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Calibration of COSMO Model,
Priority Project CALMO
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Calibration of COSMO Model,

Priority Project CALMO

Final report.

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1 Abstract

Model parameter uncertainty is a major source of errors in regional climate and NWP model simulations (Stephens et al., 1990; Knutti et al., 2002). 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 is also the case for the COSMO model where expert tuning is typically made 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. 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 a finer grid resolution). Furthermore, the lack of an objective process to re-calibrate the model is often a major roadblock for the implementation of new model features. A practicable objective multi-variate calibration method has been proposed by Neelin et al. (2010) and applied to COSMO model for regional climate simulations (RCM) by Bellprat et al. (2012a and 2012b, 2016). The objective method has shown to be at least as good as an expert tuning. Based on these results, a COSMO priority project (CALMO) has been proposed and accepted, at the COSMO GM 2012 in Lugano, aiming to implement this method for NWP applications. CALMO project officially started on January 2013 and was completed at the end of December 2016. This COSMO priority project was assigned to Working Group 3b. During these 4 years about 6.5 FTEs have been invested. The scientists involved in the project were from 4 different institutions (HNMS, IMS, MeteoSwiss and ARPA-SIMC). Although not all tasks were successful (see Sec. 4 for details), the developments done during this project resulted in a working and robust calibration framework for NWP applications, well documented, including the calibration code (see http://www.cosmo-model.org/content/tasks/priorityProjects/calmo/default.htm).

Furthermore, substantial knowledge transfer took place between ETHZ and MeteoSwiss on one side, and HNMS and IMS on the other side, which is also a very positive side effect of this project. CALMO project was implemented in three phases. In the first phase of the project the method has been tested using COSMO-7 for three parameters over two 20 days periods; in the second phase, COSMO-2 and six parameters have been calibrated over an entire year, and in the third phase calibration of COSMO-1 and five parameters over a one month period has been performed. CALMO project has shown that the method used by Bellprat for COSMO-CLM can be adapted to NWP applications. After the proper redesign, the meta-model (MM, hereafter) is able to reasonably reproduce full COSMO model simulations, for all cases considered (Khain et al., 2015, 2017). Furthermore, the optimum set of model parameters improves a COSI-type score[1], for all tested configurations, and the results of an independent verification seem to indicate that the operational verification scores are also improved (see Sec. 7 and Sec. 8). It should be noted that the history of the soil, which may substantially impact the effect of the calibration, was only switched on for the third phase of the project, and that the calibration of COSMO-1 was limited to one month, namely January 2013. This is a serious limitation, reducing the robustness of the current analysis. Furthermore, the issue of reducing the computational cost of the method has not been tackled. Therefore, considering the huge potential of this calibration method, a follow-up project called CALMO-MAX (CALibration of MOdel Method Applied on eXtremes) has been accepted by the COSMO Steering Committee, and will take place from 06.2017 to 09.2019. A successful CALMO-MAX will provide a permanent affordable COSMO framework for objective model calibration. All details are available at http://www.cosmo-model.org/content/tasks/priorityProjects/calmoMax/default.htm.

[1]COSI score is a universal verification score used by the COSMO consortium

Much documentation about CALMO already exists and will not be duplicated in this document. More specifically two COSMO Technical Reports, No 25 and 31 (Khain et al. 2015, 2017) provide a very detailed description of many aspects of the project. All this documentation is accessible on the COSMO web. In Sec. 2 of this report, a short introduction to the calibration method is proposed and the appropriate modifications required for adapting the methodology from RCM to NWP are presented. The roadmap of the project and the progress achieved within each CALMO task are presented in Sec. 3. A short description of the MM is made in Sec. 4, while Sec. 5 is focused on sensitivity experiments and a new strategy for fitting the MM. Sec. 6 summarizes the verification of the COSMO-2 simulations computed with the optimal set of parameters and with the default parameters, using the standard verification system of MeteoSwiss. Sec. 7 presents a case study using the calibrated parameters. Conclusions are made in Sec. 8. A full commented list of unconfined model parameters is available in Appendix 9, and the results of sensitivity experiments for different model parameters and for different regions are presented in Appendix 10.

2 Methodology

The main goal of the CALMO project was the implementation of the calibration method proposed by Bellprat et al. (2012b) for regional climate modelling to NWP applications. For N unconfined model parameters, the calibration process aims at finding the values of these parameters which optimize a selected performance score (a scalar measure of the model quality depending on a set of model fields and the associated observations). The basic idea of the proposed approach is to fit a set of significant model fields in parameters space via N-dimensional quadratic polynomial (for each model field, for each region and each day, separately), the significant model fields being the ones contributing to the performance score. This is the so-called meta-model (MM). Once the MM has been fitted, using full COSMO model simulations, both the effect of the parameter setting and of the parameter space used (i.e. the maximal range of optimal values) can be determined without the use of the full model, and the optimization of the performance score becomes feasible. It is important to realize that the calibration of the model is computed for a specific score, i.e. for a specific class of model applications; one derives the values of the unconfined model parameters which provide the best results for these applications. However, to avoid over fitting the model, it is also necessary to choose a score representing enough aspects of the model. Furthermore, it is necessary to choose a score with enough associated observations of good quality. One major difference with the RCM calibration is the type of measure used to quantify the quality of the model (performance score). Whereas RCM uses monthly mean values computed over climate regions, NWP uses scores reflecting the daily cycle and the day to day variability of the weather parameters. Furthermore, the spatial resolution of a NWP model, and the spatial scales of interest, are typically finer than the ones of a RCM. This has of course consequences on the choice of the most significant model parameters to use in the calibration process. It is widely known that there are numerous unconfined parameters in the COSMO model related to sub-grid scale turbulence, surface layer parameterization, grid-scale clouds and precipitation, moist and shallow convection, radiation and the soil scheme. The selection of parameters to be calibrated is made with respect to their influence on the variables associated with daily forecasts such as daily minimum and maximum 2m temperature as well as 24h accumulated precipitation. Comprehensive experiments have been conducted to measure this sensitivity and to support the final choice of the most relevant parameters for the calibration process (see Appendix 2). Note that some expert knowledge is needed to preselect the set of unconfined parameters and to define a plausibility range of values for each of these parameters. The CALMO project has been carried out in three phases of increasing

complexity. For convenience, to be able to tackle the knowledge accumulated at MeteoSwiss, all model configurations have been based on MeteoSwiss production configuration. In the first phase of the project, the model was operated with horizontal resolution of 0.0625° (approximately 7km) for a domain extending mainly over Western Europe as shown in Fig. 1. The model vertical extension reached 23.5 km (30hPa) with 60 model levels in the atmosphere. The calibration was computed for two 20-days periods in 2008 (winter and summer), for 3 model parameters: asymptotic turbulence length scale, tur_len, minimal diffusion coefficients for heat, tkhmin, and scalar resistance for the latent and sensible heat fluxes in the laminar surface layer, rlam_heat. In the second phase of the project, the model was operated with horizontal resolution of 0.02o (approximately 2.2km) for a domain covering the Alpine Arc, in particular Switzerland and Northern Italy, as shown in Fig. 2. The same vertical structure was used as in the first project phase. The calibration was computed for the full year 2013, for 6 model parameters; with respect to the first phase of the project, the following three additional parameters have been considered: c_soil, the surface-area index of the evaporating fraction of grid points over land, v0snow, the factor in the terminal velocity for snow, and entr_sc, the mean entrainment rate of boundary layer humidity into the shallow convection clouds. In the third phase of the project, the model was operated with a horizontal resolution of 0.01° (approximately 1.1km) for the same domain as in phase 2 (Fig. 2), with 80 instead of 60 vertical levels. This is the only phase of the project where the soil memory was considered. The calibration was computed for January 2013, for 5 model parameters: besides tkhmin, tur_len, entr_sc, c_soil, also crsmin, the minimum value of stomatal resistance used by the BATS scheme for the plant transpiration has been considered. The theoretical minimum required number of full COSMO simulations to fit the meta-model is [2*N + 0.5*N*(N 1) + 1], where N is the number of unconfined model parameters to calibrate; this relation has been tested, and it has been found that more simulations are required to obtain a robust calibration. This has as consequence to increase the minimal amount of computing resources required for the calibration. The length of the model integrations used for the calibration is also an important parameter; this is emphasized by the fact that a seasonal dependency on the optimum parameter values has been found. Once the optimum values of the parameters have been determined, a final COSMO simulation using these optimum parameters is performed to assess any quality gain against the reference model configuration, as measured by a standard verification procedure.

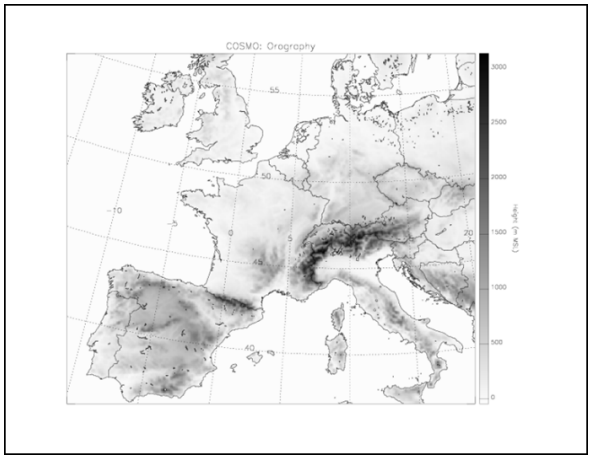

Figure 1: The simulation domain for the first phase of the project, with a 0.0625° grid size.

All necessary adaptations to transfer the calibration methodology from RCM to NWP have been performed in the framework of the CALMO project, which was defined with the following tasks:

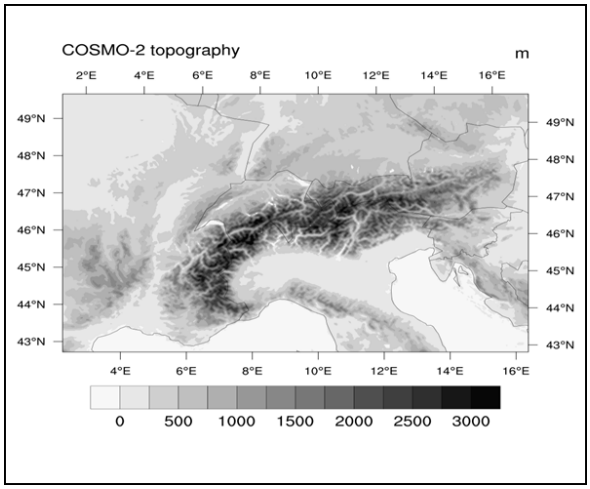

Figure 2: The simulation domain for the second and third phases of the project, with a grid size of 0.02°, respectively 0.01°.

- Preliminary work (e.g. acquire computing resources) (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)

3 Tasks and achievements

A concise account of the tasks and achievements during the project is presented in this section.

Task 0: Administration and support

Due to the distributed nature of the project team (Greece, Switzerland, Israel and Italy), regular web conferences have been performed throughout the project to ensure the good information flow between all participants. The kick-off meeting took place in Zurich and three workshops have been successfully organized in Athens; additional workshops were also organized during the parallel sessions at the COSMO GM. The mailing list of the project (CALMO-ML, herein) has been widely used in order to support communication and information exchange between project participants (mailing list archive is available on-line). Although much effort has been invested to facilitate the communication within the project team, the rapid detection of critical problems and the timely solution of technical issues remained a real challenge due to the geographically distributed knowledge and team (as proven by the misunderstanding discussed in task 2.4). More in person meetings would certainly have been beneficial (but were difficult to realize due to the multiple tasks of the contributing scientists, including bench forecasting duties).

Task 1: Preliminary work

This task was divided into 4 subtasks, namely literature survey, knowledge transfer among contributing scientists, consolidation of CALMO methodology and technical infrastructure. The main deliverable of this task was the transfer of knowledge from RCM to NWP and

the working technical framework for performing the objective model calibration. Dr. Omar Bellprat / ETHZ, who contributed to the project in 2013, prepared an updated version of the calibration code, including minor changes to improve the MM estimation, and provided the appropriate documentation (see also sub-task 2.6). The entire project required significant computer resources for tasks 2 and 3. Computer resources were made available through a production project on the Piz Daint system hosted at the CSCS, using the GPU capable version of the COSMO model (the proposal is available at http://www.cosmo-model.org/content/tasks/priorityProjects/calmo/docs/CSCS_Proposal.pdf); more than one million node hours have been allocated to the CALMO project on this hybrid GPU system. In addition, a direct line has been established with the core model development team for the identification of key model parameters and for the variables to use in the performance score; discussions on this topic are available through the CALMO-ML.

Task 2: Adaptation of the method

Task 2 was divided into 8 subtasks, namely the documentation of the tuning parameters, the selection of a performance score, identification of key variables for NWP, setting up the experimental framework, collecting the appropriate data, modification of the meta model, computing and analyzing the results, and definition of a data thinning policy. The developments successfully performed in this task resulted in a working and robust calibration framework for NWP applications, well documented, including the calibration code. This task has also shown that a quadratic meta-model is able to reasonably reproduce full COSMO model simulations, for all cases considered.

2.1: Documentation of tuning parameters and choice of parameters subspace

A document listing most of the model tuning parameters, with a short documentation on their meaning, their default value, their allowed range, the associated model sensitivity, and other useful information (such as the code modules using the parameter) has been compiled and is available in Appendix 9 (note that this document is restricted to the physical parameterization schemes available in COSMO v.5.0). A selection of the parameters affecting turbulence, radiation, shallow convection, multilayer soil model, and diffusion parameterization schemes has been made and a set of sensitivity experiments have been performed by HNMS, discussed in Sec. 4 and, in more details, in Appendix 10. A shorter list of eight parameters to be considered for the optimization process at the time of the project was obtained: rlam_heat (the product of rlam_heat*rat_sea is kept constant), tkhmin (tkmmin= tkhmin, i.e. change tkmmin accordingly), tur_len, entr_sc, v0snow, crsmin, c_soil and kexpdec (f =2 in Decharme et al. 2006 formulation for hydraulic conductivity). Considering that one main goal of the calibration approach is to offer an alternative to the expert tuning, the list of tuning parameters should be kept up-to-date, and **this task should become a permanent task of COSMO**.

2.2: Selection of performance function(s)

A normalized RMSE, using both near surface daily minimum and maximum temperature and daily accumulated precipitation, suggested by IMS, described in Khain et al. (2015) and in Voudouri et al. (2017b), has been used as the performance score during the first stage of the project. It is known (Katz and Murthy, 1997) that several different measures have to be used for fully assessing the value of the forecast, in particular when considering precipitation. Therefore, more robust performance scores have been developed in the two last phases of the project: the normalized RMSE has been further improved and a COSI type score. All details are available in Khain et al (2017).

2.3: Identification of key-variables for NWP

The choice of key model variables used in the performance function is constrained by the accessibility of associated observations, with a good enough quality. Key variables used for daily weather forecasting, such as T2m daily minimum and maximum and daily accumulated precipitation, have been originally selected for the calibration. Besides their meteorological significance, observation based gridded analysis over Switzerland was also available for these variables. Additional variables have been introduced in the later phases of the project, such as the vertically integrated water vapor content, wind, temperature and humidity at significant levels, wind shear between significant levels, and stability indices, all evaluated at the location of upper air soundings stations. All details are available in Khain et al (2017).

2.4: Experimental set-up

The aim of this task was to define the exact configuration of the model simulations. The following aspects had to be considered: base model configuration (incl. grid resolution and set of physical parameterizations), domain size and location, set of external parameters, initial and boundary conditions (incl. soil initial conditions), type of simulation (e.g. hindcast, assimilation cycle and daily forecast), usage of additional analysis modules (e.g. soil moisture analysis, SST, snow pack), simulation length used for the calibration. The following paragraphs summarize the choices made in the three phases of the project.

CALMO first phase:

During the first phase of the project, the base model configuration is the COSMO-7 operational configuration operated at MeteoSwiss at the time. In particular, the model was operated on a horizontal grid with a grid size of 0.0625° (approximately 7km) for a domain extending mainly over Western Europe as shown in Fig. 1 above. Its vertical extension reached 23.5 km (30hPa) with 60 model levels in the atmosphere. The model was computed in forecast mode, with a daily 36-hour forecast starting from a fixed and prescribed analysis taken from the MeteoSwiss COSMO-7 operational archive. Lateral boundary conditions were also taken from the same MeteoSwiss operational archive. This means that the same sets of initial and lateral boundaries are used for all tests, including the reference simulation, independently from the set of unconfined model parameters values being tested. One consequence of this design is that the effect of a different set of model parameters values on the state of the soil are not propagated forward in time from one forecast to the next, or, in other words, the long-term memory of the soil is not active. According to WMO Annual Bulletin on the Climate, winter 2007/2008 was mild in Europe and, although summer 2008 has been warmer than usual, anomalies were confined in the normal range of variability of the thee recent years, without particularly strong and persistent departure from climatological averages (WMO, 2008). Therefore, 2008 was selected for the initial objective calibration approach as it was considered representative of a mean climatology over the area of interest. Two 20 days simulation periods, one during winter and one during summer, have been selected, namely 3-20.01.2008 (winter period) and 2-20.06.2008 (summer period). Although both periods are short, the forecast performance was evaluated over three different regions, yielding to a sample size which was considered adequate for this first phase of the project. The calibration of the model was restricted to the 12- to 36-hour lead time of the daily forecast, and to a limited domain covering Switzerland (verification domain), which is divided into three climatically unique areas, according to Frei (2013). The areas defined are: the area to the north of the Alpine crest, mostly coinciding with the Swiss Plateau; the area of Alpine crest, and the area to the south of the Alpine crest that mostly coincides with the Ticino region. Note that areas used by the meta-model should not be too small to avoid a noisy signal, which is not suited for a quadratic polynomial fit by the meta-model (this concerns in particular discontinuous fields like precipitation and CAPE). Finally, an additional simulation has been computed with the optimal set of unconfined parameters values, as provided by the meta-model, to

evaluate the impact of the calibration on the default model configuration.

CALMO second phase:

The base model configuration for the second phase is the COSMO-2 operational configuration operated at MeteoSwiss at the time of the project. The model was operated with a grid spacing of 0.02° (approximately 2.2km), for a domain covering the Alpine Arc, in particular Switzerland and Northern Italy, as shown in Fig. 2. Its vertical extension reached 23.5 km (30hPa) with 60 model levels in the atmosphere. As in the first phase of the project, the model was computed in forecast mode, with a daily 36-hour forecast starting from a fixed and prescribed analysis, meaning in particular that the long-term memory of the soil is again not active. In this phase of the project, the COSMO model was computed for a substantially longer period, considering the whole year of 2013 (from 01.01.2013 till 01.01.2014) instead of the 40 days period of the first phase of the project. The calibration was based on the 12- to 36-hour lead time of the daily forecast. In addition to Switzerland, Northern Italy was also added to the verification domain used for the calibration, and additional type of observations were considered. An additional experiment has also been computed with the optimal set of unconfined parameters values, to evaluate the impact of the calibration on the default model configuration.

CALMO third phase:

The base model configuration is the COSMO-1 operational configuration operated at MeteoSwiss at the time of the project (1.1 km grid mesh size, Alpine domain as in Fig. 2, 80 vertical levels). Unlike the two first phases of the project, the model was computed in hindcast mode (i.e. a free run without assimilation of observations) from 01.01.2013 till 01.02.2013, with prescribed lateral boundary conditions from the MeteoSwiss operational COSMO-7 archive. With this configuration, the impact of a new set of model parameters values on the state of the soil is propagated forward in time during the whole simulation period. The initial conditions of the soil model at the start of the hindcast run is derived from a three-year spin-up computed with a standalone soil model (so called TSA), for each set of unconfined model parameters which directly influences the soil parameterization. The advantages of computing a hindcast instead of a full assimilation cycle and a set of regular forecast, which would also keep the soil memory active, are the simplified configuration of the experiment and the reduced computational cost. Furthermore, studies have shown that, at least for a model domain of the size considered here, the differences between a hindcast and a full cycle are not significant, even after one year of simulation. In terms of computing resources, one day 1.1 km simulation costs approximately 10 times more than a similar one day 2.2 km simulation. The re-factored COSMO model version, capable of running on GPU-based hardware architectures, based on the version 5.0 of the COSMO model, was used in phases 2 and 3 of this project (Lapillonne and Fuhrer, 2013). Note also that the original plan was to use the same configurations for both the second and the third phase of the project (except for the resolution), both including the memory of the soil. However, misunderstanding between the PL and the WGC, which was realized too late, resulted in the configurations described here.

2.5: Collection of data

A gridded analysis of minimum and maximum daily 2-meter temperature, on a 2km grid, based only on observed 2m temperature at Swiss surface stations, is available over Switzerland (Frei, 2013). This analysis has been transformed to match the grid of the COSMO model, as described in the appendix A of Khain et al. 2015 (special care is needed due to the strong height dependency of the temperature field). A gridded product combining radar and rain gauges measurements has been used over Switzerland; 24-hours accumulated

precipitation have been derived from this product. All other observations, such as gridded T2m daily minimum and maximum over Northern Italy, gridded precipitation over Northern Italy, radio soundings, and gridded cloudy brightness temperature (MSG IR 10.8, and WV 6.2, not used) have been collected. The driving model used for the boundary conditions of all CALMO experiments is the operational COSMO-7 (7km resolution) computed at MeteoSwiss, and 3-hourly analysis available in the operational archive of MeteoSwiss have been used for that purpose. As already stated, an important issue that required careful consideration was the initialization of the soil, since multiple years are required for the deep soil to adapt itself to a change in the model climate (as induced e.g. by the choice of a different set of unconfined model parameters values). This is particularly crucial when considering unconfined parameter directly related to the parameterization of the soil. The approach adapted in this project was to compute a spin-up run with a much cheaper standalone soil, driven by prescribed atmospheric forcing, before starting each calibration experiment. Thus, TERRA standalone (TSA) has been consolidated to fulfill the requirements of the CALMO project. Systematic tests (sanity, performance) have been performed by IMS and soil initialization for CALMO experiments was computed. The consolidated TSA is now available through the COSMO web site (http://www.cosmo-model.org/content/support/software/default.htm).

2.6: Modifications on the meta-model

In the first phase, many adaptations of the original meta-model provided by Dr. Omar Bellprat have been performed to support the requirements for calibrating a NWP system instead of a RCM (e.g. the introduction of different statistical measures used as performance score, the manipulation of observational data sets). Significant work was then invested to improve the quadratic meta-model: defining a new set of regions, introducing an option not to average temperature extreme over regions, adding the support of atmospheric profiles, adjusting the RMSE-type performance score and introducing a new COSI performance score (Damrath, 2009), considering the conditions for a robust fit in parameter space, introducing a new method for logarithmic transformation of selected parameters, introducing a measure of model and observation uncertainties, developing an iterative method to obtain the optimal parameters via convergence in a n-dimensional parameter space of exceptional cardinality, and estimating the uncertainties on the optimal value of the model parameters. Sanity check of the meta-model has been performed, comparing the results of the meta-model with similar results of a full model run for a set of unconfined parameters not used in the calibration, both in the first and in the second phases of the project. All modifications and tests performed with the MM are discussed in details in Khain et al. 2017 and briefly described in Sec. 4 of this report. The MatLab code and the documentation is available at http://www.cosmo-model.org/content/support/software/default.htm#calmo.

2.7: Compute experiments and analyze results

This subtask was associated with the computation of at least [2*N + N *(N-1)/2 + 1] model simulations, each with a different set of model parameters values, each time over the selected time period, where N is the number of unconfined model parameters to calibrate. In the case of the COSMO-2 calibration, considering 6 model parameters, the minimum number of required simulations is 28. However, some additional simulations have been performed to better constrain the MM, and obtain a more robust set of optimum parameter values, resulting in a total of about 50 simulations, each simulation being computed over the entire year 2013. A control simulation has also been performed, using the optimum set of parameters, and the impact of the calibration on the model quality, compared with the configuration using the default parameters, is evaluated. The results of this verification are discussed in Sec. 6.

2.8 Data thinning policy and application

The standard amount of raw data produced by a one year COSMO-1 hindcast, i.e. for a single set of unconfined model parameters values, with hourly output, is of the order of 20 TB, whereas the allocated storage for the whole calibration project on Piz Daint was 70 TB. Consequently, an aggressive data thinning policy was required. Data thinning has been designed by HNMS and MeteoSwiss to provide all required data for standard verification on the full domain (SYNOP, upper air, radar composite), and to support the calibration based on minimum and maximum 2m temperature, radar composite, satellite brightness temperature and vertical profiles. Furthermore, a daily analysis was kept, in order to be able to restart a simulation from any day. Fieldextra was used for the data thinning. The data has been transferred from CSCS to ECMWF after the end of the project on Piz Daint. Although data thinning was applied, still a considerable amount of data is now being stored at the HNMS domain of ECMWF.

Task 3: Assessing the usefulness of the calibration method

The goal of this task was to show that the method is indeed able to improve the quality of the model. In addition, the sensitivity of the optimum with respect to the model resolution should have been investigated in this task, as well as the fair assessment of the impact of an improved resolution. The plan was to first calibrate the COSMO-2 configuration, and then a similar COSMO-1 configuration, both using a full year for the calibration. However, due to the many technical difficulties encountered during the project (see the Piz Daint allocation final report at
www.cosmo-model.org/content/tasks/priorityProjects/calmo/docs/CSCS_final_report.pdf), only the COSMO-2 calibration, without the memory of the soil, has been fully completed. Nevertheless, this task has shown that the optimum set of model parameters obtained with the calibration method improves a COSI-type score, for all tested configurations. More specifically, an improvement of the COSI-type score used by the MM of about 3-4% for the COSMO-2 configuration and of about 12% for the COSMO-1 configuration has been observed (all details are available in Khain et al. 2017). Interestingly, a strong seasonal dependency of the optimal parameters values has also been observed. Finally, the results of an independent verification indicate that the operational verification scores are also partly improved (see Sec. 6 for the COSMO-2 case).

3.1: Application of the method using COSMO-1

Calibration of COSMO-1 with five parameters has been performed (tkhmin, tur_len, entr_sc, c_soil, crsmin), but only for January 2013.

3.2: Analyse results

Analysis and discussion of the results have been made in Khain et al. 2015 and 2017, Voudouri et al. 2017c, and in the present report.

Task 4: Practicability of the method

An important objective of this project was 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 reasonably powerful production system. As already mentioned under task 3, due to many technical problems met during the project, neither time nor human resources remained to tackle this issue. Instead of extending the project, it was decided to consolidate the goals already achieved, mainly a working and robust calibration framework for NWP applications, well documented, including the calibration code, and to design a follow-up project aiming at optimizing the method. The follow-up project, CALMO-MAX, has been accepted by the COSMO Steering Committee in spring 2017, and will take place from 06.2017 to 09.2019. The main goal of this new project is to provide a permanent afford-

able CALMO framework for objective model calibration. All details at http://www.cosmo-model.org/content/tasks/priorityProjects/calmoMax/default.htm.

Task 5: Documentation

A significant amount of documentation has been produced, and, in particular, the goal to make public the work performed within the COSMO Priority Project, not only to the COSMO members but also to the wider scientific community, has been achieved. A scientific paper focused on the preliminary results of this project has been published in Atmospheric Research (Voudouri et al., 2017b). Two papers (Voudouri et al., 2017a and Avgoustoglou et al., 2017) based on parts of the CALMO work have been presented at the 13th International Conference on Meteorology, Climatology and Atmospheric Physics (COMECAP 2016) which was held at Thessaloniki, in 19-21 September 2016; the contributions are included in the Conference Proceedings, published by Springer International Publisher AG as a book entitled: Perspectives on Atmospheric Sciences. Finally, a second manuscript summarizing the work using COSMO 2km has been submitted to Atmospheric Research. In addition, this final report and two COSMO technical reports are available. The documentation of the meta-model and a cookbook to facilitate its usage have also been prepared. All documentation is available on-line on the COSMO web site, at http://www.cosmo-model.org/content/tasks/priorityProjects/calmo/default.htm.

4 The Meta-model *(P. Khain, I. Carmona)*

The consolidation and extension of the MM is extensively discussed in Khain et al. 2015 and 2017, so only the basic ideas are described here. As in Neelin et al. (2010), the MM for a three model parameters combination, e.g. tur_len, tkhmin and rlam_heat, for a given day i and region r, states that the COSMO forecasted field $F_{i,r}$ (here Tmax, Tmin or Pr) may be approximated by a 3-dimensional polynomial of order 2:

$$F_{i,r} \cong F^d_{i,r} + c_{i,r} + \Sigma^3_{n=1} a^n_{i,r} x_n + \Sigma^3_{n=1} \Sigma^3_{m=1} B^{n,m}_{i,r} x_n x_m$$

where $x_{1,2,3}$ are the normalized parameters:

$$x_1 = \frac{rlam\_heat - rlam\_heat_d}{rlam\_heat_{max} - rlam\_heat_{min}}, x_2 = \frac{tkhmin - tkhmin_d}{tkhmin_{max} - tkhmin_{min}}, x_3 = \frac{tur\_len - tur\_len_d}{tur\_len_{max} - tur\_len_{min}}$$

The index d stands for the default unconfined parameter values. For default values of the 3 parameters, i.e. $(x_1 = 0, x_2 = 0, x_3 = 0)$, the approximated field should be close to $F^d_{i,r}$. The diagonal values of $B_{i,r}$ can be fitted along with the linear coefficients $a_{i,r}$ from the 2N end points of the $x_{1,2,3}$ ranges, along with the default case. Thus, an order-N first-fit procedure yields an estimate of the importance of quadratic non-linearity in addition to linear sensitivity. The off-diagonal $B_{i,r}$ coefficients can be evaluated from the corners of pairwise planes (or an equivalent number of suitably distributed points). Because the procedure is of order N2 it should in practice be done for a pruned subset of parameter directions. Thus, the minimum number of simulations to derive $c_{i,r}, a^{(n)}_{i,r}, B^{(n,m)}_{i,r}$ ($B^{(n,m)}_{i,r} = B^{(m,n)}_{i,r}$), with n,m=1,2,3, is equal to 2N + N(N-1)/2 + 1, which, for N=3, gives 10. Note that a different normalization of the unconfined model parameters than the linear transformation exemplified here with $x_{1,2,3}$ could be applied. In fact, it has been found that a logarithmic transformation provides a more robust fit when the default value of the concerned parameter is not centered in the parameter plausibility interval. It is important to realize that one polynomial is derived for each day i, for each region r, and for each meteorological field F, and that the MM is the collection of

all these polynomial functions. Once the MM has been fitted, the effect of any combination of the associated unconfined model parameters on the forecasted fields $F_{i,r}$ can be evaluated without the full NWP model. Once the MM is available, the calibration is based on the optimization of a performance score, function of the forecast fields $F_{i,r}$ and of the associated observations $O_{i,r}$. The RMSE-type performance score initially tested in CALMO first phase was adjusted, and a new **COSI performance score** was included based on the COSMO Index (COSI) developed by Ulrich Damrath (2009). The COSI score defined by user defined weights for the contributions of the various fields. In this project: $\omega_{Tmax} = 1, \omega_{Tmin} = 1, \omega_{Pr} = 1, \omega_{CAPE} = 0, \omega_{CIN} = 0$ (CAPE and CIN are usually noisy), $\omega_{TCWV} = 1$ (total column water vapor), $\omega_{WS1} = 0.33, \omega_{WS2} = 0.33, \omega_{WS3} = 0.33$ (wind shear between standard levels), $\omega_{T500} = 0.33, \omega_{T700} = 0.33, \omega_{T850} = 0.33, \omega_{RH500} = 0.33, \omega_{RH700} = 0.33, \omega_{RH850} = 0.33, \omega_{U500} = 0.2, \omega_{U700} = 0.2, \omega_{U850} = 0.2, \omega_{V500} = 0.2, \omega_{V700} = 0.2, \omega_{V850} = 0.2$ have been introduced. The adapted score for a combination of model parameters p is then defined by:

$$S_p = \frac{1}{12 \sum\limits_{\Psi=1}^{18} \omega_\Psi} \left\{ \sum_{\Psi \neq 3} \omega_\Psi \sum_{mon=1}^{12} \left[1 - \frac{\sum\limits_{\Psi regs} \sum\limits_{\Psi days} (F_{\Psi,p,d,r,mon} - O_{\Psi,d,r,mon})^2}{\sum\limits_{\Psi regs} \sum\limits_{\Psi days} (O_{\Psi,d-1,r,mon} - O_{\Psi,d,r,mon})^2} \right] + \omega_3 \frac{\sum\limits_{mon=1}^{12} \sum\limits_{\Psi regs} \sum\limits_{\Psi thr} ETS_{p,r,mon,thr}}{N_{\Psi days,mon} N_{\Psi regs,mon}} \right\}$$

where indices Ψ, r, mon, d refer to field, region, month and day of month mon, and where $1/3 < \text{ETS} < 1$ (1 is the best) is the equitable threshold score for precipitation (region averaged precipitation with amounts thresholds thr of 0.1, 1, 3, 7.5, 10mm per 24h):

$$ETS_{p,r,mon,thresh} = \frac{H - \frac{(H+F)(H+M)}{N_{\Psi regs,mon}}}{H + M + F - \frac{(H+F)(H+M)}{N_{\Psi regs,mon}}}$$

where: H - Number of hits (i.e. both the model and the observations where above the given threshold); F - Number of false alarms; M - Number of misses. The result of the calibration procedure is the values of the parameters p which maximize (or minimize) the performance score S_p. To be able to solve this extreme problem on a standard computer in a reasonable amount of time, even for a large number of parameters p, an iterative method has been developed. In addition, the accuracy of the MM to represent COSMO results, has been examined both in the first phase for COSMO-7 and also in second phase for COSMO-2. In order to validate the quality of MM, an additional test simulation was performed for a parameter combination that was not used while fitting the MM. That allowed comparing the MM predictions for the specific parameters combination with the COSMO simulation results. These results are presented in Fig. 3 and Fig. 4 for COSMO-7 and COSMO-2 respectively. More specifically scatter plots for 24h accumulated precipitation (Pr) are presented for a 20-day interval during the calibration of COSMO-7 in Fig. 3. The y-axes show the MM estimation with respect to the reference (simulation with default parameters values), while the x-axes show the COSMO simulation results with respect to the reference. For Pr each point represents regions averages. The MM was constructed using the minimum number of simulations in Fig. 3a while in Fig. 3b the MM was constructed using additional "interaction" and "constrain" simulations. In both axes, the default simulation (REF) values were subtracted. The dots lying on the black straight lines show values for a region per day, which are accurately reproduced by the MM, the cloud of deviations from the line indicates MM error and the gray band shows the 95% percentile range of deviations. Reasonably high correlations R2 between COSMO forecasts and MM are observed. This is also the case in Fig. 4 for COSMO-2 where MM prediction of precipitation (Pr) for the tested parameter combination, vs COSMO-2 simulation results during the year 2013. The correlations given

in these figures represent a single parameter combination corresponding to one point in the 3- or 6-dimensional parameters space analyzed. However, it can be seen that regarding this tested parameter combination, the correlations R2 between the COSMO forecasts and the MM estimations are generally high. Consequently, the overall method seems to prove itself; one can use the MM to reproduce COSMO forecasts for various parameters combinations.

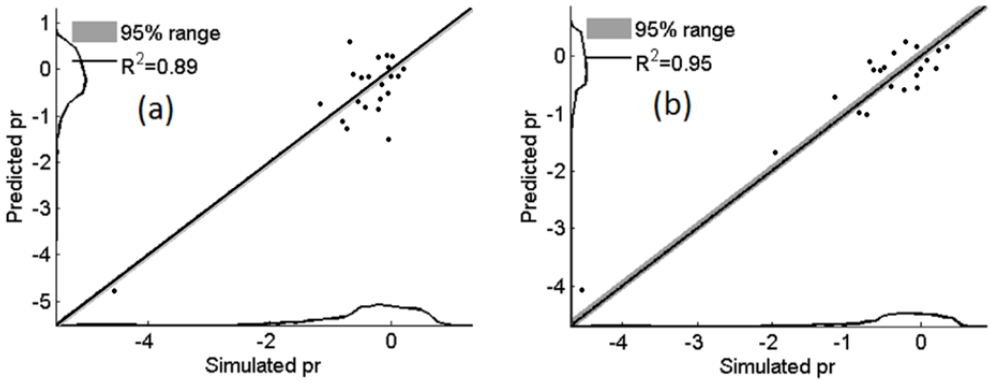

Figure 3: Estimating the MM quality for reproducing Pr field by comparing it with a test COSMO-7 simulation for the period 3-20.1.2008. (a) The MM was constructed using the minimum number of simulations; (b) the MM was constructed using additional "interaction" and "constrain" simulations. A slight improvement of the correlation is observed in this case. In both axes, the REF simulation values were subtracted.

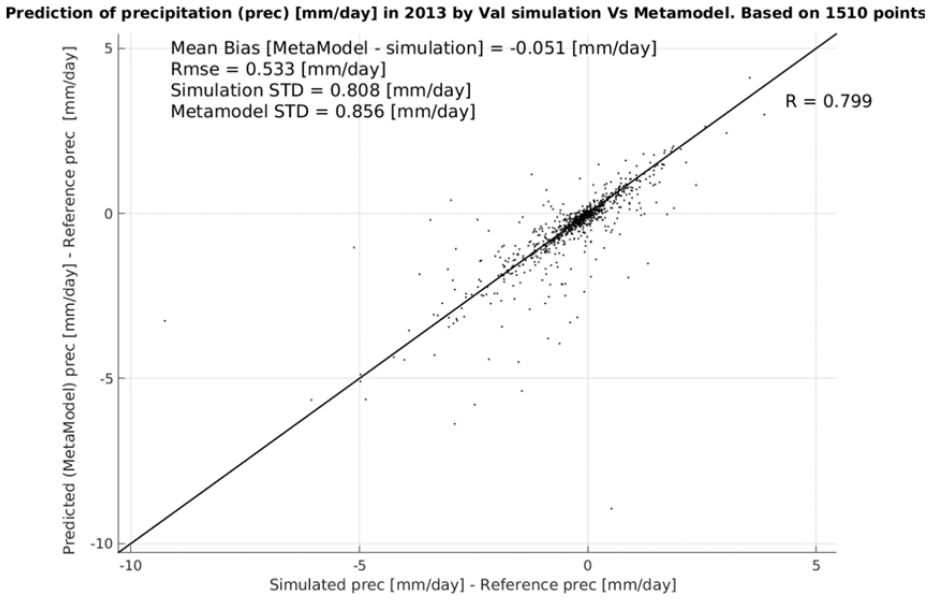

Figure 4: Pr Meta-Model prediction for the tested parameter combination, vs COSMO-2 simulation results during the year 2013. X axis presents the simulated Pr minus the reference simulation. Y axis presents the Meta-Model Pr minus the reference simulation.

5 Sensitivity experiments and fitting strategy *(E. Avgoustoglou)*

The goal of this effort was to gauge the sensitivity of COSMO model over a number of expected relatively high impact parameters. The list of parameters used for the sensitivity

experiments, extracted out of a wide list of free model parameters (shown in Appendix 9) and decided by CALMO project team over extensive communication and recommendations from COSMO experts. An extended set of parameters was tested over the wider Mediterranean area for a period of 62 dates from February, June, and December of 2013 with an emphasis over Switzerland. The sensitivity S with respect to a model variable P was estimated from the results of model runs for the two limits (min and max value) of the parameter selected, as well as for the default value, as follows:

$$S_{<P>}(\%) = \frac{< P >_{TEST} - < P >_{DEFAULT}}{< P >_{DEFAULT}} \bullet 100$$

$< P >$ stands for $< SNOWGSP >$ *or* $< TOTPREC >$ *or* $< CLCL >$ *or* $< CLCM >$ *or* $< CLCH >$ *or* $< CLCT >$

$$S_{\{\langle TOTPREC \rangle, \langle SNOWGSP \rangle, \langle CLCH \rangle, \langle CLCM \rangle, \langle CLCL \rangle\}} = \left|S_{\langle TOTPREC \rangle}\right| + \left|S_{\langle SNOWGSP \rangle}\right| + \left|S_{\langle CLCH \rangle}\right| + \left|S_{\langle CLCM \rangle}\right| + \left|S_{\langle CLCL \rangle}\right|$$

$$S_{\begin{bmatrix} TMIN\,2m \\ TMAX\,2m \end{bmatrix}} = \begin{bmatrix} < TMIN\,2m > \\ < TMAX\,2m > \end{bmatrix}_{TEST} - \begin{bmatrix} < TMIN\,2m > \\ < TMAX\,2m > \end{bmatrix}_{DEFAULT}$$

The results from the sensitivity experiments along with the highlights of this investigation are presented in Appendix 10 while an example is illustrated in Fig. 5. More details are available in Avgoustoglou et al., 2017. The impact for most of the parameters turned out to be important for all periods and domains. The weight of the parameter impact for the different domain, varies due to their climatological characteristics as expected. In principle, for almost all considered variables, at most 5 parameters show the greatest sensitivity and a choice among them should be expected to provide a sufficient kernel for the application of the MM. Towards the effort of model calibration and upon gauging the model sensitivity, when the number **n** of considered model parameters increases, the number of their pair combinations regarding their min and max values vastly increases $[O(2\mathbf{n})^2]$. **A methodology to help reduce the computing resources for fitting the meta-model is proposed here**. An efficient methodology to constrain the number of tests should be to indicate their impact according to some quantitative criteria and decide upon the resulting priority. The methodology is expected to be of practical value if two goals could be accomplished: (a) each test gets a priority number and (b) tests are performed according to it. If the number of tests becomes too expensive, the method should be flexible enough to be terminated at the priority that suits the available computational resources. The recommended truncation, however, needs to be supported by valid scientific arguments regarding the relative importance of the tests that will be included against those that will be omitted.

The specific steps followed in order to decide on the priority for model simulations needed to fit the MM is as follows: the first step is associated with the selection of the parameters to be used for calibration and decision on the model domain for which the MM will be used. The minimum number of simulations needed is [2N + N(N-1)/2 + 1] where N is the number of parameters selected including 1 simulation using default parameter value, 2 simulations using minimum and maximum value of each parameter and one simulation with an interaction terms between parameter pairs. **In order to decide on which interaction simulation per pair to use it is proposed to create a Priority Board Of Terms** (PBOT, see Fig. 6 below). It can easily be shown that the pair combinations for e.g. 7 parameters is 84. Consequently, the 84 empty white cells will be filled with priority numbers 1 to 84. Every empty white shell refers to a 2-parameters combination. The empty dark blue cells will not take any number due to single parameter assignment and due to double

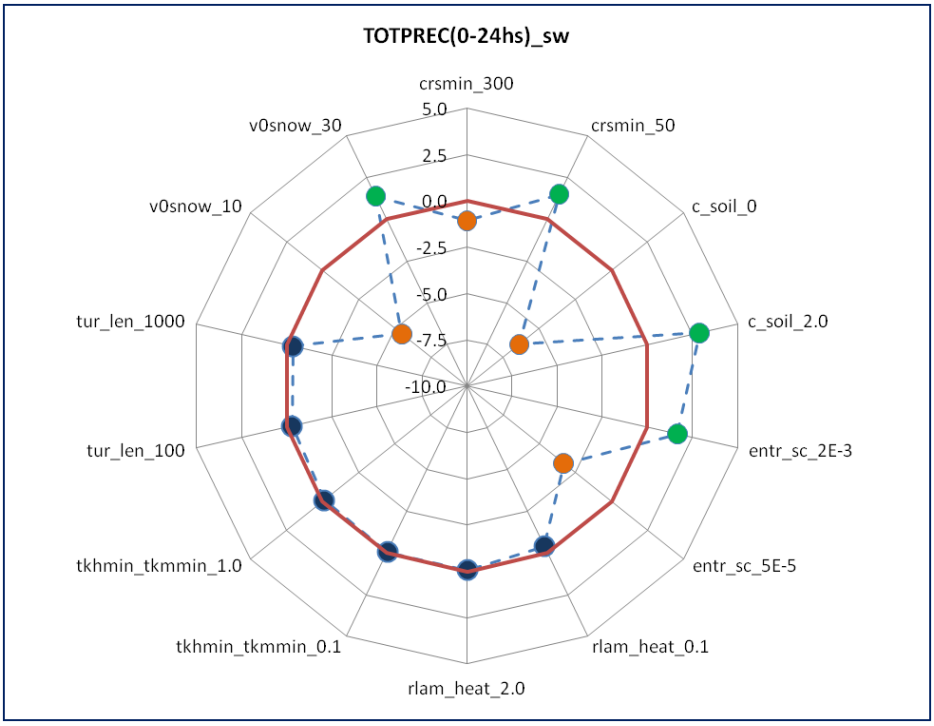

Figure 5: Spidertype graph for 24h accumulated precipitation.

counting in every test. Every number refers to the priority of the sensitivity run. For example, if the second empty white cell of the first line gets the number 5, the model runs with the combination will have priority 5, so 4 other parameter combinations have to be performed first. In addition, according to the importance of the model variables that will be used, a class is denoted in the PBOT (again, see Fig. 6 below). The subjective criteria on making this choice is discussed in detail in Avgoustoglou et al., 2017. The sensitivities (S) of the parameters used is defined and the sensitivity of the variable of the first priority class is presented in a **spider-type** graph, as shown for TOTPREC in Fig. 5. Once the spider type graph is created a set of priority numbers is given to fill the PBOT shown in Fig. 6. For example, the first set of priority numbers will be assigned to couple of parameters with opposite sensitivity, as shown by orange and green bullets on the spider graph, according to the radial distances between the orange and the green bullets. The second set of priority numbers will be assigned to PBOT according to the difference of the radial distances between couple of parameters with same sign sensitivity, etc. In more detail the methodology followed to perform the simulations needed to fit the MM can be found in:

http://www.cosmo-model.org/content/consortium/generalMeetings/general2015/parallel/WG3b_Euripides_Sept2015.pdf

and

http://www.cosmo-model.org/content/consortium/generalMeetings/general2016/wg3b/CALMO_Avgoustoglou.pdf

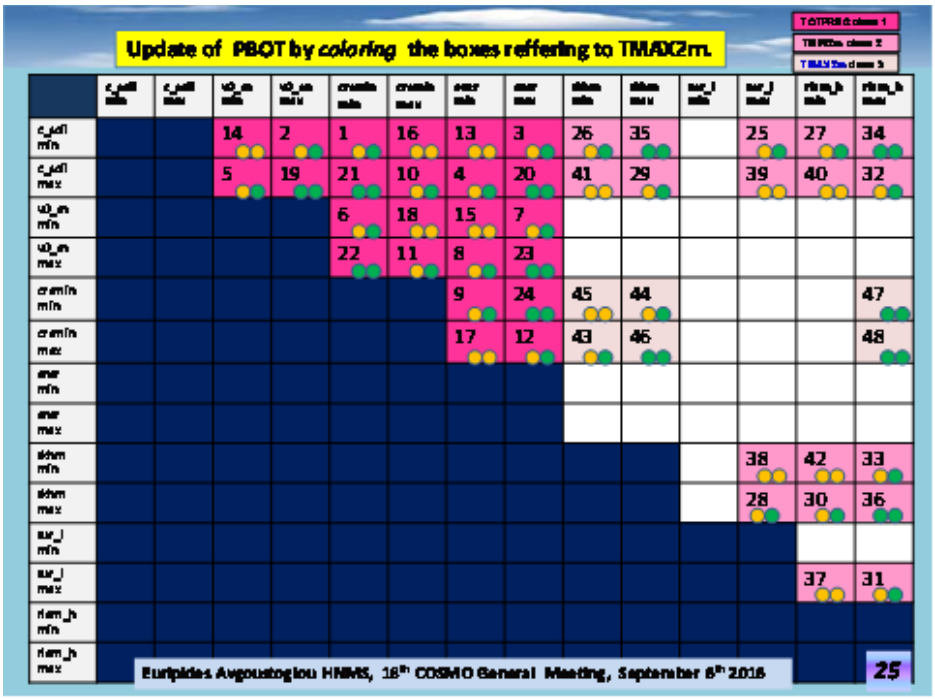

Figure 6: Final PBOT table indicating the hierarchy of interaction simulations to be performed for fitting the MM.

6 Verification of COSMO-2 calibration *(with the contribution of P. Kaufmann)*

By construction, the CALMO methodology provides a set of optimum values for unconfined model parameters, which optimizes a specified performance score (the COSI type score described in the previous section). In order to assess the robustness of this optimum, it is necessary to perform an independent verification of the simulation performed with the optimal set of parameters. A selection of verification plots produced with the standard MeteoSwiss verification system for the second phase of the CALMO project (COSMO-2 calibration) is presented in this section. Although limited in scope, this verification gives a first insight on the capacity of the CALMO methodology to provide a robust improvement of the quality of a specific model configuration. Simulations are performed over the entire year 2013, using default values (**DEF**) for 6 unconfined model parameters as well as using the optimum set of parameters (**BESTF2**) derived from the MM. The 6 parameters with their default and optimum values are summarized in Table 1. The optimum values are the ones obtained by using the COSI type performance score, with daily minimum and maximum of 2m temperature evaluated at grid points and not averaged (following the method 4 in Khain et al., 2017); a 3-4% improvement of the COSI type performance score has been obtained with BESTF2. The performance of the model for 2m temperature (T_2M), 2m dew point temperature (TD_2M), 10m wind speed (FF_10M), 12h accumulated precipitation (TOT_PREC12) and 1h accumulated precipitation (TOT_PREC1) is presented. All statistics are over the entire year 2013, the year which is also used for the calibration; all statistics are computed for Switzerland, using Swiss observing stations and the Swiss radar composite.

Diurnal cycle of mean model error in both cases DEF (blue line) and BESTF2 (red line) as well as mean model values and mean observation values (MOBS, black line) for **2m temperature** and **2m dew point temperature** are presented in Fig. 7 and Fig. 10. Improvement of 2m temperature mean error of about 0.2°C throughout the day is evident

Table 1: Calibration parameters and their values.

Parameter	**Acronym**	**Default values**	**Optimum value (after method 4)**
Factor for laminar resistance for heat	**rlam_heat**	1 (20 rat_sea)	1.273 (15.71092)
Minimal diffusion coefficient for heat	**tkhmin**	0.4	0.266
Maximal turbulent length scale (m)	**tur_len**	150	346.5
Entrainment rate for shallow convection	**entr_sc**	0.3e-3	0.1607e-3
Surface-area index of the evaporating fraction of grid points over land	**c_soil**	1	0.588
Factor for vertical velocity of snow	**v0snow**	20	12.3

in Fig. 7. This improvement is related to a warmer near surface temperature associated with BESTF2, which partly mitigates the cold bias observed with DEF over Switzerland. Considering the 2m dew point temperature, one observes a degradation of the mean error throughout the day associated with a drier surface layer, which increases the already dry bias observed with DEF. Left panel of Fig. 8 illustrates the mean 2m temperature model error for the optimum and the default cases, while mean observation and model values for all lead times during the entire year are shown in right panel. It is evident that model values obtained using the optimum set of parameters are closer to the observed ones. This is also supported by Fig. 9 where statistics for the whole 2013 are presented; incidentally, the overall minimum and maximum 2m temperature obtained with BESTF2 is closer to OBS than DEF (minimum observed is -30.9°C, with -28.9°C using BESTF2 and -28.8°C using DEF, while maximum observed is 37.1°C, with 37.9°C using BESTF2 and 38.1°C using DEF). For dew point 2m temperature, shown in Fig. 11 and Fig. 12, the observed mean value is equal to 2.13°C against 1.72°C using DEF and 1.47°C using BESTF2. It should be noted that the dew point temperature is not part of the performance score used to derive BESTF2.

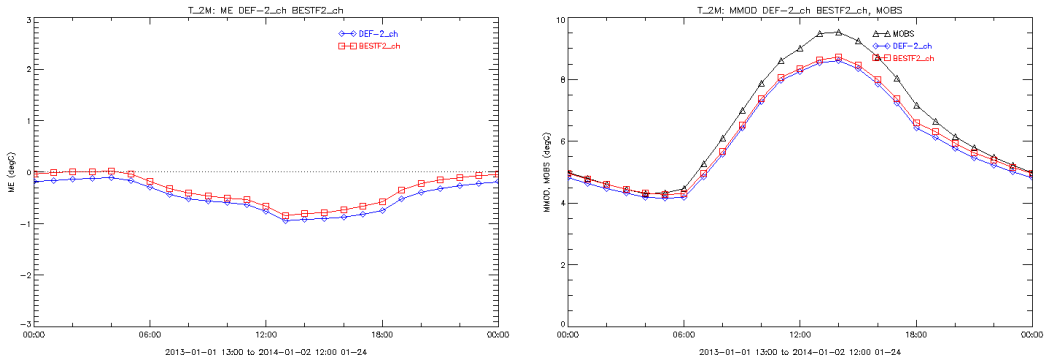

Figure 7: Verification of 2m temperature for 2013 over Switzerland. Diurnal cycle of mean model error (left panel) and mean model values compared to mean observations (right panel). An improvement of up to 0.2°C is observed.

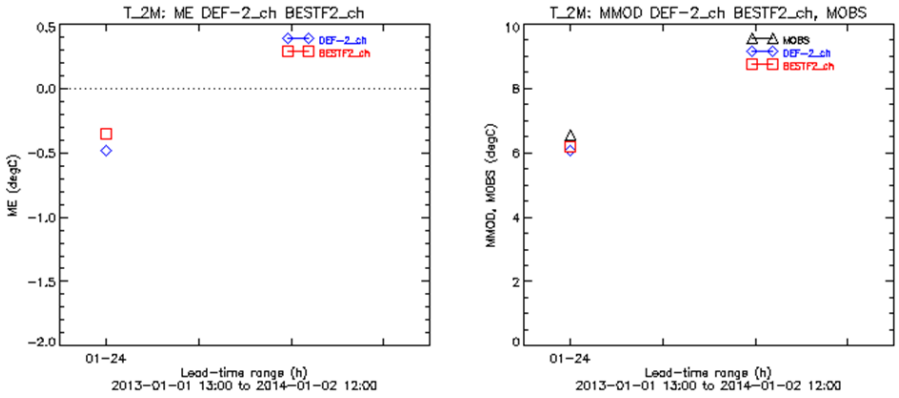

Figure 8: Verification of 2m temperature for 2013 over Switzerland. Mean model error (left panel) and mean model values compared to mean observations (right panel).

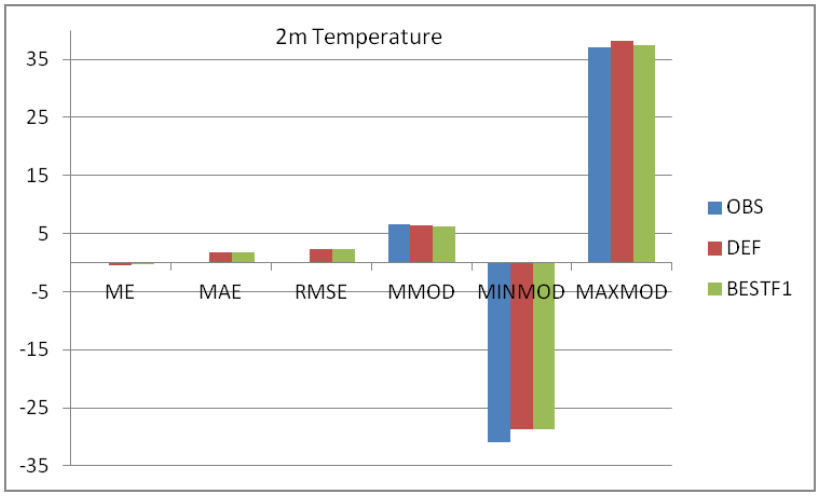

Figure 9: Statistics of 2m temperature for 2013 over Switzerland, showing observations (OBS) and model simulations using default parameter values (DEF) and optimum parameter values (BESTF2). The following quantities are shown: ME: mean error, MAE: mean absolute error, RMSE: root mean square, MMOD: mean value, MINMOD: minimal value, MAXMOD: maximal value.

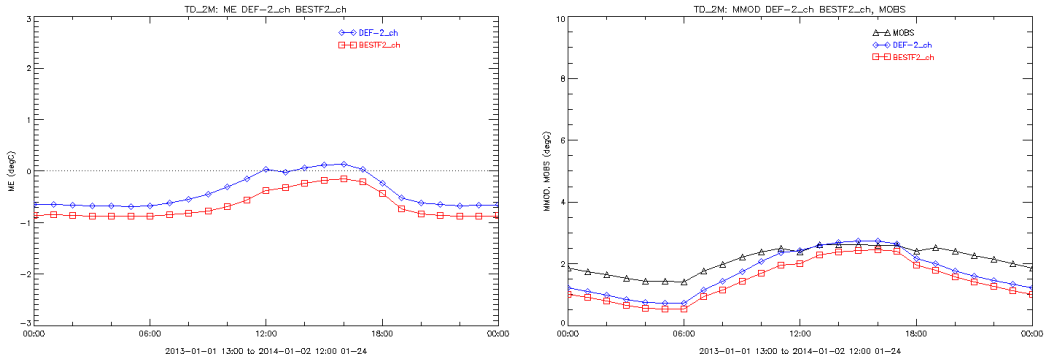

Figure 10: Verification of 2m dew point temperature for 2013 over Switzerland. Diurnal cycle of mean model error (left panel) and mean model values compared to mean observations (right panel).

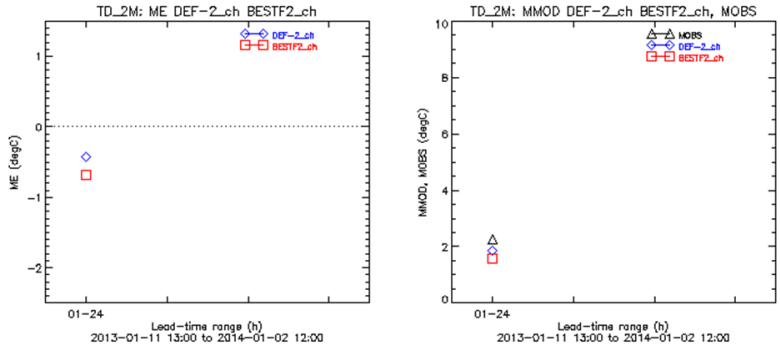

Figure 11: Verification of 2m dew point temperature for 2013 over Switzerland. Mean model error (left panel) and mean model values compared to mean observations (right panel) for dew point temperature.

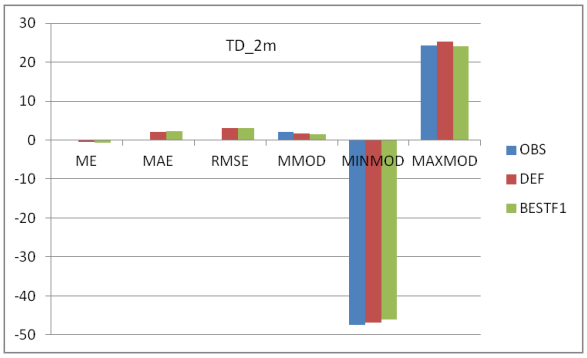

Figure 12: Statistics of 2m dew point temperature for 2013 over Switzerland, showing observations (OBS) and model simulations using default parameter values (DEF) and optimum parameter values (BESTF2). The following quantities are shown: ME: mean error, MAE: mean absolute error, RMSE: root mean square, MMOD: mean value, MINMOD: minimal value, MAXMOD: maximal value.

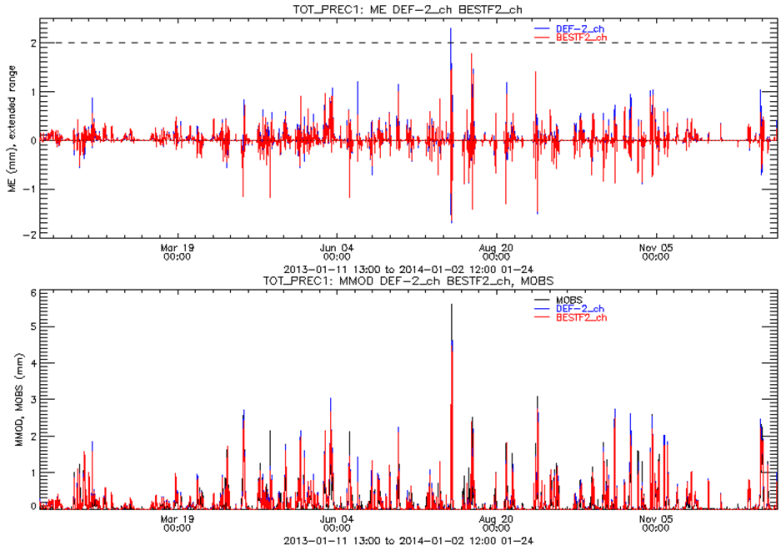

Figure 13: Time series of mean model error (upper panel) and mean model values compared to mean observations (lower panel) for hourly accumulated precipitation over Switzerland.

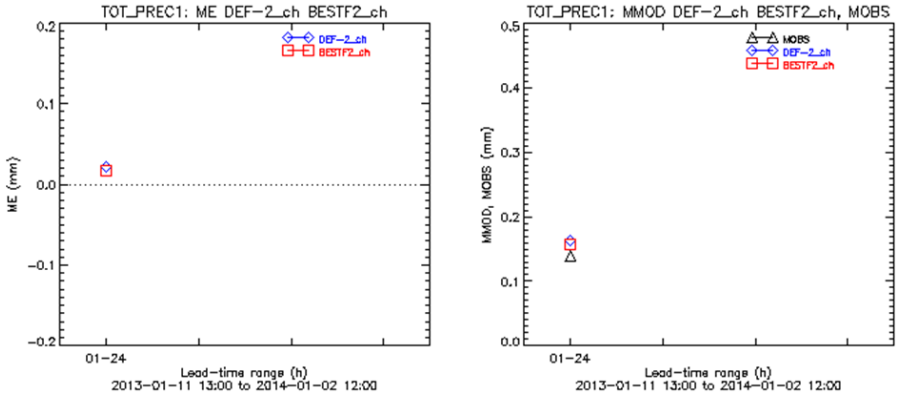

Figure 14: Mean model error (left panel) and mean model values compared to mean observations (right panel) for hourly accumulated precipitation over Switzerland.

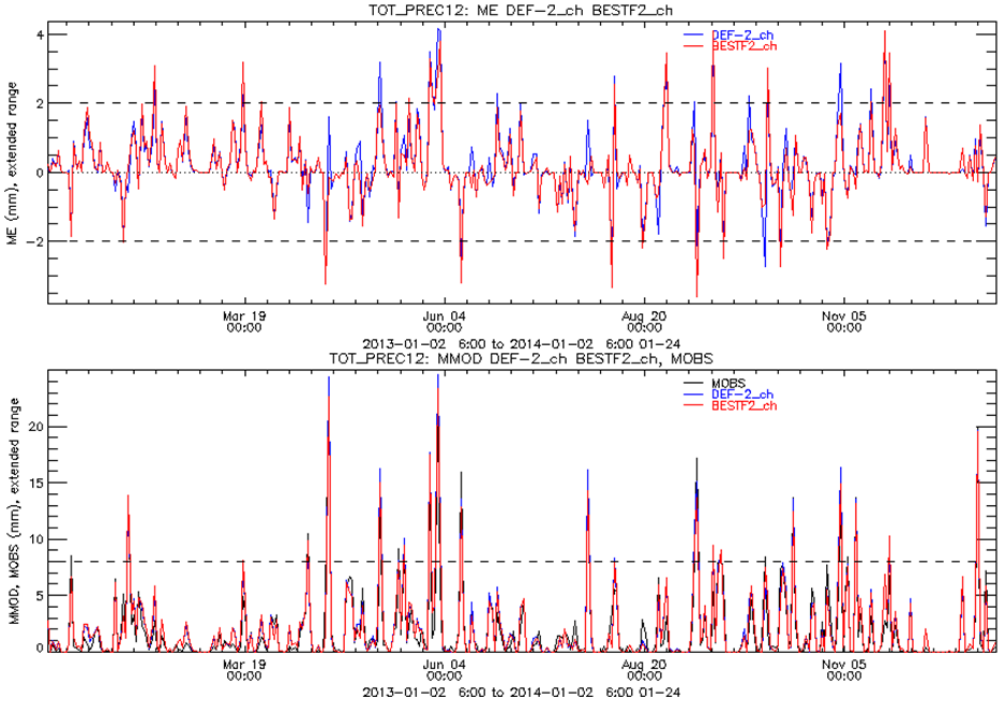

Figure 15: Time series of mean model error (upper panel) and mean model values compared to mean observations (lower panel) for 12-h accumulated precipitation over Switzerland.

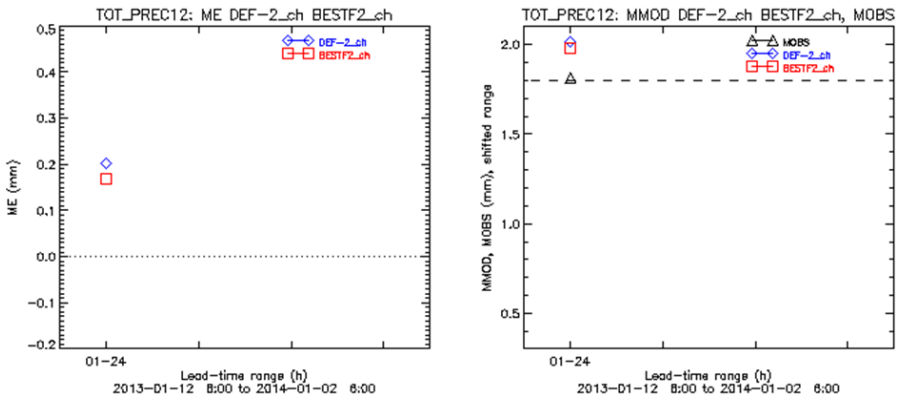

Figure 16: Mean model error (left panel) and mean model values compared to mean observations (right panel) for 12-h accumulated precipitation over Switzerland.

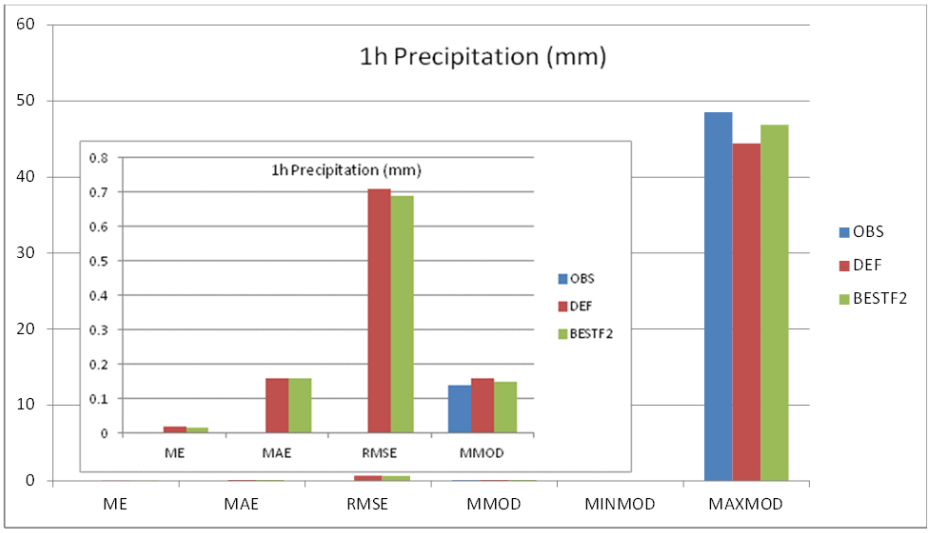

Figure 17: Statistics of hourly accumulated precipitation during entire 2013 over Switzerland, showing observations (OBS) and model simulations using default parameter values (DEF) and optimum parameter values (BESTF2). The following quantities are shown: ME: mean error, MAE: mean absolute error, RMSE: root mean square, MMOD: mean value, MINMOD: minimal value, MAXMOD: maximal value.

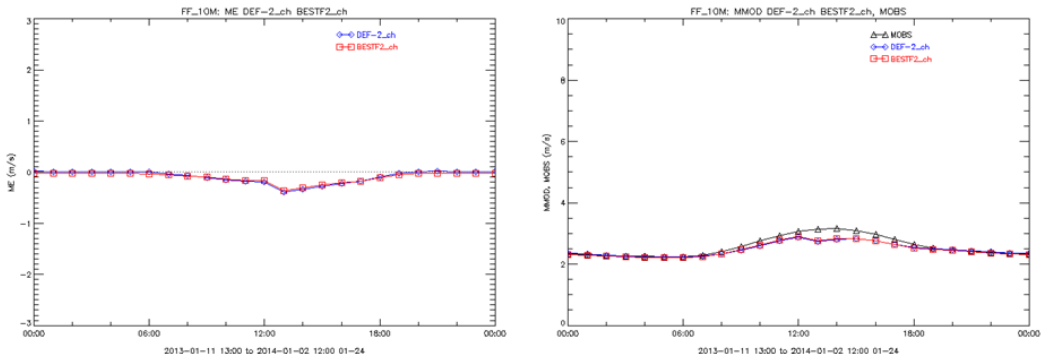

Figure 18: Verification of 10m wind speed for 2013 over Switzerland. Diurnal cycle of mean model error (left panel) and mean model values compared to mean observations (right panel).

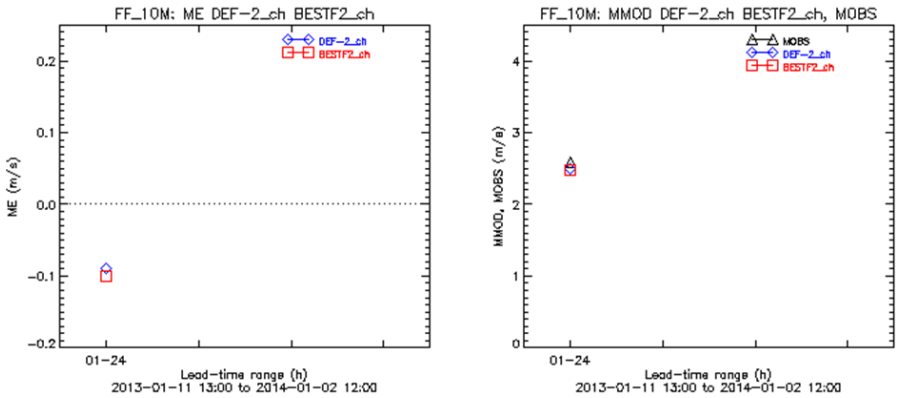

Figure 19: Verification of 10m wind speed for 2013 over Switzerland. Mean model error (left panel) and mean model values compared to mean observations (right panel).

Time series of mean model errors as well as mean model values, compared to mean observations for 12h and 1h accumulated precipitation are presented in Fig. 13 and Fig. 15 respectively. A slight improvement on mean error is visible for accumulated precipitation over the entire year, especially during the warm period of the year. Total scores for the diurnal cycle of the variable support this assertion, as shown in Fig. 14, Fig. 16 and Fig. 17: 1.79mm and 0.14mm mean observed values for 12h and 1h accumulated precipitation respectively, compared to 1.99mm and 0.16mm for the modeled values using default parameters and 1.96mm and 0.15mm using the optimum parameters.

Diurnal cycle of mean model error in both cases DEF (blue line) and BESTF2 (red line) as well as mean model values and mean observation values (MOBS, black line) for **10m wind speed** are presented in Fig. 18. Mean error total score and means for all lead times during the entire year for both model and observations is presented in Fig. 19. A very small degradation of the scores when using BESTF2 is observed (mean observed value 2.57 m/s, against 2.47 m/s using BESTF2 and 2.48 m/s using DEF).

7 A case study *(E. Bucchignani, P. Mercogliano, M. Milelli)*

The following case study illustrates the impact of using the CALMO calibrated values instead of the default parameters values. The interest of this study is that it uses the calibrated parameters with a different model configuration than the one used in the calibration, and for a different year. In the first half of July 2015, Piedmont region and Turin in particular experienced extreme temperature values and uncomfortable conditions for the population. In Turin, the maximum temperature since 1990 (38.5°C) has been recorded in July 2015. Ground stations data highlighted the presence of a UHI effect over Turin. This is the reason why this area and this period represent a suitable benchmark to test the capabilities of COSMO-CLM, and in particular of the urban parameterization. The computational domain considered is centered over Turin, discretized with 100 x 100 grid-points, employing a spatial resolution of 0.009° (about 1 km). The ECMWF IFS analysis at 0.075° have been used as forcing data. Three different simulations have been performed over the period 1 to 7 July 2015, respectively using the default set of control parameters **and two different sets of parameters derived from the COSMO-2 calibration performed in the CALMO project**[2], as listed in Table 2, in order to highlight the effects on the model results. Validation has been carried out against an observational dataset for daily values of temperature, provided by ARPA Piemonte. In the following, results related to Consolata station are shown, representative of an urban area. Table 3 shows the average observed T2m value, the average bias (model minus observation) over the simulated period and the maximum bias, obtained with the different configurations at Consolata. **Both calibrated configurations allow a significant reduction of the average bias. OPT2 allows also a reduction of the maximum bias.**

Table 2: Values of the control parameters for the three different configurations.

	Default	**OPT1**	**OPT2**
rlam_heat	1.0	0.74	1.24
tkhmin	0.4	0.176	0.233
tkmmin	0.4	0.4	0.233
tur_len	150	368.8	363.9
entr_sc	0.003	0.00014	0.000267
c_soil	1	0.663	0.492
v0snow	20	17.8	12.1
rat_sea	20	20	16.12903

Table 3: Values of observed T2m value (°C), average bias (model minus observation) over the simulated period and the maximum bias, obtained with the different configurations.

	OBS	**BIAS URB_DEF**	**BIAS URB_OPT1**	**BIAS URB_OPT2**
Average bias	29.4	0.68	0.36	0.43
Maximum bias	29.4	5.5	5.0	4.9

[2]This case study has been conducted before the definitive values of the calibrated parameters were available. This is the reason why two different sets are present, both differing from the final values listed in Khain 2017; the OPT2 set is the one which is the nearest to the final values obtained by CALMO.

8 Conclusions

The CALMO project was a considerable step towards complementing the usual expert tuning with an objective calibration methodology. Expert tuning is typically done once during the development of the model, for a certain target area, and for a certain model configuration, and is often difficult if not impossible to replicate. This is the hope placed in this new methodology to support on-demand calibration by any COSMO member, e.g. to define an optimal calibration over the target area of interest, to introduce a seasonal dependency on some unconfined model parameters values, or for a re-calibration after major model changes (e.g. higher horizontal or vertical resolution). Furthermore, the CALMO methodology could also be used for an unbiased assessment of different modules (e.g. parameterization schemes), and for optimal perturbation of parameters when run in ensemble mode. Starting with a rough model resolution of 7km and a short calibration period of 40 days, the method was extended to a finer 2.2km resolution. The simulation period was significantly increased from 40 days of 2008 to the entire year of 2013, to consistently incorporates the weather development on a seasonal basis. The verification area was enlarged to also consider Northern Italy. The daily minimum and maximum 2m temperature and the 24h accumulated precipitation was complemented with vertical wind, temperature, and humidity profiles and with total water column at soundings locations. The number of calibrated model parameters was increased from 3 to 6. The meta-model was adapted and extended. A new COSI performance score was included to act as a performance metric for NWP models. A new method for logarithmic transformation for selected parameters was developed along with an iterative method to obtain the optimal parameters via convergence in a 6-dimensional parameter space of exceptional cardinality. An estimation of error bars on the optimal parameters values has been introduced. Following these adaptations, the calibration of COSMO-2 was performed and the optimal parameters combination was obtained. Using the COSI performance score to quantify the quality of the simulation, which is a combination of root mean square score for continuous fields and equitable thread score for precipitation, a performance gain of 2-4% was observed. An independent verification of the optimal configuration shows a small reduction of the 2m temperature and precipitation biases, but also a small increase of the 2m dew point bias. This small impact is expected, given that the chosen model configuration is very similar to the model configuration used by the COSMO core development team, which has undergone exceptional expert tuning over a period of almost two decades; arguably this small impact confirms the validity of the calibration method. However, the main learning from the CALMO project is that the meta-model is able to reasonably reproduce the dependency of the model on the unconfined parameters. This is illustrated in Fig. 6, where the meta-model prediction is compared with the full model prediction for the daily accumulated precipitation at different locations. Thanks to these developments, **the calibration methodology can now be readily applied to a NWP system and the reliability of the calibration results can be trusted**. However, a full assessment of the impact of the soil memory is not available; this is an important issue, because it is expected that the impact of a new set of model parameters can be substantially stronger through the accumulation of heat and humidity in the soil over the full simulation period, as indeed observed in a preliminary experiment with a 1.1 km configuration of the COSMO model (a performance gain measured by the COSI score exceeding 10% has been observed following a one month calibration). Furthermore, in order for this method to be used by the COSMO community, **it is essential to reduce the computing cost of the calibration**. For these reasons, a follow-up project CALMO-MAX has been defined. Finally, it should be noted that the selection of unconfined model parameters used in the calibration process is a crucial but also user-dependent step. More specifically the calibration of the model towards better scores could be associated with the user specific needs for a detailed representation

of specific model variables and phenomena. Additional parameterization development and new model implementations is always needed but **calibration is always meaningful in order to complement the expert tuning!**

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9 Appendix: list of model parameters

The most interesting parameters for CALMO / COSMO-1 are highlighted:

in red: highest priority
in orange: medium priority
in yellow: lowest priority

Multilayer soil model

	name	description	value (min/max)	defined in	dependency on resolution, remarks
x	cdash	parameter for laminar conductance of heat and water vapour from leaves	0.05 $(m/s)^{1/2}$	data_soil	**not in use for COSMO-1 (aka itype_tran=2)**
x	cdmin	part of the tuning parameters for the maximum sustainable water flux in the soil	$2.5 \cdot 10^{-10} m^2/s$	data_soil	
x	cdsmin	minimum snow depth	0.01 m	data_soil	
x	cfinull	soil water suction at saturation	0.2 m	data_soil	
x	cf_snow	parameter for determination of fractional snow cover	0.015 m_{H2O}	data_soil	decrease cf_snow, if for smaller grid elements snow cover shall be increased, compare rhde for radiation
x	cf_w	parameter for determination of fractional water cover	0.001 m_{H2O}	data_soil	analogous to cf_snow
x	cik1	parameter for determination of maximum infiltration	0.02	data_soil	

	name	description	value (min/max)	defined in	dependency on resolution, remarks
x	ckrdi	scale for soil hydraulic conductivity	0.00001 m/s	data_soil	
x	cparcrit	scale for photosynthetically active radiation	100 W/m^2	data_soil	
x	crhosmax_ml	maximum density of snow	400 kg/m^3	data_soil	
x	crhosmin_ml	minimum density of snow	0.8	data_soil	
x	crhowm	fraction of saturated soil filled by water	50 kg/m^3	data_soil	
x	crsmax	maximum stomatal resistance	4000 s/m	data_soil	
x	crsmin	minimum stomatal resistance	150 s/m (50.0 – 300.0)	INPUT	
x	csatdef	scale for saturation deficit	4000 Pa	data_soil	
x	csvoro	parameter for influence of sub-grid scale orography on infiltration	1	data_soil	increase parameter for decreasing grid length to allow for more infiltration
x	ctau_i	time constant for drainage from interception store	1000 s	data_soil	modification in TERRA possible to avoid ctau_i $< 2\Delta$
x	ctend	maximum temperature for plant transpiration	313.15 K	data_soil	
x	cwimax_ml	parameter for determination of maximum interception store	0.000001 m	data_soil	
	kexpdec	hydraulic conductivity of soilr	2	src_soil_multlay.f90	

The soil model uses additional parameters which depend on the 8 soil types ice, rock, sand, sandy loam, loam, loamy clay, clay, and peat. Some additional values for sea water and for sea ice are given but not yet used in the model. All these parameters are defined in data_soil. Most of these parameters strongly effect the water and heat budgets at the soil surface. This in turn significantly effects the determination of the near surface values of temperature and humidity.

Turbulence (diffusion, vertical transport; atmosphere)

	name	description	value (min/max)	defined in	dependency on resolution, remarks
x	pat_len	length scale of subscale surface patterns over land	500 m (10.0 – 1000.0)		
x	c_diff	factor for turbulent diffusion of TKE	0.2 (0.01 – 10)		
x	a_stab	factor for stability correction of horizontal length scale	0		
x	a_heat	factor for turbulent heat transport	0.74		
x	a_mom	factor for turbulent momentum transport	0.92		
x	d_heat	Factor for turbulent heat dissipation	10.1 (12 – 15)		
x	d_mom	Factor for turbulent momentum dissipation	16.6 (12 – 15)		
x	tur_len	asymptotic maximal turbulent length scale	150 m (100 – 1000)		
x	tkesmot	time smoothing factor for TKE and diffusion coefficients	0.15		
x	tkmmin	Minimal diffusion coefficient for heat	$0.4 m^2/s$(0.0 – 2.0)		
x	tkhmin	Minimal diffusion coefficient for momentum	$0.4 m^2/s$(0.0 – 2.0)		

Turbulence (surface layer transfer)

	name	description	value (min/max)	defined in	dependency on resolution, remarks
x	rlam_mom	scaling factor of the laminar boundary layer for momentum	0.0		
x	rlam_heat	scaling factor of the laminar boundary layer for heat	1.0 (0.1 – 10.0)		
x	rat_lam	Ratio of laminar boundary thickness for q and h	1.0 (0.1 – 10.0)		
x	rat_can	Factor for canopy height	1.0 (0.0 – 10.0)		
x	rat_sea	ratio of laminar scaling factors for heat over sea and land	20 (1.0 – 100.0)		
x	c_lnd	surface area density of the roughness elements over land	2.0 (1.0 – 10.0)		
x	c_sea	surface area density of the waves over sea	1.5 (1.0 – 10.0)		
x	c_soil	surface area index of (evaporative) soil surfaces	1.0 (0.0 – 10.0)		
x	e_surf	Exponent to get the effective surface area	1.0 (0.1 – 10.0)		
x	z0m_dia	roughness length of a typical synoptic station	0.2 m (0.001 – 10.0)		

Grid scale precipitation

	name	description	value (min/max)	defined in	dependency on resolution, remarks
x	zaac	$zaac = \frac{3}{7}\frac{E_r}{\rho_w}(A_r B_r)^{2/9}$ $A_r = \rho_w \pi N_o^r$ $B_r = v_o^r \Gamma(4.5)/\Gamma(4)$ $E_r = 0.8$ $N_o^r = 8 \cdot 10^{-6} m^{-4}$ $v_o^r = 130 m^{1/2} s^{-1}$	1.72	hydor	parameter for the determination of the accretion rate
x	zaau	inverse of the time constant for autoconversion	$0.001 s^{-1}$	hydor	
x	zamc	parameter for the temperature dependent relation between mass and diameter of precipitation particles	$0.08 kg/m^2$	hydor	
x	zamelt	parameter for determination of melting of falling snow	$7.2 \cdot 10^{-6}$	hydor	
x	zamv	parameter for the temperature dependent relation between mass and diameter of precipitation particles	$0.02 kg/m^2$	hydor	
x	zanuc	inverse of the time constant for nucleation	$0.001 s^{-1}$	hydor	
x	zarim	$E_s \pi/4$ collection efficiency for snow particles	1.97	hydor	
x	zbdep	parameter β_{dep} (coef. for ice ventilation)	13	hydor	
x	zbev	parameter β_{ev} (coef. for drop ventilation)	8.05	hydor	
x	zbmelt	parameter β_{melt} (coef. for melting ice)	13	hydor	
x	zt1	parameter for the temperature dependent relation between mass and diameter of precipitation particles	253.15 K	hydor	
x	zt2	parameter for the temperature dependence of the distribution of water, ice, and mixed phase clouds	235.15 K	hydor	
x	v0snow	factor in the terminal velocity for snow	20 (10.0 – 30.0)		

	name	description	value (min/max)	defined in	dependency on resolution, remarks
x	rain_n0_fac	However, because on average, the parameterization of the frozen-phase growth processes in the current graupel scheme seems to be too inefficient to produce "enough" precipitation sized particles, we artificially reduce the evaporation of raindrops to get the "correct" rain amount at the surface, by tuning the N00 parameter with a factor rain_n0_factor ($\leqslant 1$), N00_tuned = N00 $\cdot$ rain_n0_factor	1.0		
x	mu_rain		0		
x	qc0	cloud water threshold for autoconversion	0.0002 (0.0 – 0.01)		
x	qi0	cloud ice threshold for autoconversion	0.0 (0.0 – 0.01)		
	cloud_num	cloud droplet number concentration	5.0E8		
x	zxstar	separating mass between cloud and rain	separating mass between cloud and rain		

Radiation

	name	description	value (min/max)	defined in	dependency on resolution, remarks
x	csalb	solar albedo for dry soil	soil type dependent	data_soil	**Not in use for COSMO-1 (aka itype_albedo=3)**
x	csalb_snow	solar albedo for snow	0.7	data_soil	**Not in use for COSMO-1 (aka itype_albedo=3)**
x	csalb_p	solar albedo for plant covered soil	0.15	data_soil	**Not in use for COSMO-1 (aka itype_albedo=3)**
x	ctalb	thermal albedo for all soil types	0.004	data_soil	
x	ucl	determination of cloud cover in unsaturated conditions	1	constants	should be resolution dependent (ask Matthias how we can tune width of distribution!)
x	uc1	as ucl	0.8	constants	as ucl
x	uc2	as ucl	$sqrt(3)$	constants	as ucl
x	zclwfk	fraction of saturation humidity assumed for cloud liquid water content of convective clouds	0.01	organize_radiation	
x	zclwfs	as zclwfk, for non-convective sub-grid scale clouds	0.005	organize_radiation	**not used in code ?**
	IF (lzprog_qi) THEN zclws = 0.005_wp · zsex				
x	clc_diag	cloud cover at saturation in statistical cloud diagnostic	0.5 (0.2 – 0.8)		**not used by radiation, see turbulence**
x	q_crit	critical value for normalized oversaturation	1.6 (1.0 – 10.0)		**Not used by radiation, see turbulence (check why this is red!)**

Shallow convection

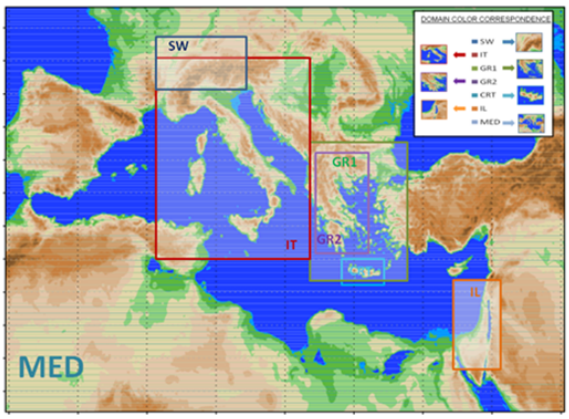
	name	description	value (min/max)	defined in	dependency on resolution, remarks
x	entr_sc	mean entrainment rate for shallow convection	3.0E-4 (5.0E-5 – 2.0E-3)		
x	thick_sc	limit for convective clouds to be "shallow" (in Pa)	2.5E4		

Sub-grid scale orographic drag

	name	description	value (min/max)	defined in	dependency on resolution, remarks
x	gkdrag	gravity wave drag constant	0.075		**Not used in COSMO-1 (aka lsso=.false.)**
x	gkwake	low level wake drag constant	0.5		**Not used in COSMO-1 (aka lsso=.false.)**

10 Appendix: highlights of sensitivity experiments

SELECTED DOMAINS



SENSITIVITY TESTS BLUEPRINT

13 parameters were considerd.

⊗

3 values/parameter including default.

⊗

The evaluation period consisted of 62 days from year 2013, i.e.: February 1-20, June 1-20, December 10-31.

⏬

2418 runs based on COSMO.v5.0

- Horizontal grid size: 0.0625^0 (~7km).
- 649x393 grid points (wider mediterranean area), 60 levels.
- Integration time-step: 30 secs.
- Integration period: 48 hs.
- Boundary conditions : 6hr IFS Analysis.
- Computational Cost ~ 10^7 b.u. on Cray X C30 of ECMWF (gratis HNMS).

INVESTIGATED VARIABLES (AREA AVERAGES)

- **< TMAX2m >:** Maximum 2m temperature for 0-24 hr periods.
- **< TMIN2m >:** Minimum 2m temperature 0-24 hr periods.
- **< TOTPREC >:** 0-24 hr period accummulated precipitation (kg m^{-2}).
- **< SNOW_GSP >:** 0-24 hr periods accumulated grid-scale snow (kg m^{-2})
- **< CLCL >:** Low cloud cover (%) average of 3hr time steps 03-24 hs.
- **< CLCM >:** Medium cloud cover (%) average of 3hr time steps 03-24 hs.
- **< CLCH > :** High cloud cover (%) average of 3hr time steps 03-24 hs.
- **< CLCT > :** Total cloud cover (%) average of 3hr time steps 03-24 hs.

! The same investigation was performed for 24-48 hr periods with approximately the same performance.

GRAPH FEATURES

- The sensitivities of the considered variables are presented for every period as well as for the total number of days in succesive clustered column graphs: SW, IT, GR1, GR2, CRT, IL, MED.
- Domain color correspondance: SW IT GR1 GR2 CRT IL MED
- The idea behind the domain choices is to display the changes in sensitivities in reference to the relative location of the domains from the SouthEast (IL) to the NorthWest (SW) which is the focal domain of CALMO project at its present stage.
- On the horizonta axis, the sensitivities are presented for every pair of the parameter values under consideration.
- ● depicts the most sensitive parameters.
- ● depicts parameters with sensitivity of order 10% of ●.
- ● the sensitivity of **qi0** is displayed but not considered at this stage of the work.

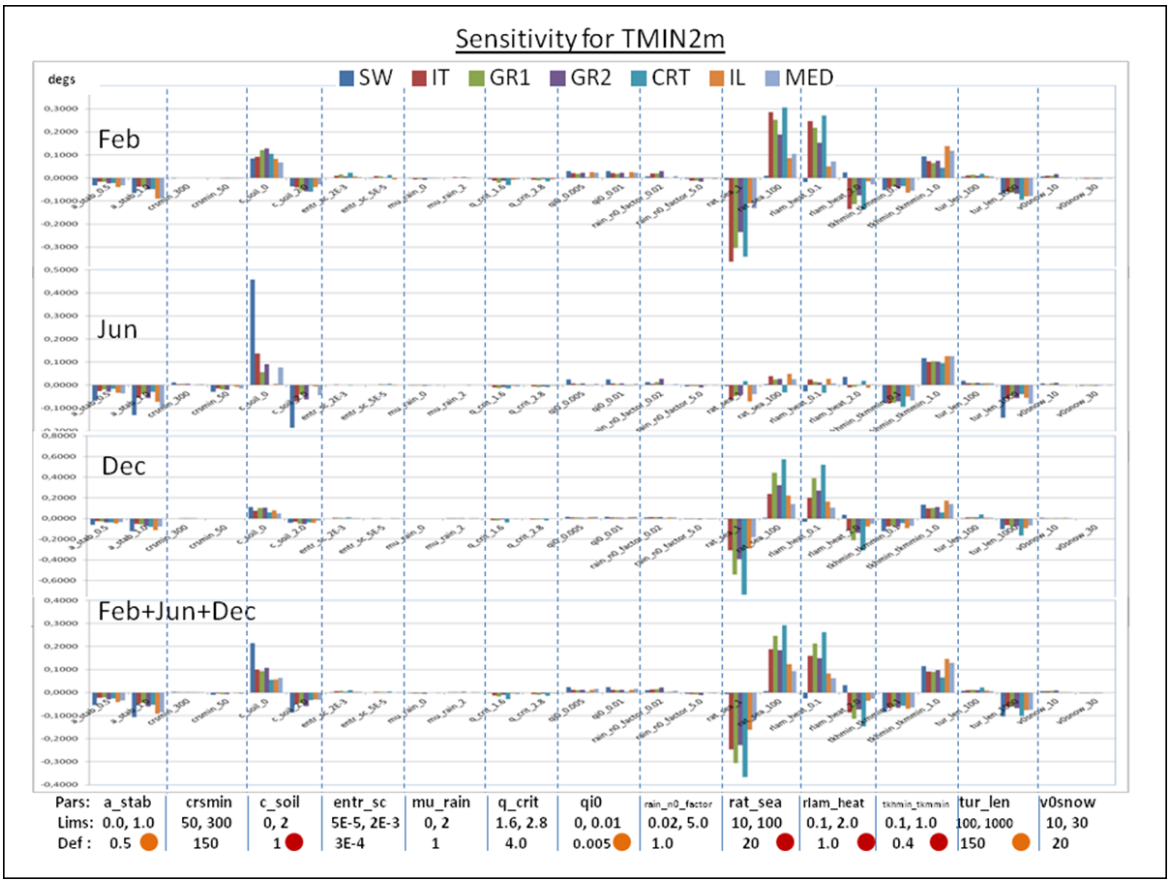
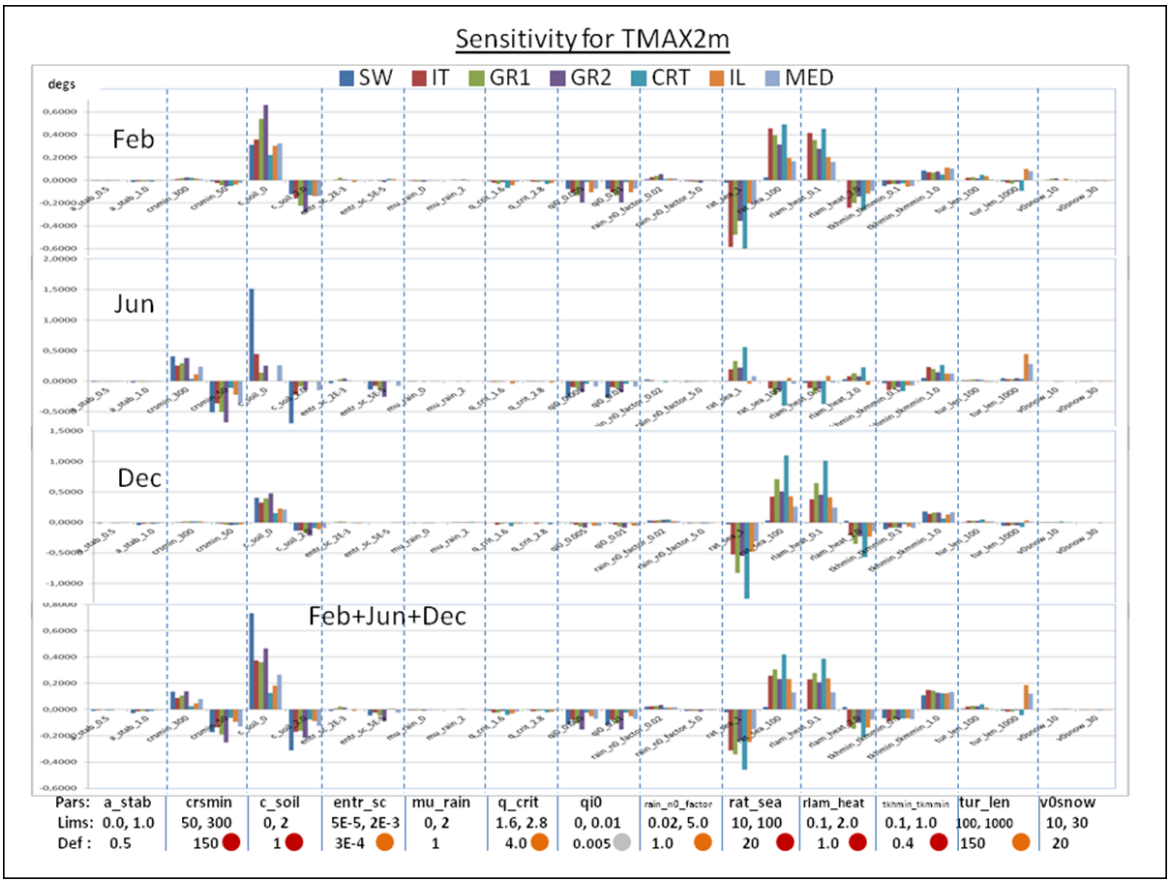
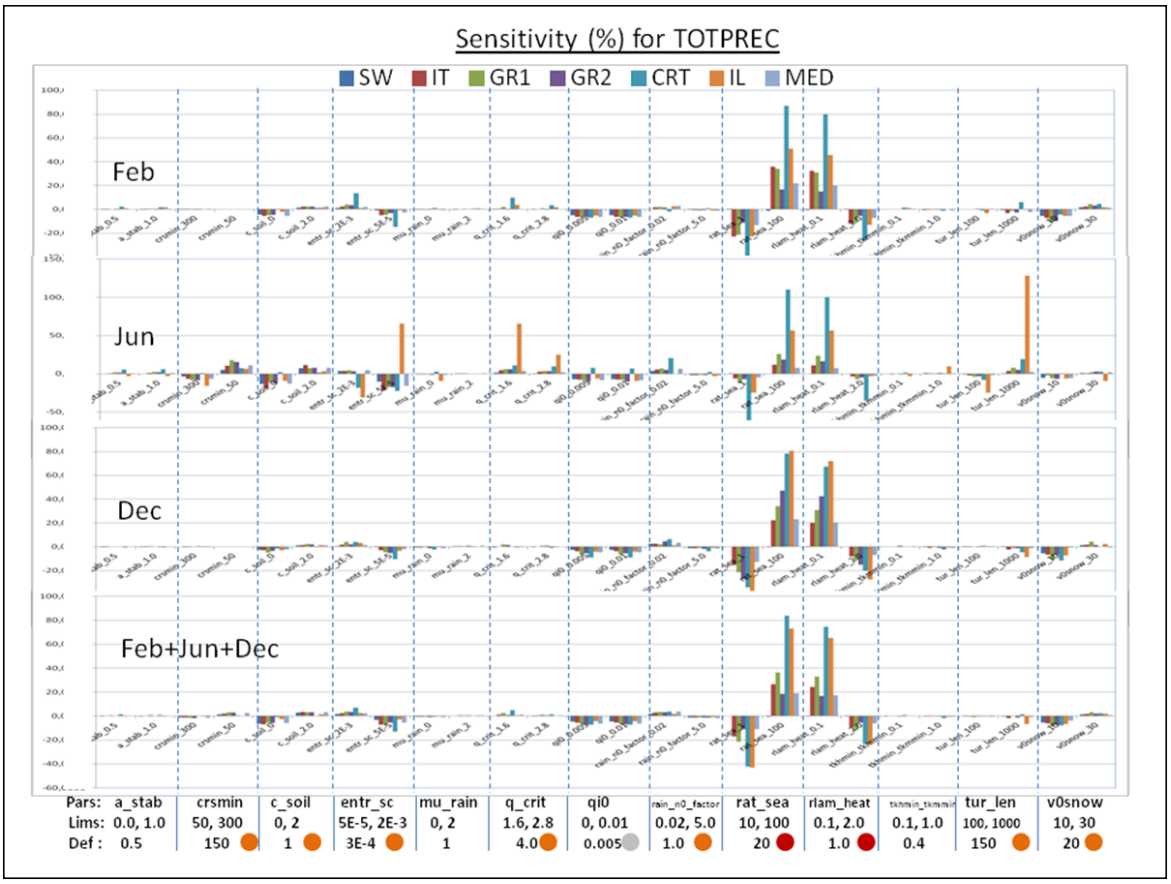
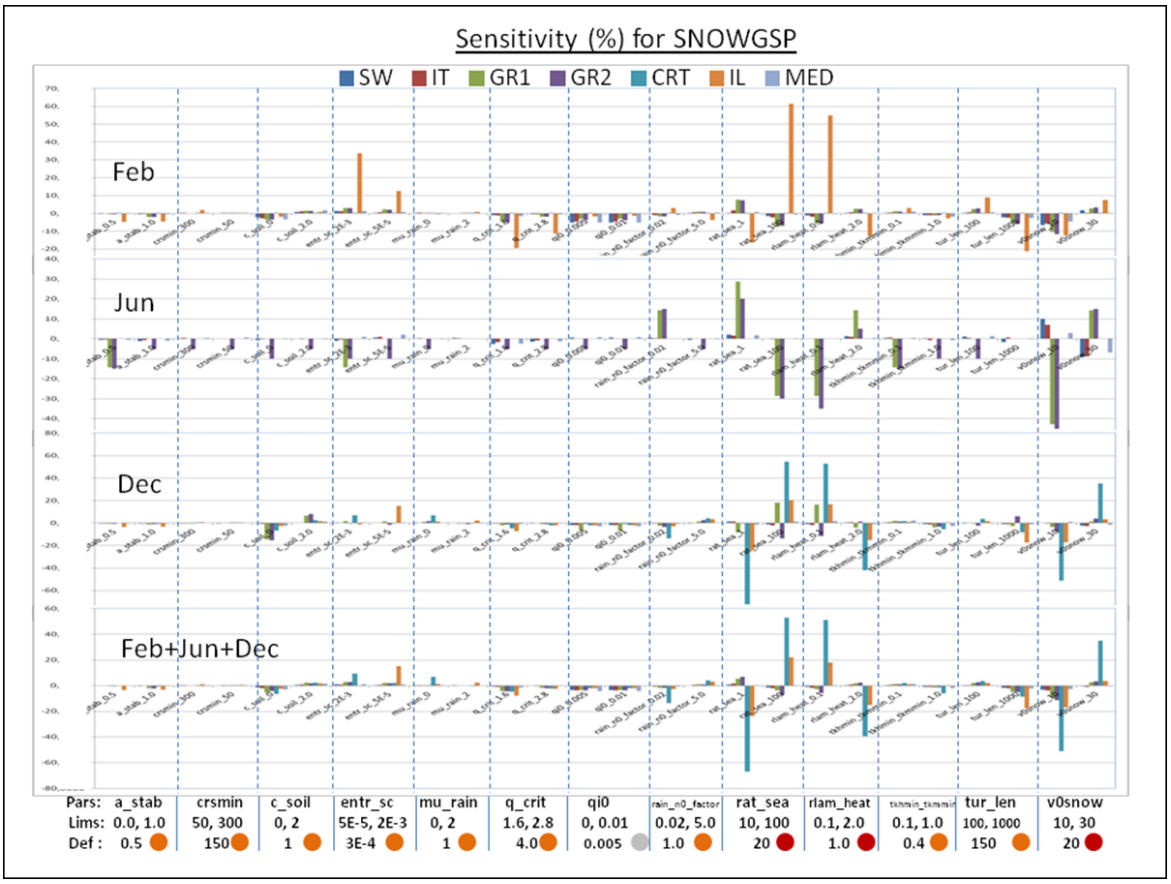
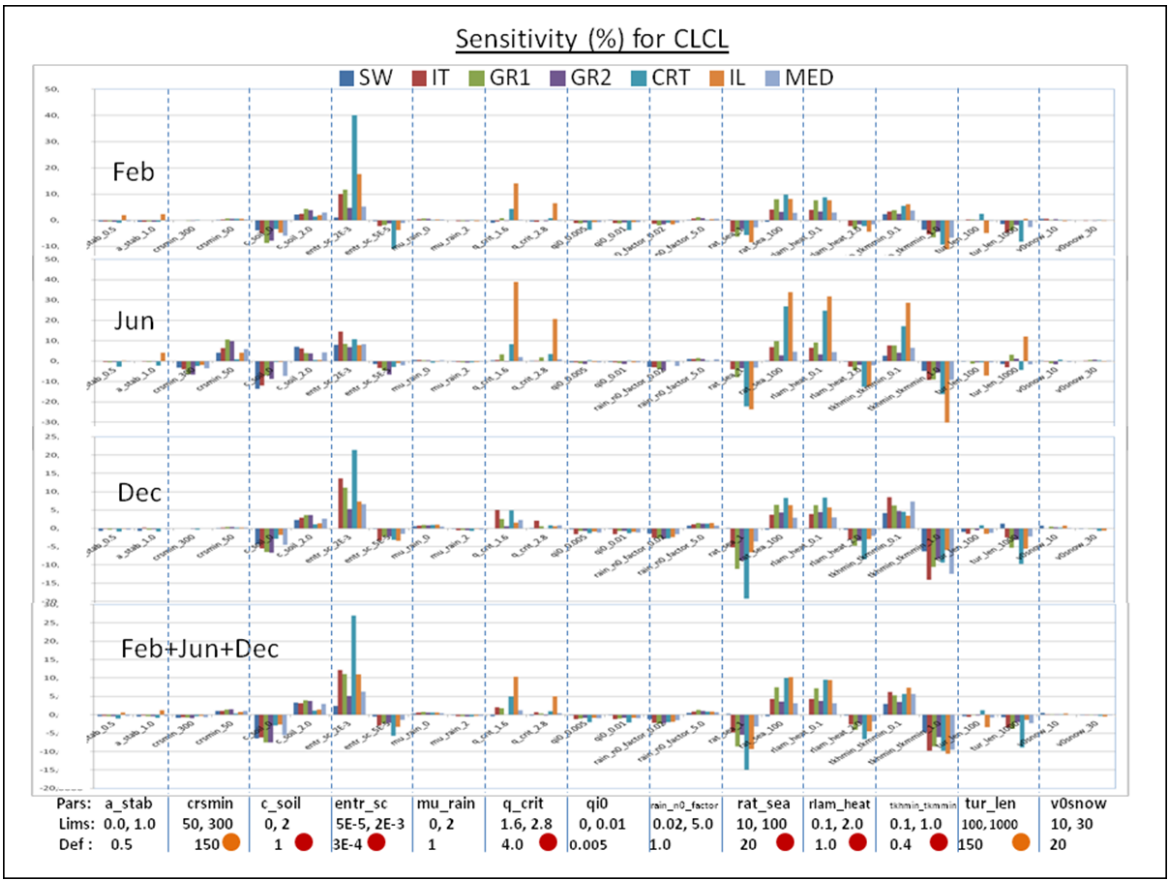


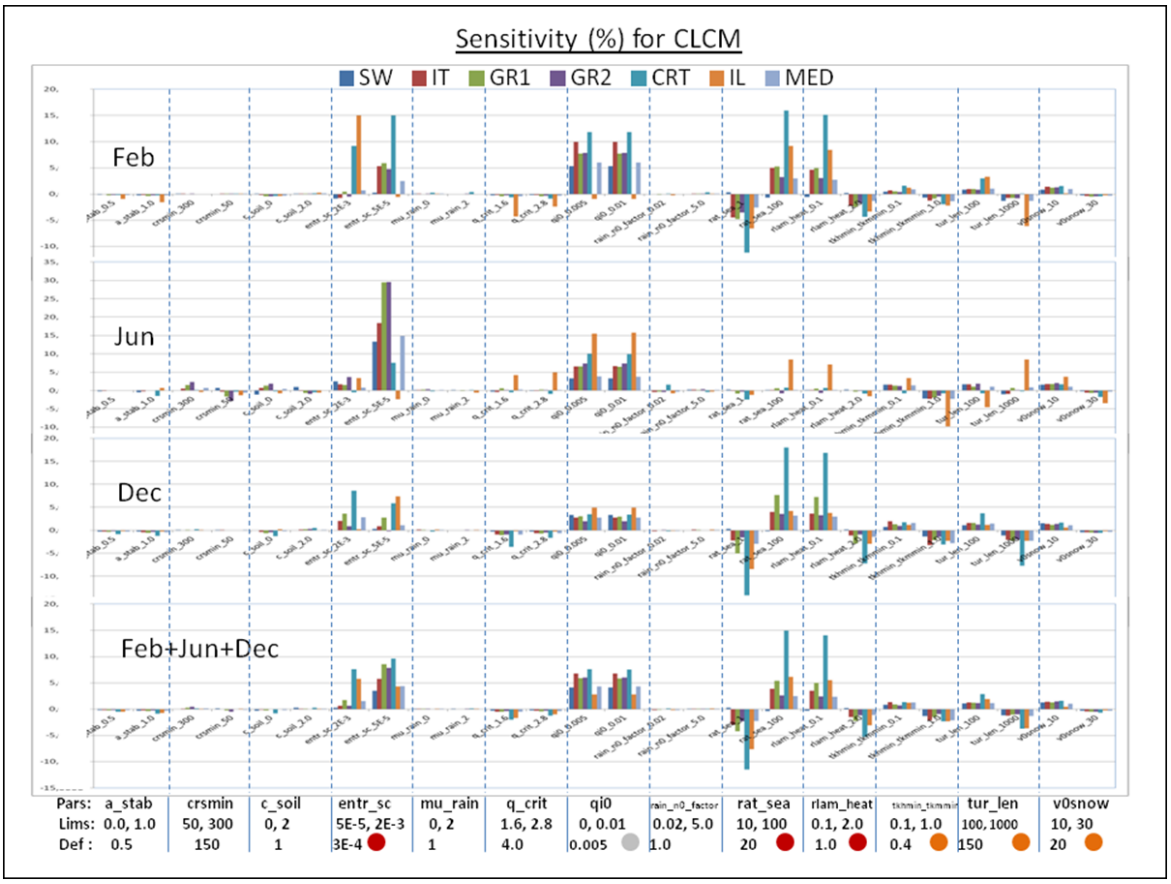
Figure 20: Description of parameter list. ∗c_lnd: Surface-area index of gridpoints over land (excluding leaf-area index). ∗∗The "gray" variable **qi0**, although its sensitivity will be shown, it is not accounted at this stage of our work due to caution regarding its use if different than its default value (communication with Axel Seifert).

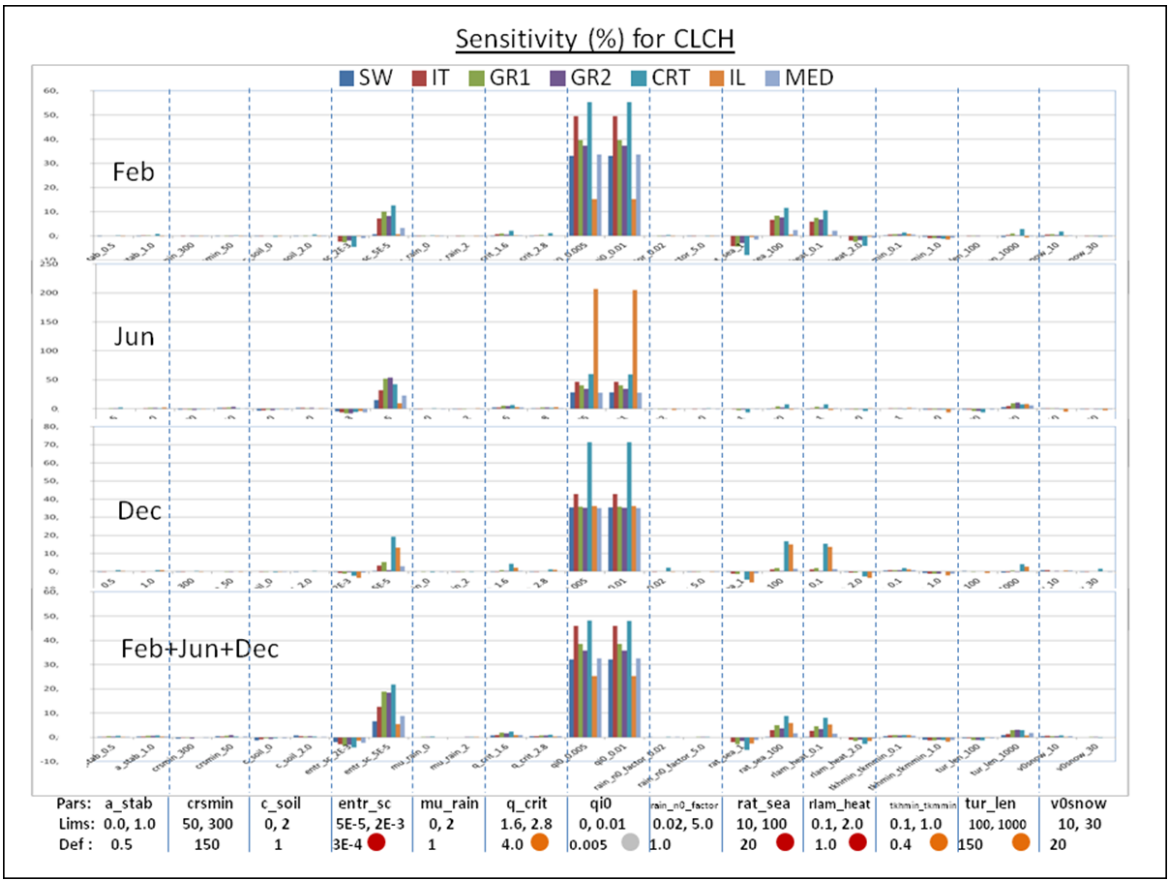

Sensitivity for TMAX2m
SW
IT
GR1
GR2
CRT
IL
MED
degs
Feb
Jun
Dec
Feb+Jun+Dec
Pars: a_stab crsmin c_soil entr_sc mu_rain q_crit qi0 rain_n0_factor rat_sea rlam_heat tkhmin_tkmmin tur_len v0snow
Lims: 0.0, 1.0 50, 300 0, 2 5E-5, 2E-3 0, 2 1.6, 2.8 0, 0.01 0.02, 5.0 10, 100 0.1, 2.0 0.1, 1.0 100, 1000 10, 30
Def : 0.5 150 1 3E-4 1 4.0 0.005 1.0 20 1.0 0.4 150 20

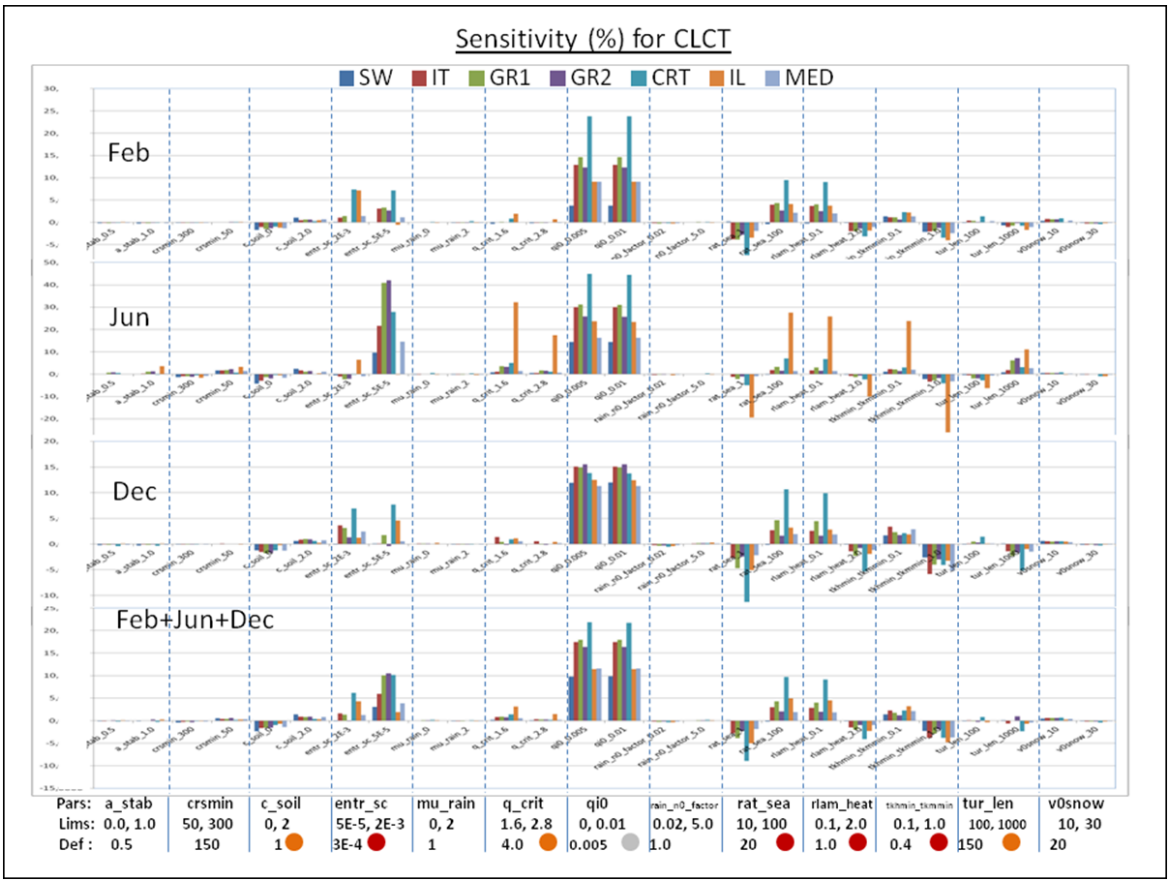

Sensitivity (%) for TOTPREC
SW IT GR1 GR2 CRT IL MED
Feb
Jun
Dec
Feb+Jun+Dec
Pars: a_stab crsmin c_soil entr_sc mu_rain q_crit qi0 rain_n0_factor rat_sea rlam_heat tkhmin_tkmmin tur_len v0snow
Lims: 0.0, 1.0 50, 300 0, 2 5E-5, 2E-3 0, 2 1.6, 2.8 0, 0.01 0.02, 5.0 10, 100 0.1, 2.0 0.1, 1.0 100, 1000 10, 30
Def : 0.5 150 1 3E-4 1 4.0 0.005 1.0 20 1.0 0.4 150 20

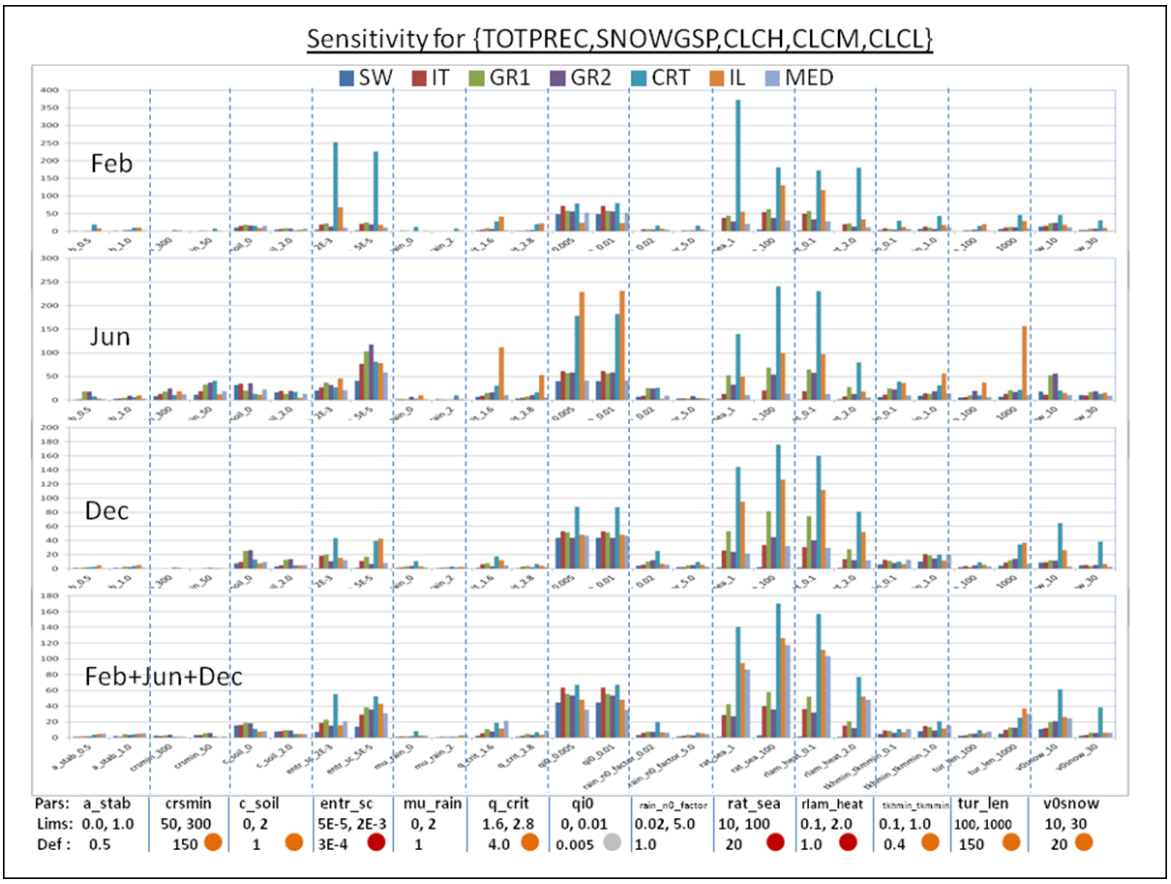

Sensitivity (%) for SNOWGSP
SW
IT
GR1
GR2
CRT
IL
MED
Feb
Jun
Dec
Feb+Jun+Dec
Pars: a_stab crsmin c_soil entr_sc mu_rain q_crit qi0 rain_n0_factor rat_sea rlam_heat tkhmin_tkmmin tur_len v0snow
Lims: 0.0, 1.0 50, 300 0, 2 5E-5, 2E-3 0, 2 1.6, 2.8 0, 0.01 0.02, 5.0 10, 100 0.1, 2.0 0.1, 1.0 100, 1000 10, 30
Def : 0.5 150 1 3E-4 1 4.0 0.005 1.0 20 1.0 0.4 150 20


Sensitivity (%) for CLCL
SW IT GR1 GR2 CRT IL MED
Feb
Jun
Dec
Feb+Jun+Dec
Pars: a_stab crsmin c_soil entr_sc mu_rain q_crit qi0 rain_n0_factor rat_sea rlam_heat tkhmin_tkmmin tur_len v0snow
Lims: 0.0, 1.0 50, 300 0, 2 5E-5, 2E-3 0, 2 1.6, 2.8 0, 0.01 0.02, 5.0 10, 100 0.1, 2.0 0.1, 1.0 100, 1000 10, 30
Def : 0.5 150 1 3E-4 1 4.0 0.005 1.0 20 1.0 0.4 150 20


Sensitivity (%) for CLCM
SW
IT
GR1
GR2
CRT
IL
MED
Feb
Jun
Dec
Feb+Jun+Dec
Pars: a_stab crsmin c_soil entr_sc mu_rain q_crit qi0 rain_n0_factor rat_sea rlam_heat tkhmin_tkmmin tur_len v0snow
Lims: 0.0, 1.0 50, 300 0, 2 5E-5, 2E-3 0, 2 1.6, 2.8 0, 0.01 0.02, 5.0 10, 100 0.1, 2.0 0.1, 1.0 100, 1000 10, 30
Def : 0.5 150 1 3E-4 1 4.0 0.005 1.0 20 1.0 0.4 150 20


Sensitivity (%) for CLCH
SW IT GR1 GR2 CRT IL MED
Feb
Jun
Dec
Feb+Jun+Dec
Pars: a_stab crsmin c_soil entr_sc mu_rain q_crit qi0 rain_n0_factor rat_sea rlam_heat tkhmin_tkmmin tur_len v0snow
Lims: 0.0, 1.0 50, 300 0, 2 5E-5, 2E-3 0, 2 1.6, 2.8 0, 0.01 0.02, 5.0 10, 100 0.1, 2.0 0.1, 1.0 100, 1000 10, 30
Def : 0.5 150 1 3E-4 1 4.0 0.005 1.0 20 1.0 0.4 150 20


Sensitivity (%) for CLCT
SW
IT
GR1
GR2
CRT
IL
MED
Feb
Jun
Dec
Feb+Jun+Dec
Pars: a_stab crsmin c_soil entr_sc mu_rain q_crit qi0 rain_n0_factor rat_sea rlam_heat tkhmin_tkmmin tur_len v0snow
Lims: 0.0, 1.0 50, 300 0, 2 5E-5, 2E-3 0, 2 1.6, 2.8 0, 0.01 0.02, 5.0 10, 100 0.1, 2.0 0.1, 1.0 100, 1000 10, 30
Def : 0.5 150 1 3E-4 1 4.0 0.005 1.0 20 1.0 0.4 150 20


Sensitivity for {TOTPREC,SNOWGSP,CLCH,CLCM,CLCL}
SW IT GR1 GR2 CRT IL MED
Feb
Jun
Dec
Feb+Jun+Dec
Pars: a_stab crsmin c_soil entr_sc mu_rain q_crit qi0 rain_n0_factor rat_sea rlam_heat tkhmin_tkmmin tur_len v0snow
Lims: 0.0, 1.0 50, 300 0, 2 5E-5, 2E-3 0, 2 1.6, 2.8 0, 0.01 0.02, 5.0 10, 100 0.1, 2.0 0.1, 1.0 100, 1000 10, 30
Def : 0.5 150 1 3E-4 1 4.0 0.005 1.0 20 1.0 0.4 150 20

List of COSMO Newsletters and Technical Reports

(available for download from the COSMO Website: www.cosmo-model.org)

COSMO Newsletters

No. 1: February 2001.

No. 2: February 2002.

No. 3: February 2003.

No. 4: February 2004.

No. 5: April 2005.

No. 6: July 2006.

No. 7: April 2008; Proceedings from the 8th COSMO General Meeting in Bucharest, 2006.

No. 8: September 2008; Proceedings from the 9th COSMO General Meeting in Athens, 2007.

No. 9: December 2008.

No. 10: March 2010.

No. 11: April 2011.

No. 12: April 2012.

No. 13: April 2013.

No. 14: April 2014.

No. 15: July 2015.

No. 16: July 2016.

No. 17: July 2017.

COSMO Technical Reports

No. 1: Dmitrii Mironov and Matthias Raschendorfer (2001):
Evaluation of Empirical Parameters of the New LM Surface-Layer Parameterization Scheme. Results from Numerical Experiments Including the Soil Moisture Analysis.

No. 2: Reinhold Schrodin and Erdmann Heise (2001):
The Multi-Layer Version of the DWD Soil Model TERRA_LM.

No. 3: Günther Doms (2001):
A Scheme for Monotonic Numerical Diffusion in the LM.

No. 4: Hans-Joachim Herzog, Ursula Schubert, Gerd Vogel, Adelheid Fiedler and Roswitha Kirchner (2002):
LLM ¯ the High-Resolving Nonhydrostatic Simulation Model in the DWD-Project LITFASS.
Part I: Modelling Technique and Simulation Method.

No. 5: Jean-Marie Bettems (2002):
EUCOS Impact Study Using the Limited-Area Non-Hydrostatic NWP Model in Operational Use at MeteoSwiss.

No. 6: Heinz-Werner Bitzer and Jürgen Steppeler (2004):
Documentation of the Z-Coordinate Dynamical Core of LM.

No. 7: Hans-Joachim Herzog, Almut Gassmann (2005):
Lorenz- and Charney-Phillips vertical grid experimentation using a compressible nonhydrostatic toy-model relevant to the fast-mode part of the 'Lokal-Modell'.

No. 8: Chiara Marsigli, Andrea Montani, Tiziana Paccagnella, Davide Sacchetti, André Walser, Marco Arpagaus, Thomas Schumann (2005):
Evaluation of the Performance of the COSMO-LEPS System.

No. 9: Erdmann Heise, Bodo Ritter, Reinhold Schrodin (2006):
Operational Implementation of the Multilayer Soil Model.

No. 10: M.D. Tsyrulnikov (2007):
Is the particle filtering approach appropriate for meso-scale data assimilation ?

No. 11: Dmitrii V. Mironov (2008):
Parameterization of Lakes in Numerical Weather Prediction. Description of a Lake Model.

No. 12: Adriano Raspanti (2009):
COSMO Priority Project "VERification System Unified Survey" (VERSUS): Final Report.

No. 13: Chiara Marsigli (2009):
COSMO Priority Project "Short Range Ensemble Prediction System" (SREPS): Final Report.

No. 14: Michael Baldauf (2009):
COSMO Priority Project "Further Developments of the Runge-Kutta Time Integration Scheme" (RK): Final Report.

No. 15: Silke Dierer (2009):
COSMO Priority Project "Tackle deficiencies in quantitative precipitation forecast" (QPF): Final Report.

No. 16: Pierre Eckert (2009):
COSMO Priority Project "INTERP": Final Report.

No. 17: D. Leuenberger, M. Stoll and A. Roches (2010):
Description of some convective indices implemented in the COSMO model.

No. 18: Daniel Leuenberger (2010):
Statistical analysis of high-resolution COSMO Ensemble forecasts in view of Data Assimilation.

No. 19: A. Montani, D. Cesari, C. Marsigli, T. Paccagnella (2010):
Seven years of activity in the field of mesoscale ensemble forecasting by the COSMO–LEPS system: main achievements and open challenges.

No. 20: A. Roches, O. Fuhrer (2012):
Tracer module in the COSMO model.

No. 21: Michael Baldauf (2013):
A new fast-waves solver for the Runge-Kutta dynamical core.

No. 22: C. Marsigli, T. Diomede, A. Montani, T. Paccagnella, P. Louka, F. Gofa, A. Corigliano (2013):
The CONSENS Priority Project.

No. 23: M. Baldauf, O. Fuhrer, M. J. Kurowski, G. de Morsier, M. Müllner, Z. P. Piotrowski, B. Rosa, P. L. Vitagliano, D. Wójcik, M. Ziemiański (2013):
The COSMO Priority Project 'Conservative Dynamical Core' Final Report.

No. 24: A. K. Miltenberger, A. Roches, S. Pfahl, H. Wernli (2014):
Online Trajectory Module in COSMO: a short user guide.

No. 25: P. Khain, I. Carmona, A. Voudouri, E. Avgoustoglou, J.-M. Bettems, F. Grazzini (2015):
The Proof of the Parameters Calibration Method: CALMO Progress Report.

No. 26: D. Mironov, E. Machulskaya, B. Szintai, M. Raschendorfer, V. Perov, M. Chumakov, E. Avgoustoglou (2015):
The COSMO Priority Project 'UTCS' Final Report.

No. 27: J-M. Bettems (2015):
The COSMO Priority Project 'COLOBOC': Final Report.

No. 28: Ulrich Blahak (2016):
RADAR_MIE_LM and RADAR_MIELIB - Calculation of Radar Reflectivity from Model Output.

No. 29: M. Tsyrulnikov and D. Gayfulin (2016):
A Stochastic Pattern Generator for ensemble applications.

No. 30: D. Mironov and E. Machulskaya (2017):
A Turbulence Kinetic Energy – Scalar Variance Turbulence Parameterization Scheme.

No. 31: P. Khain, I. Carmona, A. Voudouri, E. Avgoustoglou, J.-M. Bettems, F. Grazzini, P. Kaufmann (2017):
CALMO - Progress Report.

COSMO Technical Reports

Issues of the COSMO Technical Reports series are published by the *COnsortium for Small-scale MOdelling* at non-regular intervals. COSMO is a European group for numerical weather prediction with participating meteorological services from Germany (DWD, AWGeophys), Greece (HNMS), Italy (USAM, ARPA-SIMC, ARPA Piemonte), Switzerland (MeteoSwiss), Poland (IMGW), Romania (NMA) and Russia (RHM). The general goal is to develop, improve and maintain a non-hydrostatic limited area modelling system to be used for both operational and research applications by the members of COSMO. This system is initially based on the COSMO-Model (previously known as LM) of DWD with its corresponding data assimilation system.

The Technical Reports are intended

- for scientific contributions and a documentation of research activities,
- to present and discuss results obtained from the model system,
- to present and discuss verification results and interpretation methods,
- for a documentation of technical changes to the model system,
- to give an overview of new components of the model system.

The purpose of these reports is to communicate results, changes and progress related to the LM model system relatively fast within the COSMO consortium, and also to inform other NWP groups on our current research activities. In this way the discussion on a specific topic can be stimulated at an early stage. In order to publish a report very soon after the completion of the manuscript, we have decided to omit a thorough reviewing procedure and only a rough check is done by the editors and a third reviewer. We apologize for typographical and other errors or inconsistencies which may still be present.

At present, the Technical Reports are available for download from the COSMO web site (www.cosmo-model.org). If required, the member meteorological centres can produce hard-copies by their own for distribution within their service. All members of the consortium will be informed about new issues by email.

For any comments and questions, please contact the editor:

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