, and issues related to the NWP output, for instance to provide the information in a form which a user can base a fast decision on, e.g. for warnings. The main challenge, however, is to achieve sufficient forecast accuracy which is not outperformed by other methods used in traditional nowcasting such as Lagrangian extrapolation of observed fields and objects. This requires that the DA system is able to provide an analysis which describes accurately the weather features as observed by all kinds of different observations and simultaneously establishes a good balance and description of the unobserved fields and areas in order to avoid spin-up problems and to develop the observation impact further into the forecast. In one of the most successful attempts, the UK Met Office Nowcasting Demonstration Project 2012, NWP 2-hour precipitation forecasts were already slightly better than the output from a traditional state-of-the-art nowcasting system. The NWP system assimilated sub-hourly Doppler radial winds, wind profiler, GNSS & MSG SEVIRI data and many kinds of hourly data, including cloud information, using hourly cycling 4D-Var, and radar-derived surface rain rates every 15 minutes using latent heat nudging. Another research activity is ‘warn-on-forecast’ by a collaboration of several institutions in the USA, where the focus is on forecasting of individual strong convective storms using EnKF and EPS for lead times up to 1 hour, where the main data input is very high-resolution radar data.

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

7.2 Status and expertise of COSMO

Observation nudging (see e.g. Schraff 1997) is the standard data assimilation algorithm for the COSMO model. It is currently used in almost all convective-scale (1-3 km grid spacing) and larger-scale model configurations. Direct observations from radiosondes, aircrafts, wind profilers, surface stations, ships, and buoys are used operationally, and radar VAD wind, scatterometer wind, RASS virtual temperature profiles, and GNSS-derived integrated water vapour data can be used optionally. For the assimilation of radar-derived precipitation rates, a **latent heat nudging** (LHN; Stephan et al. 2008) scheme has been developed and is applied operationally at the convective scale at DWD and MeteoSwiss. It is currently tested for larger-scale implementations at DWD.

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 and largely flow-independent in the current implementation. 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 has been considerable work in COSMO on **retrieval techniques**. LHN may be seen as a – reasonably successful - example. However, use of temperature and humidity retrievals derived from SEVIRI, ATOVS, AIRS, and IASI satellite radiances by a 1D-Var scheme has not shown positive impact. And the adoption of the 1D-Var approach for the assimilation of surface rain rates was overall less successful than LHN.

In view of COSMO's strategic goal to further develop convective-scale EPS, a prototype of an ensemble data assimilation system based on the **4D-LETKF** (Local Ensemble Transform Kalman Filter, Hunt et al. 2007), which is a particular variant of EnKF, has been developed in the framework of the COSMO Priority Project KENDA (Kilometre-scale ENsemble Data Assimilation, see http://www.cosmo-model.org/content/tasks/priorityProjects/kenda/default.htm), which will end in August 2015. Within KENDA, one of the focal points has been (and is) on the development of adaptive methods, that is adaptive multiplicative covariance inflation, adaptive estimation of observation errors in observation space, (simple versions of) adaptive localisation, and a novel scheme for estimation of observation errors in ensemble space. Besides the use of conventional observations from radiosondes, aircrafts, wind profilers, and surface stations, observation operators have been implemented and tests have started for the use of 3-dimensional radar reflectivity and radial wind (Zeng 2014), as well as for the use of cloud top height information derived mainly from SEVIRI geostationary satellite data (Schomburg et al. 2014). In the context of the latter, some experience has been gained with strongly non-Gaussian forecast perturbations.

In addition, a 4D-LETKF system (Bonavita et al. 2010) has been developed and is already running operationally and successfully at CNMCA, albeit for coarser resolution NWP. Among other aspects, AMSU-A microwave satellite radiances over sea and land are used operationally, and experience has been gained on the use of SPPT (stochastic perturbation of physics tendencies) in the LETKF framework. Furthermore, rather extensive experience exists on **3D-Var** at DWD (operational for the global model GME), CNMCA (previously operational for the regional model HRM), and Roshydromet. Currently, a hybrid **3D-EnVar** is being developed at DWD for the new global model ICON. This combines the operational 3D-Var and an experimental LETKF into a single DA system.

A variational (2D-Var) approach is also adopted in a soil moisture initialisation scheme (Hess 2001) developed and operationally used at DWD for the COSMO model. An elaborate snow cover mask based on SEVIRI data has been developed and incorporated operationally in the snow depth analysis at MeteoSwiss.

7.3 Strategy of COSMO and actions proposed

Probabilistic forecasting based on EPS for the convective scale is a main strategic goal of COSMO. For deriving (or at least helping to derive; see chapter 8.3) perturbed initial conditions of EPS forecasts, ensemble-based data assimilation is the natural approach. 4D-Var alone cannot deliver this, and the current trend is to replace this technique due to the above-mentioned problems and costs. Therefore, COSMO will continue to develop a system mainly based on EnKF. It is noted here, that suitable perturbed lateral boundary conditions will be available for COSMO users from the global ICON EPS and 3D-EnVar that is currently being developed at DWD. A main drawback of EnKF is its assumption of Gaussian error distributions. It has been found in preliminary tests however, that the prototype LETKF can successfully assimilate cloud top height information even when the forecast perturbations are very non-Gaussian (roughly bi-modal). Even though further investigation is needed, it is an encouraging result for the LETKF. The 4D-LETKF variant of EnKF has been chosen for COSMO mainly because it is computationally very efficient, and it can assimilate observations from a whole time window in one analysis step taking into account the innovations and flow-dependent error covariances at exact observation times.

A potential viable alternative could be a hybrid EnVar which is being developed for ICON at DWD (3D-EnVar). For the analysis mean or deterministic analysis, this technique allows for localisation in background error covariance space instead of observation space, which is considered an advantage particularly for non-local observations. Also, the inclusion of prescribed full-rank background error covariances in the hybrid approach may mitigate the sampling errors, but optimizing such covariances in the convective scale is difficult due to the strong flow dependency. On the other hand, extending 3D-EnVar in time to 4D is limited in the sense that in the above-mentioned 4D-EnVar, observation times are restricted to or have to be approximated to the nearest times, at which the model states are read by the analysis scheme from files in order to re-compute the innovations at each minimisation step. In the presence of very high-frequent observations such as radar data, there is a trade-off then between frequent use of observations and costs. Generally, LETKF is computationally more efficient than EnVar, which is important in view of the increasing demand to use NWP for very short-range forecasting and even nowcasting. To arrive at a substantiated conclusion about which technique to prefer, much more practical experience is required in the next years on the LETKF for COSMO and on EnVar for ICON. If good results can be obtained and potential problems related to the specific disadvantages of LETKF can be solved in a satisfying way, the pure LETKF would be preferable for convective-scale DA.

The major strategic aim will therefore be to consolidate and further refine the current LETKF scheme. This includes a consolidation and increase of the use of observations for the convective scale, in particular of remote sensing data and observations related to the boundary layer. The data assimilation system, i.e. the setup of the scheme and the use of observations, shall also be adapted for even higher-resolution NWP for special applications, towards the nowcasting range. Even though designed and developed for the convective scale, the scheme will also be applicable to coarser-resolution regional applications, e.g. for licensees – the data set used can be extended by microwave satellite radiances, based on operational experience gained with LETKF at CNMCA.

It is noted that by design, a (well-tuned) EnKF (e.g. LETKF) should create analysis perturbations that have the same size as the analysis uncertainty (error). Although EnKF is considered a natural approach (for helping) to derive perturbed initial conditions of EPS forecasts, a tendency of the filter to suppress the fast growing modes may potentially lead to underdispersiveness of the ensemble during the forecast. Thus the relationship between the LETKF analysis and EPS performance needs to be considered. This is addressed in more detail in the chapter on ‘predictability and EPS’. The LETKF analysis perturbations may need to be adapted and possibly complemented by other perturbations for the final perturbed initial conditions of an EPS.

<u>Main actions planned in short-term perspective (2015 – 2017)</u>

1) Consolidation of the LETKF scheme, wherever it is found to be required and appropriate (depending on the results of PP KENDA and thereafter). Critical issues contain (how to account for) model error, limited ensemble size, and the ability to

use observations at high resolution when performing the analysis (locally) in ensemble space. The work includes studying the sensitivity of the analysis quality to different aspects of the DA configuration such as analysis update frequency, localisation, data thinning, covariance inflation, etc., and it may possibly include certain extensions, e.g.:

   a. multi-step analysis with variable localization for different observation types
   b. use of intrinsic stochastic physics (developed in WG3a)
   c. (other types of) additive covariance inflation
   d. Iterative (e.g. running in place like) approaches or latent heat nudging (LHN) in view of improving convection initiation
   e. use of ensemble members with lagged valid time to reduce phase errors
   f. blending techniques to combine information from the larger scales of the nesting model

   (It is noted that control runs based on the current operational DA by nudging serve as a benchmark in the development of the LETKF towards its operationalisation.)

2) Extended use of observation systems. Of special interest is high-resolution information on humidity, particularly in the planetary boundary layer (PBL), low-level convergence, but also cloud and precipitation. The use of the following data types are planned to be developed (in approximate order of priority; items a. – c. are considered most important for the convective scale and therefore have already started to be addressed in dedicated tasks of PP KENDA, but efforts will be required to continue for all of these items likely throughout the period):

   a. 3-D radar reflectivity and radial velocity
   b. Cloud top height (CTH) derived from SEVIRI data, and/or direct use of SEVIRI IR window and WV (water vapour) channels in view of assimilating cloud information
   c. GNSS slant path delay (SPD)
   d. Screen-level observations (2-m temperature and humidity, 10-m horizontal wind); these are considered important for the describing the (pre-)convective environment (low-level convergence) and for very low cloud.
   e. SEVIRI WV (water vapour) channels
   f. AMDAR humidity when available; high-resolution aircraft Mode-S (wind) data
   g. Ground-based remote-sensing data, such as microwave radiometer and Raman lidar temperature and humidity profiles, Doppler lidar wind profiles; ceilometer cloud base height
   h. SEVIRI VIS channels for cloud properties
   i. For lower model resolutions, use of MW (e.g. AMSU, HMS, ATMS) and IR (IASI) clear-sky radiances
   j. (Exploration on the) use of data related to renewable energy (power data from wind mill farms and solar power systems)

   Tentatively: Cloud radar data from EarthCare (launch 2017) in the pre-processing of SEVIRI-derived cloud information, e.g. correction of cloud top height or cloud properties. It will most likely not be possible to work on all these types of data by 2017, and external collaboration should be searched for (see ‘external collaboration’ below). It is noted that developing the use of these data types, in particular remote sensing data, typically includes substantial efforts related to data handling issues such as quality control, bias correction, and thinning.

3) Analysis and perturbation of the lower boundary conditions (BC); in the context of data assimilation, this addresses to the following variables, while other quantities of the lower BC are addressed by WG3b as external parameters:
    a. Soil moisture (soil temperature)
    b. Snow cover and depth
    c. Sea surface temperature (SST)

    Decisions on the techniques to be implemented have yet to be made. At DWD, the treatment of the lower BC is addressed first for the global ensemble DA (with DWD resources), and COSMO can benefit from that experience thereafter. Techniques for perturbations will also be developed in WG7 for the forecasting component, and some of them may also be applied within the DA system.

    For analysing (and perturbing) soil moisture (SM), two approaches are envisaged:
    a. To include soil moisture in the LETKF control vector, and possibly add SMOS/ASCAT satellite soil moisture data
    b. To deploy a 2-dimensional analysis scheme decoupled from the atmospheric LETKF at each grid point separately, either by LETKF, or by using ensemble forecasts to derive the gradient of daytime 2-m temperature with respect to a-priori soil moisture in the variational SM analysis that already exists at DWD.

4) Development towards an integrated system for nowcasting (NWC) and (very) short-range forecasting based on NWP; the following aspects are envisaged:
    a. 1-km or even sub-km model resolution
    b. very high frequent updating of analyses and very short-range forecasts, e.g. evaluation of LETKF with 5-minute analysis update using 3D radar data
    c. evaluation of adjustment of LETKF parameters (e.g. possibly reduction of localization radius to increase local match to observations), of higher weights for observations (by weaker data thinning or using smaller observation errors in the latest analysis steps), of assimilation of NWC products as pseudo observations such as objects (using non-conventional metrics), of diagnosing coherent structures to quantify position errors and correct them using pseudo-observations, etc.

5) Diagnosis: The use of FSO (Forecast Sensitivity to Observations) shall be explored in the LETKF framework in order to assess the usefulness of different observation types and help evaluating LETKF experiments. Also, the DFS (Degrees of Freedom for Signal) diagnostics is to be deployed.

6) Starting in 2017, the LETKF system has to be adapted from COSMO to the regional mode of ICON. As this implies considerable technical work, the question can be reviewed whether the further development of the pure LETKF or an adaptation of the hybrid EnVar is preferable. The standard way will be to continue with the 4D-LETKF, unless there are strong arguments in favour of the hybrid EnVar based on results and experience obtained by then with the LETKF for COSMO resp. with the global EnVar system. A main technical work to port the 4D-LETKF with the current setup to ICON will be to integrate the observation operators in the ICON model code.

It is noted that most of the above actions, notably action 4), will not be finished by 2017 and will continue thereafter. The above list is sorted according to the priority of each item as a whole. However, this does not imply equally high priority for each of the sub-items. In 2017, item 6) will attain high priority. Items 6), 1), and some sub-items of 2) (radar radial velocity, screen-level data, AMDAR humidity, Mode-S) and of 3) (snow, SST, partly soil moisture) can be seen as application research, other items as exploratory research, item 4) and some sub-items of 2) (e.g. power data) may involve even more basic research.

Apart from these main development activities related to the LETKF, few developments related to the current nudging-based DA system will be continued as they are expected to require much less resources than already invested before they can be applied operationally with benefit. This comprises the direct nudging of radar radial velocity, the use of Mode-S aircraft data, and possibly the use of ground-based GNSS-derived integrated water vapour.

In general, an upgrade of the data assimilation codes to cope with modern computing technologies (GPU, highly MPP systems) may also be needed, but this depends very much on the development of these technologies in the next years.

With COSMO-ART, COSMO has very strong modelling capabilities for environmental prediction. To benefit and better use its potential e.g. for forecasts of volcanic ash, a good description of the source terms and a dedicated DA would be required. However, developing state-of-the-art aerosol assimilation (in the EnKF framework) would require substantial additional resources, which are (currently) not available in COSMO NWS (National Weather Services). Therefore, collaboration should be sought with academic institutes which are (willing to get) strongly involved in research and development on this topic. As long as a dedicated DA is not available, MACC (Monitoring Atmospheric Composition and Climate, see https://www.gmes-atmosphere.eu/) analyses as initial conditions may be already a big improvement over using aerosol climatology.

Further actions envisaged in a longer-term perspective (2018 – 2020)

- *Conditional item:* Replacement of the 4D-LETKF by the hybrid EnVar that will be running for global DA at DWD (see also item 6) of previous list). This should be pursued (by COSMO NWS) only if LETKF results would prove unsatisfactory, and remedy of identified problems would be expected from the hybrid EnVar approach.
- Use of further satellite data:
    - Preparation for MTG-IRS (to be launched 2020)
    - MW + IR radiances over land and in cloudy areas, depending on the experience gained previously with the global EnVar DA at DWD and with the lower-resolution LETKF at CNMCA; this experience together with action item 2i will also help preparing the use of MTG-IRS
- *Conditional item*: Parameter estimation by including some physics parameters in the LETKF control vector. Investment into this conceptually appealing technique will depend on future results found in the literature. Up to now, benefit from this kind of parameter estimation in realistic setups has been found to be small even if the number of estimated parameters is kept small (≤ 3).

- *Conditional item*: Explicit representation of observation error correlations. Investment will depend on results found in the literature for the types of observations used in the COSMO LETKF, and on tests planned by Environment Canada of a methodology proposed by M. Tsyrulnikov to account for correlated errors of satellite radiances. Explicitly representing error correlations is expected to be important for MTG-IRS and potentially beneficial also for other types of data such as radar, cloud, and GNSS data.
- Data assimilation for further surface and soil properties, namely soil temperature, possibly also albedo and leaf area index.

Resources required

The basic development and completion of the LETKF system (action item 1 and part of 3) towards operationalisation requires about 4 to 6 FTE in total in the short term and is addressed mainly by ‘permanent’ staff of COSMO Meteorological Services. Most of other tasks, e.g. related to the different observation typed listed in action 2, will each require several FTE (often 3 – 5, or more, in total, allocated over several years). Most of these resources can only be attained by means of temporary positions or external collaboration. The consequences are outlined in paragraphs on 'external collaboration' and 'risk assessment' below.

External collaboration

We will continue to develop and maintain strong links and collaborations with academia. In Germany, strong collaborations have been set up with universities, in particular University of Munich (LMU), in the framework of HErZ (Hans Ertel Centre for Atmospheric Research). Project themes are arranged after consultation with DWD, taking into account the COSMO science plan (e.g. FSO in LETKF framework, use of SEVIRI VIS radiances, use of Mode-S aircraft data; or use of radar reflectivity towards nowcasting at Uni Bonn). Also related to more basic research and algorithmic developments, strong links will be maintained to German universities (e.g. Uni Göttingen: project on transformed localisation) and the University of Reading (work e.g. on improving EnKF schemes for remote sensing data, or particle filtering). To foster all this collaboration, winter and summer schools have been organized, and the International Symposium on Data Assimilation in Germany has been set up on a regular basis – these efforts will be continued. The new largely portable scripting suite to run and evaluate LETKF experiments may promote the collaboration with academia on a technical level.

On the level of European NWS, the core of the DA systems in the other consortia is 3D- and 4D-Var, but work on Ensemble DA, EnKF and hybrid approaches has increased a lot in recent years. Here, the collaboration within SRNWP may not yet have reached its full potential. Opportunities for bilateral collaboration should be screened for issues such as observation operators, as well as data exchange, data pre-processing, quality control. For the latter aspects, collaboration will be continued in the framework of EUMETNET bodies, such as OPERA for radar data, E-GVAP for GNSS data, and other European actions like COST actions, e.g. TOPROF (towards operational ground based profiling with ceilometers, doppler lidars and microwave radiometers for improving weather forecasts).

Expected outcome

The proposed effort is expected to result in improved initial conditions for the deterministic and ensemble NWP forecasts in the convective scale. This should also include a better description of the forecast uncertainty by the ensemble. Higher accuracy in particular in the very short range will pave the way towards the use of NWP for nowcasting, for further automation of forecast products and warnings, and for special applications such as airport forecasting and forecasts related to renewable energies. The system will also be applicable for coarser-resolution regional NWP, even though the focus will lie on optimizing it for the convective scale.

Risk assessment

As there is no example yet for purely using LETKF for convective-scale operational NWP at other services, the development of this new scheme is still research oriented. Currently, there are no fair comparisons yet that would show the new LETKF scheme being equal or superior to the old nudging scheme, including the latent heat nudging. Limited ensemble size and model errors may limit the ability of the filter to make optimal use of the high-resolution observations. A potential fall back option is to develop a regional version of the global EnVar scheme, which potentially may mitigate somewhat these issues, albeit at greater costs.

While the basic development of the LETKF scheme itself is addressed mainly by ‘permanent’ staff at DWD, many other important tasks, e.g. for the use of specific observation types, rely mostly on temporary positions or on projects at universities. The ability to work on the action items listed above and the quality and timely delivery of research results will depend on whether the human resources can be maintained or even increased. This implies maintaining or further enhancing the contribution from well-trained COSMO member staff and/or from COSMO internal and external temporary human resources (e.g. by continuation of HErZ after 2014).

It is noted that running LETKF experiments with COSMO requires considerable computing and storing resources. Technical problems have hampered LETKF testing at DWD in the past. A recently developed portable script suite for running and evaluating experiments has facilitated experimentation there significantly, but having sufficient computer resources for appropriate testing will remain a critical issue in general.

7.3.1 Summary of expected FTEs

FTEs for main priority actions for period 2015-2017		FTEs for secondary priority actions for period 2015-2017	
To be provided by COSMO partners		To be provided by COSMO partners	
- Already secured:	12.9	- Already secured:	2.4
- Potentially available:	6.2	- Potentially available:	0.0
- Missing:	1.6	- Missing	0.0
To be provided by academia		To be provided by academia	
- Already secured:	3.4	- Already secured:	2.8
- Potentially available:	0.0	- Potentially available:	0.0
- Missing:	0.0	- Missing:	0.0
All secured and potentially available	22.5	All secured and potentially available	5.2
All missing	1.6	All missing	0.0
Total required	24.1	Total required	5.2

2nd priority items relate to topics which are mentioned in the Science Plan, but not included in the KENDA project (and its successor, probably).

Missing FTE are small, but with more resources, the development of e.g. the use of specific observation types could be sped up.

8 Predictability and EPS

Authors: Chiara Marsigli (ARPA-SIMC), Marco Arpagaus (MeteoSwiss), Riccardo Bonanno (ARPA-Piemonte), Nicola Loglisci (ARPA-Piemonte), Andrzej Mazur (IMGW-PIB), Andrea Montani (ARPA-SIMC), Susanne Theis (DWD), André Walser (MeteoSwiss).

8.1 State of the art, scientific developments

Ensemble forecast was originally born to complement deterministic forecasts, with products such as ensemble mean for enabling medium-range predictions, ensemble spread to quantify the forecast uncertainty, meteograms for surface weather parameters, presenting a spectrum of possible alternative scenarios.

With the model resolution increase, the phenomena which are now described by NWP models are more and more stochastic in nature. For moist convection prediction, skill is manifested through the statistical properties of the forecasted convection instead of by deterministic modelling (Fritsch and Carbone 2004). Therefore, the weight given to ensemble forecast is now greater than it was before, since for the convection-permitting NWP models it is crucial to be able to forecast not only the “best scenario” but ideally the whole pdf or, more realistically, a good representation of it.

The high-resolution of these systems prevents at the moment the possibility of running consortia ensembles, as it was done in COSMO with the COSMO-LEPS system, since it is prohibitively expensive from a computational point of view to cover a large domain with the required grid spacing. DWD started to produce operational forecasts based on the COSMO-DE-EPS convection-permitting ensemble in 2012. Following this experience, the development of convection-permitting ensembles on a national scale is now taking place in several members of the Consortium. At present, it is still an open issue how to best represent initial condition and model uncertainties at the scale resolved by these models. The most suitable strategy to provide lateral boundary conditions, which should bring larger scale perturbations, is also being investigated, considering its relation to the perturbation of the initial conditions. As for model perturbations, recent works and dedicated workshops had highlighted that the explicit representation of the uncertainties intrinsic in the physics schemes is considered a promising way forward for both improving the model itself and complementing ensemble systems design. This clearly requires a strengthening of the cooperation between model and data assimilation developers as well as ensemble developers. On the one hand, ensembles cannot be longer regarded as an application, but they have now become an integral part of the modelling system. On the other hand, the description of the error affecting the whole modelling chain has now to be taken into account already in the phases of model and data assimilation development.

This change of perspective is shared by COSMO with the whole international scientific community in the field.

The problem of how to best exploit the information provided by ensemble systems is also an open issue, which should be considered from the beginning in order to target the system design towards most useful applications.

8.2 Status and expertise of COSMO

COSMO has a long-lasting experience in ensemble forecasting, with the COSMO-LEPS Consortium ensemble running since as long as 2002 on an operational basis (Montani et al. 2003). This permitted to develop several tools for the use of ensemble forecasts in the operational rooms and allowed its use in downstream applications (e.g. EFAS, the European Flood Awareness System, http://www.ecmwf.int/services/efas/).

At the German Weather Service (DWD), the convection-permitting COSMO-DE-EPS has been operational since May 2012. It is a multi-boundary and multi-physics ensemble prediction system based on the high-resolution (2.8 km horizontal grid size, 50 vertical levels) numerical weather prediction model COSMO-DE (Baldauf et al. 2011). It was run under the same conditions in a pre-operational phase since 9 December 2010, consists of 20 ensemble members, covers the area of Germany plus surroundings (421 x 461 equidistant gridpoints) and produces forecasts with lead times up to 27 hours. A new model run is started every three hours. The current setup uses different configurations of the COSMO-DE model for the variation of model physics, while the variation of lateral boundary conditions and initial conditions uses forecasts of different global models (Gebhardt et al. 2011; Peralta et al. 2011). In addition the initial conditions of soil moisture are perturbed.

In these years, expertise in COSMO has been developed in different fields of ensemble forecasting.

The role of Boundary Conditions for driving mesoscale ensembles has been studied in some detail. During the COSMO-SREPS project (COSMO Short-Range Ensemble Prediction System), developed within Priority Projects SREPS (http://www.cosmo-model.org/content/tasks/pastProjects/sreps/default.htm) and CONSENS (CONSolidation of COSMO ENSemble, http://www.cosmo-model.org/content/tasks/pastProjects/consens/default.htm), the role of the LBC diversity in relation to the number of ensemble members which is affordable to run has been analysed (Marsigli et al., 2013), indicating that variation of LBC is crucial for providing skilful forecast. More recently, the issue of LBC resolution has been addressed, also thanks to the cooperation within the C-SRNWP Programme and supported by ECMWF. At this stage, results suggest that convection-permitting ensembles (based on different models) slightly benefit from high-resolution LBCs in the short-range, up to day 2. A direct downscaling from ECMWF ENS (current resolution of approximately 32 km) to the 2.8 km COSMO model has also been tested (Marsigli et al. 2014), in comparison with a downscaling through an intermediate step with COSMO-LEPS. The direct approach showed some potential for driving a convection-permitting ensemble, especially considering the planned resolution increase (up to 20 km) of ENS to 2020.

As for the representation of the model error, resources have been devoted to studying the perturbation of the parameters of the physics schemes. This has been first applied to the 7-km ensembles, leading to the definition of a set of suitable parameters

(Marsigli 2009, Montani et al. 2011), and has then been further developed for the convection-permitting scale (Gebhardt et al. 2011). This technique is able to account for part of the model uncertainty, without degrading the forecast skill, but it is clearly not exhaustive as a representation of the model error. More recently, the SPPT scheme (Stochastic Perturbation of Physical Tendencies) developed at ECMWF (Buizza et al. 1999, Palmer et al. 2009) has been implemented into the COSMO model. Testing is currently on-going at MeteoSwiss in the COSMO-E 2.2 km ensemble, showing promising results.

At HNMS, an algorithm for the perturbation of the soil moisture fields has been developed (Marsigli et al. 2013b), but due to lack of resources it has not been tested in forecast mode.

At DWD, experiments have been carried out on perturbing the initial condition of the soil moisture. The perturbations are derived from differences between COSMO-EU und COSMO-DE soil moisture in layers down to a depth of 1m below surface. The differences are scaled in order to limit the perturbations to about 10% of soil water content. A subset of member is perturbed with positive and negative increment fields. The results of the experiments show a clear positive impact on temperature forecasts in particular in spring and summer. By improving the spread-skill relation several probabilistic verification measures could be enhanced. The method has been included in the operational COSMO-DE-EPS in January 2014.

As for the perturbation of the Initial Condition, in COSMO-LEPS a pure downscaling of global (perturbed) analyses is applied. As for COSMO-DE-EPS, up to now only global scale perturbations are added to the high-resolution model analysis.

Finally, experience has been gained in the use and interpretation of ensemble forecasts. Earlier work by Theis et al. (2005) and Marsigli et al. (2008) dealt with processing deterministic forecasts to build a prediction in probability terms and with evaluating the ensemble forecasts in terms of probability distributions, respectively. More recently, Ben Bouallègue et al. (2013), Ben Bouallègue (2013) and Ben Bouallègue and Theis (2013) focussed on how to post-process ensemble forecasts for providing useful and meaningful information to the forecasters.

8.3 Strategy of COSMO and actions proposed

The strategy of COSMO in the field of ensemble prediction is centred on the development of convection-permitting ensembles.

DWD will continue further development of COSMO-DE-EPS. Major steps will be the doubling of the number of ensemble members, an enlargement of the model domain and an increase of model levels. Investigations will be carried out on how to use KENDA initial conditions to improve the current multi-model perturbation method. New methods of the representation of model uncertainties will be adapted and tested depending on developments by physics experts in COSMO. The use of ICON-EPS for the lateral boundary condition will be a medium-term topic.

At MeteoSwiss, the COSMO-E ensemble is being developed. The set-up which is expected to become operational in 2016 is as follows: 2.2 km mesh-size for an Alpine domain, 60 vertical levels, lead-time up to +120 h and around 20 ensemble members.

Initial Conditions will be taken from an LETKF-based data assimilation system at the same mesh-size, whereas ECMWF ENS will be used for the Lateral Boundary Conditions. Model errors will presumably be modelled with a SPPT scheme.

In Italy, a COSMO-IT-EPS ensemble is being developed by ARPA-SIMC, in cooperation with USAM and ARPA Piemonte. It will consist of 10 members based on COSMO run at 2.8 km with 50 vertical levels, over a domain covering all Italy and the surrounding sea. Initial conditions will be derived from KENDA, boundary conditions will be provided by 10 members of the COSMO-ME EPS (40 members, 10 km resolution, 45 vertical levels and IC from CNMCA-LETKF, implemented by USAM in cooperation with ARPA-SIMC and ARPA Piemonte) with backup from ECMWF ENS. It is planned to introduce model perturbations, first based on perturbed parameters and then depending on the investigations which are taking place in COSMO. It is also planned to adopt a perturbation of the lower boundary initial condition, presently under development within the COTEKINO Priority Project (http://www.cosmo-model.org/content/taskspriorityProjects/cotekino/default.htm).

The development of these systems requires research at all levels, basic, exploratory and applied. Several scientific questions should be addressed, most of which at the Consortium level, involving also scientists from other modelling areas. To address these questions will be the main goal of the ensemble development in the next COSMO planning period. The items described below have been undertaken in 2014 and are planned for 2015-2016, partly within the COTEKINO Priority Project. The COTEKINO PP is structured in 3 tasks. The first deals with exchanging of results and tools for the definition of how to derive perturbed initial conditions from the KENDA LETKF. The second deals with developing and testing model perturbations for the convection-permitting ensembles. The third deals with the development and the implementation of lower boundary perturbation for COSMO at the convection-permitting resolution. The tasks are described in more detail in the appropriate section below.

Initial condition perturbation

An ensemble forecasting system at convection-permitting resolution should benefit from appropriate initial conditions, where a good representation of the initial state, obtained through the assimilation of timely high-resolution data (e.g. radar data) is combined with a comprehensive representation of the uncertainty affecting the small scale and the phenomena represented by the high-resolution model.

In COSMO, it is decided to give high priority to investigating how to derive perturbed ICs for the convection-permitting ensembles from the LETKF scheme developed in the KENDA Priority Project. This choice is motivated by the fact that LETKF has the potential for assimilating high-resolution observations, which are needed for a good representation of the initial state up to the small scale, and can also provide an estimation of the analysis uncertainty through the ensemble. The extent to which the first statement is true, will be investigated as part of KENDA development and it is addressed in Section 7, while the second issue will be addressed as part of the research about convection-permitting ensemble forecasting and will be described in this section, together with the methodology adopted to check the appropriateness of this assumption.

Applied research, carried out in cooperation between ensemble and data assimilation scientists, is planned for the definition of the set-up of the KENDA system suited for this application. Several aspects should be investigated, which may depend on the domain over which the system is implemented. Since data assimilation is dealt with, the type and density of the observations available in each domain influence the performance of the DA scheme. Therefore, the set-up will be studied separately for each country. In order to facilitate the exchange of the information, the diagnostic approach will be the same in all the countries and an exchange of diagnostic tools is already implemented. Meetings for the common discussion of the results will be regularly held. In particular investigation will focus on the set-up of the LETKF ensemble (number of members, boundary conditions, model perturbation) and the set-up of the LETKF algorithm (described in section 7), which are part of the KENDA development and which are already on-going, also based on dedicated OSSEs.

For the definition of how to derive initial conditions for the convection-permitting ensembles, applied research is planned to evaluate different methodologies. The different analyses provided by the LETKF scheme can be used directly as initial conditions of the forecasting ensemble. Since analyses are available at each LETKF step (hourly or sub-hourly, depending on the implementation), the necessary frequency to initialise the forecasting ensemble is guaranteed. These analyses could be affected by too small spread, which would imply an underestimation of the IC uncertainty, due to the choices made in the LEKTF scheme, which might be appropriate for DA purposes and less appropriate for EPS purposes. Therefore, different approaches for initial conditions generation will also be explored, e.g. by blending the small-scale perturbed KENDA analyses with analyses perturbed only at the large-scale, as the ECMWF ENS ones (51 analyses are available 2 times per day, at 00 and 12 UTC). A different approach which will be tested is the combination of LETKF and nudging, deriving the fine-scale analysis with the nudging technique and then adding the perturbations computed by KENDA to it. This last approach could be especially valuable to prevent a drift of the LETKF. The coordination of this work (meetings, links with KENDA, exchange of information) is presently carried out in the COTEKINO Priority Project.

In order to test the benefit of using KENDA-derived initial conditions, comparison with pre-existing simpler methods will be carried out in forecast mode. Convection-permitting ensembles will be run with KENDA-derived ICs (with the above mentioned different options for computing the ICs) and with ICs obtained with simpler techniques: nudging analysis combined with large-scale perturbations (as it is now operationally done in COSMO-DE-EPS) or downscaling of global forecasts, as the analyses which initialise the members of the ECMWF ENS. These simpler methodologies can provide also the back-up solution in case the KENDA-based approach does not lead to satisfactory results. In this case, different methodologies will be considered, subject to a rethinking of the strategy in this field.

The whole issue of using Initial Conditions derived from KENDA has high priority in the COSMO countries, especially for those who have or have planned a convection-permitting ensemble. Priorities should, anyway, match those of the development of the KENDA system: it is clear that a satisfactory use of KENDA for the ensemble forecasting purposes cannot leave out of consideration the capability for assimilating non conventional observations, which are believed to determine most of the gain for the km-scale.

Resources required

The research needed to derive ICs for the convection-permitting ensembles from KENDA and the related testing in forecasting mode requires a dedicated work in each of the countries which plans to use this approach for initial condition perturbations. The estimated resources for this work are up to approximately 2 FTE for each country, also depending on the issues which are taken into account in the analysis.

Lateral boundary condition perturbation

The best strategy for IC perturbation can be dependent on the type of perturbation strategy chosen for the LBCs. Therefore, it will be investigated how IC perturbations relate to LBC perturbations, and their consistency will be considered.

For LBC perturbations, different methodologies will be considered by different COSMO partners. One possibility is to use LBCs provided by a global scale ensemble (e.g. ECMWF ENS). Though, the issue of spatial and temporal resolution at which these LBCs are available should not be forgotten in the system design. Other available options are the use of DWD BC-EPS (providing higher resolution forecast but far less members and running only for 48 h) and, later on of ICON-EPS, the global ensemble currently under development at DWD.

Since the convection-permitting ensembles will likely have less members than the ECMWF ENS, mainly due to computational constraints, if IC and BC from this are used it is important to establish a methodology for selecting a subset of members from the full global ensemble. The extent to which the Clustering and Representative Member selection methodology which is adopted by COSMO-LEPS can be applied to the O(1km) scales should also be investigated. Different domains and variables of the clustering algorithm should be tested, in order to select the ensemble members that are most different on the area covered by the regional ensembles and which differences are most relevant for the convection-permitting runs. The new methodology tailored for this application could be adopted in the operational setting, if it is proved more beneficial than random selection.

As a side issue, also the number of members which is appropriate to run in a convection-permitting ensemble should be subject to investigation. Likely, more members than what is presently affordable to run would be needed for a good representation of the forecast uncertainty affecting the scale of few km. Anyway, the issue will require a dedicated investigation when the systems are in a mature stage, having completed the development of the perturbation strategy (physics, IC, soil). In particular, it should be carefully considered which indicators are suitable to express the amount of skill in dependency of the ensemble members. Currently there are no resources which can be dedicated to this topic, but some could be moved to it once the ensemble development is completed.

Resources required

The adaptation of the clustering methodology requires approximately 0.5 FTE.

The investigation on the optimal number of ensemble members is estimated to require approx 0.5 FTE.

The tests on LBC are estimated to require about 0.8 FTE.

Model perturbation

A closer cooperation between physics and ensemble developers is foreseen in this field. It has recently been corroborated in dedicated workshops (ECMWF 2011, SRNWP 2013, “COSMO Stochastic Physics Week” 2013) that the model perturbation approaches should become less heuristic and more physically-based. There is general agreement about the fact that the ensembles should aim at explicitly representing the sources of model error, instead of accounting for forecast error by means of statistical techniques. On top of this, it is believed that intrinsically stochastic physics schemes could bring benefit also to the deterministic forecast, since the NWP model benefits as a whole, becoming more effective in representing the physics phenomena.

In COSMO, DWD has started to work at the stochastic description of subgrid scale physical processes, aiming at introducing a more physically-based description of the model error in the model itself. This work is high-priority for the whole Consortium, therefore COSMO should invest resources from other Countries if they are needed. Currently, this work is not part of a Priority Project, but enforced communication with COSMO partners is enclosed in the COTEKINO Priority Project.

Recently, the SPPT scheme developed at ECMWF (Buizza et al., 1999; Palmer et al., 2009) has been implemented into the COSMO model. The scheme consists of a random perturbation of the model tendencies computed by the physics parameterisations. The purpose it to use this scheme as a mean for partly accounting for the model error both in the assimilation cycle based on KENDA (see chapter 7.2) and in the forecasting system. Several issues are brought about by the use of this scheme: first of all it was developed for a global model running at quite coarse resolution (32 km at present), therefore the extent to which it is suitable for accounting for model error at the convection-permitting scale is not a straightforward matter. On the one end, it could be investigated how to make it more suitable for the O(1km) scale, by selecting appropriate spatial and temporal structures of the random coefficient. The scale of the perturbation can be made smaller, trying to account for smaller-scale errors. At the same time, also the amplitude of the perturbation can be selected. Analyses of the scheme behaviour in COSMO at 2.2 km are being carried out by MeteoSwiss, also within the COTEKINO Priority Project. Results are quite encouraging, showing an increase of spread and a better spread/skill relation, and SPPT is now implemented at MCH in the experimental COSMO-E runs. The issue of the spatial scale of the perturbation has been discussed in different meetings and the general agreement is that the scheme works for perturbing the synoptic scale, while it is not effective for small-scale structured perturbations. If the correlation scale of the perturbations is decreased, error growth decreases significantly. This technique, though it may prove effective, is anyway quite heuristic and does not permit a description of the model uncertainties. Instabilities close to the lower boundary should also be checked in the development phase.

The Stochastic Kinetic Energy Backscattering (SKEB) scheme (Shutts 2005, Berner et al., 2009) is an alternative option to account for model errors, which has been implemented by MCH in a version of the COSMO model. Tests of its behaviour are planned in 2015 as part of MCH activity in the COTEKINO PP.

Finally, it should be mentioned that the Random Pattern Generator developed by Roshydromet (Tsyrulnikov and colleagues) in the framework of the KENDA PP, could become a useful tool to apply a suitable spatio-temporal structure to perturbations of different components of the model (e.g. upper-air physics, soil).

Resources permitting, these schemes will all be tested against what is currently available and implemented in the ensemble, namely mainly multi-parameter and multi-physics schemes. The extent to which new model perturbation approaches can add spread to the ensembles, especially for near-surface variables, will be evaluated. This will be done first by checking how a single scheme works in comparison with another (power spectra, scale of the perturbation, amplitude of the perturbation), then by assessing the impact on the forecast by means of the spread/skill relation computation, aiming at measuring how much of the forecast uncertainty is explained by the additional ensemble spread. During the SRNWP PHY-EPS Workshop in 2013, it was noted that intrinsically stochastic schemes do not perform, in real cases, as good as expected, in comparison with less-physically based perturbations. This could be due to the tuning performed when multi-physics, multi-parameters or SPPT perturbations had been implemented. Therefore, the analysis of the performance of the new technique under development will have to take this into account and allow for gaining some experience with the new schemes and their possible tuning potential before drawing conclusions about their performance with respect to the old ones.

For a proper development of suitable model perturbations, some basic research about the model sensitivity to simple perturbations would be desirable. In particular, it should be addressed how the perturbation is spread to scales different to the one to which it is applied, and how uncertainties affecting different scales interact. This can be performed by means of dedicated sensitivity studies, which should be set-up specifically for each topic under consideration. It is worth noting that parameter perturbations, though quite simple as model perturbation strategy, may be a good diagnostic tool to study the spatio-temporal characteristic of the model response to uncertainty. Also for this task, the diagnostic approach will be agreed upon among the involved partners, to be able to benefit from each other’s results. Furthermore, care should be taken in studying how the forecast is affected by the different sources of uncertainty (ICs, model, boundaries), therefore the development of the different perturbation methodologies will be carried out in a coordinated way and the results analysed homogeneously.

Clearly this more basic research should proceed in parallel with the implementation of operational ensemble systems. It could be the case that ensembles will start their operational life with configurations which are not optimal, to allow for the continuation of the developments and the refinement of the methodologies without interfering with the operational constraints.

Finally, the experimental knowledge gained with this research could feed back to model development, providing useful hints about the model behaviour and helping the development of new truly stochastic physics schemes. This process of mutual interaction between physics and ensemble, though not trivial, is expected to bring benefit to the whole modelling system over longer time scales.

Resources required

Resources for the development of intrinsically stochastic physics schemes are accounted for as part of the Physics activities. The adaptation and testing of SPPT requires an amount of resources estimated as 1 FTE. Its implementation and testing in different ensemble systems and the evaluation of its effect with respect to other perturbations requires 1 additional FTE. Additionally, 1 more FTE is required for testing other physics perturbation methods (e.g. stochastic physics) and for addressing the issue of studying the effect of the different error sources.

Lower boundary perturbation

Lower boundary perturbations are also believed to play an important role at the O(1km) scale. Surface condition uncertainties are seldom taken into account in ensemble systems, despite the sensitivity of moist atmospheric processes to soil conditions has been demonstrated in numerous studies (see e.g. Sutton et al. 2006). A non-cycling surface breeding method was proposed by Wang et al. (2010), where short-range surface forecasts driven by perturbed atmospheric forcing are used to generate surface ICs perturbations. Cloke et al. (2011) proposed a simple method in the ECMWF seasonal forecasting system, perturbing two soil scheme parameters. As mentioned above, DWD has recently included soil moisture perturbations in the operational COSMO-DE-EPS derived from differences between COSMO-EU and COSMO-DE soil moisture.

Before the implementation of further techniques for the perturbation of the soil state, the sensitivity of the COSMO model to different soil moisture and temperature initializations has been verified, as part of the COTEKINO Priority Project. At ARPA Piemonte, different soil moisture analysis and reanalysis coming from global, regional and land surface models have been used, analysing summer and winter case studies (hence including stable and unstable boundary layers). The aim of such sensitivity tests was to assess the impact of the soil moisture initialization on the short range ensemble variability, focusing the attention on the spread of some surface variables that are significantly affected by the initialization of the soil state (Bonanno and Loglisci, 2014). IMGW-PIB has performed an analysis of the influence of various model set-ups (e.g. parameter configurations, numerical schemes, physical parameterisations etc.) combined with simple changes of the selected soil-related model parameters (like surface-area index or bottom of the last hydrological active soil layer), to test the sensitivity to the soil parameters and detect the more and the less significant ones (Duniec and Mazur 2014).

Results showed a significant impact of soil condition perturbations on the spread, especially for summer cases and for cases of weak synoptic forcing, leading to the implementation of two techniques currently under test in the framework of the COTEKINO PP. The one adopted by ARPA Piemonte, proposed by Lavaysse et al. (2013), generates a two-dimensional random function on the sphere correlated in space. This approach is being tested, addressing the issues of selecting appropriate correlation length and amplitude of the perturbation. The one adopted by IMGW-PIB consists in the perturbation of few selected soil model parameters.

Eventually some more sophisticated approach could be further analyzed. In COSMO Priority Project CONSENS a methodology for soil moisture perturbation based on Sutton and Hamill (2004) was developed by the Hellenic National Meteorological Service (COSMO Technical Report No. 22). This method uses the empirical orthogonal functions (EOF) to generate random perturbations with the same spatial structure as the daily deviations of soil moisture from a running-mean climatology. The method was never tested in ensemble mode but it could be reviewed and tested on the new ensembles under development.

Resources required

The implementation and testing of the perturbation methodology requires approximately 2 FTE.

Link with other groups

The integration of the ensemble system in the model development and evaluation activities has gained momentum. Recently the link with the data assimilation group has strengthened, thanks to the development of an ensemble data assimilation scheme. Also, a link with model physics development is starting to be established, due to the aforementioned plan for intrinsically stochastic parameterisations and for sensitivity studies based on the ensemble. As for the model soil, the development of new perturbations and the elaboration of dedicated sensitivity studies will also help in increasing the integration between the two fields.

From the verification point of view, a big effort has been made to include ensemble verification among standard verification practice, in collaboration with WG5. In particular, the capabilities for ensemble verification are being implemented in the VERSUS package, aiming at operational verification of the ensemble products.

Finally, the development of an ensemble use and interpretation branch is being considered, in collaboration with WG4 and WG5.

The motivation for this link resides in the fact that the ensemble forecasts often cannot be taken as direct model output. For a proper usage of ensemble forecasts by users (here mainly forecasters), the outputs have to undergo a certain amount of processing, which can be carried out in terms of meteorological parameters, ensemble statistics and/or spatial and temporal aggregation. This processing usually must be optimised by the mean of a suitable verification (see also section 11.4). This optimisation can be of general use, or be targeted for example on extremes or specific applications.

Application of spatial techniques (neighbourhood methods) to ensemble processing is already done at DWD and ARPA-SIMC. It is also planned at MCH.

Quantile optimisation and calibration (of probabilities) are also means of processing the ensemble outputs, in order to forecast ordinary events or extremes.

These activities are partly on-going at a few centres but more structured activities will be planned once the convection-permitting ensembles will be in place in most of the COSMO countries. However, at the consortium level, the previously stated strategies will be taken into account in the planning of the development of processing (e.g. FIELEXTRA) and verification tools.

This would require some resources which are not currently available since, from the ensemble point of view, now the development of the convection-permitting ensembles themselves has higher priority. The only activity which is already foreseen is the derivation of guidelines on ensemble use for the forecasters from the experience during the Sochi Olympics.

In the framework of the EUMETNET Project C-SRNWP, coordination of ensemble activities in the different Consortia is also taking place. The aforementioned test of LBC from ECMWF ENS at coarser and higher resolution is part of this activity.

Furthermore, the EUMETNET project study SRNWP-EPS Phase I has taken place, leading to the definition of a useful and suitable cooperation between Weather Centres in the field of convection-permitting ensemble which will cover the period 2015-2017.

Italy and Switzerland are the two COSMO countries which will participate in this Programme, therefore it is expected an influence of the Programme on the planning of the research activities.

Finally, the TIGGE-LAM panel of the WMO THORPEX project should also be mentioned. Recently the panel has promoted the creation of a common archive for weather parameters, with several operational ensembles providing data for verification and comparisons

Resources required

The resources required for the activities of ensemble use can be estimated in 1 FTE.

COSMO-LEPS

The maintenance of the COSMO-LEPS ensemble is guaranteed at least for the first planning period, until other means for ensemble forecasting will be available for the COSMO Countries. The system will also facilitate research on convection-permitting ensembles, through the provision of Boundary Conditions and by providing a reference against which to test the predictive ability of the convection-permitting ensembles under development.

Moderate development of the system is foreseen, to keep it at the state-of-the-art, and a dedicated study on the ensemble reduction technique will be performed, which could also benefit the finer-resolution applications, as mentioned above.

Resources required

Resources required for the COSMO-LEPS maintenance and development are in the order of 0.5 FTE for the duration of the current Science Plan.

Long-term perspective (2017-2020)

In the long term perspective, convection-permitting ensembles are foreseen to reach the operational status in several COSMO Countries. This opens the possibility of sharing the developed perturbation methodologies and/or to provide combined products in the overlapping areas. More detailed planning on this latter issue will be addressed in close cooperation with WG4 and WG5. Also, post-processing of the new ensemble products should be taken into consideration.

With the increased use of ensembles in the forecasting chain, more applications will be likely based on ensemble outputs, requiring ad hoc products and tailoring of ensembles for the different applications (hydrology, wind and photovoltaic energy production, air traffic management, air pollution, dispersion modelling).

Depending on the timing of the availability of the global ICON-EPS, its role should be investigated in providing Boundary Conditions to the higher resolution ensembles. Naturally, all the developments of the ensemble systems are influenced by the possible replacement of the COSMO model with the ICON model. A close eye to the development of the model in general and of ICON in particular is needed to allow timely and meaningful planning from the ensemble forecasting side.

Resources required

An estimation of the resources required for each of the planned activities has been performed in the appropriate subsections above. The total amounts to about 10 FTEs at minimum.

As a general remark on resources availability and development, it is recognized that ensemble development should be carried out in close cooperation between scientists with different expertise (data assimilation, predictability, model physics, verification). In COSMO, limited resources are available outside DWD in the data assimilation and model physics fields, and this now represents a critical point for ensemble development. In fact, while the model is the same for every member of the Consortium, ensembles are different for the different members. Therefore, new resources should be developed across the Consortium in these fields. Resources from the Academia may be also available, but they can be really beneficial only if some expertise already exists in the COSMO institutions.

Finally, it is clear that not all the investigation outlined need to be carried out by all COSMO partners. If a good level of communication is established and maintained, some results obtained over a particular domain and with a particular set-up could provide useful hints for other partners. This can apply e.g. to the investigation on the scale at which to apply specific model perturbations and of course to the methodology for evaluating the experiments.

Expected outcome

The activities planned for the next few years are mainly intended to bring the most recent advancements in the ensemble forecasting field at the Consortium level. This outcome will derive from both the development and implementation of convection-permitting ensemble systems in different COSMO countries, with sharing of the necessary research, and from the integration of the activities related to ensemble with the other model-related activities, as for example verification of the operational chains and post-processing.

It is also expected a strengthening of the cooperation between model developers and ensemble developers. This is already taking place in data assimilation, but it will affect more and more the design of the model itself.

Ensembles are expected to become an integral part of the modelling system.

Risk assessment

The major risk potentially affecting this plan is the lack of resources. While for the activities scheduled within the COTEKINO Priority Project resources have already been allocated, these activities alone do not guarantee the realisation of the entire plan. It is envisaged that resources will be confirmed by the countries already involved in the ensemble development tasks. It is also desirable that cooperation with the Academia will be reinforced. This would permit to address new development lines, in case some of the activities which involve basic research do not have a positive outcome (initial conditions from KENDA, stochastic physics, lower boundary perturbation, direct downscaling of global ensembles).

8.3.1 Summary of expected FTEs

FTEs for main priority actions for period 2015-2017 (test ICs from KENDA LETKF in ensembles, physics perturbations, soil perturbations, study on clustering, Lateral BC, COSMO-LEPS)		FTEs for secondary priority actions for period 2015-2017 (e.g. investigation of optimal number of members, methods for product generation)	
To be provided by COSMO partners - Already secured: - Potentially available: - Missing:	8.4 1.2 1.4	To be provided by COSMO partners - Already secured: - Potentially available: - Missing	0.8 0.7 -
To be provided by academia - Already secured: - Potentially available: - Missing:	1.5 0.3 -	To be provided by academia - Already secured: - Potentially available: - Missing:	0 0 0
All secured and potentially available	11.4	All secured and potentially available	1.5
All missing	1.4	All missing	-
Total required	12.8	Total required	1.5

9 Validation and diagnostics

Authors: Flora Gofa (HNMS), Adriano Raspanti (USAM), Francis Schubiger (MeteoSwiss)

9.1 State of the art, scientific developments

The systematic evaluation of numerical forecasts is crucial for the development, refinement and interpretation of any modelling system and comparison between model predictions and observations is able to provide useful information on the quality and accuracy of the modelling system itself. During the last several years, the main effort in verification activities has been to develop, for the whole Consortium, a unified tool (VERSUS) in order to standardise the verification procedures, homogenise the results and to provide new kinds of information to the modellers through the exploitation of the system's Conditional Verification functionalities. The recent developments concerning very high resolution (up to 1km and more) for deterministic model and the convection-permitting ensemble will influence verification activities in the near future. 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 is known as the “double penalty” problem. The need for verification techniques that allow for some tolerance to reasonably small space and time errors is hence obvious. These different approaches 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 to detect possible connections between forecasts deficiencies and specific weaknesses in model formulation.

Finally, it has become evident that the various users of model products need dedicated and specific information and for this reason different strategies have to be identified. Verification activities shall be able to differentiate their outcomes, diversifying methodologies and approaches to meet the requirements of different user communities (model developers, forecasters, external clients).

Similar approaches are adopted in other European Consortia and, with some differences, the situation related to verification state of the art and scientific development is comparable. For instance, the common verification framework methodology adopted in the SRNWP Verification Programme reflects well the similar activity carried out routinely in COSMO for the comparison of different COSMO model implementations on both specific domains and on a common area.

9.2 Status and expertise of COSMO

Operational verification is carried out routinely by COSMO members using VERSUS, the system developed by the Consortium, and, in some cases, in parallel with some members' existing software, pending the completion of the Priority Project VERSUS2 (http://www.cosmo-model.org/content/tasks/priorityProjects/versus2/default .htm) and the availability of the complete set of required functionalities. The main activities of the relevant working group, as listed in the work packages cover the following issues:

- Common Verification framework;
- Exploitation of observational datasets for operational and scientific purposes (e.g. rain gauge networks and SRNWP data pool in PBL);
- Evaluation of convection permitting model performance;
- Neighbourhood and object-oriented techniques;
- Verification of EPS products.

At the moment in the framework of WG5 coordination, there is a main development in progress, the continuation of the VERSUS2 Priority Project, while the Priority Task NWP Test Suite ended successfully in 2014. Both activities are described briefly below.

VERSUS 2 Priority Project (extension of VERSUS)

The aim of the VERSUS Priority Project, started at the end of 2006 and concluded in February 2009, was the development of a common and unified verification 'library' including a Conditional Verification (CV) tool, with a wide range of functionality.

In the course of the VERSUS project development, most of the COSMO members moved towards higher resolution models and, in addition to the increasing horizontal (and vertical) resolution, the activities of the consortium increasingly included the development of ensemble prediction systems and associated probabilistic forecasting. Therefore, suitable verification methods for this kind of forecasts have to be applied also in order to compare them to deterministic models results and assess the potential benefits of using EPS systems.

The VERSUS 2 Priority Project aims then at complementing the common COSMO verification tool with the features mentioned above. Consequently, COSMO shall plan with respect to its priorities on the next steps with regard to the selection, development, enrichment with additional functionality (e.g. additional verification methods) and maintenance of a common verification system.

NWP TEST SUITE – Verification of Reference Version of COSMO

The aim of this priority task and its further evolution, was to build up a software environment to perform carefully controlled and rigorous testing, including the calculation of verification statistics for any COSMO model test version. This platform is the tool to be used for performing the mandatory tests prior to an upgrade of a model test version to a new release as described in the Source Code Development document. It also provides a tool available and accessible to each COSMO member for testing in a standardised way each released model version. Moreover, this test procedure could serve as a benchmark to monitor the progress of mesoscale forecast improvement through periodic re-testing as the COSMO system evolves. The system includes the actual NWP suite to run the model and VERSUS to perform verification. It is installed on ECMWF computer facilities in order to allow the greatest possible access to all COSMO members through the setup of a Special Project at ECMWF.

Furthermore, COSMO consortium through its members will participate to the international project MesoVICT. The rationale of this project is to focus on the application, capability and enhancement of spatial methods to forecasts over complex terrain, both for deterministic and ensemble forecasts. Coupled to this is the expansion to consider other parameters, especially wind, and the issue of observations uncertainty.

9.3 Strategy of COSMO and actions proposed

In line with the directions of the COSMO consortium, the main priorities in the short and medium term (up to 5 years) are described below. The actions are either on-going or closely connected and dependent on model developments and subsequent verification needs. The strategic activities are shown in order of decreasing priority, even if all of them can be considered crucial in the development of COSMO activities.

Tackling model performance improvement issues through the use of conditional verification (CV)

The classical verification of forecast products is generally based on the evaluation of single elements (e.g. T_{2m}, precipitation) over specific domains in space and time where potential interdependencies between various products are a priori ignored (e.g. cloud cover & near surface temperature). This suggests that once model errors are estimated for a certain variable through “standard” verification, afterwards those errors should be related to specific inaccurately simulated processes. The formulation of forecast verification in conjunction with the existence of additional criteria can be considered the definition of “conditional verification” (CV). Its purpose is the systematic evaluation of model performance in order to reveal the typical shortcomings of a model and the reasons behind, to monitor the model in a routine fashion, to provide information to the model developers as well as to the forecasters with regard to the situation and product dependent model reliability.

The typical process is based on the selection of forecast products and associated “mask variables” (model variables, observations or external variables) and the possibility to formulate arbitrary thresholds (conditions) for the product verification. The masking requirements may occasionally be rather complex, for example verification of T_{2M} in the presence or absence of snow or the verification of products like surface radiative fluxes or T_{2m} itself stratified by cloud cover. Finally, more sophisticated algorithms or even manual intervention could be necessary in the stratification of all cases with regard to the mask criteria. With this in mind, a unified verification system – VERSUS was developed by COSMO to respond to such needs. Among the several features available, the primary function is the implementation of modules performing flexible and configurable CV in a setup.

Over the last several years, exploiting the potential of VERSUS, several conditional verification activities have been undertaken helping restrict the sources of errors to processes, like vertical diffusion within the boundary layer, incorrect radiation fluxes at the surface or erroneous heat conductivity of the soil. The use of well-observed case studies is very useful for this evaluation of modelled processes and for testing parameterisation schemes. A standardized testing configuration can support model developers and could help to evaluate and compare different physics schemes. At the same time, as like any traditional verification activity, CV does not provide straightforward feedback regarding to what extent the model correctly simulates processes and which not, but it is crucial in the identification of the right connections between atmospheric variables and the interpretation of results. To this end, effective collaboration and coordination between WG5 and WG3 to develop a common strategy regarding how to tackle model deficiencies is essential to efficiently understand, investigate and improve model performance (see chapter 11.2 on processing verification feedback on model development).

Statistical methods to identify the skill of convection-permitting and near convection-resolving model configurations

Progress in improving skill when comparing forecasts from models as grid size has decreased from 30 km to 10 km has been steady, but this has not been the case for convection-permitting models with grid resolution on the order of 3 km and less. This is due to the fact that apart from the obvious benefit in the improved simulation of convection related weather from smaller grid size models, faster growing forecast errors (Lorenz, 1969) can develop in the finite spatial/temporal displacement of weather features. Nowhere is this more valid than in forecasting precipitation where forecast detail may be realistic but is not accurate. Surprisingly, even continuous surface parameters may not always benefit from a smaller model grid size since their detailed structure may be penalized by certain indices (e.g. RMSE) that reward smoothness.

Neighbourhood methods are designed to compare neighbourhoods of forecasts with neighbourhoods of observations with the aim of evaluating models at varying scales of resolution (spatial but also temporal) (Ebert 2008). The spatial verification techniques can fall into two categories: a) **object oriented techniques** that try to identify weather features in the forecast and observations and compare their properties (Ebert and McBride 2000, Davis 2006) and b) **fuzzy verification techniques** that require that the forecasts are in appropriate agreement (e.g. in space, or time, or intensity) with the observations. By measuring the actual strength of the agreement, feedback is provided for the temporal or spatial scales at which the forecasts should be used to meet the selected requirements (Casati et al. 2004, Damrath 2004, Weusthoff et.al. 2010). In the short-term, several metrics based on Beth Ebert's fuzzy verification framework will be incorporated as well as other methods such as SAL, which identifies objects in both observation and forecast space and gives them the attributes of Structure, Amplitude and Location (Wernli et al. 2008).

Most of these methods for high resolution verification depend on gridded observations. Despite the fact that any long-term monitoring of forecast skill against gridded observations can include biases not connected only with model evolution, these data can be valuable when comparing different model configurations. For most synoptic parameters, observation coverage is not always satisfactory in either space or time and the effects of double penalty and representativeness get enhanced. A statistical framework based on neighbourhood forecasts of varying sizes can be applied over the whole range of distribution of values or categorically using specific thresholds, helping to estimate the effect of the previously mentioned sources of error. The metrics that can be used depend on the requirements of the decision model for useful forecasts and can be both deterministic for spatial methods or based on a probabilistic approach focusing either on the verification of the distribution (CRPS) or on verification on certain thresholds (BSS) (Mittermaier 2014). A combined procedure of verifying model output point-to-point against observations with the application of neighbourhood forecasts for different windows may help to determine the inherent skilful scale of a model for a given variable. Subsequently, the comparison of one model against another of higher resolution or even against an ensemble system over forecast neighbourhoods of comparable size can facilitate the process of revealing the relative skill of one configuration versus the other.

Development of tools for probabilistic and ensemble forecast verification

Development of future verification capabilities within COSMO must take into account the future development of probabilistic and ensemble forecasting. "Convection-permitting" ensembles, which focus on short timescales (0-24h), are subject to large error growth correlated to the highly non-linear processes of convection and pose complex challenges in terms of verification, which must focus on the relative gain of using such systems with regard to improved representation of convection-based parameters. Where deterministic forecasts are concerned, neighbourhood methods can provide feedback regarding spatial mismatches between forecasts and observations, in particular for precipitation while ensemble forecasts deal better with the uncertainties associated with small-scale processes.

The common verification software in COSMO includes a module that handles probabilistic verification needs through dedicated metrics. A well established set of scores for the ensemble verification are currently employed and in the future, more statistical indexes and capabilities (CRPS, CRPSS, spread/skill relation, use of reference provided by the user (climatology) will be included. It is also recommended to evaluate the confidence of the results with some statistical inference tests, either parametric or non-parametric (bootstrapping method).

Two main factors have to be considered when comparing different ensemble systems: the difference in the number of members and in terms of horizontal resolution. The issue of the different ensemble sizes may be disregarded if the verification focuses on assessing the strengths and weaknesses of the different ensemble systems from an operational point of view, also taking into account the fact that the ensemble size has an impact on the value of the scores. For the comparison of systems of different resolution and mainly for the precipitation, it is suggested to apply spatial verification methods. In recent years much work has focused on the application of neighbourhood verification methods (described in the previous section) on ensemble forecasts (Schwartz at al. 2010, Le Duc et.al. 2013). Determining the degree of usefulness of a particular forecast by comparing it with the observed frequency of events within a specific spatial window can also be applied to EPS systems. The resulting probabilities consequently correspond to a spatially smoothed version of raw probabilities related to the ensemble members at the particular grid point (Bouallegue et al. 2013). The availability of spatial verification techniques in COSMO EPS systems will enable better evaluation of the performance of an ensemble forecasting system and will also provide feedback for producing more skilful probabilistic products.

Severe and High Impact Weather

The increased demand to provide accurate forecasts of extreme weather leads to the issue to objectively evaluate forecasts of extreme weather.

Severe events are rare thus standard skill scores are not useful as most of them depend on base rate like the widely used ETS. As the base rate tends to zero for rare events, most common scores tend to trivial limits, making them unsuitable to measure forecast ability. The odds ratio and the extreme dependency score (EDS) (Stephenson, 2000 and Stephenson et al. 2008), are independent of base rate and take asymptotic values depending on the behaviour of the forecasts, and are better candidates for assessing extreme forecasts. Due to the limited sample size of such events, all scores should be applied with statistical inference methods like confidence intervals or standard errors. The Stable Equitable Error in Probability Space score (SEEPS) has been developed explicitly with the goal of verifying categorical deterministic precipitation forecasts (Rodwell et al. 2011). In contrast to traditional deterministic precipitation verification, it makes use of three categories: “dry”, “light precipitation” and “heavy precipitation”, and it has been designed to have the characteristics to be as insensitive as possible to sample uncertainty. SEDI and SEEPS together applied can provide complementary assessments of forecast performance. SEEPS quantifies general performance in the prediction of dry weather and precipitation amount while SEDI focuses on higher threshold events. By using the climatological distribution of precipitation at each location to define thresholds, both scores assess the locally important aspects of the forecast. The biggest challenge is that everyone uses the same climatology, and updating/maintaining such a climatology is a non-trivial task that needs to be taken on by one institution.

Finally, as extreme weather is usually associated with lower predictability, ensemble forecasts are a natural way to account for the uncertainty and give more information on the likelihood of extremes than single deterministic forecasts which might fail to capture the combination of key elements, hence standard verification measures for ensembles (ROC, reliability, Brier) have been developed in VERSUS.

Exploitation of available observational dataset for operational and scientific purposes

For model-oriented verification, processing of the observation data needs to be done to match the spatial and temporal scales resolvable by the model. This requires the availability of high spatial resolution observations such as satellite or radar post-processed data that can be used to produce vertical profiles or gridded surface analysis.

Radar-derived precipitation data are burdened with a number of errors from different sources (meteorological and technical) thus various correction techniques must be employed. The combination of radar precipitation and rain gauge data is treated as the next stage in precipitation field estimation not as radar data correction, but as a better representation of precipitation from larger number of data sources. Rain gauges are assumed to measure precipitation directly with good point accuracy. However, in the case of rather sparse rain gauges network density, the radar is capable of reflecting the spatial pattern of rainfall with high resolution in time and space over a large area almost in real-time. Merging these two sources of information could lead to improvement in precipitation estimation, consequently several methods have been developed like Cokriging technique (Krajewski 1987) or trans-Gaussian kriging (Erdin et al. 2013). The COSMO verification group will stimulate the production of such data sets as well as their exchange within the different met services.

The focus of satellite observations (e.g. NWP-SAF) use has traditionally been on the physical variables of the atmosphere, such as temperature, humidity and winds. Forecast of solar irradiation and clouds will be increasingly important with the energy transition in Europe and increased use of solar power. Satellite data provided operationally as derived products from SAF as well as direct brightness temperature observations should become a primary data source for verification of cloud and irradiation forecasts (Crocker and Mittermaier 2013). Gridded SAF cloud products could be used for spatial verification purposes.

Finally, particularly important is the exploitation of controlled and possibly homogenous set of surface and near surface observations, mainly in the PBL, concerning fluxes, radiation and soil characteristics, such as those available from the SRWNP Data Pool Exchange.

With the use of model feedback files in VERSUS, all types of observations that are used in the data assimilation process such as wind profilers, AMDAR, VAD and in the future also radar radial winds and reflectivities as well as satellite radiation will be available for verification. The big advantage of using feedback files is that this data source provides quality information diagnosed during the assimilation process besides the observed value and predicted model equivalent.

Application oriented verification information

With increasing model resolution, the number of numerical products is expected to rise and the need to gauge their performance. Various users may have different needs for verification, so different verification strategies and methodologies have to be chosen. Following Brier & Allen (1951) and Wilson (2011) four classes of users can be defined:

- Administrators
- Modellers
- Meteorologically educated users
- Not meteorologically educated users

The same set of forecasts can have a different application for any of these users and, thus, even the information given by the verification system has to be adapted to the user's needs and an index of the quality of the forecast has to be provided. The index should have the characteristics of simplicity (e.g. percentage of forecasts with temperature errors within 2ºC) and the ability to aggregate information, like the COSMO index (COSI) that measures the forecasting skill as function of time.

Interests and needs of modellers are widely described in previous sections of this chapter, and concern mainly the monitoring of operational forecasts and the investigation of model errors. The verification outcomes will possibly include complex statistical scores, stratified verifications and massive use of conditional verification.

The main interest concerning verification for meteorologically educated users like forecasters is to provide detailed, reliable and “good” forecasts. In both cases they need guidance for correctly interpreting the model results while the understanding of eventual systematic errors of different elements allows them to specify more correctly the final forecast itself. Among the verification products that a system should provide, there should be simple time series of parameters, as well as conditional verification applied to a single parameter in a given situation.

Finally, the interest of non-meteorologically educated users is knowing, for example, to which extent the forecasts are trustworthy, what is the accuracy, in both time and space, of a given forecast and how to use this information in their own decision-making processes that may (or may not) have a financial impact on their activities. It is not within the scope of the COSMO consortium to strengthen the link with this kind of end-user, nevertheless the production of some scores and their correspondent skill scores can provide input for a cost-loss model as well as important information in decision-making (Nurmi 2003).

Resources required

The experience gained over the past several years indicates skilled but limited resources in the COSMO community regarding operational verification activities and implementation of new approaches and methodologies. Nevertheless, in order to finalize the planned actions within the foreseen timeframe, it is necessary to have additional human resources dedicated to verification activities in the near future.

As the lack of resources is a common problem to other European Consortia, in order to optimize them, a recommended strategy would be to monitor the efforts of the various European Consortia (e.g. through SRNWP collaboration, like in Verification Programme) in the field of verification, namely to use or adapt what has already been developed and encourage knowledge sharing amongst the scientific and operational communities regarding new methodologies, research results and approaches to verification issues.

In more details, to complete VERSUS activities connected to the project should be provided not less than about 1.5 FTEs in 2015, while the maintenance and the improvements of system should be provided, coordinated by the source code administrator, with about 2.5 FTEs in total. The activities connected to the exploitation of conditional verification capabilities, the application and further implementation of new measures dedicated to the assessment of the quality extreme weather forecasts as well as the refinement of tools for probabilistic and EPS verification and exploitation of special observational dataset should require around 7 to 9 FTE within the further 2-3 years, in total. The total amount of required FTES to perform the planned activities could reach about 11-13 FTEs.

Expected outcome

Through enhanced exploitation of available observational datasets, extending verification to include high impact weather situations, application of spatial statistical methods on both probabilistic and deterministic forecasts, and with the aid of Conditional Verification diagnostics, the expected outcome is the improvement of the knowledge of COSMO model performance and a more detailed identification of sources and reasons of errors, along with a better assessment of forecasts quality. Moreover, through the finalisation of VERSUS project and NWP test suite PT, the Consortium will provide cutting-edge tools in the field of verification and quality control of numerical models.

Risk assessment

The activities described represent the state of the art concerning research and development in the field of verification of NWP systems. At the moment it is not possible to foresee if any other direction of models development will lead to a new set of problems that verification activities will have to face.

In such a situation and to deal with this possibility, a specific strategy should be applied. From one side, part of the available human resources will have to be used in the study and research of new techniques able to identify suitable measures or procedures to support the modellers in their effort towards model improvement or towards the assessment of the real quality of forecasts; on the other side due to the significance of the application of research results in operational verification routines, is extremely important that another part of human resources to be spent with this goal, for example by improving VERSUS system functionalities.

Consequently, the lack of resources turns out to be crucial in the assessment of priorities and a strict coordination of national efforts and interests in this field appears to be a real necessity as well as a unique opportunity.

9.3.1 Summary of expected FTEs

FTEs for main priority actions for period 2015-2017 Tackling model performance conditional verification (CV), methods to identify the skill of near convection-resolving model configurations, tools for ensemble forecast verification		FTEs for secondary priority actions for period 2015-2017 Application oriented verification information, Severe and High Impact Weather, Exploitation of available observational datasets	
To be provided by COSMO partners - Already secured: - Potentially available: - Missing:	5.65 1.80 2.05	To be provided by COSMO partners - Already secured: - Potentially available: - Missing	1.2 0.7 1.6
To be provided by academia - Already secured: - Potentially available: - Missing:	0 0 0	To be provided by academia - Already secured: - Potentially available: - Missing:	0 0 0
All secured and potentially available	7.45	All secured and potentially available	1.9
All missing	2.05	All missing	1.6
Total required	9.5	Total required	3.5

10 Computational aspects

Authors: Massimo Milelli (ARPA Piemonte), Ulrich Schättler (DWD), Oliver Fuhrer (MeteoSwiss)

10.1 State of the art, scientific developments

The need of more and more accurate weather forecasts requires a particular attention towards the small-scale features of the atmosphere that, at the moment, are not resolved directly but only parameterised with physical approximations. A way to achieve this goal is to increase the resolution (horizontal and vertical) of our limited area models. This permits the reduction of the errors due to wrong or inadequate parameterisations because the physical processes would be directly described. The drawback of a resolution increase is the increase of calculation time which is not desired for operational duties.

Another way to improve the weather forecasts is to take into account the uncertainties of the model (parameterisation errors, boundary conditions, initial conditions, assimilated data, etc.) by using ensemble techniques which again require massive use of computer resources.

Therefore, whatever action will be taken, the attention has to be moved to software engineering aspects. Software engineering in fact encompasses the full range of the software life-cycle from the requirements, design, implementation, building, testing, maintenance and quality assurance. Adhering to best practices in software engineering is crucial in an environment where scientists spend an increasing amount of time building and using software, as it can substantially reduce time spent on hunting down problems and debugging errors. While a considerable body of literature exists on good software engineering practices (see e.g. Jones 2010) and coding practices (se e.g. Wilson 2013, Rouson 2011), it is a rapidly evolving field with new tools and methods emerging continually. The optimization of the software for the available hardware will reduce significantly the length of the simulations despite the larger number of grid points and/or the number of members involved.

On the other hand, we have to focus on the new available hardware since the operational tasks of the model can only be achieved 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 decades. 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.

Recently a new frontier has been opened with GPU computing. GPU computing is the use of a GPU (Graphics Processing Unit) together with a CPU to accelerate general-purpose scientific and engineering applications, creating more efficient hybrid systems. GPUs consist of thousands of smaller, more efficient cores designed for parallel performance, so serial portions of the code can still run on the CPU while parallel portions run on the GPU. The importance of this research field is demonstrated by its diffusion all over the world of NWP and more generally in the scientific community. As an example, this is a list of similar developments by other groups:

- the Non-hydrostatic Icosahedral Model (NIM) developed by NOAA/ESRL has a dynamical core running on GPUs (based on NVIDIA-CUDA),
- the JMA has a GPU-based operational atmosphere model (JMA-ASUCA) with horizontal 500m resolution (based on NVIDIA-CUDA),
- the Weather Research and Forecasting model (WRF, NCAR/NCEP) is moving towards the same direction experimenting with the NVIDIA-CUDA language,
- the Harmonie model (joint Aladin/Hirlam endeavour) has been tested both for Intel MIC and OpenACC directives,
- the CAM-SE model (Community Atmosphere Model-Spectral Elements) has a dynamical core based on OpenACC and NVIDIA-CUDA for climate simulations,
- NEMO (Nucleus for European Modelling of the Ocean) is a state-of-the-art modelling framework for oceanographic research, operational oceanography seasonal forecast and climate studies which is using OpenACC directives on GPU,
- NASA is also using its Global Cloud Resolving GEOS-5 model with a dynamical core based on NVIDIA-CUDA.

Many other examples could be shown for enlarging field of applications in physics, engineering, mathematics, because the improvements are not only limited to a time gain, but also to energy savings and, ultimately, leads to costs reduction.

10.2 Status and expertise of COSMO

Since September 2010, the COSMO Priority Project POMPA (Performance on Massively Parallel Architectures, see http://www.cosmo-model.org/content/tasks/priorityProjects/pompa/default.htm) has been investigating the performance of the COSMO-Model on existing computing platforms. A fundamental step of the project was to rewrite the dynamical model core in a way that still allows productive development by domain scientists, will run efficiently on different HPC architectures and will continue to do so in the future. The proposed solution was to separate user code from hardware specific implementation using C++, a stencil library and domain specific languages (DSEL).

The main advantages of the use of a stencil library are various:

1. the separation of the user code for domain scientists from the hardware specific optimized code for computer scientists permits to introduce optimizations on the full code in an easier way, making the code management simpler and less prone to user's error,

2. there is an improvement of the performance portability and of the GPU capability since different back-ends allow for the generation of efficient code for different hardware platforms,

3. the finite difference formulation: the code is based on a library of standard finite difference operators, so it is closer to documentation and formulation can be more easily changed,

4. the future proof: HPC architectures are changing rapidly and fundamentally and the use of a library allows to adapt while retaining the same user code. Moreover a library can be shared with other applications.

Another important step towards the software optimization is the support for user-defined working precision. This modification has been tested successfully obtaining a considerable reduction of elapsed time with respect to the standard code.

10.3 Strategy of COSMO and actions proposed

In line with the goals of the Consortium, considering the perspectives of the computer science community, the main actions planned in the future can be here summarized. They can be subdivided into short-term actions (2015-2017), long-term actions (2017-2020) and actions that have to be carried on all along the quinquennium.

Short-term actions (2015-2017)

1. *Consolidation of the results of the POMPA project and further developments*

   First of all the main POMPA Priority Project results should be well established, documented and distributed among the partners in order to be used as a starting point for the successive developments These include the single precision version and the asynchronous I/O in GRIB and NetCDF (already available in Version 5.1), but also the hybrid parallelization and re-implementation of the halo-exchange interface, which are in preparation for a subsequent version.

2. *Consolidation of the GPU-version of COSMO and testing this and also other emerging architectures (as Intel XeonPhi):*

The GPU-version has to be integrated into the official releases, following the procedure for the introduction of new developments described in the COSMO standards. This will be done in three steps:

(i) The physical parameterisations (which remain in Fortran) are ported to GPU using OpenACC and will be implemented in the official version together with the COSMO-ICON physics.

(ii) For the dynamical core only the stencil library is ported using CUDA. It will be integrated in the official version as an alternative dynamical core.

(iii) The rest of the code (also Fortran) again is ported using OpenACC.

The current GPU port works on the NVIDIA accelerators (due to the usage of the CUDA and OpenACC programming paradigms). Once it is well established on the existing computers, it is crucial to programme the following step. The hardware systems in fact are always evolving towards more advanced architectures, therefore there should be a considerable effort in COSMO to keep up with these changes. An example is the new Intel Xeon Phi, a range of coprocessors built with the new Many Integrated Core (MIC) architecture which promises to speed up the performances of our model. These efforts focus on the dynamical core because achieving performance portability across various hardware architectures while maintaining a high readability and maintainability of the code is a much higher-level challenge that cannot be foreseen in the short term.

3. *Organization of regular training courses for COSMO researchers on new architectures and programming languages/paradigms like DSEL:*

   The training of young researchers is a fundamental part of the work of a scientific community. Nowadays in the universities the most used (and taught) language is Fortran, at least inside the physics departments. This situation requires on the one hand to enforce the collaboration with informatics departments, where probably it is easier to find people with knowledge of C++ and DSEL and, on the other hand, the necessity to establish regular courses for present and new users.

4. *Automation of current procedures:*

   An automated test-suite for checking basic technical functionality of the code exists as a prototype and its use is recommended by the COSMO Standards for Source Code Development. This test-suite should be used throughout the Consortium and extended to contain a set of tests which encompasses many different configurations and a basic test of all operational applications for all members.

Long-term actions (2017-2020)

1. *Transfer of new programming paradigms (DSEL, C++) to ICON model:*

   The introduction of the ICON model forces the Consortium to think about transferring the knowledge from POMPA to ICON, in the view of an optimization of all the operational chains

2. *Code administration and maintenance:*

   The source code administration could be improved by using a distributed software development model with automatic testing as an integrated component for ensuring quality, but also by improving the awareness of developers of how to write more reliable and maintainable code.

   In line with the development of the technical and meteorological test-suite, a further push towards fully automated testing should be made. Also, efforts should be undertaken to modularize code further, which would allow testing of individual components.

Continuous actions (2015-2020)

1. *Consolidation and increase of cooperation with the COSMO numerical aspects group, with Academia and with other Consortia:*

   The previous work on the COSMO dynamical core has demonstrated that one of the keys for a successful and smooth conduct of these kind of activities is the collaboration among the different groups and, in particular, with the numerics section. In this sense a stronger link between WG6 and WG2 is recommended and encouraged. The collaboration with Universities should also be encouraged but a great effort should be put into the transfer of knowledge among the different actors: a two-way coupling should be ensured between COSMO and Academia in order to have a more and more efficient growing of people and results.

   It has to be mentioned that it is strategically important to keep the Consortium up to date with the developments and the solutions adopted by similar groups in other Consortia. This aspect is well expressed in Chapter 5 concerning the dynamical core activities which are strongly related with the ones in WG6. Through such a collaboration, the scientific exchange across Europe (mainly, but not only) would be intensified and hopefully there will be a better harmonization and optimization of the (sometimes) limited human resources.

2. *Various management issues:*

   There is a need to maintain and improve the management of the source code, taking into account the new languages/paradigms and the requests of our scientific community which includes also universities and research centres.

Therefore, new programming rules have to be defined. Moreover, the overall management of the web pages has to be addressed with the use of free tools which can provide dedicated software repositories, bug-tracker facilities, revision control system (RCS), forums, faqs and a better documentation handling. These features will ameliorate the visibility but also the usability of the web which is a key point of the Consortium. The major drawback of today's solution is the lack of a web server open to all partners for read and write access, due to limitations necessary for national weather services. Therefore we do not have an RCS, which is accessible for everybody, but only distributed systems at every weather service. It has to be stressed however that any inclusion of such new tools cannot impair good cooperation with academia. Finally, the existing COSMO web structure should be integrated with ICON model in order to have a single comprehensive web portal.

3. *Participation in European Projects:*

   A way to catch up with the latest improvements in computer science and increasing the visibility of COSMO work (and hopefully the manpower) is to join international projects. As an example, Horizon 2020, the EU Framework Programme for Research and Innovation could be mentioned. Sharing knowledge and competences is a very good initiative to promote science and go beyond obstacles.

Resources required

Numerous research papers in the field of software engineering have shown that investments in improving software development practices pay off with a reduction of overall time spent for the development process. Nevertheless, the proposed actions, will require short term resource for their introduction and general adoption. A large part of the POMPA activities are at the moment carried on in collaboration with external institutions (CSCS, ETHZ, CASPUR, C2SM), therefore the coordination among all the partners is crucial together with the knowledge transfer. In any case, more resources inside COSMO should be dedicated to this task. Moreover there should be a stronger link with universities: as it has been already mentioned, there should be a growing interest in creating links not only with Physics Departments (where Fortran is still the most used programming language), but also with Informatics Departments where other languages and programming paradigms are more studied and applied.

It is quite difficult to quantify the amount of work and translate it into numbers. Following the previous experience of the PP POMPA, something similar could be inferred. Thus about 6 to 8 FTE would be necessary in the next 5 years to fulfil the different actions.

Expected outcome

The proposed efforts should result in a more robust, reliable and maintainable software, reducing the amount of debugging time and allowing to catch flawed designs, errors and inconsistencies early in the development cycle. A distributed development model with automatic testing will allow to move forward COSMO software more rapidly and integrating new developments with a higher frequency than currently.

A full GPU version of COSMO and ICON is expected to work operationally by the end of 2020, based on the most advanced hardware architectures and software developments.

Future advances in computer science and engineering will be followed in order to allow a constant revision of the model and its alignment to the latest technologies.

Risk assessment

After having considered possible improvements/modifications to the computational aspects of the model management, we have to be aware of potential risks that are linked with the evolution described here. As the COSMO Consortium will grow and expand and its software packages along-side, the bottlenecks, debugging activities and manual testing procedures will become more time consuming. Moreover, if the coordination between external and internal personnel fails, there is the concrete danger to lose most of the progresses achieved in the previous years. The other potential threat is to fail in aligning technology-related objectives with the Consortium's “business” objectives by creating two separated groups of developers and programmers which do not communicate (separation of concerns). The synergy between them has to be enhanced and promoted in order to ensure the smoothest transition.

A disadvantage is, however, that developing scientific innovations or testing new ideas is initially slowed due to the time required for the main developers to adapt to the new programming paradigms.

It has to be mentioned also that the use of larger and larger datasets (for instance using LETKF or in pre- and post-processing software as VERSUS, Fieldextra or Extpar) may lead to troubles in I/O and data storage. A stronger coordination among all the different software administrators is necessary to mitigate and eventually solve the problem. Various hardware solutions should be investigated in order to use a sufficiently large bandwidth and high-capacity storages, including cloud storages.

10.3.1 Summary of expected FTEs

FTEs for main priority actions for period 2015-2017		FTEs for secondary priority actions for period 2015-2017	
To be provided by COSMO partners - Already secured: - Potentially available: - Missing:	1.8 1.6 0.0	To be provided by COSMO partners - Already secured: - Potentially available: - Missing	0.6 0.0 0.3
To be provided by academia - Already secured: - Potentially available: - Missing:	1.6 0.0 1.2	To be provided by academia - Already secured: - Potentially available: - Missing:	0.0 0.0 0.0
All secured and potentially available	5.0	All secured and potentially available	0.6
All missing	1.2	All missing	0.3
Total required	6.2	Total required	0.9

11 Cross-cutting issues

The discussion held during preparation of this document emphasized the importance of scientific problems which step beyond concerns of a single strategic area and a Working Group. This chapter focuses on a selection of such cross-cutting issues being especially important for the realization of the COSMO goal and defines the COSMO Working Groups involved (see the WG list in chapter 2). For definitions of abbreviations used as attributes of planned activities see chapter 6 (page 35).

11.1 3D- physics and consequences on dynamics and code structure (WG 2, 3a, 3b, 6)

Authors: Michael Baldauf (DWD), Matthias Raschendorfer (DWD), Bodo Ritter (DWD)

Basic scientific background, motivation and strategy

Since the future applications of the COSMO model for NWP tend towards resolutions of about 1 km and possibly even finer in the next years, it becomes evident (see chapter 6 on model physics) that the pure vertical column physics is no longer adequate. In contrast, 3D turbulent transport and at least quasi-3D radiation become more and more necessary.

As stated in the chapter on dynamics, the implementation of turbulent diffusion requires collaboration between the atmospheric physics group (WG3a), which develops parameterisations of the transport properties (e.g. the necessary diffusion coefficients), and the dynamics/numerics group (WG2), which delivers adequate transport schemes. This collaboration becomes even more strongly coupled in the case of 3D turbulence. Here, the divergence of scalar turbulent flux-densities and the stress tensor needs a more fundamental and coordinate invariant formulation. One starting point is the derivation of the divergence of the stress tensor in the terrain-following COSMO coordinate system (Baldauf, 2005, 2006). This derivation was performed for an isotropic diffusion coefficient. However, it is well known from turbulence measurements that the turbulent stress tensor and the strain rate tensor have different principal axis (Fiedler, 1975) and therefore an isotropic diffusion coefficient cannot be used in general. Whereas the above mentioned derivation is likewise applicable to higher rank diffusion tensors, there remains the difficult task to determine its components. In principle, such a derivation can be done in the framework of a complete 3D turbulence model, which however seems not to be feasible for NWP applications. Alternatively, a semi-empirical extension of the TURBDIFF scheme (see chapter 6.1.3 on turbulence) based on separation of a horizontal shear mode can be combined with invariance theory to end up with an invariant formulation of a resulting anisotropic diffusion tensor.

Nevertheless, this situation might relax considerably, if the model is used in a large eddy simulation (LES) mode, since in this case a quasi isotropic diffusion coefficient (derived from a pure balance between shear production and dissipation of TKE) may be used, which is a characteristic of the Smagorinsky closure (see again chapter 6.1.3 about turbulence).

A further problem concerns the numerical formulation of the diffusive transport in terrain-following coordinates. Whereas the idealized diffusion test in sinusoidal orography performed well with the current terrain-following COSMO implementation of 3D diffusion (Baldauf, 2006), further tests showed a stability limitation in steep terrain. Work has started at MeteoSwiss to implement a z-plane diffusion which circumvents these steep slope stability problems, but instead faces the problem of a much more difficult boundary treatment of diffusion.

Radiative transfer, in the end, is even a 5D problem (3 space, 2 angle dimensions) and therefore impossible to treat correctly in an NWP or climate model. Fortunately, one can apply reasonable approximations to reduce this high-dimensional problem to one that considers only the principal beam from sun to earth and simple upward and downward directed diffusive radiative fluxes. Nevertheless, in sub-km scale simulations the principal beam shouldn't consist in a purely vertical beam but should target diagonally through the model domain, in general. This approach which is commonly known under the name 'tilted independent column approximation' (TICA) has been implemented in the COSMO code in the framework of the extramural research project of DWD (see also chapter 6.2.3 about radiation), but further investigations are required to assess the potential, impact and limitations of such a scheme for operational NWP. In particular one has to bear in mind that this approach complicates not only the formulation of the radiation code but also its parallelization (a problem that belongs to WG6).

Actions proposed (see chapter 6 about model physics, WG 3a, 3b)

- A shorter term action consists in using the existing 3D-diffusion schemes available in COSMO for very small-scale ('quasi-LES') simulations. A simple (though unphysical) limiting of the Smagorinsky diffusion coefficient or of the used inclination of model layers might be applied as a first fix to cure stability problems over steep slopes. [application]
- Further, a more sophisticated solution of the mentioned stability problems should be implemented (e.g. based on z-plane interpolation), with special regard to the treatment of the lower boundary. [application to exploratory]
- For a next step, similar 3D-extensions should also be made applicable to the moist prognostic TKE scheme. Within this scheme a semi-empirical derivation of the components of the diffusion tensor should be found and extended to an invariant formulation. Basic ideas and first solutions for both exist at DWD. [application to exploratory]
- As for 3D-radiative effects, a thorough evaluation of the TICA approach based on the work done at LMU Munich should be undertaken in the context of COSMO simulations for the km-scale and below, including also effects due to topographic shading. [application to exploratory]
- As for 3D-hydrological components, their benefit and the possibilities for their implementation (e.g. as an extension of TERRA) should be investigated.

Resources required

See action plans of WG 3a, 3b within chapter 6.

11.2 Processing verification feedback on model development: WG 1, 3a, 3b, 4, 5, 7

Authors: Matthias Raschendorfer (DWD), Flora Gofa (HNMS), Christoph Schraff (DWD)

Basic scientific background, motivation and strategy

Evidently, Physical Parameterisations (PMs) can’t be developed solely by analytical derivation. Rather they must be based on various assumptions and related effective parameters in order to close the system of discretised model equations. As a consequence, measurements of the real evolution of model variables are essential for

i) finding proper formulations,

ii) verifying the assumptions and

iii) estimating proper values of local or global model parameters.

However, the atmospheric system is characterised by rather complicated non-linear interactions of processes, and measurements can never provide a complete state of the system and its temporal development. For that reason proper strategies are required in order to use the available measurements for that purpose.

While classical verification primarily aims to produce error estimates of the whole model system, the desired strategy needs to be more focused on testing of specific parameterisations with respect to the processes they have been designed for. This procedure may be called “**component testing**” and it is usually applied to special measurement configurations, e.g. at meteorological towers in order to investigate turbulent boundary layer mixing. Although these measurements may offer quite high resolution in vertical direction and time, typically neither all spatial dimensions nor all variables (being involved in a specific process) are represented. Possibly even more serious is the question, to what extent a measurement value really does **represent** a corresponding value of a grid scale model variable, and related to that issue, how far the measurements are **self-consistent** with respect to the governing budget equations. Anyhow, in order to use such measurements, a proper testbed allowing for component testing is necessary. For that purpose we have developed a special **Single Column (SC) framework** (COSMO-SCM).

On the other hand, the measurements used for data assimilation and model verification are the best available estimate of atmospheric observables and thus should be used for the purpose of model development as well. This issue may be called “**verification with feedback**” and requires the implementation of specific procedures. Nevertheless, problems with non-representative or not self-consistent measurements are present as well, and stochastic observation errors always have to be taken into consideration. In some situations, these difficulties may only be manageable by **probabilistic methods of verification** that is, e.g., by comparison of parameters describing measured and simulated distribution functions of variables within appropriate domains in space and time. Such a domain (covering at least a single grid cell) needs to be large enough to contain a sufficient number of measurements in order to estimate at least the expectation value of the real distribution function. On the other hand, **Sub-Grid Scale (SGS) model statistics** can be used to estimate the probability of the GS average of a variable to be equal to the average of all measurements taken within a grid cell, even if they are only very few (probably only one). This might provide a useful alternative version of probabilistic verification, if the before mentioned “super-observations” would require too large reference domains,

First of all the desired feedback can be achieved by “**conditional verification**”, allowing for separating the problem of unspecific model errors into several processes that are not adequately represented by the model. For that purpose, verification is applied after the data have passed conditional filters in order to preferably exclude all sources of error apart from the one that is going to be investigated. The verification tool VERSUS already provides most of the necessary functionalities. A challenge in this field is setting up a **sequence of properly chosen conditions** and to **draw the right conclusions** from the results. This necessitates a close cooperation between developers and verification experts.

Nevertheless, real component testing is not possible with this procedure, unless errors due to other model components can be avoided during a test model run, since these errors would deteriorate initial and boundary conditions for the time-space windows selected by the conditional filter. Consequently, **3D component testing** needs to be **integrated into data assimilation runs**. In such an approach, the error estimate for the model (component) should be based on **assimilation increments**, even though in a nudging framework, these increments (summed up over the relaxation period) might be influenced by unrealistic imbalances from incomplete assimilation. In any case, time series of these correction increments would facilitate the detection of systematic drifts of prognostic variables as a function of the model state. However, a sufficient spatio-temporal resolution of observation is a prerequisite. Furthermore, it needs to be clarified how far the LETKF approach would be appropriate to detect systematic errors, which are not represented by the model spread. In this respect a nudging approach might be more useful and should therefore be tested as well for this specific purpose. A similar method has already been applied for component testing within the SC framework.

A closely related challenge is the problem of **optimal parameter estimation**, which needs to be divided into “**system tuning**” and “**component tuning**”. In order to avoid **compensating errors**, only the latter, aiming to get optimal parameter values with respect to the associated processes, should be applied. Nevertheless, a final system tuning of some remaining parameters is important, not at least because component tuning might not be possible for all parameters. However, while **error functions** (i.e. error metrics that need to be minimised by the tuning) are more or less determined by the separation in case of component tuning, for system tuning these functions have to be **chosen somehow**, e.g. dependent on **interests of the main users and customers**. While an **automatic parameter optimization** procedure in the sense of system tuning is already a running development (see plan of PP CALMO, http://www.cosmo-model.org/content/tasks/priorityProjects/calmo/default.htm), a procedure for component tuning is not yet available.

Finally, it may be the case - due to still incomplete parameterisations – that optimal values for the "**internal parameters**" are not constant in space and time or "external parameters" are not only dependent on external conditions. Rather these parameters are likely to depend on the model state itself. In this case it might be a further strategy to express each physical parameter by a regression function of some model variables dependent on a few regression parameters substituting the prior physical parameter. This could be called "automatic parameterisation" or "**statistical hyper-parameterisation"** and is a kind of natural consequence of most likely always incomplete physical parameterisations (see also the crosscutting chapter 11.3 about "stochastic physics"). Another method utilizing systematic verification feedback is "**statistical post-processing**" of direct model output, designed for the final reduction of remaining systematic discrepancies between model output and observations. Although this measure doesn't affect the internal model equations, the required statistical methods may be very similar to automatic parameterisations and should be based on probabilistic verification as well.

In order to give a feedback to remaining unsystematic model errors, verification should also deal with the identification of this stochastic error in order to support the efforts of stochastic physics, e.g. by a **verification of ensemble spread** (see also the related cross cutting chapter 11.2).

Short term actions proposed (2015-2017)

- **Further development of the conditional verification tool** which has the possibility to select **arbitrary conditions** in the form of logical expressions using all model output variables, external parameters and observational information, and which preferably can also be applied to verification of ensemble spread and provides probabilistic verification facilities (extended VERSUS) [application to exploratory], concerns WG5, WG7, WG1
- **Application of that tool** to a series of properly chosen **test cases** representing the natural variability of weather situations including a couple of extreme situations as well as annual variability, while trying to identify systematic and stochastic errors [application], concerns WG5, WG3, WG7
- Further development of **component testing** within the SC framework (including forcing with 3D-correction tendencies and definition of error functions) [application], concerns WG3, WG5
- Development of a prototype **automatic parameter optimization** procedure based on **component testing** using both a proper separation strategy and a proper optimization technique (e.g. that of the variational soil moisture analysis, MOS or that being used by PP CALMO) within the SC framework, which can be applied to arbitrary locations. [exploratory], concerns WG3, WG1, WG4, WG5
- Further development of post-processing tools (like those for clear air turbulence, aircraft icing or for estimation of solar and wind energy supply) based on probabilistic verification with special regard to the representation error of used

measurements and the estimation of the related RMSE. [application to exploratory], concerns WG4, WG5, WG7, WG3

Long term actions proposed (2018-2020)

- Development of methods that provide consistent measurements particularly for SC component testing that are in accordance with physical constraints (e.g. mass or heat budget of the lower boundary) and are also comparable with the model. [exploratory], concerns WG3, WG5, Observatories
- Development of a 3D component testing facility based on a diagnostic of correction tendencies due to data assimilation, as well as on the conditional verification facilities, and using the developments in the SC framework. [exploratory], concerns WG5, WG1, WG3
- Development of statistical hyper-parameterisations facing the problem of incomplete parameterisations (prototype within SC framework, later to be integrated into 3D system- and component testing. [exploratory to basic], concerns WG3, WG4, WG1, WG5

Resources required

The short term issues are mainly represented in the relevant action plans described in previous chapters, except the SC parameter optimization based on component testing, which requires roughly another 1.5 FTE. The needed effort for the long term issues is hard to be foreseen and estimated. Providing consistent measurements for SC component testing may be a long term task for meteorological observatories and the two other points may require about 2.0 FTE each.

11.3 Stochastic Physics (WG1, 3a, 7)

Authors: Chiara Marsigli (ARPA-SIMC), Matthias Raschendorfer (DWD), Christoph Schraff (DWD)

Basic scientific background/motivation

The objective of **physical parameterisations (PMs)** is to close the system of discretised model equations in terms of numerically resolved model variables, as explained in the chapter about model physics. On the one hand, PMs are necessary in order to reduce the intractable degree of complexity with respect to source terms due to cloud processes and radiation transfer. On the other hand, they represent corrections of the discretisation error, which arises from non-linearity of the model equations and the fact that numerical representations of differentiation operators can only be applied to properly low-pass filtered variable fields.

While the temporal evolution of the **local state** (belonging to the largest macroscopic resolution) of the atmospheric system is determined by general valid equations in the classical (first order) system variables (like temperature and the wind vector), correct evolution equations of the **grid scale (GS) model state** cannot exist in principle, and in particular, if this state is restricted to only **first-order moments** (grid cell averages) from the Sub Grid Scale (SGS) distributions of local system variables. Rather, any detail of the common SGS distribution (built by all local system variables) affects the evolution of first order moments (which is an expression of the general closure problem). For that reason, the GS state needs to be extended by more information about that distribution, e.g. by higher order moments, even though that information will never be sufficient. Thus, a lot of uncertainty is involved in the numerical simulation of the GS model state: first of all, the **initial** (extended) GS state remains uncertain, which is a problem of „**data assimilation**” **(DA)**. Apart from that, the always incomplete system of model equations needs to be closed somehow. This forces the introduction of additional constraints, which however cannot be generally valid by definition (even though parameterisation strategies try to approach this). Since the formulations of these constraints always involve definitions of some **physical parameters**, the related uncertainty is reflected by the fact that optimal parameter values are never really constant in space and time. In this situation two possibilities should be discriminated:

i) In principle better parameterisations may exist, that have not been developed yet. In this case, present model parameters have still some dependency on grid scale (GS) model variables. This dependency may be called “**systematic error**” and should be minimised as a first priority.

ii) No better parameterisations are possible, since the remaining parameters do not hold any systematic dependency on GS model variables. In this case, remaining errors are no longer systematic; rather they are „**stochastic errors**”, very similar to non-systematic errors in the determination of the initial GS model state.

The elimination of the remaining systematic errors can be addressed by “**statistical hyper-parameterisations**”. Their aim is to express the dependency of physical parameters on the GS model state by **some regression functions**. The original parameters would then be substituted by corresponding regression parameters that hopefully do not have systematic errors any longer. This kind of „**statistical extensions of PMs**” and the related actions are addressed in the chapter on „processing verification feedback on model development”.

Another possibility to reduce the systematic error is to deploy „**stochastic representations of parameterisations**”. Their purpose is to **simulate directly that effect** on the GS tendencies, which is related to a specific non-linear process and caused by those natural SGS variations of physical properties that have not yet been taken into account by the parameterisations. This can be done by **repeated runs** (with somehow modified parameters or variables) of the related parts of the model, where the whole procedure may also be substituted by a repeated adequate **stochastic process**. However, the properties of the applied variations (e.g. distribution functions) need to be determined (as a function of the GS model state). At the end, the expectation values of the time tendencies for model variables from the different realizations of the SGS non-linear process are a substitute of the parameterised time tendencies of the process for those model variables. This method is applied, e.g., in Lagrangian air pollution models and can be used in particular for the simulation of SGS convection (by using stochastically varying up- and downdraft properties). In this sense, the procedure is still part of a **deterministic model forecast** and it is addressed in the chapter about „**atmospheric physics**”.

However, the remaining stochastic errors can only be treated based on a „**probabilistic model forecast**”. According to the standard procedure for that purpose, stochastic variations, reflecting the statistics of model uncertainties coming from the physical schemes, are used in an **ensemble prediction framework**. In this approach, the task of **eliminating** model errors by improving PMs is reduced to the **simulation or estimation** of model errors related to PMs. Most applications of stochastic physics are directed to the probabilistic approach and aim to **introduce missing spread** (due to unaccounted errors in model physics) into an **ensemble prediction system (EPS)**. Model runs with “Stochastically Modified Physical Parameters” (SMPP) or “Stochastically Perturbed Parameterisation Tendencies” (SPPT) belong to these efforts (see chapters 8.2 and 8.3). However, they suffer from insufficient physical foundation, and the magnitude and common distribution of variations is quite arbitrary. The so called “Stochastic Kinetic Energy Backscatter” (SKEB), injecting stochastically additional vorticity to the wind field in order to compensate too excessive kinetic energy dissipation by numerical diffusion and PMs (see chapter 8.3), is an attempt to improve this, since it introduces a **stochastic component to the model forecast** related to a physical process. A special class among these more physically based attempts, forms the stochastic component already included in the PMs and used also for deterministic forecast. They may be called „**intrinsic stochastic components of PMs**”, and some convection schemes, for instance, belong to this category (Plant and Craig 2008 or Bengtsson et al. 2013). Although all these „**stochastic extensions of PMs**” may be associated to the same SGS processes like the above mentioned stochastic representations of the related PMs, the stochastic extensions do not belong to the deterministic forecast any longer. This is because each time tendency of the parameterisation has an intended random component (stochastic contribution) now, causing that the individual runs are in principle not reproducible any longer (whereas stochastic representations contain only unintended randomness due to the limited number of repeated runs within the parameterisation). The random components are introduced according to GS deviations from some equilibrium approximations being used by the deterministic parameterisations, even though these approximations are valid only for larger scales. Nevertheless, even individual model runs (not part of an EPS), which are modified by such stochastic contributions during the run, may improve the model forecast. These stochastic contributions, however, are vanishing, if the model GS is as large as those equilibrium scales; both, stochastic representations and stochastic extensions of PMs belong to the more general term of "**stochastic parameterisations**".

Because this explicit representation of model uncertainties as part of parameterisation schemes promises to be the most reliable method to account for model error, at the 2011 ECMWF workshop on "representation of the model error", it was suggested to move towards such "integrated" approaches, in order to further improve stochastic error estimates (ECMWF Working Group Reports 2011). More recently (June 2013), a PHY-EPS workshop has been organized in Madrid in the framework of the C-SRNWP program, where these issues have been also addressed (http://srnwp-eps.aemet.es). The workshop pointed out the necessity of a closer cooperation between physics and ensemble community. In particular, it was proposed to initiate a synergic effort, in which ensembles are used as a **diagnostic tool** to evaluate their response (in terms of spread) to variations of the (uncertain) formulations of model physics, with the final aim of facilitating the derivation of physically based stochastic variations generating the necessary amount of spread.

Considering that the new DA system being developed for COSMO is based on an ensemble approach, there is an inter-dependence that affects the plans of three main areas of the consortium: Physics, EPS and DA. A good representation of the model error is crucial for both, EPS and DA, since it provides the appropriate spread to both the forecast and data assimilation ensembles. Therefore stochastic extensions for PMs should be developed.

Despite the effort aimed at introducing missing spread due to uncertainties in PMs, it should not be forgotten that the magnitude of the "needed" spread (the part of the spread which is actually representative of the forecast error) in an ensemble system is a measure of deterministic model errors. As long as these errors are systematic, the natural way to improve the whole model system should be to reduce this error instead of modelling a corresponding stochastic spread. We have the opinion that considerable parts of the model errors are still systematic and should be treated first of all by the mentioned statistical extensions. This is supported by the little spread, with respect to the large forecast error, which usually characterise LAM ensembles in terms of surface variables, which is often not sensitive to changes in the ensemble configuration, indicating that the error is largely systematic. However, this field does not yet seem to be a real issue in NWP related research as such, being assigned to the ordinary model development work. Nevertheless in a practical sense, all remaining model errors that **could not yet be eliminated systematically** need to be treated like stochastic errors!

Furthermore, some of the assumedly missing spread might be due to measurements not properly representing the grid scale model output (see also the comments on “probabilistic verification” in chapter 11.2 about “verification feedback”). The related discrepancies between model output and observation (expressed by the RMSE) are closely related to SGS variability, which is partly represented by the **second order GS model state** (e.g. variances of temperature due to turbulence and convection). Although accounting for representativeness errors as part of the observation errors is already a general matter of DA, their contribution to the RMSE should be considered carefully when developing stochastic physics. However this usage of SGS model information should not be mixed up with the consideration of (for instance) turbulent statistics within a stochastic representation of convective processes, which remains a part of deterministic parameterisation in the framework of **scale separation** (see chapter 6.1.2). Finally it should be mentioned that a probabilistic forecast is not necessarily based on EPS, since it might be possible to derive **deterministic prognostic equations for moments of the probability density functions (PDFs) of first order model variables**, similar to those for SGS distribution functions in a higher order closure framework (see chapter 6.1). This, however, is a matter of really basic research.

Main actions planned

Many planned scientific and technical actions related to this field are described in other sections of the Science Plan. The plans for evaluating the impact of stochastic parameterisations in ensemble forecasting systems is addressed in section on EPS, and the inclusion of these schemes in the data assimilation cycle are outlined in section on DA. However, the development of stochastic parameterisations is included in the “atmospheric physics” section only insofar, as they are related to a deterministic improvement of PMs. Thus this section really is addressing **the implementation of the mentioned stochastic extensions**. For that purpose a good communication in the development phase should be maintained, in order to **utilize synergy** and to facilitate the **consideration of specific requirements** for each of the involved areas of development. In this sense for instance, tools for evaluating the ensembles characteristics, particularly with respect to the model perturbations, can be shared between the different development groups. The following actions are planned:

1. Investigation of possibilities in order to detect remaining stochastic errors related to PMs, possibly by **conditional verification of EPS** forecasts in order to quantify missing ensemble spread (error variances) for diverse variables und to assign it to specific GS conditions or possibly even PMs. In order to do this, systematic errors should be subtracted from the statistics first, and the observation errors as well as the RMSE contribution from SGS variability as a function of second order model variables should be determined and accounted for. [exploratory], concerns WG5, WG7, WG1, WG3
2. Deriving parameterisations of the missing spread and its propagation, possibly by stochastic extensions of PMs, which are not addressed in the atmospheric physics chapter. In a future perspective also evolution equations for moments of

PDFs characterising the model uncertainty should be taken into account. [exploratory to basic], concerns WG3, WG7, WG1.

Resources required

Conditional verification of EPS results in terms of missing spread (action 1) may require 1 FTE with good qualifications in methods of verification, EPS and DA. For the development of stochastic extensions (action 2) roughly 2.0 FTE of qualified personal with deep insight in PMs and EPS methods are required and seem to be available at DWD. Strong cooperation with academia is expected to be important.

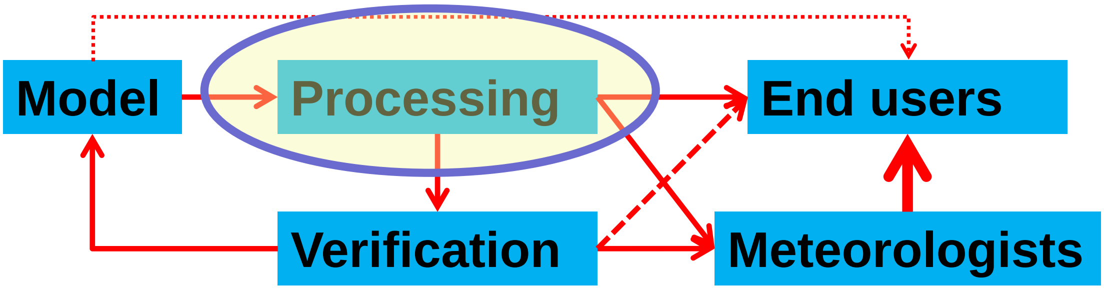
11.4 Postprocessing activities (WG 4, 5, 7)

Author: Pierre Eckert (MeteoSwiss)

Background

The goal of the COSMO consortium is to develop small scale deterministic and ensemble models. Typically O(1km) deterministic and O(2km) ensemble models will become operational in the next years (when not months). They need new interpretation and postprocessing methods, which should be based on model verification and evaluation. Certain parameters can be used and verified at a grid point level, other not. Typically, verification on the grid point is possible for wind and eventually temperature even if the choice of a good representative grid point is often beneficial. Other parameters need space and/or time aggregations to be used and even just verified. This is for instance the case for precipitation and cloudiness. Besides this, non-conventional parameters like aerosols or pollens may be introduced into the models as prognostic variables. They also need new interpretation and verification methods

Basic principle and strategy



As stated above a certain amount of parameters have to undergo a processing method before they can be verified. This statement only applies on models as a whole and not on single processes. Note also that the term “model” applies also to a full EPS including its configuration (choice of driving members, perturbations,…). The processed parameters can then be verified against observations. The verification results are used to improve the model (as a whole).

The processing methods which verify best can be used to generate optimal products, which can be distributed to the end users. Even better they must be made available to the meteorologists together with the verification results. This allows the meteorologists to interpret the model output and provide optimal information to the end users.

The goals of developing postprocessing at the consortium level are:

1) to help understanding the characteristics of model output and provide **methods** to analyse (space, time, parameter, ensemble member) combinations of the output fields; this process should be supported by corresponding verification methods.

2) to provide the users of models (including meteorological forecasters) with recommendations of use of model output; this goal only can be reached by exploiting the conclusions drawn in point 1).

As these aspects cover postprocessing, usability of models, ensemble forecasting and verification, they should be reflected in working packages of WG4, WG5 and WG7. Specifically, postprocessing of deterministic models is part of WG4, postprocessing of ensemble models is developed between WG7 and WG4, WG5 takes care of the verification of postprocessed parameters and gives a feedback on the configuration of the processing methods.

At the other end, many specific postprocessing methods are applied behind model outputs. These include various statistical methods like Kalman filtering or MOS, diagnostics of fog or thunderstorms, electric power of wind turbines and other. The latter processing can be developed locally but are not part of the consortium activity.

12 External collaboration

Over the recent 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 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 coordination group 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. That is facilitated also by the COSMO Source Code Management rules which are based on common approval of the new developments to the COSMO code on the SMC level. The new COSMO strategy calling for harmonization of COSMO and ICON developments requires also close collaboration with the ICON community, which was established recently around the Max Planck Institute for Meteorology in Hamburg and Deutscher Wetterdienst.

12.1 COSMO-CLM

Continuous collaboration between the COSMO and COSMO-CLM (http://www.clm-community.eu) communities concerns a number of areas. It helps improving physical parameterisations and model inconsistencies, especially in the domain of land-atmosphere exchange (see 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. The cooperation encompasses also such diverse fields like dynamical core research and, on the other hand, preparation and validation of geospatial data (external parameters).

12.2 COSMO-ART

COSMO-ART (http://www.imk-tro.kit.edu) extends the regional weather forecast model COSMO by integrating the simulation of processes related to the spatial and temporal distribution of reactive gases 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 3.6, 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.

12.3 ICON

ICON (http://icon.enes.org) is an ICOsahedral Nonhydrostatic general circulation model developed jointly by Max Planck Institute for Meteorology in Hamburg and the DWD. The implementation of the limited area mode of the ICON dynamical-core as well as the ICON library of physics parameterisations to the COSMO model is planned in the near future. While it is expected that the COSMO consortium will take on the responsibility for the maintenance and further development of the regional mode of ICON as well as focus on physical parameterisations of subgrid scale process for convection-permitting model applications, a strong cooperation will be needed not only to allow for smooth implementation of ICON developments within the COSMO framework but also for their further coordinated development. This will require, for instance, a strong support of the ICON community during the initial phase of the development and implementation of regional mode of ICON, assisted by COSMO-compatible standards of Source Code Management. For longer term, it will require establishing appropriate coordination mechanisms.

13 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 uneasy task of reviewing the manuscript: François Bouttier, George Craig, Barbara Früh, Marion Mittermaier, Jean-François Mahfouf, Jeanette Onvlee, Jacob Weismann Poulsen, Mathias Rotach, Bernhard Vogel and Nils Wedi.

They provided many important and insightful comments, also on very fundamental level. The comments and criticism substantially helped to consider further our strategy and its foundations. The reviewers also generously offered many invaluable suggestions concerning both the general strategy and a number of issues related to its practical implementation. We gratefully make use of them, when only possible. The reviews substantially helped us to better define and formulate our scientific strategy and to improve the COSMO Science Plan itself. Thank you!

14 References

Akkermans, T., et al., 2012: Validation and comparison of two soil-vegetation-atmosphere transfer models for tropical Africa, J. Geophys. Res., 117, G02013, doi:10.1029/2011JG001802.

Arnold D, Morton D, Schicker I, Seibert P, Rotach MW, Horvath K, Dudhia J, Satomura T, Müller M, Zängl G, Takemi T, Serafin S, Schmidli J, Schneider S, 2012: High Resolution Modelling in Complex Terrain. Report on the HiRCoT 2012 Workshop, Vienna, 21-23 February 2012, *BOKU-Met Report,* **21**, 52pp, ISSN 1994-4179 (Print), ISSN 1994-4187 (Online), available at http://www.boku.ac.at/met/report/

Aruliah, D. A., C. T. Brown, N. P. Chue Hong, M. Davis, R. T. Guy, S. H. D. Haddock, K. Huff, I. Mitchell, M. Plumbley, B. Waugh, E. P. White, G. Wilson and P. Wilson, 2013: Best practices for scientific computing. Computing Research Repository, abs/1210.0530, http://arxiv.org/abs/1210.0530

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

Baldauf, M, A. Seifert, J. Förstner, D. Majewski, M. Raschendorfer, and T. Reinhardt, 2011: Operational convective-scale numerical weather prediction with the COSMO model: description and sensitivities. *Monthly Weather Review*, **139**, 3887–3905.

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., 2013: A new fast-waves solver for the Runge-Kutta dynamical core, COSMO Technical report, **21**, online available: http://www.cosmomodel.org/content/model/documentation/techReports/default.htm

Baldauf, M., Seifert A., Förstner J. Majewski D., Raschendorfer M., Reinhardt T., 2011: Operational convective-scale numerical weather prediction with the COSMO model: description and sensitivities. Monthly Weather Review doi: 10.1175/MWR-D-10-05013.1

Baldauf, M., O. Fuhrer, M. J. Kurowski, G. deMorsier, M. Müllner, Z. P. Piotrowski, B. Rosa, P. L. Vitagliano, D. Wojcik, and M. Ziemiański, 2013: The COSMO Priority Project 'Conservative Dynamical Core' - Final Report, *COSMO-Technical Report*, **23**, online available: http://www.cosmo-model.org/content/model/documentation/techReports/default.htm

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.

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.

Bechtold, P., M. Köhler, T. Jung, F. Doblas-Reyes, M. Leutbecher, M. Rodwell, F. Vitart and G. Balsamo, 2008b: Advances in simulating atmospheric variability with the ECMWF model: From synoptic to decadal time-scales. Quart. J. Roy. Meteor. Soc. 134, 1337-1351. Also available as ECMWF Technical Memorandum No 556.

Beljaars, A. C. M. (1994). The parameterisation of surface fluxes in large-scale models under free convection. Q. J. R. Meteorol. Soc., 121, 255-270Benkner, 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.

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

Bengtsson, L, M. Steinheimer, P. Bechthold, J.F. Geleyn, 2013: A stochastic parameterisation for deep convection using cellular automata. *Quart. J. Roy. Met. Soc.*, 139, Issue 675, 1533-1543 ECMWF Working Group Reports, 2011**,** http://www.ecmwf.int/publications/library/do/references/list/201106

Berner J, Shutts GJ, Leutbecher M, Palmer TN, 2009: A spectral stochastic kinetic energy backscatter scheme and its impact on flow-dependent predictability in the ECMWF ensemble prediction system. *J.Atmos. Sci.*, **66**, 603–626.

Best, M. J., A. Beljaars, J. Polcher and P. Viterbo, 2004: A proposed structure for coupling tiled surfaces with the planetary boundary layer, J. Hydrometeor., 5, 1271-1278.

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.

Bogenschutz, P. A., S. K. Krueger, and M. Khairoutdinov, 2010: Assumed probability density functions for shallow and deep convection. *J. Adv.Model. Earth Syst.,* **2**, DOI:10.3894/JAMES.2010.2.10.

Bonanno, R., N. Loglisci, 2014: A sensitivity test to assess the impact of different soil moisture initializations on short range ensemble variability in COSMO model. COSMO Newsletter, No. 14, 95-105

Bonavita, M., L. Torrisi, and F. Marcucci, 2010: Ensemble data assimilation with the CNMCA regional forecasting system. *Quart. J. Roy. Met. Soc.*, **136**, 132–145.

Bosveld, F., P. Baas, and A. A. M. Holtslag, 2010: The Third GABLS SCM Intercomparison and Evaluation Case. 19th Symposium on Boundary Layers and Turbulence, Keystone, Colorado.

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

Bott, A., 2010: Improving the time-splitting errors of one-dimensional advection schemes in multidimensional applications, *Atm. Res*, **97**, 619-631.

Bouallègue, B, Z. and S.E. Theis, 2013: Spatial Techniques Applied to Precipitation Ensemble Forecasts: From Verification Results to Probabilistic Products. *Meteorol. Appl.*, , published online, DOI: 10.1002/met.1435.

Bouallègue, B, Z., 2013: Calibrated Short-Range Ensemble Precipitation Forecasts Using Extended Logistic Regression with Interaction Terms. *Wea. Forecasting*, **28**, 515-524.

Bouallègue, B, Z., Theis, S.E. and C. Gebhardt, 2013: Enhancing COSMO-DE ensemble forecasts by inexpensive techniques. *Meteorologische Zeitschrift*, **22** (1), 49-59.

Bougeault, P., Lacarrere, P., 1989: Parameterisation of orography-induced turbulence in a meso-beta scale model, Mon. Wea. Rev.,117,1870-1888.

Böhm U., M. Kücken, W. Ahrens, A. Block, D. Hauffe, K. Keuler, B. Rockel, A. Will, 2006: CLM - the climate version of LM: Brief description and long-term applications. – In: COSMO Newsletter, volume 6, COSMO

Brier, G.W. and R. A. Allen, 1951: Verification of weather forecasts, Comp. Meteor., Boston, Amer. Meteor. Soc., 841-848.

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.

Buehner M, Houtekamer PL, Charette C, Mitchell HL, He B., 2010. Intercomparison of variational data assimilation and the ensemble Kalman filter for global deterministic NWP. part i: Description and single-observation experiments. Mon. Wea, Rev. 138: 1550–1566.

Buizza, R., Miller, M., & Palmer, T. N., 1999: Stochastic simulation of model uncertainties. *Q. J. R. Meteorol. Soc.*, **125**, 2887-2908.

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.

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.

Chen, T. H., et al., 1997 : Cabauw experimental results from the Project for Intercomparison of Land-surface Parameterisation Schemes, J. Climate, 10, 1194–1215.

Cheng, Y., V. M. Canuto, and A. M. Howard, 2005: Nonlocal convective PBL model based on new third- and fourth-order moments. *J. Atmos. Sci.,* **62**, 2189-2204

Christen, M., Schenk, O., Messmer, P., Neufeld, E., Burkhart, H., 2009, Accelerating Stencil-Based Computations by Increased Temporal Locality on Modern Multi- and Many-Core Architectures. Proceedings of the 2009 IPDPS conference.

Cloke, H. L., Weisheimer, A., and Pappenberger, F., 2011: Representing uncertainty in land surface hydrology: fully coupled simulations with the ECMWF land surface scheme, in Proceedings of the ECMWF/WMO/WCRP workshop on "Representing Model Uncertainty and Error in Numerical Weather and Climate Prediction Models", 20–24 June 2011 at ECMWF, Reading, UK

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

Crocker, C., Mittermaier, M., 2013: Exploratory use of a satellite cloud mask to verify NWP models. *Meteorological Applications* **20**:2, 197-205

Damrath, U., 2004. Verification against precipitation observations of a high density network – what did we learn? In International Verification Methods Workshop, Montreal, 15–17 September 2004, http://www.bom.gov.au/bmrc/wefor/staff/eee/verif/Workshop2004/presentations/5.3 Damrath.pdf; 4 May 2007

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.

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

Duniec ,G., A. Mazur, 2014: COTEKINO Priority Project – Results of Sensitivity tests. COSMO Newsletter, No. 14, 106-113

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

Ebert, E.E., 2008: Fuzzy verification of high resolution gridded forecasts: A review and proposed framework. *Meteorol. Appl.*, **15**, 51-64.

ECMWF IFS Documentation, 2008

ECMWF workshop on the representation of the model error, 2011, Reading (UK), http://www.ecmwf.int/publications/library/do/references/list/201106

Erdin, R., C. Frei and H.R. Kuensch, 2013:. Data transformation and uncertainty in geostatistical combination of radar and rain gauges. *J. Hydrometeor*. (in press).

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

Fiedler, F., 1975: Turbulenter Spannungs- und Deformationstensor in der Prandtl-Schicht, *Beitr. Phys. Atmos.*, **48**, 290-300.

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.

Frick, C., A. Seifert, and H. Wernli, 2013: A bulk parameterisation of melting snowflakes with explicit liquid water fraction for the COSMO model version 4.14, Geosci. Model Dev. Discuss., 6, 2927-2966.

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.

Gebhardt, C., Theis, S.E., Paulat, M. and Z. Ben Bouallègue, 2011: Uncertainties in COSMO-DE precipitation forecasts introduced by model perturbations and variation of lateral boundaries. *Atmospheric Research*, **100**, 168-177.

George, D. D., G. Mozdzynski, D. Salmond, 1999, Implementation and Performance of OpenMP in ECMWF's IFS Code, Proceedings of Fifth European SGI/Cray MPP Workshop.

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.

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.

Herzog, H.J., U. Schubert, G. Vogel, A. Fiedler and R. Kirchner, 2002: LLM – The high-resolving nonhydrostatic model in the DWD – project LITFASS, Part I: Modeling technique and simulation method, *COSMO Technical Report No.* ***4*** online available: http://www.cosmo-model.org/content/model/documentation/techReports/default.htm

http://convection.zmaw.de

http://icon.enes.org

http://lakemodel.net

http://stommel.tamu.edu/~baum/ocean_models.html

http://www.imk-tro.kit.edu

Hess, R., 2001: Assimilation of screen-level observations by variational soil moisture analysis. *Meteor. Atmos. Phys*., **77**, 145 – 154.

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.

Jameson, A., 1991: Time Dependent Calculations Using Multigrid with Applications to Unsteady Flows Past Airfoils and Wings, AIAA 10th Computational Fluid Dynamics Conference, American Institute of Aeronautics and Astronautics.

Jones, C., 2010: Software Engineering Best Practices: Lessons from Successful Projects in the Top Companies. McGraw Hill, New York.

Kaas, E., 2008: A simple and efficient locally mass-conserving semi-Lagrangian transport scheme, *Tellus*, **60A**, 305-320.

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

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.

Kourzeneva, E., 2010: External data for lake parameterisation in Numerical Weather Prediction and climate modeling. *Boreal Env. Res.*, **15**, 165-177.

Kourzeneva, E., H. Asensio, E. Martin, and S. Faroux, 2012: Global gridded dataset of lake coverage and lake depth for use in numerical weather prediction and climate modelling. *Tellus A*, **64**, 15640. doi:10.3402/tellusa.v64i0.15640.

Krajewski, W.F., 1987: Cokriging radar rainfall and rain gauge data. , *J. Geophys. Res.* **92 (D8)**, 9571-9580.

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

Kurowski, M.J., B. Rosa, B. and M. Z. Ziemiański, 2011: Testing the Anelastic Nonhydrostatic Model EULAG as a Prospective Dynamical Core of a Numerical Weather Prediction Model. Part II: Simulations of Supercell, Acta Geophys., 59/6, 1267-1293.

Langhans, W., J. Schmidli and B. Szintai, 2012: A Smagorinsky-Lilly turbulence closure for COSMO-LES: Implementation and comparison to ARPS, *COSMO-Newsletter*, **12**, 20-31.

Lappen, C.-L., Randall, and Yamaguchi, 2009: A higher-order closure model with an explicit PBL top. Accepted, J. Atmos. Sci., June, 2009.

Lavaysse, C., Carrera, M., Bélair, S., Gagnon, N., Frenette, R., Charron, M. and Yau, M. K., 2013: Impact of Surface Parameter Uncertainties within the Canadian Regional Ensemble Prediction System. *Mon. Wea. Rev.*, **141**, 1506–1526.

Le Duc, K. Saito, H. Seko, 2013 : Spatial-temporal fractions verification for high-resolution ensemble forecasts. Tellus A, 65, 18171.

LeVeque, R.J. 2002, Finite Volume Methods for Hyperbolic Problems, Part of Cambridge Texts in Applied Mathematics, Cambridge University Press.

Linford, J, Michalakes J., Sandu A., Vachharajani M., 2009, Multi-core acceleration of chemical kinetics for simulation and prediction, to appear in proceedings of the 2009 ACM/IEEE conference on supercomputing (SC'09), ACM.

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. 1969: Atmospheric predictability as revealed by naturally occurring analogues. *J.Atmos. Sci.*, **26**, 636–646.

Lott, F., and M. Miller, 1997 : A new subgrid scale orographic drag parameterisation; its testing in the ECMWF model, *Quarterly Journal of the Royal Meteorological Society*, **123,** 101-127.

Louis, J. F., Tiedtke, M. and Geleyn, J.-F. (1982). A short history of the operational PBL parameterisation at ECMWF. In Proc. CMWF Workshop on Boundary Layer Parameterisation, pp.59-80, Reading, 25-27 November 1981.

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.

Mahrer, Y., 1984: An Improved Numerical Approximation of the Horizontal Gradients in a Terrain-Following Coordinate System, *Mon. Wea. Rev*.,**112,** 918-922.

Marsigli C., Montani A., Paccagnella T., 2013a: Perturbation of initial and boundary conditions for a limited-area ensemble: multi-model versus single-model approach. Quarterly Journal of the Royal Meteorological Society, published on-line, doi: 10.1002/qj.2128.

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

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., Diomede T., Montani A., Paccagnella T., Louka P., Gofa F. and Corigliano A., 2013b: The CONSENS Priority Project. COSMO Technical Report No. 22, available at http://www.cosmo-model.org/content/model/documentation/techReports/default.htm

Marsigli, C., Montani A. and Paccagnella, T., 2013c: Provision of boundary conditions to a convection-permitting ensemble: comparison of two different approaches. Nonlinear Processes in Geophysics, under revisionMass, 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.

Mellor, G.L. and Yamada T., 1982: Development of a turbulence closure model for geophysical flow problems. Rev. Geophys. and Space Phys., **20**, 831-875**.**

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.

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.

Michalakes, J., J. Dudhia, D. Gill, T. Henderson, J. Klemp, W. Skamarock, W. Wang, 2005, The weather research and forecast model: Software architecture and performance, Proceedings of the 11th Workshop on the use of high performance computing in meteorology, 156-168.

Michalakes, J., J. Dudhia, D. Gill, T. Henderson, J. Klemp, W. Skamarock, W. Wang, 2005, The Weather Research and Forecast Model: Software Architecture and Performance. Proceedings of the Eleventh ECMWF Workshop on the Use of High Performance Computing in Meteorology. Eds. Walter Zwieflhofer and George Mozdzynski. World Scientific, 156-168.

Michalakes, J., J. Hacker, R. Loft, M. O. McCracken, A. Snavely, N. J. Wright, T. Spelce, B. Gorda, R. Walkup, 2008, WRF nature run, Journal of Physics: Conference Series, **125**, 12-22.

Michalakes, J., M. Vachharajani, 2008, GPU acceleration of numerical weather prediction. Proceedings of the 2008 IEEE International Parallel & Distributed Processing Symposium, 2308-14.

Micikevicius, P., 2009, 3D finite difference computation on GPUs using CUDA, ACM International Conference Proceeding Series; Vol. 383; Proceedings of 2nd Workshop on General Purpose Processing on Graphics Processing pp. 79-84.

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.

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.

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., 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. 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

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., 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., 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., B. Ritter, J.-P. Schulz, M. Buchhold, M. Lange, and E. Machulskaya, 2012: Parameterisation of sea and lake ice in numerical weather prediction models of the German Weather Service. *Tellus A*, **64**, 17330. doi:10.3402/tellusa.v64i0.17330.

Mittermaier, M.P. 2014: A strategy for verifying near-convection-resolving forecasts at observing sites. *Wea. Forecasting,* **29**, 185-204.

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, Cesari D, Marsigli C and Paccagnella T., 2011: Seven years of activity in the field of mesoscale ensemble forecasting by the COSMO-LEPS system: main achievements and open challenges. *Tellus*, **63A**, 605-624.

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.

Morinishi, Y., T. S. Lund, O. V. Vasilyev, and P. Moin, 1998: Fully Conservative Higher Order Finite Difference Schemes for Incompressible Flow, *J. Comput. Phys*., **143**, 90-124.

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.

Nakajima, T., and M. D. King (1990), Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part I: Theory, J. Atmos. Sci., 47, 1878–1893.

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.

Naumann, A. K., Seifert, A., and Mellado, J. P, 2013: A refined statistical cloud closure using double-Gaussian probability density functions, Geosci. Model Dev. Discuss., 6, 1085-1125, doi:10.5194/gmdd-6-1085-2013.

Neggers, Roel A. J., 2009: A Dual Mass Flux Framework for Boundary Layer Convection. Part II: Clouds. *J. Atmos. Sci.*, **66**, 1489–1506. doi: http://dx.doi.org/10.1175/2008JAS2636.1

North, R., M. Trueman, M. Mittermaier and M. J. Rodwell, 2013: An assessment of the SEEPS and SEDI metrics for the verification of 6 h forecast precipitation accumulations. Meteorol. Appl., **20**, 164-175.

Nurmi, P., 2003: Recommendations on the verification of local weather forecasts. *ECMWF Tech. Memo.* **430**, 18 pp.

Palmer, T. N., Buizza, R., Doblas-Reyes, F., Jung, T., Leutbecher, M., Shutts, G. J., Steinheimer M., & Weisheimer, A., 2009: Stochastic parametrization and model uncertainty. ECMWF Research Department Technical Memorandum n. 598, ECMWF, Shinfield Park, Reading RG2-9AX, UK, pp. 42.

Peralta, C., Ben Bouallègue, Z., Theis, S.E., Gebhardt, C. and M. Buchhold, 2012: Accounting for initial condition uncertainties in COSMO-DE-EPS. Journal of Geophysical Research: Atmospheres 117:D7.

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.

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.

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.

Pincus R., B. Stevens, 2009: Monte Carlo Spectral Integration: a Consistent Approximation for Radiative Transfer in Large Eddy Simulations, Journal of Advances in Modeling Earth Systems, Vol. 1, Art.1, 9 pp.

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.

Plant, R. S., G. C. Craig, 2008: A Stochastic Parameterisation for Deep Convection Based on Equilibrium Statistics. *J. Atmos. Sci.*, **65**, 87–105. doi: http://dx.doi.org/10.1175/2007JAS2263.1

Polcher, J., et al., 1998: A proposal for a general interface between land-surface schemes and general circulation models, Global Planet. Change, 19, 261–276.

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.

Raschendorfer, M.,2003: Parameterisation of turbulent transport in the atmosphere. Springer Lecture Notes in Earth Science, Eds. H. J. Neugebauer and C. Simmer, Springer-Verlag, Berlin, ISBN: 3-540-41796-6, 167-185.

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.

Roches, A. and O. Fuhrer, 2012: Tracer module in the COSMO model, *COSMO Technical Report*, **20**, online available: http://www.cosmo-model.org/content/model/documentation/techReports/default.htm

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

Rodwell M. J. et al., 2011: Developments in precipitation verification. *ECMWF Newsletter*, **128**, 12-16.

Rosa, B., M.J. Kurowski, and M. Z. Ziemiański, 2011: Testing the Anelastic Nonhydrostatic Model EULAG as a Prospective Dynamical Core of a Numerical Weather Prediction Model. Part I: Dry Benchmarks, Acta Geophys., 59/6, 1235-1266.

Rotta, J. C., 1951: Statistische Theorie nichthomogener Turbulenz. Z. Phys., 129, 547–572.

Rouson, D., J. Xia and X. Xu, 2011: Scientific Software Design: The object-oriented way. Cambridge University Press, Cambridge UK.

Sagaut, P., 2001: Large eddy simulation for incompressible flows, Sringer Verlag, Berlin, ISBN 3-540-67890-5.

Schaettler, U., Krenzien E., 1997, The parallel 'Deutschland-Modell' – A message passing version for distributed memory computers, Parallel Computing, 23 (14), 2215-2226.

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

Schomburg, A., C. Schraff, and R. Potthast, 2014: A concept for the assimilation of satellite cloud information in an Ensemble Kalman Filter: Single-observation experiments. *Quart. J. Roy. Meteor. Soc*., in press, DOI: 10.1002/qj.2407.

Schraff, C. H., 1997: Mesoscale data assimilation and prediction of low stratus in the Alpine region. *Meteor. Atmos. Phys*., **64**, 21 - 50

Schulz, J.-P., 2011: Introducing a sea ice scheme in the COSMO model. *COSMO Newsletter*, No. 11, 32-40.

Schulz, J.-P., L. Dümenil and J. Polcher, 2001: On the land surface-atmosphere coupling and its impact in a single-column atmospheric model, J. Appl. Meteor., 40, 642–663.

Schulz, J.-P., L. Dümenil, J. Polcher, C. A. Schlosser and Y. Xue, 1998: Land surface energy and moisture fluxes: Comparing three models, J. Appl. Meteor., 37, 288–307.

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.

Shimokawabe, T., T. Aoki, J. Ishida, C. Muroi, 2010, GPU Acceleration of the Meso-scale Atmospheric Model ASUCA. 12th International Spezialist Meeting on Next Generation Models on Climate Change and Sustainability for High Performance Computing Facilities. Ibaraki, Japan.

Shutts G., 2005: A kinetic energy backscatter algorithm for use in ensemble prediction systems. *Q. J. R. Meteorol. Soc.*, **131**, 3079–3102.

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

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.

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.

SRNWP PHY-EPS workshop, 2013, Madrid (Spain), http://srnwp-eps.aemet.es

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

Stephenson D.B., B. Casati, C.A.T. Ferro and C.A. Wilson, 2008: The extreme dependency score: a non-vanishing measure for forecasts of rare events. *Meteorol. Appl.*, **15**, 41-50.

Stephenson, D.B., 2000: Use of the "odds ratio" for diagnosing forecast skill. *Wea. Forecasting*, **15**, 221-232.

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.

Sundqvist, H., 1978: A parameterisation scheme for nonconvective condensation including prediction of cloud water content. *Quart. J. Roy. Meteor. Soc.,* **104,** 677–690.

Sutton, C. J., Hamill, T. M. and Warner, T. T., 2004: Impacts of perturbed soil moisture conditions on short-range ensemble variability, 16th NWP/20th W&F Conference, Seattle, American Meteorological Society.

Sutton, C., Hamill, T. and Warner, T. 2006. Will perturbing soil moisture improve warm-season ensemble forecasts? A proof of concept. Mon. Weather Rev. 134, 3174–3189.

Stephan, K., S. Klink,, and C. Schraff, 2008: Assimilation of radar derived rain rates into the convective scale model COSMO-DE at DWD. *Quart. J. Roy. Met. Soc.*, **134**, 1315–1326.

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.

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

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**, 3715-3730.

Thuburn, J. and C. J. Cotter, 2012: A framework for mimetic discretization of the rotating shallow water equations on arbitrary polygonal grids, SIAM J. Sci. Comput, 34/3, B203-B225.

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

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

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.

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.*

Viterbo, P. and Beljaars, A. C. M., 1995:An improved land surface parametrization scheme in the ECMWF model and its validation, Technical Report 75, Research Department, ECMWF.

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.

Wacker, U., K.V. Jayaraman Potty, C. Lüpkes, J. Hartmann and M. Raschendorfer, 2005: A case study on a polar cold air outbreak over Fram Strait using a mesoscale weather prediction model, *Boundary Layer Meteorol.*, **117**, 301-336.

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., Kann, A., Bellus, M., Pailleux, J., and Wittmann, C., 2010: A strategy for perturbing surface conditions in LAMEPS, *Atmos. Sci. Lett.*, **11**, 108–113.

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.

Weusthoff, T., F. Ament, M. Arpagaus and M.W. Rotach, 2010: Assessing the Benefits of Convection-Permitting Models by Neighborhood Verification: Examples from MAP D-PHASE. *Mon. Wea. Rev.,* **138**, 3418-3433.

Wicker, L. J. and W. C. Skamarock, 2002: Time Splitting Methods for Elastic Models using Forward Time Schemes, *Mon. Wea. Rev.*, **130**, 2088-2097.

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.

Wyngaard, J. C., 1983: Lectures on the planetary boundary layer. *Mesoscale Meteorology—Theories, bservations and Models,* D. K. Lilly and T. Gal-Chen, Eds., NATO ASI Series, D. Reidel, 603–650

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.

Zängl, G., 2012: Extending the Numerical Stability Limit of Terrain-Following Coordinate Models over Steep Slopes, *Mon. Wea. Rev*., **140**/11, 3722-3733.

Zeng, Y., 2014: Efficient radar forward operator for operational data assimilation within the COSMO model. KIT Scientific Publishing, ISBN 978-3-7315-0128-2.

Ziemianski, M.Z., M. J. Kurowski, Z. P. Piotrowski, B. Rosa, and O. Fuhrer, 2011: Toward Very High Horizontal Resolution NWP over the Alps: Influence of Increasing Model Resolution on the Flow Pattern, Acta Geophys., 59/6, 1205-1235.

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.

Appendices

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** – 13 yrs experience of successful operational non-hydrostatic modelling – 6 yrs experience of successful operational convection-permitting modelling – 1 yr experience of successful operational convection-permitting EPS – easy worldwide relocatability – 5 licensees paying 20.000 € annually – more than 15 NMS users in developing countries – fully portable, well maintained model code – prototype model version for new HPC architecture	**Weaknesses** – insufficient use of indirect observations – some parameterisation packages require revision – weak coupling between parameterisation schemes – incomplete documentation
external	**Opportunities** – increasing demand for model data (also in private sector) – need for an integrated forecasting system for nowcasting and very short range forecasts – EPS for decision making – externally funded projects (e.g. in the field of renewable energy) – 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) – possible interoperability with other models (out of SRNWP Programme) – comparison of quality with others models possible (SRNWP Programme)	**Threats** – risk of losing focus because of high diversity of applications and requirements – strong other consortia developing HARMONIE andUnified Model (UM) – significant evolution of the HPC architecture, towards massiveparallelism (i.e., O(10k) CPUs) requiring model adaptations

A1.2 Consortium

	Helpful	Harmful
Internal	**Strength** – community of weather services developing and running the same model in operational mode – science plan defined with mechanisms to implement it (Priority Projects) – creative environment for bottom-up initiatives – joint operational applications (LEPS)	**Weaknesses** – no budget (but license fee income in the order of 100.000 € annually!) – no dedicated development team – inhomogeneous resources between members (manpower, qualification, technical infrastructure, funding) – dispersion of resources to address too many issues
external	**Opportunities** – strong links to academia – COSMO-CLM – COSMO-ART – SRNWP, especially the know-how exchange within the expert teams – Licensing	**Threats** – global models with always higher resolution – strong other consortia – pressure towards quick wins – national plans that interfere with COSMO plans, or even prevent their realisation

A2 Acronyms list

ADHOC - Assumed Distribution Higher Order Closure

AIRS - Atmospheric Infrared Sounder

ALADIN - Aire Limitée Adaptation dynamique Développment INternational; also: AROME Limited Area Decentralized International Network

ALARO – transition step between ALADIN and AROME models

AMDAR - Aircraft Meteorological Data Relay

AMSU-A - Advanced Microwave Sounding Unit-A

APA - Adaptive Parameterisation Approach

AROME - Applications of Research to Operations at MEsoscale

AROME-EPS - AROME Ensemble Prediction System

ARPA-Piemonte - Agenzia Regionale per la Protezione Ambientale – Piemonte (Regional Agency for Protection of the Environment of Piedmont)

ARPA-SIMC - Agenzia Regionale per la Protezione Ambientale - Servizio Idro-Meteo–Clima (Regional Agency for Protection of the Environment of Emilia-Romagna, Hydro-Meteorological Weather Service)

ARPS - Advanced Regional Prediction System

ASCAT - Advanced Scatterometer

ASTER GDEM - Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map

ATOVS - Advanced Television Infrared Observational Satellite (TIROS) Operational Vertical Sounder

BC - boundary conditions

BCEPS – Boundary Condition EPS (COSMO EPS system at DWD with multi-model IC/BC and parameterised convection)

BGR BÜK - Bundesanstalt für Geowissenschaften und Rohstoffe Bodenübersichtskarte (data sets of soil types of Federal Institute for Geosciences and Natural Resources, Germany)

BL - Boundary Layer

BSS - Brier Skill Score

C2SM - Center for Climate Systems Modeling

CA – Closure Assumption

CALIPSO - Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations

CALMO - Priority Project Calibration of COSMO Model

CAM-SE - Community Atmosphere Model-Spectral Elements

CASPUR - Consorzio interuniversitario per le applicazioni di supercalcolo per università e ricerca (Interuniversities Consortium for Supercomputing Applications for University and Research)

CBL - Convective Boundary Layer

CDC - Priority Project Conservative Dynamical Core; also: - Conditional Domain Closure

CELO - Priority Project COSMO-EULAG Operationalization

CIRA- Italian Aerospace Research Centre

CLM-Community – Climate Limited-area Modelling Community

CM - Cloud Microphysic

CNMCA - Centro Nazionale di Meteorologia e Climatologia Aeronautica

COLOBOC - Priority Project Consolidation of Lower Boundary Conditions

CONSENS - Priority Project CONSolidation of COSMO ENSemble

COSI - COSMO-Index for verification

COSMO- Consortium for Small Scale Modelling

COSMO-ART - COSMO Aerosols and Reactive Trace Gases

COSMO-CLM (CCLM) - CLimate Mode of the COSMO model

COSMO-DE – COSMO forecast system over Germany at DWD (convective-scale ensemble)

COSMO-DE-EPS – as above

COSMO-E - ensemble COSMO forecast system of MeteoSwiss (convective-scale)

COSMO-EU - COSMO forecast system over Europe at DWD (parameterised convection)

COSMO-EULAG - COSMO model with EULAG as dynamical core

COSMO-IT-EPS - ensemble COSMO forecast system at ARPA-SIMC (convective-scale)

COSMO-LEPS – COSMO Limited Area Ensemble Prediciton System (parameterised convection)

COSMO-RU – COSMO forecast system at Roshydromet

COSMO-RU2-EPS – ensemble COSMO forecast system at Roshydromet (convective-scale with 2.2 km horizontal resolution)

COSMO-SC - COSMO Single Column model

COSMO-SREPS - COSMO Short-Range Ensemble Prediction System

COST - European Cooperation in Science and Technology

COTEKINO - Priority Project COsmo Towards Ensembles at the Km-scale IN Our countries

CPU - Central Processing Unit

CRPS - Continuous Rank Probability Score

CRPSS - Continuous Rank Probability Skill Score

CSCS - Centro Svizzero di Calcolo Scientifico (Swiss National Supercomputing Centre)

C-SRNWP - Coordination on Short-Range Numerical Weather Prediction Programme

CTH - Cloud Top Height

CUDA - Compute Unified Device Architecture

CV - Conditional Verification

DA - Data Assimilation

DFS - Degrees of Freedom for Signal

DG - Discontinuous Galerkin

DSEL - Domain-Specific Embedded Language

D-var - variational methods

DWD - Deutscher Wetterdienst (German National Weather Service)

EarthCare - Earth Clouds, Aerosols and Radiation Explorer

EC - Environment Canada

ECMWF - European Centre of Medium Range Weather Forecast

ECMWF- ENS - ECMWF Ensemble Forecast

EDMF - Eddy-Diffusivity/Mass-Flux

EDS - Extreme Dependency Score

EFAS - European Flood Awareness System

E-GVAP - EUMETNET EIG GNSS water vapour programme

EnKF - Ensemble Kalman Filter

ENS - Ensemble Forecast

EnVar - technique which combines variational with ensemble data assimilation methods

EOF - Empirical Orthogonal Functions

EPS - Ensemble Prediction System

ESRL - Earth System Research Laboratory

ETS - Equitable Threat Score

EULAG - Eulerian/semi-Lagrangian fluid solver

EUMETNET - Network of European Meteorological Services

EUMETNET EIG - Economic Interest Grouping EUMETNET

EXTPAR - COSMO software for generation of external parameters

FD - Finite Difference

FE- Finite Element

FLake - lake parameterisation scheme

FSO - Forecast Sensitivity to Observations

FTE - Full Time Equivalents

FV – Finite Volume

GABLS3 – GEWEX Atmospheric Boundary Layer Study no. 3

GBLA - General Boundary Layer Approximation

GEOS – Goddard Earth Observing System Model

GEWEX - Global Energy and Water Cycle Exchanges Project

GKSS Forschungszentrum – currently: Helmholtz-Zentrum Geesthacht Zentrum für Material und Küstenforschung GmbH (Centre for Materials and Coastal Research)

GLASS - Global Land/Atmosphere System Study

GlobCover - Global land cover data

GME - operational global numerical weather prediction model *of* DWD

GMES - Global Monitoring for Environment and Security

GNSS - Global Navigation Satellite System

GPU - Graphics Processing Unit

GS - Grid Scale

HarmonEPS - HARMONIE Ensemble Prediction System

HARMONIE - Hirlam Aladin Research on Meso-scale Operational NWP in Euromed

HBLA - Horizontal Boundary Layer Approximation

HD(CP)^2 - High Definition Clouds and Precipitation for advancing Climate Prediction

HErZ - Hans-Ertel-Zentrum für Wetterforschung (Hans Ertel Centres for Weather Research)

HIRLAM - HIgh Resolution Limited Area Model

HNMS - Hellenic National Meteorological Service

HOC - Higher Order Closure

HPC- High Performance Computing

HYMACS - Hybrid Mass Flux Convection Scheme

IASI - Infrared Atmospheric Sounding Interferometer

IC - initial condition

ICON - ICOsahedral Non-hydrostatic General Circulation Model

ICON-EPS - ICON Ensemble Prediction System

IFS - Integrated Forecasting System

IMGW-PIB - Institute of Meteorology and Water Management - National Research Institute, Poland

Intel MIC - Many Integrated Core processor by INTEL

I/O – input/output

IPCC - Intergovernmental Panel for Climate Change

IR - Infrared

JMA - Japan Meteorological Agency

JMA-ASUCA - Non-Hydrostatic Weather Model of JMA

KENDA - Priority Project Kilometre-scale ENsemble Data Assimilation

LAM - Local Area Model

LBC - Lateral Boundary Condition

LDG - Local Discontinuous Galerkin

LES - Large Eddy Simulation

LETKF – Local Ensemble Transform Kalman Filter

LHN - Latent Heat Nudging

LMU - University of Munich

MCSI- Monte Carlo Spectral Integration

MeteoSwiss – Federal Office of Meteorology and Climatology MeteoSwiss (National Weather Service of Switzerland)

Met Office - United Kingdom's National Weather Service

MIC - Many Integrated Core

MODIS - Moderate Resolution Imaging Spectroradiometer

MOGREPS-UK - Met Office Global and Regional Ensemble Prediction System

MOS – *Model Output* Statistics

MPDATA - Multidimensional Positive Definite Advection Transport Algorithm

MPI - Message Passing Interface

MPP - Massively Parallel Processors

MSG SEVIRI - Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager

MTG-IRS - Meteosat Third Generation Infrared Sounding

MW - Microwave

NASA - National Aeronautics and Space Administration

NCAR - National Center for Atmospheric Research

NCEP - National Centers for Environmental Prediction

NDP - Nowcasting Demonstration Project

NEMO - Nucleus for European Modelling of the Ocean

NetCDF - Network Common Data Form

NIM - Non-hydrostatic Icosahedral Model

NinJo - meteorological software system

NMA - National Meteorological Administration of Romania

NOAA - *National Oceanic and Atmospheric Administration*

NVIDIA-CUDA – Compute Unified Device Architecture (GPU computing architecture by NVIDIA)

NWC - nowcasting

NWP - Numerical Weather Prediction

NWP-SAF - Satellite Application Facility for Numerical Weather Prediction

OMEGA – Operational Multiscale Environmental model with Grid Adaptivity

OpenACC – programming standard for parallel computing

OPERA – Operational Programme for the Exchange of weather RAdar information

PARTURA – dry, level-2.0 turbulence scheme

PBL - planetary boundary layer

PDFs - Probability Density Functions

PF - Particle filter

PMs – Parameterisations (Physical)

POMPA – Priority Project Performance on Massively Parallel Architectures

PPs - Priority Projects

PTs - Priority Tasks

RAMS – Regional Atmospheric Modeling System

RASS – Radio Acoustic Sounding System

RC LACE - Regional Cooperation for Limited Area modeling in Central Europe

RCS - Revision Control System

RK - Runge-Kutta

RL - Roughness Layer

RMSE - *Root-Mean-Square Error*

ROC - Relative Operating Characteristic

Roshydromet - Federal Service for Hydrometeorology and Environmental Monitoring of Russia

RRTM - Rapid Radiation Transfer Model

RT - Radiation Transfer

SAL – Structure, Amplitude and Location verification method

SAT - Surface-to-Atmosphere Transfer

SBL - Stable Boundary Layer

SC - Single Column

SCAs - The Source Code Administrators

SCM- Single Column Model

SEDI - Symmetric Extremal Dependence Index

SEDS - Symmetric Extreme Dependency Score

SEEPS - Stable Equitable Error in Probability Space score

SEVIRI - Spinning Enhanced Visible and Infrared Imager

SGS - Sub Grid Scale

SKEB - Stochastic Kinetic Energy Backscatter

SM – Soil Moisture

SMA - Soil Moisture Analysis

SMC - Scientific Management Committee

SMOS - Soil Moisture Ocean Salinity

SMPP - Stochastically Modified Physical Parameters

SPD - Slant Path Delay

SPM - Scientific Project Manager

SPPT - Stochastic Perturbation of Physical Tendencies

SREPS – Priority Project Development of Short range ensemble

SRNWP - Short-Range Numerical Weather Prediction (Programme)

SSO - Sub Grid Scale Orography

SST - Sea Surface temperature

STC- Steering Committee

STIC - Separated Turbulence Interacting with Circulations

SVAT- Soil Vegetation Atmosphere Transfer

SWOT - Strength Weaknesses Opportunities Thread (analyses)

TAG - Technical Advisory Group

TERRA – soil model of COSMO and ICON

THORPEX - The Observing System Research and Predictability Experiment

TICA - Tilted Independent Column Approach

TIGGE - THORPEX Interactive Grand Global Ensemble

TIGGE-LAM - Limited Area Model component of TIGGE

TKE - Turbulent Kinetic Energy

TKESV – TKE turbulence scheme with prognostic equations for the Scalar Variances

TL - Transfer Layer

TOPROF - Towards Operational ground based PROFiling with ceilometers

TURBDIFF - level-2.5 turbulence scheme with a prognostic TKE-equation

TURBTRAN – Surface-to-Atmosphere Transfer of COSMO and ICON

UTCS - Priority Project Towards Unified Turbulence-Shallow Convection Scheme

VAD - velocity azimuth display

Veg3D - soil-vegetation model

VERSUS - COSMO verification software

VERSUS2 – Priority Project VERification System Unified Survey 2

VIS - Visible Imaging Spectrometer

VRRL - Vertically Resolved Roughness Layer

WGs - Working Groups

WMO - World Meteorological Organization

WRF - Weather Research and Forecasting Model

WV - Water vapour