MERGE, a Strategic Research Area

What is MERGE?

The strategic research area (SRA) Modelling the Regional and Global Earth system (MERGE) brings together over 100 researchers from five Swedish universities (Chalmers, GU, KTH, LnU and LU) and SMHI, to form a cutting edge research environment with a focus on the interactions between the climate and the terrestrial biosphere, and on the development and application of detailed process models, climate models and Earth System models. It is coordinated from and hosted by CEC at the Faculty of Science, LU.

Our vision is to develop further as a multidisciplinary Swedish node providing world-leading treatments of climate-terrestrial biosphere interactions for the international Earth system modelling community and its science agenda.

To this end, MERGE conducts cutting-edge research and research education across four interlinked Research Areas (RAs) (Fig 1). RA1 develops and applies models of terrestrial ecosystems, the climate and the Earth system as a whole. RA2 develops novel historical datasets for input into climate models and for their evaluation, and seeks to understand natural long-term climate variability. RA3 develops and applies detailed process models of atmospheric chemistry, aerosols and cloud physics, informed by experiment and observations, with the aim of improving parameterizations of processes in global models. RA4 develops and applies novel mathematical and statistical techniques for evaluation of model output, improved model parameterization, and for data extrapolation for input to models. Strong and dynamic interactions exist between the RAs. MERGE funds short projects and workshops to stimulate greater RA integration and to act as seed money to stimulate the development of new ideas and applications across research topics and time scales.

MERGE research is accompanied by societal dialogue in the spirit of social learning by both scientists and stakeholders, with a particular focus on scientific basis for policy decisions relating to anthropogenic climate change. We seek to answer *Research Questions (RQs)* that are fundamental to scientific understanding and important for societal development:

- How sensitive is the global climate system to greenhouse-gas emissions, aerosols and land-use change?
- Can the uncertainties relating to climate sensitivity be further reduced?
- How do Earth System feedbacks modify the global, regional and local climate responses to natural and anthropogenic climate forcing?

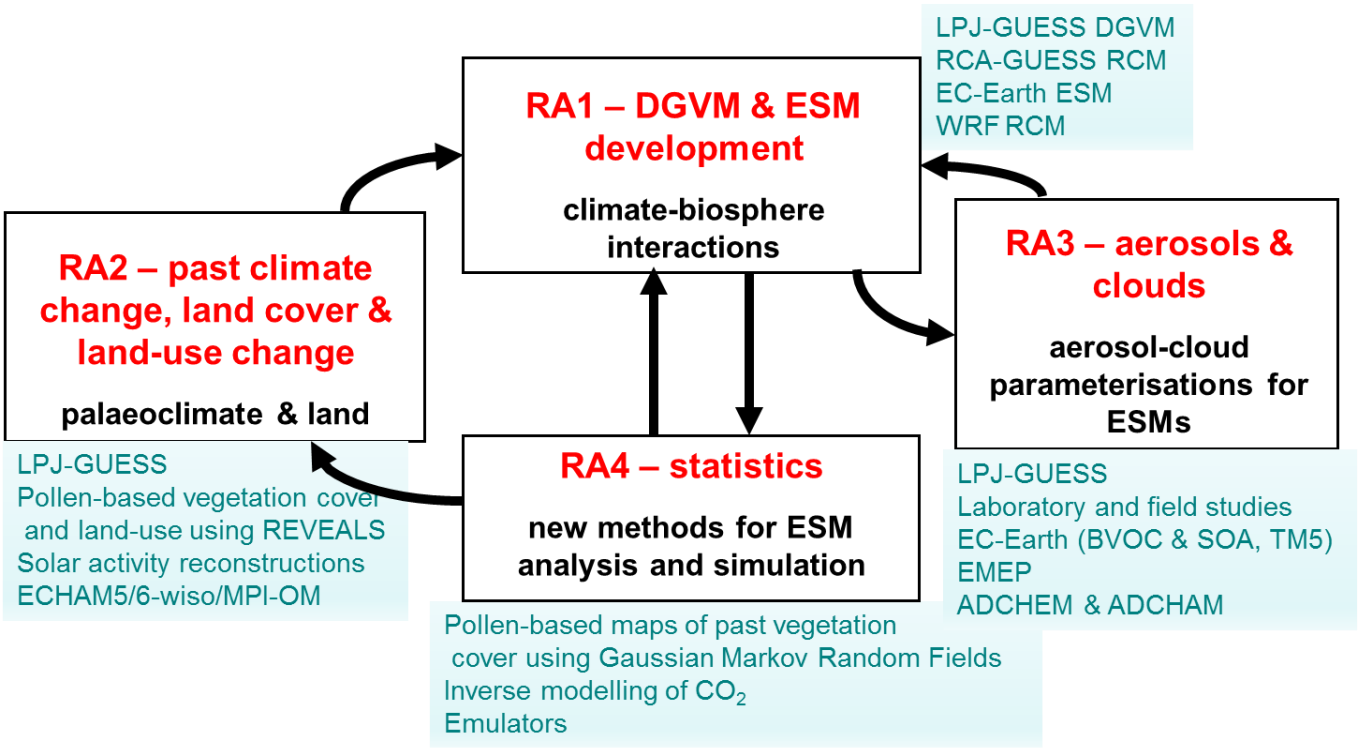

Figure 1. The MERGE Research Areas and some of our main models, methodologies and activities

MERGE Strategy for 2020-2025

Summary

The coming six years, 2020-25, will be exciting years in the development of MERGE, building on the great progress made in 2010-19 (referred to below as Phase 1). In Phase 2 we will continue our strategic focus on the core objectives of process understanding, model improvement, education and outreach, complemented by pioneering applications of our data-informed models to address some of the most urgent questions facing humankind related to climate change.

Key points in our strategy for Phase 2 are:

- To be research-question driven, i.e. we will use our modelling tools to answer our key climate-related Research Questions (RQs), as identified by the scientific community at large, stakeholders, and our MERGE members.
- To advance the state-of-the-art in climate model (GCM) and Earth System Model (ESM) development through a hierarchical modelling approach, where our detailed process-based models, in combination with greater use of data infrastructures (e.g. ICOS, ACTRIS) are used to improve process descriptions in our ESMs.
- To play a leading role in the finalization of a fully-coupled ESM with world-leading treatments of climate-terrestrial biosphere interactions, to use this to contribute to the ESM runs of the next Coupled Model Intercomparison Project (CMIP7) and Paleoclimate Model Intercomparison Project (PMIP), and to address critical research questions that can inform future IPCC Assessment Reports.
- To further improve reconstructions of past climate change and vegetation cover in order to evaluate ESMs and constrain future scenarios, including the evaluation of climate dynamics and biogeophysical feedback processes relating to of land-use change and management.
- To further strengthen ties and input to undergraduate (GU) and graduate (FU) education where a greater use of our tools and data in teaching will create unique learning environments, and where specific support for the ClimBEco graduate research school and the development of an international MSc together with SRA BECC are prioritized.
- To advance our outreach activities through deeper and strategic dialog with stakeholders, key contributions to international knowledge syntheses, and by providing targeted updates on science to policy makers and to society at large.

MERGE in context – relevant recent societal and policy developments, and development of the field since 2015

The Paris Agreement (PA), signed in 2015, and has put climate change and terms such as global temperature goals, climate mitigation and greenhouse gas emissions at the heart of public discourse and political action. The 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) came into force in 2016 and address global, interlinked challenges faced by humankind, including those related to climate and environmental change. Over the next decade, mankind must greatly reduce its emissions of greenhouse gases (GHG) to have a reasonable chance of limiting global warming in accord with PA goals, and at the same time meet each of its SDG targets. In Sweden, the climate policy framework set 2045 as the target year for net-zero emissions. Net increases in carbon uptake from land use, land-use change and forestry (LULUCF), and bioenergy with carbon capture and storage (BECCS), can be used as complementary measures to achieve net-zero emissions beyond the year 2045.

Since its 5th Assessment Report (AR5) in 2013-14, the IPCC has published two comprehensive reports of great importance to the science and politics of climate change, and to MERGE in particular. The Special Report on Global Warming of 1.5°C (IPCC 2018) summarizes the impacts of the target global warming level, specified in the PA, of 1.5°C above pre-industrial levels, and compares these impacts to those expected in the event of greater levels of warming. It also details the GHG emission pathways consistent with such a target, many of which require large-scale incorporation of land-based solutions such as LULUCF and BECCS. In 2019, the IPCC released its Special Report on Climate Change and

Land (IPCC 2019), highlighting the vital role sustainable land management can play in climate action as well as the limits to the contributions that land can make if we are to simultaneously minimize risks to food security, biodiversity and land degradation.

These societal and scientific developments place great demands and responsibility on climate scientists. Our models and climate projections are in greater focus, so they must be trustworthy, built on detailed process understanding and constructed using valid assumptions. They must be properly evaluated, to increase confidence in their use. They must be detailed enough to include all major feedback processes in the climate system. And increasingly, they must be flexible and detailed enough to allow for exploration of the consequences of proposed mitigation action for climate, the SDGs, and the environment in general. This challenge is *the inspiration for MERGE research.*

In Phase 2, we will continue to focus on model development that links climate change, human action, ecosystem management and change, air pollution, food production and biodiversity, with a focus on local, national and global dimensions, and improve the policy relevance of climate simulations

Global and regional climate models (GCMs and RCMs) continue to evolve, moving beyond their initial focus on primarily physical phenomena and processes in the atmosphere, cryosphere and oceans – though these have also seen great improvements in complexity and resolution - to become ESMs, where ecology, vegetation dynamics, LULUCF, biogeochemistry, atmospheric chemistry and biosphere-atmosphere interactions are increasingly being taken into account.

Development and evaluation of state-of-the-art ESMs is the primary focus of MERGE

In Phase 2, MERGE will build and advance on the *major achievements* made in each of the RAs since 2015 (see Appendix 1 for more details).

The LPJ-GUESS Dynamic Global Vegetation Model (DGVM) version 4 was released at the end of 2016, featuring greatly expanded LULUCF and nitrogen (N) cycling functionality. Since 2015 over 200 peer-reviewed scientific publications have used LPJ-GUESS, most of which include MERGE co-authors. MERGE led landmark studies using LPJ-GUESS coupled to the SMHI/Rossby Centre RCA-GUESS RCM, showing the complexity and strength of vegetation feedback processes in Europe, the Arctic, Africa and South America. MERGE also led the coupling of LPJ-GUESS to the EC-Earth GCM/ESM and used the model in the 6th phase of CMIP (CMIP6). The result, EC-Earth-Veg, is the first ever ESM to include both individual-based vegetation dynamics and mechanistic treatments of N cycling and LULUCF.

MERGE researchers have produced and contributed to important corrections of chronologies for records of climate proxy data, resulting in unprecedented precision of time scales and synchronisation between records. This has led directly to better process understanding of internal and forced climate variability. MERGE has also played a leading role in PAGES LandCover6k, an international initiative to produce standard land-use and land-cover change (LULC) datasets for the past 11 millennia based on pollen-based reconstructions of past land-cover (LC) changes and archaeology-based land-use (LU) changes. MERGE developed and tested new algorithms to use pollen-based land cover data to reconstruct past vegetation cover. MERGE also improved statistical methods to reconstruct past CO_2 fluxes.

MERGE has made great progress implementing improved descriptions of the coupling between land ecosystems, aerosol particles and clouds, utilizing highly-detailed model approaches derived from laboratory and field observation, something that has been a priority for many years within the community at large.

MERGE and SRA BECC have jointly funded the two-year graduate research school ClimBEco with the Science faculty at LU, offering courses examining the links between climate change, society, biodiversity loss and risks to ecosystem services, and training students in the personal and interdisciplinary skills needed to tackle these challenges.

The MERGE strategy to maintain excellence as a research environment

To keep MERGE at the absolute cutting edge of climate research, we will continue to innovate in model development, model evaluation, and the creation of unique datasets for the climate community, and combine these developments with applications of our models to address fundamental knowledge gaps and research questions in climate science.

- MERGE will continue to be an excellent strategic climate research environment with research that addresses critical research questions and makes key contributions to the next Coupled Model Intercomparison Project (CMIP7) and upcoming IPCC Assessment Reports.
- MERGE will continue to advance its model development strategy using a hierarchical modelling approach, in which improvements made to detailed process models are used to improve and evaluate GCMs and ESMs, resulting in more reliable climate simulations and impact studies. Part of this strategy is to continuously validate and test hypotheses using paleo-data and our unique access to ICOS and ACTRIS infrastructure and data (e.g. trace gas, aerosol, CO_2 and energy exchanges).
- MERGE will continue to investigate the complex relationships and feedbacks between biogenic VOC and atmospheric aerosol, making use of new measurements (e.g. from ACTRIS), new developments in organic aerosol chemistry, and a hierarchy of process and large-scale models (ADCHEM, EMEP, TM5/EC-Earth).
- MERGE will place great emphasis on further strategic improvements to the EC-Earth model beyond our CMIP6 commitments, making the next version, EC-Earth4, one of the most advanced ESMs in the world.
- MERGE will develop the unique, state-of-the-art vegetation model LPJ-GUESS beyond version 4 jointly with SRA BECC. Planned improvements in Phase 2 include wetland ecosystem and methane dynamics, permafrost physics, an improved wildfire model, nitrogen trace gas emissions, phosphorous cycling and limitations on primary productivity, ozone damage to crops and forests, herbivory and grazing, and improvements to soil biogeochemistry. These developments will then be incorporated into EC-Earth4.
- MERGE will prioritise the development of an isotope module as an important step towards improving the treatment and evaluation of hydrological cycling in EC-Earth4.
- MERGE will continue to develop *new* coupled models & frameworks, e.g. LPJ-GUESS will be coupled to the WRF RCM, allowing for very fine resolution studies of climate, hydrology and vegetation change in selected regions, and for detailed air pollution studies.
- MERGE will work to make PAGES LandCover6k datasets of past LULC available Open Access and use them for improvement and validation of land-use schemes applied in DVGMs coupled to ESMs in the next PMIP simulations. These datasets will include interpolation of point data on past LULC using advanced spatial statistical models providing unique maps of past vegetation (plant cover) and land use for the last 12,000 years.
- MERGE will continue to produce high quality, gridded historical climate field reconstructions which can be used for evaluating circulation modes and decadal to multi-decadal variability in ESMs, as well as the climate response to anthropogenic and natural climate forcing. The past and present frequency of climate extremes will be used to assess the quality of climate projections, and we will produce better estimates of the impact of volcanic and solar forcing.
- MERGE will continue to improve our understanding of the interactions between climate and the biosphere in the past, present and future by promoting dynamic interactions among MERGE members during spring and autumn meetings and a dynamic Annual Work Plan. MERGE will continue to fund Short Projects and workshops to stimulate greater RA integration and to act as seed money to stimulate the development of new ideas and applications across research topics and time scales.

MERGE will strengthen and develop education at all levels

It is an important aim of MERGE to educate a new generation of scientists skilled in Earth System science and advanced climate modelling. Our position at the cutting edge of research gives us access to the data and knowledge that can excite and inspire students. Furthermore, MERGE is well placed to identify at an early stage the educational needs of society in the face of challenges such as climate change and air pollution.

MERGE scientists across all partners are deeply committed to teaching our science at all level, and to teaching climate science not only to the next generation of climate science experts, but also to future business leaders, decision makers and citizens.

In Phase 2, MERGE will:

- communicate the most recent developments and research findings to our students, such as those arising from CMIP6 and IPCC reports,
- introduce the next version of EC-Earth (version 4) to selected graduate-level courses,
- initiate and supervise a series of MERGE-labelled BSc and MSc theses, bringing students even closer to our research,
- work with the educational leadership to enable easier cross-faculty access to courses with MERGE focus,
- continue our support for ClimBEco and initiate more graduate courses related to our research,
- work with SRA BECC to develop a new international Master programme on sustainable land-use in a world affected by global climate change, a subject where our two SRAs meet.

MERGE partnerships and interactions with other SRAs, research environments, universities and society

Cooperation and interactions with other SRAs, universities and society is fundamental to the mission and success of MERGE. The complex, interlinked global challenges facing mankind, encapsulated in the breadth of the SDGs, can only be tackled with the best science and scientists from a range of disciplines, in dialog with society, and the coming decade is a key period in this endeavour.

By its nature, climate science is an international activity. Our modelling infrastructure, experiments and field campaigns benefit from being embedded in international networks. For example, the EC-Earth Consortium brings together 27 research institutes (including MERGE at LU and SMHI) from 10 European countries to collaborate on the development of the EC-Earth ESM. Coordination of ESM development also occurs at national and Nordic levels. The NordForsk-funded NordicESM was a vital platform for cooperation at the Nordic level in Phase 1. MERGE was very active in this network, and we will support the establishment of *a successor to NordicESM* in Phase 2.

MERGE and SRA BECC are both hosted and coordinated by CEC at the Science faculty, LU. Our SRAs have complementary expertise, with BECC focusing on global climate change impacts on biodiversity and ecosystem services, with a specific focus on forest, agricultural, urban and subarctic ecosystems, including land-aquatic system interactions. *In Phase 2, we will continue to coordinate model developments (e.g. to LPJ-GUESS), hold joint BECC-MERGE spring meetings around common themes, and coordinate recruitment.*

MERGE has also a growing and successful interaction with SRA eSSENCE, which has funded projects in technical LPJ-GUESS model development and analysis of benefit to MERGE (and BECC). *We plan to continue this interaction in Phase 2*.

During Phase 1, MERGE initiated a series of meetings with the Bolin Centre for Climate Research (BCCR) with partners at SU, KTH and SMHI. Collaborative projects started during Phase 1 included studies of historical land-climate interactions. *In Phase 2, we will continue to deepen natural research interactions in the areas of climate dynamics,*

paleoclimate research and aerosol-cloud physics and dynamics. We will also work with ClimBEco to make it easier for PhD students from MERGE and BCCR to take courses in each other's graduate research school.

MERGE will continue to provide input to international knowledge syntheses in Phase 2, e.g. to IPCC ARs, through co-authorship and reviewing activities and in the form of model results. To meet demand for broad climate knowledge and understanding, MERGE issued a series of policy briefs in Phase 1 that were widely downloaded from our website and distributed. *We will continue to issue policy briefs in Phase 2, timing them to coincide with key events likely to attract media attention*, e.g. the release of IPCC AR6 in 2021.

Stakeholder dialog and interaction in Phase 1 was coordinated with SRA BECC, facilitated by CEC, LU, in the form of a Stakeholder Reference Group (SRG) consisting of stakeholders from NGOs, governmental authorities and industry. *We will increase the number of strategic discussions with our SRG in Phase 2*. In particular, we will engage our SRG in discussions of the trade-offs and benefits of climate mitigation policies.

MERGE will collaborate with university and faculty leadership

The MERGE research environment cuts across disciplines, faculties and universities. We have the flexibility to adapt quickly to new research priorities as they arise, and our earmarked funding gives our experts a certain freedom to decide MERGE's long-term research priorities. To achieve our goals we are, however, reliant on both the recruitment of talented researchers and teachers, and on the availability of adequate infrastructure. In *Phase 2, we will:*

- have continuous discussions with departmental and faculty leadership regarding recruitment strategy and infrastructure priorities,
- work actively with university and faculty leadership to give our brightest young talents access to leadership training so that they can develop their careers to the benefit of all, and
- collaborate with our sister SRAs in the LU SRA Collegium and faculty leadership to develop long-term strategies for research, education and outreach.

MERGE will meet its research infrastructure needs

MERGE has a wide variety of infrastructure needs. Access to adequate high-performance computing (HPC) resources and data storage is vital to all our modelling efforts. To date, we have primarily used SNIC resources at LUNARC (LU) and, for larger projects such as CMIP6, at the National Supercomputing Centre (NSC) through participation in a large SNIC project (S-CMIP) coordinated by ESM colleagues at SMHI and BCCR, renewed annually. In Phase 2 *we will argue and apply for longer SNIC projects*. We will also coordinate efforts to secure adequate HPC resources with ESM colleagues in our NordicESM and EC-Earth networks.

Proper code maintenance is vital as models become more complex. In addition, models now produce more data and are required to follow strict output protocols and quality standards. To meet these challenges, MERGE decided in Phase 1 to invest in a scientific programmer, based at CEC, LU. Having an expert with the time to devote to technical details of efficient computing and data management has freed our scientists to do more science, and we view this as an efficient use of resources. *MERGE will continue to devote funds to a scientific programmer in Phase 2*.

Model evaluation and calibration is a vital step in model development. *In Phase 2, MERGE will use the high quality data* from the Integrated Carbon Observation System (ICOS), ICOS-Sweden (hosted by CEC, LU) - including longer records from the ICOS Carbon Portal hosted by INES (LU) - and European Research Infrastructure for the observation of Aerosol, Clouds and Trace Gases (ACTRIS) infrastructures, to evaluate and improve model performance.

MERGE Strategy for sustainability and gender equality

MERGE values diversity and equality, and makes decisions based on these values

MERGE will always have equal gender representation in its leadership. Talented women and men coordinate our SRA, sit on the MERGE Board and lead our Research Areas. Furthermore, all partners are represented on the Board, and when replacements and renewal are needed, as was the case in Phase 1, we do so while maintaining the diversity we so value.

MERGE will work to reduce its environmental footprint

MERGE's greatest environmental footprint results from air travel. Though we have made much greater use of video conferencing and virtual meetings in recent years, replacing many research trips, saving time, resources, and reducing greenhouse gas emissions in the process, we recognize the need to go further. *We commit to working with the leadership of our university partners and SMHI to reduce our environmental footprint in Phase 2*, in line with Paris Agreement and global environmental goals, and the LU (and partner) sustainability goals.

Appendix 1. MERGE headline achievements since 2015

Major advances in model development: The LPJ-GUESS Dynamic Global Vegetation Model (DGVM) version 4 was released at the end of 2016, featuring greatly expanded LULUCF and nitrogen (N) cycling functionality. Since 2015 almost 200 peer-reviewed scientific publications have used LPJ-GUESS, most of which include MERGE co-authors. Version 4.1 of the model was finalized in 2019, incorporating wetland ecosystem and methane dynamics, permafrost physics, an improved wildfire model and N trace gas emissions. The LPJ-GUESS code repository and model development is managed by MERGE at INES, LU, and the code is shared widely with collaborators worldwide in a spirit of scientific cooperation. MERGE has led landmark studies using LPJ-GUESS coupled to the SMHI/Rossby Centre RCA-GUESS RCM, showing the complexity and strength of vegetation feedback processes in regions such as Europe, the Arctic, Africa and South America.

Policy-relevant climate simulations: MERGE led the coupling of LPJ-GUESS to the EC-Earth GCM/ESM for use in the 6th phase of the CMIP (CMIP6). The result, EC-Earth-Veg, is the first ever ESM to include both individual-based vegetation dynamics and mechanistic treatments of N cycling and LULUCF. EC-Earth-Veg was used by SMHI and LU in 2019 to produce climate scenarios as a key contribution to CMIP6, the results of which will feature prominently in the IPCC AR6 in 2021/22 and are currently freely available for download to researchers worldwide. EC-Earth has also been used within MERGE for paleoclimate studies of vegetation feedbacks and carbon cycle changes, providing unique insights into long-term changes in large scale tropical precipitation and terrestrial carbon pools.

Major improvements to paleoclimate chronologies and natural climate forcing datasets: MERGE researchers have produced and contributed to important corrections of chronologies for records of climate proxy data, resulting in unprecedented precision of time scales and synchronisation between records. This has led directly to better process understanding of internal and forced climate variability. New and improved reconstructions of solar activity and volcanic aerosol forcing have been produced for the past millennium with contributions from MERGE scientists to produce standardized forcing conditions for paleoclimate model simulations. This information has been used to detect the impact of solar and volcanic forcing on climate patterns.

Major improvements to our understanding of past land-use and land-cover change (LULC): MERGE has played a leading role in PAGES LandCover6k, an international initiative to produce standard LULC datasets for the past 11 millennia based on pollen-based reconstructions of past land-cover (LC) changes and archaeology-based land-use (LU) changes. These LULC datasets are necessary to evaluate the boundary conditions used as land-use in GCM/ESM simulations of past climate, and to evaluate the robustness of DGVMs such as LPJ-GUESS.

Novel mathematical statistical methods for model improvement and data analysis: Development and testing of spatial interpolation methods for environmental data resulted in new working algorithms to use pollen-based land cover data to reconstruct past vegetation cover and initial trials in expanding these models to space-time reconstructions. MERGE also improved statistical methods to reconstruct past CO_2 fluxes, allowing us to estimate past anthropocentric emissions and emission due to LULCC. MERGE has also begun to use artificial intelligence and machine-learning (AI/ML) optimization methods to estimate parameters in LPJ-GUESS using ICOS flux tower data.

Improved understanding of aerosol-cloud interactions: MERGE has made great progress implementing improved descriptions of the coupling between land ecosystems, aerosol particles and clouds, utilizing highly-detailed model approaches derived from laboratory and field observation, something that has been a priority for many years within the community at large.

Contributions to graduate education: MERGE and SRA BECC have jointly funded the two-year graduate research school ClimBEco with the Science faculty at LU, offering courses examining the links between climate change, society, biodiversity loss and risks to ecosystem services, and training students in the personal and interdisciplinary skills needed

to tackle these challenges. Many MERGE PhD students have benefitted from ClimBEco. Furthermore, our researchers have led and designed courses with a focus on LPJ-GUESS and process-based biosphere-atmospheric modelling, and participated in many others.