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CALMO Progress Report*

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*The Proof of the Parameters Calibration Method:
CALMO Progress Report*

by

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1 Introduction

This report summarizes the work performed so far by Pavel Khain and Itzhak Carmona under the guidance of Antigoni Voudouri (head of the project) and Jean-Marie Bettens, and in collaboration with Euripides Avgoustoglou and Federico Grazzini. The CALMO project is based on the objective calibration method which was developed and implemented in regional climate model by Omar Bellprat and Christoph Schär (ETH). The purpose of the CALMO project is to implement the calibration method of (Bellprat et al., 2012) to NWP model COSMO. This report describes the implementation of the calibration method to COSMO-7km. In summary, the calibration method is the following:

- a Define the parameters for calibration and their allowed ranges. In this work:

$$rlam_heat \in [0.1 \ 1 \ 10] \quad (1)$$

$$tkhmin \in [0 \ 1 \ 2] \quad (2)$$

$$tur_len \in [100 \ 500 \ 10000] \quad (3)$$

$$rat_sea \in [1 \ 20 \ 100] \quad (4)$$

- b Define the forecast fields to be verified (in this work: maximum and minimum 2m-temperatures, 24h accumulated precipitation);
- c Define the time periods for calibration (in this work: 3-20.01.2008 and 2-20.06.2008);
- d Define the parameters (combinations) values for performing the COSMO simulations. In this work the combinations are: the default, maximum and minimum allowed values for each of the parameters (keeping the other 3 default), at least 1 pairwise interaction for every 2 parameters (for example maximum `rlam_heat` and minimum `tur_len`, keeping the other 2 default). The minimum number of simulations to be performed is $2N + 0.5N(N - 1) + 1$, where N is the number of calibrated parameters. **The simulations design, including initial and boundary conditions designs, the extensive scripting environment, and the simulations themselves were performed by Antigoni Voudouri.**
- e After the simulations are performed, the Meta-Model is constructed (see Section 4), i.e. the forecasted fields are interpolated in parameters space via N-dimensional quadratic polynomial (for each field, for each region and each day, separately). These interpolation formulas (the Meta-Models) allow estimating the forecasted field value for arbitrary parameter values (for each region and each day) without performing real COSMO simulation.
- f At the next stage, the parameters space is filled by a large number (in this work 10000) of parameters combinations. For each parameter combination, a forecast field time series is produced (using the Meta-Model), compared with the observations, and evaluated using a performance score (see Section 5).
- g Finally, the parameters combination which obtained the best score is selected (see Sections 6 and 7).
- h In principle, it is reasonable to perform a real COSMO simulation with the selected parameters combination, and verify whether the forecasts are indeed better (than with default parameters combination).

In order the calibration method to work, one first has to select the parameters which are the **most significant for the verified fields**. For example, for the maximum 2m-temperature we may need to focus on soil and radiation schemes parameters, while for precipitation, we may need to consider also microphysical parameters, etc. Therefore, in Sections 2 and 3 we first analyze the sensitivity of the verified fields to the chosen parameters. Generally, the sensitivity was found to be relatively small, meaning that at the next stage of the CALMO project we will have to extend the set of calibrated parameters and verified fields. In Sections 4-7 we will present the calibration procedure, following the steps e-g above.

As part of the next stage of the CALMO project, it is planned to calibrate parameters from the COSMO soil scheme Terra, for example the hydraulic soil conductivity. The plan is to run the Terra “standalone” (TSA) program (for the default soil parameters, and for any change of soil parameters) prior to running the COSMO model. Section 8 summarizes the work performed so far by the IMS team with the Terra “standalone”.

2 The physically expected sensitivity to the tested parameters

2.1 tur_len

tur_len [m] is l_∞ in Blackadar formula (Blackadar, 1962) for the turbulence length, which is present in the equations for the turbulent coefficients as described, for example, in the COSMO document part II §3.4 (see below).

“...in the present scheme we stipulate the following relation between horizontal and vertical diffusion coefficients in accordance with Schlünzen (1988) and Dunst (1980). The horizontal coefficients are determined from the vertical coefficients by use of an anisotropy factor considering the aspect ratio between horizontal and vertical mesh width:

$$K_{m,h}^H = r \frac{\sqrt{(a \cos \varphi \Delta \lambda)^2 + (a \Delta \varphi)^2}}{\Delta z} K_{m,h}^V \approx r \frac{\sqrt{2} \Delta}{\Delta z} K_{m,h}^V \quad (5)$$

Tentatively, we assume $r = 0.1$, and $\Delta \approx 2.8 \text{ km}$. In particular, we have assumed the ratio between horizontal and vertical coefficients to be independent of stability. To determine the horizontal from the vertical coefficients from this relation the vertical coefficient is specified after Prandtl and Kolmogorov as follows:

$$K_m^V = \phi_m l(\bar{e})^{1/2}, K_h^V = \phi_h l(\bar{e})^{1/2} \quad (6)$$

Here, the length scale l is adopted from Blackadar (1962) as a height-dependent scale of turbulence

$$l = \frac{\kappa z}{(1 + \frac{\kappa z}{l_\infty})} \quad (7)$$

Apart from the still undetermined factors ϕ_m and ϕ_h , which are thought to be stability-dependent, we need the determination of TKE

$$\bar{e} = \frac{1}{2} \overline{(u'_i u'_i)} \quad (8)$$

...”

Meaning: the higher is `tur_len`, the higher are the turbulent coefficients (both vertical and horizontal) in the middle-upper atmospheric levels, and consequently the higher are the turbulent fluxes (mixing) for all the variables and tracers. **Precipitation:** as a result of increasing `tur_len`, the low level mixing ratio (moisture) is transported upward, increasing mixing ratio on the upper levels, leading to larger cloud development and to the increase of precipitation (see for example Helmert et al. (2008)). We expect this precipitation enhancement to be pronounced mainly in **convective** conditions (typical in **summertime** over Switzerland and inland Europe), where increased `tur_len` will lead to increase of convective clouds development. In contrast, in stratiform conditions (more typical in **wintertime** over Switzerland and inland Europe), we expect this effect to be less pronounced. Important to mention, that in coastal areas, for example over Italy (close to relatively warm Mediterranean Sea), since the precipitation is highly convective in winter, we expect high precipitation sensitivity to `tur_len` also in wintertime (and not only in summertime, as in Switzerland). **Max/Min 2m-temperature:** since higher `tur_len` increases the middle-upper levels vertical mixing (of conservative variables, such as virtual temperature) as well as increases the convective circulation, the temperature profile tends to dry-adiabata, leading to **adiabatic heating in the lower atmosphere**, which in turn, is leading to the increase of 2m-temperature, both at day and night. **Important to note:**

- a We would expect the mixing ratio (which is also conservative) to tend to be uniform with height (when increasing `tur_len`), i.e. increasing mixing ratio at upper levels, and decreasing them near surface. As part of the next stage of CALMO project, it is important to verify mixing ratio and the temperature profiles against **sounding** observations. That will prevent choosing wrong `tur_len` values which yield unrealistic profiles, although if improving 2m-temperature forecasts.
- b Under stable conditions, for example during stable nights (fogs, frost on the ground, etc.), we expect that increasing `tur_len` will decrease the stability and eliminate these events.

2.2 tkhmin

Meaning: `tkhmin` [m^2/s] and `tkmmin` [m^2/s] determine the minimum limits for the turbulence coefficients. `tkhmin` presence is evident when the turbulent diffusion coefficients (then the mixing) are small, which occurs in **stable conditions**, at night near the surface, as well as at cold days near the surface (with snow cover for example). Increasing `tkhmin` will keep alive the turbulent kinetic energy at these stable conditions, increasing the mixing and **eliminating the strong inversions**. The expected effect at **stable nights**: increasing the 2m-temperature, i.e. the minimum temperature T_{min} , as well as increasing the small convective cloudiness during these nights. Important to mention, that in order to increase the 2m-humidity during stable night and obtain fog, one should decrease `tkhmin`. The expected effect at **cold days near the surface**: slightly increasing the 2m-temperature, i.e. the maximum temperature T_{max} (the last effect should be seen over Swiss plateau but not over Italy, because the proximity to the warm sea eliminates stable conditions during days). **Topography:** we expect this effect to be pronounced mainly in valleys and flat areas. It should not be important in mountains because the wind shears keep the turbulence alive (and the conditions are never very stable). **Season:** on **winter**, the stable conditions over Swiss plateau are common at nights but also during day time, so we expect the heating effect of `tkhmin` to be important. In contrast, during **summer**, the days are often unstable, and even the nights are not very stable, so we expect that heating effect of `tkhmin` is only slightly important (and only at nights). Fig. 1 (Cerenzia et al., 2014) presents an example

of the evolution of the near surface turbulent coefficient during a period of several days. One can see that it tends to drop below $1 \text{ m}^2/\text{s}$ at nights and mornings. During these periods, tkhmin and tkmmin should play an important role.

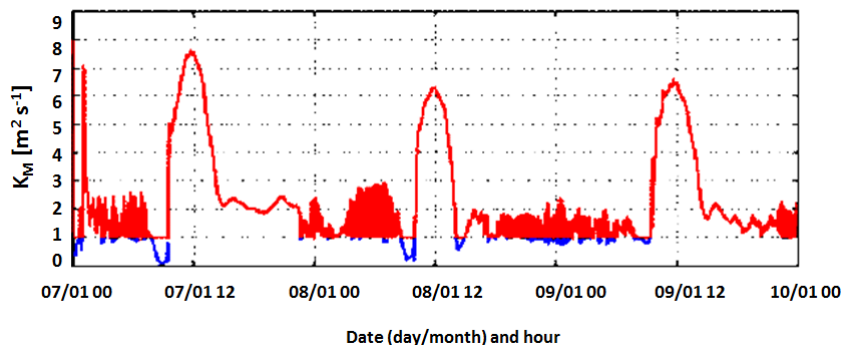


Figure 1: Time series of momentum diffusion coefficient at the lowest model level. Blue segments are the coefficients below the limit $K_M = 1 \text{ m}^2/\text{s}$.

Below we present a citation from Cerenzia et al. (2014) which describes tkhmin effect.

“...Nevertheless, some security limitations are active in order to prevent turbulence to decay. The most documented ones are the minimum limits for the vertical diffusion coefficients of momentum and scalars (namelist parameters tkmmin and tkhmin, see also COSMO User’s Guide (2014)). In principle, they force the system to continue mixing also when the diffusion coefficients would drop below the prescribed minimum values. In the shear driven SBL case study simulated with COSMO Single-Column by Buzzi, the detrimental effect of this measure on the simulation of the SBL structures has been already underlined (Buzzi, 2008). In the same case study, it appears that the largest minimum limit of the diffusion coefficients not altering the SBL representation is $K_{min} = 0.1 \text{ m}^2/\text{s}$, while in current operational setting it is $K_{min} = 1 \text{ m}^2/\text{s}$ (or $0.4 \text{ m}^2/\text{s}$ as recently suggested by DWD in order to avoid the detrimental effect on boundary layer clouds previously mentioned). In weak wind SBL, one can expect an even worse effect on the simulation, given that a stronger stratification should be established. In the case study considered here, the limitation to $K_{min} = 1 \text{ m}^2/\text{s}$ is frequently occurring (Fig. 1)...”

“Another constraint acts on the sum of buoyancy and wind shear forcings in the TKE equation when the Richardson flux number ($Ri_f = -f_h/f_m$) exceeds the critical value Ri_c (equal to 0.19 in operational setting), i.e. in very stable stratification. Essentially in this case the buoyancy term is excluded from the TKE calculation, so that the forcing sum depends only on mechanical forcing (positive definite), then the sum is prevented to become negative. Therefore, states of the system beyond Ri_c are not described by the TKE equation and are brought back to less stable conditions...”

“According to our experience, these limits strongly effect the simulation of the very SBL...”

Note: the parameter `pat_len`, which is *keeping turbulence alive* parameter (of the thermal circulation term `fc` in the equation for TKE), which takes into account the effects of turbulence forcing due to subgrid coherent circulations (like large eddies/convection), has the same effect as tkhmin: increase `pat_len` is equivalent to increase of tkhmin. `pat_len` parameter is highly uncertain, because of the lack of knowledge of this effect. For more information regarding turbulence closure models for SBL see Zilitinkevich S. et al. (2012).

2.3 rlam_heat

Meaning: rlam_heat [no units] is the parameter which linearly determines **the heat resistance length of laminar layer**; so that the higher is rlam_heat the higher is the resistance of laminar layer for heat transfer, and consequently, the lower is the heat transfer between the surface and the lower atmosphere. The vertical description of the transfer layer is illustrated in the following Fig. 2 (Buzzi, 2008):

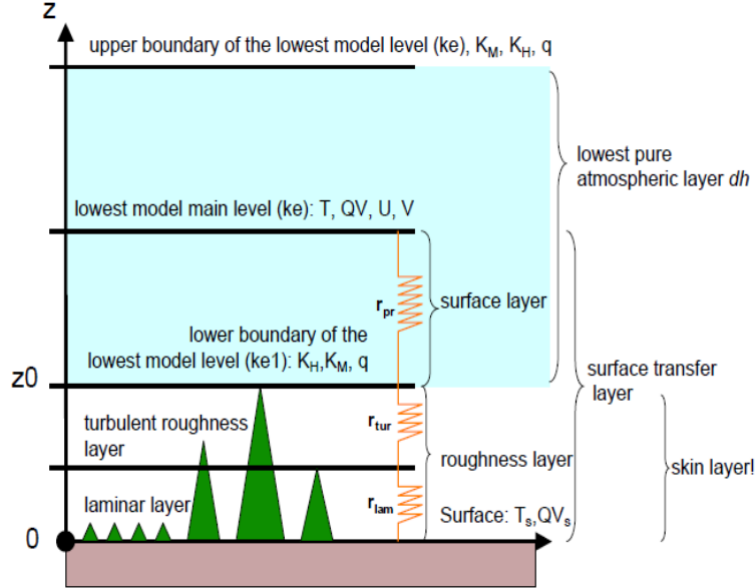


Figure 2: The surface transfer layer and its sub-layers: the surface layer (or Prandtl layer), the turbulent roughness layer and the laminar layer. For each sub-layer transport resistances for vector and scalar quantities are computed. The surface layer extends from the height corresponding to the roughness length Z_0 (level with the index ke1) to the lowest atmospheric main level (level with index ke), where the turbulent diffusion coefficients and all the model variables are known. At the bottom of the surface layer only the turbulence related variables as the diffusion coefficients are known. The roughness layer is placed below the height equal to the roughness length and is treated as a skin layer.

The formula for the heat resistance length of the laminar layer is below (Cerenzia, 2013):

“...momentum and heat resistance lengths for laminar layer are calculated according to:

$$dz_{sg,m} = r_{lam,m} \frac{z_0}{SAI} \quad (9)$$

$$dz_{sg,h} = r_{lam,h} \frac{z_0}{SAI} f_{akt} \frac{K_h con_m}{K_m con_h} \quad (10)$$

where:

- $r_{lam,m}$ and $r_{lam,h}$ are scaling factors set by default respectively to 0 and 1 and modifiable in the namelist,
- z_0 is the roughness length,
- SAI is the Surface Area Index that includes both the transpirant and the non-transpirant surfaces,

- *fakt* is a factor that increases the laminar resistance length in case the gridbox is over water:

$$fakt = 1 + (1 - NINT(fr_{land}))(rat_sea - 1) \quad (11)$$

with fr_{land} the ratio between land and water surfaces in the gridbox and rat_sea a parameter sets to 20 and modifiable by namelist,

- con_m and con_h are respectively the kinematic viscosity and conductivity.

...”

Expected effect: During days with **unstable** conditions and warm surface, typical to summertime days in Switzerland (but also to warm unstable wintertime days, for example in Italy), we expect that increasing $rlam_heat$ will decrease the heat fluxes upward from the warm surface, leading to less effective heating of the lower atmospheric layers, i.e. lower 2m-temperature and **lower Tmax (in summertime)**. In addition, that should cause to slight decrease of instability, which may lead to **decrease in convective precipitation (in summertime)**. During **stable** conditions, with cold surface, typical to wintertime nights, but also to wintertime cold days near the surface, and sometimes to summertime nights, we expect that increasing $rlam_heat$ will decrease the heat runoff from the warm atmosphere to the surface, leading to heating of the lower atmospheric layers, i.e. higher 2m-temperature. That will **increase Tmin at wintertime nights, increase Tmax at wintertime cold-surface days, and sometimes increase Tmin at stable summertime nights.**

2.4 rat_sea

Meaning: rat_sea [no units], has the same effect as $rlam_heat$, but over sea. In equation 10 (Cerenzia, 2013) for the **heat resistance length of laminar layer**, $fakt$ parameter is rat_sea in case of pure sea grid point (according equation 11).

We expect that the effect of rat_sea will be pronounced only over the sea or near sea regions, like Italy, but not over Switzerland. Generally, **the effect of rat_sea over Switzerland should be noisy**. In near coast areas (like in Italy), at wintertime, when the sea is relatively warm, the increase of rat_sea should decrease the temperature and humidity fluxes from the sea, leading to **decrease of precipitation**. In cyclonic situations, these fluxes decrease, may significantly flatten the cyclones. In near coast areas (like in Italy), at summertime, the precipitation is more often developed over the land, so the effect of rat_sea should be less pronounced. **Note:** in near coast areas (like in Italy), the effect of changes in $rlam_heat$ and rat_sea is the same! For example, increasing $rlam_heat$ from 1 to 5 will have the same effect as increasing rat_sea from 20 to 100.

Example for rat_sea effect over the sea (Eastern Mediterranean): In order to check, whether rat_sea parameter is important in regions which are affected by the Mediterranean Sea, a simple experiment was performed for the heavy rain event over the Eastern Mediterranean during 10-14.12.2013.

Fig. 3 shows the 24h accumulated precipitation over Israel for $rat_sea=100$ and Fig. 4 for $rat_sea=1$.

Fig. 5 presents the mean-sea-level pressure (for 11.12.2013 12UTC) over the Eastern Mediterranean for $rat_sea=100$ and Fig. 6 for $rat_sea=1$.

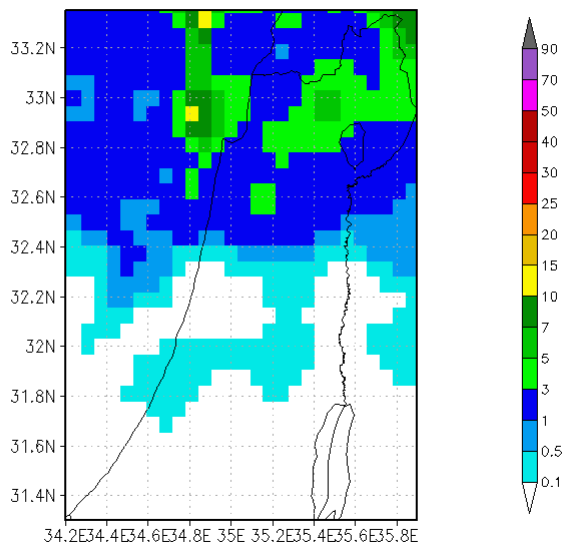


Figure 3: 24h accumulated precipitation over Israel 10.12.2013 for rat_sea=100.

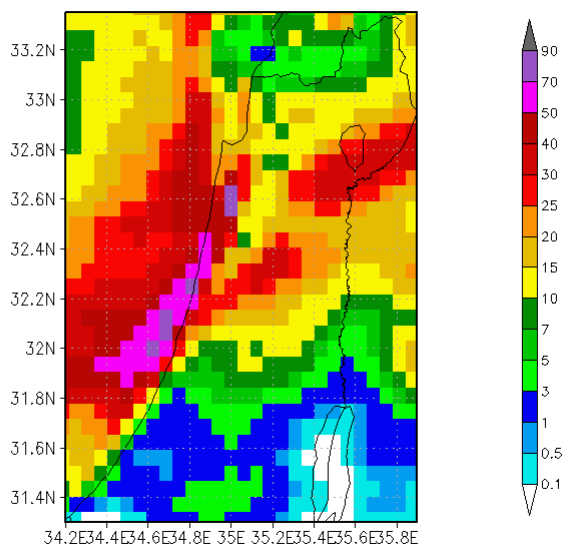


Figure 4: 24h accumulated precipitation over Israel 10.12.2013 for rat_sea=1.

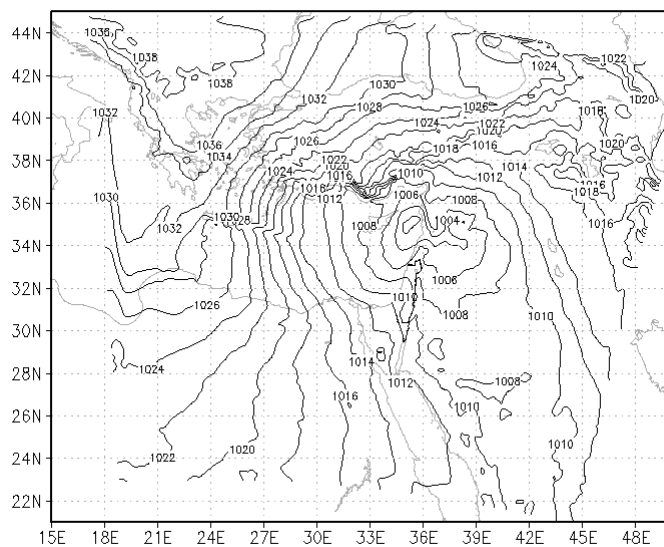


Figure 5: Mean sea level pressure (for 11.12.2013 12UTC) over the Eastern Mediterranean for rat_sea=100.

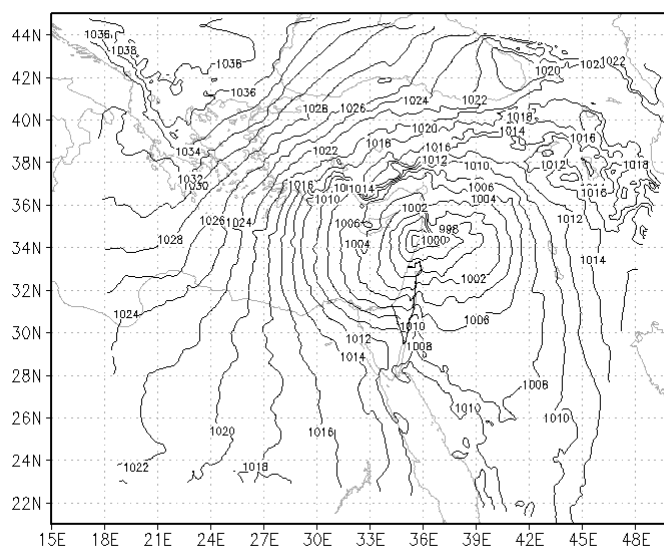


Figure 6: Mean sea level pressure (for 11.12.2013 12UTC) over the Eastern Mediterranean for rat_sea=1.

One can see that in case of $\text{rat_sea}=1$ the cyclone is much deeper and the accumulated precipitation is 10-20 times (!) larger than for $\text{rat_sea}=100$. **Conclusion: in coastal areas the rat_sea parameter might be highly important.**

3 The actual sensitivity to the tested parameters

3.1 Division of Switzerland into three climatically unique areas

In order to identify the general sensitivity of the COSMO forecasts to the parameters variations, there was a need to divide Switzerland area into a small number of climatically unique areas. Previously, Switzerland area was divided into 152 regions, yielding noisy effect of the parameters variations on the COSMO forecast, especially on the precipitation field. Therefore, we have divided Switzerland area into three climatically unique areas, according to Frei (2013), as presented in Fig. 7. The areas were defined as following:

- North - the area to the north of the Alpine crest, mostly coincides with the Swiss Plateau.
- Alps - the area of Alpine crest.
- South - the area to the south of the Alpine crest, mostly coincides with Ticino region.

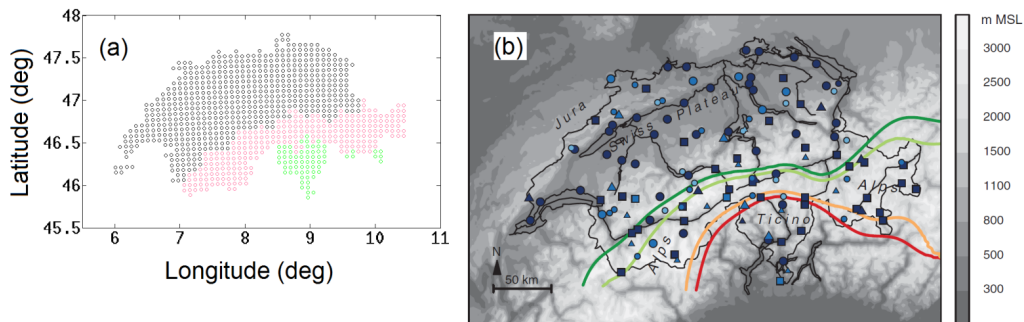


Figure 7: Division of Switzerland into three climatically unique areas, according to Frei (2013). (a) The three areas mapped to the COSMO 7km grid. (b) The original Frei (2013) topographical map. The green and the red lines were used for the areas definition.

3.2 Maximum 2m-temperature (T_{max}) sensitivity

For identifying the general sensitivity of T_{max} to the parameters variations, for each of the 4 parameters, we present 2 time series: for its minimum and maximum allowed values, respectively, while keeping the other parameters at their default values:

- rlam_heat : COSMO simulations LRLAM and HRLAM
- tkhmin : COSMO simulations LTKH and HTKH
- rat_sea : COSMO simulations LRATS and HRATS
- tur_len : COSMO simulations LTURL and HTURL

In addition, we present the time series of REF COSMO simulation (red), where all the 4 parameters keep their default values, and the observations time series OBS (black). As described in the Introduction, we have performed separate analysis for January and June 2008. Figs 8 and 9 present the 10 Tmax time series (described above) for January and June 2008, respectively.

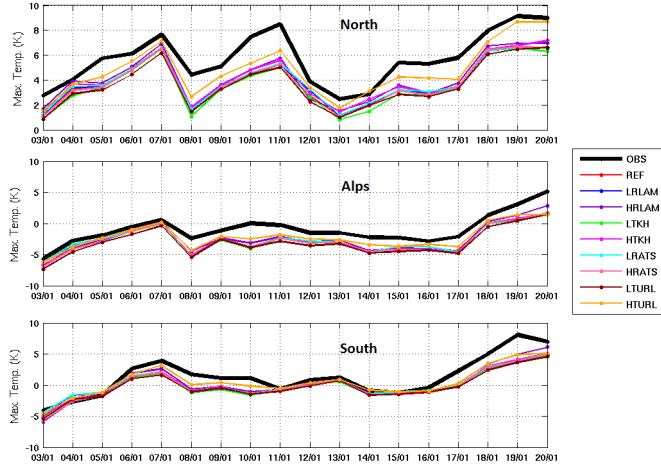


Figure 8: Tmax time series for January 2008, for the observations (black) and nine selected COSMO-7km simulations (colored).

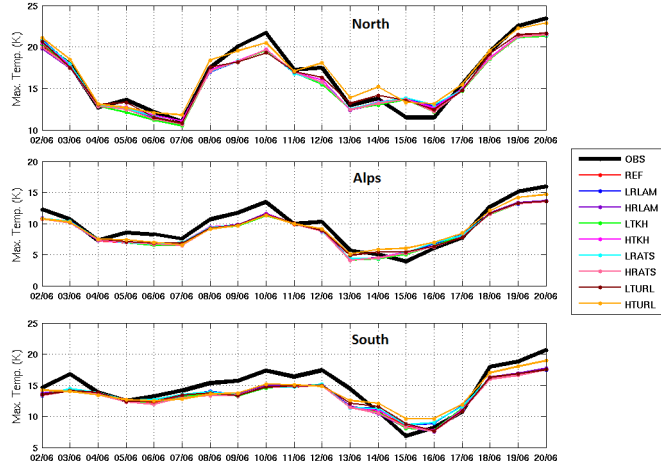


Figure 9: Tmax time series for June 2008, for the observations (black) and nine selected COSMO-7km simulations (colored).

Subtracting the observed Tmax from the simulated, we have constructed Tmax error distributions. Fig. 10 presents the Tmax error distributions for January (a) and June (b) 2008, respectively, for the nine selected COSMO-7km simulations.

In the following, we present typical examples for Tmax sensitivity for the North region

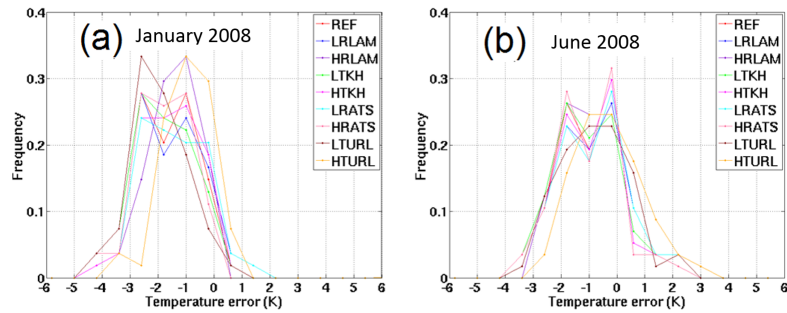


Figure 10: Tmax error distributions for January (a) and June (b) 2008, for the nine selected COSMO-7km simulations.

during different days for the 3 parameters separately (`tur_len`, `rlam_heat` and `tkhmin`; no tests for `rat_sea` due to technical problems). Several additional simulations for intermediate values of each of the parameters were performed. Fig. 11 presents Tmax sensitivity on `tur_len` parameter for 12.01.2008, typical for wintertime (a), and for 10.06.2008, typical for summertime (b), respectively. Fig. 12 presents Tmax sensitivity on `rlam_heat` parameter for 11.01.2008, typical for wintertime (a), and for 03.06.2008, typical for summertime (b), respectively. Fig. 13 presents Tmax sensitivity on `tkhmin` parameter for 11.01.2008, typical for wintertime (a), and for 03.06.2008, typical for summertime (b), respectively.

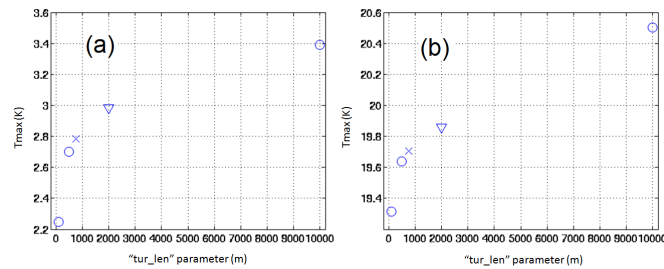


Figure 11: Tmax sensitivity on `tur_len` parameter for region North on 12.01.2008, typical for wintertime (a), and for 10.06.2008, typical for summertime (b), respectively.

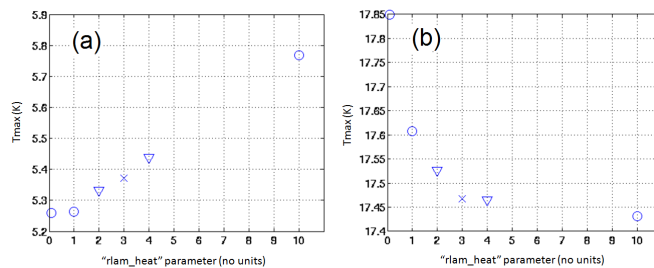


Figure 12: Tmax sensitivity on `rlam_heat` parameter for region North on 11.01.2008, typical for wintertime (a), and for 03.06.2008, typical for summertime (b), respectively.

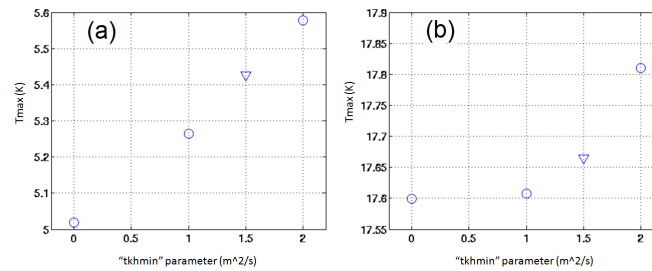


Figure 13: Tmax sensitivity on tkhmin parameter for region North on 11.01.2008, typical for wintertime (a), and for 03.06.2008, typical for summertime (b), respectively.

Conclusions regarding Tmax sensitivity to the 4 parameters variations

- The COSMO simulations of Tmax are generally colder than the observed values (as will be seen from analyzing Tmin in the next Section, the COSMO 2m-temperature day-night amplitude is too low). On January the COSMO underestimation is around 2K and on June around 1K (Figs. 8, 9, 10)
- **Generally, none of the COSMO simulations is warm enough (Figs. 8, 9). Therefore, the CALMO method will not solve the problem of Tmax underestimation using the 4 tested parameters, but only slightly improve the Tmax forecast. In order to solve the Tmax underestimation problem, one should calibrate different COSMO parameters (like soil scheme parameters, radiation scheme parameters, etc.)**
- As expected from the physical meaning of tur_len (see Section 2.1), the higher is tur_len the higher is the 2m-temperature (Figs. 10, 11). The sensitivity is very clear (about 1K) and the noise is low.
- As expected from the physical meaning of rlam_heat (see Section 2.3), the sensitivity of Tmax on rlam_heat depends on the stability conditions at specific day. On cold winter days, the stratification is often stable, so the increase of rlam_heat prevents the heat run-off from the lower atmosphere to the soil, leading to increase of Tmax. That is exactly the case on Fig. 12a. The stable stratification on that day is presented in Fig. 39 in Section 10. On summer days, the profile is often unstable, so the increase of rlam_heat prevents the warm soil to heat the lower atmosphere, leading to decrease of Tmax. That is exactly the case on Fig. 12b. The unstable stratification on that day is presented in Fig. 40 in Section 10.
- As expected from the physical meaning of tkhmin (see Section 2.2), the sensitivity of Tmax on tkhmin depends on the stability conditions at specific day. On cold winter days, the stratification is often stable, then the increase of tkhmin keeps the turbulence alive, leading to increase of Tmax. That is exactly the case on Fig. 13a. The stable stratification on that day is presented in Fig. 39 in Section 10. On summer days, the profile is often unstable, then tkhmin does not play any role, and its effect on Tmax is noisy. That is exactly the case in Fig. 13b. The unstable stratification on that day is presented in Fig. 40 in Section 10.
- It is expected that the effect of rat_sea over Switzerland is noisy. However, for technical reasons the sensitivity checks were not yet performed.

3.3 Minimum 2m-temperature (Tmin) sensitivity

For identifying the general sensitivity of Tmin to the parameters variations, for each of the 4 parameters, we present the same 10 time series, as in Section 3.2 above, both for January and June 2008. Figs. 14 and 15 present the 10 Tmin time series for January and June 2008, respectively.

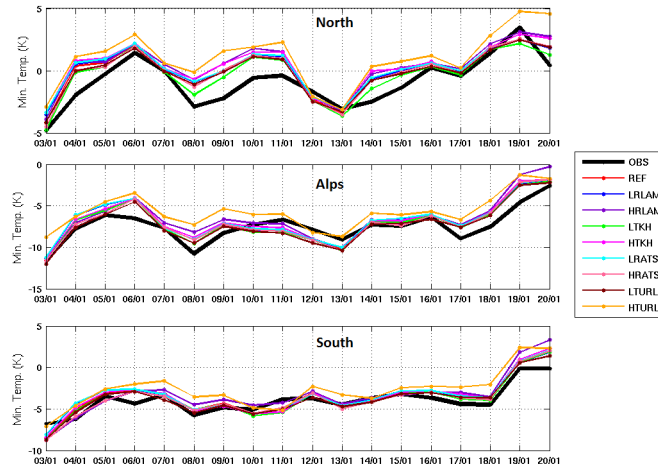


Figure 14: Tmin time series for January 2008, for the observations (black) and nine selected COSMO-7km simulations (colored).

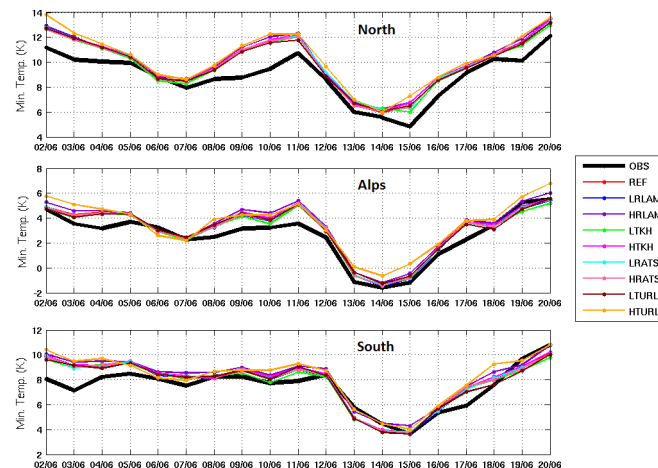


Figure 15: Tmin time series for June 2008, for the observations (black) and nine selected COSMO-7km simulations (colored).

Subtracting the observed Tmin from the simulated, we have constructed Tmin error distributions. Fig. 16 presents the Tmin error distributions for January (a) and June (b) 2008, respectively, for the nine selected COSMO-7km simulations.

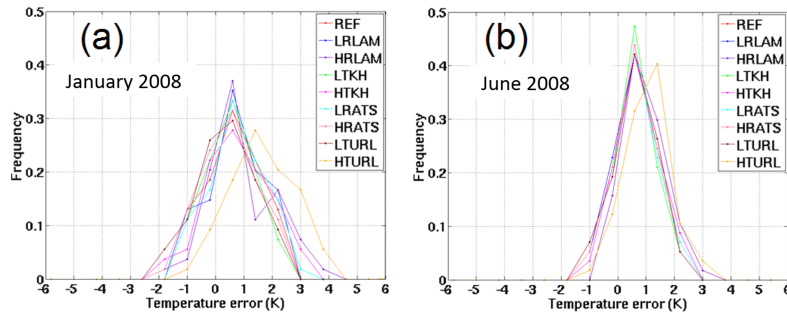


Figure 16: T_{min} error distributions for January (a) and June (b) 2008, for the nine selected COSMO-7km simulations.

In the following, we present typical examples for T_{min} sensitivity for the North region during different days for the 3 parameters separately (tur_len, rlam_heat and tkhmin; no tests for rat_sea due to technical problems). Fig. 17 presents T_{min} sensitivity on tur_len parameter for 11.01.2008, typical for wintertime (a), and for 10.06.2008, typical for summertime (b), respectively. Fig. 18 presents T_{min} sensitivity on rlam_heat parameter for 11.01.2008, typical for wintertime (a), and for 10.06.2008, typical for summertime (b), respectively. Fig. 19 presents T_{min} sensitivity on tkhmin parameter for 11.01.2008, typical for wintertime (a), and for 10.06.2008, typical for summertime (b), respectively.

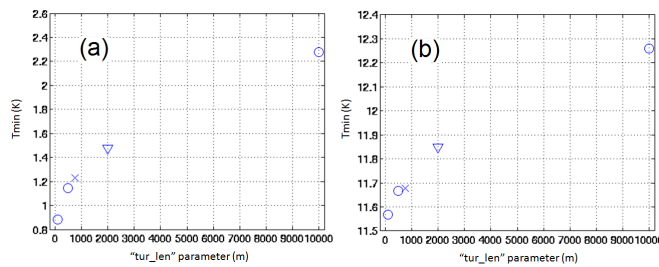


Figure 17: T_{min} sensitivity on tur_len parameter for region North on 11.01.2008, typical for wintertime (a), and for 10.06.2008, typical for summertime (b), respectively.

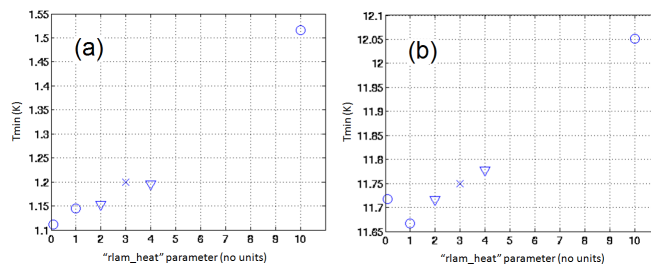


Figure 18: T_{min} sensitivity on rlam_heat parameter for region North on 11.01.2008, typical for wintertime (a), and for 10.06.2008, typical for summertime (b), respectively.

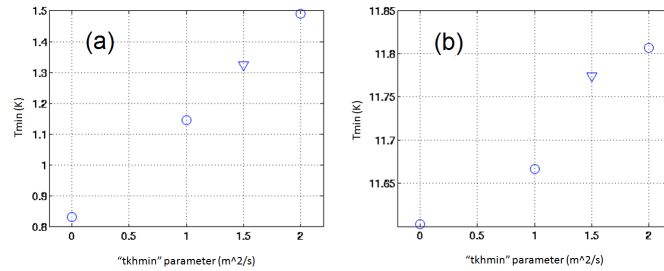


Figure 19: Tmin sensitivity on tkhmin parameter for region North on 11.01.2008, typical for wintertime (a), and for 10.06.2008, typical for summertime (b), respectively.

Conclusions regarding Tmin sensitivity to the 4 parameters variations

- The COSMO simulations of Tmin are generally warmer than the observed values (the COSMO 2m-temperature diurnal amplitude is too low). The COSMO overestimation is around 0.5-1K (Figs. 14, 15, 16).
- **Generally, none of the COSMO simulations is cold enough (Figs. 14, 15). Therefore, the CALMO method will not solve the problem of Tmin overestimation using the 4 tested parameters, but only slightly improve the Tmin forecast. In order to solve the Tmin overestimation problem, one should calibrate different COSMO parameters (like soil scheme parameters, etc.).**
- As expected from the physical meaning of tur_len (see Section 2.1), the higher is tur_len the higher is the 2m-temperature (Figs. 16, 17). The sensitivity is very clear (about 1K) and the noise is low.
- As expected from the physical meaning of rlam_heat (see Section 2.3), the sensitivity of Tmin on rlam_heat depends on the stability conditions at specific night. Generally, on nights the stratification is often stable, so the increase of rlam_heat prevents the heat run-off from the lower atmosphere to the soil, leading to increase of Tmin. That is exactly the case on Figs. 18a, 18b. The stable stratification on these nights is presented in Figs. 39 and 41 in 10, respectively.
- As expected from the physical meaning of tkhmin (see Section 2.2), the sensitivity of Tmin on tkhmin depends on the stability conditions at specific night. Generally, on nights the stratification is often stable, then the increase of tkhmin keeps the turbulence alive, leading to increase of Tmin. That is exactly the case on Figs. 19a, 19b. The stratification on winter night is generally much more stable than on summer night, leading to much larger effect of Tmin on tkhmin (Fig. 19a). The stable stratification on these nights is presented in Figs. 39 and 41 in 10, respectively.
- It is expected that the effect of rat_sea over Switzerland is noisy. However, for technical reasons the sensitivity checks were not yet performed.

3.4 24h accumulated precipitation (Pr) sensitivity

For identifying the general sensitivity of Pr to the parameters variations, for each of the 4 parameters, we present the same 10 time series, as in sections 3.2 and 3.3 above, both for January and June 2008. Figs. 20, 21 present the 10 Pr time series for January and June 2008, respectively.

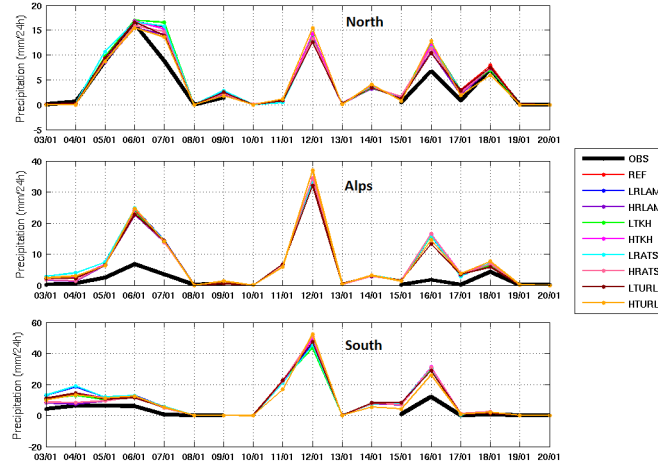


Figure 20: Pr time series for January 2008, for the radar measurements (black) and nine selected COSMO-7km simulations (colored). The period 10.01-14.01 is missing from the radar data.

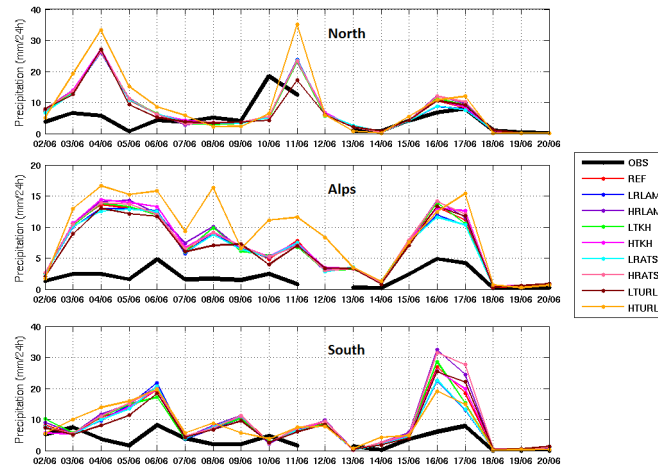


Figure 21: Pr time series for June 2008, for the radar measurements (black) and nine selected COSMO-7km simulations (colored). The day 12.06 is missing from the radar data.

Subtracting the measured Pr from the simulated, we have constructed Pr error distributions. Fig. 22 presents the Pr error distributions for January (a) and June (b) 2008, respectively, for the nine selected COSMO-7km simulations.

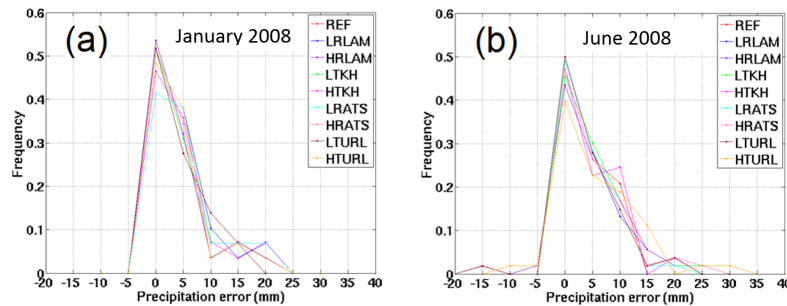


Figure 22: Pr error distributions for January (a) and June (b) 2008, for the nine selected COSMO-7km simulations.

In the following, we present typical examples for Pr sensitivity for the North region during different days for the 3 parameters separately (tur_len, rlam_heat and tkhmin; no tests for rat_sea due to technical problems).

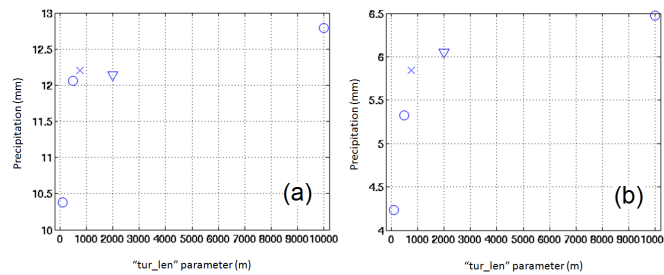


Figure 23: Pr sensitivity on tur_len parameter for region North on 16.01.2008, typical for wintertime (a), and for 10.06.2008, typical for summertime (b), respectively.

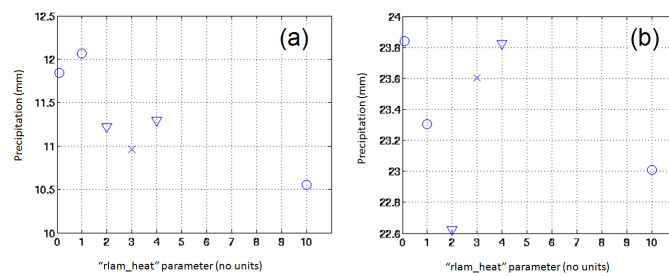


Figure 24: Pr sensitivity on rlam_heat parameter for region North on 16.01.2008, typical for wintertime (a), and for 11.06.2008, typical for summertime (b), respectively.

Fig. 23 presents Pr sensitivity on tur_len parameter for 16.01.2008, typical for wintertime (a), and for 10.06.2008, typical for summertime (b), respectively. Fig. 24 presents Pr sensitivity on rlam_heat parameter for 16.01.2008, typical for wintertime (a), and for 11.06.2008, typical for summertime (b), respectively. Fig. 25 presents Pr sensitivity on tkhmin parameter for 16.01.2008, typical for wintertime (a), and for 11.06.2008, typical for summertime (b), respectively.

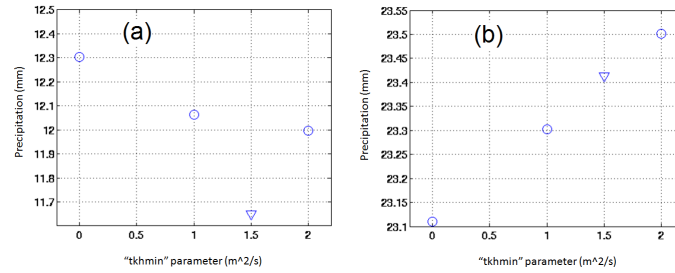


Figure 25: Pr sensitivity on tkhmin parameter for region North on 16.01.2008, typical for wintertime (a), and for 11.06.2008, typical for summertime (b), respectively.

Conclusions about 24h accumulated precipitation sensitivity to the 4 parameters variation

- The COSMO simulations generally overestimate the observed precipitation, especially on summertime (Figs. 20, 21, 22).
- **Generally, none of the COSMO simulations is dry enough (Figs. 20, 21). Therefore, the CALMO method will not solve the problem of precipitation overestimation using the 4 tested parameters, but only slightly improve the precipitation forecast. In order to solve the precipitation overestimation problem, one should calibrate different COSMO parameters (like microphysics scheme parameters, etc.).**
- As expected from the physical meaning of tur_len (see Section 2.1), the higher is tur_len the higher is the convective precipitation (Figs. 21, 22b, 23b). This sensitivity is very clear (up to 30%). However, the stratiform precipitation, more typical to wintertime (over Switzerland) generally exhibits little and noisy effect as function of tur_len (Figs. 20, 22a, 23a).
- As expected from the physical meaning of rlam_heat (see Section 2.3), the sensitivity of precipitation on rlam_heat is generally noisy (Fig. 24). On warm days with convective precipitation, we would expect that increase of rlam_heat will slightly decrease precipitation, but this effect is not presented at the examples above.
- As expected from the physical meaning of tkhmin (see Section 2.2), the sensitivity of precipitation on tkhmin (which is important in very stable conditions) is noisy.
- It is expected that the effect of rat_sea over Switzerland is noisy (in coastal areas like Italy, the effect should be very significant). However, for technical reasons the sensitivity checks were not yet performed.

4 The Meta-Model

In the following, we will focus on the 3 parameters rlam_heat, tkhmin and tur_len (rat_sea will not be used in the Meta-Model due to technical problems). Following the theory of Meta-Model construction (Neelin et al., 2010 and Bellprat et al., 2012), for any parameters combination [rlam_heat, tkhmin, tur_len], for a given day i and a region r , the COSMO field F (in our case Tmax, Tmin or Pr) may be approximated by 3-dimensional polynomial of order 2:

$$F_{i,r} \cong F_{i,r}^d + c_{i,r} + a_{i,r}^{(1)}x_1 + B_{i,r}^{(1,1)}x_1^2 + a_{i,r}^{(2)}x_2 + B_{i,r}^{(2,2)}x_2^2 + a_{i,r}^{(3)}x_3 + B_{i,r}^{(3,3)}x_3^2 + \\ + B_{i,r}^{(1,2)}x_1x_2 + B_{i,r}^{(1,3)}x_1x_3 + B_{i,r}^{(2,3)}x_2x_3 \quad (12)$$

Where:

$$x_1 = \frac{rlam_heat - rlam_heat_d}{rlam_heat_{max} - rlam_heat_{min}}; x_2 = \frac{tkhmin - tkhmin_d}{tkhmin_{max} - tkhmin_{min}}; \quad (13)$$

$$x_3 = \frac{tur_len - tur_len_d}{tur_len_{max} - tur_len_{min}}$$

The index d stands for default. 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 $F_{i,r}^d$. The constants $c_{i,r}, a_{i,r}^{(1,2,3)}, B_{i,r}^{(1,2,3 \times 1,2,3)}$ are obtained using several COSMO simulations, as described in the following. Each simulation (for given parameters values) yields $F_{i,r}$. When sufficient number of simulations is performed, one can interpolate the different known values of $F_{i,r}$ as function of $[x_1, x_2, x_3]$ using the 3D polynomial in eq. (12) above. The sufficient number is $2N + 0.5N(N - 1) + 1$, so that for $N=3$ the sufficient number of simulations to be performed is 10.

Now the question arises: what is the quality of such interpolation? The following factors are important for the interpolation to be realistic (to be able to replace the COSMO simulations):

- The choice of parameters values (combinations) for COSMO simulations should be specific. In this work the **design** is chosen according to Bellprat (2012).
- The default values of the parameters should be located close to the **center of their allowed ranges**. Otherwise, in the empty parameter regions, the parabolic fit will reach very high (or very low) unrealistic peaks. The problem is, that the default values of `rlam_heat` and `tur_len` are significantly shifted from the centers of their allowed ranges: for `rlam_heat`: [0.1 1 10], and for `tur_len`: [100 500 10000]. That problem will be discussed and solved in section 4.1 below.
- The simulated COSMO field $F_{i,r}$ should **not be noisy** as function of the parameters $[x_1, x_2, x_3]$. In other words, the sensitivity of $F_{i,r}$ on $[x_1, x_2, x_3]$ should be higher than the noise level. However, various COSMO fields are noisy for various parameters. That issue will be discussed and solved in section 4.2 below.
- Use as many as possible additional constrain simulations (for additional parameters combinations). The added value of these simulations is discussed in section 4.3 below.

4.1 The Meta-Model: solution to the parabola problem

As mentioned, the default values of the parameters should be located close to the **center of their allowed ranges**. Otherwise, in the empty parameter regions, the parabolic fit will reach very high (or very low) unrealistic peaks. For example, we focus on the `Tmax` dependence on `tur_len` parameter for the North region on 12.01.2008. Fig. 26 presents the parabolic fit (blue dashed line) for 3 `tur_len` values (a) and 4 `tur_len` values (b). One can see that in the empty `tur_len` regions, the parabolic fit reaches very high unrealistic peaks. When adding one more `tur_len` value (b), the fit improves, but still exhibits unrealistically high peak. Our solution to that problem is **fitting the parabola to logarithm of the**

parameter, or more precisely: parabolic fit to $\log(\text{tur_len}/100)$ (instead of to tur_len), and parabolic fit to $\log(\text{rlam_heat} + 1)$ (instead of to rlam_heat). In simple words, logarithm of a parameter brings the far away parameter values closer to the others, eliminating the empty parameter regions, and causing the parabolic fit to be more monotonic. Fig. 26 presents these fits by red solid lines. One can see that these fits are much more reasonable.

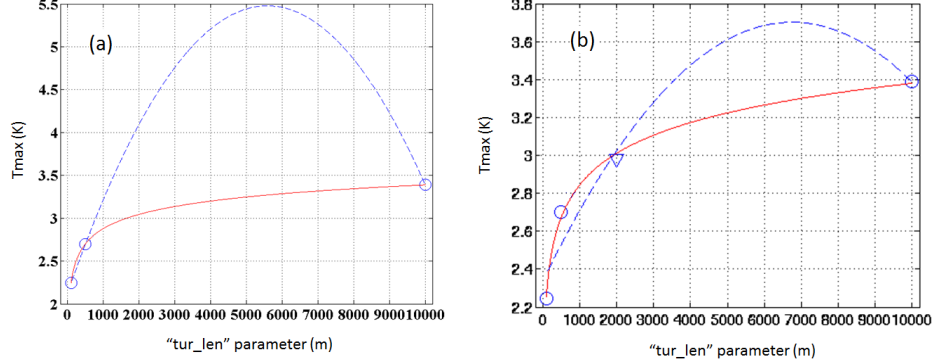


Figure 26: T_{\max} dependence on tur_len parameter for the North region on 12.01.2008. The parabolic fit (blue dashed line) and the parabola of logarithm fit (red solid line) are shown, for 3 tur_len values (a) and 4 tur_len values (b).

Important to mention:

- The exact dependence of the COSMO forecasts on its parameters is generally very complicated and not parabolic. Therefore, the parameter original definition, its logarithm or any other function of the parameter, all have the same "right to exist". So, generally, one may choose any function of the parameter which makes the parabolic fit more reasonable.
- For all the examples presented in Section 3, the parabolic fit to logarithm of the parameter yields much better results (not shown here).
- We do not use logarithm of tkhmin because its default value is located at the center of its allowed range $[0 \ 1 \ 2]$.

4.2 The Meta-Model: solution to the noise problem

The simulated COSMO field $F_{i,r}$ should not be noisy as function of the parameters $[x_1, x_2, x_3]$. In other words, the sensitivity of $F_{i,r}$ on $[x_1, x_2, x_3]$ should be higher than the noise level. However, various COSMO fields are noisy for various parameters as was presented in Sections 2 and 3 above. As mentioned, for a given COSMO field $F_{i,r}$ one has to construct the 3D polynomial interpolation (12) as function of the parameters $[x_1, x_2, x_3]$. However, in case when one (or some) of the parameters yields noisy effect on $F_{i,r}$, for example x_1 , the fit (12) will be problematic for 2 reasons:

- The fit (12) will not represent the true COSMO behavior in x_1 direction.
- The fit is performed using least mean squares method. The attempt to get the best fit in x_1 direction (which is noisy), may spoil the fit quality in the other directions (x_2, x_3), which are not noisy.

Therefore, we have implemented a new approach, which automatically detects the noisy parameter(s) for a given field/day/region, and neglects it (them) in the fitting formula (12).

The following steps are performed automatically:

- For a given field/day/region, a simple parabolic fit is performed (and the correlation R^2 is calculated) to each of the parameters separately.
- In case that R^2 is too low (we chose the threshold of 0.7), the noisy parameter is neglected in the fitting formula (12). For example, if for a given field/day/region, the parabolic fit for x_1 yields $R^2 = 0.4$, the fitting polynomial (12) will be reduced to:

$$F_{i,r} \cong F_{i,r}^d + c_{i,r} + a_{i,r}^{(2)}x_2 + B_{i,r}^{(2,2)}x_2^2 + a_{i,r}^{(3)}x_3 + B_{i,r}^{(3,3)}x_3^2 + B_{i,r}^{(2,3)}x_2x_3 \quad (14)$$

Consequently, the best possible fit will be constructed for each field/day/region. However, it is important to mention, that the effect of neglecting the noisy parameter plays an important role only in case when the response to the parameter variation is high (but noisy). However, usually when the response is high it is not noisy, and vice versa when the response is noisy, it is usually low. Therefore the procedure presented above, will usually play not significant role, but in some rare cases be, in contrast, very important.

4.3 The Meta-Model: additional constrain simulations

As was mentioned previously, the sufficient number of simulations for constructing the Meta-Model using formula (12) is $2N + 0.5N(N - 1) + 1$, so that for $N=3$ the sufficient number of simulations to be performed is 10. However, it is obvious that adding more simulations, i.e. more parameter combinations, will better define the Meta-Model fit (12). According the theory for the parameters combinations design (Neelin et al., 2010 and Bellprat et al., 2012), it is important to perform **more than one interaction simulation** (simulation when 2 parameters are shifted to their minimum or maximum allowed values). For the 3 parameters $rlam_heat \in [0.1 \ 1 \ 10]$, $tkhmin \in [0 \ 1 \ 2]$, $tur_len \in [100 \ 500 \ 10000]$ the sufficient simulations are: [1 1 500], [0.1 1 500], [10 1 500], [1 0 500], [1 2 500], [1 1 100], [1 1 10000]; and 3 interaction simulations: [0.1 0 500], [0.1 1 100], [1 0 100].

In order to demonstrate the importance of additional simulations for the Meta-Model fit quality, Antigoni Voudouri (HNMS) performed also the following simulations:

- 7 additional interaction simulations: [10 2 500], [10 1 10000], [1 2 10000], [0.1 2 500], [10 0 500], [0.1 1 10000], [10 1 100]
- and 4 constrain simulations (changing the value of 1 parameter each time): [2 1 500], [4 1 500], [1 1.5 500], [1 1 2000].

From the simulations above, 2 Meta-Models were constructed. In order to verify their quality, additional test simulation was performed [3 0.5 750], which was not used for the Meta-Model fits. Fig. 27 shows a scatter plot for simulated precipitation (as an example), where each point represents one region at one day for the period 3-20.1.2008. The y-axis shows the Meta-Model estimation minus the reference (simulation with default parameters values), and the x-axis shows the COSMO simulation results minus the reference. In Fig. 27a the Meta-Model was constructed using the minimum number of simulations, while in Fig. 27b, the

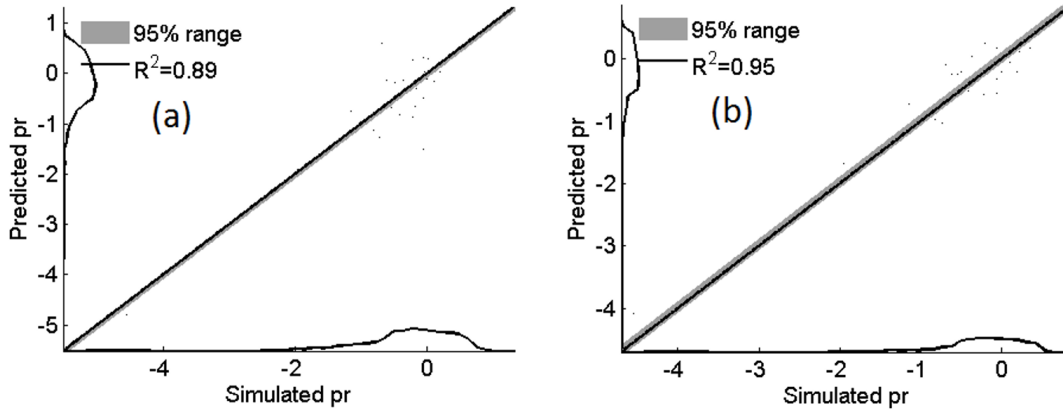


Figure 27: Estimating the Meta-Model quality for reproducing the precipitation field by comparing it with a test COSMO simulation for the period 3-20.1.2008. (a) The Meta-Model was constructed using the minimum number of simulations; (b) the Meta-Model was constructed using additional interaction and constrain simulations. In both axes, the REF simulation values were subtracted.

Meta-Model was constructed using additional simulations, as described above. Comparing the correlations ($R^2 = 0.89$ for case (a) and $R^2 = 0.95$ for case (b)), one can see a clear benefit for the Meta-Model quality when using additional simulations.

5 Performance score

After the Meta-Model is constructed, one has an estimation for the COSMO field $F_{i,r}$ for any day i and region r for any combination of the parameters [rlam_heat, tkhmin, tur_len]. The next step is to find the best parameters combination, i.e. the combination which yields $F_{i,r}$ forecasts which are the closest to the observations. In case only one field is verified, for example Tmax only, the general method is the following:

- Chose one combination of the parameters (here we define the combination index as p).
- Using the Meta-Model, calculate the forecast $F_{i,r}$ for every day and every region.
- Collect the observations $O_{i,r}$ for every day and every region.
- Calculate the RMSE for the given parameters combination:

$$(RMSE)_p = \sqrt{\frac{1}{N_{regs}N_{days}} \sum_{regions} \sum_{days} (F_{p,i,r} - O_{i,r})^2} \quad (15)$$

Where: N_{regs} is the number of regions and N_{days} is the number of days.

- Calculate $(RMSE)_p$ for large number of parameters combinations (10000 in this report).
- Among all $(RMSE)_p$, find the parameters [rlam_heat, tkhmin, tur_len] combination which yields the minimal $(RMSE)_p$.

5.1 Normalization

The calculation presented above is not normalized, and therefore does not tell the whole story. The quality of COSMO forecast strongly depends on the region and the season. For example, the forecast with Tmax error of 5K in the Alps at winter may be actually better than with error of 3K in the Swiss Plateau at summer. Therefore one needs to normalize the forecast errors by a value which reflects the forecast complexity for a given day and region. However this value should not be dependent on any parameters combination, so normalization by typical forecast error is not appropriate. Therefore, we propose to normalize the forecast errors by the observations standard deviation σ_r at a given region r over a period of about a month (the period should not be too short in order to contain large enough sample, but not too long in order to represent the variability of a specific season):

$$\sigma_r = \sqrt{\frac{1}{N_{days}} \sum_{days} (O_{i,r} - \bar{O}_{i,r})^2} \quad (16)$$

Internal COSMO variability

There is an option to normalize also by internal COSMO variability adding it to σ_r (eq. 16 above). The COSMO forecast depends on the initial conditions, so that in principle, slightly different initial conditions may slightly change the forecast. Since the initial conditions are not perfectly defined, there is a hidden internal variability in the COSMO forecasts. This internal variability could be revealed by disturbing the initial conditions and calculating the forecasts standard deviation. However, currently this option is not available and is not used in this report.

5.2 Combined score for Tmax, Tmin and Precipitation

The final purpose of the CALMO project is to be able to find the parameters combination which improves the overall COSMO forecast. Therefore, the performance score should combine as many atmospheric fields as possible. Otherwise, there is a danger of choosing parameters combination which improves, for example, Tmax forecasts but spoil other important forecast fields. The first option is to use the following combination:

$$(RMSE)_{p,tot} = \sqrt{\frac{1}{N_{regs}N_{days}} \sum_{regions} \sum_{days} \left[\frac{(F_{Tmax,p,i,r} - O_{Tmax,i,r})^2}{\sigma_{Tmax,r}^2} + \frac{(F_{Tmin,p,i,r} - O_{Tmin,i,r})^2}{\sigma_{Tmin,r}^2} + \frac{(F_{Pr,p,i,r} - O_{Pr,i,r})^2}{\sigma_{Pr,r}^2} \right]} \quad (17)$$

The normalization by σ_r as presented above will cause the Tmax, Tmin and Pr terms to be dimensionless. However, these terms generally will have different weights. Here, there is a possibility for the user, to define these weights, i.e. to define which fields are more important to him to predict correctly. In this report we define the same weights for the 3 fields Tmax, Tmin and Pr. To do so, we normalize each term by its value averaged over all the parameters combinations, i.e.

$$W_F = \frac{1}{N_{comb}} \sum_p \left[\frac{1}{N_{regs}N_{days}} \sum_{regions} \sum_{days} \frac{(F_{p,i,r} - O_{i,r})^2}{\sigma_r^2} \right] \quad (18)$$

where: N_{comb} is the number of parameter combinations (10000 in this report).

Consequently, the final score used in this report is:

$$S_p = \sqrt{\frac{1}{N_{regs}N_{days}} \sum_{regions} \sum_{days} \left[\frac{(F_{Tmax,p,i,r} - O_{Tmax,i,r})^2}{W_{Tmax}\sigma_{Tmax,r}^2} + \frac{(F_{Tmin,p,i,r} - O_{Tmin,i,r})^2}{W_{Tmin}\sigma_{Tmin,r}^2} + \frac{(F_{Pr,p,i,r} - O_{Pr,i,r})^2}{W_{Tmin}\sigma_{Pr,r}^2} \right]} \quad (19)$$

which yields the same weights for the 3 fields Tmax, Tmin and Pr. For convenience, we define additional scores for each of the 3 fields separately:

$$S_{Tmax,p} = \sqrt{\frac{1}{N_{regs}N_{days}} \sum_{regions} \sum_{days} \frac{(F_{Tmax,p,i,r} - O_{Tmax,i,r})^2}{W_{Tmax}\sigma_{Tmax,r}^2}} \quad (20)$$

$$S_{Tmin,p} = \sqrt{\frac{1}{N_{regs}N_{days}} \sum_{regions} \sum_{days} \frac{(F_{Tmin,p,i,r} - O_{Tmin,i,r})^2}{W_{Tmin}\sigma_{Tmin,r}^2}} \quad (21)$$

$$S_{Pr,p} = \sqrt{\frac{1}{N_{regs}N_{days}} \sum_{regions} \sum_{days} \frac{(F_{Pr,p,i,r} - O_{Pr,i,r})^2}{W_{Pr}\sigma_{Pr,r}^2}} \quad (22)$$

The scores 20, 21, 22 will be used in Figs. 33 and 34 in Section 6 below.

At the next stage of the CALMO project we have to reconsider the score for precipitation, since RMSE type score is not optimal for that field. The general direction should be introducing a precipitation scores based of precipitation thresholds, like Fractions Brier Score. In addition, when the additional verified fields will be defined, such as sounding temperature and humidity profiles, we will have to formulate appropriate scores for these fields.

6 Results of parameters calibration

Following the discussion in Section 4, the Meta-Model was constructed for 3 COSMO fields Tmax, Tmin and Pr as function of the parameters [rlam_heat, tkhmin, tur_len], for the periods of 3-20.01.2008 and 2-20.06.2008, separately. In order to verify their quality, additional test simulation was performed [3 0.5 750], which was not used for the Meta-Model fits. Figs. 28 and 29 show scatter plots for simulated Tmax (left panels), Tmin (centered panels) and Pr (right panels), where each point represents one region at one day, for the periods of 3-20.01.2008 and 2-20.06.2008, respectively. The y-axes show the Meta-Model estimation minus the reference (simulation with default parameters values), and the x-axes show the COSMO simulation results minus the reference. For the tested parameter combination, the correlations R^2 between the COSMO forecasts and the Meta-Model estimations are generally high. Consequently, the overall method seems to prove itself: one can use the Meta-Model to reproduce COSMO forecasts for various parameters combinations.

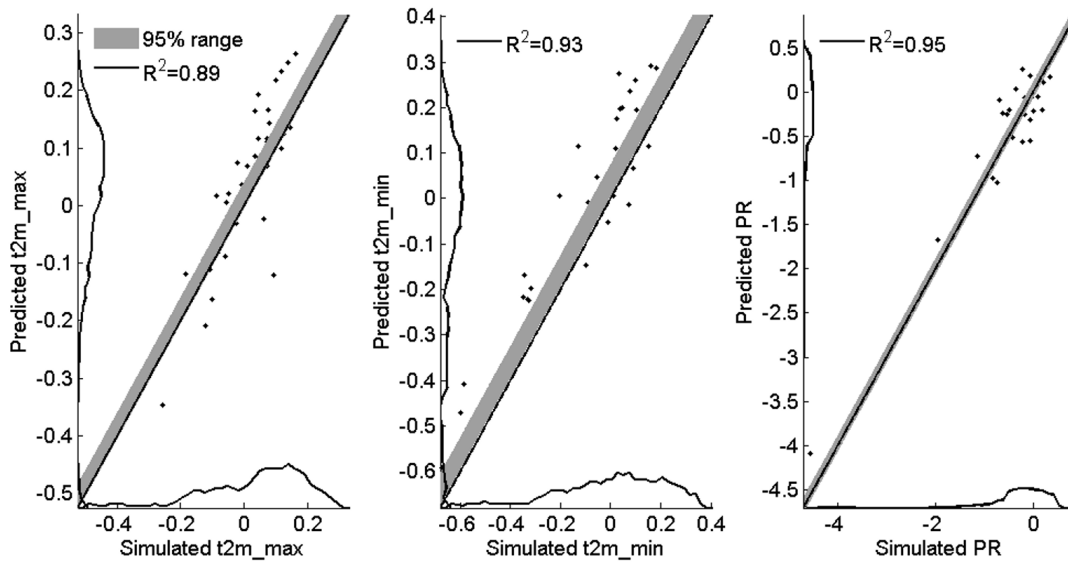


Figure 28: Estimating the Meta-Model quality for reproducing Tmax (left panel), Tmin (centered panel) and Precipitation (right panel) fields, by comparing them with a test COSMO simulation for the period 3-20.1.2008. In both axes, the REF simulation values were subtracted.

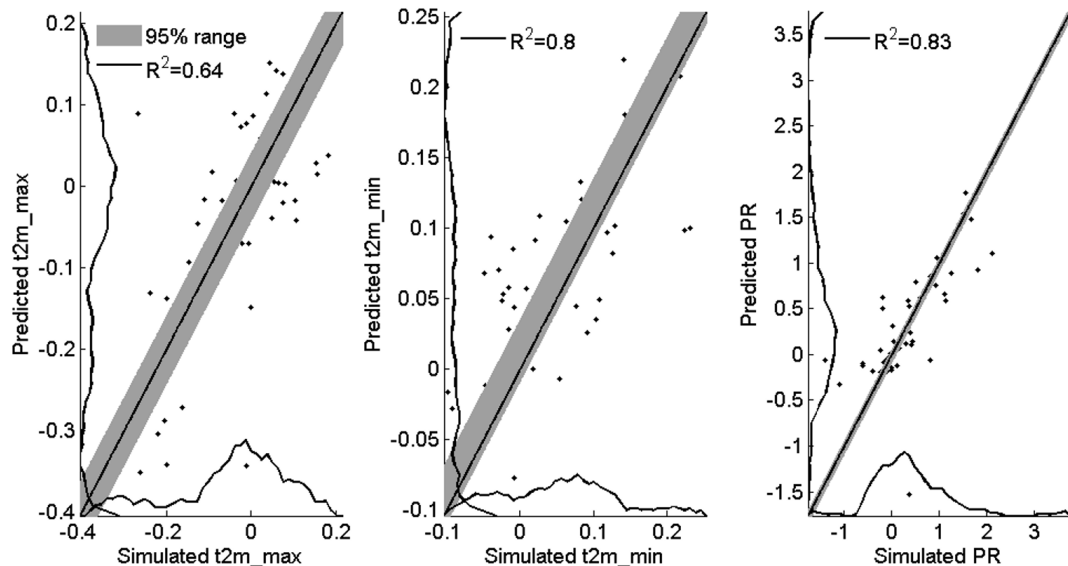


Figure 29: Estimating the Meta-Model quality for reproducing Tmax (left panel), Tmin (centered panel) and Precipitation (right panel) fields, by comparing them with a test COSMO simulation for the period 2-20.6.2008. In both axes, the REF simulation values were subtracted.

In order to analyze the general contributions of the various parameters to the constructed Meta-Model, we have calculated the normalized (by their standard deviation) and averaged (over fields, days and regions) linear, quadratic and interaction coefficients in the formula 12. These contributions are presented in Fig. 30 for the periods 3-20.01.2008 (left panel) and 2-20.06.2008 (right panel), respectively. One can see that generally `tur_len` and `ram_heat` are more dominant in the Meta-Model than `tkhmin`. This result is physically expected, since in contrast to the other parameters, `tkhmin` plays a significant role only in highly stable atmospheric conditions, and therefore is important mainly for `Tmin` but not `Tmax` and precipitation.

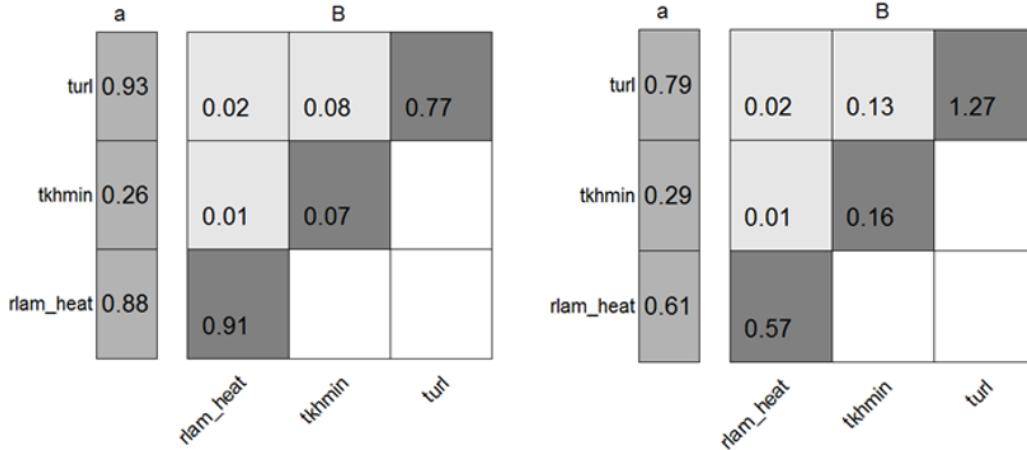


Figure 30: Contributions of the various parameters to the constructed Meta-Model. The presented linear, quadratic and interaction coefficients in the formula 12 were normalized (by their standard deviation) and averaged (over fields, days and regions). These contributions are presented for the periods 3-20.01.2008 (left panel) and 2-20.06.2008 (right panel), respectively.

Following the discussion in Section 5, we have used the Meta-Model to calculate the overall score S_p (see eq. 5.2) for any given parameters combination. Figs. 31 and 32 present the contours of S_p deviation, i.e. $S_p - \bar{S}_p$, for pairwise parameters combinations only, for the periods of 3-20.01.2008 and 2-20.06.2008, respectively. The upper panels represent `ram_heat` and `tkhmin` combinations (while keeping `tur_len` default); the centered panels represent `ram_heat` and `tur_len` combinations (while keeping `tkhmin` default); the lower panels represent `tur_len` and `tkhmin` combinations (while keeping `ram_heat` default). The lower is the S_p deviation value, the better is the score, and the better is the specific parameters combination for the forecast quality. One can see, that for improving the forecast during January 2008 (Fig. 31), the `tur_len` has to be relatively high, `ram_heat` as high as possible, and `tkhmin` as low as possible. On June 2008 (Fig. 32), all the 3 parameters should be as low as possible.

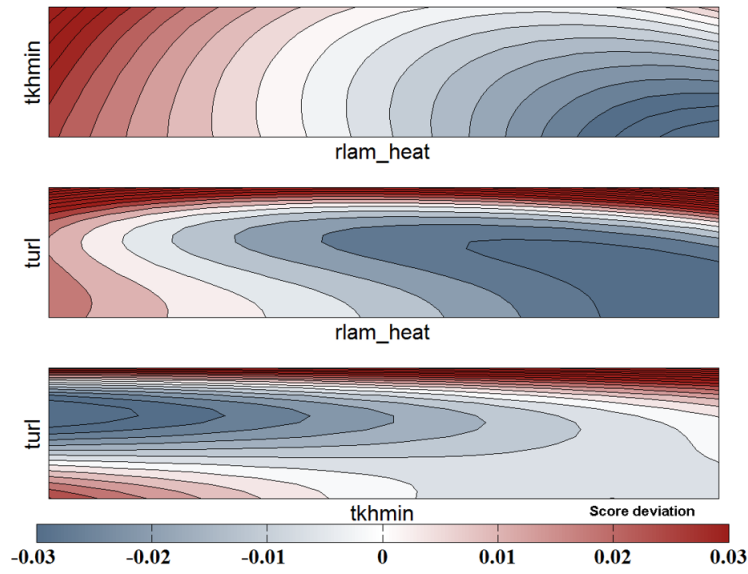


Figure 31: Contours of S_p (see eq. 5.2) deviation, i.e. $S_p - \bar{S}_p$, for pairwise parameters combinations only, for the period of 3-20.01.2008. The upper panel represents $rlam_heat$ and $tkhmin$ combinations (while keeping $turl_len$ default); the centered panel represents $rlam_heat$ and $turl_len$ combinations (while keeping $tkhmin$ default); the lower panel represents $turl_len$ and $tkhmin$ combinations (while keeping $rlam_heat$ default). The lower is the S_p deviation value, the better is the score, and the better is the specific parameters combination.

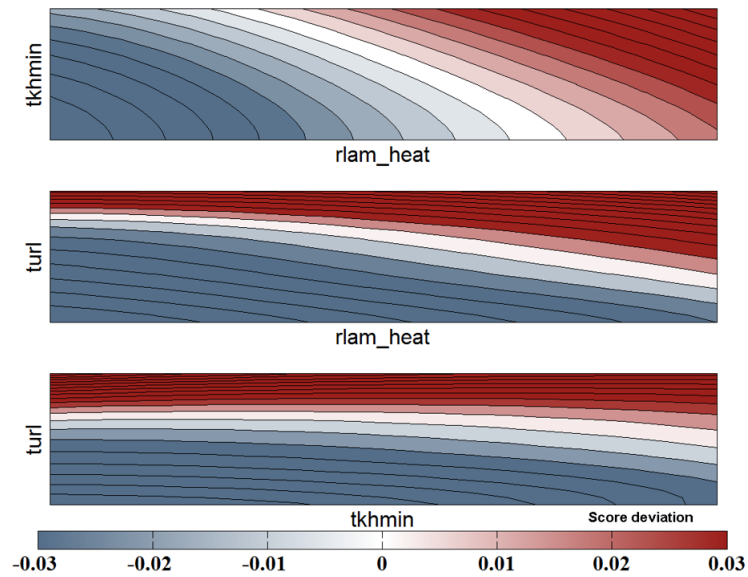


Figure 32: Same as Fig. 31 but for the period of 2-20.06.2008.

In order to analyze the origin of these results, we present similar plots for the 3 fields Tmax, Tmin and Pr, separately, using the scores 20, 21, 22 on Fig. 33 for 3-20.01.2008 and on Fig. 34 for 2-20.06.2008. Starting with the wintertime (3-20.01.2008) presented in Fig. 33, one can see the expected parameters dependencies:

- a As discussed in Section 3.2, COSMO forecasts generally underestimate Tmax, so we expect the scores to be better for higher Tmax forecasts. As discussed in Section 2, higher tur_len, higher tkhmin and higher rlam_heat (on wintertime stable conditions), all lead to higher Tmax forecasts. That explains the results of the left panels on Fig. 33.
- b As discussed in Section 3.3, COSMO forecasts generally overestimate Tmin, so we expect the scores to be better for lower Tmin forecasts, i.e. exactly the opposite of Tmax case. Consequently, lower tur_len, lower tkhmin and lower rlam_heat should lead to better Tmin forecasts. That explains the results of the centered panels on Fig. 33.
- c As discussed in Section 3.4, COSMO forecasts generally overestimate precipitation, so we expect the scores to be better for lower precipitation forecasts. As discussed in Section 2, lower tur_len should decrease precipitation, tkhmin should be not significant, and higher rlam_heat may decrease precipitation (spoiling wintertime stable conditions). That explains the results of the right panels on Fig. 33, where we clearly see the advantage of low tur_len and high rlam_heat.

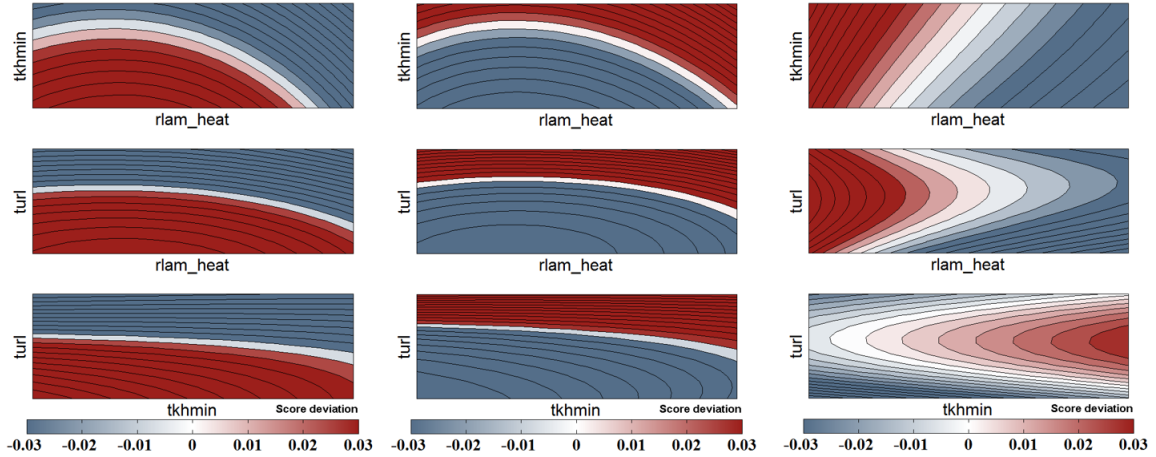


Figure 33: Contours of $S_{T_{max,p}}$ (see eq. 20) deviation (left panels), $S_{T_{min,p}}$ (see eq. 21) deviation (centered panels), and $S_{Pr,p}$ (see eq. 22) deviation (right panels), for pairwise parameters combinations, for the period of 3-20.01.2008. The upper panels represent rlam_heat and tkhmin combinations (while keeping tur_len default); the centered panels represent rlam_heat and tur_len combinations (while keeping tkhmin default); the lower panels represent tur_len and tkhmin combinations (while keeping rlam_heat default). The lower are the scores deviation values, the better is the specific parameters combination for the forecast quality.

For the summertime (2-20.06.2008) presented in Fig. 34, one can again see the expected parameters dependencies:

- d Regarding Tmax and Tmin, the results are generally similar to the wintertime. However, the increase of rlam_heat at summer day, may reduce the low levels heating (by

the warm soil), leading to unwanted decrease in Tmax. That explains the slight difference of the Tmax dependence on rlam_heat between the wintertime (Fig. 33 left panels) and the summertime (Fig. 34 left panels).

- e As discussed in Section 3.4, COSMO summertime forecasts highly overestimate precipitation, so we expect the scores to be better for lower precipitation forecasts. As discussed in Section 2, lower tur_len should highly decrease convective precipitation (typical to summertime), and tkhmin should be not significant. That exactly explains the results of the right panels on Fig. 34, where we clearly see the advantage of low tur_len. However, the low rlam_heat preference, as can be seen on Fig. 34 right panels, is not understood at this stage.

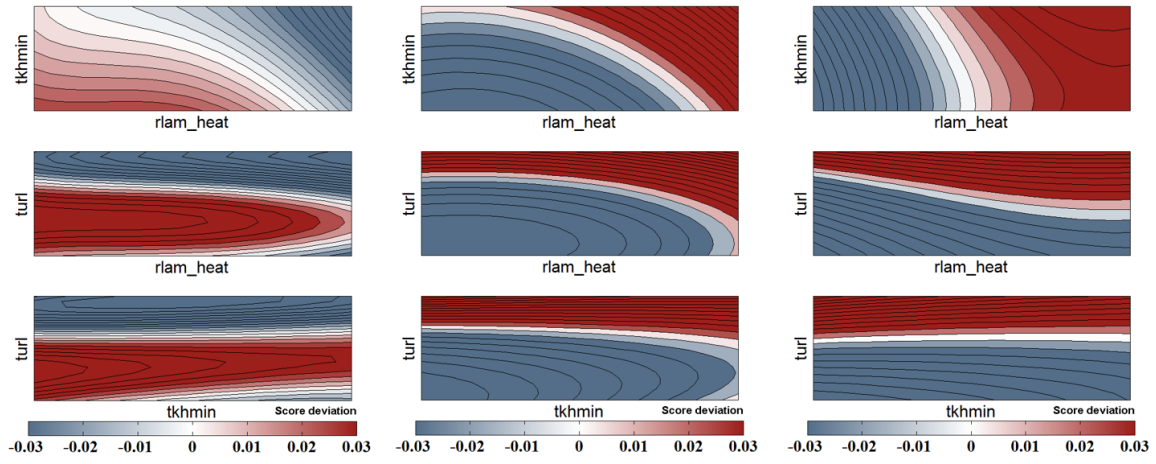


Figure 34: Same as Fig. 33 but for the period of 2-20.06.2008.

At the next stage of the calibration procedure, the S_p scores were calculated for 10000 parameters combinations, filling the parameters space in a Latin Hypercube design (Bellprat et al., 2012). Figs. 35a (for 3-20.01.2008) and 35b (for 2-20.06.2008) present S_p scores distributions, together with the score of the reference (REF) simulation (obtained using default values for all the parameters). For convenience, the distributions are presented as function of $\widetilde{S}_p = 1 - (S_p/S_{p,ref})$, so that:

- $\widetilde{S}_p < 0$ means that the score is worse than of the REF simulation;
- $\widetilde{S}_p = 0$ means that the score is equal to the REF simulation;
- $0 < \widetilde{S}_p < 1$ means that the score is better than of the REF simulation (1 is the best possible score).

One can see that definitely there are parameters combinations which should yield better forecasts than the current default parameter values (REF simulation). On summertime (Fig. 35b), the default parameters combination seems to be already well chosen (on the tail of the scores distribution), so by choosing different parameters combination, we can improve the forecast only slightly. However, on wintertime (Fig. 35a), there is a big range of parameter combinations which would significantly improve the forecast.

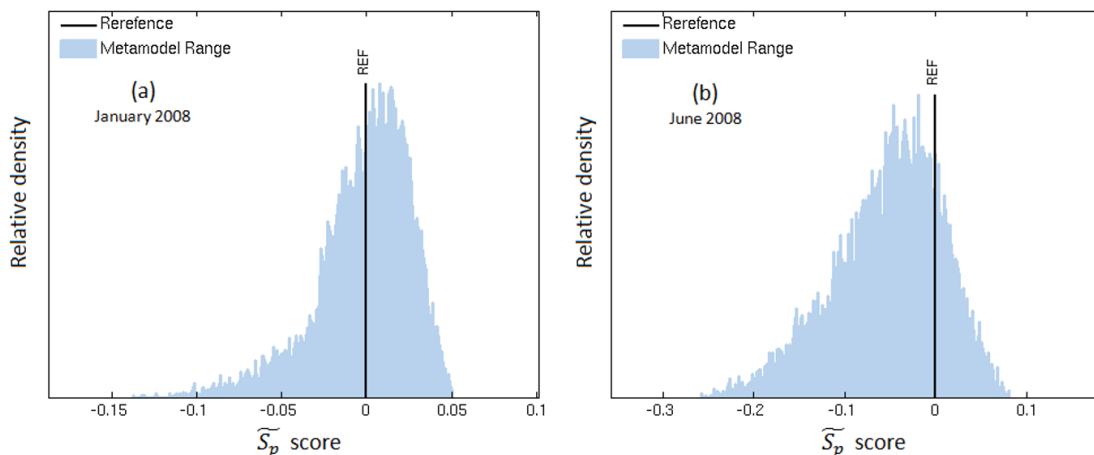


Figure 35: S_p scores distributions (for 10000 parameter combinations), together with the score of the reference (REF) simulation, for the period 3-20.01.2008 (a) and 2-20.06.2008 (b). For convenience, the distributions are presented as function of $\widetilde{S}_p = 1 - (S_p/S_{p,ref})$, so that the higher is $\widetilde{S}_p > 0$ means that the score is better than of the REF simulation.

7 Conclusions and considerations towards the next stage of CALMO project

Finally, the optimal parameters combinations for January and June 2008 were defined, and are presented in Table 1:

	rlam_heat [0.1 1 10]	tkhmin [0 1 2]	tur_len [100 500 10000]
January 2008	8.22	0.02	1037
June 2008	0.17	0.02	102

Table 1: Optimal parameters combinations for January and June 2008.

Antigoni Voudouri performed COSMO simulations with the optimal parameters combinations for January and June 2008. Figs. 36a (for 3-20.01.2008) and 36b (for 2-20.06.2008) present S_p scores distributions, together with the scores of the reference (REF) simulation and of the optimal parameters (Best) simulation.

From Fig. 36, one can see that the Best simulation indeed improved the forecasts comparing to the REF simulation! **This result is very encouraging, showing that the Meta-Model is able to reproduce the COSMO simulations in parameters space, and therefore can be used to calibrate the COSMO model.** It is also interesting, that the COSMO simulation score for the Best simulation is indeed very close to the Best possible score estimated by the Meta-Model. Pirmin Kaufmann (MeteoSwiss) performed the verifications of the optimal parameters simulation in comparison with the REF simulation, using the official MCH procedure. Generally, these verifications also show the advantage of the Best COSMO simulation over the REF simulation. Highlights of these verifications are presented in Section 11.

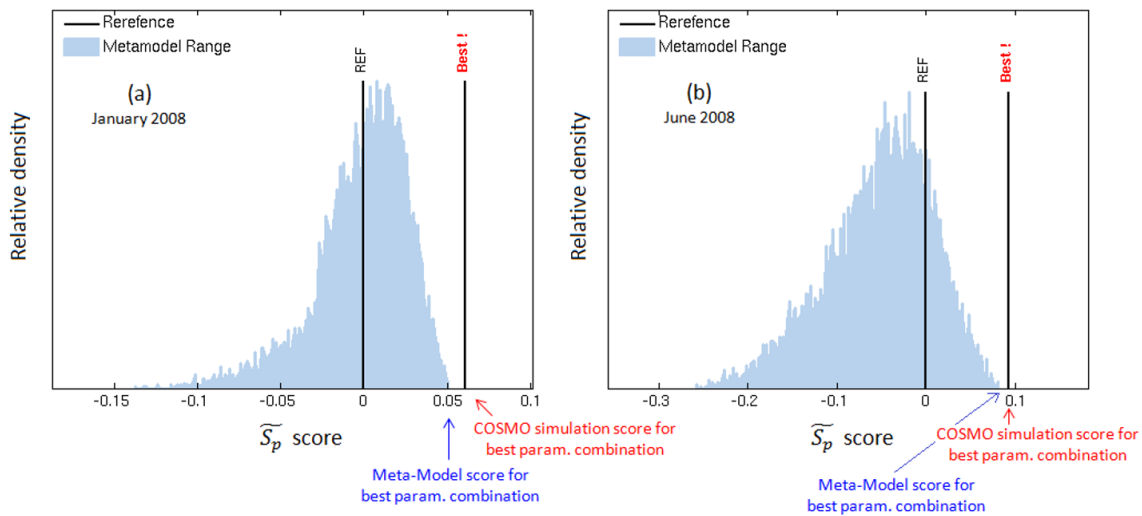


Figure 36: S_p scores distributions (for 10000 parameter combinations), together with the score of the reference (REF) simulation, and the optimal parameters (Best) simulation, for the period 3-20.01.2008 (a) and 2-20.06.2008 (b). For convenience, the distributions are presented as function of $\widetilde{S}_p = 1 - (S_p/S_{p,ref})$, so that the higher is $\widetilde{S}_p > 0$ means that the score is better than of the REF simulation. Best simulation indeed improved the forecasts comparing to the REF simulation!

Considerations towards the next stage of CALMO project

The optimal parameters combinations are very different between January and June 2008, which is generally unwanted. The following actions may improve the results and make them more reliable:

- For each of the verified fields, we have to choose (to calibrate) the **specific parameters which are the most significant for these fields**. For Tmax we may need to focus on soil and radiation schemes parameters, while for precipitation, we may need to consider also microphysical parameters, etc.
- It is important to **extend the set of verified fields** to include sounding profiles of temperature and humidity, integrated water vapor, etc. Otherwise, there is a danger of choosing parameters combination which improves, for example, Tmax forecasts but spoil other important forecast fields.
- It is important to **extend the tested periods** for at least several months. Currently the periods were definitely too short, which makes the results less reliable.
- Presumably, different parameters combinations should improve the COSMO forecast at different seasons (as shown above). Therefore, one could think of possibility to automatically modify the operational COSMO parameters on different seasons (and even for different parts of the domain), however these ideas stand beyond the scope of the CALMO project.

It is however important to mention, that even without performing the steps above, **we showed that the calibration method works and the Meta-Model is generally able to reproduce the COSMO forecasts**. In principle, it is reasonable to perform the COSMO simulation with the selected parameters combination for different periods

(which were not used to construct the Meta-Model), for example January and June but at a different year. That would be a final approval whether the forecasts are indeed better (than with default parameters combination).

8 The Terra standalone (TSA) soil scheme for the CALMO project

As part of the next stage of the CALMO project, it is planned to calibrate parameters from the COSMO soil scheme Terra, for example the hydraulic soil conductivity. In contrast to the regular COSMO parameters, the change in Terra parameters affects the COSMO forecasts with a significant delay (up to several years) via slow adaptation of the soil temperature and moisture profiles. Therefore, in order to calibrate the Terra parameters for specific year (2013 for example), one has to make the parameter changes several years earlier, and run the COSMO model in a cycle, slowly adapting the soil profiles to the parameter change. Moreover, errors in soil profiles caused by interpolation of soil fields from a coarse model disappear slowly, also on the scale of several years. Therefore, in order to obtain appropriate initial conditions in the soil (without interpolation errors), one again has to make the interpolation of soil fields several years earlier, and run the COSMO model in a cycle, slowly “forgetting” the interpolation errors. However, performing several years pre-run of the COSMO model (in a cycle mode) is computationally expensive. Instead, it is decided to use the Terra “standalone” (TSA) program driven by COSMO atmospheric analyses (from MeteoSwiss archive). The method is to initialize soil profiles from a coarse model interpolation, change the parameters of TSA (if needed), and run it for several years (prior to the tested year). Then, the obtained soil profiles will be installed as initial soil conditions for the COSMO model runs (for the tested year). With the great support from Jean-Marie Bettems (MeteoSwiss), Guy de Morsier (MeteoSwiss) and Julian Todter (Frankfurt University), we have run TSA for 3 years (2010-2012) with resolutions of 2.2 and 1.1 km (currently for the default soil parameters configuration), and prepared the soil initial conditions for the COSMO runs at the next stage of the CALMO project.

9 Appendix A: Transform of the 2m-temperature observations to the model grid

The 2m-temperature daily-mean, maximum and minimum observations data over Switzerland was originally transformed to a 2km-grid by C. Frei (MeteoSwiss), following the method described in Frei (2012). This 2km-grid (original grid) has a real (not smoothed) topography. In order to compare the 7km COSMO model results with the observations, one had first to transform the 2m-temperature observations data to the 7km **smoothed** topography grid of the COSMO model (target grid). Following the recommendation of C. Frei, the chosen method was the following:

- a For every grid point in the target grid (red dot on Fig. 37) find the nearest 9 neighbors on the original grid (blue dots on Fig. 37).
- b Plot the 2m-temperature values of these neighbors vs. their altitude (blue and red X on Fig. 38).
- c Perform a linear fit of the data, which will be the local 2m-temperature profile.
- d Having the altitude of the target grid point use the obtained linear regression to calculate its 2m-temperature.
- e Perform this operation (a-d) for every target grid point, for every day.

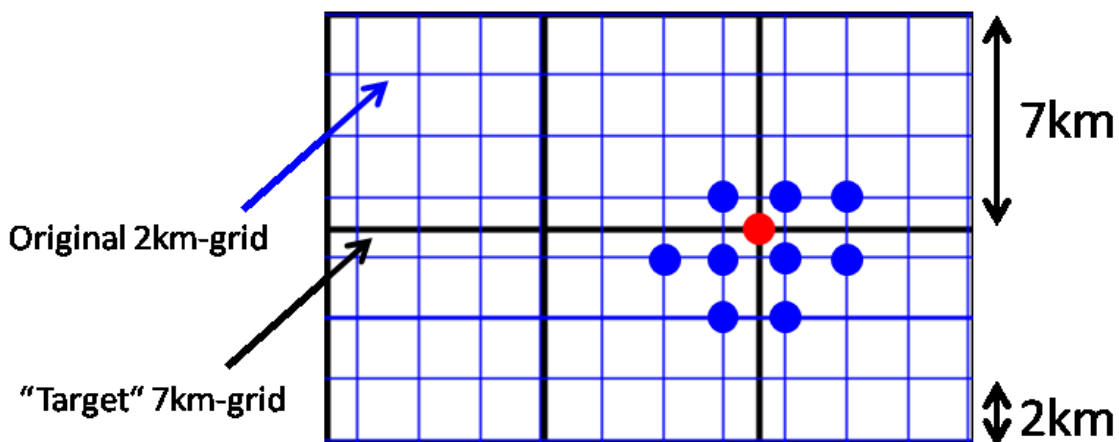


Figure 37: Transform of 2m-temperature observations from the original 2km-grid with the real topography to a target 7km-grid with a smoothed topography.

An example for the calculation of the measured 2m-temperature at a target grid point (Lat=46.07°/Lon=7.49°) on 10.01.2008 is presented on Fig. 38.

This example shows the following:

- The correction to the measured temperature (from the old method of interpolation used before to the new one) is important, of the order of several degrees Kelvin (-2K in this example).
- The local 2m-temperature profile is indeed linear (the results are similar for other regions and other days).

- The local 2m-temperature vertical gradient is unique (-5.8K/km in this example) for a given grid point area for a given day.

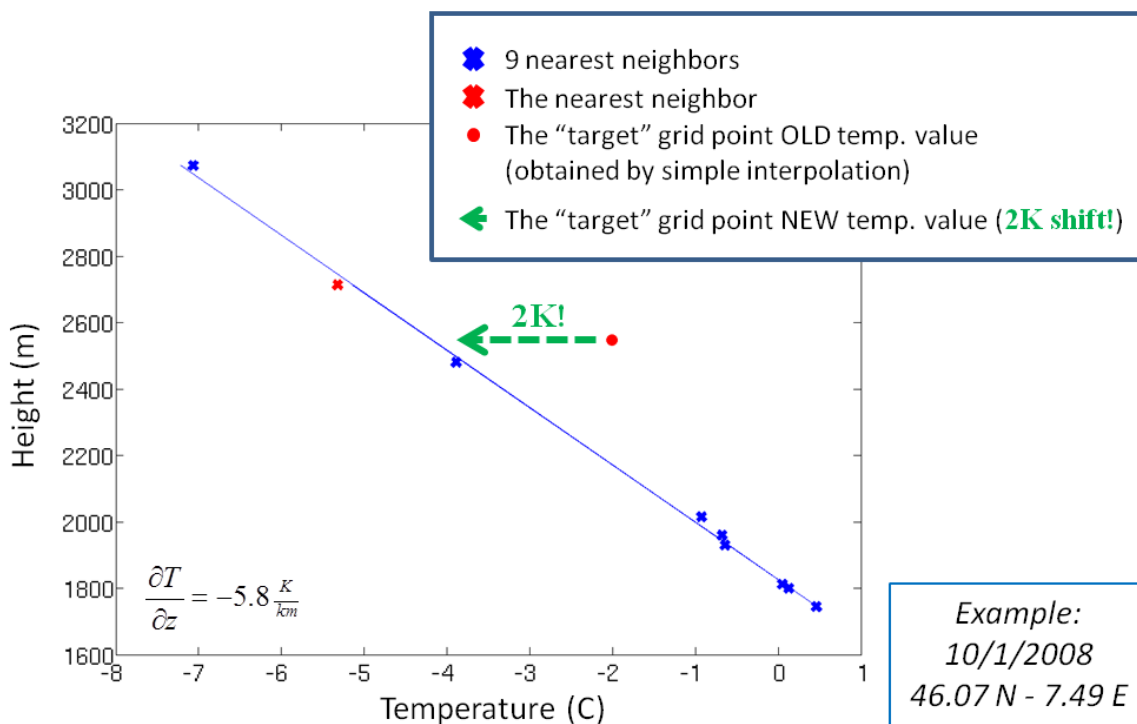


Figure 38: An example for the calculation of the measured 2m-temperature at a target grid point (Lat=46.07°/Lon=7.49°) on 10.01.2008.

10 Appendix B: Examples of stable and unstable conditions over Switzerland

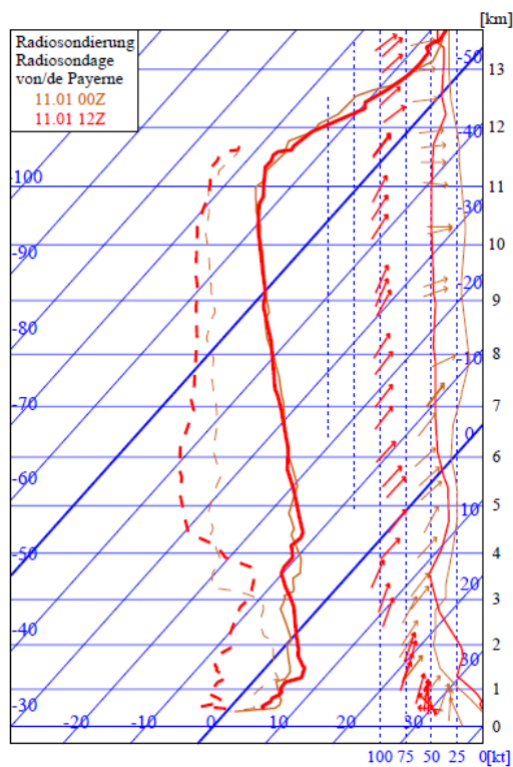


Figure 39: The stable low level stratification on 11.01.2008 (reference from Section 3).
MeteoSwiss radiosounding site at Payerne, Switzerland.

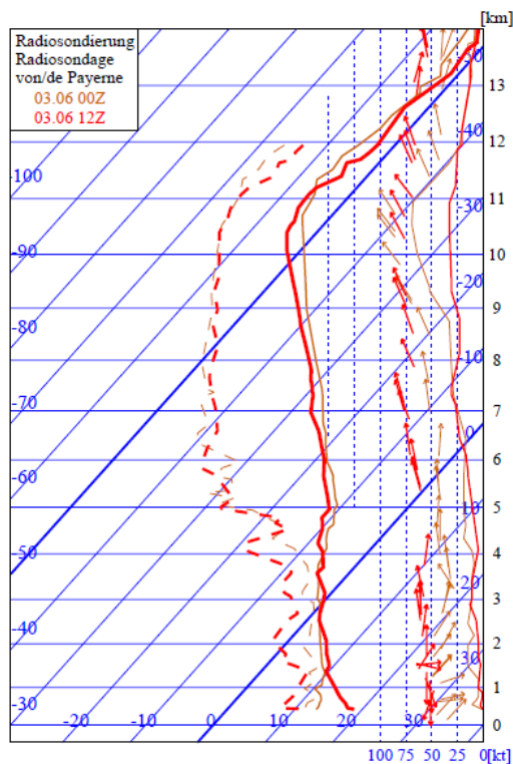


Figure 40: The unstable low level stratification on 03.06.2008 (reference from Section 3).
MeteoSwiss radiosounding site at Payerne, Switzerland.

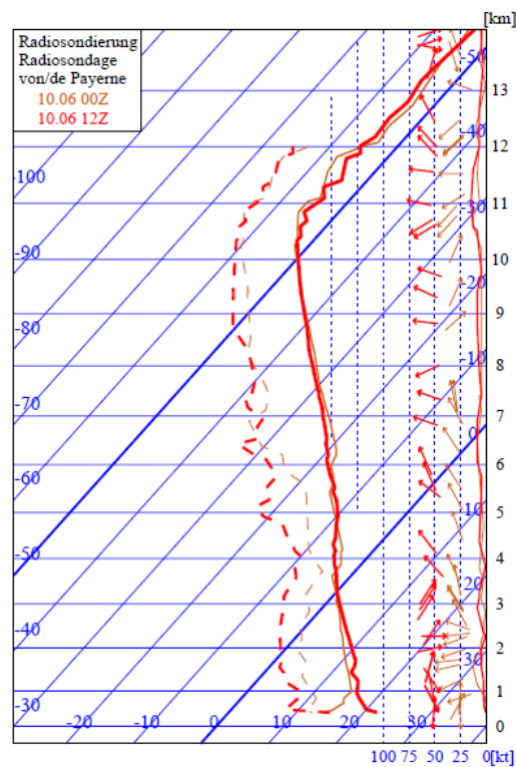


Figure 41: The stable low level stratification during night of 10.06.2008 (reference from Section 3).
MeteoSwiss radiosounding site at Payerne, Switzerland.

11 Appendix C: MCH verification results for the optimal parameters simulation

Pirmin Kaufmann (MeteoSwiss) performed the verifications of the optimal parameters Best simulation in comparison with the REF simulation, using the official MCH procedure, for the periods of 2-20/1/2008 and 2-20/6/2008. Generally, these verifications show the advantage of the Best COSMO simulation over the REF simulation. Several highlights of these verifications are presented below, for the following verification domain (Fig. 42):

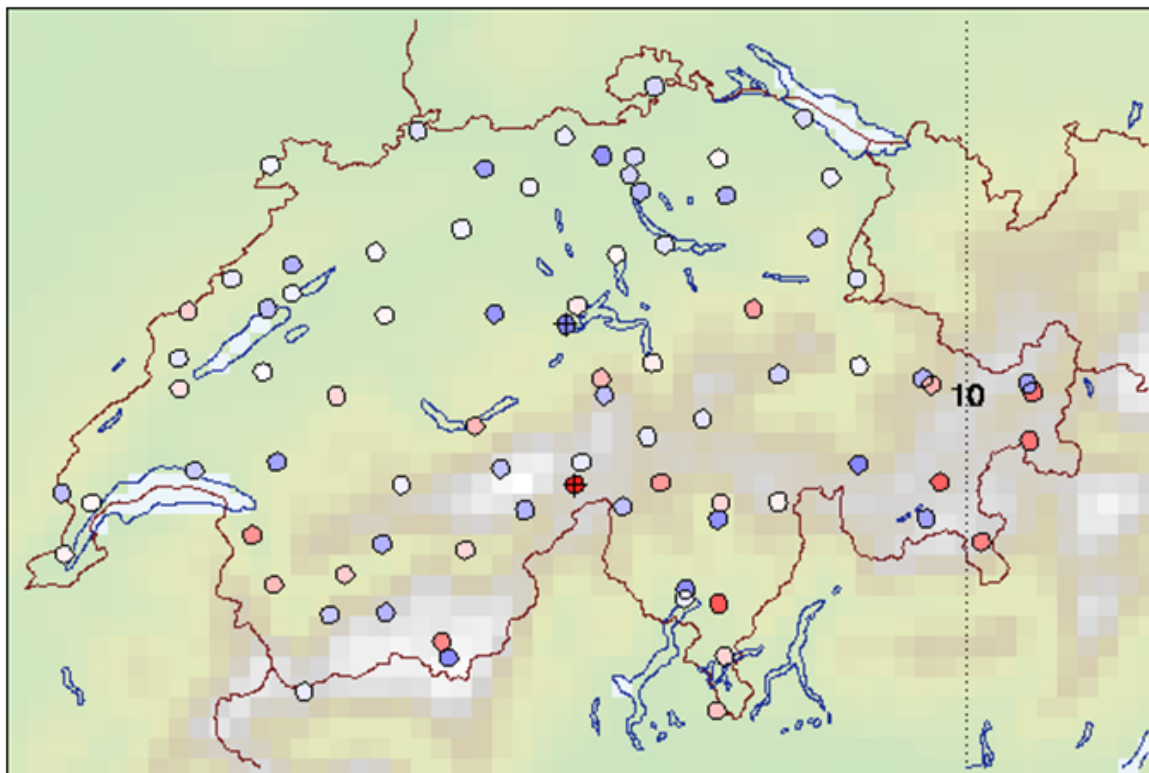


Figure 42: Verification domain.

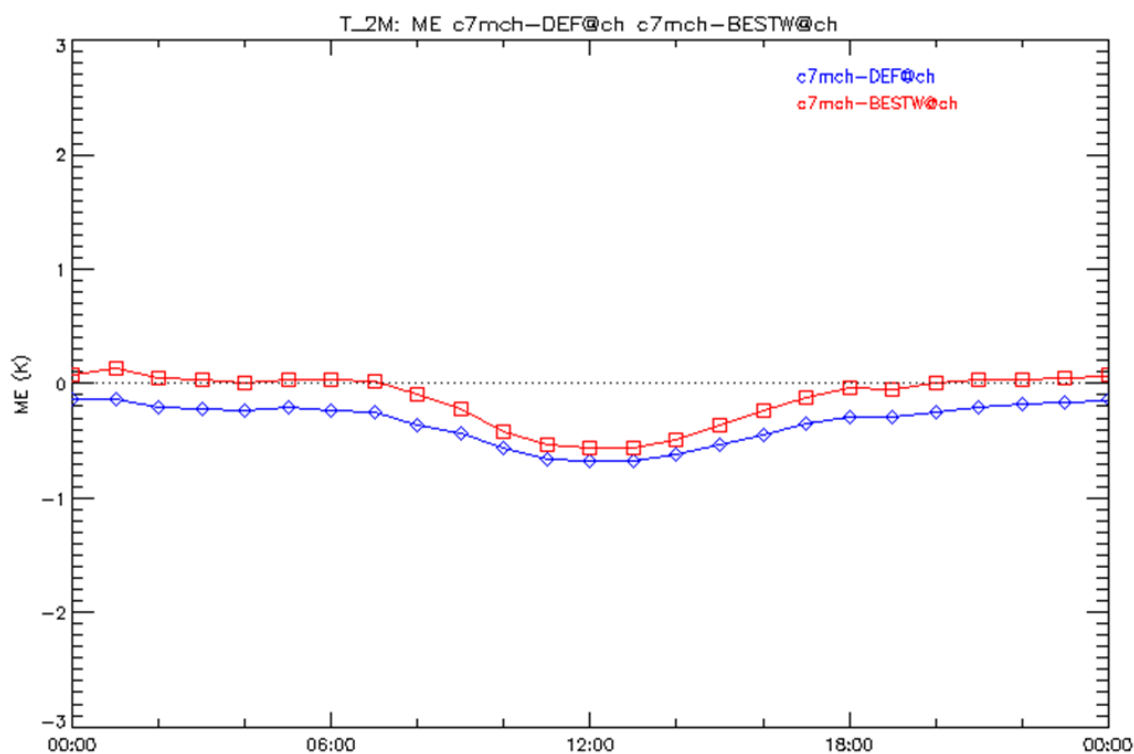


Figure 43: 2m-temperature diurnal cycle mean error for the REF (blue) and the Best (red) simulations, for the period 2-20/1/2008. The Best simulation is clearly better than REF simulation.

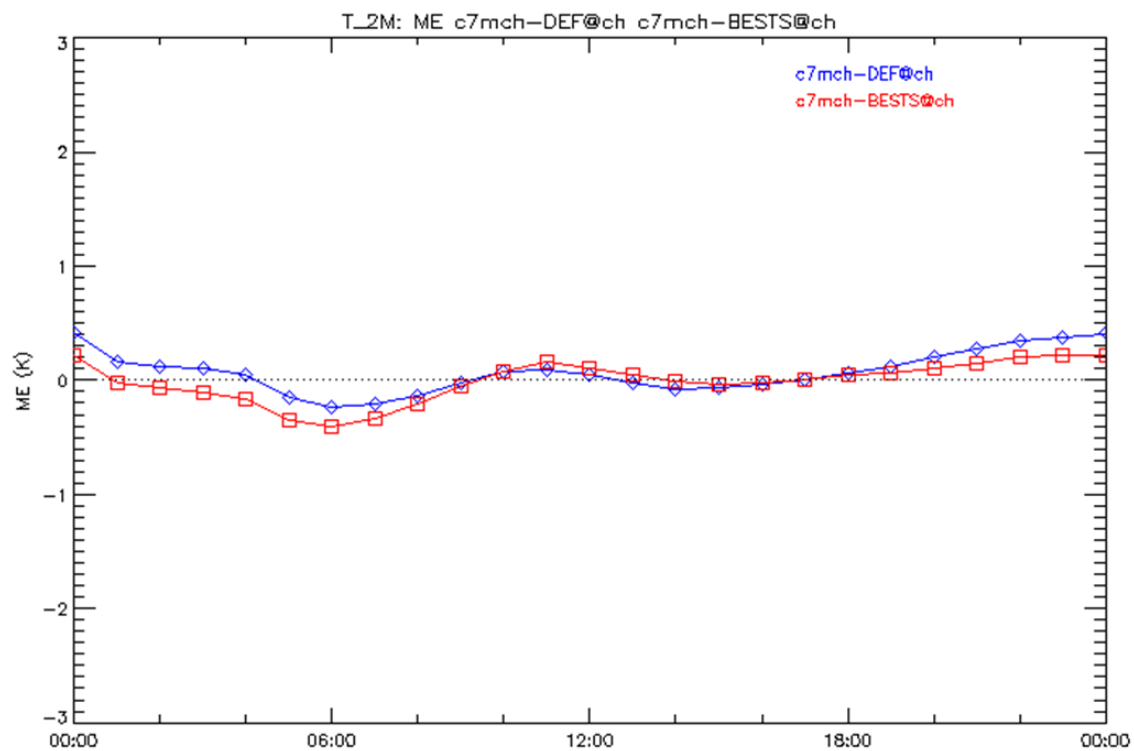


Figure 44: 2m-temperature diurnal cycle mean error for the REF (blue) and the Best (red) simulations, for the period 2-20/6/2008. The Best and REF simulations are of similar quality.

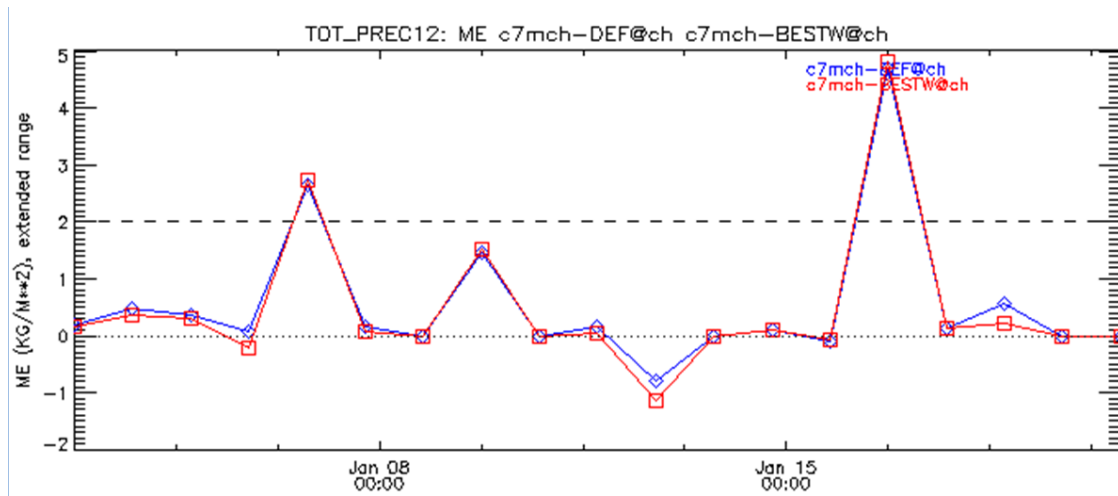


Figure 45: Mean error time series of the 12h accumulated precipitation for the REF (blue) and the Best (red) simulations, for the period 2-20/1/2008. The Best and REF simulations are of similar quality.

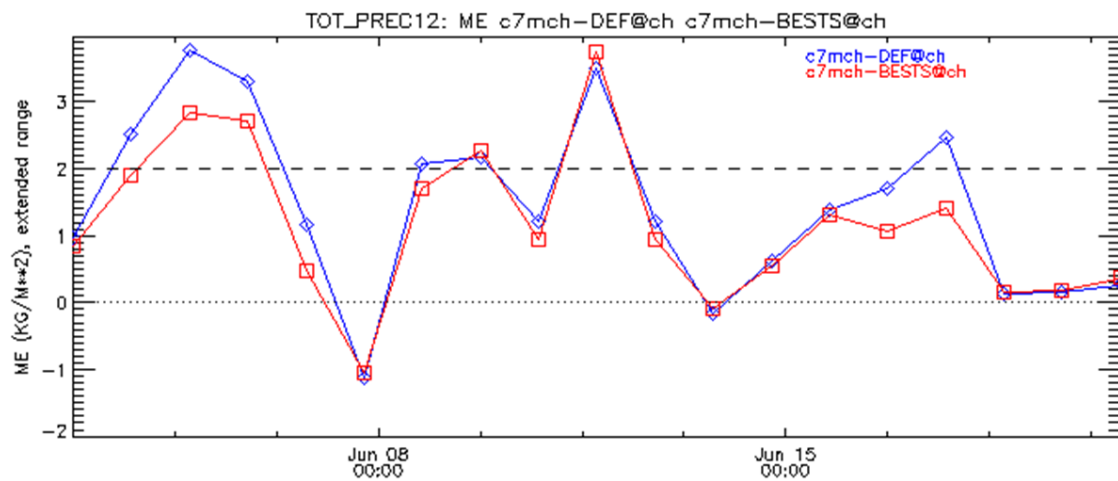


Figure 46: Mean error time series of the 12h accumulated precipitation for the REF (blue) and the Best (red) simulations, for the period 2-20/6/2008. The Best simulation is clearly better than REF simulation.

Acknowledgments

The CALMO project is based on the objective calibration method which was developed and implemented in regional climate model by Omar Bellprat and Christoph Schär (ETH). Special thanks to Omar Bellprat for providing the calibration code framework. The figures in Section 6 are based on the plots of Bellprat (2012). We are grateful for the support from and valuable discussions with Yoav Levi (head of R&D at IMS), Alon Shtivelman (IMS), Yitzhak Yosef (IMS), Simon Krichak (TAU), Guy de Morsier (MeteoSwiss), Oliver Fuhrer (MeteoSwiss), Marco Arpagaus (MeteoSwiss), Julian Tödter (GUF), and Ines Cerenzia (ARPA-EMR). We are thankful to Pirmin Kaufmann (MeteoSwiss) for performing the verifications of the optimal parameters simulation using the official MCH procedure and to Massimo Milelli (ARPA Piemonte) for the work he performed editing this report.

References

- COSMO document part II, 2011.
Available online at: <http://www.cosmo-model.org/content/model/documentation/core/cosmoPhysParamtr.pdf>
- Dunst M., 1980: Ergebnisse von Modellrechnungen zur Ausbreitung von Stoffbeimengungen in der planetarischen Grenzschicht, *Z. f. Meteorol.*, **30**, 47-59.
- Schlünzen K.H., 1988: Das mesoskalige Transport- und Strömungsmodell METRAS Grundlagen, Validierung, Anwendung, *Hamb. Geophys. Einzelschr*, **88**, 139 pp. (in German with abstract in English)
- Helmert J. et al., 2008: Single Column Simulations of COSMO for the GCSS RICO Precipitating Shallow Cumulus Case, 18th Symposium on Boundary Layers and Turbulence.
Available online at: <https://ams.confex.com/ams/pdfpapers/140006.pdf>
- Zilitinkevich S. et al., 2012: A Hierarchy of Energy- and Flux-Budget (EFB) Turbulence Closure Models for Stably-Stratified Geophysical Flows, *Boundary-Layer Meteorology*, **146**, 3, 341-373.
- COSMO document part VII, 2014.
Available online at: http://www.cosmo-model.org/content/model/documentation/core/cosmo_userguide_5.01.pdf
- Cerenzia I. et al., 2014: Diagnosis of Turbulence Schema in Stable Atmospheric Conditions and Sensitivity Tests, *14th COSMO Newsletter*.
Available online at: http://www.cosmo-model.org/content/model/documentation/newsLetters/newsLetter14/cnl14_04.pdf
- Cerenzia I. et al., 2013: Internal Report no. 2: Improvement of the PBL parameterization in COSMO model.
- Bellprat O. et al., 2012: Objective calibration of regional climate models, *Journal of Geophysical Research*, **117**, D23.
- Blackadar A. K., 1962: The Vertical Distribution of Wind and Turbulent Exchange in a Neutral Atmosphere, *J. Geophys. Res.*, **67**, 3095-3102.
- Buzzi M., 2008: Challenges in Operational Numerical Weather prediction at High Resolution in Complex Terrain. *PhD thesis*.

Available online at: http://www.meteoschweiz.admin.ch/web/de/forschung/publikationen/alle_publikationen/veroeff-80.Par.0001.DownloadFile.tmp/veroeff80.pdf

Frei C., 2014: Interpolation of temperature in a mountainous region using non-linear profiles and non-euclidean distances, *Int. J. Climatol.*, **34**, 5, 1585-1605.

Neelin J. D. et al., 2010: Considerations for parameter optimization and sensitivity in climate models, *Proc. of the National Academy of Sciences of the United States of America*, **107**, 21349-21354.

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- No. 3: February 2003.
- No. 4: February 2004.
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- 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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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) and Romania (NMA). 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 editors:

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