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Calibration of COSMO Model,
Priority Project CALMO-MAX:
Final Report

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1 Introduction

The current report summarizes work and achievements within the COSMO priority project CALMO-MAX **CAL**ilbration of **MO**del **M**ethod **A**pplied on e**X**tremes). CALMO-MAX is the follow-up project of the CALMO (Calibration of COSMO Model) project (see http://www.cosmo-model.org/content/tasks/priorityProjects/calmoMax/default.htm) and has been carried out from 06.2017 to 12.2020.

The methodology applied in the project is based on the objective multi-variate calibration method proposed by Neelin et al. (2010, 2010a) to calibrate unconfined model parameters existing in various parameterization schemes (Stephens et al., 1990; Knutti et al., 2002). Originally it was applied to COSMO model for regional climate simulations (RCM) by Bellprat et al. (2012a and 2012b, 2016). Then, in the framework of CALMO, it was implemented in COSMO for NWP applications. CALMO project has shown that the method used by Bellprat for COSMO-CLM can be adapted to NWP applications. After a proper re-design, the meta-model was able to reasonably reproduce full COSMO model simulations, for all cases considered (Khain et al., 2015, 2017, Voudouri et al., 2017c). Furthermore, the optimum set of model parameters improved a COSI-type score[1], for all tested configurations, and the results of an independent verification seem to indicate that the operational verification scores were also improved.

During CALMO-MAX project, the methodology has been applied in a finer resolution of 1km over the Swiss domain. In this work the MeteoSwiss COSMO-1 configuration has been calibrated, selecting five model parameters, using a full year statistic, with the history of the soil included (hindcast), while twenty-one meteorological fields have been considered to demonstrate the benefits of the methodology. A different year has been used to have an independent assessment of the impact of the optimization process. Results showed that a slight model performance gain of approximately 1% is obtained by using the CALMO methodology, although the chosen model configuration, based on the operational model of MeteoSwiss and close to the DWD configuration, corresponds to an already well-tuned configuration. To demonstrate the feasibility of these idea, a new calibration is currently applied over a large Central- and Eastern-Mediterranean domain, covering mainly marine instead of continental area.

The considered domain covers the Central-Eastern Mediterranean area with a horizontal mesh of 0.030^o (3.3km).The optimization technique considers observations at twenty-two Greek and sixty-five Israeli meteorological stations of 24hr accumulated precipitation, minimum and maximum 2-meter dry and dew-point temperatures at sixty dates spread over the year 2019, five for every month, in order to comply with the seasonal variability. The optimum model parameters have been evaluated by application on an independent set of sixty days chosen from the same year-period and in the same manner. An overall model performance score improvement of order 5% was obtained for both sets of test cases. This application proves that the CALMO methodology can be used as an affordable and useful tool to define the optimal calibration over a different target area of interest (or a significantly different model configuration).

Although CALMO-MAX methodology had already been described in the existing documentation of CALMO project, additional support material has been produced. More specifically, the COSMO Technical Reports No 42 (Avgoustoglou et al, 2020), 2 articles in COSMO newsletters No 19 (Voudouri et al., 2019) and No 20 (Voudouri et al., 2020), and two peer review articles (Voudouri et al. 2021, Avgoustoglou et al 2022) have been added, to provide a

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

more detailed description of the many aspects of the project. All the details of CALMO-MAX as well as relevant documentation are available on the COSMO websites http://www.cosmo-model.org/content/tasks/priorityProjects/calmoMax/default.htm and http://www.cosmo-model.org at the Documentation sector respectively.

Moreover, a short description of the project tasks and achievements of CALMO-MAX priority project is given in section 2 of the present report. The sensitivity experiments performed over the selected calibration parameters are presented in section 3. A short description of the meta-model developments at the framework of CALMO-MAX is made in section 4. Verification results of COSMO-1 calibration over the Swiss domain and Mediterranean case study are given in sections 5 and 6 respectively. Conclusions are provided in section 7.

2 Tasks and achievements

The project consisted of 6 main tasks that consolidate the previous work performed within CALMO and focus on the calibration of both COSMO-1 over a mainly continental domain that is the MeteoSwiss operational domain and a marine area, the Mediterranean Sea region using a rougher resolution. More specifically the tasks and achievements during the project are summarized in this section as follows:

Task 0: Administration and support

The distributed nature of the project team and the need to keep a good information flow among all project participants and consortium member, main objectives of this task, have been successfully addressed via regular web conferences and annually workshops. The existing mailing list of the CALMO project (see http://mail.cosmo-model.org/mailman/listinfo/ca lmo) has also been used to support communication and information exchange within project participants.

Task 1: Consolidation of CALMO outcome

The aim of this task (divided into 2 subtasks) was to consolidate the knowledge gained through the application of CALMO (1.1) and the acquisition of the necessary computing resources (1.2) throughout the project, in particular for the tasks 3 and 4. Review of the methodology and additional sensitivity experiments on model parameters, whose results are presented in section 3, have been performed. The open scientific questions that have been addressed include the dependency of the optimum parameter set on weather type, the possibility to consider a geographical dependency of calibrated parameters in relation with soil or surface properties (it they could e.g. be used for a new parameterization of the vegetation canopy, which introduces a land use dependent tuning parameter) and whether the optimization technique could be applied seasonally to lower the computational cost. For sub task 1.2 a proposal for a new allocation period on Piz Daint / CSCS has been accepted, with excellent scientific review, but with reduced allocation time budget and disk space. Thanks to the contribution of MeteoSwiss, additional computer resources for calibrating COSMO-1 were available throughout the project. Resources from the computing platform of the ECMWF HPC system were also used. More specifically, billing units from HNMS have been used for testing calibration methodology over the Mediterranean.

Task 2: Optimization of the CALMO methodology

The task is divided into 2 subtasks: 2.1 that is the calibration of COSMO-1 for a full year: 2.2 aimed to find a way to optimize the computational cost of the method.

The primary goal of this task was to complete the COSMO-1 calibration, generating a full year of statistics, with the history of the soil, as originally planned for the CALMO project. The simulations using COSMO-1 for 5 parameters have been completed and an additional independent yearly simulation has been performed. Results of this calibration procedure are discussed in section 5. COSMO-1 calibration has been performed over the operational Swiss domain shown in Figure 1, with the history of the soil, as originally planned for the project. This calibration has been used as test bed to evaluate different options to reduce the cost of the method.

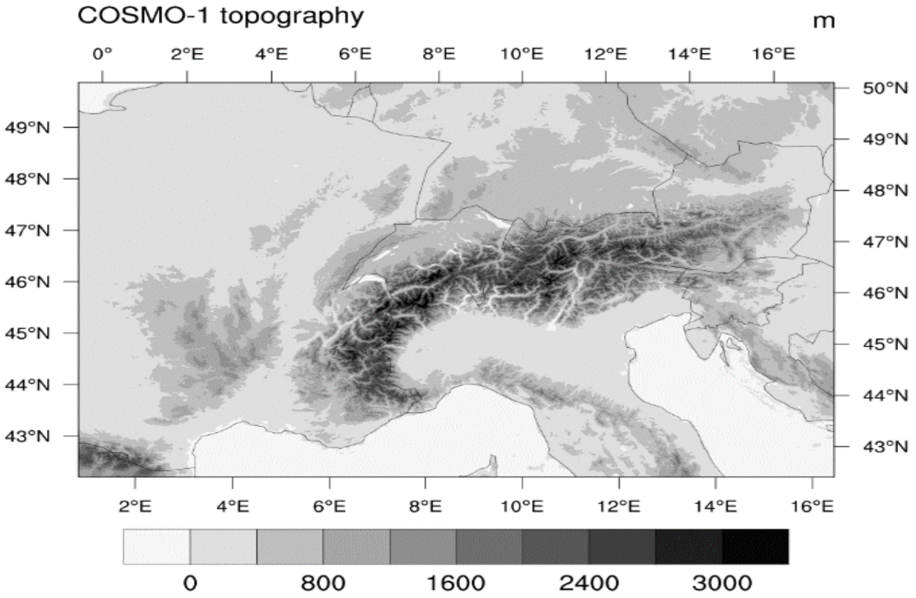

Figure 1: Topography of simulation domain.

Successively, the aim of this task was to collect ideas, and to evaluate different options to reduce the computational cost of the method, without significantly degrading the quality of the calibration. In particular, the question of the minimal number of simulations to fit the meta-model, and how this affects the accuracy of the meta-model has been addressed. The best strategy to fit the meta-model has been reviewed, using the ideas developed by E. Avgoustoglou during the CALMO project. The use of only one interaction term to fit the meta-model and reduce the required number of simulations to 2*N + N*(N-1) / 2 + 1 is then feasible without reducing the meta-model accuracy. A limited geographical domain for the calibration has also been considered and a coarser resolution (e.g. 3.0 instead of 1.1 km) has been used. Calibrate using a limited time period, over a mainly marine area were the soil memory is of minor concern, has also been applied and specifically over the Mediterranean Sea.

Finally, the idea to apply calibration methodology using partition set of unconfined model parameters in different subsets (if weak dependency between the subsets can be assumed), calibrate first subset, then next subset by building separate meta-models has been proposed but not tested.

Task 3: Establishment of a permanent CALMO platform

Task 3 was divided into 5 subtasks: 3.1: HPC framework 3.2: Data thinning policy and application, 3.3: Meta-model, 3.4: Database of unconfined model parameters and 3.5: Access to observations.

One important objective of this project is to provide a permanent infrastructure supporting the application of the calibration method, accessible to all COSMO members. Besides being used to run the calibration, this infrastructure could also serve as a demonstrative technical framework. The HPC platform selected is the HPC at ECMWF (already used by COSMO for COSMO-LEPS and for the NWP test suite), which is the most widely accessible for the COSMO community. Thus, the installation of the demonstration framework on the ECMWF HPC platform to run the COSMO model, including Terra standalone and the required pre- and post-processing operations (fieldextra for data thinning) in order to apply the CALMO methodology was included in this task. This platform is currently opened only to registered user. The meta-model code is available on GitHub and, as self-contained package, on the software page of the COSMO website. An Octave version has been prepared by IMS and is available at ECMWF in the directory (without the graphics part) /scratch/ms/il/ili/CALMOMAX/MM_Matlab_code_of_Med_Domain/main with the instructions file "*Readme.dat*" on how to run the meta-model.

Regarding calibration of COSMO-1 as the amount of raw data produced by the calibration method was huge a data thinning policy applied to make the method applicable. The policy developed during the CALMO project, implemented with fieldextra, has been applied. In addition, available full set of observations for Switzerland and Northern Italy, for years 2013 and 2017, as well as for Greece and Israel for 2019 have been collected during the project.

An updated version of the meta-model, including the neighborhood method (FSS score), uses finer temporal resolution (6h instead of 24h accumulated precipitation) and introduces near surface humidity (to avoid T2m over tuning, INCA based gridded product available over Switzerland). An attempt to introduce sunshine duration (gridded products available over Switzerland) has also been made, but erroneous simulated sunshine duration values and low correlation with observation were found and the specific field has not been used.

An exhaustive list of unconfined model parameters and their associated characteristics (default values, unconfined range, model sensitivity) has been prepared during CALMO and CALMO-MAX.

With the transition to COSMO to ICON, the establishment of a standard procedure on the documentation of model parameters represents a critical task that should be considered in the new consortium era. It should include "useful hints", such as the description of the key (most sensitive) free parameters, whose appropriate/inappropriate setting may improve/deteriorate the model performance considerably.

Task 4: Adaptation of the methodology on Extremes

Task 4 was divided into 4 subtasks namely 4.1: Support for extreme events, 4.2: Experiments using the meta-model, 4.3: Experimental set-up, 4.4: Compute experiments and analyze results.

It was aimed at applying the optimized calibration strategy developed in task 2 to tackle different open questions, using the platform prepared in task 3. In this process, the different improvements of the meta-model have also been considered. Within this task, the calibration over the Mediterranean Sea Region has been performed. More specifically two periods of 60 days in the year 2019 were considered, with 5 days from each month of the year in each group to account for the seasonal variability. The simulations have been performed over the computational facilities of ECMWF established within Task 2. The outcomes of this task are summarized in section 6 and in detail in Avgoustoglou et al., 2022.

Task 5: Documentation

In the framework of this task, a significant amount of documentation has been produced, and 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. More specifically two scientific papers focused on the calibration results over Swiss domain and over the Mediterranean Sea region have been realized, the first one published in Atmosphere (Voudouri et al., 2021), the second one in Atmospheric Research (Avgoustoglou et al., 2022). In addition, parts of the CALMO-MAX work have been presented at the 14th and 15th International Conference on Meteorology, Climatology and Atmospheric Physics that is COMECAP 2018 and 2021, which were held at Alexandroupoli and Ioannina respectively. The contributions are included in the books of Conference Proceedings, 2018 and 2021 respectively (Voudouri et al. 2018, 2021).

In addition, the current final report and the COSMO technical report No 42 will be and are available in COSMO web page respectively. The documentation of the meta-model and a 'cookbook' to facilitate its usage have also been updated.

3 Sensitivity experiments for COSMO-1 (Euripides Avgoustoglou)

The description of physical processes is achieved through sophisticated parameterization schemes existing in NWP models as COSMO, which often include many unconfined, or 'free' parameters that constitute the list of potential candidates for calibration. These parameters are related to sub-grid scale turbulence, surface layer parameterization, grid-scale cloud formation, moist and shallow convection, precipitation, radiation and soil schemes.

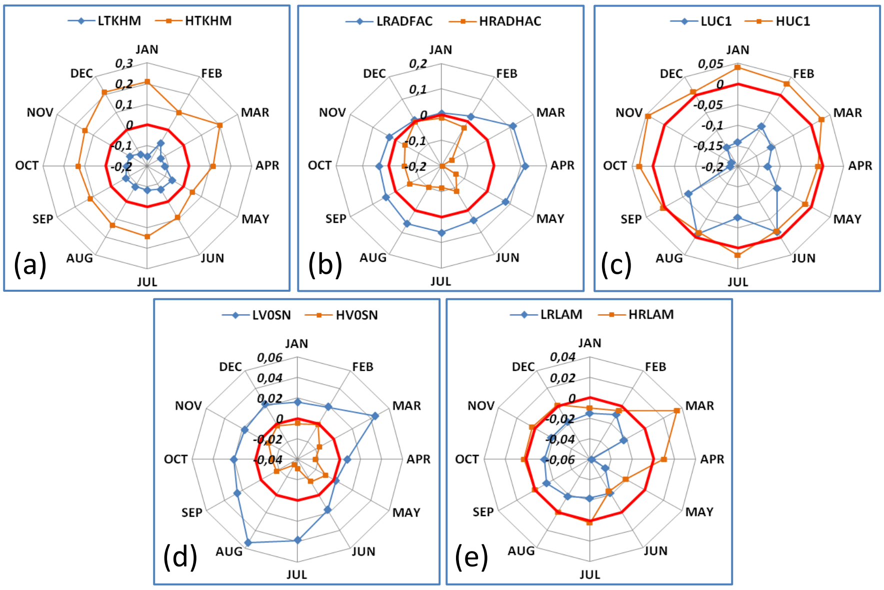

Figure 2: Monthly sensitivity of 2m temperature for (a) tkhmin, (b) rad_fac (c) uc1 (d) v0snow and (e) rlam-heat per month for year 2013. The blue line represents the lowest (L) value, and the orange line represents the highest (H) value of each parameter, while the other parameters are kept with their default values. The red circle denotes the referenced default value (the zero °C circle).

In the framework of CALMO-MAX, an extended preliminary set of eleven parameters covering turbulence (tur_len, tkhmin, tkmmin), surface layer parameterization (rat_sea, rlam_heat, crsmin), grid-scale precipitation (v0snow), moist and shallow convection (entr_sc), radiation (rad_fac, uc1) and the soil scheme (c_soil) have been tested. Several sensitivity experiments have been performed to define the subset of the most 'triggering' parameters for calibration over the Swiss domain described in Avgoustoglou et al. (COSMO Tr N. 42, 2020).

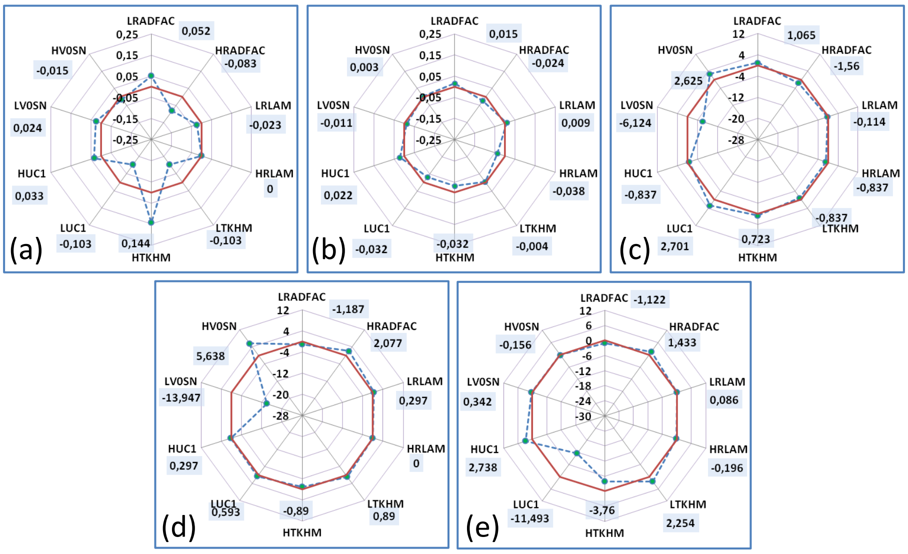

Figure 3: Yearly sensitivity of (a) 2m temperature, (b) dew point temperature °C precipitation (d) snow and (e) total cloud cover) with respect to all selected parameters for the year 2013.

The five model parameters chosen for COSMO-1 in CALMO-MAX are: minimal diffusion coefficients for heat, tkhmin[m^2/s], scalar resistance for the latent and sensible heat fluxes in the laminar surface layer, rlam_heat [no units], factor in the terminal velocity for snow, v0snow[no units], the parameter controlling the vertical variation of critical relative humidity for sub-grid cloud formation, uc1 [no units] and the fraction of cloud water and ice considered by the radiation scheme rad_fac [no units]. The selection of these unconfined parameters is based on their sensitivity with respect to meteorological fields considered in the performance score, such as 2m temperature, wind speed and direction, precipitation needed for an everyday forecast, and was tested also over a different domain. Sensitivity of 2m temperature (in ^{o}C) and dew point temperature is expressed as the difference between the 2m temperature using a test value for a parameter (Ftest) minus the one using the default (proposed by model developers) parameter value (Fdef)

$$S = Ftest - Fdef \text{ (Eq. 1)}$$

Figure 2 summarizes the monthly domain difference of the 2m temperature for each parameter, namely tkhmin (Fig 2a), rad_fac (Fig. 2b), uc1 (Fig 2c), v0snow (Fig 2d) and rlam_heat (Fig 2e). It should be noted that different scales are used, thus the graph with the largest scale range denotes the most sensitive parameter. The red polygon refers to the zero sensitivity "axis", where the test value of the parameter gives the same 2m temperature as the one you get using the default parameter value. Blue and orange lines connect monthly 2m temperature differences when the parameter takes its minimum (e.g. LTKHM for tkhmin) and maximum value (HTKHM) respectively.

As shown in Figs 2a, 2b and 2c, 2m temperature is, as expected, mainly affected by turbulence (represented by tkhmin), where temperature difference within the parameter range (blue and orange lines) reaches 0.4 ^{o}C for December, January and March and by radiation (rad_fac and uc1 parameters) with up to 0.3 ^{o}C for April and May, parameterization schemes. On the contrary a low sensitivity of 2m temperature on the surface parameterization scheme is evident, as changing scalar resistance for the latent and sensible heat fluxes in the laminar surface layer (rlam_heat) gives a maximum temperature difference of only 0.07 ^{o}C, for April (Fig 2e).

Sensitivity experiments on the effects of the five parameters throughout the year have also been performed for several meteorological fields and these yearly sensitivities for 2m temperature, dew point temperature, 24h accumulated precipitation (kg m^{-2}), 24h accumulated grid-scale snow (kg m^{-2}) and hourly total cloud cover average (%) are illustrated in Figs 3a to 3e respectively. As in Figure 2, the red polygon refers to the zero sensitivity “axis”. The sensitivities for each parameter are depicted with green bullets, where H and L stand for maximum and minimum parameter value. The dashed polygon line that connects the dots, although not necessarily in the present form of the method, denotes optically the overall sensitivity for the considered meteorological variable especially to the degree that it is convex/concave and mainly in reference to the zero-sensitivity red polygon. Different scales are used, as for 2m temperature and dew point temperature sensitivities are in ^{o}C, while for precipitation, snow and total cloud cover sensitivities are expressed as percentage. Sensitivity values (S) on the spider graphs for precipitation, snow and total cloud cover, are defined as:

$$S\,(\%) = \frac{Ftest - Fdef}{Fdef} 100 \text{ (Eq. 2)}$$

where Ftest is the meteorological field value (precipitation, snow, total cloud cover) when a test value of the parameter considered is used and Fdef represents its default parameter value. Similarly to the monthly sensitivity shown in Figure 2, 2m temperature changes up to 0.25 ^{o}C throughout the year affected mainly by tkhmin, rad_fac and uc1 (Fig 3a). Dew point temperature is less sensitive than 2m temperature to these five parameters (as the same scale is used), with higher differences being 0.05 ^{o}C for rlam_heat, rad_fac and uc1 as shown in Fig 3b. Precipitation is affected by changes in rad_fac, uc1 and also v0snow up to 8% (Fig 3c) while v0snow different values leverage, as expected, with snow up to 20% (Fig 3d). Hourly average total cloud differs up to 14% when changing uc1, namely the parameter associated with sub-grid cloud formation (Fig. 3e).

4 The Meta-model (Izthak Carmona and Yoav Lev)

Work performed within CALMO-MAX deals with the issue raised in the calibration of COSMO-1, where the significant extension of the work added some complexity to the performance scores as the number of regions and the corresponding grid-points for comparing the model with observations is considered to depend on all the twenty-one considered meteorological fields.

As described in detail in Voudouri et al. 2017, 2017a and 2018, when the meta-model is fitted it can be used as a surrogate to perform a large number of simulations, testing several parameter values in order to find the optimum ones. The goal is to use the meta-model to obtain the highest performance score that indicates the optimal set of parameters. The performance score (PS) calculated for the parameters space is based on a modification of COSMO Index (COSI) (Damrath, 2009) that is S_{COSI-p} of the forecast values *(F)* against observations *(O)*. The S_{COSI} score was introduced to quantify the quality of the simulation, as it is a combination of root mean square for continuous fields and equitable thread score for precipitation. The S_{COSI-p} score for each parameter set is defined in (Eq. 3) as:

$$S_{COSI-p} = \frac{1}{N_m \sum_{\psi=1}^{N_\psi} \omega_\psi} \left\{ \sum_{\substack{\psi = 1 \\ \psi \neq 3}}^{N_\psi} \omega_\psi \sum_{m=1}^{N_m} \left[1 - \frac{\sum_{r=1}^{N_r} \sum_{d_m=1}^{N_{d_m}} \left(F_{p,\psi,r,m,d_m} - O_{\psi,r,m,d_m} \right)^2}{\sum_{r=1}^{N_r} \sum_{d_m=1}^{N_{d_m}} \left(O_{\psi,r,m,d_m-1} - O_{\psi,r,m,d_m} \right)^2} \right] + \omega_3 \frac{\sum_{m=1}^{N_m} \sum_{r=1}^{N_r} \sum_{t=1}^{N_t} ETS_{p,r,m,t}}{N_m N_r} \right\}$$

(Eq. 3)

where indices ψ, r, m, d_m refer to field, region, month and day of month m while N_ψ, N_r, N_m, refer to their upper limit numbers of 21, 6, 12, respectively, and Nd_m that stands for the number of days per month, takes the values 31, 30 and 28 depending on the month. $\omega_{\psi=1,\ldots,19}$ stands for user defined weights to meet the expectations of improving specific 19 model variables, namely maximum (*Tmax*) and minimum 2m temperature (*Tmin*); 24h accumulated precipitation (Pr), and sixteen fields provided by soundings, that is: Total column water vapor (*TCWV*); Vector wind shear between the levels of 500mb and 700mb (*WS1*); Vector wind shear between the levels of 700mb and 850mb (*WS2*); Vector wind shear between the levels of 850mb and 1000mb (*WS3*); Temperatures at 500mb (*T500*), 700mb (*T700*) and 850mb (*T850*) respectively; Relative humidity at 500mb (*RH500*), 700mb (*RH700*) and 850mb *RH850*) respectively; East-west wind component at 500mb (*U500*), 700mb (*U700*) and 850mb (*U850*) respectively; South-north wind component at 500mb (*V500*), 700mb (*V700*) and 850mb (*V850*). These weights are introduced heuristically with $\omega_{\psi=1}$ standing for ω_{Tmax}, $\omega_{\psi=2}$ standing for ω_{Tmin}, $\omega_{\psi=3}$ standing for ω_{pr}, etc. Index p denotes the values of the corresponding specific parameter combination, where N_p stands for the number of parameter combinations.

The categorical variable ETS*p,r,m,t* for a particular parameter combination p, region r, month m and threshold index t is defined in Equation 4 as:

$$ETSp,r,m,t{=}\frac{\mathrm{H}-\frac{(H+F)(H+M)}{Ndm}}{\mathrm{H{=}M{+}F}-\frac{(H+F)(H+M)}{Ndm}} \text{ (Eq. 4)}$$

where H refers to the number of *hits* (i.e. both the model and the observations where above the given threshold); F to the number of "*false alarms*" (i.e. only the model or the observations where above the given threshold); M to the number of *misses* (i.e. only the model or the observations forecasted any precipitation) and -1/3 < ETS < 1 (1 considered as best) is the threshold dependent precipitation score while five averaged 24hr-precipitation thresholds of 0.1, 1.0, 3.0, 7.5 and 10.0 meta-model are chosen. Thus, the overall performance score (PS) used by the meta-model is defined as:

$$\mathrm{PS} = \mathrm{S}_{COSI-p}/\mathrm{S}_{COSIref-p} - 1 \text{ (Eq. 5)}$$

where the S$_{COSIref-p}$ is the score for the reference simulation which stands for model simulation where the default values of the parameters are used for the calibration. Therefore, if PS is negative then there is a reduction in the performance however, when PS is positive then there is an improvement in the performance of the model.

Once the meta-model is constructed the parameters space is divided into a large number of points, every point corresponding to a combination of parameters and the score for each of the points is calculated in order to find the optimal parameters combination. In CALMO, three parameters were calibrated by dividing the parameters space into 10000 points, i.e. roughly 21 values for each of the parameters. This was not the case, in CALMO-MAX as the number of calibrated parameters was 5 respectively, yielding about 21^5 ($\sim 10^6$) points to be evaluated in the optimization process through the direct application of the meta-model. Practically this is a task of prohibitive computational cost. Therefore, an iterative method was developed to overcome that problem via convergence to the optimal parameters' combination. This search is performed using a variation of "*Grid Search*" algorithm (i.e. Smit and Eiben, 2009). For the first iteration only 1000 points are sampled and reveal the optimal region in the N dimensional parameters space where "N" is the number of tuned parameters according to the spread of the optimal 100 combinations.

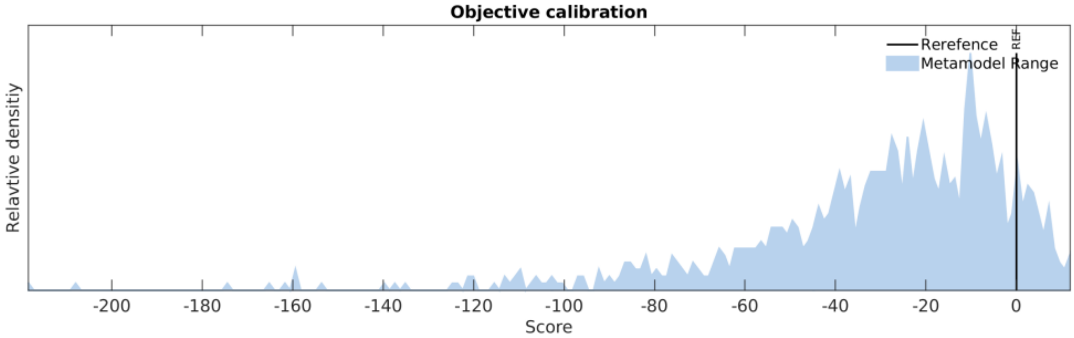

Figure 4: Distribution of the 1000 PS of the 1000 combination in the first iteration.

More specifically in each iteration the existence of a convergence is examined, by analysing the distribution of the performance score. Convergence is considered when the ratio of difference of maximum (Ps_{max}) minus minimum performance PS_{min} to PS_{max} in the specific iteration is defined as in equation 5.

$$(\mathrm{PS}_{max} - \mathrm{PS}_{min}) \;/\; \mathrm{PS}_{max} < 10^{-5} \; (< 10^{-3} \text{ for the Mediterranean}) \; (\text{Eq. } 6)$$

Figure 4, as an example, illustrates the distribution (blue area) of the 1000 PS of the 1000 combination after the first iteration where PSmax =12.4 and PSmin =-219.0. It is evident that the width of the distribution of 1000 combinations is very large as there is big uncertainty on the values of the parameter sets. There is also no convergence while there are also negative PS which indicate a worse performance score related to the one using default parameter values that gives reference simulation, namely PS=0.

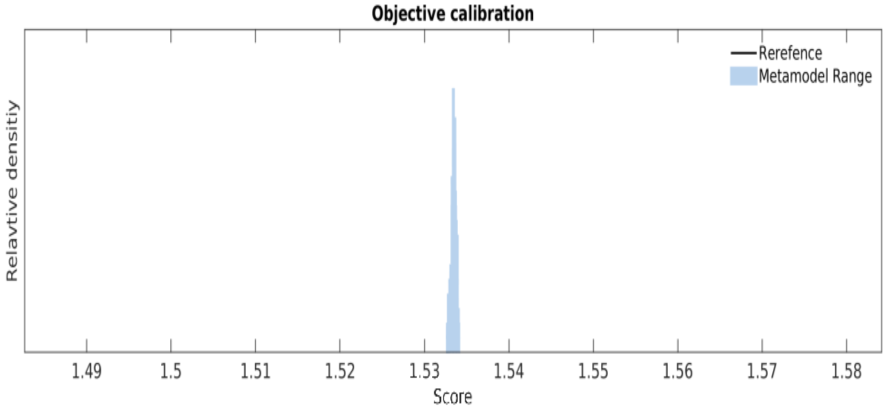

Figure 5: Distribution of 1000 PS for the 1000 combination in the 40^{th} iteration.

Over the second iteration this region is re-sampled by additional 1000 points and a new, smaller, optimal region according to the spread of the new optimal 100 combinations, is evaluated. This iteration process is continued until the solution converges to the optimal parameters' combinations. Roughly 40 iterations as sufficient for convergence to be accomplished and the process has been repeated several times to make certain that convergence led to the same parameters' combinations. This process can also be utilized to estimate the uncertainty of optimal parameters combination via the score sensitivity when slightly changing the parameters values with respect to the optimal parameters' combinations. At each successive iteration, the distribution of scores of the parameters combinations within the chosen region is provided. Every new iteration usually corresponds to better scores distribution. The given distribution is characterized by its worst score. During the iterations process, the iteration for which its worst score is 90% of the optimal one (obtained at the last iteration) is selected. The region (in parameters space) which corresponds to this iteration defines the parameters uncertainty. In case convergence is established before the 40 iterations, then the iteration process is terminated and the optimal values of the parameters are extracted from the last iteration.

In the Mediterranean study, the S$_p$, due to lack of gridded observational data, has been modified as follows:

$$S_p = \frac{1}{N_\Psi}\left\{\frac{1}{N_c}\sum_{\substack{\Psi=1\\ \Psi\neq 5}}^{N_\Psi}\sum_{c=1}^{N_c}\left[1-\frac{\sum\limits_{s=1}^{N_s}\sum\limits_{c=1}^{N_c}\left(F_{p,\Psi,s,d_c}-O_{\Psi,s,d_c}\right)^2}{\sum\limits_{c=1}^{N_c}\sum\limits_{s=1}^{N_s}\left(O_{\Psi,s,d_c-1}-O_{\Psi,s,d_c}\right)^2}\right]+\frac{\sum\limits_{s=1}^{N_s}\sum\limits_{c=1}^{N_c}\sum\limits_{t}^{N_t}ETS_{p,s,c,t}}{N_t}\right\}$$

(Eq. 7)

The letters F and O address forecasted and observed values respectively. Indices ψ, d_c refer to meteorological field, and date of case c while $N_c = 60$ refers to the number of the representative cases considered. $N_\psi = 5$ refers to the number of ψ, $N_s = 87$ refers to the total number of the Greek and Israeli meteorological stations considered (i.e. 22 and 65 respectively) and index p denotes the values of the corresponding specific parameter combination. For index $\psi=5$ referring to precipitation, the equitable threat score (Gilbert skill score) ETS$_{p,s,c,t}$ for a particular parameter combination p, station s, case c and threshold index t (with N_t standing for the number of selected thresholds) is defined as (indices neglected as they are the same),

$$ETS = \frac{h - \frac{(h+f)\ (h+m)}{N_c}}{h+m+f-\frac{(h+f)\ (h+m)}{N_c}} \qquad \text{(Eq. 8)}$$

where h refers to the number of *hits* (i.e. both the model and the observations where above the given threshold); f to the number of "*false alarms*" (i.e. only the model or the observations where above the given threshold); m to the number of *misses* (i.e. only the model or the observations forecasted any precipitation) and $-1/3 < \text{ETS} < 1$ (1 considered as best) is the threshold dependent precipitation score while five averaged 24hr-precipitation thresholds of 0.1, 1.0, 3.0, 7.5 and 10.0 meta-model are chosen. For precipitation, additionally to ETS defined in eq. 7, the more common critical success index threat score (CSITS) is presented, defined as

$$CSITS = \frac{h}{h+m+f} \qquad \text{(Eq. 9)}$$

with h, m, f the number of hits, false alarm and misses.

For better comparisons the relative score $\tilde{S}_p$ is also introduced

$$\tilde{S}_p = \frac{S_p}{S_{p,ref}} - 1 \qquad \text{(Eq. 10)}$$

as the deviation of the ratio of performance score S_p of the modified parameter set and the reference performance score $S_{p,ref}$. Negative values ($\tilde{S}_p < 0$) indicate worse model performance and positive values ($\tilde{S}_p > 0$) indicate better model performance the one regarding the default parameter values (REF simulation). It should be expected that there are numerous parameter combinations which yield better forecasts ($\tilde{S}_p > 0$) than the REF simulation used for the reference data set.

In order to visualize the meta-model calibration process, the five dimensions for the five tuning parameters were split into ten pairs of parameters, which are displayed in Fig. 6a-j. The contour line indicates the deviation of the COSI skill score (Eq.7) from the parameter pair domain average ($S_P - \overline{S_P}$).

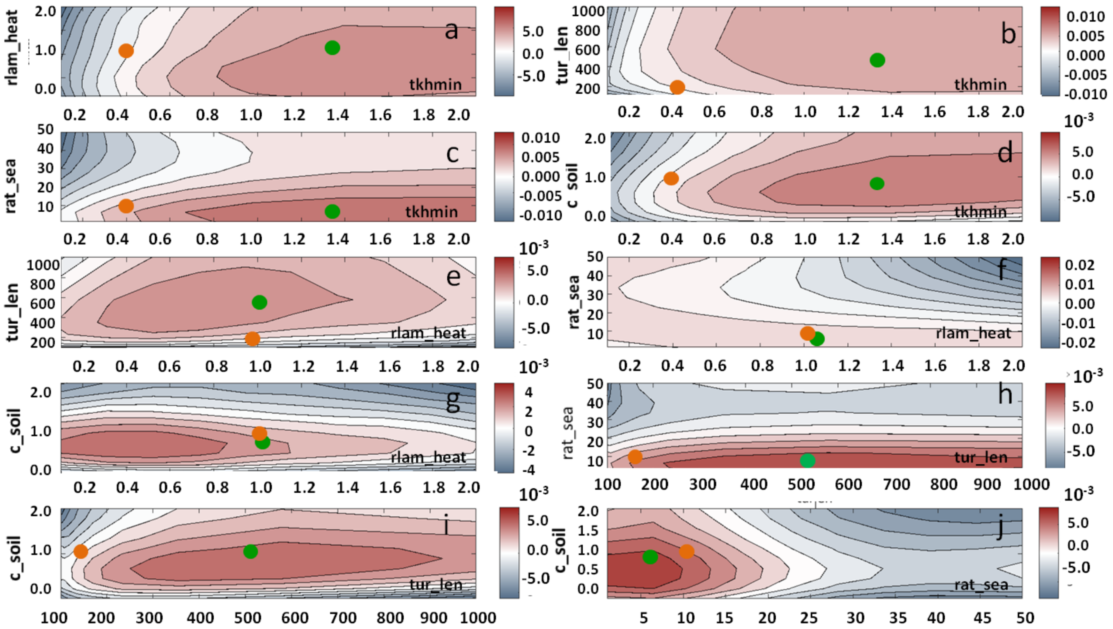

Figure 6: Contour line graphs that show the model performance score ($\tilde{S}_p$) difference from the default values calculated by the meta-model with respect to the five parameter combinations displayed in pairs on their horizontal and vertical axis and over the considered sixty cases from 2019. The green bullets display the optimum parameter values while the orange ones their corresponding default values. In all the graphs the other parameters keep their default values.

The red shades (positive values) refer to parameter combination values calculated by the meta-model of improved performance with respect to the domain average, in contrast to the blue shades (negative values) denote below-average performance, for each pair. The relative position of the green bullets corresponds to the optimum parameter values combinations and the orange ones refer to the default parameter values. It can be seen that in most of the graphs (Fig. 6a, 6b, 6c, 6d, 6h, 6e, 6i) the optimization process results in an improvement since the default values (orange bullets) have a much smaller COSI than the optimum values. The graph in Fig. 6j exhibits a moderate increase of COSI for the optimum rat_sea and c_soil versus the default parameter values. However, the optimization of rat_sea and rlam_heat (Fig. 6f) does not show a significant increase of COSI. The same is shown in the graph for c_soil and rlam_heat (Fig. 6g) which additionally exhibits a parameter region of higher COSI not included in the optimization procedure. It should be mentioned however, that for all graphs, the optimum values (green bullets) were on areas of better COSI (more reddish areas) than the default values (orange bullets).

5 Verification of COSMO-1 calibration (with the contribution of Pirmin Kaufmann)

In this section, results obtained in the framework of CALMO-MAX are presented. The NWP model used is the refactored version of COSMO 5.03, capable of running on GPU-based hardware architectures, operationally used by MeteoSwiss. The MeteoSwiss COSMO-1 configuration at 0.01^o resolution over a domain including the Alpine Arc (in particular the wider area of Switzerland and Northern Italy), shown in Figure 1 above, in hindcast mode has been calibrated. Calibration has been performed for five (5) model parameters shown in Table 1 using a full year statistic, to demonstrate the benefits of the methodology. Simulations have been performed for two independent years. The year 2013 has been chosen as climatologically representative for the target area. A different year i.e. 2017, has also been used to have an independent assessment of the impact of the optimization process.

PARAMETER	ACRONYM	PARAMETER RANGE	OPTIMUM VALUE
Factor for laminar resistance for heat	**rlam_heat**	0.100, ***1.000***, 2.000	0.929
Minimal diffusion coefficient for heat (m^2/s)	**tkhmin**	0.100, ***0.400***, 1.000	0.279
Parameter controlling the vertical variation of critical relative humidity for sub-grid cloud formation	**uc1**	0.0000, ***0.8000***, 1.0000	0.7686
Fraction of cloud water and ice considered by the radiation scheme	**radfac**	0.3000, ***0.6000***, 0.9000	0.6775
Factor for vertical velocity of snow	**v0snow**	10.00, ***20.00***, 30.00	18.95

Table 1: List of the 5 parameters of tested sensitivity based on their interpretation (first column), code names (second column) their test values range (third column) and their optimum values found by the metamodel. The default values are denoted with bold italic characters.

The minimum number of simulations for the 5 parameters, namely 21 model runs to fit the meta-model has been implemented for 2013 to retrieve the optimum set of parameters. It should be noted that although the calibration is performed over the entire year, optimum parameter values are extracted over sets of 10-days periods. An average for these 36 periods is then produced to extract the best optimum parameter set over the entire year. The optimum parameter values extracted as follows: tkhmin = 0.279 (m^2/s), rlam_heat=0.929, v0snow=18.95, rad_fac= 0.6775 and uc1=0.7686. The default parameter values were replaced by these "optimal" values, and model simulations for 2013 have been performed again to investigate the improvement in model performance. Additionally, simulations for 2017 have been performed to examine whether the optimum parameter set, calculated for the year of the calibration, is also beneficial for a different independent year.

Parameter	**T2m (^{o}C)**		**Td (^{o}C)**		**10m Wind Speed (m/s)**	
Measure/Simulation	DEF	BEST	DEF	BEST	DEF	BEST
ME	0.01	0.04	0.06	-0.01	0.13	0.11
RMSE	2.07	2.07	2.31	2.33	1.90	1.90
MINOBS	-30.7		-73.0		0.0	
MINMOD	-28.600	-28.500	-37.480	-38.670	0.007	0.001
MAXOBS	40.80		39.00		46.00	
MAXMOD	42.70	42.60	25.24	25.77	29.00	29.00

Table 2: Statistics of selected meteorological fields for 2013.

The verification of simulations using default parameter values (tkhmin = 0.4 (m^2/s), uc1=0.8, v0snow=20, rad_fac=0.6 and rlam_heat=1) (DEF) against the one using optimum parameter set (BEST) for 2m temperature, dew point temperature and 10m wind speed are presented in Table 2 and Table 3 for 2013 and 2017 respectively, over the entire simulation domain. More specifically, statistical measures such as mean error (ME), root mean square error (RMSE), minimum (MINMOD) and maximum (MAXMOD) model values, minimum (MINOBS) and maximum (MAXOBS) observed values are shown. According to the statistics of Table 2, BEST configuration allows a decrease of dew point temperature and 10 m wind speed for 2013 and 2017, while there is a small increase for 2m temperature in 2013. However, there is an overall balance between the minimum and maximum modelled temperature values compared to the observed ones, that is 0.1 ^{o}C closer to the observed minimum when using default parameter values and equally close to the maximum observed temperature when using the optimum ones. In addition, a comparison of daily cycle (averaged over the entire year and entire model domain) of 2m temperature ME when using the default (blue line) and optimum (red line) parameter values for 2013, is shown in Figure 7. An improvement is evident as there is a decrease in ME of 0.1 ^{o}C during daytime when substituting default parameter values with the optimum ones. The maximum and minimum dew point temperature calculated using the optimum parameter set is closer to the observed ones for 2013 and 2017. A decrease in the ME of the 2m temperature is observed when using the optimized configuration, that is 0.09^{o}C instead of 0.18^{o}C for 2017 as shown in Table 3.

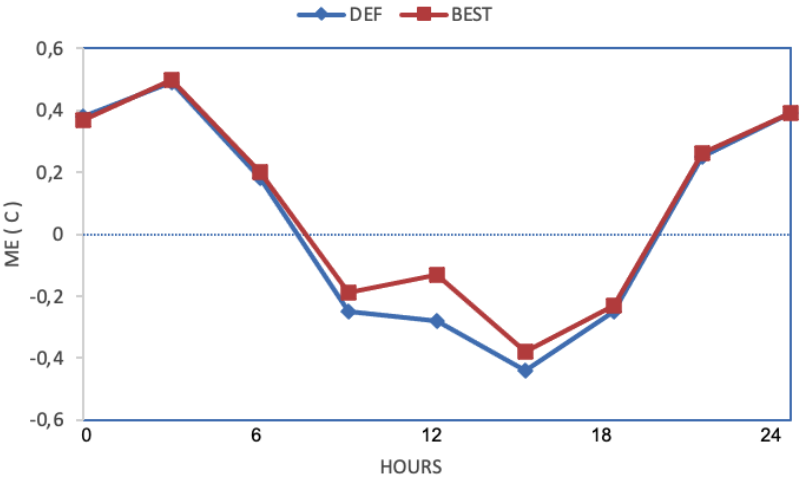

Figure 7: Daily cycle (averaged over the entire year and entire model domain) of 2m temperature of ME when using default (blue line) and optimum (red line) parameter values for 2013.

Parameter	**T2m (^{o}C)**		**Td (^{o}C)**		**10m Wind Speed (m/s)**	
Measure/Simulation	DEF	BEST	DEF	BEST	DEF	BEST
ME	0.18	0.09	-0.029	-0.029	0.115	0.104
RMSE	2.220	2.210	2.370	2.360	1.955	1.954
MINOBS	-29.6		-54.8		0.0	
MINMOD	-30.2000	-30.0000	-44.4100	-45.4700	0.0012	0.0013
MAXOBS	42.0		41.2		40.1	
MAXMOD	44.03	43.38	24,25	25.77	28.19	28.04

Table 3: Statistics of selected meteorological fields for 2017.

This is also the case for 10 m wind speed, with ME equal to 0.104 m/s against 0.115 m/s, while for dew point temperature ME remains stable, and there is also a small improvement of approximately 0.01^{o}C in RMSE of 2m temperature for 2017. Thus, the calibration procedure objectively provides a value of a ‘free’ parameter other than the one subjectively defined by the model developers that gives equally good model results and improves slightly by 1% the model performance.

6 Verification over the Meditterranean

Simulations over Central-Eastern Mediterranean area (Fig. 8) were performed with model version COSMO_5.06 on a 0.03° (∼3.3 km) horizontal grid of 890x487 grid points with 53 vertical levels up to 33 km (Avgoustoglou et al. 2022). The NWP model runs were performed for 42hr periods starting at 00 UTC. A 15 second integration time step was used and the time interval of application of the radiation scheme was 15 minutes. The model was initialized from the 6-hour analysis of the ECMWF operational model (www.ecmwf.int/en/forecasts/datasets /set-i) using a 0.10^0 (∼12Km) horizontal grid. The considered parameter list (Table 4) was assessed due to the rather obvious different climatic characteristics of the considered domain of Greece and Israel that are in the Eastern Mediterranean extra-tropical zone and contain an extensive marine area.

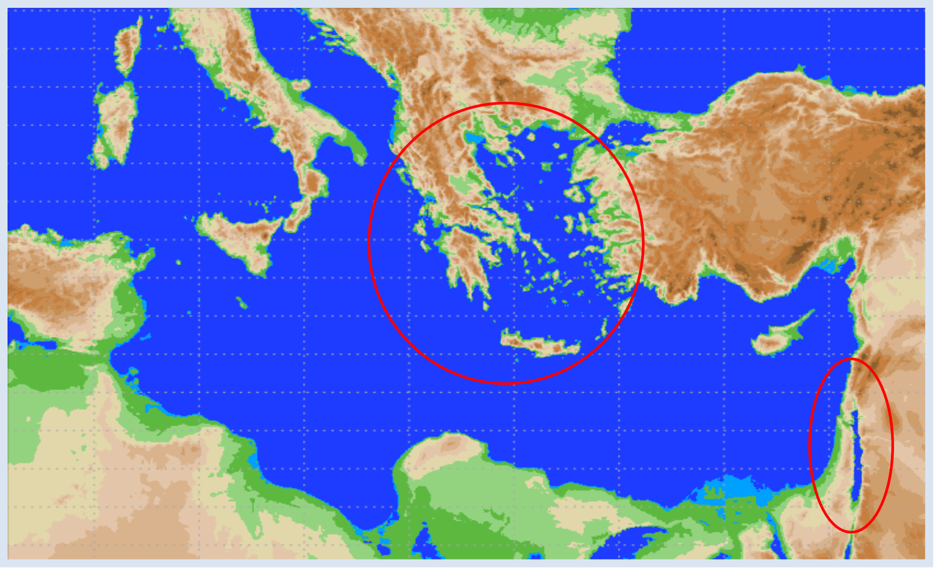

Figure 8: Domain of model runs over the Central-Eastern Mediterranean area along with the approximate areas of station locations.

The simulations for necessary interaction terms of the meta-model are conducted using combinations of minimum and maximum values of a parameter pair. The consensus was to keep the analysis at its most economical cost and to increase the number of simulations in case no optimization could be demonstrated. In this study such an extension turned out not to be necessary.

Two groups of 60 days in the year 2019 were considered with 5 days from each month of the year in each group to account for the seasonal variability. All dates were selected randomly and not necessarily continuous providing a quite reliable and consistent evaluation covering half of the year 2019. The first group is referred as *representative* cases and the second group as *test* cases. In this study the choice of the parameter pairs for interaction terms was decided with respect to their domain-averaged differences considering all 60 representative cases. For the accumulated precipitation and the maximum 2- meter temperature the averages were taken for the last 42^{nd} hour forecast while the minimum 2-meter temperature was taken for the 36^{th} hour forecast of the model run.

These times refer to the 18^{th} and the 6^{th} hour of the second day from the start of the 42hr model runs and the areal averages for the minimum and maximum parameter values are expected to display the most distinguished differences among them. For example, the interaction term with maximum rat_sea=50.0 and minimum rlam_heat=0.1 was decided as these columns displayed a relatively sizable difference regarding the accumulated precipitation. Thus, it is expected to be a lot of model sensitivity to the simultaneous change of this pair of parameters.

Following the methodology developed in CALMO, the meta-model was constructed using the above-mentioned simulations. The optimum parameter set is the one, which has the highest *performance score* (S_p). The optimum 100 parameter combinations have practically converged to the value of 0.067 meaning an improved model performance of 6.7% with respect to the default values.

PARAMETER	ACRONYM	PARAMETER RANGE	OPTIMUM VALUE
surface area index of evaporative soil	**c_soil**	0, ***1***, 2	0.825
ratio of laminar scaling factors for heat over sea	**rat_sea**	1, ***10***, 50	5.288
scaling factor of the laminar boundary layer for heat	**rlam_heat**	0.1, ***1.0***, 2.0	1.049
minimum value of diffusion coefficients for heat and momentum (both are kept equal)	**tkhmin tkmmin**	0.1, ***0.4***, 2.0	1.356
asymptotic maximum turbulent length scale (m)	**tur_len**	100, ***150***, 1000	524.66

Table 4: List of the 5 parameters of tested sensitivity based on their interpretation (first column), code names (second column) their test values range (third column) and their optimum values found by the metamodel. The default values are denoted with bold characters in the third column.

The methodology was validated by comparison of model results with observations of standard meteorological fields using the 87 meteorological stations (22 in Greece and 65 in Israel) already used for model parameter optimization. The stations are located within the red circles shown in Figure 8. In the optimization process each station has same weight. Thus, the difference in station density between the two countries might have a significant impact on the results found. We investigated this potential effect and conducted an additional run of meta-model using 22 Greek stations and 22 Israeli stations, randomly chosen from the available 65. It was found that the optimized parameter values as well as the model performance improvement were essentially the same. Thus, all 87 stations were used in the subsequent analysis.

For verification we compared the simulation results for the 120 cases (representative plus test) using default and optimum values of the model parameters with observations. The evaluation of model performance scores for optimum and default parameter values revealed an increase of the performance scores for the representative cases, also used for model parameter optimization, and the test cases of 6.7% and 4.53% respectively. We found an improvement of the mean values by usage of the optimum parameter set both for the representative and test cases and for all the meteorological fields considered but for minimum dew point temperature (TDMIN) where the default slightly preponderates. Total precipitation (TOT_PREC) exhibits an underestimation of observed mean precipitation both for the optimum and default runs against observations. For the representative cases the optimum and default average values are correspondingly 1.17 mm/day and 1.05 mm/day meta-model compared to the observed 1.57 mm/day meta-model while for the test cases the optimum and default average values are correspondingly 1.19 mm/day and 1.07 mm/day meta-model compared to the observed 1.43 mm/day meta-model. Consequently, the optimum parameters reduce the underestimation by approximately 30%.

The daily minimum 2m temperature (TMIN_2m) is slightly overestimated for the optimum and significantly underestimated by the default parameters. For the representative cases the optimum and default average values are correspondingly 15.25 ^{0}C and 14.37 ^{0}C compared to the observed 15.03 ^{0}C while for the test cases the optimum and default average values are correspondingly 14.97 ^{0}C and 14.06 ^{0}C compared to the observed 14.79 ^{0}C. Thus, the bias

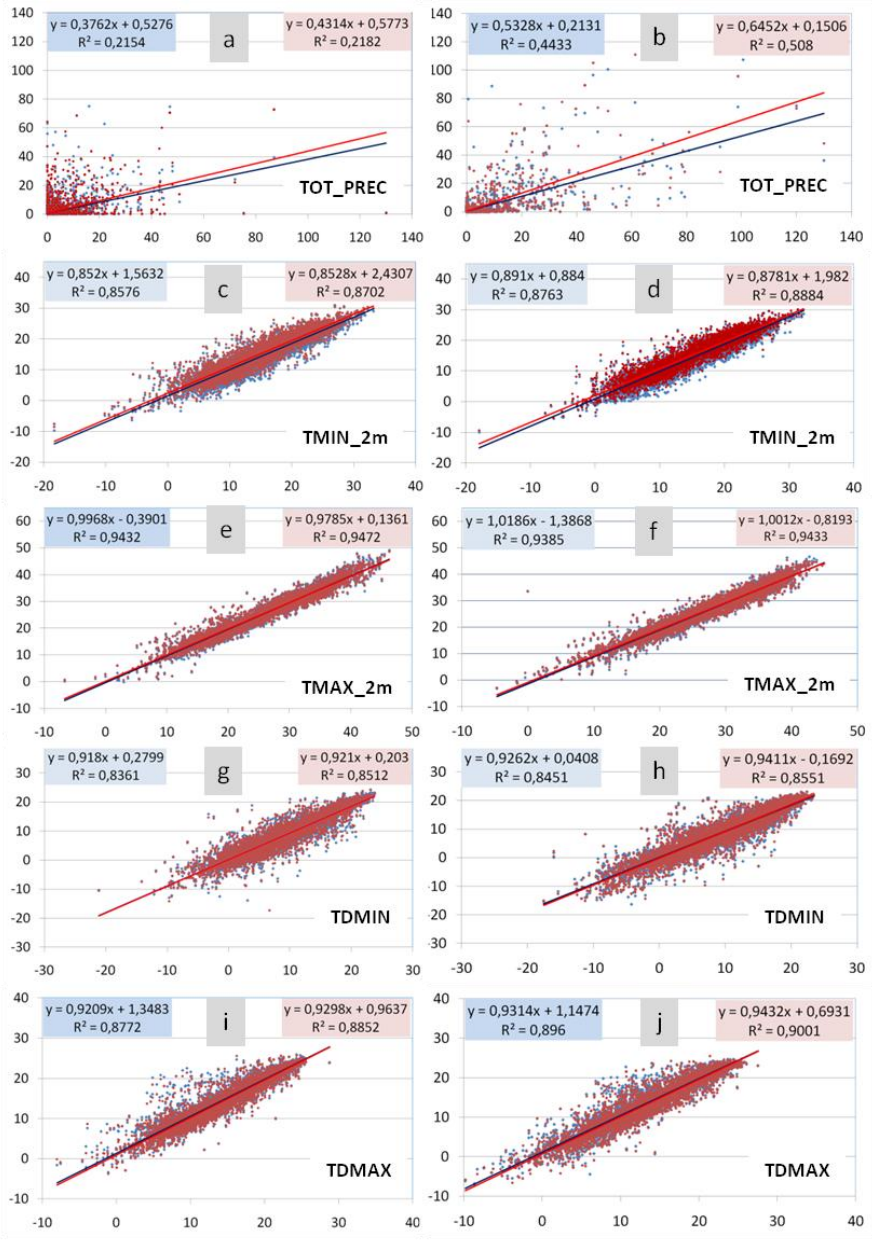

Figure 9: Scatter plots with trend lines and determination coefficients (R2) for TOT_PREC, TMIN_2m, TMAX_2m, TDMIN and TDMAX regarding representative (left column) and test cases (right column). The blue and red colors refer to the default and optimum parameter runs respectively.

for the optimum parameter values is much smaller. The daily maximum 2m temperature (TMAX_2m) is underestimated by 0.5 ^{0}C and 0.9 ^{0}C for the default parameters. This underestimation is slightly reduced by the optimum parameters (0.4 and 0.8 ^{0}C). More explicitly, for the representative cases the optimum and default average values are correspondingly 25.14 ^{0}C and 25.09 ^{0}C compared to the observed 25.56 ^{0}C while for the test cases the optimum and default average values are correspondingly 25.39 ^{0}C and 25.28 ^{0}C compared to the observed 26.18 ^{0}C. In reference to TDMIN, there is a model underestimation both for the optimum and the default against observation, but the default runs perform better here. For the representative cases the optimum and default average values are correspondingly 8.61^{0}C and 8.66 ^{0}C compared to the observed 9.13 ^{0}C while for the test cases the optimum and default average values are correspondingly 8.08 ^{0}C and 8.16 ^{0}C compared to the observed 8.76 ^{0}C. With respect to maximum dew point temperature (TDMAX), there is a model underestimation for the optimum in contrast to an overestimation of the default against observations, however, the optimum runs perform better. For the representative cases the optimum and default average values are correspondingly 14.39 ^{0}C and 14.65 ^{0}C compared to the observed 14.44 ^{0}C while for the test cases the optimum and default average values are correspondingly 14.09 and 14.37 ^{0}C compared to the observed 14.20 ^{0}C. The results indicate an increase of height of the PBL and stronger vertical mixing during day and night. Consistently, the overall improvement is found in the scatter plots shown in Fig. 9. The trend line slopes, and the corresponding determination coefficients (R^2) are closer to one for the optimum parameter runs than for the default parameter runs with exception of the trend line slopes for TMIN_2m for the test cases and TMAX_2m for the representative cases.

7 Conclusions

The implementation and consolidation of an objective calibration method on the fine resolution COSMO model over the MeteoSwiss operational domain and over the Mediterranean Sea region has been examined at the framework of CALMO-MAX project. A limited number of parameters that are associated with the main parameterization schemes affecting turbulence, soil-surface exchange and radiation has been used for the calibration. The impact of the optimization process on 2m temperature, dew point temperature and 10 m wind speed has been investigated not only for the base year of the calibration, but also for a different year to have an independent assessment. Results showed that a slight model performance gain is obtained for both years by using the specific methodology over the MeteoSwiss operational domain. However, there was a pertaining consideration if this technique could be suitable for a more general use, especially over non gridded and sparse observation networks. The results of the calibration effort over the Mediterranean, confirmed the validity of the procedure in a reliable way. An improved COSMO model performance at horizontal resolution of 0.03° was demonstrated over the non gridded observational networks of Greece and Israel together, a challenging endeavor regarding two relatively remote areas also separated by the extensive marine area of eastern Mediterranean. The seasonal variability was addressed over a set of 60 representative cases of nonconsecutive days, 5 for every month of 2019, considerably lowering the computational cost. Upon the application of the meta-model, we found a consistent and significant improvement of model performance by 6.7% on average for the meteorological fields considered i.e. total precipitation as well as daily min/max dry and dew point temperature. The verification of the optimum parameters using an independent set of 42h forecast test cases revealed an improvement of 4.4% and confirmed the results of optimization. It is expected that the application of the meta-model optimization technique can be successful in a variety of other regions and customized applications regarding model calibrations via parameter tuning. It can be also regarded as a very useful innovative technique of model performance improvement in addition to the internal model development through more rigorous analysis and oriented development of physical parameterizations and numerical methods.

Thus, it is evident that this objective calibration methodology has the potential to bring a transformative change to atmospheric model development. More specifically, the developed methodology could be used by any NWP model to define an optimal calibration over the target area of interest, for re-calibration after major model changes (e.g. higher horizontal and/or vertical resolution), for an unbiased assessment of different modules (e.g. parameterization schemes), as well as for optimal perturbation of parameters when run in ensemble mode.

Furthermore, a better understanding of the sensitivity of the model quality associated with a specific parameter value, as provided by the meta-model, could benefit the quantification of the flow-dependent model forecast and clarify the impact of a specific parameter on the overall model performance.

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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.

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No. 10: March 2010.

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COSMO Technical Reports

No. 1: Dmitrii Mironov and Matthias Raschendorfer (2001):
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No. 2: Reinhold Schrodin and Erdmann Heise (2001):
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No. 3: Günther Doms (2001):
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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.

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