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Center for Environmental Systems Research

Impact on climate by land-atmosphere interactions

approved cumulative habilitation thesis

by

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Abstract

This synthesis of the cumulative habilitation explores the uncertainties of the impact of land-atmosphere interactions due to land use and cover change (LUCC) on the regional and local climate. The results are published in several papers of climate, environmental and atmospheric journals.

Efficient emission reduction policies are needed in order to reduce the increase in the rate of climate change intensification with increasing greenhouse gas emissions. This requires the development of mitigation and adaptation strategies for a sustainable use of the resources. According to the IPCC a key role is played by land use transformations to adapt and mitigate climate change for future scenarios aiming to stabilize temperature rise up to 1.5 °C. LUCC impacts land surface processes, which determine the turbulent and radiative fluxes between the land and atmosphere. These modifications affect atmospheric temperature and humidity and thus the planetary boundary layer structure, and cloud processes. Essential for mitigation and adaptation strategies is a sufficient characterization of associated uncertainties due to LUCC in climate models.

After an introductory overview, the conceptual basis of the processes within the regional climate model is presented. Then three objectives are addressed from a LUCC perspective. The discussion contains the uncertainties due to bias correction and model spatial horizontal resolution on climate metrics, due to LUCC in climate simulations, and due to the combined effect of LUCC and spatial resolution of the climate model.

Uncertainties associated with climate change projections are inherent and increase towards the end of the century. A large ensemble of bias-corrected and uncorrected regional climate model simulations are used to exemplify future changes to the hydrological cycle by means of the Standard Precipitation Index (SPI) over Germany. The sensitivity of the SPI to modeled precipitation bias is small. These findings highlight the SPI as a resilient index for climate change studies, avoiding additional uncertainties caused by bias corrections. This index allows for the formalization of possible consequences for the vegetation during the growing season involving land management planning. Therefore, the choice of certain indices for

specific problems would allow more reliable climate model results in a user-friendly way without the use of bias correction methods.

The configuration of the model and the coherent capability of the model to represent processes explicitly depend on the horizontal resolution. Regional climate model simulations at the convection-permitting scale reduce the biases of global models and coarser horizontal resolution regional climate models. It has been shown that precipitation extremes tend to increase and show more spatial variability with increasing horizontal resolution in the model. Most of the improvements result from resolving deep convection, which results in an improvement to the afternoon precipitation peak due to convective clouds. A change in the surface energy balance and land-atmosphere feedbacks is associated with this improvement, which results in reduced summer warming (in its mean and extremes). Thus, convection-permitting simulations add value beyond the improved representation of the orography due to the increased horizontal resolution. Therefore, future directions should emphasize the convection-permitting scale in their initiatives (e.g. use in impact models).

A deforestation study in Southeast Asia showed large-scale deforestation may persistently change the climate of that region and the impact is greater than natural variability alone. Another deforestation experiment over Europe demonstrates that the summer due to the conversion to grassland can be more than 3 °C warmer. There is an inter-model disagreement in the 2 m temperature response due to de/af-forestation in mid-latitudes in summer. Different parameterizations in the land surface scheme of the regional climate models may explain this discrepancy. A sensitivity study with different albedo parameterizations in the regional climate model demonstrates that the model uncertainties due to the parameterization are higher than the potential impact of land cover change. Appropriate weather predictions and climate projections rely on accurate calculations of the underlying processes. Inclusion of reliable parameterizations in the models is necessary combined with validation and evaluation with the observational network.

A case study of increasing bioenergy crops over Germany shows that the local effect on a small spatial scale is much more pronounced than the regional effect. This results due the fact that the physical mechanisms differ strongly on local and regional scale. Furthermore, the effect of irrigation has the potential to reduce temperature extremes important for land management. LUCCs at convection-permitting scales allow drawing conclusions on such scales and need a coordinated effort.

This habilitation showed what impact researchers and stakeholder can expect from LUCC and convection-permitting climate simulations, and that impact-relevant information can be derived from convection-permitting climate simulations. The future scientific goal should emphasize a more holistic approach for atmosphere and land model development of Earth system models. Here, an extension of collaboration with the social and cultural sciences would be an essential step forward to transfer the natural science knowledge to the public community for climate sustainability. In the medium term, the strengthening of scientific elaboration should consist of fundamental research, applied research and evaluation. The establishment of more competence centers with partner companies from business and administration could be a successful goal. The centers could be based on the concept that has been implemented for many years at the University of Kassel, which is the Center for Environmental Systems Research. It offers participating partner companies a neutral platform for cooperative research. Together with the partner companies a research plan tailored to their needs could be agreed upon, which would be characterized by a high level of application orientation. Bilateral cooperation with politics, companies and planning offices would support the research work. This enables the development of mitigation and adaptation strategies for using the resources in a sustainable way.

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Synthesis

1 Introduction and objectives

The rate of climate change intensification will increase with increasing greenhouse gas emissions projected by global models in the future without efficient emissions reduction policies. This habilitation explores the anthropogenic induced changes in the interaction of the terrestrial land and climate. Humans influenced the land and thereby climate over 8,000 years ago (~ middle Holocene) by changing land surface properties and modifying atmospheric gas composition (*Brovkin et al. 2006; Ruddiman 2003*). Ever since then nearly one-third of the global land cover is modified due to land use and land cover change (LUCC[1]; *Vitosek et al. 1997*), and will be transformed in the future with unknown predictability. Presently about 75% of the Earth's ice-free terrestrial surface is managed by agricultural production and forestry (*IPCC 2019*). The main drivers of observed climate change are anthropogenic changes in atmospheric components and LUCCs (*Stocker et al. 2013*).

Many studies showed that LUCC affect the climate from regional to global scales by modifications of the surface energy, water, and carbon budget (*Pielke and Avissar 1990; Lynn et al. 1995; Henderson-Sellers 1995; Claussen et al. 2001*). This is via biogeophysical influences on the transfer of heat, moisture and momentum through surface albedo, evapotranspiration and surface roughness (*Pielke et al. 1998; Pitman 2003; Betts et al. 2007*). These biogeophysical impacts depend on the conditions in the planetary boundary layer, e.g. radiative effects of clouds, and in the soil, e.g. evaporative effects through available energy and soil moisture. Biogeophysical modifications result in a different planetary boundary layer structure and cloud cover regime (*Green et al. 2017*), thereby affecting climate extremes (e.g., heat/drought/heavy precipitation events, floods), greenhouse gas emissions or absorptions, and agriculture productivity. Further impacts are via biogeochemical influences by changing the chemical composition of the atmosphere such as CO_2, N_2O or CH_4 (*Bonan et al. 2002; Brovkin et al. 2004*). The net effect on regional and local

[1] LUCC considers anthropogenic land cover changes and land management changes as defined by Luyssaert et al. (2014).

climate is a balance of biogeochemical and biogeophysical mechanisms (*Arora and Montenegro 2011*), and is highly spatially heterogeneous. Changes in land cover and land use due to natural and human forcings alter climate through these land-atmosphere interactions, leading to amplification or reduction of projected climate change signals (Bonan 2008).

Vegetation characteristics play a major regulatory role in this balance due to their physiological and morphological properties. In the tropics, evapotranspiration effects dominate and reinforce the climate benefits of CO_2 sequestration in trees at a regional and global scale. At higher latitudes, the contribution from surface albedo is stronger, especially in areas affected by seasonal snow cover, and counteracts the carbon benefits. At mid-latitude, there are major uncertainties and spatial variability in the climate response, especially at local scales. The vegetation component adds variability due to their seasonal phenology, and due to cultivation management practices (*Tölle et al. 2014; Luyssaert et al. 2014*).

The results of global climate models from LUCID (land-use induced land cover change) and CMIP5 (Coupled Model Intercomparison Project Phase 5) confirm the impact of LUCC on regional climate trends and temperature extremes (*Lejeune et al. 2017, 2018; Kumar et al. 2013*). Different implementation strategies of LUCC in global climate models explain one third of the differences in climatic responses at the continental scale (*Boisier et al. 2012*). The direct effects of land surface changes on the local to regional climate can exceed those associated with global mean warming (*Feddema et al. 2005*). This impact plays an essential role in forcing under low emission scenarios (*de Noblet-Ducoudré al. 2012*). For most temperate regions LUCC radiative forcing can also be negative in contrast to greenhouse gas (GHG) forcing, but the impact of LUCC can be of similar magnitude (*de Noblet-Ducoudré al. 2012*). Similar comparative studies do not exist for regional climate models (*Jacob et al. 2014*), which form the basis for regional climate adaptation strategies. Moreover, the horizontal scale of recent regional climate simulations within CORDEX (Coordinated Regional Climate Downscaling Experiment) are unable to represent the small-scale changes in the landscape.

Pielke et al. (2011) and *Mahmood et al. (2014)* reviewed regional climate models (RCMs) and investigated the impacts of LUCC on climate in different regions of the world. Most of the results are applicable to different regional scales (25 to 50 km grid widths) and therefore do not allow for the derivation of robust conclusions and strategic directions on the local scale (< 4 km grid widths). A joint effort for a comparative study of LUCC with regional climate models hardly exists so far. Individual results show warming or cooling of less than half a degree Celsius in temperate latitudes at coarse horizontal resolution depending on the LUCC scenario (e.g. deforestation, afforestation), see *Li et al. 2017* or *Cherubini et al. 2018*. Several previous studies (*Heck et al. 2001; Brovkin et al. 2004; Pitman et al. 2009*) also reported only small temperature changes due to LUCC, as the local effect on temperature could not be captured by the coarser resolution models (*Prein et al. 2015*). There is consensus regarding the impact of LUCCs on winter climates due to the snow-masking effect in high latitudes (*Bonan et al. 1992*). However, high uncertainties about the impact occur in mid and southern Europe. Multi-model studies are uncertain about the biophysical impact of afforestation in the Northern Hemisphere summers, and show either a cooling or warming.

The global landscape is fragmented by land use and LUCC occurs on small spatial scales (< 4 km). For example, approximately 40% of the total land area of the European Union is used as agricultural area (*European Commission 2010*). These conditions require very high-resolution regional climate modeling at the convection-permitting scale (*Prein et al. 2015*). Generally, a change in the simulated climate elements through integration of LUCC is expected. However, the directions and strengths of the feedbacks and their mutual influence are vague. The quantification of LUCC influences is very difficult, and the strength of the impact still debated.

A separation of the biogeophysical effect of LUCC on climate from other forcing factors is difficult by direct observations. As such, climate models are the primary tools for this assessment. Therefore, an extensive quantitative analysis of land-atmosphere interactions on different temporal and spatial scales by combining dynamical and statistical approaches is presented in this cumulative habilitation. Several case and sensitivity studies are presented using a regional climate model, which demonstrates the anthropogenic impact of land surface conversion on regional and local climates related to changes in global temperature. The results are discussed from a climate impact perspective, and the role of vegetation feedback in temperature projections is formalized.

This habilitation goes beyond former studies regarding LUCC and horizontal grid resolution of RCMs. For the first time the impact of future land use/cover changes are

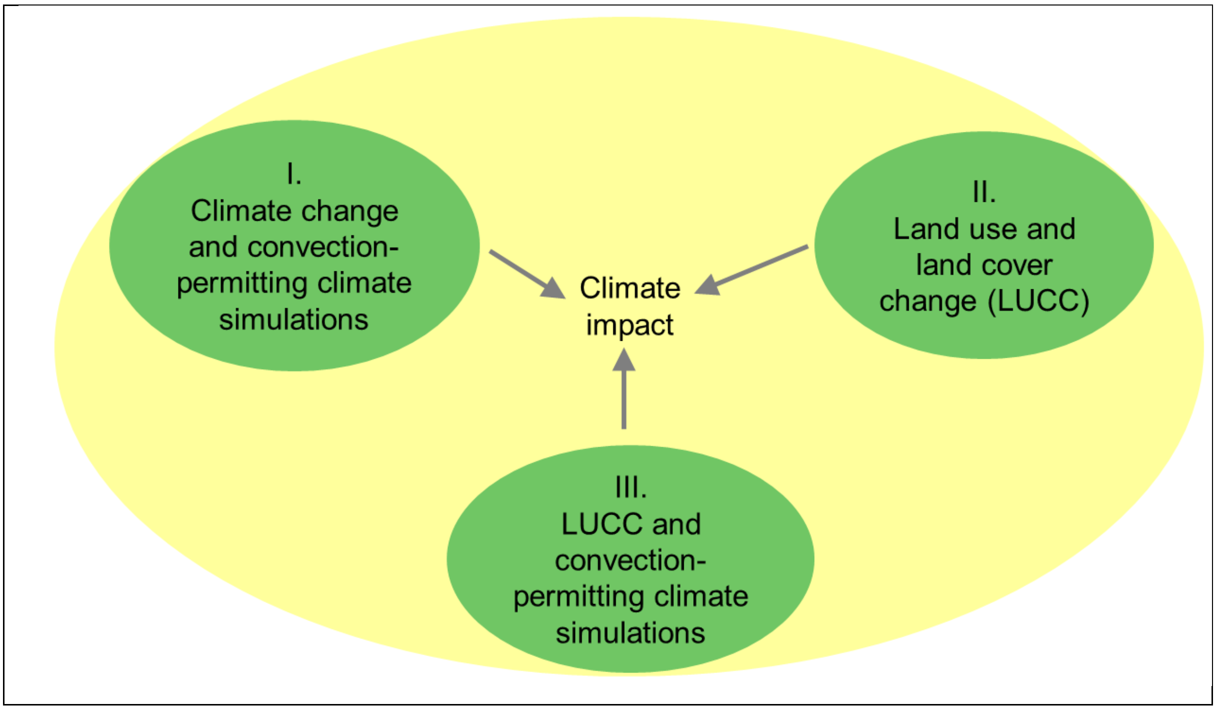

Figure 1: Schematic diagram of three main parts of the analysis of land-atmosphere interactions at different temporal and spatial scales. Own figure.

studied with a regional climate model at convection-permitting scale (*Tölle et al. 2014*, *Prein et al. 2015*). Hereby, the LUCC impact is analyzed in more detail by separating local spatial scale analysis from regional spatial scales, thus demonstrating the local scale impact of LUCC. The LUCC scenarios are in line with recent climate adaptation and mitigation strategies considering vegetation for bioenergy production. More insight is presented on the impact of LUCC in mid-latitudes, where the climate change signal is controversially discussed in the literature. Furthermore, hot spot regions of LUCC are depicted (e.g., Southeast Asia), which are studied to a lesser extent with regional climate models so far, but are areas with strong climate variability (e.g., El Niño-Southern Oscillation (ENSO)). These studies are combined with studies on the impact of bias correction and spatial horizontal resolution of RCMs on climate change signals, and the robustness of climate metrics considering the spatial resolution of the model. This results in three main research objectives of this habilitation as shown in Figure 1.

Three main research objectives are addressed in the cumulative habilitation:

I. Uncertainties due to bias correction on the impact on climate metrics and due to bias correction on the spatial resolution of the regional climate model

   Uncertainties in climate change projections result due the spatial resolution of the climate model. Using bias-correction introduces another uncertainty factor resulting from this methodology. Here, we explore how robust different metrics are facing these uncertainties.

II. Uncertainties due to LUCC

   A major part of the habilitation is concerned with processes connected with the anthropogenic impacts of LUCCs on the regional climate and climate variability. Here, a series of case and sensitivity studies over different climate regions (Europe and Southeast Asia.) are conducted and analyzed. The boundaries of such changes and the underlying processes are discussed.

III. Combined uncertainties due to the spatial resolution of the regional climate model and LUCC

   The effect of land-atmosphere interactions for temperature projections in combination with the effect of the horizontal resolution of the regional climate model are analyzed in detail. Differences between regional and local climate sensitivity and their underlying processes are explored.

The potential of LUCC in regional climate models and future directions finalize the synthesis of this habilitation.

In order to address the aforementioned research objectives the background of the climate system (chapter 2), the energy balance (chapter 3), the regional climate model and the land component (chapter 4) are presented in the following chapters. The overall results are described in chapter 5 ending with a summary and conclusions in chapter 6.

2 The climate system

The climate system of Earth consists of different components, which all interact with each other at different temporal and spatial scales. The natural climate system can be separated into six main components: the atmosphere, hydrosphere, cryosphere, lithosphere, pedosphere, and biosphere (see Figure 2). The atmosphere is the gaseous envelope surrounding the Earth. The hydrological component of the climate system comprises the liquid surface and subterranean water, such as oceans, seas, rivers, lakes, and underground water. The cryosphere includes all regions on and below the ground throughout the world and in the ocean where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers, ice sheets, and frozen ground, which includes permafrost. The lithosphere comprises the upper layer of the solid Earth, including both continental and oceanic crust, which includes all crustal rocks and the cold, mostly elastic part of the uppermost mantle. The pedosphere exists at the interface of the lithosphere. The pedosphere is composed of soil and subject to soil formation processes. The biosphere component of the climate system includes all ecosystems and living organisms including dead organic matter, such as litter, soil organic matter and oceanic detritus. The interactions of those components with their subcomponents and between these compartments occur via physical, chemical and biological processes, such as electromagnetic radiation, fluid motions, precipitation, gas exchange, and chemical transformations.

In the climate system, the main fluxes are those associated with the transport of matter, energy, and momentum, which cross the various boundaries, and affect the properties of adjacent regions (*Peixoto and Oort 1996*) and ultimately affect the energy budget of the planet. Central to this habilitation is the atmosphere and land surface boundary, and the fluxes across this interface. Hereby, the land surface includes parts of the pedosphere and biosphere. The Anthroposphere is an additional major component that interacts with the six compartments to form a complex and dynamic system. The associated length scales range from planetary for the large-scale motions of the oceans and atmosphere to micro-scale for the important processes such as cloud condensation and dissipation of turbulent energy. The temporal scales range from hundreds of thousands of years for the cyclic variations in Earth’s orbit around the sun to seconds for the time it takes a wave to break on the shore. Exchanges in energy, momentum and matter, such as water and carbon, connect the components of the climate system and lead to interactions between them. The highly irregular surface constitutes of the orography of the continents, topography, such as hills and valleys, the nature of the soils, the vegetation coverage, and the spatial distribution of manmade structures, which all influence the behavior of the lower atmosphere. The climate of a region is the outcome of a system that is influenced by several of these parameters. The atmospheric and oceanic circulation redistribute the heat and moisture.

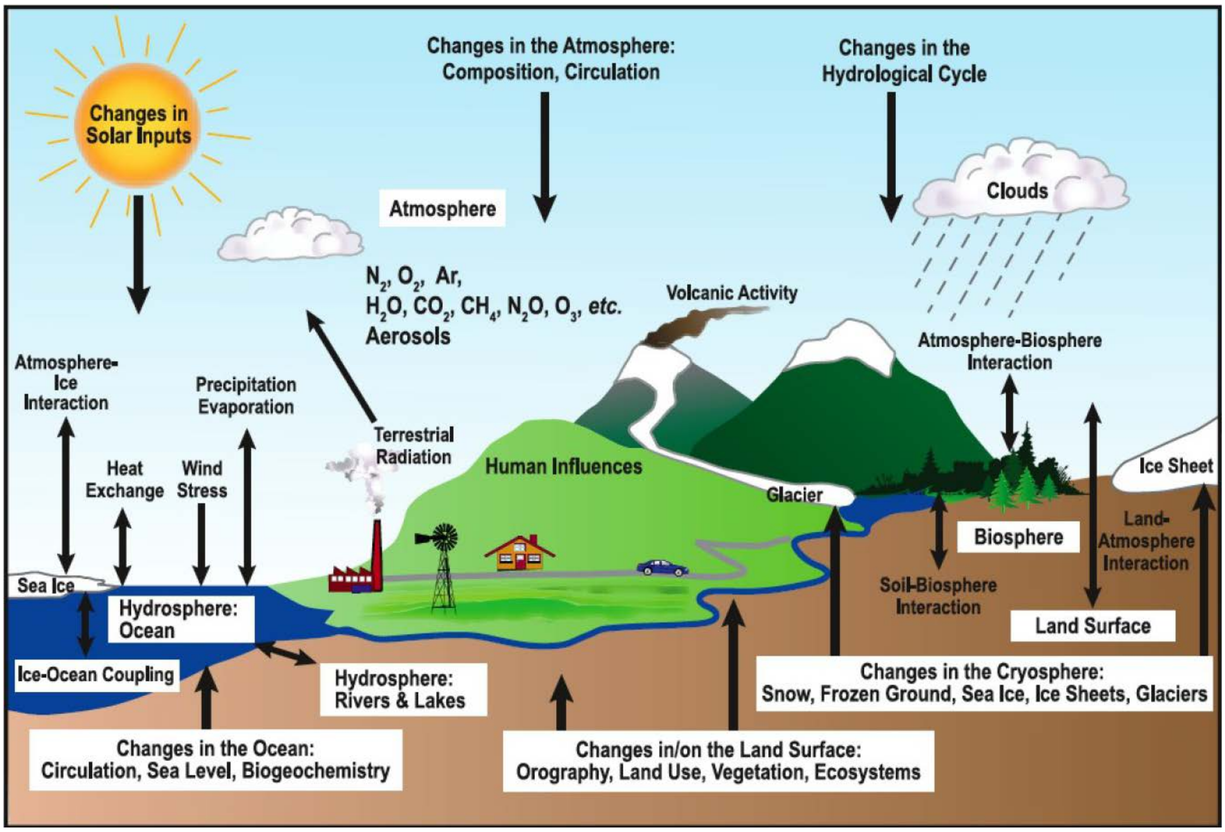

Figure 2: Schematic representation of the components of the climate system, their interactions and processes. FAQ 1.2, Figure 1 of Le Treut et al. (2007).

3 The energy balance of the surface

Understanding the surface energy balance is important for understanding climate and its dependence on external constraints. The energy balance of the surface determines the amount of energy available to evaporate surface water and thereby influencing the surface temperature. Earth's surface is the lower boundary between the atmosphere and the land or ocean (*Hartmann 1994*). The exchange at the lower boundary is through radiative and turbulent fluxes. These surface processes play an important role in determining the overall energy balance of the planet.

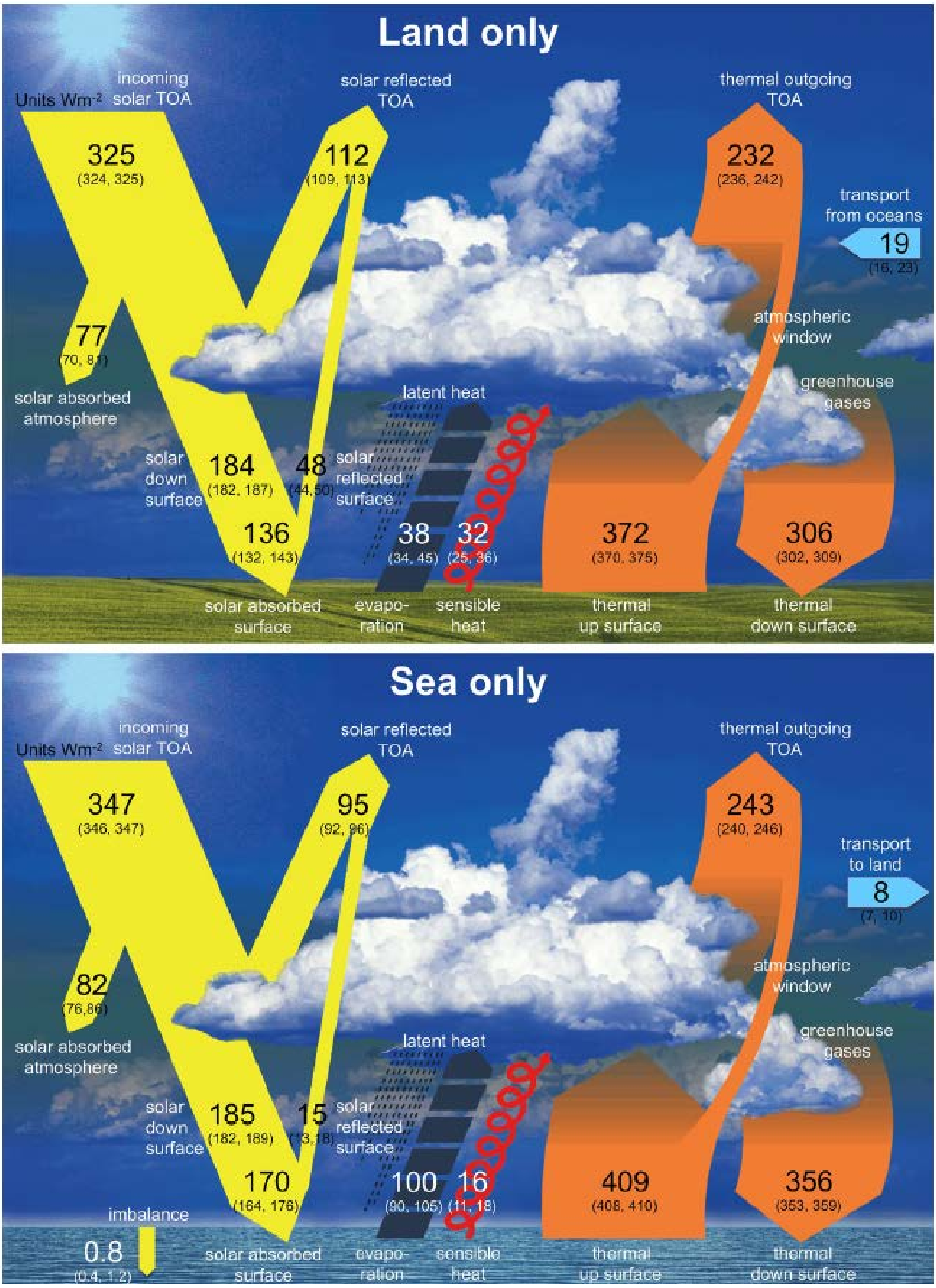

Figure 3: Annual mean energy balance of the Earth averaged over land (upper panel) and oceans (lower panel) as a schematic diagram at the beginning of the twenty-first century. The magnitudes of the energy balance components together with their uncertainty ranges (in parentheses) are indicated as numbers. The units are in W m^{-2}. Figure 2 of Wild et al. 2015.

The absorbed solar radiation at the top of the atmosphere is the main source of energy. Another source of energy is geothermal energy, which has only marginal effects on the atmosphere. Incident solar radiation at the top of the atmosphere, which averages 340 W m^{-2} globally (*Wild et al. 2015*), is reflected and absorbed in the atmosphere and from the surface. The separation of energy components across the land and ocean domains (see Figure 3) results in a different energy distribution. Hereby, the land surface receives 325 W m^{-2} of solar energy and 347 W m^{-2} is derived over the ocean. Approximately 57% (53%) of the solar radiation flux reaches the land (ocean), and 42% (49%) of this is absorbed by the land (ocean) surface. These values correspond to a gain in the spectral shortwave range of 136 (170) W m^{-2}, respectively. The surface radiates part of this energy as longwave radiation back to the atmosphere depending on its temperature due to the Stefan-Boltzmann law. As the atmosphere emits longwave radiation according to the Stefan-Boltzmann law, part of this radiation is reabsorbed by the surface. Thus, the surface loses approximately 66 W m^{-2} in the longwave spectral range over land, and 53 W m^{-2} over ocean. Overall, the surface gains 70 W m^{-2} (117 W m^{-2}) of the solar energy flux from the radiation balance over land (ocean).

This surplus of energy at the land (ocean) surface, is compensated by the turbulent transport of sensible *H* and latent heat *LE*. How the energy is partitioned between sensible and latent heat is significantly different over the land than over the ocean (Kabat 2004). Hereby, approximately 32 W m^{-2} (16 W m^{-2} for ocean) is returned to the atmosphere by the sensible heat fluxes, and another 38 W m^{-2} (100 W m^{-2}) is returned by the latent heat fluxes (*Wild et al. 2015*). Energy and moisture are directly exchanged through the surface, or vegetation, respectively. The albedo of the surface and vegetation determines how much of the insolation is available as energy, and how much is reflected to the atmosphere. The conversion into turbulent heat is partly determined by the properties of Earth's surface (such as wetness, and roughness) and vegetation (stomatal conductance, assimilation rates, etc.), and the characteristics of the overlying atmosphere (stability, etc.). Through evapotranspiration, the surface energy balance is related to both the hydrologic cycle and the water balance.

The land surface plays an eminent role in land-atmosphere interactions. Therefore, the processes at the surface are described here in more quantitative terms.

The complete energy budget of the surface is balanced on climatological time scales and can therefore be described by the ground heat flux:

$$G = R_s - H - E \ , \tag{1.1}$$

where R_s is the radiative balance at the surface, which is described by:

$$R_s = (1 - \alpha)S_d \ + \ \varepsilon \left(L_d - \sigma T_{sfc}^4\right) , \tag{1.2}$$

where α is the shortwave albedo of the surface, S_d is the shortwave radiation flux (global solar radiation), ε is the emissivity of the surface, L_d is the longwave radiation flux (downward terrestrial radiation), T_{sfc} is the temperature of the surface and σ is the Stefan-Boltzmann-constant.

Energy is exchanged between the atmosphere and the surface through conduction and turbulent processes, which are triggered by shear and buoyancy. The turbulent flux of sensible heat is defined as:

$$H = \ \rho_a \ c_p \ (\overline{w'\Theta'})_{sfc} \ , \tag{1.3}$$

where ρ_a is the air density, c_p is the specific heat capacity of the air. $(\overline{w'\Theta'})_{sfc}$ is the covariance of the vertical wind velocity and the potential temperature near the surface.

The energy exchange by latent heat is through the turbulent transport of water vapor as follows:

$$E = \ L \, \rho_a \ (\overline{w'q_a'})_{sfc} \ , \tag{1.4}$$

where L is the specific heat of vaporization, q_a is the specific humidity of the air near the surface, and $(\overline{w'q_a'})_{sfc}$ is the covariance of the vertical wind velocity and the specific humidity near the surface. The transport of humidity results from the evaporation of the non-vegetated surface or water bodies, including interception, and via transpiration of vegetation.

To reproduce the energy and water balance at the surface, these processes need to be exactly described and quantified. This requirement generated a wealth of land surface models, which are coupled to atmospheric models. These models are based on the development of SVAT-modules (soil vegetation atmosphere transfer), which accurately describe the processes in the soil and vegetation, and their interactions with the atmosphere. There have been major developments in the land modules for climate models over the last decade. The most sophisticated and complex land models are JSBACH (*Roeckner et al. 2003*), the Community Land Model (*Oleson et al. 2013*), ORCHIDEE (Krinner et al. 2005), and NOAH (*Niu et al. 2011*). *Wulfmeyer et al. 2014* and *Davin et al. 2014* expanded different regional climate models with complex land surface models (CLM and NOAH) to more realistically represent the interaction between the surface water and the surface energy balance.

4 Regional climate model COSMO-CLM and the surface component

Different transport processes through the atmosphere and ocean reduce the gradients of the energy distributed between the equator and the poles. Human characteristics influence the changes in the climate system. The consumption of fossil fuels changes the concentration of radiation-relevant gases in the atmosphere, and thus modifies the radiative processes. To project the influence of such changes global climate models (GCMs) are used, which reproduce the atmosphere-ocean-land system in a simplified way. Due to the coarse spatial resolution of such models and the requirements for detailed spatial information, regional climate models are applied to restricted regions with high horizontal spatial resolution and to account for local phenomena. The GCM outputs on coarser scales provide initial and boundary conditions for the regional climate models, which downscale the climate fields produced by the GCMs.

The climate version COSMO-CLM (*Rockel et al. 2008*) of the state-of-the-art weather prediction model COSMO (Consortium for Small Scale Modelling, *Steppeler* *et al. 2003*) is used in the studies of this habilitation. This version is a non-hydrostatic limited-area atmospheric model that was designed for applications for the meso-β to the meso-γ scale. The model describes compressible flow in a moist atmosphere, thereby relying on the primitive thermodynamic equations. These equations are solved numerically on a three-dimensional Arakawa-C grid (*Arakawa and Lamb 1977*) based on rotated geographical coordinates and a generalized, terrain following height coordinates (*Doms and Baldauf 2015*). The model applies a Runge-Kutta time-stepping scheme (*Wicker and Skamarock 2002*). The parameterization of precipitation is based on a four-category microphysics scheme that includes cloud, rainwater, snow, and ice (*Doms et al. 2011*). The physical parameterizations include a radiative transfer scheme (*Ritter and Geleyn 1992*), and a turbulent kinetic energy-based surface transfer and planetary boundary layer parameterization. This model is extensively described and documented (*Doms and Baldauf 2015; Doms et al. 2011*).

The lower boundary of COSMO-CLM is the land surface model TERRA-ML (*Schrodin and Heise 2002*), which describes various thermal and hydrological processes within the soil and vegetation based on empirical relationships. TERRA-ML is a quasi 2nd generation of land surface models using the big-leaf approach. This model controls the surface energy and water balances at the land surface and in the ground based on the first principles of mass and energy conservation.

The surface temperature and specific humidity are provided by TERRA-ML as lower boundary conditions for computing the energy and water fluxes between surface and atmosphere (*Doms et al. 2011*). The land surface scheme does not distinguish temperature and energy fluxes for the canopy and ground. The scheme has only a single interface with one temperature, and bulk fluxes are computed. Evapotranspiration includes bare soil evaporation, plant transpiration, evaporation from interception storage, and the sublimation of snow. The impact of plants on evaporation from the ground via transpiration is taken into account by a Penman-Monteith type formulation. Stomatal conductance is based on the biosphere-atmosphere transfer scheme (BATS) after *Dickinson (1984)*. Radiation fluxes are based on grid scale albedo and temperature. COSMO-CLM requires the leaf area index (LAI) as input and the vegetation albedo to compute the fraction of photosynthetically active radiation (fPAR) absorbed by vegetation to obtain transpiration. LAI is defined as the one sided leaf area per unit ground area for broadleaf canopies or the projected needle leaf area for coniferous canopies. The soil temperature is calculated by the heat conduction equation. The soil hydrology is described by the Richards equation, which is solved for the multi-layer soil column. This equation accounts for surface runoff and subsurface runoff when the layer is at field capacity. The lowest soil layer temperature acts as a lower boundary condition for the heat conduction equation and is set to a climatological annual mean value. The snow processes are solved by a single mass balance equation. This equation accounts for partial coverage of snow.

Every surface grid is assigned to one land cover type. Arbitrary unevenly spaced vertical soil layers can be chosen. In general, for climate applications and high horizontal resolution, 10 soil layers with a total soil depth of 15.24 m are considered for heat transport, and up to 5 snow layers are used. The active soil layers (approximately 8 layers in climate mode) for the transport of water have a total soil depth of 3.82 m. The surface input data required for each grid cell include soil type and land cover type. Each land cover type is assigned a set of time-invariant parameters: optical properties (albedo), morphological properties (roughness, leaf area index, plant coverage, root depth). The leaf area index and root depth follow a seasonal cycle.

The terms of the energy balance equations are considered in more detail as they are the main components of the analysis in the habilitation. The most important processes are based on the documentation of *Doms et al. 2011*. Figure 4 shows the processes incorporated in TERRA-ML. The starting point is the consideration of the energy balance of the surface, which is formulated in TERRA-ML as follows:

$$G_0 = R_s - H - E. \tag{1.5}$$

The radiative balance at the surface R_s is given by equation (1.2) as the sum of the shortwave and longwave energy fluxes. The emissivity of the surface has a constant value of $\varepsilon = 0.996$. The shortwave albedo α consists of multiple components:

$$\alpha = f_s\,\alpha_s + (1 - f_s) * (f_v\,\alpha_v + (1 - f_v)\,\alpha_{so}(st, sm)) , \tag{1.6}$$

where α_s, α_v, and α_{so} are snow, vegetation and soil albedos. st is the soil type and sm is the soil moisture of the topsoil layer. f_s and f_v are the area fractions of snow and vegetation cover, respectively. α_v has a constant value of 0.15. α_s depends on the age of the snow coverage. This variable can vary in time between 0.4 and 0.7. α_{so} depends on soil type and soil moisture and varies between 0.1 and 0.44. The seasonal albedo cycle is determined by the seasonal cycle of snow and vegetation fraction.

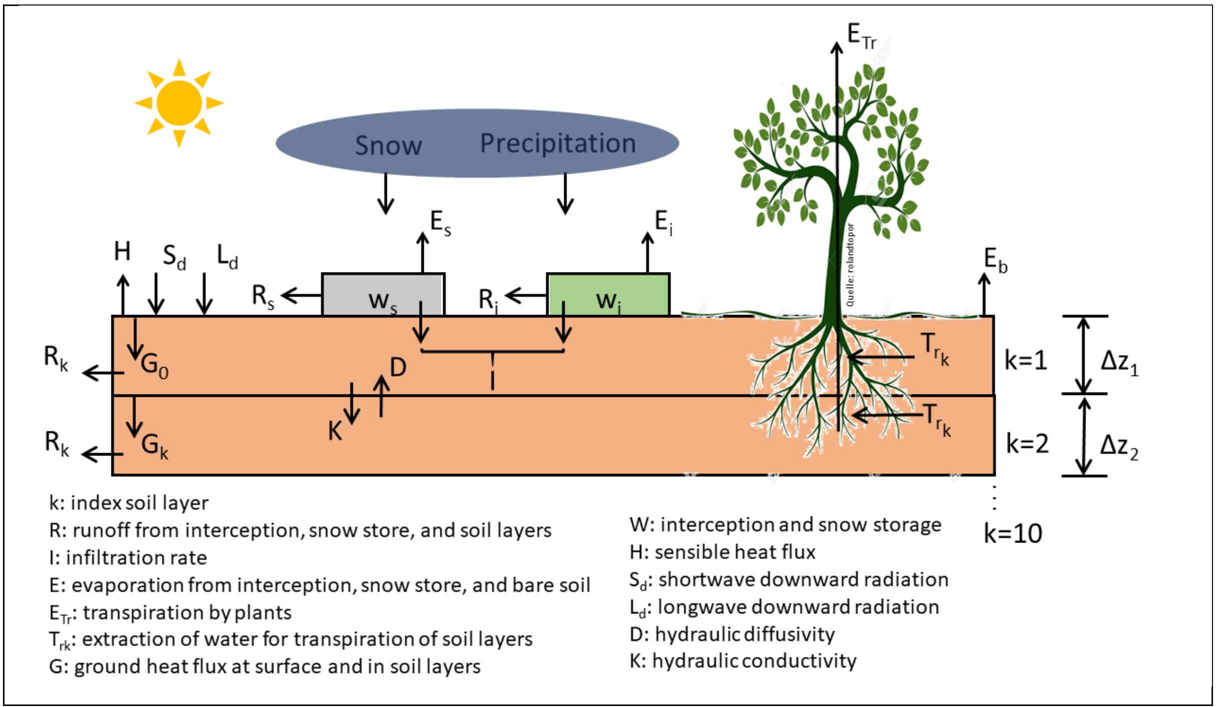

Figure 4: Schematic representation of the energy and water balance in TERRA-ML. Own figure.

The albedo formulation uses a constant background albedo of 0.15 regardless of the vegetation type. Thus, the type of vegetation does not determine the albedo and the energy surplus of the surface. This condition implies almost identical albedo values in the model domain in Northern Hemispheric summer, then a large-scale area is covered by up to 80% vegetation. A more realistic albedo parameterization is examined in a sensitivity study in *Tölle et al. 2018b*, which is part of this habilitation, where an albedo dependency on vegetation type is considered.

The Penman-Monteith approach (*Monteith 1965*) is used to derive potential evapotranspiration by adding water vapor pressure deficit as a driving gradient.

Hereby, the water vapor fluxes of the different sources are summed up to a total vapor flux. The equation for the latent heat flux is obtained with this approach:

$$E = E_0 = L * (E_{Tr} + E_b + E_i + E_s), \tag{1.7}$$

where L is the latent heat of vaporization, E_{Tr} is transpiration, E_b is evaporation from non-vegetated surfaces, E_i is evaporation from interception reservoirs, and E_s is evaporation (or sublimation) of the snow layer.

Plant transpiration in TERRA-ML follows *Dickinson (1984)*. The temperature of the plant foliage is the same temperature as the surface temperature for simplicity. Considering the resistances of the water vapor transport from the plant foliage to the air inside the canopy (r_f), and from the air inside the canopy to the air outside the canopy (r_a) results in the following formulation for transpiration:

$$E_{Tr} = f_v * (1 - f_i) * (1 - f_s) * \frac{1}{r_f + r_a} * \rho_a \left(q_{sfc,sat} - q_a\right). \tag{1.8}$$

f_v, f_i, and f_s are the area fractions of vegetation, interception storage, and snow layer, respectively. ρ_a is the density of the air, $q_{sfc,sat}$ is the saturated specific humidity depending on the temperature of the surface, and q_a is the specific humidity of the air. The aerodynamic resistance of the transpiration is determined by:

$$r_a^{-1} = C_q |v_h|, \tag{1.9}$$

where C_q is the transport coefficient for water vapor, and $|v_h|$ is the horizontal wind. The transport coefficient in the current version of TERRA-ML is equal to the transport coefficient of heat C_h, which is used to calculate the sensible heat flux. The resistance of the vegetation layer depends on the leaf area index and is given by:

$$r_f^{-1} = (r_{la} + r_s)^{-1} * LAI, \quad (1.10)$$

where LAI is the leaf area index, r_{la} is the resistance of the water vapor transport between the leaf and the surrounding air. By dividing by the LAI in equation (1.10), the larger leaf surface is accounted for compared to a plane surface. TERRA-ML has no canopy layer. Therefore, r_{la} = 0. The stomatal resistance is given by:

$$r_s^{-1} = r_{s,max}^{-1} + \left(r_{s,min}^{-1} - r_{s,max}^{-1}\right)[F_{PAR} F_w F_T F_q], \quad (1.11)$$

where $r_{s,min}^{-1}$ and $r_{s,max}^{-1}$ are the minimal and maximal stomatal resistance, respectively. The functionsF_{PAR}, F_w, F_T, and F_q describe the impact on the stomatal resistance of the radiation, soil water content, ambient temperature, and ambient specific humidity, respectively.

The evaporation of a non-vegetated surface is parameterized as:

$$E_b = (1 - f_i) * (1 - f_s) * (1 - f_v) * \min(E_{pot}; E_m), \quad (1.12)$$

where E_m is the maximal possible water vapor flux of the ground, and determined empirically after *Dickinson (1984)*. The potential evaporation is presented as follows:

$$E_{pot} = \rho_a \; C_q |v_h| \left(q_{sfc,sat} \; - q_a \;\right), \quad (1.13)$$

$q_{sfc,sat}$ is the saturated specific humidity depending on the temperature of the respective surface (interception reservoir, snow layer, or soil type). Therefore, E_b depends mainly on the surface and its respective parameters in addition to the area fraction of the snow layer, the interception storage, and the vegetation layer.

The amount of water in the interception reservoir for evaporation depends on the area fraction of vegetation. Evaporation of the interception reservoir E_i follows the potential evaporation formula depending on the corresponding temperature of the interception reservoir. The evaporation of the snow storage E_s is determined analogous to E_i:

$$E_i = E_{pot}(T_s) \text{ and } E_s = E_{pot}(T_{snow}). \tag{1.14}$$

The total evapotranspiration is diagnosed by equation (1.7), and is used in the following bulk formula to derive a virtual specific humidity q_{sfc} at the surface:

$$E_0 = \rho_a\ C_q |v_h| \big(q_{sfc}\ - q_a\ \big). \tag{1.15}$$

The virtual specific humidity can then be calculated by inverting equation (1.15). The outcome is required at a flat surface to maintain the diagnosed latent heat flux of (1.7). The impact of vegetation is taken into account with this approach.

The sensible heat flux is parameterized by a resistance description of the surface-to-air temperature gradient as a bulk formulation in TERRA-ML:

$$H = \rho_a\ c_p \frac{1}{r_a} \big(T_{sfc}\ - \theta_a\ \pi_{sfc}\big), \tag{1.16}$$

where c_p is the specific heat capacity of the air, T_{sfc} is the temperature of the first soil layer, θ_a is the potential temperature of the lowest atmospheric layer, and π_{sfc} is the scaled air pressure at the ground. The aerodynamic resistance $\frac{1}{r_a}$ is calculated analogously to equation (1.9). Here, the determination of the transport coefficient for heat C_h is based on the method of *Louis (1979)*, where it is related to the roughness length z_0, the height *h* of the lowest atmospheric layer, and the bulk-Richardson-number *Ri*. This condition allows for accounting for the properties of the surface as well as for the atmospheric stability relation.

The ground heat flux can be calculated from the heat conduction equation, in which the transport of heat in the soil is described (*Doms et al. 2011*). This equation follows the Fourier law. Further assumptions are that the heat conduction is in only the vertical direction and that there is no heat transport with water. The heat capacity and heat conduction depend on the properties of the soil. The ground heat flux is described by the temperature difference of two soil layers divided by the difference of the soil layer depths, and reads for each soil layer:

$$G_k = -\lambda \frac{(T_{so})_{k+1} - (T_{so})_k}{z_{m,k+1} - z_{m,k}}, \tag{1.17}$$

where $z_{m,k}$ is the depth of the center of layer *k*, T_{so} is the soil temperature, and λ is the mean liquid water content. The latter value is constant over the soil profile, and does not change with time. Thus, the ground heat flux does not depend on the actual water content of the soil. This condition disentangles the energy balance from the water balance, which results in no feedback to the energy transport in the soil and the soil temperature, and finally to the sensible heat flux for long-term simulations with seasonal variations in the water content of the soil. The ground heat flux G_0 at the topsoil layer is obtained from the residuum of the radiation balance and the turbulent fluxes of equation (1.5).

5 Land use, land cover change and climate interaction

Land use and land cover change is one of the main human induced activities that alter the Earth system and thereby affecting climate and hydrology (*Wang et al. 2008*). However, opposing results due to LUCC are found in the literature. Replacing forests with agriculture or grasslands reduces the surface air temperature (*Bounoua et al. 2002*) and the number of hot summer days (*Anav et al. 2010*) in mid-latitudes. Other studies show that forests cool the air leading to reduced extreme temperatures compared to grass- and croplands and contributing to increased precipitation rates in the growing season (*Hogg et al. 2000; Sánchez et al. 2007; Tölle et al. 2014*). Long-term studies show that LUCC has much weaker influence on the atmospheric circulation compared to greenhouse gas forcing (*Betts 2007; Wramneby et al. 2010*). However, in smaller areas and regions with strong land-atmosphere interactions the feedback processes can significantly affect and modify the weather and climate and their extremes (*Seneviratne et al. 2006; Seneviratne et al. 2010; Stéfanon et al. 2014*). Here, the direct effects of land surface changes can exceed those associated with global mean warming (*Feddema et al. 2005*). This plays an essential role by regarding the forcing by the low emission scenarios (*de Noblet-Ducoudré al. 2012*).

Pielke et al. (2011) and *Mahmood et al. (2014)* reviewed regional climate models (RCMs) and investigated the impacts of LUCC on climate in different regions of the world. Most of the results are applicable to different regional scales (25 to 50 km grid widths) and therefore do not allow for the derivation of robust conclusions and strategic directions on the local scale (< 4 km grid widths). A joint effort for a comparative study of LUCC with regional climate models hardly exists so far. Individual results show warming or cooling of less than half a degree Celsius in temperate latitudes at coarse horizontal resolution depending on the LUCC scenario (e.g. deforestation, afforestation), see Li et al. 2017 or Cherubini et al. 2018. Several previous studies (*Heck et al. 2001; Brovkin et al. 2004; Pitman et al. 2009*) reported of minor temperature changes due to LUCC. This is mainly because the coarser resolution models could not capture the local impact. There is a consensus regarding the impact of LUCCs on winter climates due to the snow-masking effect in high latitudes (*Bonan et al. 1992*). However, high uncertainties occur in mid and southern Europe. Multi-model studies are uncertain about the biophysical impact of afforestation in the Northern Hemisphere summers, and show either a cooling or warming.

The estimation of future climate and extreme climate events poses a great challenge to the scientific community. The prevalence of various extreme events, such as droughts, heat waves, heavy precipitation events, and floods are often the result of a combination of large-scale drivers (e.g., sea surface temperatures, sea ice extent, Rossby waves) and regional-scale feedbacks (e.g., soil moisture, vegetation and snow conditions; *Zhang et al. 2010*). The uncertainties in climate projections (*IPCC (SREX) 2012*) could be reduced by overcoming the uncertainty of feedback mechanisms over various land surface conditions. According to WCRP[2] the role of past and future LUCC forcing in the occurrence of extreme events on land is still poorly quantified. There is a need for more reliable projections of key climatological variables such as temperature and precipitation and their extremes for specific regions and land use types. A key role is played by land use transitions to adapt and mitigate climate change for future scenarios, aiming to stabilize temperature increases at 1.5 °C (*Popp et al. 2017*). Hence, there is a need to better understand the underlying biophysical processes and to reduce model errors, which ensures higher quality climate projections.

The application of LUCCs in regional climate models is not a new concept. Different research groups apply these methods with different complexity and detail. This cumulative habilitation is not aimed at describing the uncertainty due to the whole General Circulation Model (GCM) – Regional Circulation Model (RCM) – Land Surface Model (LSM) modeling chain. Rather, new process oriented analysis approaches and potentials for future directions are given. LUCC is a global problem with different strengths and consequences. LUCC can include land transformations due to increases in either bioenergy crops (e.g., grass, maize, poplar, willow), such as in the mid-latitudes, or cash crops (e.g., oil palms, rubber plants), such as in the tropics. In the tropics, the effects of evapotranspiration dominate and reinforce the climate benefits of CO_2 sequestration in trees at regional and global scales. At high latitudes, the contribution from surface albedo is strong, especially in areas affected by seasonal snow cover, and counteracts the carbon benefits. At mid-latitudes, there are major uncertainties and spatial variability in the climate response, especially at local scales.

5.1 Uncertainties due to bias correction on the impact on climate metrics and due to bias correction on the spatial resolution of the regional climate model

Bias correction and drought index

The uncertainties related to climate change projections are high and increase towards the end of this century. *Tölle et al. 2013* analyses the changes in water supply

[2] World Climate Research Programme: http://www.wcrp-climate.org

patterns due to the climate based on existing regional climate simulations from ENSEMBLES (*Heinrich and Gobiet 2012*). Water supply patterns are statistically analyzed by including bias correction methods and calculations of drought indices.

Here, the water supply pattern is investigated over Germany by the standardized precipitation index (SPI) based on 6-month precipitation sums over present and future periods. The projections of water supply patterns indicate wetter winters and consequently a delayed soil drying in spring and early summer, but reduced summer precipitation in Germany (*Tölle et al., 2013; Chamorro et al. 2019*). This effect potentially affects seasonal turbulent fluxes and vegetation development. Further, we find that the sensitivity of the SPI to modeled precipitation bias is small. These findings highlight the SPI as a resilient index for climate change studies avoiding additional uncertainties caused by bias corrections. This finding allows for the formalization of potential consequences for vegetation during the growing season, including land management planning.

Impact of horizontal resolution on climate change signal of extremes

Regional climate simulations at the convection-permitting scale reduce the biases of precipitation and temperature of global models and coarser horizontal resolution regional climate models as exemplified for two case studies over Germany in *Tölle et al. 2018a*. Local precipitation intensities tend to increase and show more spatial variability and structure with increasing horizontal resolution compared to the coarser horizontal resolved climate model simulations. This information is important for agricultural planners extending across the complete agricultural production chain, which is affected by weather and climate variability (*Deryng et al. 2016*). Most of the improvements come from resolving deep convection, which results in an improvement to the afternoon precipitation peak due to convective clouds. A more realistic resolved land surface and topography with steeper gradients also contributes to the improvements seen in the model results. For future projections, there is evidence that summertime extreme precipitation events are increased with explicitly resolving deep convection (*Tölle et al. 2018a*). *Prein et al. 2015* and *Coppola et al. 2018* report of qualitatively modified responses of summertime convective precipitation extremes to climate changes.

With regard to temperature, the convection-permitting scale simulations project decreased mid-European summer warming (in its mean and extremes) compared to the coarser simulations. This finding could partly be attributed to reduced biases in shortwave and sensible heat fluxes as discussed in *van den Broucke et al. 2017*. The change in the surface energy balance has an immediate effect on the land surface feedback. Thus, convection-permitting simulations add value beyond explicitly resolving deep convection and improved representation of the orography due to increased horizontal resolution.

Further evidence of less future extreme warming and increase in future extreme precipitation in summer is provided by the new convection-permitting model ensemble in the World Climate Research Program's (WCRP) Coordinated Regional Downscaling Experiment (CORDEX) Flagship Pilot Study on Convective phenomena at high resolution over Europe and the Mediterranean

5.2 Uncertainties due to land use/cover change

LUCC and climate variability

Land management influences the seasonal water availability and energy budget. This is of concern especially in the South-East Asian (SEA) region, where the monsoon dominate the annual cycle of rainfall and the ENSO circulation amplifies the monsoon climate. SEA experiences intense and rapid deforestation of land due to the new cultivation of oil palm plantations, and is considered an area with rampant LUCC. It is still unexplored what impact deforestation may have on ENSO events. A LUCC experiment with the regional climate model COSMO-CLM showed that the impact of deforestation of the whole of SEA on air temperature is greater in magnitude and reversed in sign than the effect of La Niña, and amplifies the impact of El Niño leading to increased socioeconomic vulnerability (*Tölle et al. 2017, Tölle et al. 2020*). Moreover, it is revealed from the results that precipitation events have become more intense, and extreme temperature increased after large-scale land clearing. The major climate disturbance from an abrupt (e.g. rapid) land transformation occurs directly in the year of the conversion. The persistent land modification leads to a decline in evapotranspiration and precipitation and a significant warming due to reduced latent heat flux during the simulation period between 1990 and 2004. The strongest effect is seen in the lowlands of SEA.

LUCC, albedo sensitivity and inter-model comparison

Multi-model studies are uncertain about the biophysical impacts of afforestation in the Northern Hemisphere mid-latitude summers and show either cooling or warming. The magnitude and direction remain uncertain, which has implications for the surface energy balance and temperature response. The climatic extent of afforestation depends on the ratio between the increased net shortwave radiation and the increased aerodynamic roughness/evapotranspiration of the forest. This proportion, however, strongly depends on the regional climate model used and the corresponding model uncertainties in the parameterization. The question of whether these model uncertainties are higher than the potential impact of land cover change has not yet been investigated. Therefore, the regional climate response is compared due to different albedo parameterizations in the state-of-the-art regional climate model COSMO-CLM (v5.09) with the impact of extreme land use change scenarios by covering the whole of Europe with forest or grass (*Tölle et al. 2018b; Davin et al. 2019*). The standard operational albedo configuration is considered in the model, which depends on the background albedo, and two modified versions accounting for the impact of the vegetation and soil moisture. The relative strengths of the seasonal and latitudinal biophysical effects on the temperature response are quantified from a surface energy balance perspective. The summer warming due to deforestation to grassland can increase more than 3 °C and is much stronger than the impact due to afforestation. Depending on the albedo parameterization in the model, the temperature effect due to afforestation can turn from cooling to warming by half to one degree Celsius in mid-latitude summers. Although the resulting changes are small, they are consistent over the simulation period and can be explained by the different physical processes. Here, the model uncertainties in the parameterization are higher than the potential impact of land cover change. Changes in albedo due to vegetation changes are a crucial part of land-climate-management, which can either cool or enhance seasonal temperature.

An inter-model comparison of LUCC experiments with changing the land cover to grassland (deforestation experiment) or forested land (afforestation experiment) over the whole of Europe is further shown in *Davin et al. 2019*. A large inter-model spread in the simulated climate response to de/af-forestation for temperature changes in summer is demonstrated. This spread is attributed to the representation of the land processes. Models sharing the same Land Surface Model (LSM) exhibit more similarity in their response compared to models sharing the same atmospheric model but different LSMs. Inter-model disagreement can be partly linked to evapotranspiration changes, which in the case of COSMO-CLM depends on the albedo parameterization in the model. Furthermore, the 2 m temperature is limited to assess the effects of land use changes among the models. A consistent inter-model response to afforestation in the diurnal temperature cycle was found when the temperature of the surface and the lowest atmospheric model level was considered (*Breil et al. 2020*).

5.3 Combined uncertainties due to the spatial resolution of the regional climate model and land use/cover change

LUCC and spatial resolution

Germany plays an increasingly prominent role in its commitment to reduce greenhouse gases through alternative energy sources, e.g. plants for bioenergy production. The impact of increasing bioenergy crops on the future climate is uncertain. There is no robust quantification of the associated processes acting on regional and local scales. Seasonal vegetation development is one of the uncertainties for appropriate climate projections and seasonal predictions. Combined with land management (plant allocation, rain fed agriculture and irrigation), seasonal vegetation development forms complex feedbacks critical for climate change.

The effect of LUCC due to increases in plants for bioenergy production is quantified for future climate changes and seasonal effects at convection-permitting resolution *(Prein et al. 2015*) using the regional climate model COSMO-CLM (*Rockel et al. 2008*) over Germany. Using high-resolution modeling approaches at the convection-permitting scale enables the analysis between the land and atmosphere as its initial communication occurs on a local scale through the planetary boundary layer (*Santanello et al. 2015*). A new parameterization that accounts for bioenergy crops is introduced into the regional climate model to account for new vegetation types such as poplar or maize and irrigation. A statistical allocation procedure determines the agricultural fields that are suitable for bioenergy management. This method infers plausible areal extents and spatial distributions of LUCC. To quantify the magnitude and nature of the climate change signals due to LUCC, the impact of the vegetation scenarios is compared to the impact of global warming. The results of potential LUCC simulations with the regional climate model are further analyzed using advanced statistical tools.

Figure 5 demonstrates the experimental set up for the quantification of the effects of LUCC to bioenergy crops on the climate. Areas of arable land suitable for bioenergy plants are converted to either irrigated poplar, non-irrigated poplar or maize. Here, a one-way downscaling nesting approach is used to reach the convection-permitting resolution. The results are compared to the control simulation without land use changes. While land conversion by bioenergy crops directly alters the interaction between the land and atmosphere, the vegetation's phenology associated with the annual cycle of greening and dormancy introduces a seasonal component that affects the seasonal energy and water cycle.

Results of future LUCC indicate that increases by bioenergy crops have a detectable role in dampening temperature extremes by up to 2 °C during the growing season. The variations in land-atmosphere fluxes that affect water availability and temperature during seasons depend on the vegetation type (irrigated poplar, non-irrigated poplar or maize) and its characteristics (e.g., leaf area index, root depth, roughness length, plant coverage), and its planting and harvest dates (*Tölle et al. 2014*). Variations can also occur across Europe due to the background climate as shown by *Cherubini et al. 2018*. Principal component analysis helps to determine the relevant processes that act on local and regional scales. With local, it is referred to sites, which are converted to bioenergy crops, whereas regional means non-converted sites. Principal component analysis indicates a cooling effect at local scales in summer due to changes in the turbulent fluxes. Here, the surface energy balance is directly influenced by LUCC via a decrease in surface albedo. This may increase net shortwave radiation, which is balanced by the turbulent fluxes. Although, if evapotranspiration is increased due to higher leaf area index, less energy is available for sensible heat and the temperature decreases.

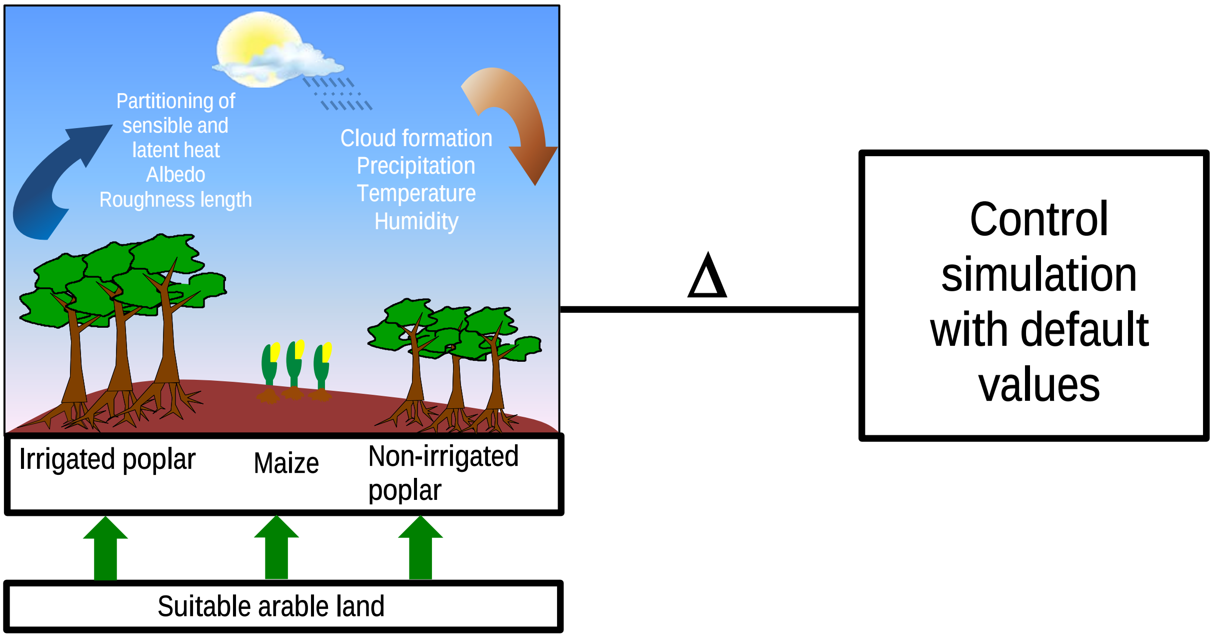

Figure 5: Experimental set up for quantification of the effect of land use and land cover change to bioenergy plants on the regional and local climate using the regional climate model COSMO-CLM. Areas of arable land that are suitable for bioenergy plants are converted to either irrigated poplar or non-irrigated poplar or maize. The difference of the results to the control simulation without land use changes is analyzed. Own figure.

Increases in cloud cover is the dominant factor for regional cooling inferred from principal component analysis. Here, regional climate changes result from advective processes (*Winckler et al. 2017*). Thus, local changes in atmospheric temperature or moisture is transferred to other regions by advection. The higher humidity increases cloud coverage, strengthens the downward longwave radiation, and reduces the incoming radiation. This influences the surface energy balance, and results in a cooling effect.

The influence of LUCC on future extreme temperatures and energy fluxes is more pronounced when the convection-permitting scale is considered. Moreover, this impact is dominant on local than regional scales, suggesting that local effects of land management are more important than previously thought (*Tölle et al. 2014*). Thus, convection-permitting climate simulations are advantageous for quantifications of the impact of LUCCs. Considering the sustainability of LUCC, land-climate-management by irrigation plays a crucial role in reducing temperature extremes by cooling up to 2 °C locally.

5.4 Final remarks

Land processes have strong control over local climate, and the impact of land transformation plays a major role in climate projections. Most of the studies in this habilitation are idealized simulations because realistic LUCC scenarios for the model regions are missing. These scenarios should come from other societal and economic disciplines, which need to be incorporated into the climate models. The relevant processes out of these scenarios need to be simulated in a realistic way. Thus far, the land module of the regional climate model COSMO-CLM is still too simplified. Therefore, to realistically guide decisions for strategic land use/cover management further research and development of regional climate models are required.

Herein, cases are considered with the climate model simulations, where special human influences on the land surface are adapted in the model for impact analysis. This anthropogenic forcing is currently not sufficiently represented in RCM climate change projections. Further, RCMs need a more careful and time-varying representation of the heterogeneous land surface and its vegetation types. Although the data are compared to remote sensing studies, the question remains whether these land cover change studies are reliable enough to guide decisions. The answer to this question requires a realistic representation of the land surface properties and the associated parameterization of surface turbulent fluxes. Understanding how these properties and parameterizations compare to surface observations is an essential next step. A denser observational network is needed to constrain those underlying processes by observations. Decadal measurements from the FLUX communities recently became available to foster such comparisons.

Most models underestimate the biosphere response to radiation and water availability (*Green et al. 2017*). For example, model errors that arise from missing land use/cover dynamics need to be identified to improve simulated impacts by linking vegetation cover with ecosystem water use and energy balance. Here, a collaboration with initiatives such as FACE2FACE (*Obermeier et al. 2017*) would be essential. A coordinated effort on convection-permitting resolution to overcome uncertainty for climate projections is underway in the EUropean COoRdinated Downscaling Experiment (CORDEX-EU) Flagship Pilot Studies (FPS) Convective Phenomena (*Coppola et al. 2018*). At the same time another new coordinated initiative CORDEX-

EU FPS Land Use Change Across Scales (LUCAS) was formed to benchmark the biogeophysical role of idealized and realistic LUCC scenarios, where various regional climate models and land surface models are combined (*Davin et al. 2019*) for various temporal and spatial scales. A combination of convection-permitting simulations with LUCC studies will be fostered in these new initiatives.

6 Summary and conclusions

On the one hand, we are facing a global problem of climate change affecting all sectors of society. On the other hand, the human influence via LUCC is a global phenomenon affecting climate change. This influence can include land transformations due to increases in bioenergy crops as in the mid-latitudes or due to increases in cash crops as in the tropics. The impact of these changes is relevant for decisions on sustainable land management, but is highly uncertain. The spatial resolution of regional climate models represents additional uncertainty. This cumulative habilitation demonstrates new methods and findings to the benefit of downscaling with regional climate models to high spatial resolution, to the process based evaluation of LUCCs, and to the analysis of extremes.

Section 5.1 sheds light on the uncertainty of climate change due to the spatial resolution of regional climate models and due to bias correction. The uncertainties associated with climate change projections are inherent. Therefore, a large ensemble of bias-corrected and uncorrected regional climate model simulations are used to exemplify future changes to the hydrological cycle by means of the SPI over Germany. The sensitivity of the SPI to modeled precipitation bias is small. These findings highlight the SPI as a resilient index for climate change studies, avoiding additional uncertainties caused by bias corrections. This index allows for the formalization of possible consequences for the vegetation during the growing season involving land management planning. Therefore, the choice of certain indices for specific problems would allow more reliable climate model results in a user-friendly way without the use of bias correction methods.

The configuration of the model and the coherent capability of the model to represent processes explicitly depend on the horizontal resolution. Regional climate model simulations at the convection-permitting scale reduce the biases of global models and coarser horizontal resolution regional climate models as shown for two case studies over Germany. It has been shown that precipitation extremes tend to increase and show more spatial variability with increasing horizontal resolution in the model. A change in the surface energy balance and land-atmosphere feedbacks is associated with this improvement, which results in reduced summer warming (in its mean and extremes). Thus, convection-permitting simulations add value beyond the improved representation of the orography due to the increased horizontal resolution and resolved processes. Therefore, future directions should emphasize the convection-permitting scale in the CORDEX initiative if computer power allows.

Section 5.2 sheds more light on the uncertainty of climatic changes due to modeled LUCCs of idealized cases such as deforestation and afforestation experiments in Europe and Southeast Asia. The climate of the region may persistently change and can have a greater impact than natural variability alone.

There is an inter-model disagreement in the 2 m temperature response due to de/af-forestation in mid-latitudes in summer. Different parameterizations in the land surface scheme of the regional climate models may explain this discrepancy. A sensitivity study with different albedo parameterizations in the regional climate model COSMO-CLM confirms this hypothesis. It is concluded that the model uncertainties due to the parameterization are higher than the potential impact of land cover change. Accurate weather predictions and climate projections rely on appropriate considerations of the processes in the models. Inclusion of reliable parameterizations in the models is necessary combined validation and evaluation with the observational network.

Section 5.3 sheds more light on the uncertainty of climatic changes due to the combination of horizontal resolution and LUCC including irrigation. A case study of increasing bioenergy crops over Germany shows that the local effect on a small spatial scale is much more pronounced than the regional effect. This results due the fact that the physical mechanisms differ strongly on local and regional scale. Furthermore, the effect of irrigation has the potential to reduce temperature extremes important for land management. Similar comparative studies do not exist for regional climate models, which form the basis for regional climate adaptation strategies as adaptation and mitigation strategies occur on regional and local scales. Moreover, the horizontal scale of recent regional climate simulations within CORDEX are unable to represent the small-scale changes in the landscape. Therefore, land use changes at convection-permitting scales allow drawing conclusions on such scales and need a coordinated effort.

The studies in this habilitation concentrate on the impact of climate change on the energy and hydrological cycle. Most studies evaluate such approaches by looking at different global emission and concentration scenarios of greenhouse gases, which are determined according to different patterns of economic and social development. This top-down approach does not allow us to derive conclusions on how an anthropogenic change in the land use/cover influence the climate. Such impacts, regarded as a bottom-up approach, have greater effects at the regional or local scale, which is increasingly relevant for political decisions and land planners, who need national-level estimates to address global climate change.

This habilitation showed what impact researchers and stakeholder can expect from LUCC and convection-permitting climate simulations, and that impact-relevant information can be derived from convection-permitting climate simulations. Nevertheless, the interaction of the biosphere/anthroposphere with the atmosphere in climate models is still assumed in a rather simplified way. New parameterizations regarding dynamical vegetation allowing for different plant species and different spatial scales and climate-model-integrated agent-based models to account for human influence need to be developed. An interdisciplinary approach would be advantageous to truly benefit from such developments. This approach requires different disciplines to open up their curriculum. As this is a difficult task and often results in objections from established institutes, the installation of such interdisciplinary collaborations is still in development.

An international network formed in the frame of these research activities described in my habilitation such as the World Climate Research Program's (WCRP) Coordinated Regional Downscaling Experiment (CORDEX) Flagship Pilot Study on Convective phenomena at high resolution over Europe and the Mediterranean, and Land Use Change Across Scales (LUCAS). These are the first common community efforts for inter-comparison studies with the regional climate models.

Convection-permitting models (CPM; ~3-1 km spatial horizontal resolution) have the capability to generate long-term projections at a spatial and temporal resolution useful for impact studies. The simulation results have added value in multiple aspects (e.g. sub-daily precipitation statistics, extremes) and the bias compared to observations is in the range of the bias between different observational datasets (*Ban et al. 2021*). Further, direct downscaling experiments without any additional nesting step avoid the high computational demand (see *Coppola et al. 2018* and *Ban et al. 2021*). These high-resolution physically consistent simulation results are currently exploited in my interdisciplinary EU project MAPPY (Multisectoral Analysis of climate and land use change impacts on Pollinators, Plant diversity and crops Yields) and serve as input for impact studies with dynamic vegetation models for the response of agricultural yields and forestry to climate change. Social impacts will be evaluated by a series of relevant ecological, economic and social indicators. Stakeholders and the local government are strongly involved in these studies. The results will contribute to the next Intergovernmental Panel on Climate Change (IPCC) scientific assessments and to the Copernicus Climate Change (C3S) Services. This fosters interdisciplinary collaboration to design effective measures at the regional and local level to adapt to climate change as well as to inform mitigation decisions.

Parallel to these activities the vegetation module of the regional climate model is further developed to account for different vegetation types, which dynamically react to environmental conditions. First results show new evidence that the annually-recurring standard phenology of COSMO-CLM is more realistic by the new calculation of leaf area index dependent upon surface temperature, day length, and water availability. Results with the new phenology implemented in the model show a significantly higher correlation with observations than simulations with the standard phenology. A more realistic growth period is shown for extreme warm or dry summers (*Hartmann et al. 2020*). This project is funded by the German Science Foundation (DFG) to reduce climate uncertainties in the future and improve our understanding of the vegetation-atmosphere interactions on regional scales.

In the medium term, the strengthening of scientific elaboration should consist of fundamental research, applied research and evaluation to integrate the UNFCCC Paris

Agreement, DAS[3], Green Deal, United Nations SDGs[4]. The establishment of more competence centers with partner companies from business and administration could be a successful goal. The centers could be based on the model that has been implemented for many years at the University of Kassel, which is the Center for Environmental Systems Research. It offers the participating partner companies a neutral platform for cooperative research. Together with the partner companies a research plan tailored to their needs could be agreed upon, which would be characterized by a high level of application orientation. Bilateral cooperation with politics, companies and planning offices would support the research work. This enables the development of mitigation and adaptation strategies for using the resources in a sustainable way.

The future scientific goal should emphasize a more holistic approach for atmosphere and land model development of Earth system models. Here, an extension of collaboration with the social and cultural sciences would be an essential step forward to transfer the natural science knowledge to the public community for climate sustainability. The Eduard-Brückner-Award was established by Prof. Dr. Hans von Storch, Dr. Gudrun Rosenhagen, and Prof. Dr. Martin Claußen to foster such an interdisciplinary initiative. With that, uncertainties on the regional and local climate resulting from the impact of LUCC will be reduced, and strategies for LUCC management will be identified to establish sustainable development goals to convey the Paris target of 1.5°C[5]. This requirement is of high relevance supporting societies in their growth of well-being in the world regions. It is undeniable that there are potentially large societal and economic benefits from a quantitative understanding of the complex interactions between climate change, land use change, ecosystem management practices, and plant diversity.

[3] Deutsche Anpassungsstrategie
[4] Sustainable Development Goals, https://sdg-portal.de/
[5] http://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf

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