COSMO Priority Project CALMO :
Calibration of COSMO Model (Extended Version)

Version 7.1, 9.06.2015

Project leader : **A.Voudouri / HNMS**

Project duration : **09.2014 – 09.2016**

Project resources : **~3.6 FTE**

Contributing scientists :

A.Voudouri / HNMS	**2015: 0.8 FTE, 2016: 0.6 FTE**
E. Avgoustoglou /HNMS	**2015 0.25 FTE, 2016: 0.3 FTE**
P. Khain /IMS	**2015 0.55 FTE, 2016: 0.35 FTE**
I. Carmona /IMS	**2015 0.25 FTE, 2016: 0.25 FTE**
JM. Bettems / MeteoSwiss	**2015: 0.1 FTE, 2016: 0.1 FTE**

(in addition, support from MeteoSwiss will be provided as needed)

Summary

Uncertainties in atmospheric models used for numerical weather prediction (NWP) and climate modelling stem in a significant part from the parameterization schemes of the physical processes within the models. In particular, the parameterization schemes include many free or poorly confined parameters. In order to eliminate the uncertainties induced by these unconfined parameters and consequently improve the agreement of forecasts with available observations, expert tuning is typically performed for a certain target area, and for a certain model configuration during model development. It is questionable whether such a calibration is still optimal for different target regions (e.g. with a different climate) or for other model configurations (e.g. with an increased grid resolution). Furthermore, the lack of an objective process to calibrate the model often inhibits the implementation of new model features.

A practicable objective multi-variate calibration method has been developed by Bellprat et al. (2012a and 2012b) and implemented for a regional climate model. The objective method has shown to be at least as good as an expert tuning. Based on these results, the priority project (CALMO) has been proposed and accepted with the aim to investigate the usefulness of this method for NWP applications.

In the first phase of CALMO, the method has been applied to COSMO-7; in the extended CALMO project COSMO-2 and the new **kilometric** configuration of the COSMO model, COSMO-1, will be used. Since many research groups and operational centres are moving towards (convection-permitting) kilometric resolutions, there is a particular interest for calibrating high-resolution configurations. At the same time, the potential to show a significant impact of the calibration method on COSMO-1 is much larger than with COSMO-7, since the kilometric configuration differs substantially from the configurations used in the development process at DWD. However, the need to span a significant subset of the model parameter space and the size of the computational mesh requires access to significant computing resources. Therefore a proposal has been submitted to the CSCS and accepted, to have access to a large amount of computing resources for calibrating COSMO-1, with computing capacity

available from October 1st 2014. **To use this computing capacity within the framework of CALMO, a project extension is required.**

Besides assessing the usefulness of the calibration method for an NWP model, the two additional scientific goals of this project are to understand the sensitivity of the NWP model quality with respect to some of the model parameters and to optimize the calibration procedure, in order to make it practicable on a standard HPC production system. Both aspects can not directly be transferred from the experience with the calibration of the climate version of COSMO due to the very different performance scores and time scale involved in climate and weather forecasts.

The main scientific impact of a positive outcome of this project is the generation of an objective calibration tool to determine the optimal setting of free or poorly defined model parameters. Depending on available computing resources, modellers will be able to objectively and reproducibly calibrate their NWP modelling system whenever needed: e.g. after major model changes, for an unbiased assessment of different modules (e.g. parameterization schemes), for optimal perturbation of parameters when run in ensemble mode, for a better understanding of the sensitivity of the model quality to a specific model parameter, etc. What today is only done once ('expert tuning') will in the future be done as often as needed!

Motivation, goals

It has been shown that model parameter uncertainty is a major source of errors in regional climate model simulations (Stephens et al., 1990; Knutti et al., 2002; Webb et al., 2013). State-of-the-art NWP models are commonly tuned using expert knowledge without following a well-defined strategy (Duan et al., 2006; Skamarock, 2004; Bayler et al., 2000). This 'expert tuning' is typically made only once during the development of the model, for a certain target area, and for a certain model configuration, and is difficult if not impossible to replicate. To circumvent this problem, an objective calibration method (Neelin et al., 2010) for COSMO-CLM, has been applied at the Institute of Atmospheric and Climate Science of the ETHZ (Bellprat et al., 2012b). After having identified key COSMO model parameters (Bellprat et al., 2012a) and defined a performance score representative for the model quality, a cost-effective meta-model describing the model performance in the space spanned by these model parameters has been derived. The optimal parameter configurations for the full model are then found by optimizing the model performance of the meta-model with respect to the performance score used.

The use of an objective method such as the one applied in Bellprat et al. 2012b, is highly attractive due to its efficiency, wide calibration range and transparency. A calibration of the model parameters should be applied each time a significant change in the configuration is introduced, or when the model is used on a target region with a significantly different climatology. Model development could thereby be accelerated, because the expert knowledge required for the tuning is often not readily available, and testing new model parameterizations would ideally be accompanied with a proper calibration. Additionally, a major stumbling block to model improvements are compensating errors, where the systematic error in a certain part of the model is adjusted by manual tuning of another part of the model and thereby introducing another systematic (but balancing) error. As a result, compensating errors often lead to a degradation of model quality if a significant improvement is made to the model component with the systematic error. An automatic re-calibration methodology can help to surmount this deadlock by being able to rapidly find new optimal parameter settings.

CALMO project is based on applying the calibration method proposed by Bellprat et al. (2012b) for regional climate modelling NWP. However although many adjustment have been made a few still need to be made to transfer thoroughly the method to NWP. For example the selection of the performance score used to assess model quality applicable to NWP model, the length of the NWP model integrations which is much shorter (days) than regional climate model integration (years). Thus, there is considerable potential to optimize the simulation strategy with respect to the minimal amount and distribution of NWP model forecasts required for a reliable calibration. During the first year of CALMO project, basic research was conducted, required for proving the effectiveness of the calibration framework developed at ETHZ in the context of regional climate simulations for NWP applications, making the necessary adaptations, and assessing its practicability. Significant experience has already been gained since the beginning of CALMO project.

Preliminary results show that the method is valid for NWP. Meta-model can be adjusted to reproduce COSMO NWP outputs, while the NWP forecast quality seems to be improved when the set of optimum parameter values is used. One has though to consider that different optimum values sets for the three parameters tested for winter and summer, have been extracted. Thus it is suggested that the method should be expanded to more than three model parameters. Furthermore, the current implementation of the method should be shifted to mesh-sizes which are more relevant to current and future model implementations.

Note that, the proposed objective calibration methodology has the potential to bring a transformative change to atmospheric model development and significantly reduce model development cycle times. The calibration method will be a very useful tool to improve the quality of the multiple configurations of atmospheric models running in Europe and beyond. More specifically, the developed methodology could be used by each COSMO member to define an optimal calibration over the target area of interest, for re-calibration after major model changes (e.g. higher horizontal and / or vertical resolution), as well as for an unbiased assessment of different modules (e.g. parameterization schemes), and for optimal perturbation of parameters when run in ensemble mode. Furthermore, a better understanding of the sensitivity of the model quality associated with a specific parameter value could benefit the quantification of the flow dependent model forecast error. Last but not least, the implementation of the methodology for a specific parameter can clarify the impact of the specific parameter on the overall model performance. Once the meta-model has been fitted to the full COSMO NWP model both the effect of the parameter setting and parameter space used (i.e., the maximal range of optimal values) can be determined without the use of the full NWP model.

Actions proposed

- Preliminary work (Task 1)
- Adaptation of the existing method for NWP applications (Task 2)
- Assessing the usefulness of the calibration method (Task 3)
- Define optimal methodology in terms of computing time and quality gain (Task 4)
- Documentation and dissemination of results (Task 5)

Main deliverable:

1. Provide an objective and practicable methodology, a tool that can substitute expert tuning for calibrating NWP models.
2. Provide the associated technical and scientific documentation.
3. Understand the sensitivity of the NWP model quality with respect to the unconfined model parameters.

Description of individual tasks

Note: *Estimated resources for each task are referred only to extended CALMO*

Task 0: Administration and support

Due to the distributed nature of the project team, a particular effort will be necessary to keep a good information flow between all participants (e.g. by organizing regular phone or web conferences).

Deliverables:

(1) Project coordination, meeting and web conference organization.

Estimated resources:

J.M. Bettems / MeteoSwiss 2015: 0.05 FTE, 2016: 0.1

A. Voudouri /HNMS 2015: 0.05, 2016: 0.05

Task 1: Preliminary work

Literature survey and knowledge transfer between contributing scientists belongs to this task. The computing resources for tasks 2 and 3 are guaranteed during this phase of the project. This task is divided into the following sub-tasks:

1.1: Literature Survey
Literature survey of relevant scientific papers, with respect to the choice of the statistical measure (performance score), parameterization of physical processes and experimental design is included in this sub-task. In order to proceed with the selection of related NWP variables and associated parameters, discussions with/or relevant references obtained from scientists responsible for the parameterization schemes is required.

1.2: Knowledge transfer
This task initially included interaction among the contributing scientists for the implementation of the CCLM method in COSMO for NWP. However the establishment of a “direct line” on model developers and CALMO scientists is important in order to determine the most important/sensitive ‘unconfined’ parameter existing in the parameterization schemes of physical processes implemented in the model.

1.3: Technical Infrastructure
The most important issue of the specific task is guarantying the required computing resources during this phase of the project. The configuration of the tools on the provided computing platform is included in this task.

For the project extension, the required computer resources have been calculated so that the method could be applied both at different model resolutions as well as in case of basic changes in the model configuration. Computer resources are now available from CSCS within the October 2014-March 2016 allocation period.

1.4: Consolidation of CALMO methodology

Consolidation of previous results obtained with COSMO 7 in terms of required steps to be followed. A guide on the re-generation of the results, with the specific parameters calibrated in CALMO is the main deliverable of this task. Refinement and testing of the calibration method will be performed with COSMO-2.

Deliverables:

(1) A list of papers related to key model parameters, variable selection and quantification of model performance.
(2) The technical framework for performing objective model calibration.

Estimated resources:

J.M. Bettems / MeteoSwiss 2015: 0.05 FTE

A.Voudouri / HNMS 2015: 0.05 FTE, 2016: 0.05

P.Khain/IMS 2015: 0.05FTE

Task 2: Adaptation of the method

This task touches the scientific aspects of the project and aims on answering the following questions: "What is the gain for the quality of NWP forecasts using the calibration framework developed at ETHZ?" and "Which adaptations are necessary in order to establish the work developed within CALMO as a calibrating tool?"

A (non exhaustive) list of aspects to consider are:

- Which performance function (verification score)? How robust is the performance ranking with respect to this choice?
- Parameters subspace to consider (convection resolving scale and convection parameterization scale)?
- Which base configuration (initial condition of the soil, data assimilation or none, simulation length)?

This task is divided into the following sub-tasks:

2.1: Documentation of tuning parameters and choice of parameters subspace

Compile a document listing for most of tuning parameters in the model, with a short documentation of the meaning, the default value, the allowed range, the model sensitivity, and any other useful information. The choice of the parameter subspace to consider for the optimization process will be made on the basis of this document extracted through a series of sensitivity experiments.
The importance of replacing expert tuning with objective calibration dictate the extension of the project, as additional parameters could be used for calibration. The list of parameters to be tested will be updated. This could be considered as an on-going task, following model developments whenever additional 'free' parameters are added.

2.2: Selection of performance function(s)
An important aspect to be considered for the implementation of the method is the selection of the performance score for the model quality since it critically influences the sensitivity of the forecast quality with respect to the various unconfined model parameters. For temperature, we initially used root mean squared error (RMSE) as the performance score, which is widely used for temperature verification (Murphy, 1988). For precipitation RMSE was also tested, though it is known (Katz and Murthy, 1997) that several different accuracy measures have to be used to fully assess the value of the forecast.

However the aim of the specific task is the evaluation of the model performance in terms of a statistical measure appropriate for all variables (e.g. both T2m and precipitation) and therefore the introduction of a unified and robust performance score for NWP applications remains as the final goal of this task.

2.3: Identification of key-variables for NWP
Implementation of the CCLM method in COSMO for NWP requires identification of the key variables that are essential to weather forecasting, mainly minimum and maximum 2m temperature and precipitation as they exhibit a larger variability than monthly means used in case of COSMO-CLM, Bellprat et al. (2012a). This task is associated with task 2.1, as selection of parameters mainly affecting these variables should be considered for calibration.

2.4: Experimental set-up.
The aim of this task is to expand existing configuration in CALMO in terms of base model configuration, domain size and location, initial condition of the soil, data assimilation or free run, simulation length, as well as possible selection of dynamical parameter for calibration rather that the ones based on expert tuning.

The refactored version based on the version 5.0 of the COSMO model capable of running on GPU-based hardware architectures will be used (Lapillonne and Fuhrer, 2013) once it is available. The computationally most expensive model setup will be based on the research configuration MeteoSwiss is using for the 1.1km model named COSMO-1. The domain has a size of 1158 x 774 grid points in the horizontal and 80 vertical levels and spans the greater Alpine region.
The 2.2 km version of the model will also be used for the development of the calibration method, which is computationally much less expensive. This will yield an objective inter-comparison between the known ‘expert tuning’ of that version as well as an inter-comparison between two model versions.
The 2.2 km simulations will be executed over the same domain but has only 60 vertical levels, and thus the computational cost is reduced by a factor of approximately 10 with respect to a corresponding 1.1 km simulation.

2.5: Collection of data
Special attention is required when selecting the observations used for the determination of the model performance, as they have to be consistent with the modeling framework and resolution. High-quality gridded datasets of both precipitation and temperature are available for long time periods (e.g. Isotta et al., 2013; Frei, 2013) and will be used for the verification of the calibrated model. Once the simulations have been performed, different scores or combinations can be applied rapidly and without requiring further model integrations.

The initial and boundary conditions for all experiments will be taken from an analysis run at 2.2 km resolution. An important issue that requires careful consideration is the initialization of the soil, since the typical time-scale for the adjustment of the soil moisture to a change in the model climate is of the order of years. One possible approach will be a spin-up run with a much cheaper coarser model, before starting each calibration experiment. Thus TERRA standalone will also be used for CALMO project and will consist an important tool for calibrating the COSMO model. Systematic tests (sanity check, performance of TERRA standalone) will be performed, so that soil initialization for CALMO will be done using TSA outputs.

2.6: Modifications on the meta-model
Once the key variables and the appropriate parameters to be calibrated have been chosen, further adjustments of the meta-model have to be performed. For example scripts considering different statistical measures as performance score, manipulation of data etc.

2.7: Compute experiments and analyse results
Compute at least [2*N + N *(N-1)/ 2] COSMO model integrations, where N is the number of parameters selected to specify the meta-model, and use the meta-model to find the optimum.The current implementation of the method should be shifted to mesh-sizes which are more relevant to current and future model implementations and expanded to more parameters than the ones used with COSMO 7. As a consequence, the number of required simulations will be increased and a significant amount of computing resources is required. As these integrations are also time consuming, it is important to well coordinate the different experiments and relevant tasks.

2.8 Data thinning policy and application

The amount of raw data produced during the simulations is estimated being of the order of 70 TB for the entire amount of simulations. Thus the actual amount of storage capacity needed is extremely high. To address this problem, a data thinning policy will be employed.

Deliverables:

(1) An updated documentation of the tuning parameters in the COSMO model.

(2) The definition of a performance function applicable on NWP.

(3) The documentation of the experimental set-up.

(4) An updated version of the meta-model.

(5) A scientific discussion of the results obtained.

(6) A protocol on model calibration.

Estimated resources:

A.Voudouri / HNMS 2015: 0.25 FTE, 2016: 0.25 FTE

E.Avgoustoglou/HNMS 2015 :0.20 FTE, 2016: 0.15 FTE

P.Khain/IMS 2015:0.25 FTE, 2016: 0.15 FTE

I. Carmona/IMS 2015: 0.20 FTE, 2016: 0.15 FTE

Task 3: Assessing the usefulness of the calibration method

The goal of this task is to show that the method is indeed able to improve the quality of the model. The sensitivity of the optimum with respect to the model resolution will be investigated in this task, as well as the 'fair' assessment of the impact of improved resolution. This task could be used as a test bed to refine the developments of task 2. This task is also strongly affected by the available computing resources. It will start after the end of Task 2 and will be divided into:

3.1: Application of the method using COSMO-1

Experience gained by using the calibration methodology and its applicability to NWP models will be transferred from simulations using COSMO-2 to selected COSMO-1 simulations. More specifically the aim of this subtask is the calibration of the 1.1 km mesh-size COSMO version using at least 4 parameters to test the calibration method for a convection-permitting COSMO configuration. An objective inter-comparison between the COSMO-2 and COSMO-1 as well as an assessment of the added value of higher resolution will then be feasible.

3.2: Analyse results

Once simulations are finalized the meta-model will be applied. Both model and meta-model results will be analysed and gain of meteorological quality when using the optimal configuration against the standard configuration will be examined.

Deliverables:

(1) Refinement of the method to be used for higher-resolution configurations.

(2) An objective inter-comparison between the two model versions COSMO-2 and COSMO-1

(3) Dissemination of analysis results to be discussed among scientific groups responsible on model development.

Estimated resources:

A.Voudouri / HNMS 2015: 0.25 FTE, 2016: 0.15 FTE

E.Avgoustoglou/HNMS 2016: 0.1 FTE

P.Khain/IMS 2015: 0.15 FTE, 2016: 0.1 FTE

I. Carmona/IMS 2015: 0.05 FTE, 2016: 0.1 FTE

Task 4: Practicability of the method

The third important objective of this project is to optimize the calibration procedure with respect to the required amount of computing resources, such that a model re-calibration can be computed on any standard production system.

This task aimed at finding a compromise between the forecast quality gain and the computing cost of the method. Therefore, the extend that the data set of full model runs can be reduced to still obtain a robust and good quality calibration result will thoroughly be investigated.

It is now scheduled to start after the end of tasks 2 and 3, in 2016.

Deliverables:

(1) Practicable methodology in terms of computing resources, associated tools.

Estimated resources:

A.Voudouri / HNMS 2015: 0.1 FTE 2016: 0.05 FTE

P.Khain/IMS 2015: 0.05 FTE, 2016: 0.05 FTE

Task 5: Documentation

Publish scientific results of the project in a peer reviewed journal on the basis of the task 2 (and 3 if the associated results are available soon enough).

A complete description of the methodology, including a ‘cookbook’ to facilitate the usage of this method by other COSMO members, will be made available in a COSMO Technical Report.

Deliverables:

(1) Peer reviewed scientific papers

(2) Technical description of the method, including ‘cookbook’, final report

Estimated resources:

A.Voudouri / HNMS 2015: 0.1 FTE 2016: 0.05 FTE

E.Avgoustoglou/HNMS 2015: 0.05 FTE, 2016: 0.05 FTE

P.Khain/IMS 2015: 0.05 FTE, 2016: 0.05 FTE

Risks

One of the main risks of the project was the acquisition of the necessary computer resources. However the project proposal for computer resources on Daint was approved by CSCS and the allocation period is now coherent with the extended CALMO PP. Therefore the main risk is that the method remains prohibitively expensive in terms of computing times. Another significant risk is that we are not able to find the proper scalar measure defining the model quality and that consequently or the expected benefit on the forecast quality is not significant.

Links to other projects or work packages

WG5 for the choice of the performance function.

WG2, WG3a and WG3b for the selection of the model parameters.

References

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Task	Contributing scientist(s)	FTE- years	Start	Deliverables	Date of delivery	Preceding tasks
0	Antigoni Voudouri (HNMS) Jean-Marie Bettems (MeteoSwiss)	0.05-2015 0.05-2016 (**0.1 HNMS**) 0.05-2015 0.1-2016 (**0.15 Meteoswiss**)	09.2014	(1) Project coordination, meeting and web conference organization, support	08.2016	
1	Antigoni Voudouri (HNMS) Jean-Marie Bettems (MeteoSwiss) Pavel Khain (IMS)	0.05-2015 0.05-2016 (**0.1 HNMS**) 0.05-2015 (**0.05 Meteoswiss**) 0.05-2015 **(0.05 IMS)**		(1) A list of papers related to key model parameters, variable selection and quantification of model performance. (2) The modified technical framework for performing objective model calibration.	03.2016	
2	Antigoni Voudouri (HNMS) Evripides Avgoustoglou (HNMS) Pavel Khain (IMS) Izthak Carmona (IMS)	0.25-2015 0.25-2016 0.2-2015 0.15-2016 **(0.85 HNMS)** 0.25-2015 0.15-2016 0.20-2015 0.15-2016 **(0.75 IMS)**	09.2014	(1) An updated documentation of the tuning parameters in the COSMO model. (2) The definition of a performance function applicable on NWP. (3) The documentation of the experimental set-up. (4) An updated version of the meta-model. (5) A scientific discussion of the results obtained. (6) A protocol on model calibration.	03.2016	1
3	Antigoni Voudouri (HNMS) Evripides Avgoustoglou (HNMS)	0.25-2015 0.15-2016 0.10-2016 **(0.50 HNMS)**	08.2015	(1) Refinement of the method to be used for higher-resolution configurations. (2) An objective inter-comparison between the two model versions COSMO-2 and COSMO-1 (3) Dissemination of analysis results to be discussed among	08.2016	2

	Pavel Khain (IMS) Izthak Carmona (IMS)	0.15-2015 0.10 -2016 0.05-2015 0.10 -2016 **(0.40 IMS)**		scientific groups responsible on model development.		
4	Antigoni Voudouri (HNMS) Pavel Khain (IMS)	0.10 2015 0.05-2016 (**0.15 HNMS**) 0.05-2015 0.05-2016 **(0.10 IMS)**	01.2016	Practicable methodology in terms of computing resources, associated tools.	08.2016	2(, 3)
5	Antigoni Voudouri (HNMS) Evripides Avgoustoglou (HNMS) Pavel Khain (IMS)	0.10-2015 0.05-2016 0.05-2015 0.05-2016 **0.25 (HNMS)** 0.05-2015 0.05-2016 **(0.10 IMS)**	09.2014	(1) Technical description of the method. (2) Peer reviewed scientific paper.	08.2016 09.2015	4 2(, 3)