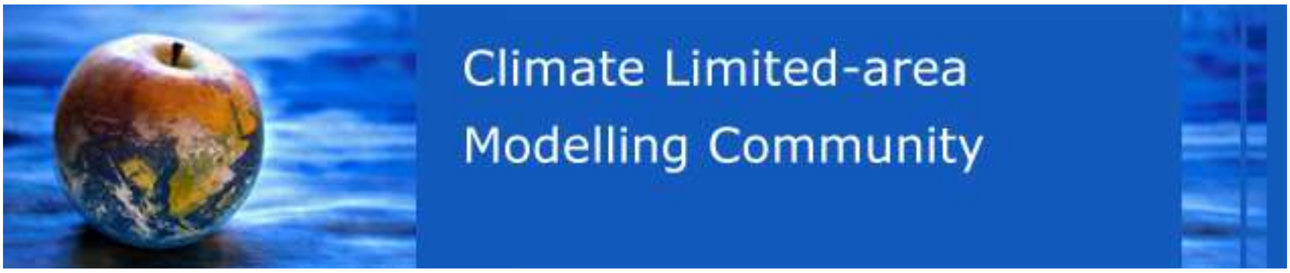

Strategy of the CLM-Community 2021-2026

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0. Introduction

The present document defines the strategy and goals of the Climate Limited-area Modelling Community (CLM-Community) for the period 2021-2026. The CLM-Community is an open international network of scientists working in the area of regional climate modelling and climate change research. The community relies on voluntary contributions of its members and operates without direct funding. All members accepted the CLM-Community agreement, which forms the basis for the collaboration. The CLM-Community is primarily a platform for scientific exchange and collaboration. The main purpose of the community is the joint development and application of the community models (COSMO-CLM and ICON-CLM). The collaboration in the community supports the work of the members, reduces the efforts for model development and maintenance for each institution and helps the members to achieve their goals.

The community as a whole does not work directly on scientific questions. It builds the framework and provides a network and the tools for the members to do so. Consequently, this document does not outline scientific questions that will be addressed in the future. Instead, it analyses the goals and needs of the core/member institutions as well as demands on regional climate models from external sources (e.g. CORDEX). Based on this, the document defines community activities and model development tasks that support the attainment of these goals and ensure the availability of a state-of-the-art modelling system to enable the institutions to conduct their research and achieve their goals.

The CLM-Community strategy is written by the CLM-Community Coordination group (CLM-CO) and the members of the CLM-Community Scientific Advisory Board (CLM-SAB). It provides plans and guidelines for coordinated model development and community activities that enable and foster the work and activities of its members.

1. Demands on the CLM-Community and the community model(s)

In summer 2021, the CLM-Community had around 230 members from 75 climate research institutions all over the world. The composition of the community is very heterogeneous and includes members from universities, research institutions and national meteorological services from many different countries. Hence, the community members work on a wide range of scientific topics, try to address different research questions and apply the community models in very different ways.

The common ground of all members is the use of a regional climate model for their work, but given the size and heterogeneity of the community, the demands on the model, the needs of the users and the fields of applications are very different. This section provides an overview of the main topics the community members work on, the different areas of application of the community models and the goals, which the member/core institutions want to achieve in the future. This overview is mainly based on the plans and strategies of the core institutions, but also takes general trends and activities in global and regional climate modelling and requirements from external sources (e.g. CORDEX) into account. The different areas of application and plans go along with different requirements the models have to meet now and in the future. The compilation and analysis of these requirements form the basis for the strategy and goals of the CLM-Community in the next few years. The following part provides an overview of the different areas of application of the community models and the plans and goals of the core institutions.

The main focus of the work at the Chair of Atmospheric Processes of the Brandenburg University of Technology Cottbus – Senftenberg (BTU) will be the analysis, application and further development of the regional climate model ICON-CLM. BTU will support the systematic evaluation of new or modified model versions on the hydrostatic scale over Europe (grid spacing of about 11 km) and will extend this evaluation to the convection permitting scale (grid spacing around or below 3 km) with a specific focus on Germany and its subregions. BTU will further contribute to the generation of regional climate change scenarios in the context of EURO-CORDEX and other national and international scientific programs. In the future, regional climate models must consider more processes and components than just an increase in global greenhouse gas concentrations. Especially on the regional scale, modifications in land use and aerosol concentrations as well as the dynamical interaction between land/sea surfaces and the atmosphere can play an important role for the structure and intensity of local to regional climate development. These general aspects result in the following scientific objectives:

- Quantification of the simulation quality of ICON-CLM in relation to the well-established COSMO-CLM.
- Improvement of the ICON-CLM performance by modification of model- and simulation-configurations on regional and convection permitting scales.
- Investigation and improvement of the information about regional to local climate change signals over Europe and Germany by additionally downscaling of CMIP6 simulations down to the kilometre scale. A particular focus will be on the future changes of heavy precipitation events and intensive precipitation episodes.
- Investigation of the combined impact of global climate change and local land use transformations on the development of regional climate and hydrological resources for small subregions in Germany.

The DLR Institute of Atmospheric Physics investigates the physics and chemistry of the global atmosphere from the Earth's surface up to the upper boundary of the middle atmosphere at about 120 km height. One focus is an improved understanding of chemical and physical processes of the atmosphere and an improved representation of these processes in global/regional chemistry-climate models. With an on-line nested version of COSMO-CLM/MESSy, DLR performs simulations with resolutions down to 1 km. These simulations are performed for specific periods, either to compare the model results with measurements (incl. in-situ ground level and research aircraft measurements and satellite data) or to investigate the impact of specific processes (such as transport emissions) on the atmospheric composition.

With the increase in resolution and complexity of COSMO-CLM and ICON-CLM the amount of output written by the models increases dramatically. Especially for detailed analyses, comparisons to observations or sophisticated diagnostics, it is not feasible to save the full model output with the temporal resolution required for such analyses. Many members of the CLM-Community have recognized this obstacle. The MESSy software includes many diagnostic tools for output reduction. An ICON-CLM version with MESSy interface will be provided in the future.

The main goals of DLR are:

- Improved understanding of chemical and physical processes in the earth system and improved process descriptions for regional and global models.
- Investigation of the impact of transport emissions on regional and global air-quality and climate.
- Implementation of the MESSy interface in ICON-CLM for performing online diagnostics.
- Development of a coupled global-regional ESM based on ICON/ICON-CLM.

The focus of the Deutscher Wetterdienst (DWD) is on the development of a seamless earth system model based on ICON with physical parameterisations from the numerical weather prediction. Supported by the activities currently being launched by DWD, MPI-M, KIT and DKRZ for the development of a global climate prediction system (ICON-Seamless), the modules and components developed or revised there should also be used efficiently for regional climate modelling. The latter is particularly relevant for the creation of regional climate projections, as various climate services of DWD are developed based on and rely on regional climate projections.

DWD's research focus will be

- On the development of an optimum model configuration for regional climate projections following the CORDEX protocol for Europe and for convection-permitting projections covering Germany with the rivers draining into Germany.
- Contributing to the CMIP6 EURO-CORDEX ensemble to estimate the impact of climate change on infrastructure, society, etc. and enable adaptation measures.
- Coupling of an ocean model to ICON-CLM.
- Evaluation of new features and components that become available in the context of the ICON-Seamless development.

The Goethe University Frankfurt's (GUF) Institute of Atmospheric and Environmental Sciences carries out active modelling research on topics from the Earth's surface, through the atmospheric boundary layer and the convective troposphere, up to the stratosphere. GUF applies the models at convection permitting grid spacings in various climate zones (esp. Europe and South Asia). A particular focus is on extending the community models with marginal sea components into a coupled regional climate system model. The community models are also used for teaching. Ongoing research topics are the investigation of the role of

- land and water bodies in regional climate processes and regional climate memory and predictability.
- the atmospheric boundary layer in the land-atmosphere water cycle, esp. in mountainous regions.
- the local and regional climate systems in a global context.
- climate change on weather and climate extremes.

Work at the Institute of Coastal Research at the Helmholtz-Zentrum Hereon (HEREON) concentrates on high-resolution representations of the climate and hydrology and their changes. High resolutions of up to 3 km grid width allow analysing the development of extreme events and the influence of wind farms on the local and regional climate. Another important focus at HEREON is the coupling between different compartments of the coastal system such as atmosphere, land, hydrology and ocean. HEREON also models water and material transports on the land surface, e.g. in lakes and rivers to reproduce the water cycle and the biogeochemical cycles, especially at the land-ocean transition. Main goals at HEREON are:

- Understand the feedback mechanisms between different compartments of the earth system in coastal regions.
- Understand the effect of atmospheric conditions on the marine ecosystem on long time scales.

Among the research topics at the Institute for Meteorology and Climate Research at the Karlsruhe Institute of Technology (KIT) are regional climate modelling, climate variability and extremes in Europe and other regions (e.g. Africa). Extreme events like heavy precipitation, windstorms and heat waves as well as the climate variability on various temporal and spatial scales will be investigated, also with respect to the related processes in the earth system. With this aim, high-resolution regional ensemble simulations will be performed to assess climate variability and change and the related uncertainties. This research will provide climate information for impact studies and stakeholders. KIT will migrate from COSMO-CLM to ICON-CLM and contribute to national and international collaboration efforts in the field of regional climate predictions, projections and reconstructions. Specific goals are:

- Adequately describing the climate effects of land use changes by modifying the biogeophysical and biogeochemical characteristics of the land surface in ICON-CLM, which requires a coupling of the atmospheric component to more sophisticated land-surface models.
- Using KI/neural networks to improve coupling between the land surface and the boundary layer.
- Regional paleoclimate modelling with ICON-CLM. The simulation of past climates, in particular glacial climate periods such as the Last Glacial Maximum, enables us to test the capabilities of regional models under different climatic boundary conditions by comparing the simulation results to proxy data.
- Analysis of (large) RCM ensembles for a better assessment of climate variability, the associated uncertainties, and the scale dependent representation of the relevant processes.

The regional climate studies (RCS) group of KU Leuven is part of the department of Earth and Environmental Sciences. The main mission of the department is to carry out state-of-the-art scientific research with respect to the functioning of geo- and ecosystems at different spatial and temporal scales, including the interaction between humans and the environment and the sustainable management of natural resources. The RCS group provides the atmospheric component and its linkages to the earth surface. COSMO-CLM is the main tool, complemented with in-situ, ground-based, satellite-based remote sensing and statistical techniques. Scientific ambitions of the group for the next ten years are:

- Resource assessment of offshore wind zones, taking into account the full interaction between wind farms and atmospheric flow, on timescales of hours to lifetime of the wind parks.
- Assessment of past, present and future climate change in Antarctica, taking into account the interaction between ocean, sea-ice, atmosphere and ice sheet.
- Projections and understanding of climate extremes with focus on the tropics, building on present work with convection-permitting models.
- Determine climate change impact, by feeding models developed for specific sectors (e.g. building sector, agricultural yield) with information from climate models.

The brief compilation of the activities and plans of the core institutions already gives an idea of the range of applications and (future) demands on the CLM-Community and the community models. Therefore, it is necessary to identify the prime factors of these demands and define some general requirements, which can then be used to develop future development lines and tasks.

The most important and overarching goal of the CLM-Community is, of course, the provision of a state-of-the-art regional climate model to its members at any time. The CLM-Community has developed and applied the COSMO model in climate mode (COSMO-CLM) for almost two decades. However, the main developers of the COSMO model, Deutscher Wetterdienst and the Consortium for Small scale modelling (COSMO) have decided to stop the development and operational use of the COSMO model and switch to an ICON based modelling system. Thus, there is also a need for the CLM-Community to switch to an ICON based system, to be able to benefit from the advantages and future developments and improvements of ICON. At the time of writing, the transition to ICON-CLM is already underway. Thus, the focus for the period 2021-2026 will be on the transition to ICON-CLM and all new developments and model improvements will focus on ICON. However, this does of course not mean that the COSMO model cannot be used for research by the member institutions for some more years.

Beside the technical developments that are necessary to establish a new ICON based modelling system, it is also necessary to increase the knowledge about the new system in the community and to simplify the start with the new model for the members. Therefore, an ICON-CLM training course, similar to the COSMO-CLM training the CLM-Community offered together with DWD in the past, is a very important element. A low entrance barrier also simplifies and fosters the use of the model for teaching, master and PhD thesis at universities and thus builds the ground for the next generation of users and developers.

However, the provision of the modelling system alone is not sufficient. The application of the model in scientific projects and especially in the production of simulations for CORDEX requires a well-tested and evaluated system to ensure the quality of the results. This is even more important against the background that the model will be used for a wide range of resolutions, including convection permitting resolutions, and for many different domains in the world. Thus, the provision of a well-tested system and recommended setup for the different applications is an important aspect of the community work. Testing and optimizing new model versions, defining the best possible configuration for the target region and performing an in-depth analysis of evaluation runs has always been a cornerstone of the work in the CLM-Community. This can be seen as a very first step in a long chain of quality assurance activities, which have been implemented in the production, publication and user consultancy of climate model data in climate service frameworks in recent years, and is therefore an essential activity that must be continued.

The participation in large international coordinated activities has always been an important aspect of the collaboration in the community. Many core and member institutions have already indicated their willingness for a contribution to the downscaling of CMIP6 simulations. This will mainly, but not exclusively be done within the framework of CORDEX. The participation in CORDEX will certainly be a major topic for the upcoming years. Agreements between and a good coordination of the work of the participating groups is important to avoid double work and benefit from potential synergies. The working group Climate Projections has an important role in this context.

Once the transition to ICON-CLM is completed, the community members have a modern and efficient modelling system at their disposal. However, the ICON modelling framework, and especially the NWP physics package, has mainly been developed for NWP applications up to now and there is certainly a need to improve and optimize the representation of several processes for climate applications. On top of that, the overview of the applications and plans of the core institutions summarized above clearly indicates the need for flexible extensions and additions of submodels for different components of the earth system. A large step into that direction will be the development of ICON-Seamless where the specific needs for global climate simulations will already be implemented. An open issue will remain with the testing and possible further adjustments of the ICON-Seamless developments for the limited area mode of ICON. In the medium term, regional climate models must include more components of the earth system than just the atmosphere. They must be developed towards regional earth-system models. Otherwise, these tools will soon be outdated and replaced by high-resolution global earth system models. Hence, it is necessary to ensure that it is possible to improve and extend the model in many different ways.

From an administrative perspective, the necessary steps have already been taken with the “development partnership agreement between DWD and the CLM-Community with respect to the ICON software”, but the technical possibilities have to follow. Furthermore, it is of uttermost importance that all developments towards a regional earth system model are implemented in a way that they are available for all community members and flow back to the main ICON code. Otherwise, they will not be compatible with new developments from other ICON developers, model versions will quickly diverge and eventually the developments will get lost or only be usable for a very small subset of the community members in “private” code versions. Important improvements and extensions have to be included in new ICON releases to ensure a sustainable development and to be able to continue to build on earlier achievements.

The demands for the community and the model system can be summarised in a few keywords:

- optimization
- quality assurance
- improvement
- flexibility
- expansion
- (joined) application
- training

These considerations translate into the goals for the CLM-Community that are outlined in part 2 of this document.

2. Goals of the CLM-Community

2.1. Quality assurance and support

2.1.1. Transition from COSMO-CLM to ICON-CLM

The transition from COSMO-CLM to ICON-CLM is a central task of the CLM-Community. A precondition is that ICON-CLM provides at least the same technical features for performing long-term climate simulations and demonstrates a comparable simulation quality as the current standard version of COSMO-CLM. To achieve this goal, the limited area version of ICON-NWP, on which the regional climate version ICON-CLM is based, has to be extended by components, which are available in COSMO-CLM for a long time, but have not been integrated in ICON so far or are not completely available and/or usable without problems. The adaptation of the model code is coordinated by the CLM-Community project group ICON. It is intended to transfer this work into a permanent working group "Model Development' (working title)' to ensure an improved cooperation for all future model extensions from different application areas. The scope and status of upcoming enhancements are currently managed via a ticket system on the RedC pages of the CLM-Community. One of the most urgent tasks for the near future is to enable the model to read and process simulation data from different global climate models of the CMIP6 ensemble directly, so that the newest climate change scenarios can also be downscaled with ICON-CLM for different regions with various resolutions.

Furthermore, it must be ensured that the quality of regional climate simulations with ICON-CLM is at least comparable to or even better than the results of the established COSMO-CLM. For this purpose, the model configuration, which has been taken from the model setup for numerical weather prediction so far, must be adapted to the requirements of regional climate simulations in a target-oriented way. This will be done in a first step by selecting suitable versions of already included parameterizations and by optimizing the numerous tuning parameters (see also section 2.1.2) with the goal of an improved reproduction of regional climate statistics for Europe and other regions of the world. This work is coordinated in targeted project studies by the working group Evaluation (WG EVAL) and, if sufficient resources are available, also carried out by the group itself within a sophisticated and standardized evaluation framework (see also section 2.1.3). In a second step, model components should be improved or new components developed, to improve the functionality of ICON-CLM step by step and expand it towards a regional earth system model for climate simulations. These developments must be done in close cooperation with the "ICON-Seamless" activities, a joint initiative essentially by DWD, MPI-M, DKRZ and KIT to unify and further improve ICONs NWP physics package for climate predictions and projections.

2.1.2. Identify optimal model configurations for climate simulations for Europe and other domains

The main target of the evaluation and calibration process, which is led by WG EVAL, will be new recommended model versions for COSMO-CLM and ICON-CLM along with recommended setups for regional and convection permitting simulations. Once a reference configuration for the European domain has been identified, a general approach for porting the recommended model version and setups to other regions of the world needs to be developed, based on previous experience with COSMO-CLM. For the calibration process, the exploration of new metrics to be used in the objective calibration method of Bellprat et al. 2012 should be considered. At the same time, given the current and future increase of applications considering high spatial resolutions (12 km and less) and the faster development cycles in ICON, it will be of fundamental importance in the next years to reconsider the value of the in-depth tuning and evaluation process for the CLM-Community compared to less sophisticated but cheaper and faster approaches.

2.1.3. Preparation of a common evaluation framework

Having in mind the goals of the community to find an optimal model configuration or to release recommended versions, an easy and fast way to analyse the performance of climate simulations is urgently needed. An evaluation of various model versions becomes a very complex task and doing it manually is not feasible. Based on the experiences with the EvaTool, the Helmholtz-Zentrum Hereon started to develop the Hereon-EvaSuite. This tool is very flexible and designed for very complex workflows, which consider different types of models, reference data sets, atmospheric variables and evaluation metrics.

One main goal for the near future (beginning of 2022) is to implement the Hereon-EvaSuite (i.e. a simplified version called ‘EvaSuite Lite’) into the runtime environment SPICE. Thus, the user of ICON-CLM has the possibility to evaluate a climate simulation within the runtime environment immediately. Moreover, it will be possible to include at least one additional simulation into the evaluation workflow. The user’s climate simulation can then also be validated against the results of this reference simulation. Finally, this workflow might also help the scientists in the CLM-Community to decide about a recommended version of ICON-CLM. However, the main challenge with the ‘EvaSuite Lite’ is the maintenance of the observational datasets. For instance, a catalogue with data sets available for the evaluation needs to be documented and made accessible for all CLM-Community members.

A long-term goal is the implementation of a link between the capabilities of the Hereon-EvaSuite and the FREVA framework (efficient and comprehensive access to the model database as well as to evaluation data sets) installed at the DKRZ. This step will give access to the numerous climate simulations and observational datasets provided within the FREVA archive. Moreover, the evaluation process is documented and the results (figures) can be shared with other users. However, the functionality of the FREVA system has to be extended to handle a bunch of datasets within one single evaluation experiment. Additionally, it is expected to archive the numerical output of the evaluation and validation in a database-like format to establish an information platform for all community members.

2.1.4. Provide training course for ICON-CLM

COSMO-CLM has been used by many people in the last two decades and is still applied by many community members in more than 80 institutions all over the world. An important reason for that success is the low entry threshold when starting the work with the model. The easy to use starter package together with the annual training course provided a very good entry point for new model users. Many participants of the training course, but also group leaders who send Ph.D. students and/or new project staff to the course, have always highlighted how important the technical infrastructure, training course and the support are for a good and easy start.

The NWP training course, organized by the DWD research department, already switched to ICON in 2018. The last COSMO-CLM training took place in 2019. Up to now, it was unfortunately not possible to elaborate a new training course based on ICON-CLM. A starter package for ICON-CLM (SPICE, Starter Package for ICON-CLM Experiments) is already available, but the remaining components of the course have not been transferred/adopted to the new model system yet, due to a lack of resources. This is an urgent task, because the community should be able to provide an ICON-CLM training course as soon as the first recommended model version is available. This is expected for the end of 2021 or beginning of 2022.

2.1.5. Provide and maintain runtime environment for community models

Running a climate simulation requires the precise and timely execution of many tasks to handle the data flow and the job management. The first step is the preparation of the initial and boundary data provided by global climate model or reanalysis data sets as well as the climatological data on the chosen regional climate model grid. The second step is the interpolation of the initial and boundary data to the grid of the regional model. The next step is the setup of the regional model itself through appropriate namelist settings. After the model step has been completed, the output of the simulation must be post processed, which includes the computation of time series for selected quantities and the archiving of the output. Due to computing time and disk space limitations the different steps cannot be performed in a single run-through for long climate simulations, but the whole simulation period must be divided into small parts (mostly months). This requires scripts (called runtime environment) that create a loop over the sub-periods.

The creation of such a runtime environment is time consuming and requires a lot of experience and background knowledge of the single steps. The CLM-Community therefore provides a runtime environment for new members. In the annual training course, new members have the opportunity to learn the basics of the runtime environment and perform simulations. These runtime environments are very similar for COSMO-CLM and ICON-CLM. For COSMO-CLM the runtime environment has no specific name, it is just called “starter package for COSMO-CLM'', for ICON-CLM it is called SPICE (Starter Package for ICON-CLM Experiments). The maintenance and, if necessary, the adaptation of the runtime environment (e.g. in case the HPC system changes or new components should be added to the model system) is a very important task, which is covered by WG SUPTECH. The CLM-Community has to ensure that enough resources for this task are provided continuously. A comparatively small investment here saves a lot of working time for many others and in many cases puts users in the position to run the model at all.

2.1.6. Standardization of model output

Standardization of model output is required by coordinated projects of the World Climate Research Programme (WCRP), such as CMIP or CORDEX, before the data can be published via the data nodes of the Earth-System-Grid Federation (ESGF). The CMOR (Climate Model Output Rewriting) tool was developed to transfer the model output into the required format in a joint effort by several member institutions. The tool must be flexible and must work with various model output, over various domains and for various spatial and temporal resolutions. The code is made available through the C2SM GitHub repository: https://github.com/C2SM-RCM/CCLM2CMOR.

The standardization process is divided into two steps. The first step is the post-processing phase of model output. It uses shell scripts that extract the original model output, cut off the relaxation zone, generate time series and create additional necessary variables. The second step is the actual CMORization step. It is based on Python scripts that process each variable at the required resolution, derotate wind fields, create standard directory and filename structure, and add required global and variable attributes. The CMORization step is mandatory to pass the Quality Assurance checker developed at DKRZ, which is a prerequisite for data publication via ESGF. The tool is well designed, efficient and easy to use. However, the user needs to invest some time and effort to make sure that the CMOR outputs are generated accordingly. It is therefore absolutely necessary to read the various documentations made available within the tool.

Nonetheless, the tool requires maintenance and it is necessary to provide some support for the users. Depending on the hardware of the user, it might also be necessary to adapt the code (e.g., different Python libraries or shell/CDO versions). The tool will likely have to be adjusted to the new standards that will be defined in the context of the upcoming CMIP6 downscaling.

Some possibilities for improvements have already been identified:

- Creation of a 3D soil moisture output (under discussion within CORDEX) including information about soil layers bounds.
- Creation of generic batch scripts, which can be adapted depending on the HPC system on which the software is used.
- Creation of a formal user's guide.
- Implementation of additional informative warnings and error messages (e.g., derotation of averaged wind fields).
- Investigation of potential memory issues with high-resolution high-frequency fields.

2.2. Model development: improve and extend ICON-CLM to produce better simulations results

ICON is a modelling framework that has been developed for NWP and climate applications essentially by DWD, MPI-M, DKRZ and KIT in the last 20 years. Up to the end of 2020, the framework included two different and non-exchangeable physics packages (one for NWP and one for climate applications). Meanwhile, a decision has been taken by the ICON consortium, that all future developments will only be based on the NWP physics package. The CLM-Community always relied on the NWP physics package for regional climate simulations, in COSMO as well as in ICON. Nevertheless, since the NWP physics package of ICON was developed for NWP applications, many adaptations, extensions and further development are necessary to prepare the model for regional climate applications and especially to further develop the model towards a regional earth system model that includes more components of the earth system than just the atmosphere. Some specific goals in this direction are described in the subsequent parts of this chapter. The first part will focus on some general aspects and overarching topics.

Beside the quality of the results, a (regional) climate model must fulfil some technical requirements to be applied in an efficient and reasonable way. A key criterion for a climate model is the number of simulation years at the target resolution that can be produced per unit of time. This requires a high runtime efficiency and usability on new and powerful computer architectures, especially if simulations should be done at very high spatial resolutions for long periods. Working on the improvement of runtime efficiency and the portability of the model code to new architectures is not among the core tasks of the CLM-Community, and at the time of writing also beyond the resources that are available in the community. Fortunately, the ICON consortium itself has very strong interest in these topics and the CLM-Community can take advantage of the improvements and new developments. Therefore, it is necessary to monitor the ongoing work in the ICON consortium, ensure that the improvements can also be applied for the limited area mode of ICON, perform tests with ICON-CLM and provide feedback to the developers. However, it has to be mentioned that using the model on new architectures requires of course access to appropriate HPC systems and this might not be fulfilled for all (maybe even many) community members. Therefore, it must be ensured that the model can still be used on established systems like massively parallel multiprocessor supercomputers in the future.

As already mentioned at the beginning of this chapter, the ICON consortium decided at the end of 2020 to stop the development of the climate physics package and to switch to the NWP physics package for all applications and future developments. This requires of course major changes and extensions in the NWP physics packages to prepare it for climate applications as well as seasonal and decadal predictions. Among these necessary extensions are the use of transient aerosol changes, an improved land-surface model, coupling of an ocean model and a better representation of sea ice. The new ICON version that will result from these developments is named “ICON-Seamless”. ICON-Seamless will include many components and features that are also very relevant and helpful for regional climate simulations. A similar line of reasoning as for the technical requirements can be applied here. The CLM-Community has to monitor and support the ongoing activities and try to ensure that all relevant extensions and features can also be used within ICON-CLM. The community should at least test new functionalities for usability in regional climate applications and provide feedback to the ICON consortium, but ideally also support and participate in the development and implementation of new features for the limited-area mode where possible and necessary. This is a unique chance to make a big leap towards a full-fledged regional earth system model with moderate work input.

Other important topics with respect to model development are availability and sustainability of code changes and new developments. In the past (for COSMO-CLM) many improvements and extensions of the code were done in private versions at the different member institutions and have never been transferred back to official COSMO releases. This is not only contrary to the community idea, but also not efficient and sustainable. Only developments that flow back to the main code version and become part of official releases can be used, improved and taken as a starting point for further developments by others. In addition, the compatibility of code changes and new features with changes from other groups within the ICON consortium can only be tested and guaranteed, when they are available in official versions. Therefore, it is absolutely necessary that any developments and all code changes in ICON from members of the CLM-Community that are potentially interesting/helpful for others are merged back to the main code. The administrative basis for that has been set with the “Development partnership agreement between DWD and the CLM-Community with respect to the ICON software” and the practical workflow has been defined and a documentation provided by PG ICON and the coordination group together with the COSMO contact person and some of the core developers of ICON. For the period of validity of this strategy document, it is absolutely important that the community members fill these frameworks with life and establish workflows and technical knowledge that allow an efficient and sustainable development of ICON-CLM.

2.2.1. Implementation of a generalized interface

The members of the CLM-Community cover a wide range of scientific interests. Therefore, COSMO-CLM has been expanded by a lot of additional functionalities, e.g. additional diagnostics or whole models: different ocean models are coupled, the Community Land Model was used instead of TERRA, TERRA was expanded by TERRA_URB, a wind gust diagnostic has been added as well as at least three atmospheric chemistry modules, among them the Modular Earth Submodel System (MESSy), which can now be used by all CLM-Community members for on-line diagnostic (see section 2.2.7).

ICON has also the potential to allow for a wealth of new scientific applications for a wide community of researchers modelling the Earth System. However, state-of-the-art modelling of the Earth System often requires additional model components like global or regional ocean models, land or vegetation models, atmospheric chemistry models, and advanced on-line diagnostic capabilities (e.g. feature tracking). Furthermore, for scientific applications it is often necessary to add new or other submodels for these components than the ones, which are already available in the standard ICON modelling framework.

As the CLM-Community is moving towards ICON-CLM, most of the member institutions want to transfer the developments they have done and implemented in COSMO-CLM also to ICON-CLM. However, incorporating such codes into the ICON framework requires two-way access to internal ICON variables and data structures. This is largely inhibited by the fact that ICON lacks a modular design with clean and clear interfaces (API) to allow for additional components. Depending on the specific needs, the latter could be either internally or externally coupled.

Therefore, the CLM-Community sees the need for bridging the gap between the extremes of a highly optimized and tailored model for operational NWP on the one hand-side, and a very flexible research platform for a wider community on the other hand-side.

The CLM-Community tries to achieve this goal in cooperation with other interested scientific groups. Therefore, the development of a Generalized Interface In ICON (GI3) was proposed to the ICON steering group by a broad initiative of scientific institutions working on climate modelling. Only the implementation of such a generalised interface will avoid the evolution of several individually altered ICON derivatives, which are no longer compatible among each other and with new ICON developments. The generalised interface in ICON would facilitate the easy exchange of code and ICON extensions in the ICON user community. In addition, using GI3 will significantly reduce the resources required to keep CLM-Community specific expansion up to date for the community.

The CLM-Community will promote a solution for an interface that allows for a flexible coupling of other submodels to ICON. Many community members expressed their willingness to support and contribute to developments in this direction. The CLM-Community of course recognizes that an accepted and robust solution requires agreement among and coordination with all patterns involved in the ICON development and especially with the ICON Consortium.

2.2.2. Improve representation and treatment of aerosols

State-of-the-art earth system models (ESMs) used for climate change studies are no longer considering only the effect of increasing greenhouse gases on global and regional climate. Most of them can already take further anthropogenic influences on the Earth system and its climate development such as changes of land use and of aerosol concentrations in the atmosphere into account. Most of the regional climate models currently used by the modelling groups worldwide, including COSMO-CLM and ICON-CLM, lag behind these capabilities of global ESMs. Therefore, it is very important to complement the physical processes represented in ICON-CLM with these additional features. Otherwise, ICON-CLM would only be able to transfer parts of the GCM forcing to the regionalization of past and future climate developments.

This demand is in line with the currently discussed requirements for the next generation of CORDEX simulations. The modelling groups are explicitly encouraged to apply up-to-date regional or global aerosol datasets with realistic variability in time (monthly variation and trend) and space, as observed for evaluation runs and consistent with the aerosol forcing in the driving CMIP6 simulations for historical and future periods. Within the CLM-Community, the topic will be covered by WG CCAR. In order to consider both effects of aerosols, the direct effect on the radiation transfer and the energy budget of the earth system, and the indirect effect via the influence on microphysical processes for the formation of clouds and precipitation, the necessary model development could be realized in four steps:

- Modification of the already prescribed climatological monthly values for the aerosol optical depth (AOD, based on Tegen) by an appropriate time-dependent data set of monthly and annual varying AODs.

- Adjustment of aerosol treatment to analysed or projected aerosol concentration instead of AODs.
- Extension of the microphysical parameterizations by taking into account the specified time-dependent aerosol concentrations.
- Coupling of ICON-CLM with a prognostic treatment of aerosols and an extended microphysics as provided by ICON-ART or MESSy.

2.2.3. Improve representation of land cover and land use change

For climate applications, the representation of land surface processes in the model is still insufficient, but some developments are already ongoing (e.g. vertical inhomogeneous soil texture, multi-layer snow model, carbon cycle, phenology, hydrology). Furthermore, a new ICON version, which is coupled to JSBACH, will be made available in 2022 in the context of ICON-Seamless. Some of these developments go along with the need to develop or improve external parameters for the model to account for temporarily changing and spatially heterogeneous biogeophysical properties (e.g. soil characteristics, land cover, plant functional types, urban fabric, etc.) at high resolution.

One goal in this context is the implementation of dynamic vegetation changes for climate time scales, which further includes a carbon exchange between land surface and atmosphere. The implementation must account for the additional processes, but also be computationally manageable at the same time. The approach should be flexible and account for various purposes (e.g., natural and managed land) and diverse climatic regions in the world. Processes can be included by coupling of sub-models or direct implementation. The new features can be switched on or off according to the scientific question and desired complexity of the model system. Changes for the treatment of vegetation and soil in the model will ultimately lead to changes in the radiation (regarding e.g. albedo) and turbulence schemes (turbulent fluxes).

Due to these developments, the complexity of land-atmosphere interactions will be better represented in the model. Such improvements are necessary in order to assess the impact of land use changes on the regional climate conditions, as it is done in the coordinated model-intercomparison project Land Use and Climate Across Scales (LUCAS). In the framework of this project, COSMO-CLM was coupled to different Land Surface Models (LSMs; e.g. Community Land Model, VEG3D). The coupling of these or similar LSMs to ICON will also be needed in future to consider the uncertainties in land-atmosphere modelling.

For urban climate studies, TERRA_URB will be applied for different regions of the world. For this purpose, the urban input parameter datasets need to be collected, processed, and provided. Further studies will investigate the representation of urban hydrology and urban water use, as well as vegetation and urban fabric changes (e.g., greening).

The added value due to better resolved land surface processes will be explored especially with respect to the presentation of extremes (vertical inhomogeneous soil texture, further develop multi-layer snow model, carbon cycle). Here, new reference data sets need to be explored (e.g., REA6, eddy-covariance measurements, vertically resolved information from towers, aircraft or radiosondes, 3D snapshot information from cloud radars or doppler lidars). All activities in this context will be led by and coordinated within WG SOILVEG.

2.2.4. Coupling of an ocean model

Many modelling studies have shown a positive impact of coupling ocean and atmosphere in regional simulations. Improvements can be seen directly over the coupled ocean but also over land areas in the modelling domain. The coupling is especially beneficial when applied with high resolution in space and time over the regional ocean surfaces. Thus, developing a performative regional climate model with explicit modelling of the atmosphere-ocean interactions is an important factor to represent the regional climate and its change adequately.

COSMO-CLM itself does not include an interactive ocean module and is thus missing the dynamical feedback between ocean and atmosphere. This limits the possibility to understand regional climate interactions, like for instance the importance of atmosphere-ocean coupling for extreme events. Furthermore, an uncoupled model depends highly on the SST provided by the driving model and inherits its SST biases. To overcome these limitations, several groups in the CLM-Community have developed coupled atmosphere-ocean versions of COSMO-CLM for different regional oceans in the past decade. The regions cover so far the Mediterranean (coupling the NEMO model), the North Sea and the Baltic Sea (coupling also NEMO), the Arctic and Antarctic Ocean (coupling FESOM), and the South Atlantic (coupling ROMS). Studies using these coupled versions of COSMO-CLM have shown a clear added value compared to using an uncoupled ocean.

The CLM-Community has neither the capability nor generally the oceanographic knowledge to develop the dynamical components of a regional ocean model for a specific sea, let alone for all oceans of the world. Thus, the coupling (with the exception of FESOM) has been achieved by implementing a unified interface in COSMO-CLM_4.8 with the commonly recognised, and fully parallelised, OASIS3-MCT coupler. Although this does not provide a regional modelling system with all the main components of the climate system included, the unified interface with a widely used coupler provides a modular and flexible solution to include multiple regional ocean models (and more) adapted to the region and tested by experts for these models.

The idea of a flexible unified interface was revived in the implementation of the Generalized Interface In ICON (GI3) as proposed earlier on (section 2.2.1). This approach is broadly based in the CLM-Community, supported by the knowledge and willingness to contribute to developments in this direction by several members. An alternative approach would be the use of the ocean model ICON-O that is globally available and can be regionally refined with a higher resolution in the area of interest. ICON-O is being coupled to ICON (NWP physics) in the context of the ICON-Seamless development. At least one of these two approaches needs to be followed. Only this will give the CLM-Community a tool to study feedback mechanisms between the atmosphere and ocean with a state-of-the-art modelling system also in the future, and to provide climate change simulations taking atmosphere-ocean interactions into account. Ocean coupling activities will be led by and coordinated within WG AIO.

2.2.5. Development of a coupled global-regional ESM

State of the art global earth system models incorporate a variety of key processes to describe changes of the Earth’s climate such as detailed land, ocean and vegetation models, aerosol dynamics and detailed atmospheric chemistry. However, due to their large complexity, the resolution that can be used for long-term simulations is still limited. Key regions cannot be resolved adequately. Therefore, regional earth system models (RESMs) are applied for key regions. These models offer a high resolution, but limited spatial coverage. In addition, they require adequate boundary conditions. Usually, these are provided from previous simulations with a coarser resolution (off-line nesting). Especially for configurations with complex atmospheric chemistry and aerosols, however, an offline nesting is not feasible, as boundary data is required for 100 - 1000 prognostic variables.

To overcome this issue the MECO(n) model has been developed within the MESSy consortium. The model couples a global ESM, based on the ECHAM5 dynamical core, with a regional chemistry climate model based on COSMO-CLM. The global and regional model are coupled on-line, i.e. boundary conditions are exchanged during runtime.

Generally, ICON already offers a ‘nesting’ possibility. However, the change of the grid spacing from one nesting step to the next is limited to a factor of two. Very complex model configurations have the need for much larger resolution jumps (around 5). Here, the coupling solution developed for MECO(n) is much more flexible as the coupling solution currently available in ICON. Therefore, it is planned to develop a successor of MECO(n) that is based on ICON.

To achieve this goal, the MECO(n) coupling strategy needs to be adapted to ICON. In addition, the development of ICON-CLM towards a regional earth system model (see section 2.2.6) will help to improve the amount of incorporated processes on the regional side. Based on this development, the CLM-Community could participate in CORDEX also using a variable resolution global circulation model (VR-GCM), without the need of using classical off-line nesting, but instead with using on-line nesting of ICON-CLM into ICON.

2.2.6. Develop ICON-CLM towards a regional earth system model

The creation of a regional earth system model (RESM) is a long-standing goal in the CLM-Community and in the regional climate modelling community as a whole. Global climate models have evolved from atmosphere only models to full-fledged regional earth system models in the last decades. The need to improve and extend also regional models in that direction has also been identified a long time ago and many steps have already been taken in that direction. COSMO-CLM for example has been coupled to a regional ocean model and a runoff model and more sophisticated land models have been integrated and used for sensitivity studies. However, it was not possible up to now to provide a complete and ready-to-use package that includes at least the main components of the climate system, because this is challenging from a scientific as well as from a technical point of view.

Nevertheless, the recent CORDEX protocol encourages/recommends the use of more components of the earth system than just the atmosphere for regional climate projections and clearly states that efforts towards RESMs, which include additional model components to represent other processes, must be increased. It is only a question of time until RESMs will be the standard in regional climate research. The CLM-Community has to prepare for that and invest resources in the development of an ICON based RESM. The surrounding conditions to achieve this goal are better than ever. The developments and activities in the context of ICON-Seamless will bring many functionality and components to the NWP physics package that are necessary for an RESM. The CLM-Community should take advantage of that, contribute to these developments and provide the necessary resources to make the developments also available in the limited-area mode of ICON. This goes hand in hand with the necessity to bring developments and extensions from the community back to the main ICON code. If both points are pursued consistently in the next few years, it is possible to have an ICON based RESM available by the end of the validity period of this strategy document.

2.2.7. Implementation of flexible online diagnostics

Alongside increasing computing power in modern HPC systems, regional climate modelling moves forward to higher and higher resolutions. However, the storage space is not increasing in the same manner and post-processing work is increasing exponentially with the resolution. Thus, to keep the data management of high-resolution simulations feasible and keep the added value from the increased resolved details in the simulations, the usage of online diagnostic tools calculating the target variables directly during the model simulation will be inevitable in near future. Only these tools enable a sufficient data reduction.

The required on-line diagnostic covers a wide range of applications: Starting with on-line statistics (e.g., accumulation of fields, determination of minima and maxima w.r.t. time or event counts), it also encompasses data reductions to specific locations (e.g., to measurement stations, flight paths, ship tracks or satellite orbits) or on iso-surfaces such as pressure and height levels or potential temperature iso-surfaces and is reaching out to feature tracking and the calculation of much more complex key-figures as the lightning potential index (LPI) or a clear air turbulence diagnostic index (TI).

The COSMO model itself includes only a small number of these diagnostics. However, COSMO-CLM has been coupled to the Modular Earth Submodel System (MESSy) for a decade now and MESSy does include a wide range of on-line diagnostic tools. Therefore, the MESSy-Community provided a COSMO-CLM/MESSy version to all CLM-Community members, which enables them to use the high number of namelist driven on-line statistic tools available in MESSy. Furthermore, the runtime environment was also expanded to run with COSMO-CLM/MESSy. This version will be used for the evaluation of COSMO 6.0.

Obviously, the need for on-line diagnostic tools will not become less when switching to ICON-CLM. ICON itself contains some more on-line statistics, but does still not cover the range of on-line diagnostics required by the CLM-Community. Therefore, in the same way, as for COSMO-CLM, ICON-CLM and the SPICE runtime environment will be expanded to work in conjunction with MESSy.

2.3. Application

Besides the application of COSMO-CLM/ICON-CLM for scientific research projects within the member institutions, the major community effort in the upcoming years is the downscaling of CMIP6 simulations and the participation in CORDEX.

2.3.1. Downscaling of CMIP6 simulations and participation in CORDEX

The CLM-Community will continue to contribute to coordinated international efforts to provide up-to-date regional climate projections. This includes in particular the participation in the downscaling of CMIP6 within CORDEX and EURO-CORDEX. In addition, community members take part within other coordinated projects, like the CORDEX Flagship Pilot Studies (e.g. FPS Convection, FPS LUCAS, FPS ELVIC) and further projects within or beyond CORDEX. This requires joint and coordinated contributions from several member institutions of the CLM-Community to avoid redundant work. The CORDEX activities within the CLM-Community will be coordinated by WG CP and WG CRCS.

The coordination includes numerous activities: the selection of suitable global forcing data and the assignment of the simulations to the member institutions, the provision of the suitable converters for the GCM data and the necessary input data, harmonized model setups and joint analysis with common tools. Especially the (CMOR-) standardisation tool that transfers the raw model output to the format requested by CORDEX and other activities is very important in this context. Without this tool, a publication of the simulation data via the data nodes of the ESGF, and therefore the participation in the coordinated downscaling projects, is not possible. A standardization tool must be available, updated and further developed if necessary at any time (see section 2.1.6). Furthermore, the representation of the community by some of its members within these projects is important to be able to coordinate the work in the CLM-Community with the overarching activities.

3. Abbreviations

Abbreviation	Description
AOD	Aerosol optical depth
BTU	Brandenburg University of Technology Cottbus - Senftenberg
CDO	Climate Data Operators
CLM-Community	Climate Limited-area Modelling Community
CLM-CO	Coordination Group of the CLM-Community
CLM-SAB	CLM-Community Scientific Advisory Board
CMIP6	Coupled Model Intercomparison Project - Phase 6
CMOR	Climate Model Output Rewriting
COSMO	Consortium for Small scale Modelling
COSMO-CLM	COSMO model in Climate Mode
CORDEX	COordinated Regional Downscaling EXperiment
DKRZ	Deutsches Klimarechenzentrum (German Climate Computing Center)
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DWD	Deutscher Wetterdienst
ECHAM5	Atmospheric Model for climate applications developed by MPI-M
ESGF	Earth-System-Grid Federation
ESM	Earth System Model
ETHZ	Swiss Federal Institute of Technology Zurich
EURO-CORDEX	Coordinated Regional Downscaling Experiment for Europe
FPS	Flagship Pilot Study
GUF	Goethe University Frankfurt
HEREON	Helmholtz-Zentrum Hereon
ICON	ICOsahedral Non-hydrostatic General Circulation Model
ICON-ART	ICON with extensions to enable the simulation of gases, aerosol particles and related feedback processes in the atmosphere
ICON-CLM	ICON in Climate Limited-area Mode
ICON Consortium	DWD, MPI-M, KIT ,DKRZ
ICON-NWP	ICON with NWP physics package
ICON-Seamless	ICON model based on NWP physics package able to operate seamlessly on weather as well as climate time scales
JSBACH	Land component of the MPI-M earth system models
KIT	Karlsruhe Institute of Technology
LSM	Land Surface Model
MESSy	Modular Earth Submodel System
MPI-M	Max-Planck Institute for Meteorology
NWP	Numerical Weather Prediction
PG ICON	CLM-Community Project Group ICON
RESM	Regional Earth System Model
RCM	Regional Climate Model
RCS	Regional Climate Studies
SPICE	Starter Package for ICON-CLM Experiments
UKa	University of Kassel
VR-GCM	Variable resolution global climate model
WCRP	World Climate Research Programme
WG AIO	CLM-Community Working Group Atmosphere, Ice and Ocean
WG CCAR	CLM-Community Working Group Chemistry, Clouds, Aerosols and Radiation
WG CP	CLM-Community Working Group Climate Projections

WG CRCS	CLM-Community Working Group Convection resolving climate simulations
WG EVAL	CLM-Community Working Group Evaluation
WG SOIL VEG	CLM-Community Working Group Soil and Vegetation
WG SUPTECH	CLM-Community Working Group Support and Technical Issues