Climate Limited-area Modelling Community

CLM-Community Science Plan 2014-2018

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1 Outline of the science plan

The present CLM-Community Science Plan defines the goals of the community for the period 2014-2018, identifies a strategy and outlines proposed actions to achieve these goals. Furthermore, the related research challenges and the ongoing scientific developments in the CLM-Community as well as the status and expertise of the CLM-Community are discussed.

The CLM-Community science plan is written by the CLM-Community Coordination group and reviewed by the members of the CLM-Community scientific advisory board in order to provide a guideline for the community activities and as an orientation for the members working in a specific field.

2 Challenges of regional climate modelling

Climate change continues to be one of the major challenges in our research community. The recent 5th assessment report of the IPCC (IPCC 2013) has largely confirmed the previous 4th report, but there are still major uncertainties regarding continental and sub-continental-scale regional climate change, as well as the associated impacts on the water cycle and extreme events.

Especially the estimation of the occurrence of future extreme events pose a great challenge to the scientific community since on the one hand it is difficult to statistically ascertain their representativeness (because of their infrequence) but on the other hand they could cause great damages and losses touching many sectors of social and economic life. The IPCC SREX report finds relatively small projected changes in the coming decades compared to the natural climate variability where even the sign of the projected changes in some climate extremes is uncertain (IPCC (SREX), 2012). For projected changes by the end of the 21st century the uncertainty is even higher. Depending on the extreme investigated either model uncertainty or uncertainties associated with emissions scenarios used becomes dominant (IPCC (SREX), 2012).

For a successful climate change mitigation and adaptation policy this uncertainty needs to be reduced. This requires a profound understanding of the climate system and expected climate change. The improved understanding for the underlying physical processes and the reduction of model errors finally needs to enter state-of-the-art climate models to ensure higher quality climate projections. Unfortunately, the identification of the model insufficiencies is difficult due to the high complexity of the climate system.

For decision makers it is of high importance to receive the information needed on a regional to local scale. Because the horizontal resolution of global climate models is still rather coarse (approx. 200 km) regional climate projections at higher spatial resolutions are needed. So, several regional climate model (RCM) scenarios are made available within the CORDEX initiative[1] (Jacob et al., 2013; Vautard et al., 2013; Nikulin et al., 2012).

Key questions of regional climate change impacts like flood risk, water availability, water quality, and crop productivity cannot be directly answered by RCMs. Others, like the persistence of hot days (e.g. Paris in summer 2003) or snow amounts need to be answered with higher confidence than by present day model systems. For instance, in hydrological impact studies Maraun et al. (2010) define these needs as the correct representation of (1) intensities, (2) temporal variability, (3) spatial variability, and (4) physical consistency between different local scale variables. Thus,

- there is a need for more reliable projections of key climatological variables like temperature and precipitation for specific regions and land use types,
- not only the climate change signal but also the climate itself is of particular importance for climate change policy in different regions of the world and
- there is a need for an extended range of applicability.

3 Potential of the CLM-Community and COSMO-CLM

The **C**limate **L**imited-area **M**odelling-Community (CLM-Community[2]) is an open international network of scientists who accepted the CLM-Community agreement as a basis of joint efforts in COSMO-CLM development and application. By the end of 2015 it had 250 scientific members from 70 climate research institutions all over the world. It is the largest obliging cooperation in the field of regional climate modelling aiming to address the challenges of model development stated above, to efficiently use the computing resources and to make substantial contributions to answer the key questions of regional climate modelling.

The Climate Mode of the COSMO model (COSMO-CLM or CCLM) is one of the most advanced limited area model systems with respect to model dynamics, numeric and physical parameterization (Rockel et al., 2008). A lot of studies demonstrate that COSMO-CLM can realistically simulate weather and its statistics in comparison to observations (e.g. Kotlarski et al., 2014;

[1] http://wcrp-cordex.ipsl.jussieu.fr/

[2] http://www.clm-community.eu/

Panitz et al., 2013). However, the advantages of RCMs compared to GCMs become obvious mainly in regions with inhomogeneous or complex topography.

COSMO-CLM is of high relevance for climate research, climate mitigation and adaptation studies since the COSMO model or COSMO-CLM is one of the few limited area numerical model system designed for spatial resolutions down to 1 km, which

- has a well-tested range of applicability encompassing operational numerical weather prediction (COSMO), regional climate modelling of past, present and future (CLM), idealised studies (ITC) and the dispersion of trace gases and aerosol (ART) on short to medium time scales,
- was successfully applied in several regions of the world,
- has widely been used to downscale the results of global climate models and,
- is well documented.

COSMO-CLM is based on the non-hydrostatic compressible COSMO model. COSMO was originally developed by the Deutscher Wetterdienst (German Meteorological Service, DWD) for operational numerical weather prediction and is now applied and further developed by the COnsortium of national weather services for Small scale MOdelling (COSMO), the CLM-Community, the ART research groups and further universities and research centres. The idea to regularly provide a unified model version for weather and climate became a guiding principle of the further model development. The joint development of one model system allows bringing together the expertise from different institutions and perspectives. The close cooperation with COSMO culminating in a regular unified model version for weather and climate combines the expertise of NWP and RCM and guarantees high standards of a community model.

COSMO-CLM is an atmosphere model coupled to the soil-vegetation model TERRA. Additionally, there is the possibility to use COSMO-ART (Vogel at al., 2009), which enables the calculation of the interactions of trace gases and aerosol with the atmospheric radiation. Other regional processes in the climate system like ocean and ice sheet dynamics, plant responses, aerosol-cloud interaction, and the feedback to the GCM driving the RCM are prescribed or neglected. The dynamical treatment of these physical processes would increase the reliability of the model, if the quality - in terms of the models ability to reproduce the recent past - remains at least the same. Thus the next steps to improve the model's reliability and to extend its applicability are to include other processes in the model system like e.g. an ocean model, a river routing scheme, and an appropriate urban or glacier model. The development of such a regional climate system model is a challenge, which can only be met by a well-organized scientific community like the CLM-Community.

The quality of COSMO-CLM already achieved is documented in evaluation reports comparing the observed with the simulated regional climate of the recent past for previous and current model versions (Jacob et al., 2007). The evaluation report for cosmo_4.8_clm17[3] for Europe exhibits a substantial reduction of the mean temperature bias down to 0.3 K for the annual mean temperature at 1000 km scale in comparison to the previous model version CLM3. However, the precipitation bias and the diurnal cycle are still not satisfactory, in particular for adaptation and mitigation studies.

A huge variety of applications of COSMO-CLM exists within more than 200 scientific projects in the field of regional climate modelling covering high resolution simulations of megacities to medium resolution simulations of continents, tropical to arctic latitudes, paleo studies, the recent

[3] http://www.clm-community.eu/dokumente/upload/34daa_Evaluation-report_CCLM_4.8_v8.pdf (accessed 07 May 2014)

past, seasonal to decadal predictions and climate scenarios for the 21st century. The conduction of ensemble simulations for the 21st century for Europe and other continents is one of the key activities of the community.

4 Goals

The scientific objectives of the CLM-Community for the next four years are to

- improve the understanding of regional climate systems and climate feedback by conducting and analysing suitably designed RCM experiments (Chap 5.1),
- sharpen the predictive skill of the COSMO-CLM model by improving its formulation and use,
- extend the versatility and applicability of COSMO-CLM by adding new modules and processes aiming towards the development of a regional earth system model (Chap. 5.2)
- reduce the systematic errors of COSMO-CLM (Chap 5.3),
- ensure the usability of COSMO-CLM for the simulation of climate forecasts of seasons and decades to multiple centuries for climate projections and paleoclimatological reconstructions (Chap. 5.4, 5.5),
- ensure the applicability of spatial scales ranging from the coarse resolution (50 km) to the convection-permitting scale (1-3 km) (Chap 5.6),
- provide recommended model configurations including an intensive evaluation for different regions in the world (Chap. 5.7),
- provide a continuous update of the technical and scientific model documentations to guarantee the proper use of the model especially by new members of the consortium (Chap.5.8) and
- prepare the COSMO-CLM to emerging hardware architectures (Chap 5.9).

5 Strategy

To achieve the CLM-Community goals listed above, they have to be underpinned by respective activities. Thus, several working and project groups were established to foster the collaboration of CLM-Community.

5.1 Understanding of climate feedbacks at regional scale

A lot of studies demonstrate that RCMs can realistically simulate weather and its statistics in comparison to observations (e.g. Früh et al., 2010; Semmler et al., 2004). However, differences between RCM and GCM simulations are not always obvious for time-averaged quantities on larger scales or in homogeneous regions. The advantages of RCMs are mainly found in coastal or mountainous regions as well as in areas with inhomogeneous surface characteristics (e.g., lake district in Finland) exhibiting a high spatial or temporal variability (e.g., Feser et al., 2011) with respect to the meteorological parameters. In these regions the explicit simulation of such small-scale features leads to an added value compared to coarser resolved simulation results. The quantification of this added value is of common interest. It is the main justification for all our efforts in this field of research.

In order to contribute to the understanding of climate feedbacks, we aim to develop a tool for idealized cases (ITC) of feedbacks. These idealised tests should be conducted over time scales necessary to obtain stationary statistics at high accuracy.

It is also intended to investigate the feedback of the regional climate to the large scale or to neighbouring regions by a two-way nesting of COSMO-CLM with the ECHAM/MPIOM driving model. The accuracy of the atmospheric dynamics might be improved by taking into account the relevant feedback of the regional scale atmospheric dynamics on the large to planetary scales and vice versa.

5.2 Establish a Regional Earth System Model (RESM)

Another aim is to establish an earth system model encompassing all relevant components of the climate system like e.g. dynamical regional oceans, dynamical vegetation, a river routing scheme, or a 2-way coupling with global models (i.e. ECHAM or ICON). Furthermore, the dispersion of trace gases and aerosol (CCLM-ART or COSMO-CLM/MESSy) on climatological time scales has to be realised.

In order to develop a regional earth system, all components of the climate system need to be addressed in a regional earth system model (RESM). Since this issue asks for a wide range of expert knowledge and experience, it is tackled by coupling the component models to the atmosphere model COSMO-CLM. Thus, the key strategy in the CLM-Community is to provide a standard coupler (OASIS3-MCT) for all external climate system components.

The current COSMO-CLM (and COSMO) prescribes the surface temperatures over sea and sea ice surfaces. A coupled atmosphere-sea ice-ocean model is expected to better describe the interaction processes between atmosphere and ocean or sea ice and provides a physically consistent simulation of heat and freshwater fluxes between ocean and atmosphere (Meier et al. 2011). The coupling of regional oceans of high interest (Mediterranean, Baltic and Northern Seas, South Atlantic, Artic, Antartica, etc.) is ongoing (Ho et al., 2012, Pham et al., 2014; Akhtar et al., 2014). The coupled models enable to assess the impact of the atmosphere – ocean interaction. In addition, the differences in the implementations need to be assessed, evaluated, and understood.

Several aspects of the soil and vegetation physics in COSMO-CLM which are potentially relevant on climatological time scales are not or insufficiently represented by the native land surface scheme (TERRA) in COSMO-CLM. To alleviate this issue, more advanced Land Surface Schemes (Community Land Model and Veg3D) are coupled to COSMO-CLM resulting in improvements in the simulated mean climate conditions over Europe (Davin et al., 2011; Davin and Seneviratne, 2012) as well as in the representation of interannual variability and temperature extremes (Lorenz et al., 2012). In addition, TERRA is planned to be further developed with respect to consider dynamical vegetation, urban structure, changes to the groundwater table, a vertical inhomogeneous soil texture, river routing, as well as sea and lake ice surfaces. It is intended to perform an intercomparison of the impact of the different land surface schemes TERRA, Community Land Model, and Veg3D over different regions to elaborate the advantages of each approach. In addition, a participation in the global offline experiments protocol Global Soils Wetness Project phase 3[4] (GSWP3) is planned with the Community Land Model and TERRA.

Furthermore, it is necessary to better understand the role of land-atmosphere interactions at the regional scale. Therefore, it is of great importance to implement processes like e.g. the dynamical change of vegetation, the thawing of the permafrost, the transient change of land use (natural or anthropogenic), or the soil-moisture precipitation feedback at the regional climate.

For urban land investigations respective high resolution parameterizations are already implemented in COSMO-CLM (Schubert et al., 2012; Trusilova et al., 2013; Wouters et al., 2012). The outcome of these parameterizations is compared and the impact to the regional climate is assessed in Trusilova et al. (2014).

[4] http://hydro.iis.u-tokyo.ac.jp/GSWP3/

Aerosol particles modify atmospheric radiative fluxes and interact with clouds. However, as documented in the IPCC 2007 report the global influence of natural and anthropogenic aerosol on the atmosphere is not well understood. On regional scale the knowledge is even worse. Therefore, two coupled model systems are developed: COSMO-ART (aerosol and reactive trace gases), which is based on the operational weather forecast model COSMO of the German Meteorological Service (DWD)) and COSMO/MESSy which is based on COSMO-CLM. The M7 aerosol package with a much simplified chemistry will be incorporated in COSMO-ART to enable simulations over long time periods analogous to COSMO/M7 (Zubler et al.,2011). In addition, the climate mode of COSMO-ART will also be further developed.

COSMO-CLM/MESSy already includes M7 and other aerosol modules with alterable complexity. COSMO-CLM/MESSy needs to be further developed to include the full aerosol-radiation and aerosol-microphysics feedbacks. It is expected that a more realistic treatment of the aerosol have considerable impact on the regional climate.

5.3 Reduction of systematic errors

The climatological bias of present day RCMs is still in the same order of magnitude as the climate change signal for precipitation as well as extreme weather event statistics and other climatological variables, like radiation components. Climate impact studies require significantly higher precision and accuracy since the impact on economy and society depends sensitively on threshold values of relevant climatological variables.

For purpose of reducing the systematic errors all aspects concerning the ability to simulate at higher spatial resolutions should be revisited, since e.g., the numerical approximations are of increasing importance due to steeper slopes of the orography and the vertical discretisation is most probably a major source of uncertainty. The development of higher order numerical methods opens the opportunity to achieve higher accuracy at the expense of higher computing costs. The optimization of the lateral and top boundary relaxation for reference applications reduces unphysical boundary effects on the solution in the limited area. In addition, on long time scales the violations of the conservation properties are of increasing relevance.

Another source of model errors is the model physics. On long time scales and from a regional climate feedback perspective the analysis and improvement of the hydrological cycle including boundary layer mixing, convection, cloud microphysics and soil moisture, the surface fluxes, the turbulence parameterization, and the diurnal cycle are regarded as most relevant.

Approaching higher resolution simulations, some of the external parameters need to be replaced since they do not feature the small scale variety of physical properties of soil characteristics, land use, and vegetation.

To facilitate the introduction of new model versions and the application to new model domains at different resolutions, the tuning concept suggested by Bellprat et al. (2012) needs to be consolidated. Because of the high uncertainty induced by poorly confined model parameters of parameterized physical processes in climate models, an approach for an objective calibration is desirable. The common practice adjusting uncertain model parameters manually, often referred to as expert tuning, lacks objectivity and transparency, frequently leading to a hindrance of the implementation of new model parameterizations.

In close cooperation with the COSMO community, the analysis of the NWP (numerical weather prediction) and RCM (regional climate model) should be combined in a transpose AMIP manner[5] (running the regional climate model COSMO-CLM in weather-forecast mode). Since the CLM-Community is in the outstanding situation of having one model system for both climate

[5] http://www.metoffice.gov.uk/hadobs/tamip/

simulations and weather prediction, the transpose AMIP approach is an even more helpful tool as compared to only running weather forecasts with climate models. Understanding the drift of the forecast from a well initialised state can provide significant insight into the cause of the biases exposing a basis for future model development. Since many sources of model uncertainty originate from 'fast processes' (e.g. clouds), analysing climate models on these timescales could yield greater understanding of why their longer timescale response differs. As a very positive and most welcomed side effect this approach also strengthens the cooperation between both expert groups.

Some of the stationarity and balance assumptions in the model system are not necessarily valid on long time scales. The dynamical treatment of these assumptions increases the number of degrees of freedom of the model and thus increases the reliability of the climate change signal if the accuracy can be kept constant or can even be increased.

5.4 Seasonal to decadal prediction

Regional information is not only needed for weather or climatological time scales but also in the sense of a seamless prediction for intermediate time scales like the seasonal or decadal forecast. A deterministic forecast for these time scales is not possible because of the limited predictability of the climate system on time scale beyond about ten days. Therefore large ensembles of forecasts are simulated providing a likelihood for future occurrence of certain climate conditions (Deser et al., 2012; Fischer et al., 2013).

For this issue the demand to the model is a bit different since at these time scales the initial condition of the climate system is of higher importance than for long term climate projections. Therefore methods for better describing the initial state especially of the slowly changing components of the climate system like the soil or the ocean need to be improved.

The probability of occurrence of a future climate state might be derived by perturbing the initial (or boundary) conditions, disturbing model physics or including a multi-model forcing approach in order to receive an ensemble from the non-linear system. Different approaches for establishing sufficiently dispersive ensembles, e.g. by spatial shift of the atmospheric forcing (Sasse and Schädler, 2014) need to be developed. An important issue in this respect is to quantify the reliability and predictability of the forecasting systems, regional climate projections and climate change signals.

Another challenging task for research is the issue of statements on the robustness of the ensemble or the minimum number of ensemble, since it is assumed to be depending on the meteorological variable to be investigated, the regions of the world in focus, and the time scale for the forecast or the projection.

5.5 Paleo-climate reconstructions

The climate system varies and changes over all time scales, and it is instructive to understand the contributions that external forcing and lower-frequency patterns of climate change might make in influencing higher-frequency patterns (Prömmel et al., 2012, Tang et al., 2013a, Tang et al. 2013b). In addition, an examination of how the climate system has responded to large changes in climate forcing in the past is useful in assessing how the same climate system might respond to the large possible changes in the future.

Because of the very long time periods necessary for paleo-climate reconstructions, usually simulations at coarse resolutions of about 50 km are performed. Therefore, the skill of COSMO-CLM simulation at this rather coarse resolution still has to be assessed.

5.6 High resolution climate simulations

The increasing computing capacity allows tackling several tasks, e.g. the direct numerical simulation of mesoscale processes (e.g. the flow over idealised mountain chains or convective systems) at approx. 100 m horizontal resolution and the increase of the spatial resolution of real case application down to 500 m (Langhans et al. 2012a; Berg et al., 2013; Wagner et al., 2013). As part of this work, a large-eddy simulation (LES) parameterization has been implemented and tested in COSMO (Langhans et al. 2012b).

Work has also begun to exploit such convection-permitting/resolving resolution (grid spacing around 1-3 km) for climate studies. Recent studies show improvements in the representation of the diurnal cycle of precipitation (Hohenegger et al. 2008, Prein et al. 2013) and of short-term (hourly) precipitation statistics (Ban et al. 2014). The approach has also been used for real-case and idealized studies of the soil-moisture precipitation feedback (Hohenegger et al. 2009, Froidevaux et al. 2014). For a further improvement at these horizontal scales more effort will be put on

(1) balancing the model’s interplay between the numerical core and parameterisations which is a necessary step because relevant processes (e.g. deep convection) on former unresolved (parameterised) scales become resolved (cf. Leung et al., 2003),

(2) implementing highly resolved land surface information as input for the model’s lower boundary conditions (Brunsell et al., 2011) and

(3) the usage of observational data containing the full spatial/temporal variability (e.g. from special observation campaigns) and other alternative reference data, like data from nowcasting systems (Prein et al., 2013).

In addition, special statistical methods like the Fractions Skill Score (Roberts and Lean, 2008) need to be applied in model evaluation, because at smaller scales, one has to deal with the *double penalty* problem (i.e. shifts in time/space between modelled and observed processes which are limiting the applicability of traditional error statistics).

5.7 Evaluation and application

A continuous model evaluation effort is needed to regularly check the released model version which shall then be used for climate simulations in various regions in the world. Participating in regional model intercomparison projects (RMIP) or the CORDEX initiative[6] (Panitz et al., 2013; Feldmann et al., 2013, Kotlarski et al. 2014) helps to uncover model deficiencies.

A coordinated parameter testing (COPAT) project was performed to systematically evaluate the new model version of COSMO-CLM. COPAT supports the continuous model evaluation effort which is needed to regularly check the released model version. COPAT procedure can be transferred to test the model for other regions in the world

5.8 Continuous update of the model documentation

A good mirror of the community work is the availability of a scientific and technical documentation. Thus, an important issue is to keep the model documentation up-to-date with the ongoing developments and publish the key results regularly in peer reviewed publications.

5.9 Adaptation to emerging computer architectures

Another challenging issue is the efficient performance of COSMO-CLM at massively parallel computing architectures. In the framework of the Swiss “High Performance and High Productivi-

[6] http://wcrp-cordex.ipsl.jussieu.fr/

ty Computing" (HP2C)[7] initiative with the participation of the Swiss National Supercomputer Center (CSCS), MeteoSwiss, and ETHZ the dynamical Runge-Kutta core of COSMO was re-written to facilitate the adaptation to newly emerging computer architectures by the development of a domain specific language library in C++ for stencil computations (STELLA, see Gysi et al. 2014, Fuhrer et al. 2014). Further the physical parameterization schemes needed for cloud re-solving simulations were ported for use on GPUs (and possibly other accelerators) by adding OpenAcc[8] directives to the existing FORTRAN code (Lapillonne and Fuhrer, 2014) so that a prototype version of COSMO-CLM is available that runs on hybrid CPU/GPU architectures. This version will be used at ETHZ to run decadal simulations in climate mode at cloud resolving scales for the European continent. To open this development to a broader range of applications further parts of COSMO-CLM need to be ported. The HP2C initiative run out in summer 2013, but the work will be continued within the PASC[9] project.

5.10 Future challenges

At DWD the new modelling system ICON[10] (13 km grid spacing, 90 layers) will replace the cur-rent operational global NWP model GME (13 km grid spacing, 60 layers) in the last quarter of 2014. A few months later, a higher resolution European nest (6.5 km grid spacing) in ICON will replace the current operational regional model COSMO-EU (7km grid spacing, 40 layers). For the next few years, COSMO will still be used in very high-resolution regional applications (COSMO-DE, COSMO-DE-EPS), but until 2020 the whole COSMO system is planned to be replaced entirely by ICON modelling. There is already a limited area version of the atmospheric part of the ICON model available which is currently tested for a domain over Germany. It is im-portant for the CLM-Community to be involved in the development of ICON for the migration to the ICON modelling framework. For this purpose a project group ICON is already installed within the CLM-Community.

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[7] http://www.hp2c.ch/

[8] OpenACC (for Open Accelerators) is a programming standard for parallel computing developed by Cray, CAPS, Nvidia and PGI. The standard is designed to simplify parallel programming of heterogene-ous CPU/GPU systems.

[9] http://www.pasc-ch.org/

[10] Co-developed by Max Planck Institute for Meteorology Hamburg and DWD: http://www.mpimet.mpg.de/en/science/models/icon.html

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Abbreviations

Categories: A: abbreviation D: Data F: Format I: institution M: model P: research program

Abbreviations	Description	Categ
ART	Aerosol and Reactive Trace Gas	M
CLM-Community	Climate Limited-area Modelling Community	A
CLM	Community Land Model	M
CCLM-ART	Climate Mode of ART for the COSMO model	M
COSMO	Consortium for Small scale Modelling	I
COSMO/M7	COSMO model coupled with M7	M
COSMO/MESSy	COSMO model integrated in MESSy	M
COSMO-ART	COSMO model with ART module	M
COSMO-CLM	COSMO model in Climate Mode	M
DWD	Deutscher Wetterdienst	I
ECHAM	Atmospheric global circulation model of the MPI-M	M
ETHZ	Swiss Federal Institute of Technology Zurich	I
GCM	Global Circulation Model	M
GME	Generic Modelling Environment	M
HPC	High-Performance Computing	A
HP2C	Swiss Platform for High-Performance & High-Productivity Computing	P
HZG	Helmholtz-Zentrum Geesthacht - Centre for Materials and Coastal Research	I
IC	Initial Conditions	A
ICON	ICOsahedral Non-hydrostatic General Circulation Model	M
IPCC-AR5	Intergovernmental Panel on climate change – 5th assessment report	P
LM	Lokalmodell (now named COSMO model)	M
MESSy	Modular Earth Submodel System	M
MPI-M	Max-Planck-Institute for Meteorology, Hamburg	I
NEMO	Nucleus for European Modelling of the Ocean	M
NWP	numerical weather prediction	A
OASIS3	Ocean Atmosphere Sea Ice Soil version 3	M
OASIS3-MCT	OASIS3-The Model Coupling Toolkit	M
RCM	Regional Climate Model	A
SVAT	Soil Vegetation Atmosphere Transfer System	M
TERRA	Soil-Vegetation-Model of COSMO model	M
Veg3D	Vegetation model - three-dimensional version	M