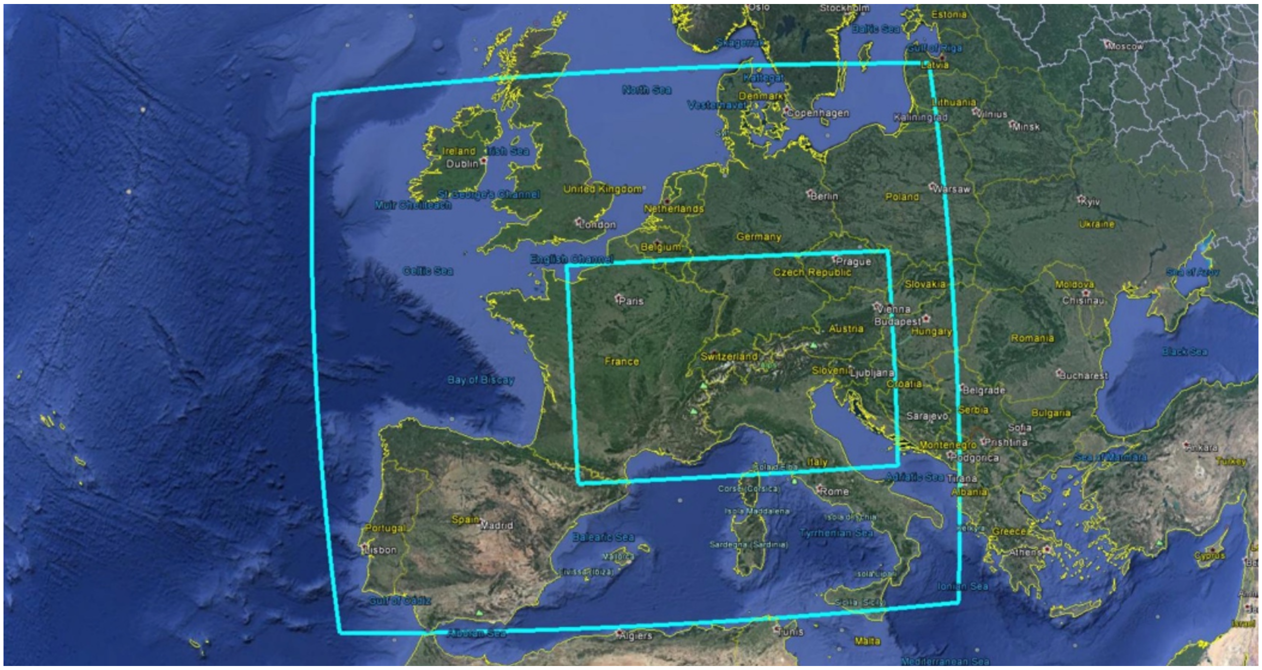

Master thesis proposal

Evaluation of COSMO-CLM^2 in weather mode

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Summary

The benefits of coupling an atmospheric model to an advanced land surface model (LSM) has been demonstrated in the context of climate simulations. However, similar studies for the numerical weather prediction (NWP) model COSMO have not yet been conducted.

Advanced (third generation) LSMs represent turbulent fluxes between land surface and atmosphere more adequately, most prominently by directly simulating stomatal conductance and photosynthesis. In contrast, earlier (second generation) LSMs use empirical relationships to represent surface fluxes. Furthermore, they mostly do not allow for vertically heterogeneous soil layers or account for canopy water.

Especially in the context of hot summer extremes, where the soil moisture feedback can amplify the intensity of an extreme, sensible and latent heat fluxes play a key role in the development of an heat extreme. Correctly representing the surface fluxes during such an event in NWP models is of crucial importance for reliable weather forecasting and risk prevention.

This study aims to investigate the added value of an advanced surface representation to a numerical weather prediction system. For this purpose, two instances of the Consortium for Small Scale Modeling (COSMO) model are compared to assess their performance in the anomalously hot European summers of 2003, 2006 and 2015. (1) MeteoSwiss' COSMO is using the second generation LSM TERRA, while (2) COSMO-CLM^2 has a third generation land surface scheme. The final aim of the study is to propose possible enhancements to the COSMO model operationally used by MeteoSwiss for weather forecasting.

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1 Introduction

1.1 Motivation

The importance of a reliable and precise weather forecast cannot be stressed enough. Numerical weather prediction (NWP) models have proven to hold their ground as a central piece in todays weather forecast (Bauer et al., 2015). Sharing resolution in space, but not in time, regional climate models (RCMs) are an important tool to explore the effects of climate change on a local scale. Embedded in global models, they exploit available computational capacity with finer grid resolution and can for the first time adequately resolve land cover heterogenity and extreme weather events (Davin et al., 2011). Improving the forecast quality of both model families is therefore a priority to weather services (e. g. Ziv 2017). Most prominently, both share the need for detailed land cover representation.

The complex biological and ecological processes taking place on the land surface in vegetation and soil cannot be represented in the model from first physical principles, but rather need careful parameterisation reasoned by sound knowledge of the processes involved. Land surface processes, however, have shown to be of crucial importance especially for the representation of heat waves and droughts (Seneviratne et al., 2006; Fischer et al., 2007b), both of which are expected to become more frequent, severe and longer lasting (Perkins, 2015; Seneviratne et al., 2012; Meehl and Tebaldi, 2004) with climate change. The question arises if the representation of the land surface is one of the current weak links in NWP models, like already stated for RCMs by Davin et al. (2016).

However, Davin et al. (2016) used a climate model. With the weather models in this study, in contrast, output can be validated with observations. Weather models are running at most a couple of days, and with the initial conditions being regularly refreshed, the state of the land surface can in principle be corrected on the basis of observations. Furthermore, in the time frame of several days, especially soil moisture with its integrated nature does not change much. These two arguments make the need of having a complex LSM in a NWP model weaker than in an RCM and is one reason why enhanced land surface models are implemented more readily in RCMs than in NWP models. However, this argumentation oversees the fact that data assimilation is especially challenging for soil conditions, since horizontal heterogenity is high and the number of in-situ measurements low. An improved surface model is hence also beneficial to data assimilation quality and at the same time can potentially increase forecast quality of NWP models in the same order of magnitude than for RCMs shown by Davin et al. (2016).

1.2 Scientific Basis

Hot summer extremes in central Europe are mostly occuring during anticyclonic blocking situations (Black and Sutton, 2007). Recent studies suggest desiccated soils, for example due to a dry spring, amplify (Fischer et al., 2007a) or are even conditional for such summer hot extremes to occur (Quesada et al., 2012). This positive feedback mechanism in the land-atmosphere coupled system is mostly controlled by latent and sensible heat fluxes. Soil moisture changes are slow compared to precipitation patterns, leading to the soil moisture memory effect, where integrated precipitation of several months determines to the current soil moisture content. Low soil moisture, for example from a dry spring period, distorts the ratio of incoming radiation fed back to the atmosphere towards less evapotranspiration and more release of sensible heat in transitional soil moisture regimes (Ferranti and Viterbo, 2006) (for an introduction to soil moisture regimes see Seneviratne et al. 2010). Therefore, little precipitation in spring can amplify summer temperatures by keeping the soil moisture low and allow for more sensible heat to be released by the surface.

The summers of 2003, 2010 and 2015 showed the highest summer temperatures in central Europe since the beginning of the last century (Orth et al., 2016). Model simulations suggest increasing climate variability over Europe with climate change (Vidale et al., 2007; Schär et al., 2004). In the light of these findings, correctly representing the possible feedback mechanism on hot and dry extremes of land surface interactions in NWP models is a crucial puzzle piece to produce reliable forecasts for these kind of important events. Furthermore, improving land surface representation in NWP models is urgently needed and could possibly lead to fast enhancements in forecasting and representing such events in NWP models.

1.3 Research Question

There are ongoing efforts in the COSMO consortium to evaluate and improve land surface processes representation in COSMO (Ziv, 2017). An improved representation of sensible, latent and radiative fluxes as well as daily maximum temperature has already been shown (Davin et al., 2016) in COSMO *climate mode* using the Community Land Model (CLM) land surface scheme compared to a EURO-CORDEX ensemble (*Climate mode* hereby refers to a model run with lower temporal and horizontal resolution, without data assimiliation and a focus on temporal means). It is the aim of this study to compare the performance of both models to see if a more complex LSM is also beneficial to NWP forecasts. The final aim is to suggest improvements to the land surface model used for weather forecasting at MeteoSwiss.

2 Objectives

In the proposed work, MeteoSwiss' (1) COSMO-TERRA-ML in its versions (1.1) TERRA5 and (1.2) TERRA5.5 and the (2) COSMO-CLM^2 model are compared with the aid of several gridded satellite and ground observation datasets as part of the COSMO priority task. The aim of this study is to

research area 1 define and characterize the main difference between the two LSM especially in the context of the representation of summer heat extremes.

research area 2 suggest outlines for possible improvements in the operational COSMO-TERRA-ML model used for weather forecast at MeteoSwiss using CLM as benchmark.

research area 3 (optional) perform sensitivity analysis to get insight into the influence of land surface parametrization on representation of heat extremes in NWP models.

The expected outcomes of the research areas 1-3 are as follows:

to 1 The differences between the models (see Section 3.1) will help pinpoint the different behaviour of the models during summer heat extremes. The more sophisticated representation of land surface processes in CLM is likely to lead to an improvement in overall model performance and, in particular, calculation of surface temperature, wind, boundary layer behaviour and latent and sensible heat fluxes.

to 2 The particular implementations in COSMO-CLM^2 leading to its possibly better performance in summer heat extremes means that implementation into the already existing COSMO_TERRA weather model is feasible. A bullet-point like list of possible directions of improvements in COSMO_TERRA is the goal of this research area.

to 3 A comprehensive understanding of both land surface schemes, their respective performance during hot summer extremes as well as an overview of the most important features of COSMO-CLM^2 that enhance land surface representation during summer heat waves is the aim of this research area.

3 Methods

3.1 Model description

The COSMO model is a regional, non-hydrostatic atmospheric model (COSMO, 2017). An instance of it is used for operational weather forecasting by the Federal Office for Meteorology and Climatology of Switzerland (MeteoSwiss). The land surface scheme (land surface model, LSM) used by MeteoSwiss is TERRA_ML.

The COSMO model is furthermore used as a regional climate model for research purposes and takes part in the EURO-CORDEX project (Jacob et al., 2014). In this context, COSMO-CLM^2 is an instance of COSMO jointly developed by the Consortium and the Climate Limited-area Modelling Community (CLM) (Davin et al., 2011). The exponent in CLM^2 denotes the fact that the Community Land Model (CLM) is used in this COSMO instance, instead of TERRA_ML, sharing its acronym with the Climate Limited-area Modelling Community.

The COSMO instances used in this master thesis therefore differ only in their LSM, having different complexities of land surface process representation (see also Davin et al. (2016)). TERRA_ML belongs to the second generation land surface schemes. The main simplifications and limitations of second generation LSM are the empirical relation of stomatal behaviour and the vegetation being represented only as one ”big leaf” without accounting for vegetation diversity and dynamics. The former leads in particular to a maximised water use efficiency, neglecting the carbon limitation imposed on a plant when closing its stomata due to limited water availability. In contrast, CLM is a third generation LSM. It couples water and carbon via the photosythesis model by Farquhar et al. 1980 and the stomatal conductance model by Collatz et al. 1991. Furthermore, vegetation dynamics are accounted for.

The particular differences between the two concrete LSMs in use are listed in Davin et al. 2011 and repeated here for convenience:

Sub-grid Surface Heterogenity TERRA_ML does not account for sub-grid surface heterogenity, whereas in CLM this heterogenity is represented in a tile approach. The main result is different flux calculations, since the mean of the ”tiled” fluxes does not equal the flux estimated via a homogeneous ”mean” land surface per grid cell.

Radiation CLM explicitly represents radiative fluxes in a two-stream approximation for both soil surface and canopy layer, shortwave and longwave radiation and diffuse and direct sun radiation. This includes dividing the canopy into a sun-lit and shaded part. In contrast, TERRA_ML parameterizes radiation from temperature and surface albedo of each grid cell.

Turbulence For turbulent fluxes, CLM uses the Monin-Obhukov similarity theory, while TERRA-ML works with a TKE-based scheme. Only CLM partitions sensible and latent heat fluxes between vegetation and ground.

Hydrology CLM models both saturation excess and infiltration excess surface runoff, whereas TERRA-ML is capable of capturing only saturation excess. Snow cover is represented in more detail in the CLM LSM.

Stomatal conductance and Photosynthesis TERRA-ML parameterizes stomatal conductance from empirical relationships, whereas CLM links stomatal conductance with photosynthetic activity.

Surface Datasets An imporant difference between the model surface representation consists in TERRA-ML only considering the surface layer of soil, while CLM can take into account different soil textures vertically.

3.2 Model experiments

The data used is simulation output from the two models described above. The possible dimensions of the analysis are discussed in the following:

Regions COSMO can be run for the following regions: western Europe, eastern Mediteranean and the northern part of european Russia

Time Periods For the European region, the simulation will be computed for the following time periods, representing extraordinary warm european summers: JJA 2003, JJA 2006 and MAMJJA 2015.

Models The models that are compared are COSMO_TERRA in its versions 5.0, 5.05/standard and 5.05/advanced as well as COSMO-CLM^2.

Resolution The horizontal grid resolution of the model is 6.6 km

Variables Gridded output variables include 2m temperature, 10m wind, precipitation, air pressure, atmospheric profile, latent heat and sensible heat

This master thesis focuses on intermodel comparison in western Europe (see Figure 1) of the available models. Simulations will be made for the anomalously warm european summers in 2003, 2006 and 2015. A comparison of model performance between ”warm” and ”normal” summers is therefore not the first aim of this study. It will, however, be evaluated if possible already existing runs can provide data to conduct this analysis. The good model performance under ”normal” conditions has been shown already elsewhere for both models (Davin et al., 2011) in *climate mode*. The output variables will be compared to different observational data sets and variables.

Since the sensitivity analysis will be conducted with the goal of suggesting concrete improvements to be implemented in TERRA-ML, both COSMO models use the same parameters, which

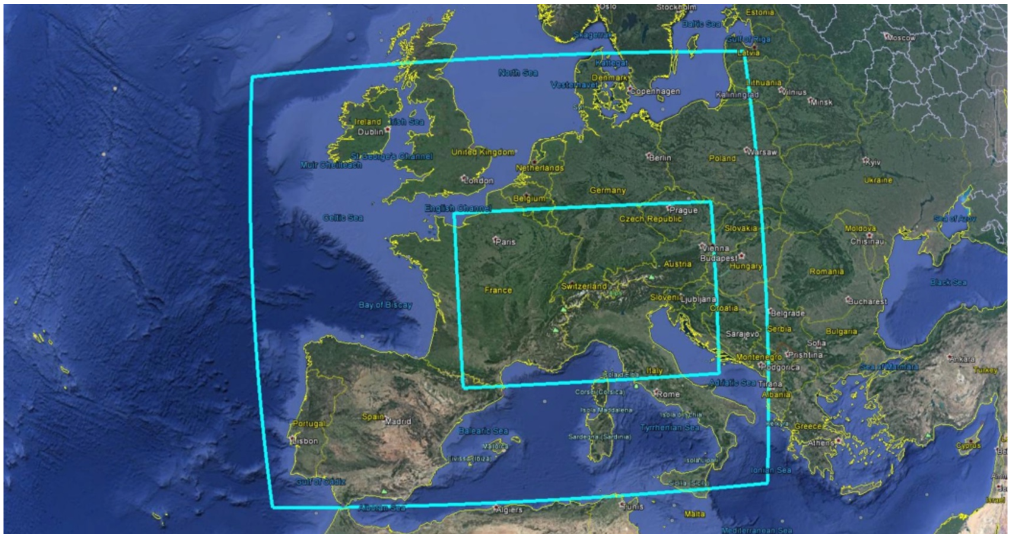

Figure 1: Extent of the European domain of the COSMO model (Figure taken from Ziv 2017). The bigger frame represents the extent of the 6.6 km resolution model, while the small one represents the 2.5 km grid resolution model. Only the former will be used in this study.

are optimized for use with TERRA_ML. This can lead to lower performance in COSMO-CLM^2 compared to COSMO optimized solely for CLM. However, Davin et al. (2011) showed, that for climate simulations CLM still outperforms TERRA_ML despite this hindrance. We therefore argue this fact to only have minor influence on the outcome of this study.

3.3 Evaluation datasets

The observational datasets available for comparison include

- radiative ground temperature from satellite observations at a resolution of 2km, regridded and transformed to 2m temperature (LST, unpublished, for methodology see Duguay-Tetzlaff et al. 2015).
- a land surface hydrology dataset derived from model simulations including soil moisture, runoff and evapotranspiration (SWBM dataset, see Rene Orth and Seneviratne 2015).
- a global multi-data evapotranspiration dataset (Mueller et al., 2013).
- temperature and precipitation data from ground observations interpolated and gridded for the European area (EOBS, see Haylock et al. 2008).
- information on turbulent fluxes from interpolated and gridded Fluxnet ground observations (FLUXNET-MT, see Pastorello et al. (2017)).
- other datasets to be agreed on depending on the final focus of the study.

3.4 Analysis Strategy

Forecast quality is assessed by applying the following measures on the datasets produced:

to RA 1.1 A range of standard measures including RMSE, bias and MAE, provided by the MeteoSwiss evaluation tool (Moveo, Rdfbk) of 2m mean temperature, precipitation, surface pressure, and 10m wind.

to RA 1.2 Correlation measures including pearson correlation, possibly enhanced correlation methods insensitive to biases (for example Sippel et al. 2016) to examine the correlation between temperature and evapotranspiration as a measure of weather extremeness.

to RA 1.3 An ensemble of common extreme event definitions to see if the models are able to capture the extremeness of the summer heat waves. And vice versa, see which extreme event definition is most suitable in the context of recent LSM model setup.

The objectives are categorized after priority tasks and optional tasks. The priority tasks encompass **research area (RA) 1 and 2**. The planned experiments are summarised in the following table:

priority	**RA**	**spatial extent**	**time periods**	**observational datasets**	**model resolution**	**variables**
priority	1.1	Western Europe	all	all	6.6km	meteorological variables
	Description: Comparison of 2m temperature, 10m wind, air pressure, precipitation, latent and sensible heat fluxes from the models to observations (gridded and point data) according to *standard scheme from priority task* with a defined analysis statistical set for western Europe					
priority	1.2	Western Europe	all + ref	flux data	6.6km	turbulent fluxes
	Description: Use advanced statistics to further characterize extremeness representation in both models, e.g. *correlation analysis* of T and ET. If available compare to ”normal summer” behaviour.					
priority	1.3	Western Europe	all	LST, EOBS	6.6km	T, precip
	Description: Check whether different *definitions of heat extremes* are more suitable in catching the extremeness of the three summers in the representation of the model					
priority	2					
	Description: Suggest improvements to TERRA_ML land representation in MeteoSwiss operational weather forecast model					
optional	3.1	Western Europe	all	all	6.6km	meteorological variables
	Description: Do a sensitivity analysis of the parameterisations in COSMO-TERRA-ML.					
optional	3.2	additional runs				
	Description: Run model myself with changed parameterisation.					
optional	extended analysis					
	Description: Frame a more general idea of heat extreme representation in NWP models.					

4 Timeline and Milestones

The tentative schedule for the master thesis starting mid-October to beginning of November is framed as follows:

Weeks	**Length**	**Activity**
1	1 week	Literature review
2	1 week	Study model output
Milestone I		Decide on analysis set, set up analysis tools, be familiar with provided model output
3-4	2 weeks	**RA 1.1** Perform standard analysis from priority task
5-7	3 weeks	**RA 1.2** Perform advanced statistical analysis
8-10	3 weeks	**RA 1.3** Check impact of heat extreme definition
including	*1 week*	*Christmas break*
Milestone II		**Research area 1** investigated. Provided runs are characterized and results available in bullet-point style.
11	1 week	**RA 3.1** Understand model parameterization, find starting points for sensitivity analysis
12-15	3 weeks	**RA 3.2** Own model runs of new parameterization, including analysis
16-18	2 weeks	**RA 2** Suggest possible improvement directions for COSMO_TERRA land surface parameterization
Milestone III		**Research area 2** and **3** investigated. Formulate thesis results and define open questions
19-20	2 weeks	Spare time. Catch up with time table or extend analyses.
Milestone IV		Data analysis completed
21-24	4 weeks	Write thesis and hand in chapters for revision as soon as they are completed
25-26	2 weeks	Finish revisions and apply corrections
Milestone V		Submission of master thesis

The following events to communicate and discuss the work are proposed:

- Visit MeteoSwiss in May to discuss possible research directions with Jean-Marie Bettems and Oliver Führer, possibly accompanied by Edouard Davin.
- Present master topic especially to DWD and to the larger COSMO Consortium on the COSMO General Meeting, 11th to 14th of September in Jerusalem, Israel.
- Present results of master thesis to DWD in Darmstadt, possibly on next COSMO user seminar in March 2018 in Darmstadt.

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