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# Content

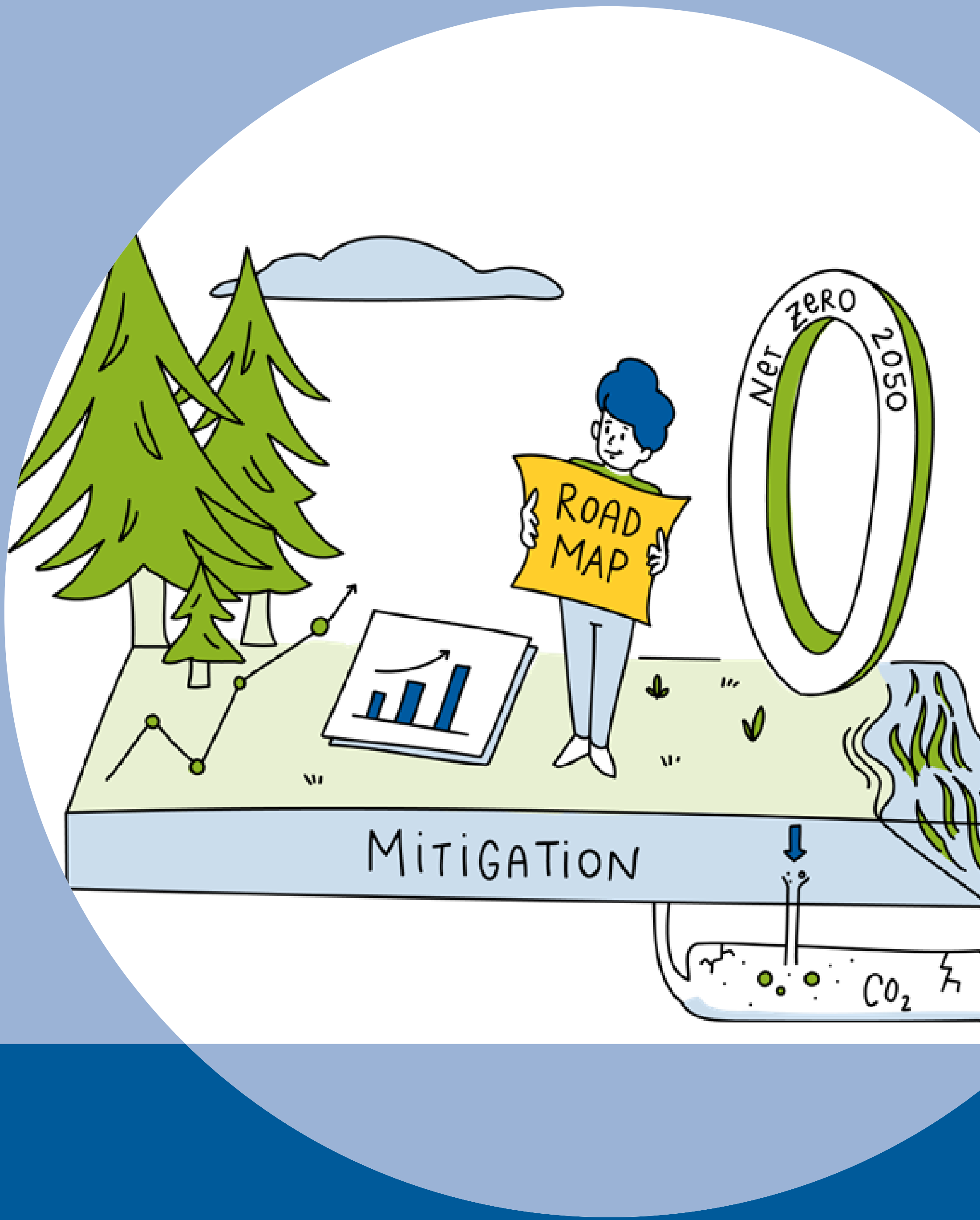
# Researching climate change systemically – a preliminary remark

The events of the summer of 2021 made it clear to us again with all force: With climate change, we are facing enormous challenges for society as a whole worldwide. On the one hand, it is important to limit climate change with rapid greenhouse gas reductions. On the other hand, we have to adapt our society to extreme events to be expected in the future. The IPCC Sixth Assessment Reports (AR 6) of the Working Groups I, II and III, published in August 2021, February 2022 and April 2022, underline this with all clarity. The resulting order for the Helmholtz Association is unavoidable - and has long been identified: Helmholtz has been making important contributions to climate research for many years. The centers of the "Earth and Environment" research area are particularly well positioned. However, climate-relevant research also takes place in the other five research areas of the Helmholtz Association. Against this background, the Helmholtz Climate Initiative (internal: HI-CAM) was launched on July 1, 2019.

The initiative combines research on climate protection and adaptation - two sides of the same coin. From this, the sharpened scientific priorities "Net-Zero-2050" (mitigation) and "Adaptation to extreme events" (adaptation) are derived. In a total of 13 research projects, Helmholtz scientists are driving climate research forward. In the past two years, they have networked even more closely to research the topic of "climate change" systemically, to cross the boundaries of specialist disciplines and to find answers that do justice to the complexity of this challenge. The climate initiative also focuses on entering into a lively dialogue with society. For this purpose, a communication cluster based in Berlin was set up, which is closely linked to the scientific clusters. Until March 31, 2022, the Climate Initiative was financed from the Helmholtz President's Initiative and Networking Fund. Twelve million euros were available for this purpose. A total of 15 of the 18 Helmholtz centers are involved in the initiative.

Most of the work in HI-CAM took place under the difficult conditions of the corona pandemic. At this point we would like to expressly thank everyone involved for the fact that the work in our projects has progressed so impressively and that the originally defined goals were largely achieved. Many of the results have the potential to further increase the visibility of the Helmholtz Association as a relevant climate player and to implement the research results even more effectively. A second phase should pursue the further utilization of information and data obtained so far and promote the new and further development of products and tools for users.

In the following, the three clusters of the Helmholtz Climate Initiative present their final report, in which they show what has been achieved as of March 31, 2022.




# CLUSTER I

# Cluster I: Net-Zero-2050 (Mitigation)

by Prof. Dr. Daniela Jacob | Bettina Steuri, 31.03.2022

## INTRODUCTION

There is no doubt, as evidenced by Volume 1 and 3 of the IPCC Sixth Assessment Report (AR6), that human impact has warmed the climate system. In order to limit climate change, net $CO_2$ emissions must at least drop to zero and other greenhouse gas emissions must be drastically reduced. Rapid and far-reaching reductions in emissions of all greenhouse gases are therefore important measures, and $CO_2$ must also be removed from the atmosphere. This can be stored, for example, in natural sinks such as soil and forests. In addition, the carbon dioxide removed from the atmosphere can be converted back into energy carriers through chemical processes.

In Net-Zero-2050, Cluster I of the Helmholtz Climate Initiative, such strategies and new paths were scientifically examined and evaluated in four projects with regard to the German framework conditions. In addition, two case studies were carried out with participants from practice. The results were incorporated into a pilot roadmap for a carbon-neutral Germany by 2050 and were intended to advance the public and political debate on carbon neutrality at various levels - including in the Helmholtz Association itself.

Net-Zero-2050 focused exclusively on $CO_2$ emissions and the associated carbon neutrality.

The four research projects were:

- **Project 1**: Roadmap and scenarios [HEREON/GERICS, DLR, FZJ/IEK-8, GEOMAR, UFZ]
  Project 1.1: National Roadmap Net Zero [HEREON/GERICS, DLR, FZJ/IEK-8, GEOMAR, UFZ]
  Case Study: Climate-neutral City: Dialogues with Citizens and Stakeholders
  Project 1.2: Integrated Scenario analyses [DLR, FZJ ,GERICS]
- **Project 2**: Circular $CO_2$ approaches [KIT, UFZ, HZB, HEREON/IfP, DLR]
- **Project 3**: Potential and integration of underground storage solutions [GFZ, KIT, HZDR, HEREON/IfN]
- **Project 4**: Storagesolutions in nature [FZJ/IBG-3, GFZ, FZJ/JSC, GEOMAR, HEREON/GERICS, AWI]

Scientists from five research areas and ten Helmholtz centers were participating in Cluster I. In order to promote interdisciplinary cooperation in a targeted manner, various communication formats were used, including a series of seminars for and with postdocs every two weeks, monthly meetings with the PIs and a cluster workshop every six months. The results were continuously published at ***www.netto-null.org***.

# CLUSTER I:
# NET-ZERO-2050
## Project 1

# CLUSTER I:
# NET-ZERO-2050
## Project 1.1
## National Roadmap Net Zero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## SUMMARY

Project 1 consisted of two sub-projects. The sub-projects dealt with synthesizing the results of the whole project – task of Project 1.1 - and focusing on the energy sector – task of Project 1.2. The results of Project 1.1 are presented here. The overarching aim was to combine the main results of all Net-Zero-2050 projects to compile them in a target group-oriented manner. Four major products were developed:

- A "pilot roadmap Net Zero", called the **Netto-Null-2050 Wegweiser**, pools together all contributions from Net-Zero-2050 by presenting a framework for action with suggestions on when and what activities are required to achieve the goal of $CO_2$ neutrality in Germany.
- A portfolio of exemplary units of Carbon Dioxide Removal (CDR) options called **CDR model concepts**, defines CDR options which could potentially be deployed in Germany.
- An evaluation matrix, called **Technology Assessment Matrix (TAM)**, provides an overall assessment on methods and concepts for extracting, using and storing $CO_2$.
- An interactive web atlas, called **Netto-Null-2050 Web-Atlas**, presents the Net-Zero-2050 outcomes on $CO_2$ storage potentials of various technologies and measures across Germany.

As a basis for all activities in Net-Zero-2050, a **Netto-Null-2050 System** was developed and a **national carbon budget** was defined. In a participatory process, the **Netto-Null-2050 Wegweiser** was co-designed with the Net-Zero-2050 partners from all Net-Zero-2050 research fields. The **Netto-Null-2050 Wegweiser** is a report in German that contains a catalog of 127 strategic recommendations for action for the transformation of the energy system and the $CO_2$ removal technologies but also for analytical tools to support decision-making in relation to $CO_2$ removal. This is underpinned by different components for $CO_2$ neutrality scenarios for a net-zero $CO_2$ Germany by 2050.

Another focus of Net-Zero-2050 was on $CO_2$ removal concepts that could be implemented in Germany. For better understanding of how those concepts could be implemented in the real-world setting, we developed model concepts of selected CDR options based on the transdisciplinary expertise available in the Net-Zero-2050 Cluster. The model concepts define key characteristics of the CDR options based on quantitative data. The design of model concepts is described in factsheets forming a portfolio of CDR options that could be deployed in Germany. The **Technology Assessment Matrix (TAM)** contributes to the growing field of assessing the feasibility of CDR. options. CDR is needed to compensate for emissions that are hard to abate and thus plays a key role in achieving net-zero emissions. However, these approaches have not been tested at the scale that is envisioned in low warming/high mitigation pathways. Against this backdrop, the main objective of the **TAM** was to understand the feasibility of deployment of CDR for Germany. We identified important knowledge gaps, including a lack of national level assessments and of assessments that take many different dimensions of deployment into consideration. The **TAM** is a comprehensive, national level assessment, contributing to filling the identified research gaps. It considers technological, environmental, economic, institutional (i.e., political and legal), and social aspects of deployment, as well as the system utility of CDR approaches. As such, the **TAM** is a decision-making tool ready to be used by any stakeholder interested in assessing the feasibility of deploying CDR approaches. While the feasibility assessment has been tailored to the German context, it can be used as a starting point for assessments elsewhere. We have also completed the assessment for Germany for a large number of different CDR approaches. At a time when the political interest in CDR is growing, our assessment is ready to inform climate governance in Germany today.

Together with all project partners an interactive **Netto-Null-2050 Web-Atlas** has been designed and implemented to publicize the project results. Along with the formats of picture stories or maps, methods, technologies and elements required to achieve $CO_2$ neutrality in Germany are presented for different target groups. In addition, long-term strategies for decarbonization in a global perspective (national roadmaps according to UNFCCC) are analytically prepared and presented. The **Netto-Null-2050 Web-Atlas** is a digital knowledge transfer product available at ***https://atlas.netto-null.org***.

## ACHIEVED RESULTS

### The Net-Zero-2050 System: Carbon-Emission-Based System and Framing System

To achieve net-zero $CO_2$ emissions in Germany, all sectors must be taken into account. To this end, the **definition of a system** is essential. The respective Net-Zero-2050 System developed by the Net-Zero-2050 project can be divided into two levels. The first level, the Carbon-Emission-Based System, includes all sectors, with their constituent parts, where $CO_2$ emissions occur and where they can be avoided, reduced or removed. The Framing System, the second level of the Net-Zero-2050 System, surrounds the first level. A publication about the Net-Zero-2050 System is in preparation and will be submitted in spring 2022.

For the first level, we defined the Carbon-Emission-Based System together with all project partners, following an iterative approach. Firstly, we used the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and the 2019 Refinement's categorization as a basis for the structure of the Carbon-Emission-Based System. In a next step, it was supplemented by new categories consistent with the projects' inputs. Furthermore, existing roadmaps, e.g., the 'CCC Net-Zero report' by the UK, were considered to ensure that the Carbon-Emission-Based System and structure do not lack relevant aspects. It was then evaluated by external, scientific experts, which entailed minor amendments.

Beyond that, the Carbon-Emission-Based System was understood as a dynamic and evolving concept, meaning that subcategories were added or adjusted during the project phase. The seven main categories are "Energy", "Industrial Processes and Product Use", "Agriculture, Forestry and other Land Use", "Waste", "Other", "Carbon Dioxide Removal (CDR)" and "Circular Carbon Approaches". In line with this, important factors to take into account included the definitions of natural and anthropogenic sinks and a clear distinction between measures that contribute to negative emissions and circular carbon approaches (i.e., difference between carbon dioxide removal (CDR) and carbon capture and use (CCU)).

After defining the first version of the Carbon-Emission-Based System, a gap analysis was carried out to identify all research topics of the involved project partners that are connected to net-zero research topics. The result was that the Helmholtz community has expertise to assess major parts of the emissions of Germany. Simultaneously, all project partners were consulted to identify potential partners for future collaboration.

The second level of the Net-Zero-2050 System, which surrounds the Carbon-Emission-Based System, is the Framing System. The purpose of this system level is to understand and consider all contextual elements and framework conditions that are relevant to achieve $CO_2$ neutrality in Germany. It was thus developed to ensure a holistic approach to defining the Net-Zero-2050 System. It consists of five dimensions (the economic, institutional, technological, socio-cultural and natural environment dimensions). Both levels of the Net-Zero-2050 System closely interact. The Framing System was also reviewed by internal and external scientific experts.

## National carbon budget

For achieving net-zero $CO_2$ emissions in a way that is consistent with the Paris Agreements' temperature goals, a **defined carbon budget** is a clear guide to the underlying ambition and the time needed to reach the target. Different methodologies can be used to calculate the carbon budget. In Net-Zero-2050, we took Germany's capacities and capabilities as well as global justice considerations into account. Based on the contraction and convergence approach, Germany's emissions first reach equal-per-capita by 2035, and then follow a global sustainable growth pathway until net-zero in 2050.

This approach results in a remaining German carbon budget of 6.9 Gt $CO_2$ (from January 1, 2021 to 2050 and 2100). The remaining carbon budget served as a basis and target for all activities within Net-Zero-2050. In particular, this means that the 6.9 Gt $CO_2$ from January 1, 2021, as the national remaining $CO_2$ budget is needed to be broken down by sector (e.g. energy, land use, industrial processes, and man-made sinks and sources) in order to provide a consistent approach across work packages.

## Netto-Null-2050 Wegweiser

Another task was to bring together and integrate all projects' and work packages' findings of Net-Zero-2050 into a "pilot roadmap Net Zero" as the final deliverable of the project. The report is written in German and is entitled: *„**Netto-Null-2050 Wegweiser:** Strategische Handlungsempfehlungen und mögliche Wege für ein $CO_2$ neutrales Deutschland bis 2050"*. The **Netto-Null-2050 Wegweiser** intends to advance the public, political and scientific debate on $CO_2$ neutrality at various levels - including the debate within the Helmholtz Association itself. The publication demonstrates how different centers of the Helmholtz Association contribute through their scientific knowledge and activities to enable the transformation to a $CO_2$neutral Germany by 2050. The **Netto-Null-2050 Wegweiser** is a snapshot. It maps the findings from July 2019 to December 2021. On the one hand, the report reveals the need for research, also for scientific actors outside the Helmholtz Association. On the other hand, it serves as a reference for cooperation between research and industry, research and innovation policy, and investment. The publication provides a framework for action with suggestions which activities are required to achieve the goal of $CO_2$ neutrality in Germany. Based on scientific findings, the publication provides a discussion framework for all relevant actors and stakeholders.

In particular, the **Netto-Null-2050 Wegweiser** tackles the crucial question: How do we deal with the $CO_2$ emissions that, despite all efforts, continue to be emitted annually and remain in the atmosphere? We show possible ways in which carbon dioxide could be removed from the atmosphere to compensate for the residual emissions that are unavoidable according to current knowledge. The results show that, due to those emissions that are hard to abate, around 60 million tons of $CO_2$ per year still need to be removed in 2050 and onwards (see Figure 1). Biological processes alone are not enough. Only a combination of biological and chemical $CO_2$-removal options will allow us to reach net-zero $CO_2$. Moreover, focusing only on the potential of how much $CO_2$ the options take out of the atmosphere falls short. A holistic view of their impact on the environment and society is required.

The **Netto-Null-2050 Wegweiser** publishes 25 detailed recommendations for action to restructure the energy system and 102 recommendations address $CO_2$ removal. We have compiled these in a Net-Zero-2050 catalog of recommendations for action. The next few years up to 2030 are crucial. By 2030, everything must be done to maximally reduce and avoid $CO_2$ emissions. In particular, energy-related $CO_2$ emissions must be halved by 2030. At the same time, $CO_2$ removal technologies must be researched and tested, and the conditions for successful use created to the extent that they can be deployed at the appropriate time must be met. Almost all 102 Net-Zero-2050 action recommendations related to $CO_2$ removal options must be implemented by 2030.

Few recommendations related to slow, natural storage of $CO_2$ based on plant growth extend to 2050. For the debate on solely chemical $CO_2$ removal options, actors from industry, politics and public administration - in cooperation with research - are in particular required. $CO_2$ removal must become feasible in time. Therefore, demonstration and pilot projects must be set up now in cooperation with the Helmholtz Association to test technologies on a larger scale. The **Netto-Null-2050 Wegweiser** supports a fact-based discourse and reveals that the new German government urgently needs to initiate a political as well as societal debate on $CO_2$ capture and storage processes.

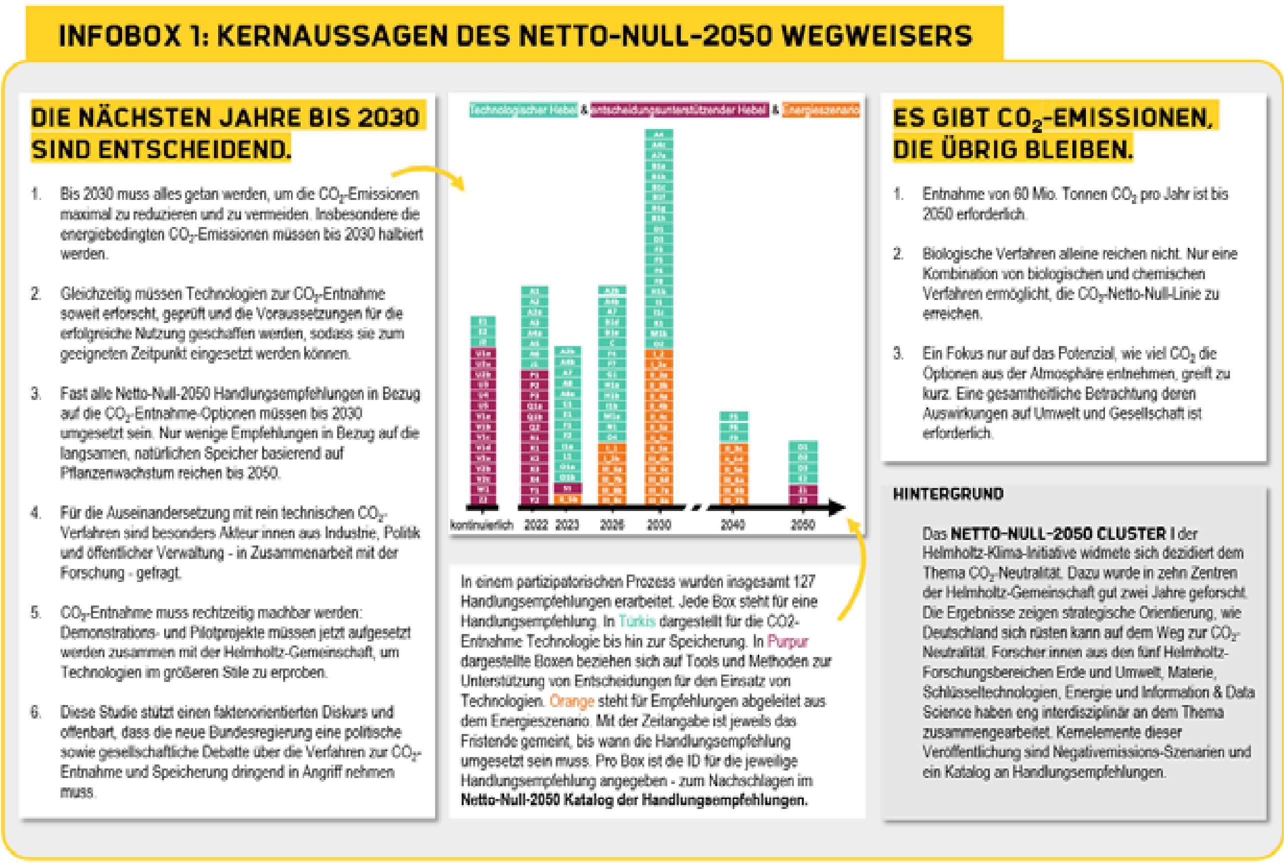


Figure 1: Infobox with key messages summarizing the results as published in the **Netto-Null-2050 Wegweiser**.

## CDR model concepts

There are many options through which CDR could be realized today (e.g., biological, chemical, hybrid). They all come with special requirements, potentials and limitations which should be taken into account while considering their deployment. There are no "silver bullets" or "one-fits-all" options meaning their configuration and deployment will wary from country to country and from region to region (e.g., due to changing natural conditions, existing infrastructure, or policy priorities). To address this issue and to see how the implementation of different CDR options could look like in the deployment environment, for each CDR option we developed a dedicated model concept - its exemplary unit, e.g., plant/installation for hybrid and chemical CDR options, or unit of area (e.g., 1 ha) in case of Enhanced Rock Weathering (ERW) and options for natural sink enhancement. In total we prepared model concepts of thirteen near-to-application CDR options which were evaluated in parallel in P2-P4. Those options are: two concepts of direct air carbon capture (DACC; centralized

DACC farms and decentralized applications in HVAC systems), six bioenergy with carbon capture technologies (BECC; biomass combustion for heat and power co-generation (CHP), gasification for biofuels production, slow pyrolysis for biochar production, and three concepts of biogas CHP – each based on different type of biomass, including waste, manure and energy crops mix, paludiculture biomass, and macroalgae), and five Nature-Based Solutions (NBS; peatland rewetting, afforestation of cropland, cover crops application, enhanced rock weathering, and seagrass meadows expansion). Additionally, to complement the necessary information on BECC and DACC, we created a factsheet on underground $CO_2$ storage for Germany.

The quantitative data gathered to describe those model concepts has been structured into factsheets with unified set of indicators across all CDR options. We used different information channels to collect the data, including literature review, expert's knowledge, and process simulations. In the factsheets we divided the data into seven categories:

- concept characteristics – describing general aspects of the concept, e.g., its technical maturity, available infrastructure, sitting conditions
- input data – specifying required resources, e.g., land, energy, water
- output data – specifying generated (co-)products
- environmental parameters – describes impacts e.g., on soil, water, air
- economic parameters - addresses economic performance of the options, e.g., $CO_2$ removal costs, OPEX, CAPEX
- systemic parameters – considers, among others, $CO_2$ removal potentials, permanence
- scalability – describes reproducibility of the model concept

Thanks to such approach we were able to provide a harmonized dataset on different CDR options. That allowed us to analyze CDR options from different perspectives, e.g., according to their $CO_2$ removal potential, specify their possible locations, estimate time of their possible deployment.

## Technology Assessment Matrix (TAM)

Despite their prominent role in modelled low emission pathways and a growing political interest, there are still considerable uncertainties regarding the feasibility of deploying CDR at scale. Previous research has raised concerns about the risk of mitigation deterrence – that the very idea of generating future carbon removal could slow down climate action today (e.g., Low and Schafer, 2020; Waller et al., 2020). Indeed, in models, the greater the contribution from CDR is, the slower the rate of decarbonization becomes (Holz et al., 2018; Butnar et al., 2020). The risk of delayed decarbonization becomes even more pronounced if CDR approaches do not deliver as assumed in models. Against this backdrop, it is pivotal to better understand the feasibility of the deployment of CDR approaches on the ground. Our assessment framework (policy tool) and a **Technology Assessment Matrix (TAM)**, contribute to a growing research effort to better understand the feasibility concerns of CDR under current conditions instead of focusing on theoretical future potential (see also e.g., Boysen et al., 2017; Geden et al., 2018).

An important step of the work progress towards the **TAM** was to review the state of the art of CDR. To this end, we reviewed all Long-term Low Emissions and Development Strategies (LT-LEDS) under UN Framework Convention on Climate Change (UNFCCC) that were available at the time (17 in spring 2020), and conducted an overview of different types of assessments (e.g., Oschlies et al., 2017; Fuss et al., 2018; Fridahl et al., 2020; Thrän et al. 2021). We compared the LT-LEDS with the assessment in the Special Report on Global Warming of 1.5°C by the Intergovernmental Panel on Climate Change (IPCC SR1.5, see de Coninck et al., 2018). We found that LT-LEDS tend to focus on bio-geophysical dimensions and technology, and consequently identified a need for disaggregated, national analyses and a greater focus on socio-cultural dimensions (Thoni et al., 2020).

While many LT-LEDS include some form of natural climate mitigation (such as afforestation), the plans are vague in terms of implementation (ibid.).

To address the identified gaps, our assessment framework is comprehensive and includes previously underexplored dimensions. In total, it covers six different dimensions (**see Figure 2**), namely technological, environmental, economic, social, institutional (i.e., political and legal), and system utility, 27 criteria, and 67 indicators with a corresponding traffic light system for assessment. Examples of indicators include air quality, Technology Readiness Level (TRL), marginal removal cost, ethical reservations, conformity with existing laws, and risk of carbon loss due to climate change.


**Figure 2:** Overview of thematic dimensions included in the feasibility assessment framework of carbon dioxide removal (CDR) options. (source: UFZ/Conor Ó Beoláin, Helmholtz Climate Initiative // Julia Blenn, Creative Commons CC-BY NC 4.0 licence)

Our assessment of a range of options for carbon removal approaches for Germany shows that the estimated effort for deployment varies between options, but that all have some hurdles that would need to be addressed if it is decided that these options should be deployed. One clear outcome was that only the combination of different CDR approaches, namely Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture (DAC), afforestation and adapted agricultural practices, could provide significant $CO_2$ removal. However, all approaches have their specific challenges: For BECCS, the effort needed varies between biomass options, but all face potential challenges in terms of environmental impact and most face land-use conflicts (see also e.g., Dooley et al., 2020). It also appears that it currently would be easier to deploy both BECC and DAC, as a circular carbon approach without a storage component, not least due to legal barriers, low political acceptance, and public opposition (see also e.g., Dütschke, 2011; Linzenich et al., 2019; Mayer, 2019; Otto et al., 2021). That being said, the scholarly literature suggests a discursive shift from fossil CCS to the generation of negative emissions, which could help legitimize storage solutions (Wallquist et al., 2012; Otto and Gross, 2021). For DAC, key challenges include high costs and energy demand, in line with previous assessments (see also e.g., Honegger et al., 2020). Key challenges of natural climate solutions, such as peatland rewetting, afforestation, salt marsh protection, and seagrass restoration, vary between options but include limited removal potential, risk of reversals/non-permanent storage of carbon, and potential land-use conflicts (see also Borchers et al. submitted; Dooley et al., 2020). In general, the effort needed depends on scale of deployment, with small-scale deployment being associated with lower effort. That however, also needs to be assessed against removal potential and positive side-effects of carbon removal.

## Worldwide mapping and a synthesis of existing roadmaps

There is a vast number of roadmaps on the topic climate mitigations from many countries available. Existing roadmaps were recruited from the open-accessible online UNFCCC data base (*www.unfccc.int*). Selected were each national "Long-Term Low-Emission Development Strategies" (LT-LEDS) with a range beyond 2030 which have been submitted so far (32, as of October 15th, 2021) and which, respectively, are available in English (30 in total). With this, a worldwide mapping and a synthesis of existing roadmaps on the basis of the key parameters for both climate mitigation and climate action has been carried out and prototype-like visualized (**Figure 3**). While existing analyses are focusing on climate pledges and targets, this new analysis focuses on the "how-to", i.e., the strategies, measures and instruments outlined in these national LT-LEDS required and to be implemented over the period of the next two to three decades. The feature allows for comparison with the assessment of national climate targets, pledges and "Nationally Determined Contributions" (NDCs) by each party. But it also provides the possibility of direct and online plausibility checks in terms of national climate targets and underlying strategies and measures on how to reach those goals on a long-term timescale, both sectoral and cross-sectoral. This enables, moreover, a faster check whether climate targets and pledges by each nation are consistent with the mitigation measures described in the according roadmap, and vice versa. Finally, with this direct comparison tool, knowledge transfer and an inspiring mutual discussion on how to increase climate action and how to implement more ambitious climate mitigation strategies can be promoted, both on a national and international level.

As further countries are still submitting a national LT-LEDS with UNFCCC, or updating their existing one, the roadmap assessment as well as the corresponding visualization of the results in the **Netto-Null-2050 Web-Atlas** is an ongoing process based on "living documents".

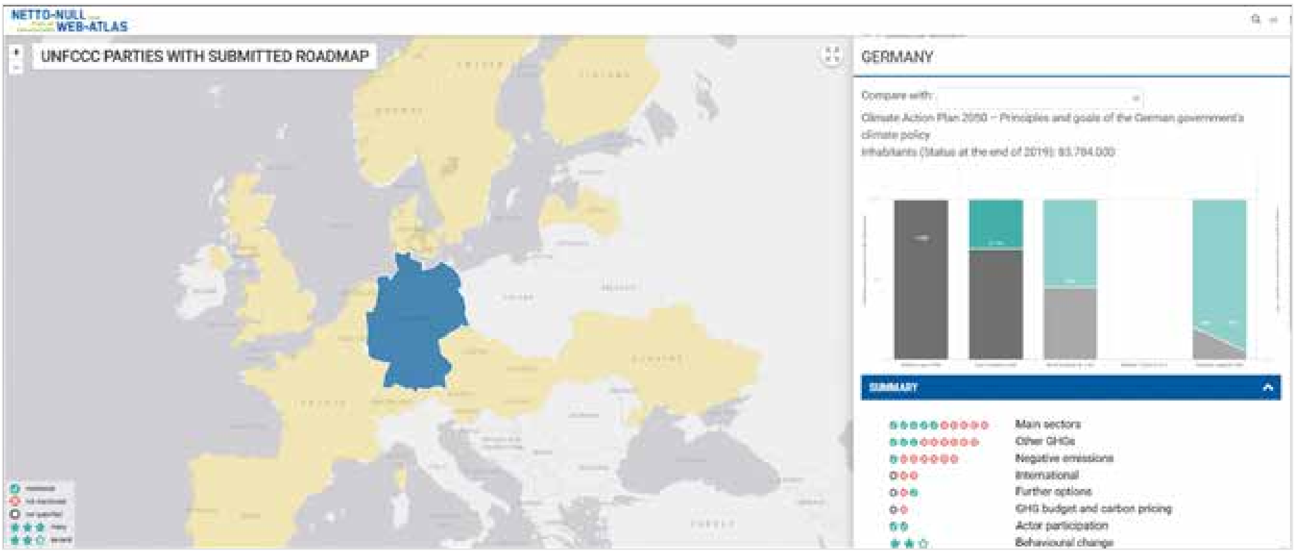


**Figure 3:** Visualizations of roadmaps according to UNFCCC in the **Netto-Null-2050 Web-Atlas**. This feature allows the users to benchmark and discuss long-term pathways on climate mitigation strategies and action.

## Netto-Null-2050 Web-Atlas

The **Netto-Null-2050 Web-Atlas** presents all research fields addressed by Net-Zero-2050. The web-page *atlas.netto-null.org* shows project results that are important for $CO_2$ neutral Germany up to 2050. Net-Zero-2050 is intended to promote the public and political debate on $CO_2$ neutrality on various levels. The scientific content and results within Net-Zero-2050, were contributed by the interdisciplinary Net-Zero-2050 team.

The **Netto-Null-2050 Web-Atlas** is a platform for digital knowledge transfer. It functions as a showcase for the research contributions of a total of ten Helmholtz Centers that have contributed their expertise to Net-Zero-2050. It presents the results of the Net-Zero-2050 clearly and understandably and answers the question: Which technical and biological options and political decisions can support Germany becoming $CO_2$ neutral? The target groups include the interested professional public, environmental policy at federal to regional level and municipal, technical experts. Therefore, the **Netto-Null-2050 Web-Atlas** transfers knowledge from science to actors in politics, public administration, and other "climate-relevant" decision-makers. The current scientific findings compiled and processed on this platform are intended to highlight building blocks and elements that will support the transformation of Germany into a $CO_2$ neutral country by 2050 at the latest.

The users can easily navigate the topics bundled into four different chapters (Figure 4). The chapter structure of the **Netto-Null-2050 Web-Atlas** is adapted to the project structure developed for the **Net-Zero-2050 Wegweiser**. Therefore, two levers are crucial to guide Germany to $CO_2$ neutrality: the technological and the decision-support lever. Under the technological lever, the user will find contributions from Net-Zero-2050 that cover topics ranging from synthetic and biological $CO_2$ avoidance and removal to $CO_2$ and other gases storage. Under the decision-support lever, the user will find contributions from the Net-Zero-2050, such as carbon accounting, feasibility assessment of carbon removal options, and case studies and cross-sectoral pathways for possible decarbonization strategies.

Another chapter is reserved for synthesis and visualization of the long-term national mitigation strategies according to the UNFCCC (see sub-chapter '**Worldwide mapping and a synthesis of existing roadmaps**'). The fourth chapter is dedicated to receiving more information about the Net-Zero-2050 partners.


**Figure 4:** Screenshot of **Netto-Null-2050 Web-Atlas** home page. At the bottom the fourth chapter elements are shown.

Based on former web-atlas experiences (Preuschmann et al., 2017) and an inventory and as-sessments of five well-known online-based approaches, the design of the **Netto-Null-2050 Web-Atlas** was derived. This exercise enabled us to derive recommendations that characterize successful elements of building a web platform. These recommendations served as specific success criteria for the **Netto-Null-2050 Web-Atlas** requirements. For example, visual elements such as selecting modules via tiles were for the **Netto-Null-2050 Web-Atlas**. The selection of chapters via tiles also combines an attractive appearance with modern functional habits.

The communication of scientific content in a narrative form is another element that was picked from the inventory assessment. For the **Netto-Null-2050 Web-Atlas**, this idea was taken up and developed specifically for the presentation of content without geo-referenced maps. Furthermore, the **Netto-Null-2050 Web-Atlas** tries to reach a comprehensive range of potential users by integrating different levels of information. As far as possible, the content is presented at a generally understandable language level, which facilitates the inclusion of interdisciplinary users. In particular, the so-called overview level aims at the general public, readers in a hurry or from outside the discipline. The thematization of opportunities and risks supports the development of users' strategies for action at the practical level – the provision of the content in German and English aims to expand the audience's reach.

Furthermore, with its background level concept, the web atlas offers users a self-determined way to dive deeper into the subject matter. In handling the elements of **Netto-Null-2050 Web-Atlas**, the design is determined by the consideration of accessibility. Most importantly, the **Netto-Null-2050 Web-Atlas** is designed to be comfortable to use on all devices.

During the development and conception of the Netto-Null-2050 Web-Atlas, numerous dialogues, group discussions, and workshops were held, contributing to the optimization of the **Netto-Null-2050 Web-Atlas** product. The developers were able to draw on many experiences and requirements for digital knowledge formats from well-known products developed at GERICS and discussed new ideas within Hereon and GERICS in several meetings within the communication teams. Hereon/GERICS developed the **Netto-Null-2050 Web-Atlas** in cooperation with the software development branch of X-Net Services GmbH from Linz, Austria, with regular, weekly development meetings.

At the beginning of the project, a workshop on the contribution possibilities and system requirements with main partners took place. In the following, some project partners from the centers GEOMAR, UFZ, AWI, FZJ, as part of the **Netto-Null-2050 Web-Atlas** development team, acted as a reflection team in various online meetings during the development phase. The reflection meetings served as a concept check and feasibility analysis for the scientific contributions of the project partners.

The exchange of experience on knowledge communication formats was reflected within the Helmholtz Climate Initiative, especially with Communication Cluster III. Cooperation was deepened through a jointly organized process for the linguistic editing of scientific contributions. In individual cases, there were various group discussions with our project partners on optimizing the structure and language of the contributions.

## WORK PROGRESS

In Project 1.1, a list of seven milestones were suggested in the proposal of the HI-CAM project. The milestones are listed below alongside with a brief description:

- M-P1.1.1: Mapping of existing roadmaps and gap analysis
- M-P1.1.2: System definition and integration of key actors
- M-P1.1.3: Stocktaking and evaluation of existing approaches towards the interactive and online-based provision of decision-relevant information
- M-P1.1.4: User dialogue regarding the "National Net Zero Atlas"
- M-P1.1.5: Construction of assessment matrix
- *Please note: M-P1.1.6 and M-P1.1.7 are described separately in the chapters' Final report of Case Study I' and 'Final report of Case Study II'*
- P1.1.8: National Net Zero Atlas (online concept available and technical report)
- M-P1.1.9: National Roadmap Net Zero

### M-P1.1.1: Mapping of existing roadmaps and gap analysis

Drawing-up and the submission of existing national climate mitigation roadmaps (LT-LEDS) is a continuing process that did not end after six months of assessment according to the description in the project proposal. For the first report, reflecting the state of affairs as of February 28th, 2020, 14 national LT-LEDS available in English have been assessed. These assessments were also used for the first stage of visualization in the **Netto-Null-2050 Web-Atlas**. For the second report and the according to **Netto-Null-2050 Web-Atlas** visualization of the results, 30 officially submitted national LT-LEDS available in English could be taken into account (with the particular case of the EU-27 "roadmap" that could not be visualized since the territorial definition had to be based/focused on the national state level).

Since there is no international agreement or obligation on which criteria and parameters will be relevant and used to draw up a national roadmap each, the roadmap assessment had to deal with a pretty heterogeneous setting of criteria, reflecting the various structures and needs of each national state. In order to make the results as comparable as possible, a set of 50 different check-off parameters had been developed. Partly deviating from some of the roadmap descriptions, the official GHG inventory of UNFCCC has been checked in terms of national GHG data available according to a 1990 emission baseline in order to make GHG emission trends comparable as far as possible, also for visualization.

### M-P1.1.2: System definition and integration of key actors

In this milestone, the overall **Net-Zero-2050 System** and its boundaries were defined in the Carbon-Emission-Based System and the Framing System. The Net-Zero-2050 System was developed, as planned in the proposal, in a participatory process involving all project partners as well as external experts. The key topics were identified and processed within the Helmholtz Association. Furthermore, a gap analysis was carried out to identify all Helmholtz research topics connected to net-zero as well as new partners. In accordance with the proposal, social areas and sectors were identified and defined in the Framing System. The national carbon budget, which was used for the project activities, was defined at the beginning of the project phase. The report was submitted on time. Currently, it is still under internal review and not publicly available.

### M-P1.1.3: Stocktaking and evaluation of existing approaches towards the interactive and online-based provision of decision-relevant information

The report M-P1.1.3 by Preuschmann & Köhnke (2020) has been completed on schedule. Currently, it is still under internal review and not publicly available. The report consists of two main parts. First, the report contains a rough inventory and short assessments of five exemplary online-based approaches. For this reason, five knowledge transfer platforms were selected that offer online applications to present scientific content. These websites comprise web-atlas functions or related scientific topics, each using different knowledge transfer tools and features. An evaluation matrix was developed to compare the websites based on three main criteria with twelve sub-criteria and 34 individual criteria, mainly in a question format. Five team-related in-house reviewers completed the evaluation matrix for each product for the evaluation process. Subsequently, two supervisors synthesized the reviewers' answers. The product research provisionally sounded out which solutions and implementations appealed to the reviewers as potential test end-users and which functions were perceived as less valuable. The results were synthesized and incorporated into a catalog of requirements for the web-atlas. Building on this catalog, general recommendations for developing the Netto-Null-2050 Web-Atlas was defined.

The second part of the report describes the technical and structural concept of the **Netto-Null-2050 Web-Atlas**. This part deals with the general, conceptual, and structural framework and the data upload and optimization process.

### M-P1.1.4: User dialogue regarding the "National Net Zero Atlas"

Regarding the milestone **M-P1.1.4**, the initial plan of organizing one user workshop was changed. Instead, various project-internal capacity-building workshops and dialogue formats were conducted to present the project partners' results effectively and in a user-friendly way and communicate the benefits of their results. Four capacity-building workshops were held to introduce the content technically and bring it into the desired form. Afterwards, there were more than 50 individual dialogues and training sessions in which individual optimization possibilities were addressed. The final synthesis report M-P1.1.4 is submitted by Preuschmann & Görl (2022).

### M-P1.1.5: Construction of assessment matrix

With an extended deadline, the milestone M-P1.1.5 (concept/report) has been achieved. We have published part of the work (Thoni et al. 2020; Otto et al. 2021), the assessment matrix as a decision-making tool is under review with Frontiers in Climate, and the results of the **TAM** for Germany are to be submitted for peer review. The team was negatively affected by the pandemic in different ways and we believe that we could have otherwise published our results earlier, but all in all the work could be carried out as planned.

To produce the assessment framework, an interdisciplinary team was established, with representatives from engineering, economics, law, social sciences and natural sciences. We used the feasibility assessment presented in IPCC SR1.5 (Table 4.10 in de Coninck et al., 2018) as well as the assessment of feasibility of bioenergy strategies in Germany (Thrän et al., 2020) as starting points. This resulted in the identification of six important dimensions for our assessment, namely technological, environmental, economic, social, institutional, and system utility. The members of the team were responsible for different dimensions, but we had regular meetings where the whole team discussed, inter alia, progress made and common obstacles.

As our assessment framework focuses on the German national level, we aspired to identify the most important criteria and indicators for the German context. In practice, this meant drawing on the most recent, relevant assessments and material from Germany. Examples include: assessments of economic barriers to the deployment of new technologies in Germany (Agora Verkehrswende, 2020), assessment of the German bioenergy system

(Thrän et al., 2020), tools for environmental impact assessment for Germany (e.g. UBA, 2020), and survey data from Germany (Braun et al., 2018; Merk et al., 2019). Moreover, indicators already used within established planning and assessment processes were preferred in order to ensure useful information transfer to decision makers. In addition to basing the assessment framework firmly on the scholarly literature and/or established practices, we also drew on available HI-CAM expertise. For the creation of the **TAM**, we organized an internal review process among 32 experts from HI-CAM. Similarly, we based the assessment of CDR and circular carbon approaches for Germany (the filled TAM with color-coding for each indicator) on scholarly literature, established practices, and/or expert elicitation. We met multiple times with experts engaged in the establishment of **CDR model concepts** (see Project 2) to integrate their knowledge in the process. As the result factsheets of CDR model concepts were designed.

### P1.1.8: National Net Zero Atlas (online concept available and technical report)

The main milestone **M-P1.1.8** of development process was reached on time. The **Netto-Null-2050 Web-Atlas** (*atlas.netto-null.org*) went online on time for the HI-CAM final conference on November 17, 2021 at 9:30 a.m.

For the technical implementation of the **Netto-Null-2050 Web-Atlas**, a subcontract was awarded to the company X-Net Services GmbH. The content contributions were made possible in close cooperation with the project partners. While developing the **Netto-Null-2050 Web-Atlas** with the project partners, the need for journalistic assistance for formulations was identified. Therefore, an unscheduled linguistic review was added in consultation with Cluster III. Thus, support for the design and adaptation of graphics for a uniform look in the Helmholtz Climate Initiative style was also included, which was only possible through the support of Cluster III. However, during the project, the budget for the **Netto-Null-2050 Web-Atlas** had to be increased for several unforeseeable adaptations.

For example, integrating features such as feedback collection or playing videos within a story-based contribution. In addition, the very individual processing of the map contributions and the UNFCCC roadmaps on the GeoServer was unexpectedly labor-intensive and thus cost-intensive. The **Netto-Null-2050 Web-Atlas** was launched November 17, 2021. The final technical report **M-P1.1.8** is submitted by Preuschmann & Görl (2022).

### M-P1.1.9: National Roadmap Net Zero

There are no significant deviations from the original milestone M-P1.1.9. The report was written in German for the German target groups. Therefore, we needed a German equivalent for the term "pilot-roadmap". The report was entitled „***Netto-Null-2050 Wegweiser:*** *Strategische Handlungsempfehlungen und mögliche Wege für ein $CO_2$-neutrales Deutschland bis 2050*". The **Netto-Null-2050 Wegweiser** was co-designed with all Net-Zero-2050 partners. For over 10 months, three workshops with partners from all work packages were organized (see sub-chapter 'Events'), three expert rounds were held, a presentation given in the "Seminar Series for HI-CAM-Postdocs", and 31 one-to-one meetings. The report is currently under internal review by all project partners and will be published in spring 2022.

## SPECIAL FEATURES

### The Net-Zero-2050 System: Carbon-Emission-Based System and Framing System

The definition of the Net-Zero-2050 System followed a participatory approach, which involved all project partners. We supplemented the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and the 2019 Refinement and thus, new elements could be included. By adding the new categories concerning $CO_2$ sinks, we could lay special emphasis on $CO_2$ removal, which was not as apparent before. The **Framing System** was equally essential to develop, incorporating a holistic, systemic view on how to reach $CO_2$ neutrality. The applied approach to define a remaining carbon budget for Germany offered an alternative to existing estimates, which do not take Germany's infrastructural lock-ins into account.

### Netto-Null-2050 Wegweiser

The **Netto-Null-2050 Wegweiser** with the negative emissions scenarios and its catalogue of 127 recommendations for actions is a source of inspiration for future collaboration within the Helmholtz Association but also outside. It states research gaps and where there is need to continue research activities but it also shows that there are cooperation options with external actors. For instance, the vast majority of actions under the technology lever call for demonstrations projects together with industry partners. We had established a successful bottom-up approach through a participatory process for the design and development of the **Netto-Null-2050 Wegweise**r. This approached allowed us to involve as many partners as possible in the design process of the **Netto-Null-2050 Wegweiser**. This was beneficial as the final **Netto-Null-2050 Wegweiser** makes the diversity of project topics visible and reflects all research topics of Net-Zero-2050.

### CDR model concepts

The information available on individual CDR options is vast, but scattered across many different research fields and levels of assessment (Minx et al., 2018). Our unique approach of creating model concepts of CDR options was designed to put this information into specific context of Germany and to make CDR easier to manage and imagine in the real-world, as they focus on concrete examples (e.g., a bioenergy plant, unit of afforested area, etc.). In this way they may serve as a possible inspiration for CDR deployment in Germany. Their implementation in form of tabular factsheets not only structures the data, but also makes it easier to navigate and improves readability. These structured considerations can further serve as a basis for comparison and deeper evaluations of different CDR options as well as indicate pathways with the highest potential to support achieving net-zero $CO_2$ emissions in Germany. They can be further used in climate research and policy actions, such as research and demonstration of CDR options, as well as climate and energy scenario development.

### Technology Assessment Matrix (TAM)

CDR options are gaining political interest, not least against the backdrop of the Paris Agreement, calling for a balance of emissions and removals. CDR approaches were included in all emission pathways with no or limited temperature overshoot included in the IPCC Special Report on 1.5 degree global warming, and there is growing consensus that we will not reach net-zero emissions without these approaches (Otto et al., 2021). However, as discussed above under "Achieved results", the inclusion of CDR in global models and assessments has received criticism for running the risk of delaying decarbonization by promising removal of carbon in the future. Instead of starting with a specific goal, such as the 1.5 degree C temperature goal, asking what it would take to get there, feasibility assessments ask what current conditions look like and what challenges would need to be addressed to get to a certain point (Thoni et al., 2020). To understand what role CDR can play in climate policy, we need both. This is because what is theoretically and technically possible is not necessarily the same as what is plausible or desirable. Our assessment framework differs in several ways to global efforts and models and complement these by 1) offering a national level, contextualized, assessment, and 2) offering an assessment that combines qualitative and quantitative aspects and a broad range of dimensions. One challenge of models is that important aspects to enable deployment such as acceptance and trust are subjective and context-dependent and cannot be easily aggregated by models. Our assessment framework is, to the best of our knowledge, the most comprehensive national level assessment to date. The completed **TAM** for Germany for a large number of different CDR and circular carbon approaches (13 in total – see Project 2) is timely given the growing political interest in these approaches. While the assessment has been tailor-made to the German context, it can be used as a starting point for other assessments such as for other national contexts or at the local level.

When it comes to the specific features of the assessment framework, we would like to highlight the added value of our traffic light system, used to evaluate the impacts and effects of deployment. We followed the approach used by Thrän et al. (2020) in the context of biomass, and developed a traffic light system for each indicator of the assessment framework, hence adapting the traffic light system to the context of CDR. The color-coding goes from red to green in five steps for most indicators, with red indicating large hurdle/effort needed while dark green indicates no hurdle/effort needed and/or positive effects (see also similar approaches used by e.g. Climate Action Tracker 2021 or Boehm et al., 2021). The aim of the traffic light system is to provide a systematic overview of challenges and opportunities for CDR options and to communicate these in an effective and intuitive way. Our traffic light system with its indicators to assess the feasibility of deployment of CDR options is adapted to the German national context and is, to the best of our knowledge, the only one with this scope. The color-coding, together with the combination of qualitative and quantitative indicators, is a tool that can support science-policy processes on the development and deployment of CDR and circular carbon approaches, as it helps structuring and evaluating available information on the feasibility of these options. Moreover, by unpacking technologies and analyzing CDR options in their contexts, the TAM contributes to making these approaches and their effects more grounded and easier to visualize. This is particularly important as some of these approaches currently only exist as pilots and none has been implemented at the large scale envisioned in global low-emission pathways.

### Worldwide mapping and a synthesis of existing roadmaps

For the first time, national LT-LEDS have been assessed, mapped and compared and made online available in the **Netto-Null-2050 Web-Atlas**. This feature of the **Netto-Null-2050 Web-Atlas** allows the users to benchmark and discuss long-term pathways on climate mitigation strategies and action much easier.

### Netto-Null-2050 Web-Atlas

With the **Netto-Null-2050 Web Atlas**, an interdisciplinary team from ten different Helmholtz Centers has succeeded in presenting the scientific content and results in a form that non-academics can also understand. In contrast to a geo-referenced atlas, the particular challenge in the Net-Zero-2050 was that most project partners do not produce results displayable in maps. The **Netto-Null-2050 Web-Atlas** met this challenge with the possibility of two different presentation formats: Map-based contributions or story-based contributions. A map-based contribution shows geo-referenced maps with explanatory texts along with structural questions on different levels of information. A story-based contribution is like a picture story along with a given structure, although this can also be formulated in a free story. Further, a story-telling technique is used at least for one contribution. Another unique feature is that the **Netto-Null-2050 Web-Atlas** contents are prepared in a way that users can quickly identify the depth of information relevant to them. To this end, there are three levels of information: Overview | Practice | Background, which is identifiable with corresponding markers. At the end of each contribution, users are offered further and more in-depth information. In addition, a flash survey is integrated into the **Netto-Null-2050 Web-Atlas** so that a user profile and initial information on the outcome, i.e., the short-term effect on the target group of **Netto-Null-2050 Web-Atlas** can be evaluated.

## OUTLOOK ON FUTURE WORK

### The Net-Zero-2050 System and carbon budget

The **Net-Zero-2050 System** can be used in different contexts and may guide others in the process of defining a system for their respective contexts. In terms of transferability, the Net-Zero-2050 **carbon budget** approach can be applied to calculate corresponding carbon budgets for other regions, and allows for the global carbon budget (i.e., the sum of all regional budgets) to remain consistent with Paris Agreement temperature goals.

### Netto-Null-2050 Wegweiser

A dissemination idea for the Net-Zero-2050 catalogue of recommendations of the **Netto-Null-2050 Wegweiser** is to transfer them into an online web format, e.g., into the Net-Zero-2050 Web Atlas. This would allow the users to easily navigate through and select appropriate recommendations. A follow-up step could be to present the recommendations to decision makers from cities, industry, and others to discuss the implementation of actions. This could be done in a series of thematic workshops for each target group. The **Netto-Null-2050 Wegweiser** is a snapshot. In regular intervals an update of the recommendations is necessary. On the one hand, this keeps the document up to date. One the other hand, this would allow us to monitor the implementation process of the recommendations into actions. The same applies for the potentials of each $CO_2$ removal option. Keeping the "numbers" up to date and to enrich the components for comprehensive net-zero scenarios are follow-up steps.

### CDR model concepts

The portfolio of CDR options for which model concepts and factsheets have been created will be further developed in the BMBF funded project BioNET (Multi-level assessment of biomass bio-based CDR options). BioNET will build on the **model concepts and TAM** and knowledge gained about CDR. The aim of the project BioNET is to provide a comprehensive knowledge base for and assessment of bio-based CDR options in Germany, combining novel social science research, active stakeholder engagement, and state-of-the-art biomass competition modelling with trade-off analysis to support local and national policy makers. The project will also explore trade-offs with regard to different Sustainable Development Goals. Additionally, the model concepts-based study has been submitted to Frontiers in Climate and is currently under revision (Borchers et al., in review).

### Technology Assessment Matrix (TAM)

The full **TAM** is to be submitted for peer review. Submission during winter 2021/2022 is envisioned. The peer review will increase the quality of work further, and, in case of successful publication, increase outreach opportunities.

An important research gap identified during the work on the **TAM** is the lack of data on public acceptance of different CDR approaches. One effort towards filling this gap is Conor Ó Beoláin's master thesis on the public perception of seagrass Blue Carbon in Germany (and Ireland, for comparison), to be completed by the end of the year, supervised by HI-CAM members. In order to further the applicability of the assessment framework, transdisciplinary research will be carried out in the ASMASYS ("Bewertungsrahmen für marine $CO_2$-Entnahme und Synthese des aktuellen Wissenstandes") project, which will use the developed assessment framework as one basis for discussion.

The assessment framework has been presented to the GESAMP working group 41: Ocean Interventions for Climate Change Mitigation, which will make use of the structure and suggested indicators to be adapted for ocean-based climate intervention.

### Worldwide mapping and a synthesis of existing roadmaps

The **mapping and the assessment of existing roadmaps** as well as the according visualization of the results in the online web-atlas is an ongoing process based on "living documents", since further countries are still submit-ting a national LT-LEDS with UNFCCC, or updating their existing one. With 30 countries having sub-mitted or updated a national LT-LEDS so far, there is a potential of another ~160 countries more to draw-up and submit a LT-LEDS since the Paris Agreement (2015) has been signed and ratified by about 195 countries worldwide.

### Netto-Null-2050 Web-Atlas

The Netto-Null-2050 Web-Atlas is designed to be a living document. The **Netto-Null-2050 Web-Atlas** is hosted and technically supported by Hereon. GERICS is responsible for the maintenance and content de-sign of **Netto-Null-2050 Web-Atlas**. It will continue to grow as more topics and stories are added. In the long term, with financial support, the **Netto-Null-2050 Web-Atlas** is open to including contributions coming from the Adaptation Cluster II and other parties with the same interest. Suggestions from users to make the **Netto-Null-2050 Web-Atlas** even more user-friendly can be implemented if funds are available. The **Netto-Null-2050 Web-Atlas** is capable of presenting videos or streams. A development of contributions using this feature is still pending.

## EVENTS

### W.P 1.1.1: Mapping of existing roadmaps, system definition, integration of key actors, development of a pilot National Roadmap Net Zero

1. **Dialogue Series #3: Spatial Heterogeneity & Working towards CDR bundles**
   Organizers: Nadine Mengis (GEOMAR), Fiona Köhnke (GERICS | Hereon)
   Date: 18 March 2021
   Format: online
   Participants: project representatives P1–P4, incl. case studies (project-internal)

2. **Dialogue Series #4: Our ‚big deliverable‘: The Netto-Null-2050 Roadmap - All actors on stage**
   Organizers: Juliane El Zohbi, Fiona Köhnke (GERICS | Hereon)
   Date: 10 and 11 June 2021
   Format: online
   Participants: project representatives P1–P4, incl. case studies (project-internal)

3. **SRI2021: The Sustainability Research & Innovation Congress 2021**
   Organizers: Future Earth
   Date: 14 June 2021
   Format: online and onsite in Brisbane
   Participants: international conference participants from different disciplines connected to sustainability research
   Active role as presenter: Fiona Köhnke (GERICS | Hereon), session title: Session on Just Transitions: Mapping the Political Economy of Pathways to Net-Zero, presentation title: Net-Zero-2050, Formats for Communicating $CO_2$ Mitigation Potentials in the German Context

4. **One-to-One meetings (in total 31 follow-up meetings to Dialogue Series #4)**
   Organizers: Juliane El Zohbi, Fiona Köhnke (GERICS | Hereon)
   Date: from 15 June - 15 September
   Format: online
   Participants: project representatives P1–P4, incl. case studies (project-internal)

5. **Dialogue Series #5 - Discourse on Roadmap Scenarios**
   Organizers: Fiona Köhnke (GERICS | Hereon), Nadine Mengis (GEOMAR)
   Date: 25 August 2021
   Format: online
   Participants: project representatives P1–P4, incl. case studies (project-internal)

6. **Dialogkonferenz „Ein Klima - viele Disziplinen"**
   Organizers: HI-CAM Cluster III
   Date: 17 November 2021
   Format: hybrid
   Participants: project representatives P1–P4, Cluster II and III (project-internal), external guests from different sectors
   P1.1 contributed to Impulse Presentations I and IV; active role as a podium guest: Juliane El Zohbi (GERICS | Hereon)

### W.P 1.1.2: Construction of assessment matrix

1. **Dialogue Series #1: Technology Assessment Matrix (TAM)**
   Organizers: Johannes Förster (UFZ), Nadine Mengis (GEOMAR) ), Malgorzata Borchers (UFZ)
   Date: 21 January 2021
   Format: online
   Participants: project representatives P1–P4, incl. case studies (project-internal)

2. **Dialogue Series #3 & #5 - Working towards CDR bundles - speeddating of CDR-experts & Discourse on CDR Scenarios**
   Organizers: Fiona Köhnke (GERICS | Hereon), Nadine Mengis (GEOMAR)
   Date: 18 March and 25 August
   Format: online

3. **Model Concepts meets TAM - filling out the TAM, expert elicitations**
   Organizers: Johannes Förster (UFZ) ), Malgorzata Borchers (UFZ)
   Date: 14 October and 12+15 November 2021
   Format: online
   Participants: Project representatives P1 (TAM) and technological experts, representatives from P2-P4 (project-internal)

4. **One-to-One meetings on the development of CDR model concepts**
   Organizer: Malgorzata Borchers (UFZ)
   Date: 25 February 2021 – 3 November 2021
   Format: online
   Participants: project representatives P2–P4

5. **Workshop: Wege zu Netto-Null-$CO_2$-Emissionen Deutschland (pathways to net-zero $CO_2$ emissions for Germany)**
   Organizers: Terese Thoni (UFZ), Nadine Mengis (GEOMAR)
   Date: 25 October 2021
   Format: online
   Participants: 15 external experts/representatives from NGOs and 8 internal HI-CAM-experts (Cluster I and III)

### W.P 1.1.3: Development and implementation of the "National Net Zero Atlas"

1. **HI-CAM Post-Doc Seminar Series #4:**
   Netto-Null-2050 web-atlas - the showcase of research from Cluster I
   Date: 09 June 2021
   Format: online
   Participants: Cluster I, Cluster II and Cluster III.

2. **Web-Atlas - Cluster III Kooperation-Meetings**
   Organizers: Swantje Preuschmann, Knut Görl (GERICS | Hereon)
   Several Dates starting 2020 until atlas launch 17 November 2021
   Format: online
   Participants: Cluster III working group, Cluster I Atlas-Team.
3. **User Workshops: How2-Netto-Null-Atlas**
   Organizer: Swantje Preuschmann (GERICS | Hereon)
   Date 07+08+12+13 July 2021
   Format: online
   Participants: in total: 23 project representatives/contact persons for the contribution upload across all work packages P1–P4

4. **One-to-One meetings (more than 50 follow-up meetings to How2-Netto-Null-Atlas)**
   Organizers: Swantje Preuschmann, Knut Görl (GERICS | Hereon)
   Date: from 07 July - 17 November 2021
   Format: online, phone
   Participants: project representatives P1–P4, incl. case studies (project-internal)

5. **One-to-One meetings**
   (Several first impression on atlas concept and atlas implementation  meetings)
   Organizers: Swantje Preuschmann (GERICS | Hereon)
   Date: from January 2021 - 17 November 2021
   Format: online
   Participants: individual project representatives, external interested partners.

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# Case Study: Climate-neutral city: Dialogues with citizens and stakeholders

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## SUMMARY

The Helmholtz Climate Initiative puts particular emphasis on entering into a lively dialogue with society, since achieving climate neutrality involves not only tolerance but also active acceptance and participation of the citizens. Historically, a key role in such transformation processes and the related necessary societal changes is attributed to cities. On the way to climate neutrality, this case study focuses on different related opportunities and challenges in the urban environment. Being one of the German pioneering cities with the goal of climate neutrality, exchange with practitioners in the city of Karlsruhe was planned during various activities.

The Corona pandemic hampered the initial concept including workshops with stakeholders and scientists, but triggered the development of new approaches in interaction with public. First, the initial focus was widen from specific activities in Karlsruhe to the development of additional demand-oriented products with overriding importance and relevance to support cities on their way to climate neutrality. Furthermore, lessons learned for a possible continuation of this case study in particular – but also for future participatory research in general – have been discussed. In this context, advances in digital communication achieved during the pandemic period have been used to develop new and also pandemic-resilient formats for citizen and stakeholder dialogs – also to be used in a post-pandemic period. In this context out of co-design experiments towards a climate neutral city, monitoring concepts of activities related to the transformation processes involving scientists and public were initiated within the case study. Central element of these concepts is the transparent publication of data in public space to fulfill the most-mentioned success criteria “transparency”. The citizen science project will be part of the future research in the HI-CAM network.

## ACHIEVED RESULTS

Within the core framework of the case study, mainly the following products have been developed, which are of overriding importance for municipal practice and aim to support cities on their way to climate neutrality. Due to the regional focus on Germany, these products are currently available in German only. A brief overview of each activity is provided below.

**Städte auf dem Weg zur Klimaneutralität - Beispiele und unterstützende Initiativen ("Cities on the way to climate neutrality - examples and supporting initiatives")**[1]
Municipalities play an important role in achieving climate neutrality. More and more cities in Germany are therefore deciding to push ahead with climate change mitigation. Thereby also initiatives that support cities and municipalities are of great importance. Within the framework of an online synthesis report, twelve structurally and institutionally very different cities are presented as role models for cities pursuing the goal of climate neutrality. The report outlines the framework conditions in the cities, the used scenarios as well as measures that have already been taken or are in the planning stage. In addition, ten of the most relevant initiatives for cities in Germany are presented. The aim of this synthesis is to provide information on how cities and municipalities can actively participate within the initiatives. This should enable other cities to learn from these experiences in order to become even more active in climate change mitigation in the future.

**Kommunaler Klimanotstand - Eine Kurzübersicht aus rechtlicher Perspektive ("Municipal climate emergency - a brief overview from a legal perspective")**[2]
Against the background of the great importance and necessity of achieving climate neutrality, the so-called climate emergency has increasingly been declared in recent years. The aim is to strengthen climate change mitigation at different levels. Although the resolutions on climate emergency are primarily intended to draw attention to the issue, it is questionable within which legal framework they operate. The main question is whether municipalities have the necessary authority to declare a municipal climate emergency and what legal consequences this can trigger. This publication outlines essential legal aspects against this background, in order to provide municipalities with a first practical overview. In summary, one could argue that a climate emergency resolution is more a kind of political self-commitment at the municipal level, whereby increasingly clear and concrete contents for improved climate change mitigation can already be identified. In particular, the evaluation of planned measures within a municipality with regard to their climate change impact has to be highlighted. Thus, the benefit of a climate emergency is particularly to be seen in the fact that it contributes to the local social identification as well as the mobilization and strengthening of climate change mitigation.

[1] The synthesis „Städte auf dem Weg zur Klimaneutralität - Beispiele und unterstützende Initiativen" is available online: *https://www.netto-null.org/Projektergebnisse/Syntheseberichte/index.php.de*.

[2] Groth, B.J., Groth, M. und Bender, S. (2021): Kommunaler Klimanotstand - Eine Kurzübersicht aus rechtlicher Perspektive. Climate Service Center Germany (GERICS), Hamburg. Further information and the study itself are available online: *https://www.helmholtz-klima.de/aktuelles/was-ein-klimanotstand-fuer-kommunen-bedeutet.*

**12 Schritte zur kommunalen Klimaneutralität ("12 steps to municipal climate neutrality")**[3]
Municipalities have a pioneering role to play in climate change mitigation. However, it is often still unclear in practice, which key aspects they should be taken into account on the way to climate neutrality. Therefore, this guideline provides a concise and practical related overview, whereby the following procedural steps are taking into account: **1.** awareness raising and social identification, **2.** anchoring of personnel and institutional responsibilities, **3.** definition of the system to be considered, **4.** preparation of the climate footprint, **5.** preparation of a climate change mitigation concept, **6.** preparation of climate change mitigation scenarios, **7.** examina-tion and safeguarding of climate change mitigation financing, **8.** selection, prioritization and implementation of climate change mitigation measures, **9.** establishment of an accompanying communication strategy, **10.** monitoring and further development of climate change mitigation measures, **11.** compensation and storage of unavoidable emissions, **12.** integrative consideration of climate change mitigation, sustainable development and adaptation to the impacts of climate change.

**Klimaschutz und Anpassung an die Folgen des Klimawandels – Synergien und Zielkonflikten im Rahmen kommunaler Konzepte und Strategien („Climate change mitigation and adaptation to the impacts of climate change - synergies and conflictings in the context of municipal concepts and strategies")**[4]
Also at the municipal level, the integration of climate change mitigation and adaptation to the impacts of climate change increasingly needs to be improved, in order to pave the way for properly achieving the necessary transformation towards a sustainable, climate-neutral and climate-adapted society. The currently existing municipal concept and strategy papers consist of frequently recurring and differently detailed aspects. Many of these papers also contain concrete measures that relate individually to the most important fields of action in the city. They form the basis of this report. It analyses more than 60 municipal climate change mitigation (sub)concepts and adaptation strategies in Germany. On the one hand, the report provides a clear and focused overview of climate change mitigation and adaptation components currently applied in practice. On the other hand, it shows which specific synergies and conflicts exist in this context and how they can successfully be addressed.

**Development of a Citizen Science concept for infrastructure implementation in the framework of a climate neutral city**
In a co-design approach in the associated project GECKO, online-interaction with public has been tested in the framework of the implementation of energy infrastructures that contribute to the climate-neutral city of Karlsruhe. In online workshops success criteria have been established with different stakeholder including action groups. The workshops used commercial software for online video conferencing and whiteboards. Successful implementation of the workshops required adapting the delivery of the content to the online formats. Conveying complex information, e.g. geological subsurface structures, is a challenge in non-contact communication, as face-to-face presentations use speech and gestures for this purpose.

Following the most-mentioned success criteria, i.e. "transparency" within the Helmholtz Climate Initiative, further pandemic-resilient communication concepts for the climate-neutral city of Karlsruhe have be developed. The focus here was on transparent dissemination of the monitoring results during the implementation of the infrastructure. The aim was to establish suitable formats for successful stakeholder/citizen communication

[3] Groth, M. (2022): 12 Schritte zur kommunalen Klimaneutralität. Climate Service Center Germany (GERICS) *https://www.helmholtz-klima.de/sites/default/files/medien/dokumente/12_Schritte_Klimaneutralitaet_0.pdf, Hamburg.*

[4] Bender, S., Groth, M., Seipold, P. und Gehrke, J.-M. (in press): Klimaschutz und Anpassung an die Folgen des Klimawandels - Synergien und Zielkonflikten im Rahmen kommunaler Konzepte und Strategien. Climate Service Center Germany (GERICS), Hamburg.

that ensure that complicated information can be communicated in a barrier-free and contactless manner, so that uninterrupted communication of information is possible even in situations where contact is limited. This also improves international communication among scientists against the backdrop of a reduction in global $CO_2$ emissions.

## WORK PROGRESS

According to the planned work schedule, the starting point of the case-study activities was to carry out a synthesis of municipal examples and activities as well as relevant initiatives in Germany ("Städte auf dem Weg zur Klimaneutralität - Beispiele und unterstützende Initiativen" // "Cities on the way to climate neutrality - examples and supporting initiatives").

In addition to this synthesis, two workshops were initially planned as key components of the case study, involving actors from politics, administration, business and the public sector in Karlsruhe, as well as scientists from the Helmholtz Climate Initiative. Thereby it was intended to support a close exchange between science and practice at eye level, with one workshop planned for the second half of 2020 and one for the first half of 2021. As a summary of the key results of both workshops, a final report should be prepared by the end of 2021. Due to the Corona pandemic, however, it was no longer possible to carry out the workshops and business trips from spring 2020 onwards.

In addition to the originally planned work in the context of the case study, new activities have been carried out in the overall context of climate neutral cities in Germany. Thereby further products for municipal practice have be created and published as follows: i) "Kommunaler Klimanotstand - Eine Kurzübersicht aus rechtlicher Perspektive" ("Municipal climate emergency - a brief overview from a legal perspective"), ii) "12 Schritte zur kommunalen Klimaneutralität" ("12 steps to municipal climate neutrality"), iii) "Klimaschutz und Anpassung an die Folgen des Klimawandels - Synergien und Zielkonflikten im Rahmen kommunaler Konzepte und Strategien" („Climate change mitigation and adaptation to the impacts of climate change - synergies and conflictings in the context of municipal concepts and strategies"), and iv) "Auswirkungen der Corona-Pandemie auf Bürger- und Stakeholderdialoge am Beispiel der Fallstudie Klimaneutrales Karlsruhe" ("Effects of the Corona pandemic on citizen and stakeholder dialogues using the example of the climate-neutral Karlsruhe case study").[5]
The concept of Citizen Science for infrastructure implementation in the framework of a climate neutral city has been developed and the necessary equipment is currently being installed in the case study city Karlsruhe. The related database development Kadi4geo has been started and will be carried on to allow for set into operation the Citizen Science project in 2022. The project will run at least until 2024.

## SPECIAL FEATURES

Within the framework of the case study, novel and demand-oriented products have been developed that are of overriding importance for municipal practice. Thus, they can be an important support for municipalities on the way to climate neutrality. The practical relevance of the prod-ucts is also shown by their media coverage. For example, after its publication, the document on the municipal climate emergency was referred to in the

[5] Groth, M. und Schill, E. (2022): Auswirkungen der Corona-Pandemie auf Bürger- und Stakeholderdialoge am Beispiel der Fallstudie Klimaneutrales Karlsruhe. Climate Service Center Germany (GERICS), Hamburg. *https://www.helmholtz-klima.de/sites/default/files/medien/dokumente/RL_Auswirkung_Corona_220124_2.pdf*

„Behörden Spiegel“ - the highest-circulation independent newspaper for the public sector in Germany with a print run of 103,000 copies per month. Hence, it was also possible to increase the visibility of the Helmholtz Association among local decision-makers.

Furthermore, based on the scenarios developed in the associated project GECKO, pandemic-resilient communication concepts for the climate-neutral city of Karlsruhe have been developed within the framework of the Helmholtz Climate Initiative. Suitable, according to current estimates, is 3-D visualization by means of modern large-area 3-D screens with adapted control technology, which is capable of vividly depicting the 3-D models that are now common in science and thus enhancing understanding. These can be used in public spaces to give citizens in particular access to the implementation of scientific and technical projects. In combination with Citizen Science, an interactive non-presence-based communication can take place and lead the above-mentioned co-design into a next level of co-production of knowledge. 3-D visualization can additionally significantly improve the quality of scientific exchange in times of pandemic contact restrictions. Synchronized databases can be used to display objects three-dimensionally and to discuss and edit them together. This system functions independently of location and can also be used as a communication tool across Helmholtz Centers - regardless of a pandemic situation.

## OUTLOOK ON FUTURE WORK

As part of a possible continuation of this case study from 2022 onwards, the focus would be on key aspects of cooperation with local stakeholders, taking into account the current lessons learned. In retrospect, this appears to be the even more effective approach - also irrespective of the pandemic-related restrictions - as it is now possible to draw directly on existing results from the Helmholtz Climate Initiative, which will serve as a basis for the planned future workshops. As part of the original concept, it was planned to carry out the case study workshops in parallel with the other activities in the Helmholtz Climate Initiative. However, looking back, this would have meant that these specific results could not have been included appropriately in the workshops, because they have not been available at that time. Taking into account the experience outlined above, three workshops would be seen as appropriate for a future case study, with the aim of continuing to be an on-site implementation, but with alternative formats such as hybrid events being considered and planned from the outset. The basic content of the first two work-shops will remain as initially planned. Hence, the first workshop should address the current status and further steps already planned by the city of Karlsruhe on its way to become a climate-neutral city, as well as the elaboration and structuring of current needs and requirements from practice to science. The second workshop should present and discuss how the practical needs and requirements expressed in the first workshop have been addressed or will be addressed by the scientific community, whereby it should be discussed whether the circle of participants from the scientific community should extend beyond the institutions of the Helmholtz Association. As an additional third workshop, a synthesis workshop with participants of the first two workshops is considered. The aim is to bring together the results of the first two workshops and to develop proposals on how the results should be addressed in concrete terms in various measures. In addition, existing research needs and questions will be identified and discussed, which should be addressed in the context of new research projects.

The concept of Citizen Science for infrastructure implementation in the framework of a climate neutral city includes a related database development Kadi4geo, which has been started and will be carried on to allow for set into operation the Citizen Science project in 2022. The project will run at least until 2024.

# CLUSTER I:
# NET-ZERO-2050
## Project 1.2
## Integrated Scenario analyses

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## SUMMARY

The integrated scenario analysis consists of three major tasks – a synthesis study on existing research on a $CO_2$- neutral Germany; the development of an energy transition pathway which is limited by a total $CO_2$ budget; and the multicriteria assessment of energy transition pathways. The budget approach was developed in close cooperation with Project 1.1. which lead to an allocation of < 7 Gt to the German energy system for 2021 until 2050.

The synthesis study summarizes the key findings from three recent publications that describe a transformation of Germany into a $CO_2$- or, respectively, climate-neutral economy and society by the middle of this century at the latest, including the climate policy instruments and measures required to achieve this goal. The main objective of this synthesis study within Net-Zero-2050 is to show which key climate policy steps need to be focused on and implemented, especially in the years up to 2030, which are at the same time mandatory prerequisites for achieving the goal of a $CO_2$- or climate-neutral Germany.

This synthesis is then integrated into a newly developed energy scenario. We apply a normative backcasting approach for scenario building, relying on historic data and assumptions from existing scenario studies. Additionally, a new energy and LCA-focused modeling was developed for the industrial sector, providing insights on hard to avoid or residual $CO_2$ emissions from the steel and cement sectors. The energy system modeling approach was successfully extended by a model coupling: The energy system model based on an accounting framework (ESM) was integrated with REMix, a cost minimizing optimization model for power, heat and sector coupling. To achieve the necessary $CO_2$ reduction, the scenario focuses on electrifying all end use sectors until 2030. Thus, the scenario envisages a doubling of power demand by 2050, with power supplying also for electric vehicles, heat pumps for space heat and the production of synthetic fuels (e.g. $H_2$) which will be required for heavy duty transport, aviation & navigation and the transformation of industrial processes. The results indicate a significant regional focus of hydrogen production in the North Western Germany, including all necessary infrastructures .

Next the modeling results were provided to the multicriteria assessment framework for further analysis of regional heterogeneity and stakeholder aspects. Stakeholders have differing interests and goals and tend to support the transformation pathway that suits their best interests and show resistance to pathways that do not. By applying an MCDA approach, we show that attitudes of stakeholders (incl. private households and utilities) differ with respect to the preferred transformation pathways. In particular, we show that transformation pathways with a higher share of biomass in combination with CCS face a lower level of preference among all stakeholders. Since biomass in combination with CCS and similar technologies will be necessary for reaching the net-zero goals, measures have to be taken quickly to reduce resistance, e.g. among households.

Regions differ greatly in their geological, geographical as well as regional economic conditions. This also affects the potential for mitigation measures for greenhouse gases. Thus, it is to be expected that some regions will benefit more from decarbonization measures than others, while individual regions run the risk of economic losses. Accordingly, the question arises as to what extent benefits and losses need to be redistributed regionally. A successful energy transition which will be supported by at least a majority of stakeholders has to take heterogeneity across scales, resources, technologies, and regions into consideration.

## ACHIEVED RESULTS

The main objectives of the integrated scenario analysis are the modeling and assessment of net zero emissions pathways, with a focus on energy transition. The integrated approach is based on the overall assessment of possible technical options, their contributions to GHG mitigation, and their systemic interactions. This approach specifically considers previous work which has been assessed in a  synthesis report. Additionally, the combination of different quantitative and qualitative assessment criteria is essential and requires a suitable instrument for knowledge integration. In this project these aspects were considered within two main tasks - the development of an energy scenario for a Net-Zero-2050 Germany and a comprehensive assessment of a variety of transition pathways, including this specific scenario.

## SYNTHESIS STUDY ON POLICY INSTRUMENTS AND REGULATION

As one prerequisite element to assess the current research need regarding coordinated interaction of climate change mitigation and adaptation, a synthesis study focusing on policy frameworks, instruments, and measures to achieve the goal of carbon neutrality in Germany by 2050, at the latest, has been carried out.

This synthesis study (Görl et al., 2021) summarizes the key findings from three recent publications that describe a transformation of Germany into a $CO_2$- or, respectively, climate-neutral economy and society by the middle of this century at the latest, including the climate policy instruments and measures required to achieve this goal. This synthesis also outlines obstacles and uncertainties on this path to a $CO_2$ -neutral Germany that need to be addressed quickly in light of a dwindling national $CO_2$ budget. The main objective of this synthesis study within Net-Zero-2050 is to show which key climate policy steps need to be focused on and implemented, especially in the years up to 2030, which are at the same time mandatory prerequisites for achieving the goal of a $CO_2$- or climate-neutral Germany.

The formulation of consistent and realistic recommendations for action on viable paths for achieving $CO_2$ neutrality by 2050 at the latest requires, on the one hand, an inventory of the political-regulatory framework conditions, instruments and measures already available in this context at national and international level. On the other hand, in the event of significant inconsistency of the climate policy strategies and measures taken in relation to the remaining national $CO_2$ budget (please refer also to the decision of the Federal Constitutional Court, published on 29 April, 2021 (Bundesverfassungsgericht, 2021)), feasible alternative $CO_2$ reduction pathways must be identified. These pathways may differ significantly from the approaches that have existed to date in terms of scope and/or speed of implementation and monitoring and follow-up obligations, if applicable. In this context, „instruments“ refer to the means and control elements to be used to achieve the objectives, while „measures“ refer to the specific individual elements of an overarching (longer-term) strategy for implementing and achieving the objectives.

The synthesis study compiled the results developed in the context of two work packages of the Helmholtz Climate Initiative with an overview of existing policy frameworks, instruments and measures to achieve a $CO_2$-neutral Germany (Markus et al., 2020) and the remaining national $CO_2$ budget (Project Briefing #2, see Mengis et al., 2021). In addition, it outlines the current state of research with a particular focus on key action and implementation deficits on the path to a $CO_2$-neutral Germany by 2050 that urgently need to be addressed. Based on a synthesis of three current climate policy studies, it identified, furthermore, possible alternative strategies and pathways and remaining knowledge gaps and potential research needs in this area. These alternatives paved the ground for developing a specific energy scenario for Net-Zero-2050 as presented in the next section.

## ENERGY SCENARIO FOR NET-ZERO-2050 IN GERMANY

With energy transformation and consumption being responsible for more than 90% of German $CO_2$ emissions, the scenario analysis focused on mitigating emissions from the energy system. It is obvious that far-reaching technological transformations are required that will fundamentally change the way we generate and use energy. There are different views on key options and development paths for this, which have been and are being presented in numerous scenario-based studies and modeling (see e.g. (Naegler et al., 2021)). Milestone 1.2.3 summarizes relevant Net-Zero-studies for Germany (Görl et al., 2021), thus serving as input for the energy scenario development. While previous energy scenarios for Germany focus on reaching 100% RE (renewable energy) or net-zero by 2050 or 2045, so far, only one presented a rough sketch for 2035 in the implications of complying with a carbon budget (Kobiela et al., 2020). In this study we therefore first focused on developing a $CO_2$ budget constraint as a normative target for the energy system. This was carried out based on the carbon budget calculations for Germany and in close cooperation with Project 1.1 (Mengis et al., 2021). This carbon budget served as a normative target for our exemplary energy transition pathway.

We developed a normative energy scenario with a backcasting approach, covering the time span from 2020-2050. The project targeted the advancement and combined application of models and methods for integrated scenario analyses as well as a further assessment of energy transition pathways. We successfully coupled an energy system model (ESM) based on an accounting framework with the cost optimization model (REMix), focusing on power, heat and sector coupling. The transformation is limited, among other things, by the potential for renewable energies. The energy system model maps the expansion of renewable energy technologies on a national level. It is coupled with REMix, which calculates the most cost-effective transformation of the power sector and all sector-coupling applications. The optimization model determines an optimal design for the expansion e.g. of wind and photovoltaics and the necessary grid infrastructure in different regions of Germany. Both models and the established model coupling are described in detail in milestone 1.2.1 (Simon et al. 2020).

For Net-Zero-2050, both the energy demand must be reduced - for example, by insulating buildings and switching to electromobility - and the remaining energy demand must be covered by renewable energy sources such as solar, wind, biomass or geothermal energy - a complete transformation of the energy system. To comply with the carbon budgets, $CO_2$ emissions from the energy system must already be halved by 2030 compared to today.

To achieve this, all consumption sectors (households, industry, commerce, transport) as well as the power plant and conversion sector must contribute.

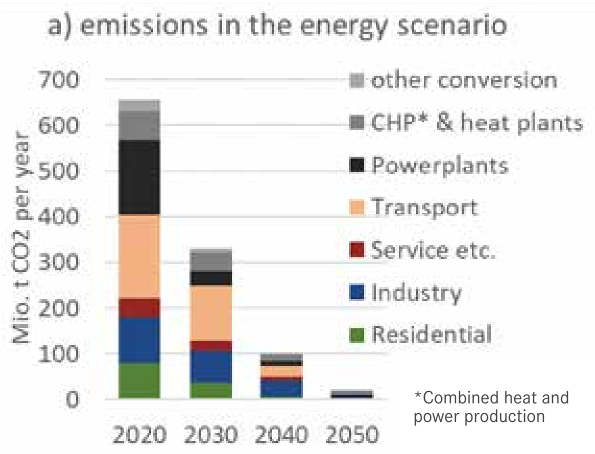


**Figure 1**: Necessary reduction in $CO_2$ emissions from the energy system to limit climate change below 2°C (Simon et al., 2022)

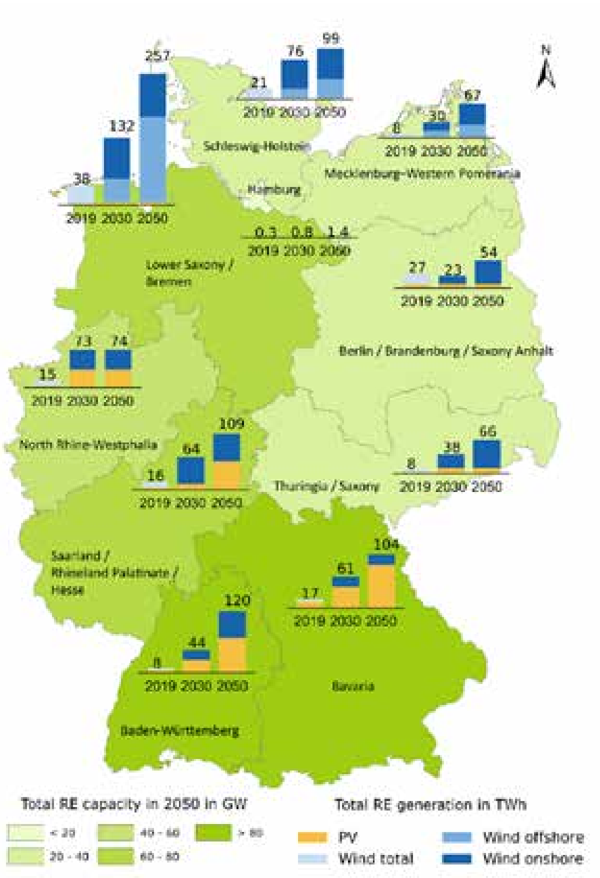


**Figure 2**: Exemplary expansion of renewable power capacity in Germany by 2050 (Simon et al., 2022)

**Figure 1** shows our exemplary development pathway for all end use sectors and the power sector. A detailed documentation of the applied scenario assumptions and results is provided by milestone 1.2.2, which will be published in (Simon et al., 2022). In summary additional 16 Mio. electric vehicles and 5 Mio. heat pumps are required in the scenario until 2030 in the scenario. We specifically assessed how the steel and cement sectors can contribute to this mitigation targets by technology and fuel switch, leading to a reduction of up to 90% of $CO_2$ emission (see (Harpprecht et al., submitted)).

The electricity demand in the scenario will rise strongly in the future both for traditional consumption such as lighting and appliances, but also for electromobility, hydrogen and synthetic fuel generation etc. The combined energy system modeling shows that in the next 10 years coal-fired power generation will have to be phased out. Key technologies such as wind and photovoltaics, or electric mobility and heat pumps, will have to be largely expanded (see **Figure 2**). Our exemplary pathway features renewable power capacity of 310 GW in 2030 and 530 GW in 2050; 120 GW of new grid capacity and 100 GW of hydrogen electrolyzers are necessary by 2050 to ensure the balancing of variable sources, the backup for periods with low wind and solar production as well as the supply of sectors that cannot be directly electrified. The regionalization shows, that infrastructures such as electrolyzers and $H_2$-pipelines are concentrated in the wind dominated north, that also provides the necessary cavern storage capacity for $H_2$.

The regionalized results of the energy scenario were then further assessed in comparison with other energy scenarios by the multicriteria assessment task of project 1.2.

## SCENARIO ASSESSMENT FOR NET-ZERO-2050 IN GERMANY

In the project, we introduced an MCDA (Multi Criteria Decision Analysis) approach for assessing the energy scenarios: we consider four groups of stakeholders, namely households, utilities, industry and government. Each stakeholder has a set of preferences, some of which are unique and some which are shared with other stakeholders. In order to take heterogeneity within private households into consideration, we use household income as a differentiating characteristic. To assess scenarios, a set of criteria has to be selected. Though there is no hard and fast rule about the number of criteria, it is considered best to have as few criteria as possible as long as they are consistent. Decision making that involves projects with complex technical features usually has a large set of criteria. This number can be as high as 100, however, it is usually between 6 and 20 (Dodgson et al., 2009). While it is impossible to consider all the criteria, it is possible to catch the criteria that are most important to the stakeholders. These criteria are operationalized by indicators which assign a numerical value to the criteria, thus making the assessment possible. All in all, we consider 15 criteria.

Surveys and socio-economic experiments were not part of the project. Hence, we had to use information provided by literature and expert adjustments as a starting point for the weighting of the criteria from the perspective of stakeholders. Thus, the employed assessment approach has to be considered as a pilot study. A total of seven scenarios were selected for our study. Each of these scenarios is a combination of different levels of deployment of electricity generation technologies. These scenarios vary substantially in stock, capacity additions and the utilization of these technologies. The list of scenarios consists of the scenarios Global Ambition (GA) and Distributed Energy (DG) published by Entso-E (Entso-E, 2020), a scenario with CCS (based on GA), the scenario of DLR developed for HI-CAM (Simon et al., 2022), a scenario with extensive use of hydrogen (Robinius et al., 2021) and two scenarios with extensions in the use of biomass for power generation, one with and one without CCS.
By assuming that economic factors are still more important for stakeholders than others and that with increasing income the meaning of the economic factors decrease, the results in Table 1 show that, focusing on 2030, most households will prefer scenarios with a significant increase in decentralized technologies.

| | | | | 2030 | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **M1** | **M2** | **M3** | **M4** | **M5** | **M6** | **M7** | **M8** | **M9** |
| **DG** | 0.35 | 0.31 | 0.28 | 0.24 | 0.20 | 0.17 | 1.55 | 1.13 | 0.00 |
| **GA** | -0.09 | -0.08 | -0.10 | -0.09 | -0.09 | -0.09 | -0.45 | -0.38 | -0.67 |
| **GACCS** | -0.04 | -0.03 | -0.04 | -0.04 | -0.04 | -0.05 | 0.12 | 0.00 | -0.56 |
| **DLR21** | 0.45 | 0.39 | 0.43 | 0.37 | 0.36 | 0.37 | 0.66 | 0.97 | 3.61 |
| **H2** | -0.26 | -0.22 | -0.23 | -0.18 | -0.17 | -0.17 | -0.52 | -0.68 | -1.78 |
| **BIO** | -0.13 | -0.12 | -0.11 | -0.10 | -0.09 | -0.08 | -0.41 | -0.48 | -0.32 |
| **BIOCCS** | -0.28 | -0.25 | -0.23 | -0.20 | -0.17 | -0.15 | -0.95 | -0.54 | -0.28 |
| | | | | **2030** | | | | | |
| **DG** | 0.15 | 0.14 | 0.16 | 0.15 | 0.14 | 0.12 | 2.33 | 1.17 | 0.16 |
| **GA** | -0.05 | -0.02 | -0.01 | 0.01 | 0.01 | 0.01 | 0.75 | 0.23 | -0.23 |
| **GACCS** | 0.02 | 0.04 | 0.05 | 0.07 | 0.07 | 0.06 | 1.22 | 0.63 | -0.02 |
| **DLR21** | 0.12 | 0.03 | -0.03 | -0.12 | -0.15 | -0.17 | -2.75 | -0.60 | -0.19 |
| **H2** | -0.32 | -0.35 | -0.38 | -0.41 | -0.40 | -0.39 | -3.38 | -1.83 | -2.55 |
| **BIO** | 0.05 | 0.07 | 0.09 | 0.10 | 0.11 | 0.11 | 0.59 | -0.05 | 0.48 |
| **BIOCCS** | 0.04 | 0.09 | 0.13 | 0.19 | 0.22 | 0.25 | 1.24 | 0.45 | 2.34 |

**Table 1**: Preferred scenario by stakeholder

Remarks: Green: Most favored scenario, Red: Scenario has less support, * GA: Global Ambition, DG: Distributed Energy, GACCS: GA with CCS, DLR21: scenario of DLR, H2: hydrogen with high share of hydrogen, BIO: scenario with a higher share of biomass-fired power plants, BIOCCS: scenario with a higher share of biomass-fired power plants equipped with CCS.

Source: (Entso-E, 2020), (Simon et al., 2022), (Robinius et al., 2021))

Focusing on the year 2040, the decentralized scenario DG will be favored by a greater number of actors. In our calculations, both households with higher incomes and the government see the scenario biomass in combination with CCS or similar technology as an interesting option.

The calculation carried out with the help of assumptions about attitudes of stakeholders towards selected criteria shows that the time horizon plays a key role in the support of transition pathways. In addition, the calculations emphasize the need to take the heterogeneity of stakeholders into consideration.

In order to analyze the importance of spatial heterogeneity for the energy transition and towards achieving net zero, we investigated five different topics. First, energy resources that are differently distributed across Germany are especially relevant for the change towards renewable energy. Second, centralized energy and $CO_2$ storage possibilities to secure energy requirements and to deposit $CO_2$ are a non-negligible factor in achieving net zero and keeping future emissions to a minimum. Additionally, energy intensive industries, especially those that are located in particular regions with geographical proximity to abundant energy sources, should be considered when analyzing where the highest energy consumption is to be expected. This also holds for private households that settle mostly - but, importantly, not exclusively - in dense urban areas of the country. It is vital to include their location, as public acceptance of transition measures and infrastructure is a key element for a successful transformation of the energy system towards Net-Zero-2050.

Innovative ways of engaging stakeholders could help to increase acceptance of local energy projects. In Karlsruhe, for instance, co-creation processes, involving the participation of stakeholders and citizens through workshops and interviews, was implemented to reduce the risk of rejection of a geothermal heat project (Schill et al., 2021). Furthermore, participatory processes are essential to inform society and build trust that can counter the regime resistance often present in relation to fundamental changes like the energy transition (Halbe et al., 2020). Moreover, considering another recent development as an example, the Covid-19 pandemic has highlighted the extent to which society is vulnerable to damage to the ecosystem and this may lead to greater public attention on environmental issues and greater willingness to embrace radical social innovations that are required (EEA, 2021).

Considering spatial differences of energy types, storage and industry needs, whilst paying attention to household characteristics like income or household age/size, a mixed portfolio of measures seems to be most sensible. A mixed set of place-based regional policy and incentivizing acceptance by households through $CO_2$ consumption taxes could be an option for a successful, efficient policy-supported energy transition.

Overall, the spatial dimension of the energy transition is neither only a challenge nor only an opportunity; it is characterized by a mixture of both. It is necessary to take into account the different resource potentials, diverging storage capacities and energy needs across the country in addition to the interests of various stakeholders affected by the energy transition. Geographically differentiated regional energy policy, often with strong disparities in the balancing of needs and losses, with a focus on stakeholders, could provide essential guidelines for a sustainable, successful energy transition across all scales, resources, and technologies.

## WORK PROGRESS

The main activities in Project 1.2 were successfully carried out within the planned budget. The project report on **Milestone 1** "Scenario definition and consistent parametrization of all models" was jointly prepared by all involved partners. The report is already published on the project website (***https://www.netto-null.org/Projektergebnisse/Reports/***) and gives an overview over the methodology, the background of the energy system modeling as well as the model coupling.

The results for the energy scenario which are due under **Milestone 2** are published as a peer-reviewed paper (Simon et al., 2022, see publication list). Our results highlight the necessity of accelerating energy transition within the next decade, shifting the focus from predominantly long-term targets to short-term available technologies. Additionally, we highlight the need for short term technology development of key technologies.

Due to delays in the Roadmap and Technology Assessment Matrix no dedicated CDR options were integrated into the energy scenario framework. However, this strand of energy scenario development has become an integral part of research activities within energy systems analysis at DLR (DLR-VE-ESY).  and the integration of assessment results of CDR options from the HI-CAM initiative will be pursued in the POF-activities. To bridge the gaps between dedicated technology development and simulation and a potential integration into integrated energy system models requires significant effort in upscaling, technology assessment and the prospective analysis which will have to be continued over longer time spans e.g. in the ESD program.

The resulting time sequence limited the development of further scenario variants and thus the possibility of a Life Cycle Analysis (LCA) -based evaluation of the scenarios. We therefore redirected significant time into the dedicated energy and LCA modeling for the industry sector with a focus on heavy industry. Our activities provided an extension of the existing energy system model  with a focus on the steel and cement sectors, including opportunities for a more detailed LCA-assessment of future energy scenarios.

**Milestone 3**, the Synthesis study on policy instruments and regulation is published on the website. For this study, the scientific literature on this topic published since the signing of the Paris Climate Agreement in December 2015 has been reviewed, with a regional focus on Germany and the regulatory linkages between Germany and the European Union.

Particular attention has been paid to three publications published in 2020 that dealt in depth with possible decarbonization pathways for Germany up to 2035 and 2050, respectively, including the addressing of climate-damaging subsidies.

These three studies were excerpted and the respective core statements on the most important measures were summarized, arranged according to the central sectors, cross-sectoral aspects and needs for action. Due to the thematic proximity, the results from two studies weresynthesized and the key differences in terms of findings and accentuations between these two studies were compared in tabular form. Milestone 3 is published on the project website (***https://www.netto-null.org/Projektergebnisse/Reports***)

**Milestone 4**, the assessment of scenarios was achieved as planned. Due to time and budget constraints, we focused the assessment on the electricity sector. It becomes clear that an assessment of the overall scenario will require significantly more efforts. The work will be continued by FZJ-IEK-STE in the ESD program.

Our analysis supports the observation that actors differ with respect to the preferred future. Since heterogeneity seems to be a key challenge for transition pathways, we conducted a workshop. In the workshop spatial aspects were emphasized. The workshop shows that there is a need for further research on measures for lowering negative impacts on regions in the transition process. As a result, we published a policy brief focusing on spatial heterogeneity.

## Contributions beyond the work plan

As networking between research programs and partners is a central goal of HI-CAM, a significant amount of funding and working time has been invested in collaboration between projects. Beyond the planned tasks in the proposal the partners in P1.2 supported several joint activities of various subprojects for knowledge integration:

DLR was a key partner in the definition of the carbon budget in Project 1.1 for all activities which were covered by Cluster I as well as the definition of a joint system boundary and scenario concept across all subprojects. These activities led to the publication of several project briefs in Cluster I, assisted by Cluster III - Communication (see ***https://www.netto-null.org/Projektergebnisse/Project_Briefings/index.php.de***).

Despite the burdens and limitations of the COVID-19- pandemic the HI-CAM initiative led to well established cooperation between partners in P1.2 and specifically in P1 and P2, which led to a joint cross project publication by Mengis et al. 2022 “Net-zero $CO_2$ Germany - A retrospect from the year 2050”.

P1.2 also provided significant input for other cross-project products, e.g. five contributions to the net-zero web atlas, as well as numerous recommendations for action for the net-zero roadmap.

## SPECIAL FEATURES

The Helmholtz project provides a transdisciplinary network, integrating climate researchers, with technology developers and energy system analysts; this is a prerequisite for a systemic approach to climate protection research, which is currently not possible in third party funded or thematic centered research in the energy system.

### Synthesis study on policy instruments and regulation

In view of the large number of newly published studies and recommendations for action on $CO_2$ or climate neutrality, a summarized classification and assessment of the most important aspects, which were developed from different perspectives, appears to be useful and necessary within the framework of a synthesis study.

Against the background of the studies analyzed for this synthesis, Net-Zero-2050 has set the goal of bundling the scientific findings and activities in the Helmholtz Association for a $CO_2$-neutral Germany in a Net-Zero-2050 "guidepost". Thus, on the one hand, it shall be integrated into a framework for action with recommendations as to when which activities are required to achieve the goal of $CO_2$ neutrality in Germany by 2050. On the other hand, this synthesis is intended to provide a discussion framework for all relevant actors and stakeholders. Within the system boundaries defined for the project (Köhnke et al., 2020, Project Briefing #1), Net-Zero-2050 considers how $CO_2$ can be avoided, reduced, and removed from the atmosphere in a wide range of sectors.

To this end, a scenario concept was developed in Net-Zero-2050 (Project Briefing #4, Simon et al., 2020) that integrates these three climate mitigation pathways. The analysis is based on $CO_2$ abatement options that focus on the expansion of renewable energy. The focus of the project is the detailed mapping of the relevant technologies for the reduction and removal of $CO_2$ in projects 2-4, which are subjected to a comparative assessment (project 1, Technology Assessment Matrix, TAM) for the roadmap. Based on this technology comparison, Carbon-Dioxide-Removal-Scenarios (CDR scenarios) can be created for this purpose, which bundles reasonable combinations of CDR measures and technologies.

Moreover, the Net-Zero-2050 Web Atlas created as part of the Helmholtz Climate Initiative (see WP 1.1.3) will present key results from the individual work packages in the form of a cartographic representation or storyline. For this purpose, research results from the different disciplines of the Helmholtz Climate Initiative have been visualized and explained in a comprehensible way by the end of 2021, and the respective contribution of decarbonization methods and technologies to GHG reduction in Germany, in terms of $CO_2$, will be quantified. This will also include two case studies from practice.

### Energy Scenario for Net-Zero-2050 in Germany

Within project 1.2 the partners contributed significantly to the advancement of the research field of energy system analysis, which was significantly fostered by the close cooperation across research fields. Specifically, the interaction between energy and climate research lead to the first detailed carbon budget constraint energy scenario for Germany, which additionally integrated regional and stakeholder aspects.

Based on this cooperation the energy scenario P1.2 now consistently links an energy transition pathway to a nationally fixed carbon budget derived by climate science experts. The carbon budget for Germany was further broken down and a share allocated for the energy system, which serves as a target for the normative scenario. Based on this allocation we analyzed on what would be necessary to comply with a carbon budget specifically for the energy sector in Germany in line with the 1.5°C target.

The cross-program interaction within HI-CAM enabled us to expand the view beyond existing carbon limits focusing on a specific year, which currently is state of the art. Analogous to two studies analyzed for the synthesis study, as described in Project Briefing #4 (Simon et al., 2020), the basic goal of a largely climate-neutral energy sector in 2050 was first established. Numerous energy scenarios with greenhouse gas reduction targets of >90% for Germany were evaluated (see Project 1, Milestone 1.2.1, including (Fette et al., 2020; Nitsch et al., 2012; Öko-Institut et al., 2015; Purr et al., 2020)).

HI-CAM enabled the energy system analysis to consider the burden of previous carbon emission and the necessary speed in which a climate protecting energy transition has to be deployed. From this, an outlook for the German energy system within the Net-Zero-2050 project was derived, which is almost entirely based on renewable energies. This energy scenario with the underlying assumptions on demand and supply as well as the relevant techno-economic data, is currently documented in Milestone 1.2.2 of the Helmholtz Climate Initiative. The interaction of CDR scenarios and energy transformation pathways as a contribution to a Net-Zero-2050 “guidepost” is a key research task in the further course of the project. The way there requires a rapid transformation of all mentioned sectors in order to achieve a corresponding emission pathway. Significant insights were gained on the necessary acceleration of the energy transition in Germany until 2030 and how the transition must be maintained beyond that until 2050.

### Scenario Assessment for Net-Zero-2050 in Germany

In the project we emphasized the meaning of heterogeneity in relation to stakeholders’ attitudes towards transition pathways. By comparing energy scenarios, we showed that due to differences in preferences and restrictions, stakeholders assess pathways differently. Hence, it is not surprising that some stakeholders show resistance towards certain developments.

An analysis of the impacts of transition pathways on regions showed that there is a need for measures aiming to help regions to mitigate negative impacts of the transition processes: the decarbonization of the German energy system will be linked with structural changes on a spatial level. Some regions will suffer from the transitions process whereas others might benefit. With our study we stress that for limiting resistance against transition processes, it is important to take heterogeneity into consideration in order to be able to identify and introduce policies that are supported by a majority of the public.

Biomass-fired power plants in combination with CCS or CDR will not be the favorite option by all actors. Hence additional measures are necessary to ensure a broad societal acceptance of pathways which include this technology.

## OUTLOOK ON FUTURE WORK

Future activities include both - a continuation of existing activities as well as a continuation of the established network. Currently concluded activities will lead to the publications of a variety of peer reviewed papers. Several have already been mentioned and their conclusion, submission and peer review and publication are envisaged for 12/2021 -02/2022:

- Simon, S., et al. A pathway for the German energy sector compatible with a 1.5°C carbon budget. Sustainability, Sustainability (2022). https://doi.org/10.3390/su14021025
- Harpprecht, C., et al., Decarbonization scenarios for the iron and steel industry in context of a sectoral carbon budget: Germany as a case study, Journal of Cleaner Production (submitted).
- Mengis, N., Kalhori A., Simon, S. et al. (2022) Net-zero CO2 Germany - A retrospect from the year 2050. Earth's Future, 2021. https://doi.org/10.1029/2021EF002324.

In the follow-up period, IEK-STE and DLR aim to publish joint papers. The papers will be based on knowledge gained in the project with respect to the assessment of possible transformations pathways by individual actors and by taking spatial heterogeneity into consideration. They will focus on the assessment of impacts of transition paths of regional energy systems from different perspectives.

DLR-VE plans to extend the energy scenario development by including the energy-related CDR options into the assessment, accounting for additional energy demand and potential extensions of the carbon budget within the ESD activities and future third party funded projects.

HI-CAM enhanced existing cooperation between energy systems analysis and established new cooperation across all sub-projects. Thus, future activities will rely on this extended network, envisaging new project cooperation. The experience gained within project 1.2. strengthened IEK-STE and DLR cooperation with the ESD Program.

A joint application was prepared by HI-CAM partners GERICS, DLR-VE, FZJ-IEK-STE and KIT within the “Helmholtz Sustainability Challenge” in 12/2021.

Additionally, further activities are planned, assessing the integration of CDR technologies in energy systems, including technical, social and ecological aspects.

# EVENTS

## In Project 1.2 IEK-STE organized and conducted one project workshop:

**Project-internal workshops:**

- **Dialogue Series #3: Spatial Heterogeneity: Challenge and Opportunity for Netto-Null**
  Organizers: Imke Rhoden/Christopher Ball/Stefan Vögele (Institut für Energieforschung - Systemforschung und Technologische Entwicklung (IEK-STE), Forschungszentrum Jülich)
  Date: 18 March 2021
  Format: online
  Participants: project representatives P1–P4, incl. case studies

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HELMHOLTZ
CLIMATE INITIATIVE



# CLUSTER I:
# NET-ZERO-2050
## Project 2
## Circular Carbon Approaches


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## SUMMARY

Cluster I within the Helmholtz Climate Initiative (HI-CAM) is dedicated to mitigate any further greenhouse gas (GHG) emissions, especially $CO_2$. Project 2 focuses on a circular carbon approach, which provides climate neutral carbon-based products, e.g. fuels or plastics. It is based on taking the carbon in form of $CO_2$ from the atmosphere and converting it into the desired products. At the end of the product lifecycle the $CO_2$ is eventually returned to the atmosphere and the circle is closed. Before this, it is always favorable to keep the carbon in the circle by material and chemical recycling as long as possible to decrease the required removal capacity.

In the topic of carbon removal from air, KIT researched the technological option, while KIT and UFZ linvestigated the hybrid ones. The conversion into useful products were assessed by KIT, DLR, UFZ, HZB and Hereon, whereas the regulatory framework aspects of CCU were looked at by UFZ.

In case of hybrid solutions such as bioenergy with carbon capture and storage or utilization (BECCS/U), $CO_2$ is removed from the atmosphere by plants. This biomass is further converted in various processes into different forms of bioenergy. The $CO_2$ generated in this process can either be released back into the atmosphere (in so-called carbon-neutral technologies), or captured and permanently stored under the ground (BECCS) or utilized (in greenhouses, beverages, or for production of chemicals - BECCU). In case of BECCS technologies, there is a trade-off between their energetic efficiency and $CO_2$ capture potential. Those systems can be streamlined to maximize bioenergy provision or $CO_2$ removal. As biomass-based technologies, BECCS options may compete for land with other land use forms (e.g. agriculture), therefore it is crucial to use only sustainable sources of biomass, including wastes, residues, or novel approaches such as paludiculture practices or macroalgae farming. Despite those possible limitations, relatively high TRL of some BECCS options could enable their fast and widespread deployment.

Direct Air Capture (DAC) is an energy driven process to filter $CO_2$ from air using technological means. By Power-to-X-processes hydrocarbon products can be produced using hydrogen or electrical power. In this project a novel approach of modular building integrated DAC and conversion technologies has been assessed taking account of their unique set of requirements. In this context miniaturizable, simple and safe technologies are preferrable to ensure a wide spread deployment in the future. Promising technologies in this context are low-temperature-DAC plants with a combined solar thermal production of syngas, which can be converted directly into a variety of useful hydrocarbons, e.g. gasoline or plastics.

Still in a very early development stage are purely electrical DAC (Electro Swing Adsorption (ESA)) and conversion technologies (direct electrochemical conversion ($CO_2$e)). Those technologies are potent candidates for decentralized systems due to their simplicity and scalability. Additionally, they can be operated at ambient conditions, adding to their safety and automatability.

Apart from technological considerations, the assessed technologies have also been put into context of the existing regulatory system. This approach allowed identification of gaps, which presently affect their deployment. New laws, which take CDR measures into account and consider atmospheric $CO_2$ differently than the fossil counterpart, have to be developed. A comparison to other, non-technological CDR measure has provided an interdisciplinary overview for policy makers and other actors. To publicize CDR-meassures and inform the broader public about the concepts, necessary communication work should be done, e.g. by introducing the topic into the public debate, providing explanatory media including factsheets and articles.

Our scientific results can serve as an information basis for further detailed analysis and scenarios development. Proof-of-concept plants are necessary to test and further improve the concepts, e.g. their techno-economic or social perception. Also, those demonstrators can put a spotlight on CDR-measures to make them part of related climate related in politics and public.

## ACHIEVED RESULTS

### Project scope

Cluster 1 within the HI-CAM Project has the goal to derive strategies to mitigate further GHG emissions into the atmosphere, thus contribute to limiting the resulting temperature rise to the targeted 1.5°C by 2050. Apart from substituting emitting technologies by non-emitting ones, (e.g. electrifying the transportation sector, or decreasing the emissions by energy savings or increased process efficiencies), it is necessary to additionally compensate future GHG emissions. Those coming from dispersed sources like planes or ships, which cannot be efficiently captured at the source and must be removed from the atmosphere. In the near future, there will likely still be a need for hydrocarbon fuels or products, which will be incinerated by using them or after their product life. If the released carbon was previously removed from the atmosphere, the products would be carbon neutral. This scenario is a more favorable compared to putting fossil carbon into the air and having to store the $CO_2$ somewhere permanently. This is why in project 2, options for such man-made circular carbon approaches are as-sessed.

### Removing $CO_2$ from air:

Circular carbon economy starts with the removal of the $CO_2$ from the atmosphere to employ it as feedstock. Currently there are two known options to remove carbon dioxide from the air:

1. Through biomass, e.g. in Bioenergy with Carbon Capture and Storage or Utilization (BECCS/U): via photosynthesis - plants convert carbon dioxide and water to biomass using energy of the Sun. The carbon is bound in the biomass,until it is converted into bioenergy.
2. Direct Air Capture (DAC): Specialized filter materials bind specifically $CO_2$ and thus removing it from the air. By introducing energy in the form of heat or electricity, those reversible bonds are broken again and $CO_2$ can be gained pure.

There are several studies and reports, among others the IPCC[1]-report, stating, that negative emissions are needed to reach a net-zero carbon emissions until 2050. A newly published dena study2 calculates the need for $CO_2$ removal by BECCS for 107 Mt of $CO_2$ and at least 40 Mt $CO_2$ from DAC, while the Wuppertal-Institut[2] estimates removal of at least 20 Mt $CO_2$ by DAC and 43 Mt by BECCS for negative emissions alone.[3]

[1] IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable devel-opment, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press.

[2] Prognos, Öko-Institut, Wuppertal-Institut (2021): Klimaneutrales Deutschland 2045. Wie Deutsch-land seine Klimaziele schon vor 2050 erreichen kann Langfassung im Auftrag von Stiftung Kli-maneutralität, Agora Energiewende und Agora Verkehrswende

[3] dena (2021): dena-Leitstudie Aufbruch Klimaneutralität. Hg. v. Deutsche Energie-Agentur GmbH.

### Bioenergy with carbon dioxide capture and Storage/Utilization (BECCS/U):

**UFZ/IKFT**

In case of hybrid solutions such as bioenergy with carbon capture and storage or utilization (BECCS/U), $CO_2$ is removed from the atmosphere by plants. This biomass is further converted in various processes (e.g. combustion, gasification, pyrolysis, anaerobic digestion) into different forms of bioenergy (e.g. electricity, heat, or biofuels). The $CO_2$ generated in this process can either be released back into the atmosphere (in so-called carbon-neutral technologies), or captured and permanently stored under the ground (BECCS) or utilized (in green-houses, beverages, or for production of chemicals - BECCU). In case of BECCS technologies, there is a trade-off between their energetic efficiency and $CO_2$ capture potential. Those systems can be streamlined to maximize bioenergy provision or $CO_2$ removal. As biomass-based technologies, BECCS options may compete for land with other land use forms (e.g. agriculture), therefore it is crucial to use only sustainable sources of biomass, including wastes, residues, or novel approaches such as paludiculture practices or macroalgae farming. Despite those possible limitations, relatively high TRL of some BECCS options could enable their fast and widespread deployment.

The first approach, bioenergy with carbon capture and storage/ utilization (BECCS/U), was investigated by KIT (IKFT) and UFZ. This option relies on plant growth to bind the $CO_2$ from the atmosphere. The biomass is then converted (e.g. combusted, gasified, pyrolysed, digested) into energy carriers (e.g. electricity, heat, or biofuels), and the resulting $CO_2$ is captured in technological process (e.g. by gas washing or membrane separation of the flue- or biogas) for storage or utilization. In some processes also long-term products such as biochar or biooil are produced. The technologies have a rather high TRL (7-9) and are therefore ready for deployment in a short term.

In this project different BECCS process configurations were assessed within the Preferred Technology Options-Report. The first approach is the classical direct combustion of lignocellulosic biomass in a power plant for heat and power generation (CHP) with capturing the $CO_2$ from the flue gas, which is also the least efficient process. The next three options are based on biogas production for CHP – each based on different type of biomass (including waste, manure and energy crops mix, paludiculture biomass, and macroalgae). Another benefit of producing biogas is the opportunity to upgrade and feed it into the existing gas grid to serve as a carbon neutral methane substitute. If the biomass is gasified instead of combusted, the existing syngas can be converted into useful hydrocarbon products of different sorts. This not only equates to a higher energetic efficiency, but also provides valuable products for e.g. the chemical industry. The last options are the efficient slow and fast pyrolysis, which can produce biochar or biooil. Those products can serve as a carbon source for a variety of processes or can be stored long-term to create negative emissions.

In the Technology Assessment Matrix (TAM), the Roadmap as well as in the Backcasting Paper (Mengis et al., in press) and the publication on model concepts of different CDR options (Borchers et al., submitted), selected BECCS options have been put into perspective with other CDR measures and their potential to help reach net zero in Germany has been assessed. To disseminate the assessed information to a broader public a factsheet on BECCS, more specific about pyrolysis and gasification, has been prepared, and contributions to the Web-Atlas have been added.

### Direct Air Carbon Dioxide Capture and Storage/Utilization (DACCS/U):

The purely technological $CO_2$ removal from the atmosphere has been investigated at KIT. While most public and private research focuses on large centralized plants, here decentralized building integrated systems are in the focus. Although large plants definitely benefit from scaling effects directly, the large demand for DAC in the future will require all options to be deployed. By integration filter-modules into existing ventilation systems, some synergies could be achieved:

- The installed ventilation can serve a double purpose of moving air through the building and the DAC unit
- In a closed system the air quality can be increased, while decreasing the heating demand for the building
- The small-scale systems allow a large quantity of private investors to participate in the negative emissions business
- Standardized modules could be mass-produced economically

### Currently there are different DAC-technologies with different unique properties:

**High-Temperature DAC and Low-Temperature DAC:**

The first process, mainly developed by Global Thermostat, uses potassium hydroxide (KOH) as sorbent. The $CO_2$ is chemically absorbed and can be regenerated by heating the solution to approx. 900°C. The process is only feasible at large scales, which makes it uninteresting for the investigated scheme.

The corresponding low-temperature-DAC uses solid, amine-functionalized materials to bind the $CO_2$ to the surface (Chemisorption). For regeneration, steam is introduced at around 100°C at a rough vacuum (0.1 bars). The water is later removed by condensation. Although the regeneration temperature is a lot lower than with the HT system, the energy demand is basically the same. However, the lower temperature level allows the use of a wider variety of heat sources, e.g., waste heat. This system is a promising candidate for installation into ventilation system, due to its ability to be scaled down and the low pressure drop over the module. Additionally, only harmless substances are used and the temperatures are in a moderate range. The process is automatable and large plants are starting to become comercially available, which makes it currently the best option for a decentralized system.

A purely electric system is the Electro-Swing-Adsorption (ESA). Here, special electrochemical substances bind the $CO_2$ chemically, depending on the polarity. If the voltage is reversed, the reaction is reversed as well, leading to the release of the bound $CO_2$. The system promises a significantly lower energy consumption of around 250 to 500kWh per ton of $CO_2$. It is automatable and availabe in small scales, just as LT-DAC but the early stage of development makes this approach more of a far future solution.

### Demand and potential

Depending on the source, it is likely that Germany will have to install a DAC-capacity of up to 75 Mt per year. This would equate to a large number of DAC farms, that have to be built and supplied with renewable energy. For Heating Ventilation and Air Conditioning (HVAC)-integrated systems we calculated a potential of 15Mt per year if the largest buildings will be equipped with such systems. This number, combined with the ability to use waste heat, makes the decentralized approach a promising option for negative or circular carbon approaches. To explain the topic to a broader public a Factsheet about DAC and the decentralized approach has been created as well as contributions to the WebAtlas. Contributions to the TAM, Backcasting Paper and Model concepts put DAC into perspective to other CDR measures.

### Syngas production

If the $CO_2$ is meant to be used in a circular manner, the unreactive gas has to be activated, so that it can be converted into useful products such as bulk chemicals or fuels. The most common path currently is to first produce synthesis gas, or short syngas. This mixture of hydrogen and carbon monoxide is highly reactive and can easily converted into a range of hydro-carbons, depending on the selected catalyst. The first option to produce syngas is by gasifying biomass (see BECCS/U). If the syngas has to be made from $CO_2$ there are three options:

- Reverse Water-Gas-Shift reaction: Hydrogen, produced renewable, reacts at high temperatures (900°C) with $CO_2$ to form CO and water. Water can be removed to get pure syngas.
- Co-Electrolysis: Water and $CO_2$ are split directly in an electrolyzer at high temperatures
- Thermochemical Cycle: Water and $CO_2$ are split using concentrated solar power (CSP)

The thermochemical approach, investigated by DLR, has a great potential, using solar power directly without converting it into electricity. The simplicity could benefit to a decentralized small system, e.g. in form of a small Heliostat collector on large buildings. The concept has been displayed in a project briefing and is part of the Webatlas, the Backcasting Paper, the Model Concepts, the Roadmap and has been featured in the publication "Synergies between Direct Air Capture Technologies and Solar Thermochemical Cycles in the Production of Methanol".

### Fuel Synthesis

The syngas can be converted to a variety of products. In the Preferred Technology Options-Report Methane, Methanol and Fischer-Tropsch-Synthesis (FTS) have been investigated. The efficiencies are rather similar, which leads to the conclusion, that the easiest process with the most versatile product should be preferred. In this case this excludes the FTS, because it requires more downstream processing leading to more complicated process schemes. Methane could be a promising option, since it can be fed into the existing gas grid, similar to bio-gas and therefore reduce the need for further infrastructures.

A different approach to avoid the high temperature production of syngas is the direct electrochemical conversion of $CO_2$ into useful products, investigated at HZB. Here, not only one major process step is omitted, the process also works at ambient conditions. The small scale of the systems could also enable the ventilation integration. Benchmarking of such cells by simulations and calculations revealed that they are able to compete with the classical fuel synthesis on regard of efficiency. Being the low energy demand per ton of $CO_2$-especially interesting for the creation of formic acid at similar efficiencies. This would therefore be a very promising synthesis for decentralized systems, where the energy supply is one major challenge. But since the TRL is low, this solution is more a far future option.

### Energy supply and infrastructure

As stated before, one major challenge for a decentralized PtL-Scheme is the energy supply. Building integrated Photovoltaics (BiPV) could provide part of the energy, especially the electric demand. This has been investigated in a Bachelor thesis at HZB. But it also became obvious, that the large thermal demand will not be met with BiPV alone. Here other energy sources like waste heat are needed. Especially when on site conversion should be implemented, energy must be imported for example in the form of hydrogen. The most sensible concept would therefore be a grid integration of such systems instead of non-connected, isolated solutions. Thus, they could help to stabilize the grid and use excess power when available and shut down when there is a shortage. When producing energy carriers such as methane, they could serve as coupling link between the energy sectors, provide added flexibility in the energy system.

## Enhancing the process with membranes

To enhance the described processes and to separate $CO_2$ from gas mixtures with higher $CO_2$ content, membranes can be used. Such concepts have been studied at Hereon.
According to the theoretical study, replacing conventional reactors with membrane reactors can facilitate carbon conversion to high-market-volume chemicals such as methanol and dimethyl ether. The results revealed that the heat management of the reactor becomes even more important when membrane reactors are substituted for their conventional counterparts.
The deeper analysis conducted to integrate the membrane reactor into the process shows that when green methanol is the target product, the state-of-the-art water selective membrane materials still need improvements to be effective for this application. Minimum requirements of the membrane properties were proposed, which are an important information for future research directions in this field. This approach for the determination of the membrane's minimum requirement is expected to be more broadly applied to the other membrane reactor aided processes proposed in the literature, such as syngas, methane, and Fischer–Tropsch syntheses.

Hereon developed membranes and the associated technology consisting of membrane module, process and simulation tools to separate $CO_2$ from various gas streams in the recent years. Whilst not being an integral part of the HI-CAM research, the technology is nevertheless well suited to separate $CO_2$ from a variety of different gas streams. It is easily scalable to different process sizes and neither requires complex integration into existing process designs nor the usage of potentially harmful separation agents. The separation is effected by applying a partial pressure (or fugacity) driving force across the membrane and applying a membrane material preferentially permeable to $CO_2$. The contributions are presented in the Webatlas as well as two scientific papers highlighting the membrane reactor research.[4,5]

## Legal and economic framework conditions

The research, development, and possible deployment of DAC falls within the scope of various legal regimes, such as climate law, energy law, immission control and construction law. However, none of these regimes has been designed specifically for this purpose. Our analysis reveals that the content and structure of the regulatory framework (economic and legal) is crucial to enable the potentials and limit the risks of so-called Negative Emission Technologies (which include DAC). To this end, we identified the position of NETs within the international climate regime and developed a synopsis of European and German laws affecting the development and deployment of DAC, highlighting important existing regulatory gaps. In addition, the policy hazards arising from regarding avoidance and removal activities as perfect substitutes were identified and elaborated. Furthermore, in a more indepth analysis, an assessment was made on the potential for the use of DAC and other circular carbon approaches for renewable energy production within the framework of EU energy legislation. For this purpose, the following directives were analyzed: (1) Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (RED II) and (2) Directive (EU) 2010/31/EU on the energy performance of buildings (EPBD).

In addition, with the objective of analyzing the feasibility of deployment of DAC and other technologies with the potential to remove $CO_2$ from the atmosphere, we also contributed to the elaboration and evaluation of the TAM in the institutional (political and legal) and economic aspects, as well as in the evaluation of the portfolio

[4] Hamedi, Homa; Brinkmann, Torsten (2021): Rigorous and Customizable 1D Simula-tion Framework for Membrane Reactors to, in Principle, Enhance Synthetic Metha-nol Production. In: ACS Sustainable Chem. Eng. DOI: 10.1021/acssuschemeng.1c01677.
[5] Hamedi, Homa; Brinkmann, Torsten; Shishatskiy, Sergey (2021): Membrane-Assisted Methanol Synthesis Processes and the Required Permselectivity. In: Mem-branes 11 (8). DOI: 10.3390/membranes11080596.

of carbon dioxide removal options. Also, considering that for the feasibility of DAC deployment it is also important to include the role of society's participation, a report on the legal aspects of DAC has been published and a contribution has been made to the Web Atlas on this topic. Interdisciplinary collaboration was crucial in conducting this research.

### Closing the circle:

The described products, fuels and energy carriers can be used in conventional combustion engines, planes, ships, etc. without altering any of the infrastructure. It is clear, that every measure to reduce the use of fossil fuels and linked emissions has to be taken. Nevertheless, there will be hydrocarbon fuels and products used in the future. Those have to be made using carbon separated from the atmosphere to achieve carbon neutrality and hence this use closes the man-made carbon circle investigated in Project 2. If this circular carbon approach can be implemented on a large scale and existing technological, economical, societal and legal questions can be answered, we will be a significant step closer to stopping global warming.

## WORK PROGRESS

**In Work Package 2, a list of five milestones were suggested in the proposal of the HI-CAM project. The milestones are listed below alongside with a brief description:**

- M-P2.1: Identification of regulatory gaps on European and German level regarding the new technology proposed in scheme 2.
- M-P2.2: Preferred technology options for both schemes based on results of assessment.
- M-P2.3: Proof-of-concept plant for scheme 2 to provide data for technology assess-ment and as an effective showcase to the public.
- M-P2.4: Assessment of potential of schemes 1 and 2.
- M-P2.5: Proposal for the inclusion of the technology into the law on promotion of re-newable energies.

At the end of the project, the status of each milestone has been assessed and the causes for delays and/or deviations identified. A summary of the assessment can be found below:

### Milestone P2.1

The UFZ team successfully achieved this milestone. The final report was submitted in July 2020 (almost a month after the deadline) and after a review by Cluster III. It was published on the Helmholtz Climate Initiative website in September 2020

### Milestone P2.2

The preferred technology report was achieved as a result of an extensive collaboration between several researchers from several institutions (Hereon, HZB, UFZ, DLR and KIT). The final document was submitted in July 2021 and was published by the end of the year after revision by Cluster III.

The delivery of the report was 6 months delayed. The cause was personnel shortage due to disruptions during the hiring process, which were mainly a consequence of COVID-19 pandemic.

### Milestone P2.3

The proof-of-concept plant for scheme 2 has been delayed and is in final planning stages. However, it is worth to mention the different development level that each involved partner has achieved:

- KIT (DAC part): the team has suffered delays in the construction of the pilot plant due to materials and personnel shortage.
- HZB (Electrochemical reactor): the scaling-up was successfully achieved and high conversion rates recorded, but the integration was deemed premature due to challenges with catalyst selectivity and stability during extended operation.
- Hereon (Membrane reactors for methanol production): a rigorous model was developed, but delays were suffered due to time-consuming recruitment procedures.
- DLR (Solar reactors): Calculation and assessment of an approach that uses solar power (both concentrated solar power and photovoltaics) to produce synthesis gas.
- HZB (Building integrated photovoltaics): Sizing of a photovoltaic installation that satis-fies the energy needs of DLR's concept.

### Milestone P2.4

A formal report with the potential assessment of schemes 1 and 2 as a main topic has not been developed due to time constraints. Nevertheless, the potential of each technology has been quantified and reported within joint deliverables of HI-CAM as well as independent publi-cations:

- The so-called "Backcasting Paper" ("Net-zero $CO_2$ Germany – A retrospect from the year 2050" by Mengis et al., in press), which was written by collecting contributions of partners across HI-CAM, includes a quantification of the potential of BECCS (scheme 1) and DAC (scheme 2) in Germany.
- The data collected on each technology in scheme 1 and scheme 2 has been used as an input for the Technology Assessment Matrix (TAM)
- Model concepts paper ("Contribution to Net-Zero-2050 Germany – the portfolio of car-bon dioxide removal options" by Borchers et al., submitted) which presented fact sheets of the most relevant CDR concepts, including 6 options of BECC and 2 concepts of DAC.
- Several partners have also published the aforementioned quantifications in peer-reviewed journals and/or grey literature:
  - KIT: Nutzung von $CO_2$
  - aus Luft als Rohstoff für synthetische Kraftstoffe und Chemikalien.
  - DLR: Synergies between Direct Air Capture Technologies and Solar Thermo-chemical Cycles in the Production of Methanol.
  - Hereon: Rigorous and Customizable 1D Simulation Framework for Membrane Reactors to, in Principle, Enhance Synthetic Methanol Production; Membrane-Assisted Methanol Synthesis Processes and the Required Permselectivity.
  - HZB: Electrocatalyst Derived from Waste Cu–Sn Bronze for $CO_2$ Conversion into CO.

### Milestone P2.5

The UFZ team also achieved this goal. With the extended deadline (2 months), the deliverable was submitted as a scientific publication in September 2021. However, because the paper has not yet been published, a sum-mary of the results of this research was also attached.

Last but not least, thanks to the accurate estimations in the project's proposal, no budget deviations need to be highlighted in Work Package 2.

## SPECIAL FEATURES

### Overarching issues

- Scheme 1 and two 2 covers the investigation of technological CDR options both $CO_2$ capture and usage from direct air capture as well as carbon capture from energetic use of biomass. Decentralized applications for both schemes but also central processing and $CO_2$ separation of biomass by combustion and gasification in large facili-ties have been considered. Thus, the potential of CDR on a broad range of scales has been investigated to derive recommendations for further implementation.
- For the first time, different technologies relevant for application in Germany have been evaluated coherently assessing the CDR potential of single plants, the technology readiness levels, and the total potential they may provide assuming certain scenarios. Figure 1 shows the $CO_2$ removal potential of different CDR options together with their possible scalability.
- In the dena Leitstudie, issued in 2021, all these technologies play a significant role. Here, it is assumed that a GHG reduction of 97 % becomes possible until 2050. According to Figure 2, 24 Mt of $CO_2$ are removed by BECCS, 40 Mt of power-to-liquids products are derived from DAC while additional 25 Mt of green methanol and naphtha are imported to meet the carbon demand for the then-used fuels and chemistry. These numbers underline the necessity of further research, development and innovation work in this field as covered with project 2.1

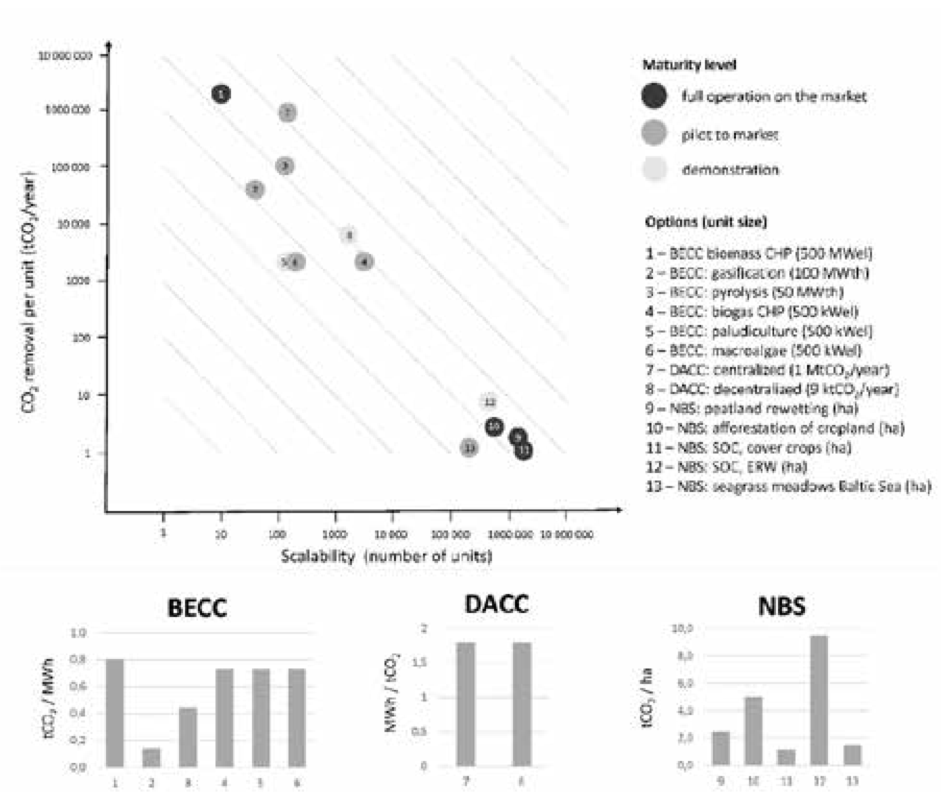


**Figure 1:** Overview of $CO_2$ removal potential of selected options. Top: Scalability of options expressed as a number of units available for deployment by 2050 and CO2 removal per unit. Bottom: Amount of $CO_2$ removed per unit of energy produced by BECC technologies. C: Amount of energy needed per tonne of $CO_2$ removed by DACC technology. D: Amount of $CO_2$ removed per hectare by nature-based options.

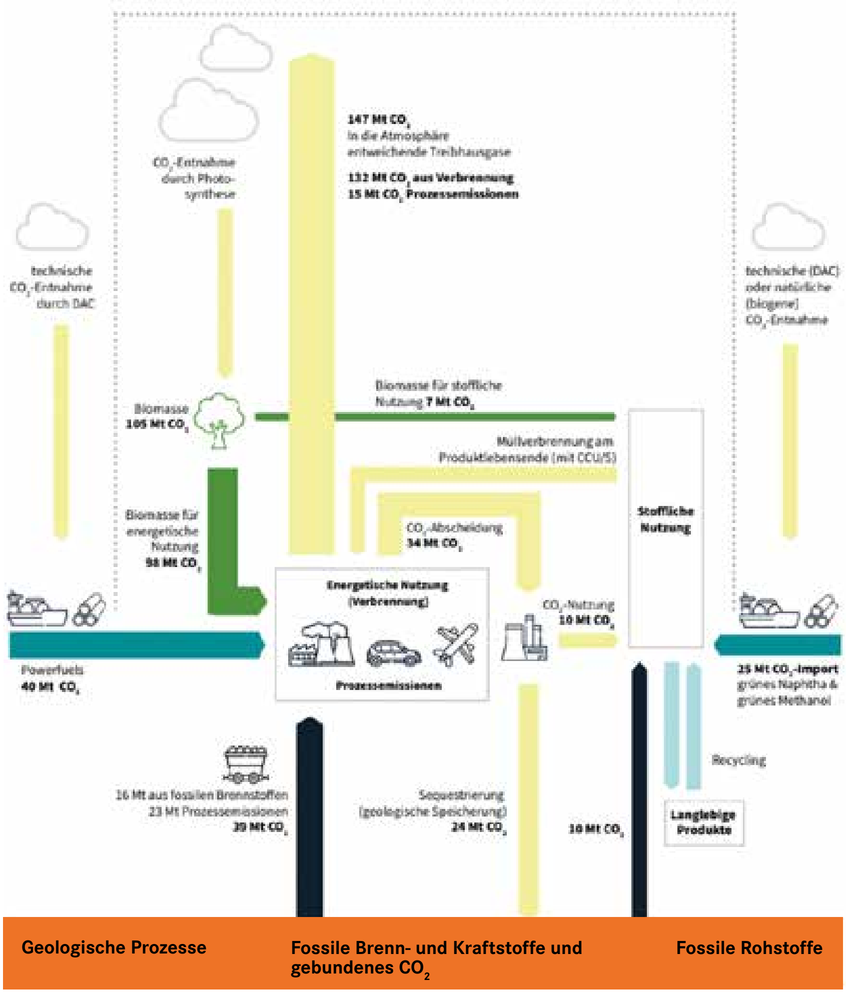


**Figure 2:** Grafics from: EWI/ITG/FIW/ef.Ruhr (2021). dena-Leitstudie Aufbruch Klimaneutralität. Klimaneutralität 2045 - Transformation der Verbrauchssektoren und des Energiesystems. Zusammenfassung. Published by Deutschen Energie-Agentur GmbH (dena).

### Project 2.1: Bioenergy with carbon capture and storage

BECCS scenarios play an important role in most of the climate protection model scenarios. However, there is no coherent comparison of the different technology options available so far. This does not only depend on the CDR potential in terms of mitigated emissions, but also on the extent and type of bioenergy demanded by 2050. Bioenergy can be produced in form of heat, electricity, liquid and gaseous fuels in larger and smaller facilities. CDR can be carried out by CCS but also by the production of biocoal. Some bioenergy products provide larger flexibility towards energy production than others and may be more suitable for sector coupling issues. In project 2.1, the most relevant technology options of high technology readiness level were identified, and assessed in terms of CDR potential of single plants and in total amounts of mitigated carbon.

### Project 2.2: Direct air capture of $CO_2$ and on-site conversion

To broadly assess scientific and technological routes to achieve a circular carbon economy, Project 2 required a diverse range of expertise which was uniquely possible within the Helmholtz Association. By bringing together researchers from five different Helmholtz centers and representing three different Helmholtz Research Fields (Energy, Earth and Environment, Information), the project instigated completely new interactions between research groups which had not previously cooperated. This enabled an interdisciplinary evaluation of the different technological and regulatory components that contribute to the circular carbon vision.

While there are many research institutions worldwide working on the subject of circular carbon approaches, research groups typically focus on single topics (e.g. material synthesis, $CO_2$ capture, conversion technologies, hydrogen production), and there have been few demonstrated initiatives to bring these fields together for a holistic assessment and envisioning of how the technologies would work together practically. Our multidisciplinary research group gathered a full spectrum of experts from material developers to process system engineers under the same roof to design a system with a more integrated approach, assess and compare the key available technologies in a more systematic way.

Some key aspects of added value resulting from Project 2 are summarized as follows. The SEKO (Sector Coupling) project was expanded to demonstrate HVAC 2.0 systems, in efforts derived from HI-CAM milestone P2.3 but broadened to incorporate various DAC and conversion technologies with more holistic heat integration. This included study of integrating thermochemical cycling with DAC.

A portfolio of BECCS technologies which could be deployed in Germany has been expanded by options which use novel, previously not used (in Germany) types of biomass: paludiculture and macroalgae. This can potentially help to address environmental and land-use concerns.

In the $CO_2$ conversion domain, P2.2 included initiation of benchmarking analyses allowing evaluation of disparate technologies by a common set of metrics. This included carbon conversion by catalytic, electrocatalytic, solar thermochemical, and plasma routes. This ongoing effort to assess the technology options across a wide range of technology readiness levels will be valuable in identifying strengths and shortcomings, helping to guide future work and facilitate roadmap development.

**Project 2.3: Legal and economic framework conditions**
An integrated (legal and economic) assessment provides a legally sound, environmentally sound and efficiency-directed orientation for the development of the regulatory framework, which is a crucial point for enabling the potentials and limiting the risks of NETs measures. In this respect, WP2.3. highlights the usefulness of its research for practical decision-making in politics, administration and justice. For example, the Federal Constitutional Court referred to our publication[6] on the feasibility of NETs deployment in its Decision (24.03.2021) on the Federal Climate Change Act of 12.12.2019.

Project 2 partners initiated several activities aimed at stimulating networking and collaboration. KIT led an initiative to develop a community of researchers broadly working on NETs (negative emission technologies). Helmholtz-wide workshops on topics such as electrochemical and plasma-based $CO_2$ conversion were organized within the project, bringing together researchers across all Helmholtz centers and stimulating exchange and collaboration.

The interdisciplinary consortium of Project 2 was key in bringing together the range of expertise needed for targeted follow-up efforts within e.g. the Helmholtz Sustainability Challenge (see below).

[6] The Markus, T.; Schaller, R.; Gawel, E.; Korte, K.: „Negativemissionstechnologien als neues Instrument der Klimapolitik: Charakterisiken und klimapolitische Hintergründe“, Natur und Recht (2/2020), 90 ff.

## OUTLOOK ON FUTURE WORK

Though a myriad of advances is being studied nation-wide in various directions of carbon capture, storage and utilization (CCUS) to put Germany on course to reach the goal of "Carbon net zero by 2050", several obstacles and concerns still persist, such as the high costs of the technology's deployment, regulatory hurdles, and a lack of social consent due to safety. These challenges can be resolved through creative stimulus packages to orient investment towards sectors and technologies, tax policy tools, and expediting research, development and deployment. To this end, we are planning to strengthen our contributions to the topic by sup-plementary investigation on the already raised issues throughout the HI-CAM project. Meantime, we seek to maximize the Helmholtz association's impact in this area by exploring further challenges and opportunities via involvement in new collaborations and funding initiatives.

Given our promising results, the following topics merit further investigations in each respective Helmholtz center to build on our initial work or demonstrate the effectiveness of the technologies at the pilot scale:
DLR will conduct a system analysis consisting of a techno-economic and life cycle assessment for a plant that integrates direct air capture and a thermochemical cycle. Based on this analysis a pilot plant will be developed for demonstration of the concept.

A similar approach will be followed by KIT (IMVT). The integration Direct Air Capture (DAC) into the Heating Ventilation Air Conditioning (HVAC) system will be analyzed in detail. A new generation of DAC technologies will also be in the research focus. This includes the development of a novel, efficient electro swing adsorption module as well as investigations into amino-acid absorbers.

BECCS com be implemented in different plant scales. Depending on these scales and site specific conditions, different carbon capture technologies could be preferrable. KIT (IKFT) plans to fill the existing knowledge gap systematically comparing more established technologies as chemical absorption using amines with technologically newer options as membrane technology.

Membrane reactors as a means of process intensification for the utilization of $CO_2$ stemming from DAC or other carbon capture methods will be experimentally investigated by Hereon based on the simulation studies conducted in HICAM. Next to methanol, dimethylether will be considered as a product and included into the investigations. The general membrane expertise can potentially contribute to other partner's research plans.
As already indicated: a bracket and a possible starting point for future collaboration between the HICAM partners will be more thorough system analyses as were possible within the scope of HICAM. This includes life cycle assessment and techno economic analyses as well as legislative (UFZ) and societal acceptance aspects. Another possibility for future collaboration is the development of the Helmholtz Energy Transition Roadmap, where HZB plans to involve HICAM partners and results.

In order to stay on the cutting edge of the technology in this field, several other collaborations have already been formed or are anticipated within the Helmholtz community and other partners.

UFZ plans to cooperate with GFZ on a proposal of a national $CO_2$ network that integrates industrial and biogenic $CO_2$ sources. KIT (IMVT) will investigate different PtL schemes based on the electrochemical approach in its SEKO (Sektorkopplungs-project) rooftop lab. KIT (IKFT) is involved in the EU $H_20_20$ project Pyro$CO_2$ where $CO_2$ fermentation to chemical products employing $CO_2$ captured from point sources is the subject. Another relevant EU $H_20_20$ funded project is FlowPhotoChem, where HZB and DLR are amongst the partners. The subject is the development of a modular photo-driven system for the conversion of $CO_2$ to ethylene via carbon monoxide. Yet another $H_20_20$ project is INNOMEM where Hereon and partners from all over Europe make their pilot plant infrastructure accessible for third party applied research. Test cases include $CO_2$ and $H_2$ separation. Furthermore, projects initiated by Hereon for $CO_2$ and $H_2$ separation from industrial process and flue gases employing membrane technology are planned.

The Helmholtz sustainability challenge provides a timely and excellent means of further foster-ing collaborations between Helmholtz centers that started in HICAM. Several proposals are in preparation. DACStorE will combine the expertise of several centers (FZJ, KIT, GFZ, Hereon, HZB, UFZ) in the fields of Direct Air Capture and Carbon Storage with Life Cyle and Technology Assessment as well as societal aspects.
UFZ and GFZ collaborate in the proposal aiming at the investigation of a national $CO_2$ network for the integration of industry with biogenic $CO_2$ sources.

At the beginning of 2022 UFZ (BEN and UPOL) is going to lead the BMBF-funded project Bio-NET (Multi-level assessment of bio-based Negative Emission Technologies). The project will extend the knowledge gathered within HICAM, e.g. by expanding the portfolio of BECCS op-tions and addressing regional context of their deployment. The aim of the project is to provide a comprehensive knowledge base for an assessment of bio-based NETs in Germany, com-bining novel social science research with state-of-the-art biomass competition modelling and trade-off analysis to support local and national policy makers.

UFZ (Department of Economics and Department of Environmental and Planning Law) will lead the BMBF-funded project GONASIP to be launched in early 2022 and will build on the knowledge gained in HICAM. The project assesses the opportunity costs and co-benefits of soil carbon sequestration through the use of selected natural land-based carbon sinks as a CDR option in Germany and analyzes options for their efficient consideration in the relevant regulatory framework.

## EVENTS

- **KIT (IMVT):**
  DAC-Workshop at ESD Kickoff event:
  Organiser: Roland Dittmeyer, Dominik Heß
  Format: Online
  Date: 02.07.2021
  Participants:
  Moderator: Roland Dittmeyer, Anja Buckel (both KIT)
  Presenters: Till Markus (UFZ), Peter Viebahn (Wuppertal Institut),
  Andre Bechem (Climeworks) , Dominik Heß (KIT)
  Workshop on the role of DAC in a carbon neutral world

- **PMP 2021, 4th International Symposium**
  Presentation Title: Membrane-Assisted Methanol Synthesis:
  From Equipment Modeling to Process Simulation [online event, 29-30 September 2021]

- **IEA Bioenergy Webinar:**
  Deployment of Bioenergy Combined with Carbon Capture and Storage or Utilisation (BECCS/U)
  Organizer: IEA Bioenergy
  Date: 16 June 2020
  Format: online
  Participants: Daniela Thrän (UFZ, BEN) as a presenter plus three other speakres;
  open public event

## WORKSHOPS

- **Helmholtz Workshop – $CO_2$ Electroconversion 2021**
  Organizer: Matthew Mayer (HZB)
  Date: 6 July 2021
  Format: online
  Participants: 67 researchers from 8 Helmholtz centres (incl. P2 representatives from HZB, KIT),
  keynote talk from R. Krause (Siemens Energy)

- **Workshop Benchmarking P2X Technologies**
  Organizer: Alexander Navarrete (KIT)
  Date: 16 July 2021
  Format: online
  Participants: Researchers from Helmholtz centres plus 3 guest speakers

# CLUSTER I:
# NET-ZERO-2050

## Final report of project 3

Potential and integration of subsurface storage solutions


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**Centers involved:**

GFZ Helmholtz-Zentrum Potsdam

KIT Karlsruher Institut für Technologie

HZDR Helmholtz Zentrum Dresden Rossendorf

Helmholtz-Zentrum hereon

## SUMMARY

Project 3 “Potential and integration of underground storage solutions” links the storage potential that is needed (1) to reduce greenhouse gas emissions such as heat, (2) to boost CCU technologies such as $H_2$, and (3) to finally remove greenhouse gases from the atmosphere in a repository. Besides storage in conventional underground facilities, these three technologies envisage storage in the same aquifers.

Based on analyses of underground storage potentials, preferred regions and their $CO_2$ emission reduction potential for the co-storage of heat/cold and gases ($CO_2$, $H_2$) in deep aquifers were quantified for the first time across Germany. The storage potential acquisition for heat and cold in Germany supports the increase of the renewable energy capacity, taking into account customer structures and technically necessary adaptations. Long-standing research projects of the GFZ in Berlin and the KIT-Campus North served here as practical cases. In addition, the potential of $CO_2$ storage in aquifers was investigated, together with a possible use of the stored supercritical $CO_2$ as a heat transfer fluid for deep geothermal energy and for the production of synthetic methane. For $CO_2$ emissions from the process industry that are difficult to avoid, a feasibility concept for safe and permanent $CO_2$ storage was developed and extended to include the option of temporary $CO_2$ storage. For the integrative approach to storing heat and gases in the subsurface, the analysis of closed power-to-gas/gas-to-power storage circuits was carried out on the basis of an energy system study and the proof of their basic feasibility. In connection with the synthetic methane, benchmarking of various $H_2$ storage options has been considered and evaluated, based on their technical parameters. Moreover, first models and experiments towards carbonization of $CO_2$ in deep saline aquifers were reveal considerable potential for final disposal of $CO_2$ as a co-production during heat storage.

In a new network approach, relevant parameters were identified and studied to develop an optimised logistics concept for $CO_2$ transport from industrial sources to potential sinks, located at suitable storage sites. To implement a thermal-material storage cycle (heat-$CO_2$-$H_2$), Project 3 (partly in cooperation with project 2) has proposed concepts for a practical demonstrator.

## ACHIEVED RESULTS

All milestones have been achieved and the final project phase has been used for innovative approaches to integrating the various technologies of the project. This includes the integration concept of the individual plants analysed so far, such as underground and technical storage ($CH_4$, $CO_2$, $H_2$), methanisation, Allam Cycle as well as a design concept for geological heat storage with supercritical $CO_2$, and in cooperation with project 2 a concept including direct air capture and carbonization of $CO_2$ for the case of KIT-Campus North. It has been successfully demonstrated that the partners’ expertise in geological storage and material research provides the ability for heat/cold and gas storage solutions requested by the national industry. A positive driver for the project progress was the Geological Data Act (GeoIDG) which came into force on 30 June 2020 and supported the development of realistic and reliable geological models of the underground infrastructure for geothermal applications and $CO_2/H_2$ storage. Because the law’s practical data retrieval was possible more than one year after the project start, it brought considerable delay for the underground models.
Key results of P3 are described below:

## Scenario Development Net-zero Germany 2050

The scenario development Net-Zero Germany 2025 involves simulations on different levels as well as involving different technologies. It bases on the compilation of the most relevant parameters for the modelling framework of the HI-CAM test sites for heat storage, DeepStor (KIT) and Berlin (GFZ), and for Carbon Capture Usage and Storage (CCUS), Ketzin (GFZ), as well as the technical benchmark of $H_2$ storage (Hereon) that has been established as a protocol in Milestone M-P3.1. Innovative potential seen here is, as e.g., (i) 10 TWh per year storage potential for high temperature heat in former hydrocarbon fields in the Upper Rhine Graben (Stricker et al., 2020), (ii) conclusions from the full-life cycle of a $CO_2$ storage reservoir as pre-requisite for future large-scale $CO_2$ storage networks, and (iii) development of hydrogen storage materials and systems for the future integration of synthetic methane production.
As contribution to the "Climate-neutral Helmholtz Association", a proto-type scenario for climate-neutral heat using local resources, in this case geothermal and high temperature heat storage potential, has been proposed for the case of KIT. Transfer potential to other 10-15 Helmholtz centers is indicated. Linked to case study I "The climate-neutral city of Karlsruhe" such scenarios have been developed in a co-design process with public .[1]

## Heat storage for urban areas

With respect to the search for heat storage sites the results of our studies show that sandstone aquifers offer significant potential. In detail this means we can provide green and sustainable large-scale storage of heat. The estimation of the ability of the underground to store heat for the North German Basin remains a challenging task: based on sparse and partly uncertain subsurface data, the structural and depositional architecture of the underground needs to be integrated in adequate 3D subsurface models. We used newly available models of the subsurface of the North German Basin (BGR TUNB Project) which resolve the latter in high detail. We combine this basin-wide structural interpretation of depth horizons of the main stratigraphic units with estimates of the subsurface temperature form a 3D transient thermohydraulic model (Frick et al. in review).
Based on structural and temperature data and a reservoir facies identification, the potential for heat storage for virtual well doublet systems was calculated yielding large potential for aquifer thermal energy storage in geologically favorable regions. These are distributed across the entirety of the North German Basin. Hence, they also include identified areas of areas of high heat demand (i.e. high population density, high industrial heat demand). These data therefore point at numerous regions in Northern Germany where the large-scale storage of heat can help mitigate greenhouse gas emissions.
Given the uncertainties in the input data of any structural geological model, the applied methods and combined data are most powerful in identifying promising regions for economic subsurface utilization. After identifying these regions, it is therefore of utmost importance to carry out more detailed studies aiming at in depth geological analysis beforehand to decrease exploration risk.

Geologically younger deposits were investigated in the Upper Rhine Graben and South German Molasse basin. About one third of the surface of Molasse basin reveals potentially high storage potential in a depth of > 400m. In a volumetric analysis[2], formations of the Oligocene sandstone deposits with porosities between 5 and 31 % have been investigated.

## New methodological tools for carbon network analysis

New methods were developed and applied to support the technical and economical analysis of industrial $CO_2$ sources and potential underground storage sites as sinks, together with their corresponding transport lines in a national network (Yeates et al. 2020, 2021a). The new methods consist of heuristic algorithms that pro-

[1] https://atlas.netto-null.org/contribution/112
[2] https://atlas.netto-null.org/contribution/102

pose minimum-cost solutions for infrastructure network design problems under various constraints (Yeates et al. 2021b). Model pipeline networks were proposed for industrial emissions within Germany, and real-world cost-functons were implemented. Care was taken to integrate preexisting pipeline routes in the optimization process. The compiling of geological and surface data enables to creation of realistic large-scale carbon networks. Distinct examples of large-scale $CO_2$ reduction infrastructure is focused on the process industries (cement, steel, fertilizer production etc.).

## Energetic Storage Assessment

For the investigated dual generation system with geothermal heat recovery and the main power cycle (Allam cycle), deep subsurface stores offer the best boundary conditions for heat recovery. First steps consist in the development of a fully closed carbon loop for large scale energy storage and the determination of optimum technical equipment for the individual carbon loop processes.
The most suitable power-to-gas process consists of solid oxide electrolyzer cells in combination of Sabatier methanation. The storage capacities as well as potential locations for the subsurface storage of methan and $CO_2$ was analyzed. Furthermore, the location of relevant $CO_2$ point sources and grid connections for the methane were determined. Various gas-to-power cycles were studied and the semi-closed direct fired supercritical $CO_2$ ($sCO_2$) power cycle, also known as Allam-cycle, was found to be the most efficiency one. An energetic assessment of the carbon loop was performed, including a forecast for the energy system in Germany in the year 2050. The required storage volumes as well as syngas generation and power plant capacities were determined (Fogl et al., submitted). See also M-P3.2 and M-P3.4.

## Hydrogen Storage Options

During the work at the benchmarking of the hydrogen storage technology, a deeper understanding of the interaction between the different systems was developed. Therefore, two different scenarios were considered, the storage of hydrogen in the underground, similar to methane and $CO_2$ and the technical storage of hydrogen directly between the electrolyzer and the methanation.

In this concept the hydrogen is mostly used to create synthetic methane, therefore a technical storage was chosen. This allows many different technologies, e.g. pressure storage, liquid storage, metal hydrides and liquid organic hydrogen carrier (LOHC). To decide which hydrogen storage system fits best to the surrounding system, different points have to be considered. The usage of liquid hydrogen can be excluded due to the high energy demand of the liquefaction as well as the extreme low temperature of 20K. Likewise the storage in LOHC can be excluded due to the high energy demand and the needed process technology for the loading as well as the unloading of the hydrogen.

Therefore, pressure vessels and metal hydrides are considered for the integration inside the overall systems. Pressure vessels have the advantage to be a very common technology, but to store hydrogen in a pressure vessel, it has to be compressed. The problem with the compressors is their expensive cost and comprehensive maintenance.

The other option is to use metal hydride hydrogen storage, where the hydrogen is stored with a chemical reaction inside the metal lattice. This allows a very compact storage of hydrogen which can be easily integrated into other parts of an existing facility. Since the metal hydride works at the same hydrogen pressure which the electrolyzer can deliver, no additional infrastructure elements are needed. Only heat is needed to unload the hydrogen storage, but here the waste heat either of the methanation process or the electrolyzer can be used.

## WORK PROGRESS

### M-P3.1 Relevant parameters for test sites compiled

This milestone was achieved as planned. It was delivered a bit later than originally planned because the partners agreed on the selection of parameters in order to derive meaningful statements for all three storage applications (heat, $CO_2$, $H_2$).

### M-P3.2 Concept for $CO_2$ reconversion with geological storage

Within WP3.2 a concept for closed-loop $CO_2$ conversion/reconversion cycle for the large-scale emission-free storage of renewable energy and all required intermediate gases (e.g. $CO_2$, $CH_4$ and $H_2$) has been developed. The proposed energy storage system incorporates technologies such as thermocatalytic methanation of $CO_2$, high temperature electrolysis (SOEC) for $H_2$ production, metal hydride H2 storage, reconversion power cycles based on supercritical carbon dioxide as well as subsurface storages (e.g. caverns and porous saline aquifers). In the framework of this work package, a thorough literature study has been carried out prior to the conceptualization phase of the storage cycle. Based on the developed energy storage concept, a review paper was compiled and submitted in August 2021 (Fogel et al., final decision pending). The respective milestone of the previously described work (M-P3.2) was delivered in project month 26. According to the initial project proposal the delivery of milestone M-P3.2 was planned for month 12 of the project schedule.

### M-P3.3 Subsurface models for test sites finished

The static DeepStor subsurface model bases on the re-processed and re-interpreted seismic data and reveals three undisturbed sandstone horizons within the Oligocence deposits that are predisposed for high temperature heat storage. Reactive transport modelling of high temperature heat storage reveal dissolution of divalent ions that are necessary for carbonization of $CO_2$. Such dissolution processes have been reported crucial for $CO_2$ mineralization in the worldwide only commercial site in Iceland. Against this background, first reactive flow experiments have been carried out and reveal clogging of reservoir analogues in the lab.

A detailed case study of a temporary underground $CO_2$ storage was performed, in collaboration with the largest industrial $CO_2$ emitter of the Berlin-Brandenburg region. The study focused on establishing the feasibility of a yearly $CO_2$ injection-extraction cycle in a shallow storage location within a larger synfuel production chain. The study demonstrated the technical potential and safety of the proposed solution but highlights the requirement for more detailed constraining of the geological parameters of the test site model. An internal report was prepared, and an article is under construction from the material.

### M-P3.4 Energetic assessment of geological s$CO_2$ storage finished

Following the concept development in WP3.2 (M-P3.2), an energetic assessment of the proposed storage system based on subsurface storage of $CO_2$ and $CH_4$ has been carried out. The assessment was conducted for specific forecasts of the German energy system in 2050, thus revealing required storage capacities for $CO_2$, $CH_4$ and other relevant cycle gases in case of a large scale deployment of the proposed P2G-G2P system in Germany by 2050. This work package represented consecutive step to the works conducted with respect to M-P3.2. Furthermore, the initial work plan was extended and the energetic assessment was carried out for the entirety of the proposed storage system instead of just the geological storage operation. Hence, the planned delivery date (project month 18) of the corresponding milestone (M-P3.4) was not met according to plan. The milestone was delivered in project month 26.

### M-P3.5 Benchmarking of $H_2$-storage options finished

The different $H_2$-storage option were analyzed and presented inside a report as well as in a publication which is in preparation. The benchmarking show that there are several $H_2$-storage options, which are market ready and can be implemented. Therefore, the chosen storage option deepens strongly on the specific application. The four market ready or nearly market ready options are: pressurized hydrogen, liquefied hydrogen, metal hydrides as well as liquid organic hydrogen carrier (LOHC). The other storage option which are for example cryo-compressed hydrogen or the adsorption on Metal-Organic-Frameworks or highly porous carbon are still in basic research or only demonstrator are available.

Therefore, the four most promising technologies were considered for the benchmarking. Therefore, it could be shown in which field of applications which technologies have their strengths. To give some examples: Pressure storages are very common in all applications, where neither space nor room is crucial. If salt caverns are used as pressure vessel, pressurized hydrogen storage offer the largest possible storage capacities. Liquid hydrogen storage are use if weight and space is the most relevant criteria. They are used in space application and for hydrogen transport in trailers. Liquid hydrogen is also discussed for airplanes, ships and trucks. Metal hydride have the benefit of high volumetric energy densities at low pressure and moderate temperature. Also as auxiliary systems only a heat management system are needed. For example, metal hydride hydrogen storages are used at submarines and stationary application.

LOHC have the benefit that it can be transported and stored in the infrastructure of fossil fuels. But the disadvantage is, that for unloading and loading of hydrogen always an external reactor and high temperature heat are needed. LOHC are mostly expect for the transportation of large amounts of hydrogen. For the analyzed PtG-GtP concept a metal hydride storage fits best, since it can be integrated into the system between the electrolyzer and the Sabatier process as hydrogen puffer and it reduce the necessary auxiliary infrastructure, since only heat and no compressor or other external devices are needed.

### M-P3.6 Concept for (heat) system integration at test sites finished

The implementation of aquifer thermal energy storage systems (ATES) in urban heating and cooling systems requires a concept that integrates the single technical sub-systems (i.e. subsurface, technical components and plant-specific components, grid structure and user) into a coherent energy system. The local subsurface knowledge on suitable geological reservoir formations and the surface energy situation are combined into an overall system design to evaluate the economic and environmental perspective. Based on these results, design and dimensioning parameters are determined for the construction and operation of the ATES system in an urban heating grid. A small-scale pioneering example for this technology is operating under the buildings of the German parliament for years.

### M-P3.7 Design concept for a pilot $CO_2$-based geothermal system

In project P3, the combination of heat and gas ($CO_2$, methane and hydrogen) storage was addressed for the first time in this unique manner and will support the supply of green commodities and the development of a circular economy. In order to progress this idea, a design concept has been suggested for a $CO_2$-based geothermal system as demonstrator example. This concept for an energy-storage system with a carbon loop was already reported in the Intermediate Project Report from September 2021, on a power plant colloquium in October 2021 (Fogel et al, 2021; Unger et al., 2021), and is shown in more detail in the subchapter 'Outlook on future work' of this report.

## SPECIAL FEATURES

### Developments towards carbonation of $CO_2$ in deep saline aquifers

Worldwide, $CO_2$ carbonation has been proven in mafic to ultra-mafic rock. In the Hellisheidi geothermal power plant (Iceland), the CarbFix company uses basalt with a high proportion of $Mg^{2+}$ and $Ca^{2+}$ (Matter et al., 2011). This rock and the geothermal fluid reveal 5-6 mole/kg and < 0.5 mmole/kg divalent ions, respectively (Alfredsson et al., 2013). Ca-isotopes show that up to 93 % of dissolved Ca is removed into calcite (Pogge von Strandmann et al., 2019). Similarly rock types occur in the Permian formations in NE Germany and parts of the Upper Rhine Graben (URG) (Snæbjörnsdóttir et al., 2020).

Many of the geothermal systems in the URG including DeepStor at KIT Campus North reveal significant more divalent ions in their formation fluids. (Banks, J., Poulette, S., Grimmer, J., Bauer, F., & Schill, E. (2021). Geochemical Changes Associated with High-Temperature Heat Storage at Intermediate Depth: Thermodynamic Equilibrium Models for the DeepStor Site in the Upper Rhine Graben, Germany. Energies, 14(19), 6089.

In addition, $CO_2$ carbonation may benefit from co-storage of high-temperature heat and $CO_2$ through retrograde solubility of $Ca^{2+}$. A preliminary flow-through experiment using a DeepStor reservoir rock analogue and synthetic reservoir fluid (without excess $CO_2$) revealed clogging at reservoir condition (Schaible, 2021). The observed clogging was reproduced in a second experiment.

### Methodological developments

The development of a network design tool has been successfully finished. It is a capacitated graph optimization tool, applicable for typically pipeline transport networks ($CO_2$, $H_2$), stored in a Github repository *(https://git.gfz-potsdam.de/yeates/network-design)*.
The developed Atlas Python codes are also accessible *(https://git.gfz-potsdam.de/yeates/netto-null-atlas)*.

### Engineering design

A result which wouldn't have been achieved without HI-CAM is the combination of storage for hydrogen, methane and $CO_2$ to supply green commodities and allow seasonal energy storage.

### Collaborations & Dialogues

High temperature heat storage scenarios that were developed in a co-design processes with different stakeholders and action groups have been transferred through the case study DeepStor at KIT to decision makers of the Helmholtz Association[3] and energy providers as well as such as Stadtwerke Karlsruhe or EnBW Energie Baden-Württemberg. A stakeholder dialogue was started and has additionally fostered the contact with industry, regulators (e.g., the mining authority for underground regulations).

Regular working meetings with the cement industry in Brandenburg (CEMEX) and Siemens Energy were conducted to develop a joint CCUS concept. A cautious communication approach about the progress of this collaboration has been agreed between the parties.

Based on the achievements of the Project 3 results, new proposals may be elaborated with the partners in future funding frames, in collaboration with European and international scientists.

[3] atlas.netto-null.org/contribution/110

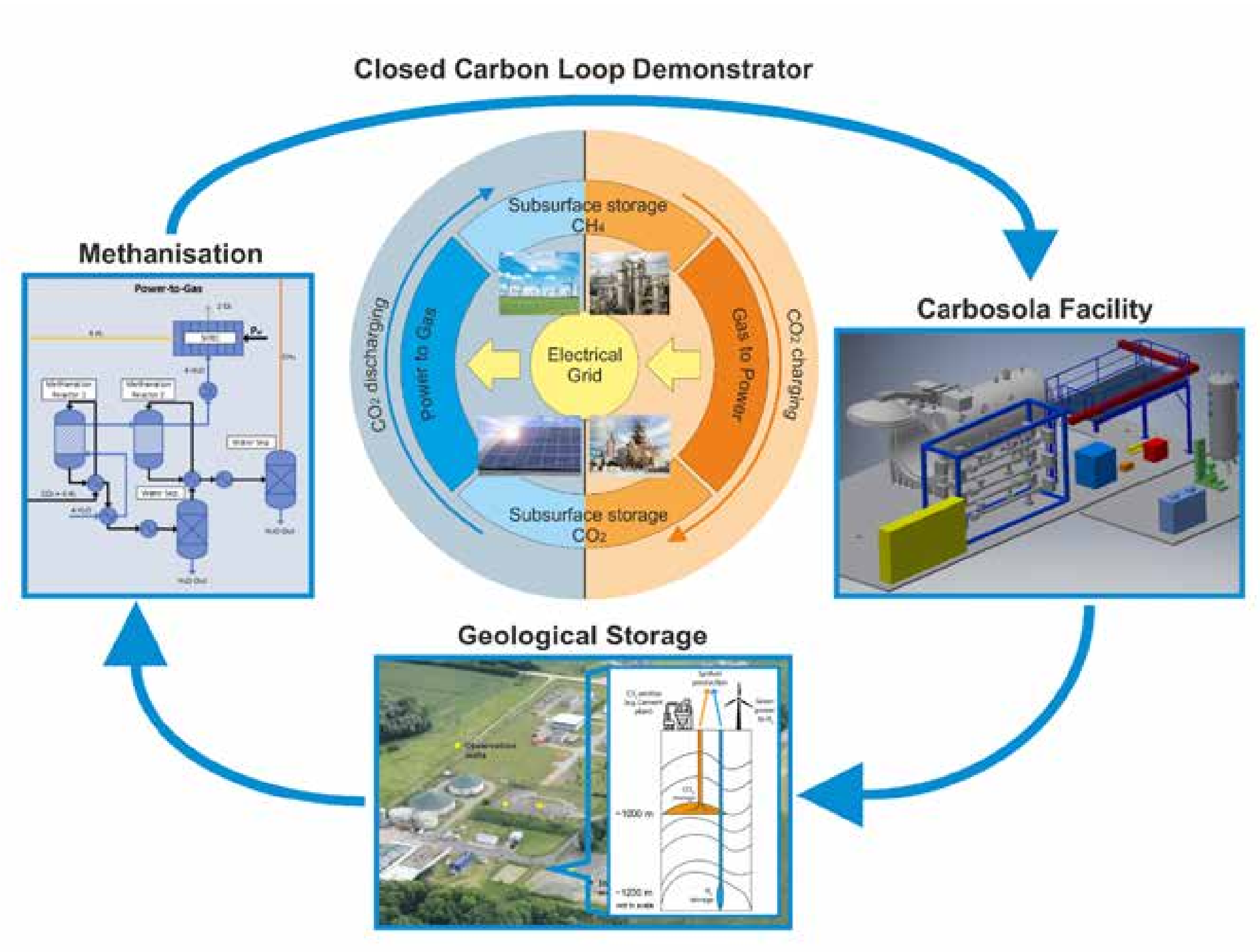
## OUTLOOK ON FUTURE WORK

In order to foster the further expansion of the ATES technology on a larger and industrial scale, we are developing in cooperation with industry partners a demonstrator for the integration of a seasonal ATES system in the heating grid of Berlin. Here, we combine the expertise from miscellaneous disciplines. In the first, currently running phase of the so-called GeoFern project, the GFZ is drilling an exploration well, opening the subsurface of Berlin for various exploration methods, geophysical and hydraulic tests and petrophysical and -chemical analysis. One goal of these activities is to analyse and understand the subsurface thermal geosystem in greater detail, in particular the potential interactions between porous reservoir sandstone and the circulating fluid and all aspects that affect the long-term stable and secure operation of such a system. It opens also the opportunity to locally validate the estimations of the heat storage potential based on real data. After a successful drilling and the proof of the reservoir suitability, a second project phase aims for the construction of the surface installations and the technical and operational integration into the heating grid.

Furthermore, in the framework of project 3 a concept for an energy-storage system with a carbon loop was developed. $CO_2$ is separated from a flue gas stream, temporarily stored in a subsurface structure, extracted and converted to a carbon-based fuel, e.g. methane, via green hydrogen. This fuel is fed into a supercritical $CO_2$ power cycle to generate electricity, in case of positive residual load. $CO_2$ is separated from the generated flue gas stream of the turbine system as described before and the carbon loop is closed. During the subsurface storage a certain part of the $CO_2$ may become trapped as gas, dissolved in the formation water or co-mineralized, depending on the subsurface conditions. This allows carbon capture and storage from hard-to-decarbonize industries, such as cement or other point sources. Within HICAM relevant technologies were identified and the most efficient system design was determined. The system concept is also suitable for existing locations of coal-fired power plants after their shutdown. There, the existing electrical grid connection and transport infrastructure can be used. This opens economic perspective and employment for the transformation of such coal regions. A combined regional evaluation of geological storage capacity and listing of relevant industry $CO_2$ sources is feasible with the prospect of creating cost-efficient localized $CO_2$ transportation networks.

A next step can be a pilot demonstrator. At first the demonstrator will be developed as conceptual laboratory with the Carbosola facility in the centre (see schematic figure below), which includes the design of the required system and components as well as the planning of the request for tenders, construction, instrumentation, commissioning and operation of the complete carbon loop cycle as well as hydrogen production and storage infrastructure. The established closed carbon loop could incorporate a $CO_2$ subsurface storage according the proven concept of the Ketzin Pilot Site, operated by the GFZ. At the pilot demonstrator, cyclic storage technology and $CO_2$ injection in and withdrawal from the underground reservoir can be investigated, optimized and fed in as working parameters into the carbon loop. As a positive side-effect, the cycle can be used to harvest geothermal energy which can enhance the round-trip efficiency when used in the synthesis stage (contributions by GFZ, HZDR, KIT). Experimental studies can be conducted at the CARBOSOLA facility at HZDR where fundamentals of power to gas to power processes at pressures up to 300 bar and temperatures up to 650°C as well as $CO_2$ transport in porous aquifers may be studied. Demonstration may be up to a power of 20 MW. To close the loop, the synthetic methane has to be produced out of hydrogen and the cycled $CO_2$. In the concept, developed by WP3, a high temperature electrolyzer is chosen. Therefore, a buffer storage for hydrogen is necessary to couple the electrolyzer and the methanation. Therefore, a metal hydride based hydrogen storage should be used and analyzed, since thus less auxiliary equipment is needed and the electrolyzer, the metal hydride based hydrogen storage, and methanisation can be thermally coupled. This allows for increasing the overall efficiency of the carbon loop. This thermal integration and design optimization of the metal hydride based hydrogen storage for the overall system can be done by Hereon, based on the existing knowledge of building and integrating hydrogen storage systems.

The interaction of the particular components in such a closed carbon loop has never been applied before and therefore fulfils the required degree of novelty. The components represent potential 'industrial uptakes' to become transferred after their final development towards industrial application.



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# CLUSTER I:
# NET-ZERO-2050
## Final report of project 4
Storage solutions in nature


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## SUMMARY

Supplementing a compilation of literature data with multi-year records of own continuous $CO_2$ and $CH_4$ flux observations from two typical rewetted peatlands in Germany, we derived more robust emission factors that are stratified by IPCC land use categories on natural or rewetted as well as drained peatlands. We combined these improved emission factors with a 30 m resolution land cover and land use map and produced spatially explicit estimates of $CO_2$ avoidance and $CO_2$ removal potentials that could be realized by rewetting previously drained organic soils (mostly peatlands) in Germany. We estimated a preliminary avoidance potential of 27 Mt $CO_2$ per year (range 11 - 42 Mt) and $CO_2$ removal potential of 5 Mt $CO_2$ per year (range 2 - 10 Mt).

We further estimated the carbon storage potential in agricultural soils and assessed the impact of mitigation measures in a prognostic modeling approach. The carbon storage potential was estimated with a land surface model for different land management options in relation to a business-as-usual management under climate change scenarios.

To facilitate the transfer of knowledge on the mitigation potential of these agricultural soils, a prototype "soil carbon app" was developed for actors in agriculture, administration and politics. The app is a novel digital format that makes new data from research directly available to the target groups, connected through an innovative data science workflow. It provides access to simulation results of soil carbon variables from the Community Land Model (CLM), and climate model simulation data. Users can choose from pre-defined options to browse through the data and can do their individual and region specific data exploration.

Along the North Sea and Baltic Sea coasts, we assessed the carbon storage potential of seagrass and saltmarshes. Salt marshes in the Wadden Sea are often well-drained and experience less waterlogging than other natural marshes around the world which lowers their carbon storage potential. Seagrass meadows in the Wadden Sea, however, store even less carbon as the aboveground biomass of the dominant seagrass species Zostera noltei is almost completely lost in winter by shedding leaves, while the total belowground biomass (live and dead) does not change between winter and summer.

Seagrass meadows along the German Baltic Sea coast store more carbon - an average of 7,785 $gC/m^2$, which is 13 times more than other parts of the Baltic Sea (outside of Germany) and 3-55 more organic carbon than adjacent unvegetated sediments. They also prevent erosion of ancient terrestrial carbon stocks (such as forested peatlands) submerged during the last deglaciation along the German Baltic Sea coast. Collectively, German seagrass meadows in the Baltic Sea are preventing 8.14 Mt of future $CO_2$ emissions and if we apply the average sequestration rate of Zostera marina reported in the literature, the meadows can sequester up to 103 kt $CO_2$ per year in negative emissions.

## ACHIEVED RESULTS

### WP4.1 Organic and agricultural soils

About 95% of the organic soil area in Germany (predominantly peat) are currently drained for mostly agricultural purposes and are estimated to emit 43 Mt $CO_2$ per year (53 Mt $CO_2$-eq per year), which is almost 7% of the total German emissions and about 40% of the emissions in the agricultural sector. Both these emission estimates and estimates of the mitigation potential are based on static emission factors derived from a very limited set of data. This is true in particular for IPCC Tier 1 emission factors, but still valid for emission factors used in the national inventory reporting.

In order to enhance the robustness of emission and mitigation estimates, we set up a structure to compile existing literature data of $CO_2$ and $CH_4$ emissions from both drained and rewetted peatlands in the temperate climate zones and, in addition, processed almost ten years of direct $CO_2$ and $CH_4$ flux measurements at two typical rewetted peatlands in northeast Germany.

These own estimates of $CO_2$ and $CH_4$ emissions along with the compiled data from literature sources are summarized into updated emission factors that are stratified by the IPCC land use categories on rewetted or natural as well as drained peatlands. We produced a spatially explicit estimate of climate mitigation potentials by peatland rewetting across Germany by combining these updated emission factors with a 30 m land cover and land use map. The climate mitigation potentials are explicitly separated into $CO_2$ avoidance and $CO_2$ removal potentials based on the recommendation from a discussion on the Net-Zero roadmap of Germany within the Net-Zero cluster. While further improvements are needed and under way to reduce the uncertainties in the values of 30m grid cells in these maps, the current maps provide valuable information on the spatial pattern of climate mitigation potentials across Germany to guide the prioritization of peatland rewetting from a purely mitigation-centered perspective.

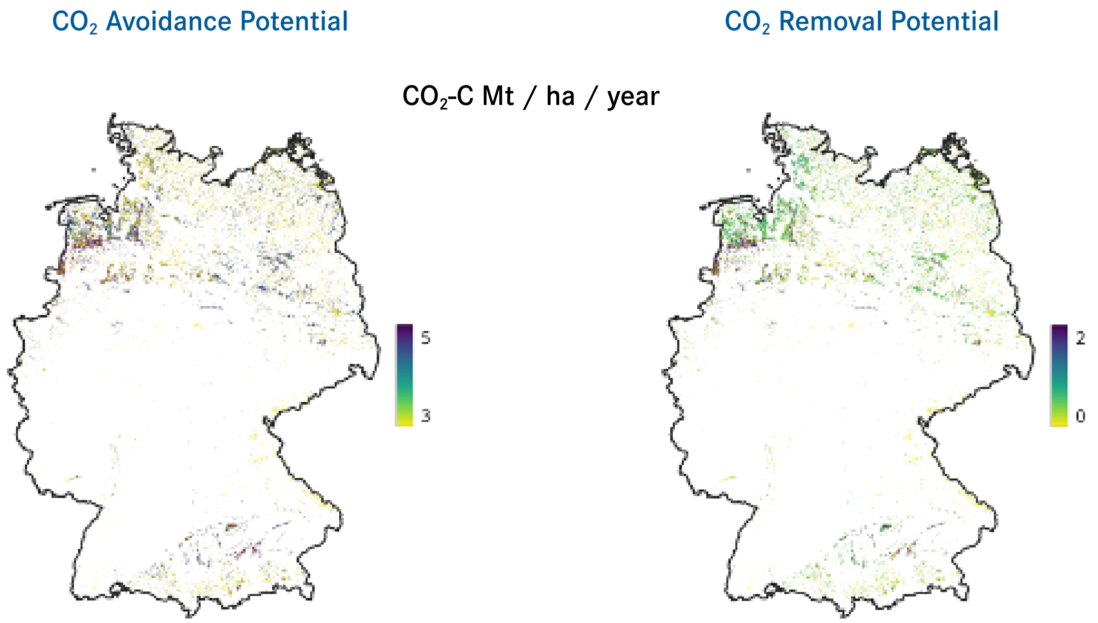



**Fig. 1**: $CO_2$ avoidance and removal potential by peatland rewetting in Germany. Only areas on organic soils are shown.

To assess the carbon storage potential in agricultural soils the Community Land Model Version 5 (CLM5) was run on the JURECA and JUWELS supercomputer. The following field crops were in-vestigated: corn, spring cereals, winter cereals, rapeseed, potato, and sugar beet. The model domain comprises Germany, subdivided into 8 x 8 km grid cells (5015 grid cells with >5% cropland in total). Additional datasets with finer spatial resolution than the CLM5 default setup were implement: (1) soil texture (2) land use, and (3) nitrogen fertilizer application. The model was spun up for approx. 3000 simulation years to reach equilibrium. The CLM5 model was forced with climate data (RCP2.6 and RCP8.5), which was generated with the three dimensional hydrostatic REgional climate MOdel (Remo-RCM). Different land management options (LMOs) were simulated from 2020 to 2050: (1) conversion of 10% cropland to grassland (LMO1), (2) conversion of 75% cropland grown with sugar beet and potato to summer cereals (LMO2), (3) a combination of both (LMO3), and (4) cover crops grown in the off-season of summer crops (i.e., corn, sugar beet, potato, and summer cereals; LMO4). In addition, a business-as-usual scenario (BAS) was simulated as control. The prognostic simulation runs calculated changes in soil organic carbon in space and time. The interaction of climate change and land management has often been neglected in previous studies. First trends on the carbon storage potential under different land management for agricultural soils in Germany were estimated (**Fig. 2**).

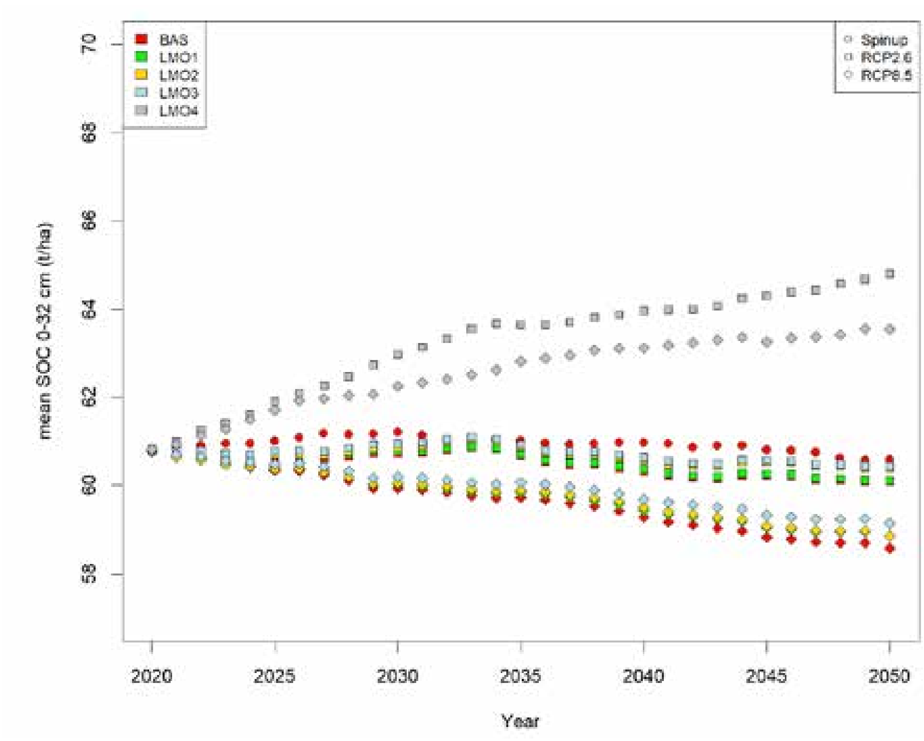



**Fig. 2**: Mean soil organic carbon (SOC in 0-32 cm soil depth, t/ha) in cropland soils in Germany over time for the spinup simulation (no climate change), and two climate change scenarios (RCP2.6 and RCP8.5) for business-as-usual (BAS) and four land management options (LMO1-4).

## WP4.2 Prototype „Soil Carbon App" for "Net-Zero-2050" toolbox

A prototype "soil carbon app" was developed as a novel digital knowledge transfer format that makes new data from climate and agricultural research directly available to actors in agriculture, administration and politics. The app enables users to perform individual and region specific data exploration on the mitigation potential of agricultural soils in Germany by 2050 under changing climate conditions. An innovative service-oriented data provision workflow was developed that covers the whole chain from model simulation results to the app frontend, using a raster array database and a RESTful middleware web service (**Fig. 3**).

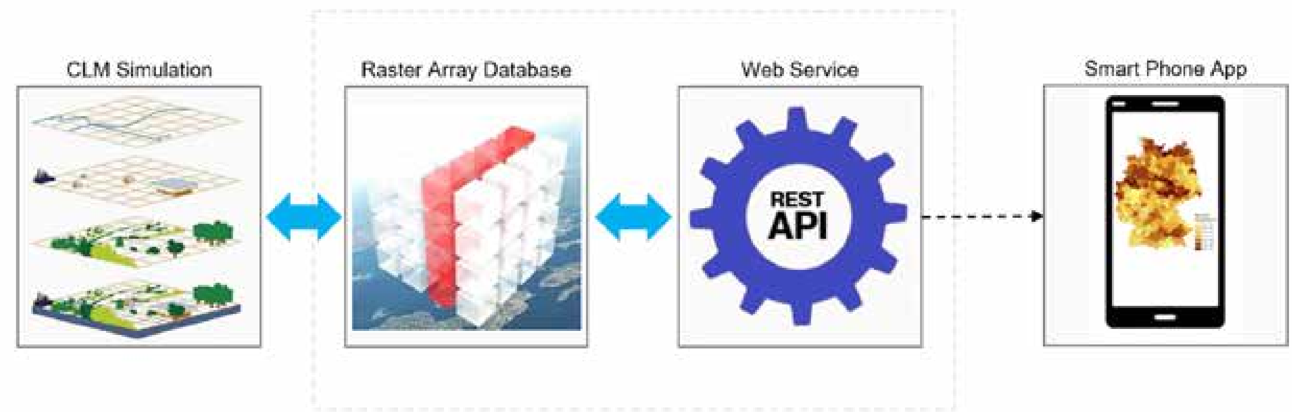



**Fig. 3**: Service-oriented data provision workflow (Sources: omnisci, buildfire, rasdaman, DLR, mulesoft)

## The middle-ware - the technics inside

The challenge in developing the data provision workflow was to integrate high-volume numerical model results and the information derived from existing databases into an interoperable service concept, which provides data aggregates in a format that is directly usable by the app. We used modern raster array database technology for delivering customized model fields including a tracking concept for model data. This ensures that the data status is always visible through its metadata database. We successfully ingested file-based high-dimensional input daily climate data (tens of Gigabytes) and annually carbon data from simulation output into the raster array database. A RESTful web service was developed that acts as an interpreter between the data backend and the frontend users. This web service has four main objectives: Translation between request and query, providing meta- and scheme data, offering analytics and visualization, and improving flexibility. This web service enables concurrent data access and offers resilience by decoupling the frontend app and the backend raster array database. Server side rendering using geoscience oriented web technology is utilized to visualize ingested raw data in the raster array database and verify database queries in a one-click simple way.

## Conceptional and synthesizing work

During the work on the concepts for the app, structured process guidelines were designed for the stakeholder engagement, consisting of a concept with "*steps*", "*goals*", and "*how to*?", *where* "*steps*" are broken down into 5 measures or action areas (e.g., "*research and synthesis of existing knowledge*", "*categorizing and development of stakeholder profiles*"). Two main target groups were identified, a) actors in administrative or institutional entities, and b) actors in the agricultural practice. Further work focused on group a), at all levels from the federal to the county level.

The app design was based on careful analysis of user needs and expectations and included consideration of the technical requirements. The most important aspects were identified as:

- The app should consist of a "*data driven*" and a "*background*" area.
- "*User questions*" are key to the usability of and guidance through the product.
- Due to the data volume and complexity, analyses of the data are pre-defined and most data are provided in aggregated form through the middleware layer
- Flexibility and usability need to be carefully balanced.
- The pre-definition is linked with the "user questions", which can be mirrored in the app's architecture and functionalities.

### Implementation of data visualization and user functionalities in the app frontend

The app's frontend provides a gridded data view, a map covering Germany. More regional and individual analyses are possible through use of the location function (for the case of smart devices) or by entering a postal code or place name. Three types of visualization are possible: gridded maps, time series and bar charts of spatially aggregated data. Users can choose from several parameters, e.g., soil carbon content from the CLM or air temperature from the climate model data. Three different land management options (LMOs) and a baseline run (BAS) are simulated by the CLM model. Differences between LMO and BAS results represent the effects through changed land management. More details on the LMO as well as on the driving climate model data are given in WP4.1. Figure 4 shows example displays from the frontend.

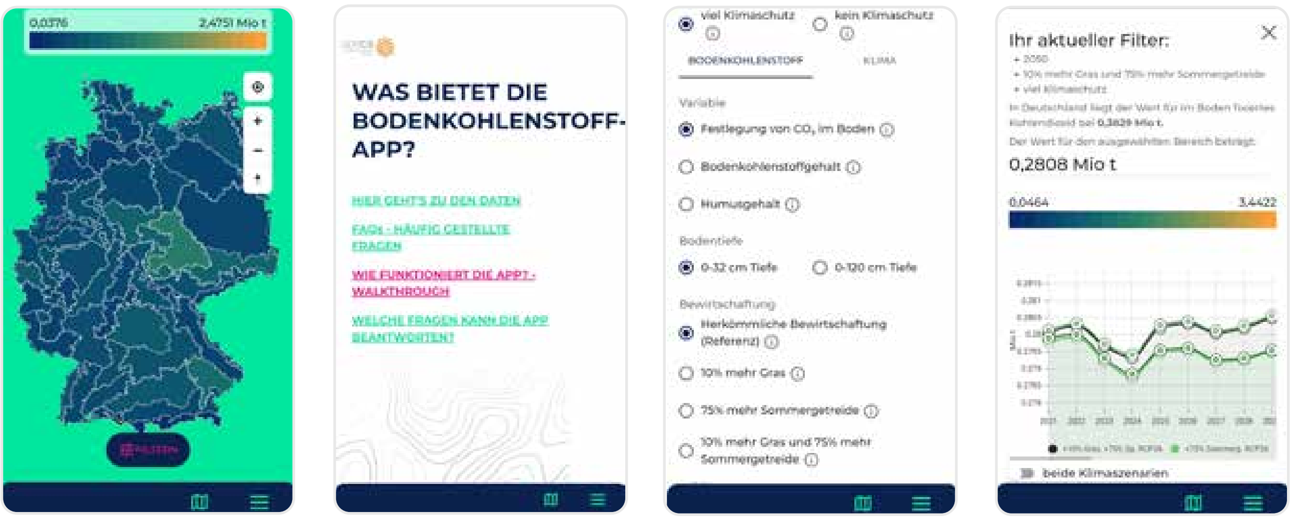



**Fig. 4**: Example displays of the "soil carbon app" (source: *Kopfarbyte.com*).

## WP4.3 Marine carbon storage

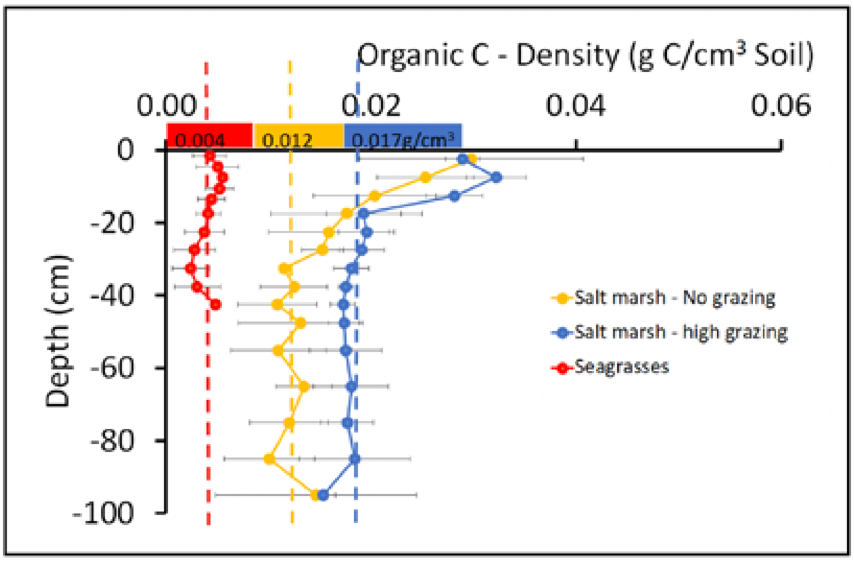
The main research objective in this WP was to investigate and quantify the carbon storage and carbon sequestration in the vegetated coastal zones along the German North Sea and Baltic Sea Coast. Salt marshes and seagrasses have been identified as coastal habitats, accounting for more than 30-50 times higher burial rates of carbon, than for example temperate and boreal forests (McCleod 2011).

## North Sea

The Wadden Sea is the coastal sea of the southeastern North Sea, where greater areas of salt marshes and seagrass beds are located. Belowground burial of carbon was assessed in 3 seagrass beds on sandy substrate, which is typical for the Wadden Sea. Sediment cores were taken down to 45-50cm depth. Vertical profiles of sediment organic matter, which could be considered permanently buried were measured, excluding carbon from fresh biomass and carbon originating from inorganic sources. The permanent carbon storage was really low, and the organic carbon content was below 0.5 %.

Carbon storage was also investigated along 3 transects at salt marshes at Hamburger Hallig in areas with (1) no grazing; (2) low density grazing and (3) high density grazing. The organic content was higher in intensively grazed marshes (4–2 %) than in the ungrazed marshes (3.5–1.5 %) and the low-density grazing fell right in between. The organic content was higher in intensively grazed marshes (4 % near the surface – 2 % in deeper sediments) than in the ungrazed marshes (3.5 % near the surface – 1.5 % in deeper sediments) and the low-density grazing fell right in between.

Wadden Sea salt marshes (grazed and ungrazed) have a much higher carbon storing capacity than seagrass beds. A stable level of organic carbon density is reached at approximately 40 cm depth in the marshes, at levels of 0.012 and 0.017 g/cm$^3$ for ungrazed and grazed marshes. In salt marshes, the carbon stocks of organic soil carbon (not including biomass) for 0-1m depth is 147 (T/HA) in grazed marshes and 195 (T/HA) in ungrazed marshes. Grazed marshes can store more carbon, because the sediment is more compacted and thereby more waterlogged and anoxic. In contrast, a very low carbon density of 0.004 g/cm$^3$ is shown throughout the seagrass profile. In the seagrasses, the carbon stock in the top 50 cm was 17 (T/HA). This may be partly due to seagrasses being sampled on sandy substrates, which is known for its low carbon content.




The organic carbon content in the sediment of Wadden Sea salt marshes and seagrass meadows. The content decreases with increasing depth.

### Baltic Sea

Across the Baltic Sea, we cored 20 sites from Flensburg fjord to the bay of Greifswald. Here, via SCUBA diving, we collected 180 short and long cores to examine the carbon stocks and sequestration rates of seagrass meadows. In order to capture the greatest variation as possible, we selected sites that differed in wave exposure, anthropogenic input, proximity to rivers, and considered seawater depth and sediment composition in our analyses.

In order to address this spatial heterogeneity, we sampled 20 locations across the Baltic Sea coast of Germany to quantify carbon stocks and sources in Zostera marina seagrass-vegetated and adjacent unvegetated sediments. To predict and integrate the Corg inventory in space, we measured the physical (seawater depth, sediment grain size, current velocity at the seafloor, anthropogenic inputs) and biological (seagrass complexity) environment to determine regional (between sites) and local (within site) drivers of Corg variation.

Here we show that seagrass meadows in the German Baltic Sea constitute a significant Corg stock, storing 2,151 to 22,518 g $C/m_2$, on average 7,785 g $C/m_2$, 13 times greater than meadows from other parts of the Baltic Sea (outside of Germany), and four-fold richer than adjacent unvegetated sediments. Corg stocks were highly spatially variable; they differed widely between (by 10-fold) and even within (by 3 to 55-fold) sites. At a regional scale, Corg was controlled by seagrass complexity, fine sediment fraction, and seawater depth. Autochthonous material (seagrass-derived material and large infauna) contributed to 78% of the total Corg in seagarss-vegetated sediments and the remaining 22% originated from outside the habitat (e.g. phytoplankton, drift algae Pilayella littoralis, and other macroalgae). However, relic terrestrial peatland material, deposited approximately 6000 years ago,during the last deglaciation, was an unexpected and significant source of Corg.

In order to make these measurements useful, we convert these to $CO_2$ equivalent units and provide a conservative up scaling of these carbon stock measurements (integrated to 25 cm sediment depth, using a realistic 20% expansion for the range minima and optimistic 60% for the range maxima for negative emissions gained through future restoration activities). Collectively, German seagrass meadows in the Baltic Sea are currently (already existing seagrass area) preventing 8.14 Mt of future $CO_2$ emissions, and if we apply the average sequestration rate of Zostera marina reported in the literature, seagrasses in the Baltic Sea could sequester up to 103 kt $CO_2$ per year in negative emissions. Because Corg is mostly produced on site, and not imported from outside the boundaries of the meadow, the richness of this pool may be contingent on seagrass habitat health. Disturbance of this Corg stock could act as a large source of $CO_2$ emissions. However, the high spatial heterogeneity seen across the region warrant site-specific investigations to obtain accurate estimates of blue carbon, and a need to consider millennial timescale deposits of Corg beneath seagrass meadows in Germany and potentially other parts of the southwestern Baltic Sea.

## WORK PROGRESS

The extremely short period between funding decision and official start of the initiative led to a delayed start of the organic-soil related work (January 2020), which was soon thereafter affected by the first Covid lockdown and the much delayed return of the PI from the MOSAiC expedition. We compensated for these obstacles by stopping the time-consuming collection and processing of GHG exchange data from sources outside our direct control and focused on updated literature-sourced and own data instead. This compilation was then used as refined emission factors, which we then stratified by both management options (drained vs. rewetted) and land use pathways (cropland vs. grassland vs. forest, etc.) as planned in the proposal. By combining these stratified emission factors with a recent 30 m land cover / land use map based on multisource remote sensing images, we produced the envisioned national maps for a preliminary and synoptic evaluation of the mitigation potentials of organic-soil dominated landscapes. These mitigation potentials are explicitly expressed in the two components of avoidance and removal for clarity and transparency. The original goal of including $CH_4$ in the analyses was abandoned both in the interest of a timely delivery of the overall framework, which can now be continuously refined with additional data, and because of a Cluster-wide focus on $CO_2$ rather than $CO_2$-equivalents. Insecurity with regard to the continuation of the initiative led to the early departure of a critical project member and an additional reduction in efficiency while alternative personnel was identified and tasks and budget were shifted accordingly.

For carbon storage simulations in agriculture, a domain was set up which is based on the sampling grid for the German agricultural soil inventory. Additional gridded data on land use, fertilizer use, and soil data were implemented. Crop parameters were changed to reflect residue inputs. Climate data was aligned to the domain grid. The model was spun up and verified with observed or mapped data. First prognostic runs were made with business-as-usual and different land management option scenarios. There was a period of approximately three months, where the supercomputers at Jülich Research Center could not be used for simulations owing to cyber-attacks. Furthermore, CLM5 is only partially capable to reflect agriculture in Germany: options such as organic fertilizer application, tillage activities, and certain crops are not implemented. Additional simulations with more RCP scenarios are needed to confirm the presented trends, which would require substantial computing power.

The development of the database and web service started with an evaluation of available technologies and metadata extraction. Several feasibility studies with the raster array database were conducted together with rapid prototyping of the RESTful web service in order to optimize the workflow and service designs. After receiving the climate model data, they were rapidly ingested into the database and the middleware web service was implemented. Soil carbon data from CLM5 was delayed, but due to preparation of the soil carbon data workflow they were also ingested within a short time after it had been received. After the app design was finalized, the required data aggregations (mean values) were computed and uploaded to the database. REST service endpoints for accessing these data aggregates were added. All milestones were met with a short time delay. Some delays were encountered due to Covid-related work restrictions. There were no major unexpected technical problems. The long delay before the CLM5 simulation output became available created some issues with budget planning and time management, but these could be mitigated through temporary assignment of staff to other third-party projects. The project budget could be spent as planned. Due to COViD 19, the stakeholder engagement could not be deepened as envisaged at the planning and start of the project.

Late hiring also resulted in a delayed start on the research for AWI-Sylt. There was a general delay of AWIs project activities due to Corona-lockdown preventing fieldwork and laboratory access. Additional related research activities that could be conducted from home were added to the planned work as compensation (see secondary results). Salt marsh sampling proved to be challenging due to unexpected problems with compaction, and excessive amounts of time was spent optimizing sampling methods, which at the end succeeded, but caused delays. The selected field-sites for investigations of carbon-storage in seagrasses turned out to be highly bioturbated with very low carbon content. Consequently, the radio-isotope dating for determination of sediment accretion rates was discarded after consulting isotope dating experts. Sediment accretion rates in salt marshes are based on date from sediment-erosion bars, the data is made available to the project and implementation is ongoing.

At GEOMAR, there were also many delays with fieldwork due to the 2021 shut down. All field-work and carbon stock analyses have been completed. However, this fieldwork delay has seriously set back the more time-consuming items of the project. For example, carbon flux reconstructions from Pb210 and Cs137 measurements in the sediment are still pending. These samples (x25) take six weeks to mature in the lab and a minimum of one week each to measure in the gamma counter. While the instrument has been measuring Pb/Cs concentrations all summer, data will not be available until January 2022 for this phase of the project as reconstructions must then be modelled afterwards. The ongoing work is financed by other means, primarily by the GEOMAR base budget (position to Dr. A. Stevenson).

## SPECIAL FEATURES

Our maps of mitigation potentials in organic-soil-dominated landscapes in Germany provide a synoptic and spatially-explicit overview of the $CO_2$-related benefits of rewetting previously drained organic soils. While this map is a bit more preliminary than originally planned due to Covid effects and staff fluctuation, the continued refinement of the map will result in a product that is not only educational to the general public but also helpful for stakeholders assessing the mitigation potential of planned rewetting projects. Integrating long-term continuous measurements of carbon fluxes from TERENO and ICOS sites is essential to our refinement of emission factors and a special feature that goes beyond the usual methods for deriving emission factors. We also recognized the need for imagery time series at spatial resolutions higher than the current 30-m land cover/use map to reduce uncertainties in upscaled estimates of carbon emissions on organic-soil-dominated landscapes that are usually spatially heterogeneous and temporally dynamic. We have been exploring the latest burgeoning CubeSat multispectral images at very high resolution (5 m) to resolve the two major cofounding effects on carbon flux measurements, the temporal variations in environmental controlling factors and the spatial variations in surface types covered by eddy-covariance measurement footprints. Important progress has been made, but some further work is needed to estimate cover-specific fluxes and establish an improved upscaling procedure. Strategically, the benefits of the initiative so far have been to establish GFZ more solidly (because underpinned by Postdoc positions) in the peatland community and has resulted in invitations to and leading positions in two HorizonEurope and Green Deal proposals as well as an SFB TransRegio proposal.

We could simulate the combined effect of climate change and land management on soil carbon changes in space and time in agricultural soils in Germany. This can help stakeholders to make educated decisions on how agricultural activities can impact the soils in Germany, and how atmospheric carbon can be stored in agricultural soils. It can also help to estimate which management options are most likely to store high amounts of atmospheric carbon in which region in Germany. In addition, growers can investigate how land and crop management can affect soil organic matter changes over time in their local area. The major advantage of CLM5 is the possi-bility of regional to global simulations. This requires high computing power, which is facilitated by the JURECA and JUWELS supercomputer environment at the Jülich Research Center. This is a unique selling point for the Helmholtz Association, because it can provide the infrastructure for large-scale climate change simulations in agriculture. In addition, the further development of the CLM5 model for simulating agricultural activity for Germany improved the simulation out-comes for soil organic carbon. This will foster new scientific approaches on CLM5 simulations at the Agrosphere institute, FZJ.

We successfully deployed a modern web service architecture with a raster array database as a high-capacity data backend together with a RESTful middleware web service, which provides custom-tailored data products to the end-user soil carbon app. Compared with many implementations in the Earth system science domain, the automated workflow of this pilot study provides a very flexible and efficient service-based data storage, processing and provision, and the results can be transferred to future projects conveniently. In the work of the database, we have realized the concurrent storage and query of massive data based on geographic information, and data transmission and visualization based on different interactive formats. In the work of the middleware, we successfully realized the decoupling of the application front-end and the data back-end through data abstraction, and designed the interactive interface according to the data structure, which greatly reduced the consumption of computing resources. In addition, we provide a concise data inspection method through the server-side rendering technology. The most notable outcomes from these developments are the demonstration of feasibility of applying state-of-the-art IT technology to a domain specific data workflow, and a substantial automation upgrade compared to the traditional file-based approaches. When comparing the soil carbon app's concepts with other products with a similar aim, some unique features are:

- It provides gridded carbon and climate data, covering Germany, from land surface modelling and from the respective driving climate model data, using combinations of different land management and climate (RCP) scenarios in one product
- This enables to address "*two sides of the coin*" in one application, namely the aspects climate mitigation and adaptation with a focus on agriculture and in particular croplands
- It allows to address future perspectives, since projections of the coming decades are provided
- It provides user specific data exploration in a region of interest with pre-defined functions
- As users have access to the complete database of model results, custom-tailored analysis workflows can be easily developed based on the REST API interface

Our field surveys have shown the present carbon stock and the long-term organic matter burial in seagrass beds and salt marshes in the Wadden Sea. As the carbon storage potential especially of salt marshes is expected to be greatly affected under future climate conditions, we took our research within HiCAM a step further: a large-scale mesocosm experiment was conducted to determine future biomass production in salt marshes under higher $CO_2$ concentrations and in-creased temperature. As increased sea-level rise is also expected, making the marshes wetter, the measurements were carried out under waterlogged conditions in the low marsh and the pioneer zone. In response to increased $CO_2$ and temperature, the salt marshpioneer zone showed higher above-ground biomass, but no effect on belowground biomass. In response to increased temperature, the low salt marsh showed higher aboveground biomass. No significant effects on belowground biomass was found in the low marsh. However, there was a tendency towards lower belowground biomass under future conditions. In general, belowground biomass contributes directly to sediment carbon storage, whereas the contribution of aboveground bio-mass is unknown. Hence, the impact of future climate conditions on carbon storage based on the input from biomass production in marshes remains unresolved. Scientifically, our data has provided:

- The first account of carbon stocks beneath seagrass meadows in the German Baltic Sea and has also identified the source of carbon stored in these systems, including local ancient carbon hotspots from submerged forested peatlands.
- Sequestration rates for this species has not been well established globally as available data is consumed by large error margins. Our team is in the process of refining these numbers via a newly developed model. Our analyses will soon provide the first carbon sequestration rates for Zostera marina seagrass in the Baltic Sea (analyses are ongoing).

Due to our collaborations with Cluster 3 and discussions with local/federal government, our project has been very well received by the public and law makers:

- We have already received over 100 expressions of interest by citizen divers and diving associations who wish to help restore the Baltic Sea coast of Germany. From this, we have created a database to assemble citizen scientists (divers and snorkelers) to help with planting operations once we are ready to scale up our restoration activities. We consider this to be extremely important as one criterion to ensure permanence in the carbon certification process of these systems is to first ensure public acceptance and positive perception, which this has helped achieved.
- Seagrass blue carbon and their many other co-benefits are now on the national political agenda. Staff member Steffi Lemke, Green Party member of the German Bundestag, has specifically reached out to us to request information about seagrass restoration and blue carbon to include in their policy briefing for their upcoming coalition negotiations.
- Recently there was also the request by the Social Democratic Party Schleswig-Holstein to amend they election platform with respect to inclusion of seagrass conservation/restoration along with peatland protection as nature based solutions
- Our results were presented at a HELCOM workshop on the „Blue Carbon Potential in the Baltic Sea region“ on 17/18 November and provided baseline data to include such efforts also in the HELCOM context and policy agendas such as the Baltic Sea Action Plan.

## OUTLOOK ON FUTURE WORK

The potential for emission reduction by rewetting drained organic soils is significant, but further work towards a robust monitoring, reporting and verification system (MRV) is needed in order to provide accurate and rapidly updatable emission reduction estimates for these spatially complex, temporally dynamic, and essentially novel ecosystems. We are currently developing an approach to better disaggregate the ecosystem-scale flux measurements at spatially heterogenous peatland sites into cover-specific fluxes. These disaggregated cover-specific flux estimates will improve upscaled and spatially-explicit estimates of $CO_2$ avoidance and removal potentials at rewetted peatlands. As part of an MRV system it will help keep upcoming large-scale efforts of peatland rewetting (e.g. under the “Bund-Länder-Zielvereinbarung zum Klimaschutz durch Moorbodenschutz”) on track. Additionally, more direct observations from TERENO, ICOS, and other partner sites still need to be incorporated as originally planned and increased $CH_4$ emissions post-rewetting need to be accounted for and options to reduce these $CH_4$ emissions need to be identified.

Concerning the simulations of carbon storage in agricultural soils, further simulations are need-ed to verify the presented trends. Each RCP (representative concentration pathway) scenario requires a stand-alone spin-up of the model, which is computing-power intensive. Further improvements of CLM5 should be considered: implementing organic fertilizer application, tillage, and silage corn, among others. Both will substantially improve the simulation outcomes. Simulating other output variables such as crop yield, soil moisture, and soil nitrogen may broaden the aspect of climate change simulations. This may be of interest for other research groups within the Helmholtz Association or in universities, and may foster future collaborations in soil-crop-atmosphere interactions and climate change research.

The developed data provision workflow presents great expandability, especially in earth system science applications. Possible applications would be coupling other geographical or climate science related web apps for user friendly data visualization and knowledge transfer, or integrate itself into other grouped or clustered data workflows to enable cross node federated data storage and provision services. The good experience of using server side rendering for data visualization inspired us to further explore visualized workflow monitoring for Earth system data management. With some work on generalization, the HI-CAM software bundle consisting of the database backend, the web service middleware, and a monitoring tool can be transferred to other application scenarios so that Earth system scientists will be able to provide their data through such state-of-the-art concepts without the need of a detailed technical understanding. Although we have successfully mastered and used raster array database technology in this project, the employed software was not ideal because of inconvenient file-only ingestion approach, limited metadata types and occasional performance issues. Hence, a next level pilot study of evaluating modern NoSQL database technologies with standardized data structures, common query languages and in memory operations and high performance availability for storing and managing earth system data appears warranted. However, this would require a substantial investment in creating or adapting the geospatial service layer, which has been a major criterion for choosing the raster array database in the first place. Finally, this automated data provision workflow makes quick access to required data in other application domains via predefined interfaces possible. For example, machine learning applications on climate data currently retrieve data from raw data files and write results back in intermediate formats, which is a cumbersome process with little flexibility. Database and web-driven workflows may help in the future to build more efficient, automated and flexible domain specific machine learning workflows. The new prototype workflow from model simulation results to the app frontend can easily be extended with ensemble climate and land use model data to consider modelling uncertainty. It can also be transferred to other data and applications. The concept and guidelines for the stakeholder engagement can be transferred and used in future projects with a similar overall objective.

The research targeting carbon storage and carbon sequestration in Wadden Sea salt marshes and seagrasses was a major stepping stone for AWI-Sylt to be involved with a large consortium of German research institutions specifically targeting the mechanisms controlling carbon storage and sequestration in vegetated coastal ecosystem. The consortium work under the project sea4soCiety which is one of a total of six collaborative research consortia in the research mission of Deutsche Allianz Meeresforschung (DAM). Sea4soCiety will determine the quantity and quality of the „blue carbon“ stores in four different types of coastal ecosystems including the German North Sea and Baltic Sea coasts as well as the Caribbean and the Indonesian Sea. The research conducted in HiCAM on carbon storage and sequestration on the German coasts was an important precursor for the research-plans developed for the sea4soCiety-project facilitating a direct continuation of research in HiCAM, assuring implementation and usage of results and experience derived under the HiCAM project.

Dr. Ketil Koop-Jakobsen worked as a post-doc on the HiCAM P4.3 project. After the conclusion of the HiCAM project, Dr. Koop-Jakobsen will continue his research on related topics as part of the Faculty at the Marine Biological laboratory (MBL) in Woods Hole, MA. This has paved the way for a trans-Atlantic collaboration between AWI and MBL (MOU is being developed), which will facilitate a continuation of the research areas established at AWI, due to their involvement in the HiCAM project. This collaboration will continue research into the Carbon storage potential under future environmental conditions.

Scaling up restoration operations will also necessitate: changes in policies to allow resource managers to be more flexible and less conservative when issuing permits; optimization of restoration techniques (e.g. Sea-Store, ongoing); and overcoming the manpower bottleneck to scaling-up restoration activities nationwide via citizen science (e.g. "underwater community gardening" via dive groups along the Baltic Sea) and partnerships with industry (e.g. engineering seed planting robot via Kiel submarine engineer company, barges to scale up transplantation and overwintering of seeds via Kiel international shipping company). Also, there is a need to locate and map ancient submerged peat material via potential collaborations with colleagues at the State Archeology Department, CAU Geography Department, and diving associations of Schleswig-Holstein.

## EVENTS

- Visit of FZJ/IBG-3 and GERICS at Institut für Agrarklimaschutz / Thünen Institut 16th December 2019 in Braunschweig
- **Blome, T** (2020): Development of a „Soil Carbon App" for the agricultural sector – con-cept, Seminar Series for HI-CAM-Postdocs, 28. October 2020 (online)
- **El Zohbi, J** (2020): Development of a „Soil Carbon App" for the agricultural sector – stakeholder involvement, Seminar Series for HI-CAM-Postdocs, 28. October 2020 (online)
- **Sun, J** (2020): Net-Zero-2050 Soil Carbon App Data Flow, Seminar Series for HI-CAM-Postdocs, 11. November 2020 (online)
- **Dold, C** (2020): Mitigation potential of agriculturally used soils - CLM Simulations, Seminar Series for HI-CAM-Postdocs, 11. November 2020 (online)
- **Sun, J** (2021): A multi-layer web service architecture for HI-CAM Net-Zero-2050 Soil Carbon App, 5th Data Science Symposium, virtual event, https://portal.geomar.de/web/data-science-symposium.
- **Dold C**, Herbst M, Weihermüller L, Vereecken HJ (2021): Achieving Net-Zero $CO^2$ in Germany - the potential of carbon sequestration in agricultural soils, Eurosoil 2021, Geneva, Switzerland.
- **Dold C**, Herbst M, Weihermüller L, Vereecken HJ (2021): Carbon sequestration in agricultural soils as potential climate change mitigation strategy for Germany, ISMC Conference 2021.
- **"Soil Carbon App" development team: Netto-Null Cooperation meetings**
  Organizer: Tanja Blome (GERICS // Hereon)
  Several Dates starting May 2020 until October 2021, roughly monthly frequence
  Format: online
  Participants: App development team: C. Dold, M. Herbst (Forschungszentrum Jülich IBG-3), J. Sun, M. Schultz (Forschungszentrum Jülich JSC), T. Blome, D. Rechid (GE-RICS/hereon)
- **"Soil Carbon App" development team: Cooperation meetings with web agency**
  Organizer: Agency Kopfarbyte (*https://kopfarbyte.com/*)
  6 - 8 dates starting August 2021 until December 2021
  Format: online
  Participants: partners from Kopfarbyte, GERICS and JSC app development team
- **Dold C**, Herbst M, Weihermüller L, Vereecken HJ (2021): Achieving Net-Zero CO2 in Germany - the potential of carbon sequestration in agricultural soils, Eurosoil 2021, Geneva, Switzerland.
- **Dold C**, Herbst M, Weihermüller L, Vereecken HJ (2021): Carbon sequestration in agricultural soils as potential climate change mitigation strategy for Germany, ISMC Conference 2021.

- Invited talk: Li, Z., Scheffler, D., Coops, N.C., Leach, N., Weituschat, M., Sachs, T., 2021. Demonstrating the Generation and Application of Analysis Ready Data of Optical CubeSat Images at a Rewetted Peatland Site. Presented at the ARD21 Satellite Data Interopera-bility Workshop.

- OnlineCOP 26, Glasgow 2021: Organizers: Kalhori, A. & Sachs, T. Aram Kalhori on the panel entitled "Meeting our Sustainable Development Goals through an integrated car-bon management approach"; sub-theme: Nature-based solutions (e.g. peatland re-wetting)
  Date: 01 November 2021
  Format: online

- COP26 side event entitled "Climate change mitigation and adaptation through coastal ecosystems conservation and restoration". Session co-organizers: A Stevenson & TBH Reusch (speaker), with ICRS and Friendship - Blue Mangrove Fund.
  Date: 3 Nov 2021
  Format: hybrid (remote and in person)
  Location: Glasgow, Scotland
  Participants: 172 (international)

- GEOMAR 10years@Helmholtz. Speaker: A. Stevenson, talk entitled "Seagrass Blue Carbon in Germany: Climate mitigation via seagrass conservation and restoration"
  Date: 18 May 2022
  Format: in person.
  Location:Kiel
  Participants:>70

- Green Party expert briefing "Moore; Wälder, Seegraswiesen, Ökosysteme und ihre Rolle im Kampf gegen die Klimakrise". Poster presentation on "Seagrass Blue Carbon" by A Stevenson, P Schubert, TBH Reusch.
  Date: 10 Feb 2020
  Format: in person
  Location: Berlin (Parliament)
  Participants: >50

- International Marine Conservation Congress (IMCC6) session co-organizers „SSO-10 Esti-mating, protecting and enhancing the blue carbon potential of coastal oceans" by A Ste-venson & TBH Reusch, C Bertram (from IFW).
  Format: online
  Participants > 60

- Kiel Plant Centre online Symposia, session speaker: A. Stevenson, talk entitled "Seagrass conservation and restoration in Germany can help mitigate climate change"
  Date: 14 June 2021
  Format: online
  Participants: > 40

- Kieler Salon meeting. Speaker: A. Stevenson, talk entitled "Blue Carbon in Germany: Seagrass conservation & restoration for climate mitigation"
  Date: 4 May 2022
  Format: in person.
  Location: Kiel
  Participants: > 70

- VDST Tauchsport Landesverband Schelswig-Holstein E.V. annual meeting. Speaker: A. Stevenson, talk entitled “Seagrass conservation and restoration in Germany can help mitigate climate change”
  Date: 31 Oct 2021
  Format: in person
  Location: Kiel
  Participants: > 50

- Lions Club Kiel 70. Annual meeting. Speaker: TCÓ Corcora, slide preparations by A. Stevenson, talk entitled “Seagrass conservation and restoration in Germany can help mitigate climate change”
  Date: 7 Sep 2021
  Format: in person.
  Location: Kiel
  Participants: > 50

# CLUSTER I:
# NET-ZERO-2050
## Cross-cutting teamwork and publication overview

### AUTHORS

**Climate Service Center Germany (GERICS) | Helmholtz-Zentrum Hereon**
Daniela Jacob
Bettina Steuri

**Centers involved:**

GERICS Climate Service Center Germany
Eine Einrichtung des Helmholtz-Zentrums **Hereon**

# Cross-cutting teamwork and publication overview

## CROSS-CUTTING TEAMWORK

In Net-Zero-2050, a wide range of expertise was bundled across ten Helmholtz-Centers to develop science-based strategies and new ways of dealing with climate change and carbon-neutrality in Germany. To identify and align the existing competencies in the best possible way and to incentivize cross-cutting research among the five involved research fields (Earth & Environment, Energy, Information & Data Science, Key Technologies, Matter), it was jointly decided at the beginning of the project to develop and implement several supportive communication formats.

### Events

Several Cluster-specific events were held over the entire duration of the project. Each format pursued a specific goal and addressed different target groups within the project:

- Bi-weekly online seminar for postdocs (see box) to promote knowledge exchange across work packages and research fields.
- Monthly jour fixe for PIs to discuss strategic topics and trigger potential cross-cutting research activities within the upcoming POF IV period.
- Bi-annual project meetings to get a comprehensive picture of the status of the four projects and two case studies as well as to clarify organizational issues. Two of them took place in Hamburg (see figure), two of them were held online.
- Dialogue series (five workshops in total) to combine the expertise from the individual work packages and to ensure the transfer of knowledge to the overarching Cluster products developed in P1.1 (Netto-Null-2050 Wegweiser, Technology Assessment Matrix (TAM), Netto-Null-2050 Web-Atlas).

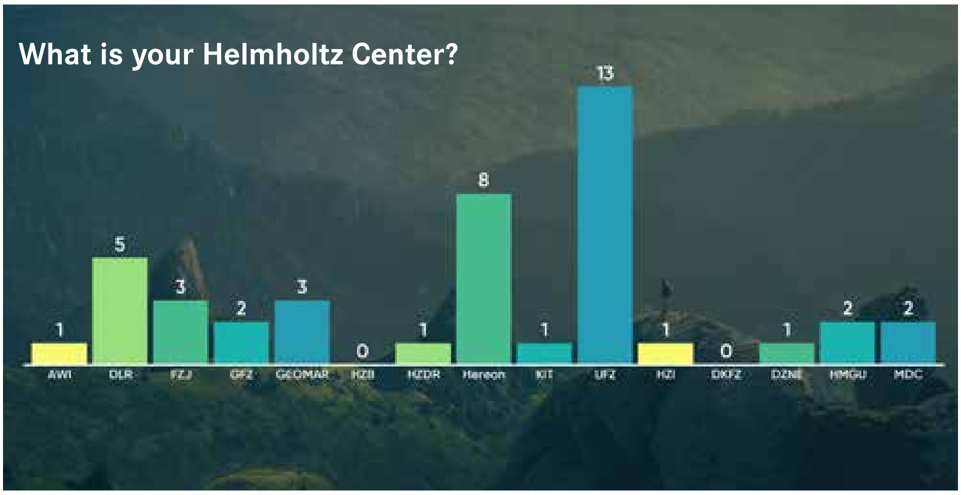
### Online Seminar Series for Postdocs

Each seminar involved two lectures by postdocs and early career scientists on their specific research topic, followed by discussion rounds and intermitting elements (usually “icebreakers” to get to know each other a bit better). The seminars aimed to open interactive discussions with regard to challenges – objectives – strategies for reaching a net-zero Germany, exchange ideas and data sets between different work packages and finally brainstorm future collaborations. Thus, the series was envisioned to be a fun and fruitful exchange across work packages, disciplines and research areas.

Cluster I initiated* the seminar series in September 2020; in April 2021 it was opened to postdocs** from the entire Helmholtz Climate Initiative and, thus, supplemented by the topics of adaptation and communication. All in all, 25 seminars took place; three of them were dedicated to external guests (Mojib Latif on “Experiences in Science Communication”, Torsten Sachs on the “MOSAiC expedition” as well as Noemi Bender and Bernhard Steinberger on “The Helmholtz Employee Initiative for a Climate-Neutral Helmholtz Association”).

* Committee Members: Malgorzata Borchers (UFZ), Aram Kalhori (GFZ), Nadine Mengis (GEOMAR), Bettina Steuri (GERICS // Hereon), Mengzhu Xiao (DLR)
** All members of the Clusters I, II and III that are (rather) at the beginning of their career.

The Netto-Null-2050-team at the second project meeting. It was held in Hamburg on February 18 and 19, 2020 (Source: GERICS).




The question "What is your Helmholtz Center?" was asked at the beginning of each online seminar to get an overview of the participating centers. On average, between 25 and 40 postdocs and early career scientists participated.


This figure shows the result of the icebreaker question "Where is your favorite place on earth?". Other questions included "What is your superpower?" and "What is your favorite season in Germany?".

## Documents

A document series called “Project Briefings” was initiated after the second project workshop. The aim of the project briefings was to clarify important building blocks for successful cooperation and to write them down for the entire Cluster. This included, for example, the clarification of the temporal and geographical system boundaries and the definition of "net-zero" or "net-zero $CO_2$ emissions" (#1), the derivation of the underlying carbon budget (#2), the definition of the scenario approach (#4) or an overview of stakeholder activities within Cluster I (#9). The following ***project briefings*** were written and posted on the website:

- **Structure of project 1 within the Cluster I Net-Zero-2050**
  *Daniela Thrän, Nadine Mengis, Matthew Mayer, Bettina Steuri, Andreas Oschlies, Sonja Simon, Malgorzata Borchers, Knut Görl*
  Project Briefing #1, 2021 (updated version)
- **Project Briefing #2 // Defining the German carbon budget**
  N*adine Mengis, Sonja Simon, Terese Thoni, Angela Stevenson, Knut Görl, Bettina Steuri, Andreas Oschlies*
  Project Briefing #2, 2021 (updated version)
- **Avoided and removed emissions**
  *Johannes Förster, Nadine Mengis, Eva Schill, Mengzhu Xiao, Daniela Thrän*
  Project Briefing #3, 2021 (updated version)
- **Defining the scenario approach**
  *Sonja Simon, Nadine Mengis, Knut Görl, Malgorzata Borchers, Bettina Steuri, Andreas Oschlies*
  Project Briefing #4, 2021 (updated version)
- **Overview of data sets - part 1 // How-to**
  *Bettina Steuri, Dominik Heß, Roland Dittmeyer, Christian Dold, Aram Kalhori, Judith Vesper, Christopher Yeates*
  Project Briefing #5, 2021 (updated version)
- **Klimaneutrale Stadt Karlsruhe: Bürger- und Stakeholderdialoge**
  *Markus Groth, Norbert Hacker, Eva Schill*
  Project Briefing #6, 2021 (updated version)
- **National Mitigation Roadmaps Worldwide**
  *Knut Goerl, Bettina Steuri, Sophia Kassim*
  Project Briefing #8, 2021
- **Stakeholder Activities within the Net-Zero-2050 Cluster in HI-CAM**
  *Juliane El Zohbi, Bettina Steuri, Christopher Ball, Ulrike Bernitt, Tanja Blome, Aljoscha Born, David Bruhn, Markus Groth, Fiona Köhnke, Nadine Mengis, Eva Schill, Swantje Preuschmann, Terese Thoni, Stefan Vögele*
  Project Briefing #9, 2021

## PUBLICATION OVERVIEW

### Scientific Publications [published]

- **A Pathway for the German Energy Sector Compatible with a 1.5 °C Carbon Budget**
  *Sonja Simon, Mengzhu Xiao, Carina Haprprecht, Shima Sasanpour, Hedda Gardian, Thomas Pregger*
  Sustainability, 2022, ***https://doi.org/10.3390/su14021025***
- **Comparison of heuristic methods for achieving minimum-cost capacitated networks with a new metaheuristic based on node valency**
  *Christopher Yeates, Cornelia Schmidt-Hattenberger, Wolfgang Weinzierl, David Bruhn*
  Networks and Spatial Economics, 2021, ***https://doi.org/10.1007/s11067-021-09550-9***
- **Determining Structure-Activity Relationships in Oxide Derived Cu–Sn Catalysts During $CO_2$ Electroreduction Using X-Ray Spectroscopy**
  *Laura C. Pardo Pérez, Alexander Arndt, Sasho Stojkovikj, Ibbi Y. Ahmet, Joshua T. Arens, Federico Dattila, Robert Wendt, Ana Guilherme Buzanich, Martin Radtke, Veronica Davies, Katja Höflich, Eike Köhnen, Philipp Tockhorn, Ronny Golnak, Jie Xiao, Götz Schuck, Markus Wollgarten, Núria López, Matthew T. Mayer*
  Advanced Energy Materials, 2021, ***https://doi.org/10.1002/aenm.202103328***
- **Electrocatalyst Derived from Waste Cu–Sn Bronze for $CO_2$ Conversion into CO**
  *Sasho Stojkovikj, Gumaa A. El-Nagar, Frederik Firschke, Laura C. Pardo Pérez, Léo Choubrac, Metodija Najdoski, Matthew T. Mayer*
  ACS Applied Materials & Interfaces, 2021, ***https://doi.org/10.1021/acsami.1c05015***
- **E-mobility from a multi-actor point of view: Uncertainties and their impacts**
  *Christopher Stephen Ball, Stefan Vögele, Matthias Grajewski, Wilhelm Kuckshinrichs*
  Technological Forecasting and Social Change, 2021,
  ***https://doi.org/10.1016/j.techfore.2021.120925***
- **Geochemical Changes Associated with High-Temperature Heat Storage at Intermediate Depth: Thermodynamic Equilibrium Models for the DeepStor Site in the Upper Rhine Graben, Germany**
  *Jonathan Banks, Spencer Poulette, Jens Grimmer, Florian Bauer, Eva Schill*
  Energies, 2021, ***https://doi.org/10.3390/en14196089***
- **Membrane-Assisted Methanol Synthesis Processes and the Required Permselectivity**
  *Homa Hamedi, Torsten Brinkmann, Sergey Shishatskiy*
  Membranes, 2021, ***https://doi.org/10.3390/membranes11080596***
- **Negativemissionstechnologien als neues Instrument der Klimapolitik: Charakterisiken und klimapolitische Hintergründe**
  *Till Markus, Romina Schaller, Erik Gawel, Klaas Korte*
  Natur und Recht, 2021, ***https://doi.org/10.1007/s10357-021-3804-8***
- **Negativemissionstechnologien und ihre Verortung im Regelsystem internationaler Klimapolitik**
  *Till Markus, Romina Schaller, Erik Gawel, Klaas Korte*
  Natur und Recht, 2021, ***https://doi.org/10.1007/s10357-020-3755-5***
- **Plant-Mediated Rhizosphere Oxygenation in the Native Invasive Salt Marsh Grass Elymus athericus**
  *Ketil Koop-Jakobsen, Robert J. Meier, Peter Mueller*
  Frontiers in Plant Science, 2021, DOI: 10.3389/fpls.2021.669751

- **Rigorous and Customizable 1D Simulation Framework for Membrane Reactors to, in Principle, Enhance Synthetic Methanol Production**
  *Homa Hamedi, Torsten Brinkmann*
  ACS Sustainable Chemistry & Engineering, 2021, ***https://doi.org/10.1021/acssuschemeng.1c01677***
- **Synergies between Direct Air Capture Technologies and Solar Thermochemical Cycles in the Production of Methanol**
  *Enric Prats-Salvado, Nathalie Monnerie, Christian Sattler*
  Energies, 2021, ***https://doi.org/10.3390/en14164818***
- **Towards analysis ready data of optical CubeSat images: Demonstrating a hierarchical normalization framework at a wetland site**
  *Zhan Li, Daniel Scheffler, Nicholas C. Coops, Nicholas Leach, Torsten Sachs*
  International Journal of Applied Earth Observation and Geoinformation, 2021, ***https://doi.org/10.1016/j.jag.2021.102502***
- **Deployment of Negative Emissions Technologies at the National Level: A Need for Holistic Feasibility Assessments**
  *Terese Thoni, Silke Beck, Malgorzata Borchers, Johannes Förster, Knut Görl, Alena Hahn, Nadine Mengis, Angela Stevenson, Daniela Thrän*
  Frontiers in Climate, 2020, ***https://doi.org/10.3389/fclim.2020.590305***
- **Ungrazed salt marsh has well connected soil pores and less dense sediment compared with grazed salt marsh: a CT scanning study**
  *Amr Keshta, Ketil Koop-Jakobsen, Jürgen titschack, Peter Mueller, Kai Jensen, Andrew Baldwin, Stefanie Nolte*
  Coastal and Shelf Science, 2020, DOI: 10.1016/j.ecss.2020.106987
- **The Potential of Depleted Oil Reservoirs for High-Temperature Storage Systems**
  *Kai Stricker, Jens C. Grimmer, Robert Egert, Judith Bremer, Maziar Gholami Korzani, Eva Schill, Thomas Kohl*
  Energies, 2020, ***https://doi.org/10.3390/en13246510***

## Scientific Publications [accepted]

- **Framework for assessing the feasibility of carbon dioxide removal options within the national context in Germany**
  *Johannes Förster, Silke Beck, Malgorzata Borchers, Erik Gawel, Klaas Korte, Till Markus, Nadine Mengis, Andreas Oschlies, Romina Schaller, Angela Stevenson, Terese Thoni, Daniela Thrän*
  Frontiers in Climate
- **Scoping CDR options for Germany – their potential contribution to Net-Zero $CO_2$**
  Malgorzata Borchers, Daniela Thrän, Yaxuan Chi, Nicolaus Dahmen, Roland Dittmeyer, Tobias Dolch, Christian Dold, Johannes Förster, Michael Herbst, Dominik Heß, Aram Kalhori, Ketil Koop-Jakobsen, Zhan Li, Nadine Mengis, Thorsten B.H. Reusch, Imke Rhoden, Torsten Sachs, Cornelia Schmidt-Hattenberger, Angela Stevenson, Terese Thoni, Jiajun Wu, Christopher Yeates
  Frontiers in Climate
- **How to develop new digital knowledge transfer products for communicating strategies and new ways towards a carbon-neutral Germany**
  *Swantje Preuschmann, Tanja Blome, Knut Görl, Fiona Köhnke, Bettina Steuri, Juliane El Zohbi, Diana Rechid, Martin Schultz, Jianing Sun, Daniela Jacob*
  Advances in Science and Research

- **Imagine atmospheric $CO_2$ as resource for renewable energy production - A European Energy Law perspective on direct air capture fuels**
  *Romina Schaller, Till Markus, Klaas Korte, Erik Gawel*
  Review of European, Comparative & International Environmental Law (RECIEL)
- **Net-zero $CO_2$ Germany - A retrospect from the year 2050**
  *Nadine Mengis, Aram Kalhori, Sonja Simon, Carina Haprrecht, Lars Baetcke, Enric Prats, Cornelia Schmidt-Hattenberger, Angela Stevenson, Christian Dold, Juliane El Zohbi, Malgorzata Borchers, Daniela Thrän, Klaas Korte, Erik Gawel, Tobias Dolch, Dominik Heß, Christopher Yeates, Terese Thoni, Till Markus, Eva Schill, Mengzhu Xiao, Fiona Köhnke, Andreas Oschlies, Johannes Förster, Knut Görl, Martin Dornheim, Torsten Brinkmann, Silke Beck, David Bruhn, Zhan Li, Bettina Steuri, Michael Herbst, Torsten Sachs, Nathalie Monnerie, Thomas Pregger, Daniela Jacob, Roland Dittmeyer*
  Earth's Future
- **SNG based energy storage systems with subsurface $CO_2$ storage**
  *Stefan Fogel, Christopher Yeates, Sebastian Unger, Gonzalo Rodriguez-Garcia, Lars Baetcke, Martin Dornheim, Cornelia Schmidt-Hattenberger, David Bruhn, Uwe Hampel*
  Energy Advances

## Other Publications

- **12 Schritte zur kommunalen Klimaneutralität**
  *Markus Groth*
  Short Report, 2021
- **Auf Tauchgang nach versteckten Klimaschützern**
  YouTube video, 2021, in collaboration with film maker Klaus Russell-Wells
  *https://www.youtube.com/watch?v=SqYHHKdqLDk*
- **Auswirkungen der Corona-Pandemie auf Bürger- und Stakeholderdialoge am Beispiel der Fallstudie Klimaneutrales Karlsruhe**
  *Markus Groth, Eva Schill*
  Short Report, 2022
- **Biodiversity and colonization success of newly restored seagrass meadows in the Kiel Bight**
  *M.B. Lehamann*
  M.Sc. student thesis, 2021, University of Kiel, co-supervisors: Angela Stevenson, T.C.Ó. Corcora, Thorsten Reusch
- **Comparing public perceptions of seagrass as a blue carbon measure in Ireland and the German Baltic Sea area.**
  *CÓ. Beoláin*
  M.Sc. student thesis, 2021, Justus Liebig Universität & University College Dublin, co-supervisors: Terese Thoni, Angela Stevenson
- **Neue digitale Formate für die Kommunikation von $CO_2$-Einsparungspotentialen für Deutschland**
  *Juliane El Zohbi, Swantje Preuschmann, Tanja Blome, Christian Dold, Fiona Köhnke, Bettina Steuri, Jianing Sun, Diana Rechid, Martin Schultz, Daniela Jacob*
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  Conference contribution (video) at EMS Annual Meeting, 2021,
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- **Kommunaler Klimanotstand – Eine Kurzübersicht aus rechtlicher Perspektive**
  *Benjamin Julius Groth, Markus Groth, Steffen Bender*
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- **Politische Rahmenbedingungen, Instrumente und Maßnahmen zur Erreichung von $CO_2$-Neutralität: Eine Synthese ausgewählter Studien für Deutschland**
  *Knut Görl, Markus Groth, Bettina Steuri, Sonja Simon, Stefan Vögele, Daniela Jacob*
  Report, 2021
- **Regionale Differenzen: Herausforderung und Chance für Netto-Null 2050 in Deutschland**
  *Imke Rhoden, Stefan Vögele, Christopher Ball, Wilhelm Kuckshinrichs, Sonja Simon, Nadine Mengis, Lars Baetcke, Christopher Yeates, Bettina Steuri, David Manske, Daniela Thrän*
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- **Spatial Heterogeneity - Challenge and Opportunity for Net-Zero Germany**
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- **Direct Air Capture**
  *Dominik Heß, Roland Dittmeyer,* Factsheet #04, 2020
- **Wasserstoff**
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- **GERICS coordinates scientific underpinning for a $CO_2$-neutral Germany**
  *Bettina Steuri, Daniela Jacob*
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- **Nutzung von $CO_2$ aus Luft als Rohstoff für synthetische Kraftstoffe und Chemikalien**
  *Dominik Heß, Michael Klumpp, Roland Dittmeyer*
  Studie im Auftrag des Ministeriums für Verkehr Baden-Württemberg, 2020
- **Scenario definition and consistent parametrization of all models**
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- **Seagrass and carbon storage**
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  *Markus Groth, Lea Griesing, Bettina Steuri*
  Online Synthesis, 2020
- **Zum regulatorischen Rahmen direkter Abscheidung von Kohlendioxid aus der Luft (Direct air capture – DAC)**
  *Till Markus, Romina Schaller, Klaas Korte, Erik Gawel*
  Short Report, 2020
- **BIPV: More than the module**
  *Björn Rau*
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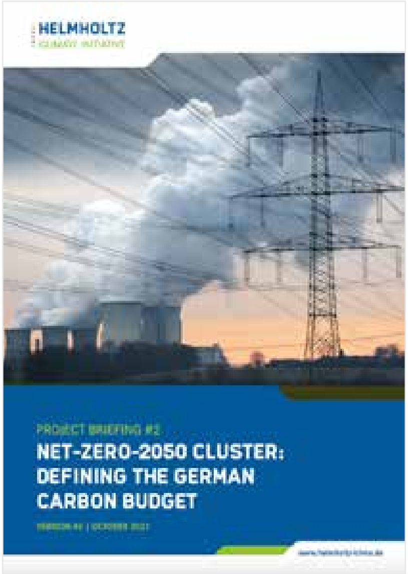
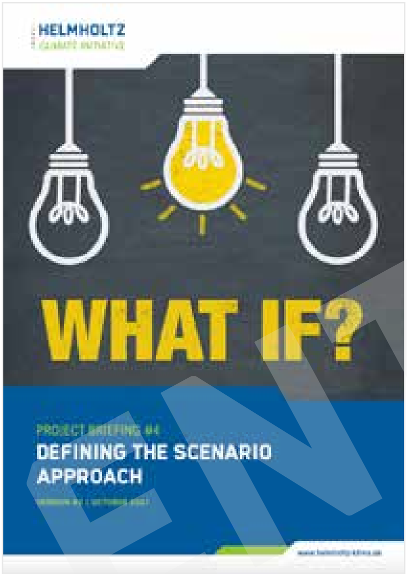
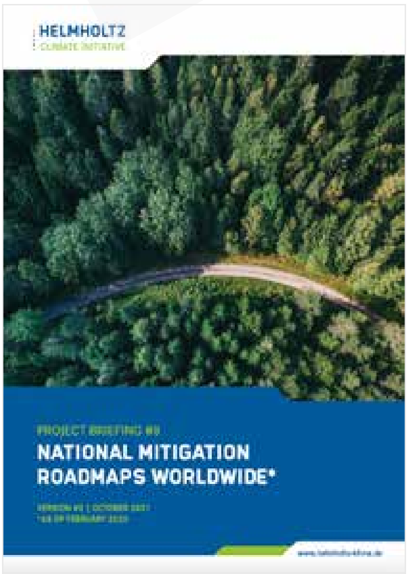
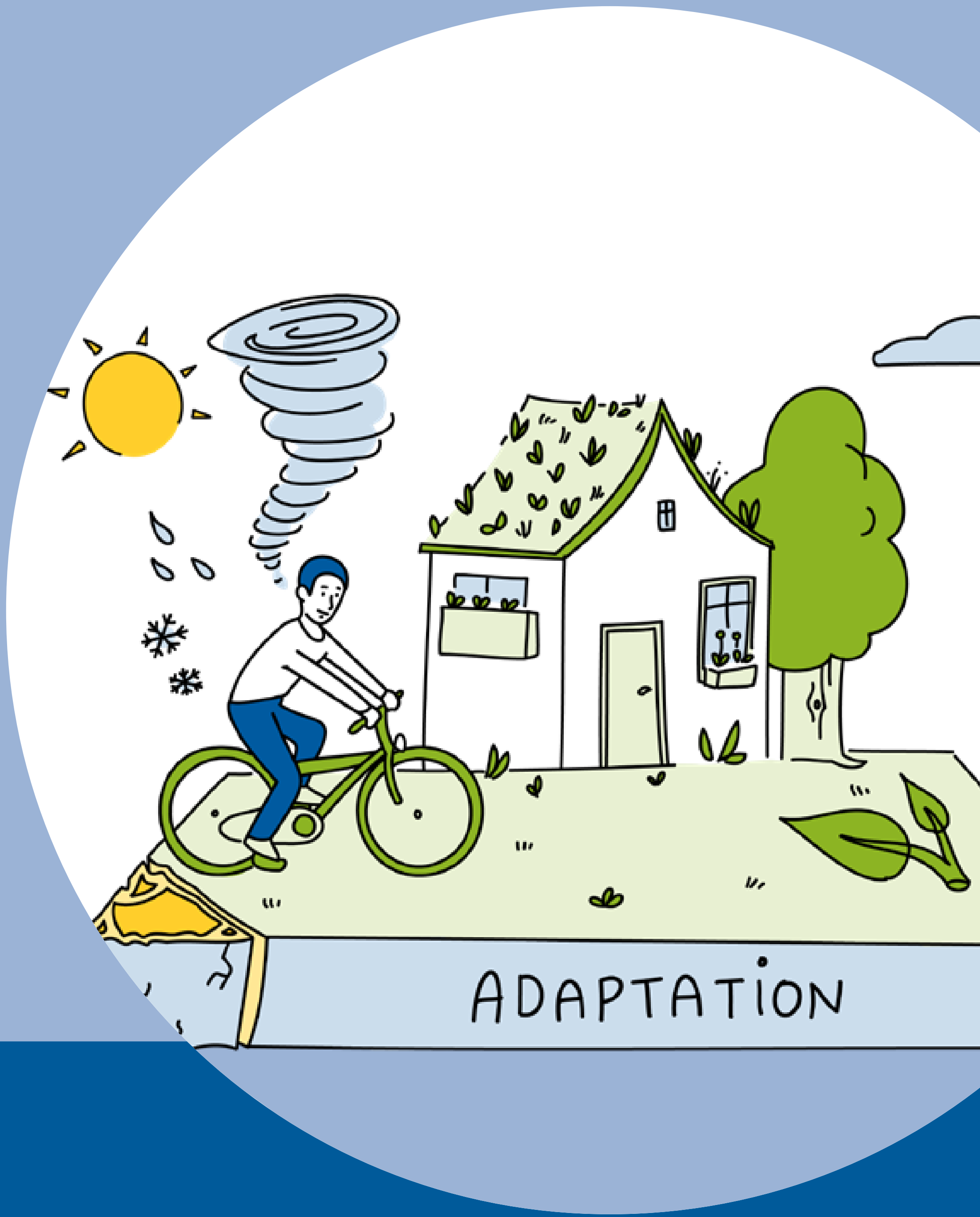



## PROJECT BRIEFINGS

- **Structure of project 1 within the Cluster I Net-Zero-2050**
  *Daniela Thrän, Nadine Mengis, Matthew Mayer, Bettina Steuri, Andreas Oschlies, Sonja Simon, Malgorzata Borchers, Knut Görl*
  Project Briefing #1, 2021 (updated version)
- **Project Briefing #2 // Defining the German carbon budget**
  *Nadine Mengis, Sonja Simon, Terese Thoni, Angela Stevenson, Knut Görl, Bettina Steuri, Andreas Oschlies*
  Project Briefing #2, 2021 (updated version)
- **Avoided and removed emissions**
  *Johannes Förster, Nadine Mengis, Eva Schill, Mengzhu Xiao, Daniela Thrän*
  Project Briefing #3, 2021 (updated version)
- **Defining the scenario approach**
  *Sonja Simon, Nadine Mengis, Knut Görl, Malgorzata Borchers, Bettina Steuri, Andreas Oschlies*
  Project Briefing #4, 2021 (updated version)
- **Overview of data sets - part 1 // How-to**
  *Bettina Steuri, Dominik Heß, Roland Dittmeyer, Christian Dold, Aram Kalhori, Judith Vesper, Christopher Yeates*
  Project Briefing #5, 2021 (updated version)
- **Klimaneutrale Stadt Karlsruhe: Bürger- und Stakeholderdialoge**
  *Markus Groth, Norbert Hacker, Eva Schill*
  Project Briefing #6, 2021 (updated version)
- **National Mitigation Roadmaps Worldwide**
  *Knut Goerl, Bettina Steuri, Sophia Kassim*
  Project Briefing #8, 2021
- **Stakeholder Activities within the Net-Zero-2050 Cluster in HI-CAM**
  *Juliane El Zohbi, Bettina Steuri, Christopher Ball, Ulrike Bernitt, Tanja Blome, Aljoscha Born, David Bruhn, Markus Groth, Fiona Köhnke, Nadine Mengis, Eva Schill, Swantje Preuschmann, Terese Thoni, Stefan Vögele*
  Project Briefing #9, 2021




# CLUSTER II

# Adaptation to extreme events

by Prof. Dr. Georg Teutsch | Dr. Andreas Marx, 31.03.2022

## INTRODUCTION

The Helmholtz Climate Initiative started in 2019 in order to be able to make better use of the diverse knowledge in the Helmholtz Association for climate adaptation through cross-centre cooperation. In the adaptation part, the very large improvements in process knowledge in recent years, the immense progress in computing power and the massive increase in the availability of high-quality data from innovative sensors and remote sensing enabled the development of robust future images with a high level of detail. The combination of large-scale climate models and detailed local impact models was key to this initiative. Particular attention was paid to extreme situations and the derivation of adaptation measures.

Extensive data and information were produced in a total of nine sub-projects, which were successfully incorporated into communication, the derivation of concrete products and the work of stakeholders. **Fig. 1** provides an overview of the sectors being investigated. The drivers project combined existing as well as novel scenario-based simulations focusing on natural drivers and climate change projections emphasizing European extreme events simulated with impact models. Based on that, the first of the urban areas projects looked into existing and future scenarios and impacts of urban extreme heat, drought and wind using urban heat transport and wind models – the aim being to develop adaptation options. The second urban project focused on urban flash floods and sewerage. There, not the drought conditions but the frequency and intensity of heavy rainfall and the relation to atmospheric blocking have been analysed. The project looked into the entire effect-chain and aims at a catalogue of adaptation measures including structural and non-structural measures. In parallel, the mobility project analysed how future mobility is affected in rural and urban areas, and calculated related emissions and the total energy consumed. In the first health project, infectious diseases and allergies, ecologically explicit data and system modelling for health-cases like tick-borne borreliosis as well as data from models have been used with regard to pollen and spores as well as the correlation between thunderstorms and asthma attacks. The second health project covered impacts on health in NAKO & Rhineland study. Urban and rural heat maps, a wind and dust generation model and epidemological data have been used to analyse the impact of extreme weather on cardiovascular, metabolic and cognitive functions, mental health, assess the prevalence of lyme disease as well as explore the effects on infectious disease antibodies. In one of the two rural area projects, the agricultural and aquatic systems has been analysed, the aim being to quantify the impact on todays farming and soil functions as well as the change of aquatic systems and related water quality in the river systems.

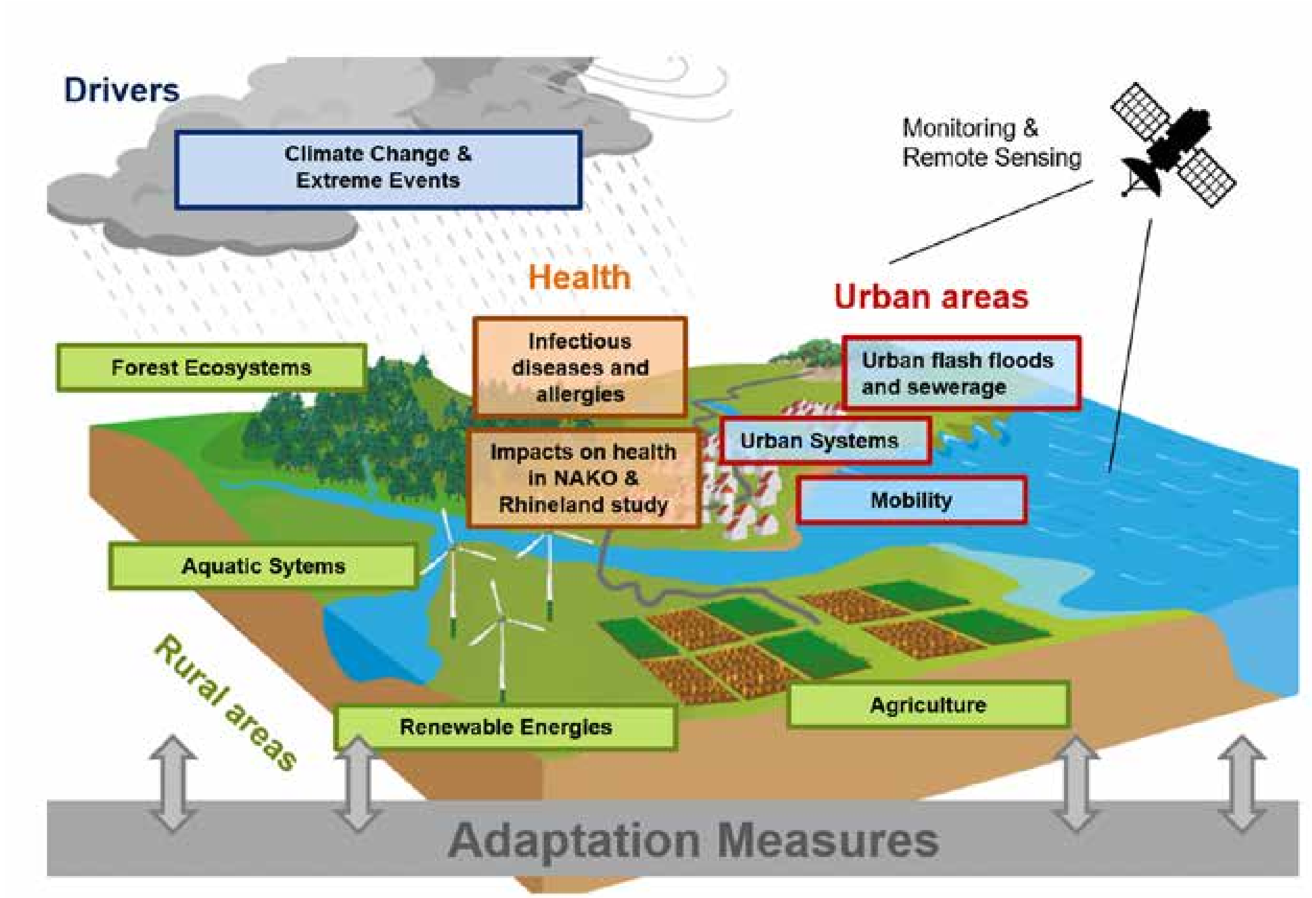



**Figure 1**: The nine adaptation projects in the landscape framework and thematic summary into the four adaptation sub-chapters in this report.

In the second rural project, the impact of extreme events on forest systems, which cover 30% of entire Germany has been analysed. In specific, the change in fluxes of forest systems under extreme drought conditions, turning them from a carbon sink to a carbon source is considered critical. Forest models have been used to assess future strategies regarding the development of stocks and productivity for a variety of German forests, derived from inventories and remote sensing data. Finally, the power generation from volatile renewable energies (VRE) project investigated the effects of extreme events on the provision of VRE from terrestrial and offshore areas and associated effects on power supply and demand.

In the following, the nine adaptation projects have been grouped into four sub-chapters, covering drivers and extreme events, urban systems, health impacts and adaptation and rural areas.

# CLUSTER II:
# HI-CAM-ADAPTATION
## The Drivers project

**Centers involved:**

ALFRED-WEGENER-INSTITUT HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel

KIT Karlsruher Institut für Technologie

UFZ HELMHOLTZ Zentrum für Umweltforschung

JÜLICH Forschungszentrum

GERICS Climate Service Center Germany
Eine Einrichtung des Helmholtz-Zentrums Hereon

# The Drivers project: Changes in atmospheric and terrestrial extreme events

The changes of the jet stream and thus the change of extreme events have been investigated methodically at AWI, GEOMAR and KIT as well as transferred into storylines and published. A series of jet stream diagnostics were developed at GEOMAR to compare reanalysis and model data. This involved repeated 100-year AMIP-style model simulations with 2018 heat and drought conditions and scenarios of 1.5-2-3 and 4 K global warming. Through collaboration with AWI, the potential for an idealized study of two-way ocean-atmosphere interaction was identified. Exten-sive media work was carried out by the AWI, as well as exchanges with stakeholders (including e.g. Vattenfall). Ocean boundary data (sea surface temperatures and sea ice coverage) from transient AWI climate integrations have been used in the project “Jet streams under climate change: Time slice experiments with ICON-ART” at KIT to produce ensemble quasi-equilibrium climate simulations for certain target years that correspond to threshold warmings detected in the AWI integrations. The data allow the comprehensive estimation of probability density func-tions of atmospheric climatic states in a warmer world and are available to all partners.

HI-CAM generated an extensive climate impact dataset on the water budget in the first phase. A climate-hydrology reference ensemble consisting of 88 simulations under three climate scenari-os was created at the UFZ, which is already being used in follow-up orders for the German Tech-nical and Scientific Association for Gas and Water (DVGW), among others, and will thus be the reference for water supply in Germany.  At FZJ, a consistent, coupled surface-groundwater cli-mate impact simulation was also contributed.

For the first time in Germany, a kilometer-scale high-resolution bias-adjusted climate ensemble was created in cooperation between GERICS and UFZ. In addition, GERICS provided the required climate data in the adaptation subprojects. Non-specialist Helmholtz scientists were advised and supported in the interpretation, possibilities and limitations of climate simulation data.

# Storylines of recent extreme events in a coupled climate model with atmospheric nudging

**Authors: Sánchez-Benítez, A.[1], Goessling, H.[1], Pithan, F.[1], Semmler, T.[1], Jung, T.[1,2]**
Affiliation(s): [1] Alfred Wegener Institute Helmholtz-Center for Polar and Marine Research, Bremerhaven,
[2] University of Bremen, Institute of Environmental Physics, Bremen.
Email (Corresponding Author): antonio.sanchez.benitez@awi.de

## INTRODUCTION

Europe has recently experienced several exceptional extreme events such as the July 2019 heatwave, which redrew the temperature record map of western and central Europe, or the July 2021 floods in Central Europe, which killed more than 200 people and is expected to have caused damages in excess of 30 billion €. There is consensus that large-scale dynamics, associated with meandering of the jet stream, are the main trigger of such events. However, thermodynamic processes and the previous state of different components as the soil moisture or sea surface temperature also have an important contribution to exacerbate them (e.g., Sánchez-Benítez et al., 2018; Wehrli et al., 2018; Van Garderen et al., 2021).

Climate models and observations have been used to quantify how the odds of extreme temperatures or precipitations during specific events have changed from the past and how they will change in the future (e.g. Vogel et al. 2019). Despite some obvious successes of this probabilistic approach, as argued by Shepherd (2016), it has some limitations: a) projected changes of the polar jet stream in a warmer climate are still highly uncertain; b) it is rather challenging to find good analogues that capture the temporal evolution of all components of the system prior the extreme event; and c) the probabilistic approach does not make the anticipated changes in a warmer world readily accessible to the general public and decision-makers.

In contrast, in this project we explore a new deterministic storyline approach, where these extreme events are simulated in alternative past and plausible future climates, using a coupled climate model in which the large-scale dynamics from some years before the event are nudged towards reanalysis data. So, we make the climate change impact more tangible to scientists, decision-makers, and the general public.

## DATA AND METHODS

In this work, for the first time, this approach has been applied using a coupled model, as our simulations are based on the Alfred Wegener Institute Climate Model (AWI-CM-1-1-MR, Semmler et al. 2020), which has contributed to CMIP6. We have used spectral nudging to impose the observed large-scale atmospheric circulation for certain vertical layers using divergence and vorticity from ERA5 (Hersbach et al. 2020). See Sánchez-Benitez et al. (2021) for more details on the nudging configuration. We have run nudged storyline experiments from 1st January 2017 to 31st July 2021 in pre-industrial, present, 2 and 4K warmer climates. For each of them, a five-member ensemble has been produced.

## RESULTS

Before we turn to a quantitative analysis, we have verified that our methodology generates excellent analogues of these exceptional events (**see one example in Figure 1**). First of all, we have verified that our methodology does not only work well for single extreme cases; more generally, it also captures daily to seasonal variability in Europe, with sizeable correlations for critical variables that are not nudged in our simulations.

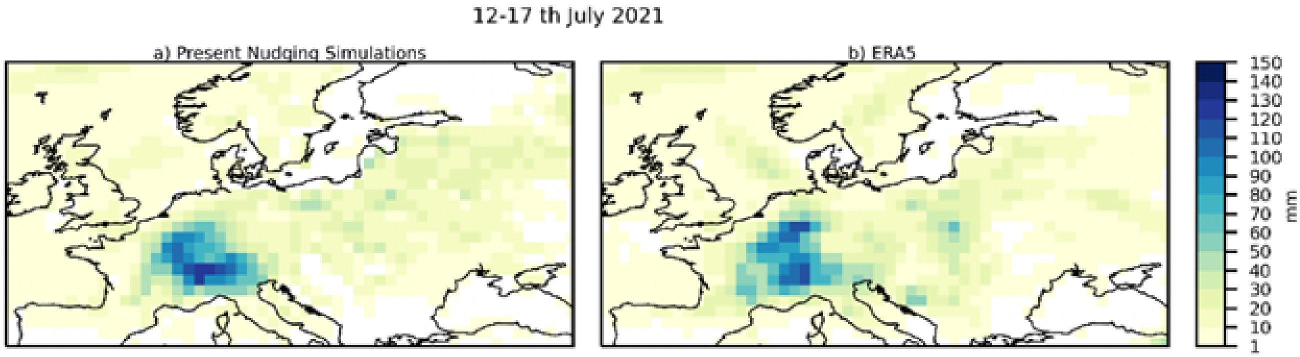



**Figure 1**. Accumulated precipitation between 12th to 17th July from our present-day nudging experiments (left) and ERA5 remapped to the model resolution (right).

Next, we analyze how these extreme events might have evolved in pre-industrial times and how they might unfold in future 2 and 4K warmer climates (see more details in Sánchez-Benítez et al. 2021). In Germany, the July 2019 heatwave peak (**Figure 2**) would be around 5.5K warmer in the 4K warmer world (0.8K in the +2K climate) and is now around 2.0K warmer than in the pre-industrial climate. Hence, there is evidence for global warming amplification in phase with this event, particularly in the 4K warmer climate (2-fold increase), sugge-sting that there might be some feedback mechanism generating a higher than expected warming in the future. Be-sides, anomalously strong warming signals can be found locally in some regions (e.g., northeastern Spain or southwestern France), with up to 10 K for the difference between 4K warmer and present-day climates.

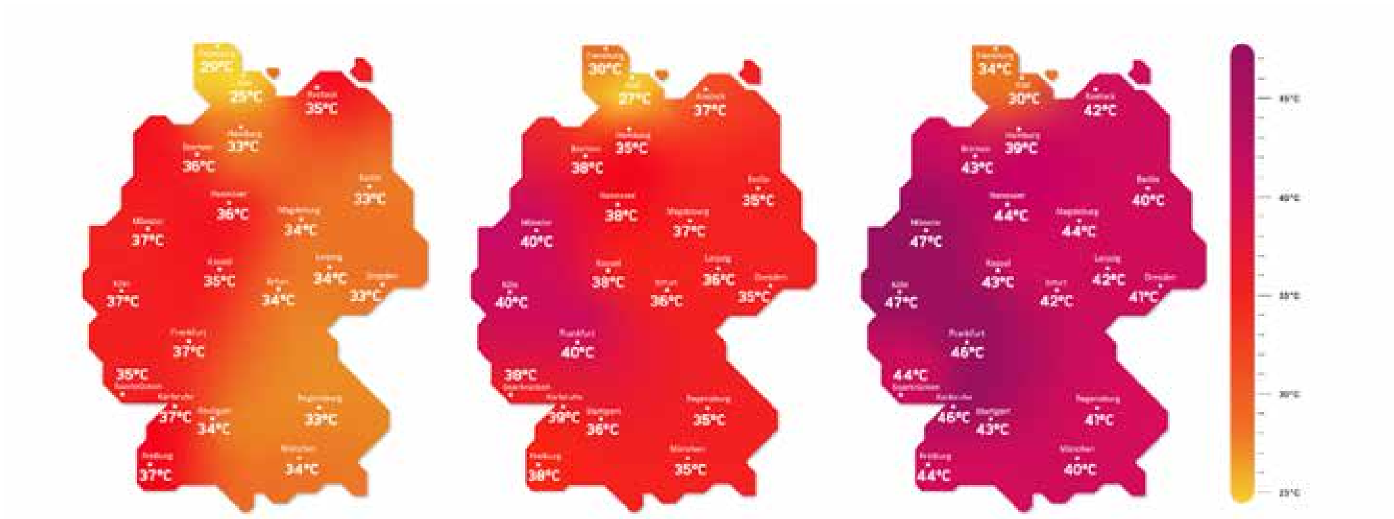


**Figure 2**. Schematic maps of 2m temperature for weather conditions in Germany at 1500 UTC on 25 July 2019: (left) for a pre-industrial climate, (middle) present-day conditions, and (right) a 4K warmer world. The maps have been produ-ced by graphic designers of the communication team of the Helmholtz Climate Initiative.

## CONCLUSIONS

This study presents a new methodology for computing storyline scenarios using spectral nudging in a coupled climate model. This methodology helps to illustrate how recent extreme events such as the July 2019 heatwaves or the July 2021 floods would have evolved in a pre-industrial climate and how they would evolve in the future depending on our climate action. We have quantified that if the July 2019 heatwave would have happened in a pre-industrial climate, the most extreme temperatures would have remained well below 40°C. The fact that record-breaking temperatures (with values around 42°C in some places) were observed, therefore, can be clearly attributed to anthropogenic warming. Meanwhile, in a future 4K warmer world temperatures nearing 50°C in heat waves can be expected in Central Europe.

The value of this approach for understanding and communicating the impact of climate change could be further enhanced by using these storylines scenarios to drive impact models.

### Data Availability statement

Data from the AWI-CM-1-1-MR free runs are available in the Earth System Grid Federation (ESGF) data nodes (e.g., ***https://esgf-data.dkrz.de/search/cmip6-dkrz***/; see "Source ID," etc.). The nudging experiments are stored in the supercomputer Levante from DKRZ and are available online (Zenodo: ***https://doi.org/10.5281/zenodo.6348822***). ERA5 reanalysis data used in this study can be accessed from the European Center for Medium-Range Weather Forecasts (ECMWF; ***https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5***).

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# Drivers of jet stream anomalies

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## INTRODUCTION

The aim of the project is to understand how heat waves over Europe are generated and which jet stream conditions favor them. A special focus lies on the summer of 2018 as one of the most recent and extreme heat waves that Europe endured. A systematic analysis of the jet stream in reanalysis will be carried out and compared to FOCI climate model simulations (Matthes et al., 2020).

Model experiments include the reanalysis historical period 1980-2019, and time-slices with repeating 2018 conditions as well as 1.5-2-3-4K global warming scenarios.

Our initial approach focused on two main studies: Duchez et al. (2016), who found low N. Atlantic SSTs related to the 2015 European heatwave via a trough-ridge couplet, an SST pattern very similar to that found later in the 2018 summer; and Kornhuber et al. (2019), who related the 2018 heatwave to a stationary wave pattern in the jet stream, amplified via resonance, and hinted at the stationary wave being in phase with the above-mentioned SST anomaly in the N. Atlantic.

One scientific goal was to establish the validity of the following hypothesis, relating N. Atlantic SSTs that force an anomalous Jet stream wave pattern, which in turn bring long-lasting anticyclonic conditions downstream over Europe.

## DATA AND METHODS

ERA5 upper tropospheric winds and geopotential, 2m temperatures, SST, sea ice concentration. AMIP-style simulations with the FOCI model at T63 resolution (whose atmospheric component is ECHAM6) were performed at HLRN Berlin, prescribing SSTs and sea ice taken from ERA5.

The collection of runs listed as deliverables include: the historical period 1980-2019, a time-slice with 2018 conditions (repeated for 100 years), and 1.5-2-3-4K global warming scenarios with 2018 SST anomalies superimposed and also repeated for 100 years. Such settings permit a good statistical analysis of the occurrence of 2018-like heatwaves in future scenarios.

ERA5 and ECHAM6 model results are intercompared with the following diagnostics:

- Jet stream latitude/strength compositing with low-high SSTs, sea ice, T2max.
- Wave diagnostics: amplitude, speed, position composited in the same way.
- Heat wave (e.g. heatwave days/year) and extreme value (e.g. Tmax 20-year return event) statistics.

## RESULTS

All simulations fulfilling the project's deliverables were completed during 2021. Also an additional ECHAM6 T127 historical simulation was performed for comparison, and a 2nd and 3rd ensemble members of T63 historical period will be run before the end of 2021 for improved statistics.

An example comparing heatwave occurrence in ERA5 and various ECHAM6 simulations done within HI-CAM is shown in Figure 1. Historical (1980-2019) and repeated (x100) 2018 simulations show 5-10 heatwave days per year, a range that increases to 30-60 days in the +4K global warming scenario (note the different color scale). An underestimation of heatwave occurrence in central Europe by ECHAM compared to ERA5 can also be seen. The high occurrences over Scandinavia are because no fixed temperature threshold is used – different heatwave definitions will be tested.

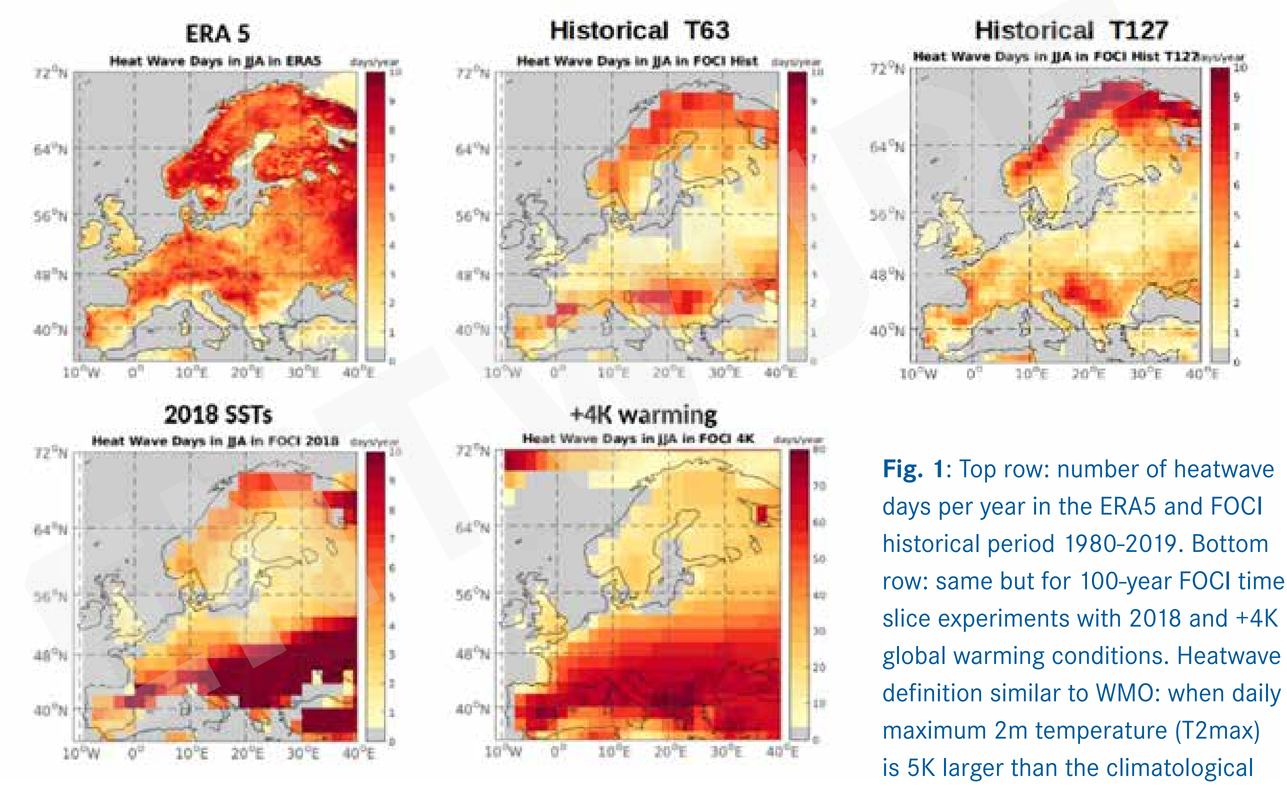


**Fig. 1**: Top row: number of heatwave days per year in the ERA5 and FOCI historical period 1980-2019. Bottom row: same but for 100-year FOCI time slice experiments with 2018 and +4K global warming conditions. Heatwave definition similar to WMO: when daily maximum 2m temperature (T2max) is 5K larger than the climatological average (1980-2019) for at least 5 consecutive days, a heatwave day is counted within summer JJA months. © Sabine Bischof (2021).

Analysis of the FOCI data is ongoing and at least one publication is planned for 2022. We've composited jet stream position, strength, and its undulation properties (wave amplitude, speed and position at different scales) with heatwave occurrence over Europe, N.Atlantic SSTs and Arctic SIC (with and without detrending), comparing FOCI results to ERA5. No consistent relations have been found yet across all datasets, and instead of wave stationarity with colder N. Atlantic SSTs, we rather encountered recurrent travelling waves similar to those described by Röthlisberger et al. (2019) during the 1994 summer. Thus we can state that **our initial hypothesis was refuted**.

## CONCLUSIONS AND OUTLOOK

We identified the need to account for tropospheric expansion when diagnosing jet stream properties and trends, therefore the current effort is on obtaining winds on the 2PVU surface – or the dynamical tropopause (instead of a fixed pressure level) from FOCI model level data. With this novel approach the processed data will show Jet stream anomalies that are not an artifact from it moving vertically, which should reduce noise and increase the robustness of the results.

Follow-on work on the topic will continue in 2022 using internal funding. We envision additional simulations with higher resolution T127 to also compare warming scenarios at different resolutions and find which anomaly structures are robust and not resolution-dependent.

Another interesting addition to the 2018 case study would be a 100-year experiment with repeating (x100) 2021 conditions, to study statistics about the extreme American NW and Medi-terranean heatwaves that occurred that summer.

### Data Availability (or) Available Information

Data from all our model simulations is available upon request.

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# Jet streams under climate change: Time slice experiments with ICON-ART

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## INTRODUCTION

Climate change is caused by emissions of carbon dioxide and other greenhouse gases into the Earth's atmosphere. Greenhouse gases absorb and store the heat radiated from the Earth leading to the increase in surface temperature. The major effect is not only heating of the lower atmosphere but also of the ocean – potentially lowering Earth's surface albedo when sea-ice is lost. In addition, the stratosphere will cool and thus meridional temperature gradients at all altitudes – from the surface throughout the stratosphere – might change. This structural change may impact the configuration of the jet streams. In this study we focus on the link between climate change and jet streams, including strengths, position and variability. To carry out this objective, we use the ICON(-ART) global modelling system (Zängl et al. 2015; Rieger et al. 2015; Schröter et al. 2018) in time-slice integrations for given time horizons that correspond to the exceedance of some critical temperature thresholds. The model was applied using recent and future emission conditions. The results of our study reveal how the jet stream responds to the tropospheric warming and the stratospheric cooling and how wave driving is a possible underlying mechanism in moderating the modelled jet changes.

## DATA AND METHODS

Time-slice experiments are useful tools to investigate sensitivities in the climate system (e.g. Braesicke et al. 2013) and help to understand the robustness of certain changes under "global warming". Such simulations have been configured and performed here. We present results from three simulations, using ICON-ART with a global resolution of 160km and integrating the model for 50 years/realizations. Here, the ICON-ART model uses the same basic settings as for AMIP-type runs. However, the transient boundary conditions are replaced with annually invariant ones. First, we start with a run for the recent past by performing a time-slice experiment with the recurring boundary conditions for the year 2000. Then, we performed another two simulations for the years 2040 and 2090 under the following assumptions: 1) the forcing, e.g. the increase of the atmospheric $CO_2$ and other greenhouse gases (GHG) was chosen in accordance with the RCP8.5 mixing ratio suggestions (based on years that exceeded threshold temperatures in a transient integration with the CMIP6 AWI-CM-1-1-MR (Semmler et al. 2020) the sea surface temperature (SST) and sea ice (SIC) were taken from the same transient CMIP6 AWI-CM-1-1-MR integration that is based on the SSP370 scenario.

## RESULTS

**Figure 1** shows the time-series of annual-mean global-mean 2m-temperature from the 2000 run and the future runs simulating the "global warming" at two different time horizons. For the recent-past run (2000) we obtain a realistic increase of the near surface temperature (0.9 °C) compared to the known historical baseline. The projected changes in temperature from the future runs are predicted – by definition of the experimental design – to rise by approximately 2K and 4K by the years 2040 and 2090, respectively. These data demonstrate that our simulations are well specified with respect to the threshold temperatures chosen and that the amount of warming modelled in ICON-ART corresponds to the results of the AO-GCM that supplied the boundary conditions.

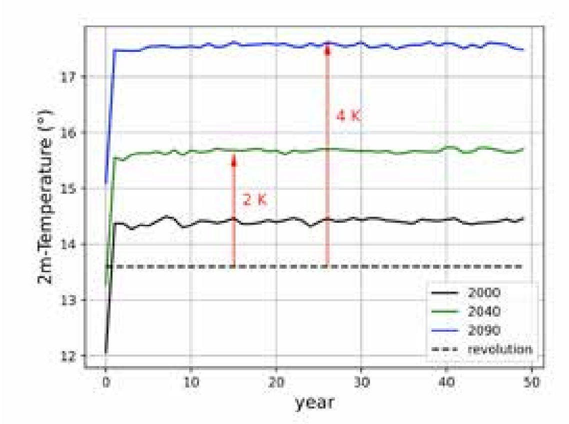


**Fig. 1** Time-series of annual-mean global-mean near-surface temperature. The dashed line (black) indicates the pre-industrial baseline (13.6 °C). The solid (black, green, and blue) lines correspond to modeled 2m-temperature in the years 2000, 2040, and 2090, respectively. Note that by definition the year axis corresponds with the number of realizations of a particular year in a given time-slice integration. The rapid temperature increase in the beginning is a spin-up effect that is excluded from the later analysis.

**Figure 2**(a) shows the zonal-mean temperature in wintertime (Dec.–Feb., DJF) for the year 2000. It illustrates the well-known characteristics of the climatological mean state that is linked to the polar night in winter. Figure 2(b) shows the temperature difference for (2040-2000). The finger-print of global warming is clearly visible, with temperatures increasing in the troposphere and decreasing in the stratosphere. The largest increase can be seen near the Earth's surface in the north polar region, the so-called Arctic amplification, presumably enhanced by seaice loss under increasing $CO_2$. The temperature change for (2090-2000) is illustrated in Figure 2(c). In line with Fig. 2(b), temperatures are even lower in the stratosphere and higher in the troposphere. In addition, Arctic amplification is even more pronounced. Temperature distributions shown in the upper row of Fig. 2 are closely linked to the wind data visualised in the lower row (keyword: thermal wind relation).

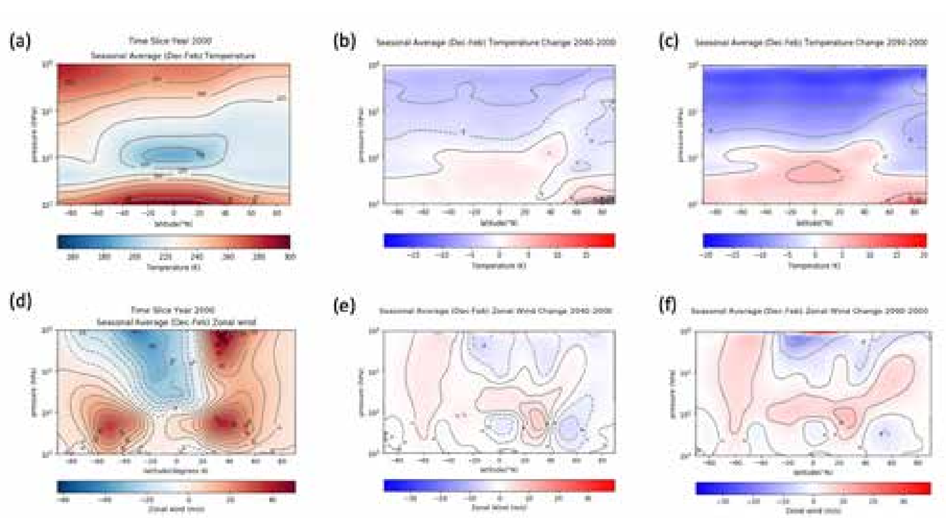


**Fig. 2** Zonal-mean and seasonal-mean (DJF) (a) temperature as a function of latitude and pressure, (b)-(c) difference in temperature for the years 2040-2000 and 2090-2000, (d) corresponding zonal wind, and (e)-(f) difference in zonal wind for the years 2040-2000 and 2090-2000.

Figure 2(d) shows the wintertime-mean zonal-mean zonal wind as a function of latitude and pressure. There are two strongly coupled jet characteristics visible: tropospheric jets, which are just below the tropopause and a wintertime polar stratospheric jet (vortex), which is consistent with the seasonal temperature configuration. The tropospheric jet maxima are located at latitudes around 50 °S and 40 °N and at an altitude of around 200 hPa (roughly 10-12 km) with a zonal wind speed of about 35 m/s. Figure 2(e) depicts the wind differences for (2040-2000). Our results show a meridional jet-shift in the NH by 10 degrees towards the equator and more of a strengthening in the SH. The dipole structure indicates a general shift in position and wind speed of the jet in the northern hemisphere (NH). Figure 2(f) shows the wind difference for (2090-2000) with a similar 10 degree shift and a weaker dipole signature.

There are two potential phenomena that affect the tropospheric and stratospheric jet changes: on the one hand the reduction of the meridional temperature gradient at some altitudes due to the Arctic amplification in DJF that slows the jet down and could make it wavier. On the other hand, we find that due to the increase of the temperature gradient with altitude above the polar stratospheric jet is strengthened. The different regimes are even better captured by a Fourier analysis (not shown here) and also affect variability (not shown here). Due to the strong coupling between the tropospheric and the stratospheric jets, also the subtropical wind speeds increase as can be clearly seen in Fig. 2(f). Similar observations can be made in Fig. 2(e); however, the wind speed increase in the lower stratosphere is less pronounced.

## CONCLUSIONS

Using the time-slice methodology we investigated the evolution of the physical properties of the jet streams (here exemplified for NH winter) for the years 2000 to 2090. Our model incorporates as forcings the increase of atmospheric $CO_2$ and other greenhouse gases, the sea surface temperature and the sea ice data in accordance with well-established CMIP6 AWI-CM scenario integrations. Vertical and meridional temperature distributions (and variations, not shown) are consistently reproduced. Starting from this, a comprehensive analysis of the jet stream amplifi-cation and meridional shifts have been carried out, also using a Fourier analysis technique (Satitkovitchai et al., to be submitted). Consequently, a mechanism involving strong coupling between the polar stratospheric and the tropospheric jets has been proposed as an explanation of the modelled amplification and shift, providing a potential caveat for storyline integrations that transplant recent jets into future climates.

## Data Availability (or) Available Information

Data is available upon request.

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# High-resolution bias-adjusted and disaggregated climate simulation ensemble

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## INTRODUCTION

A large number of climate simulations are already available for Germany. These cover a wide range of future climate developments. For the estimation of climate impacts, there are two fundamental challenges for simulations with dynamic climate models: 1. the spatial resolution of the models has increased significantly in recent years, but with about 12.5 $km^2$ the models are still very coarse for local estimations and 2. the directional error (bias) of the simulations makes their use in climate impact simulations influenced by threshold values difficult. To overcome these weaknesses, UFZ and GERICS, as part of the project DRIVERS within HI-CAM's Cluster II, generated high resolution, bias-corrected climate simulation data from state-of-the-art multi-model-multi-scenario regional climate model (RCM) ensemble simulations.

The daily-resolved bias adjusted and spatially disaggregated ensemble is provided based on regional climate projections which were created in the context of the EURO-CORDEX initiative (Jacob et al. 2014) as well as regional climate projections provided by the ReKliEs-De project (following the CORDEX protocol). The most recent EURO-CORDEX ensemble consists of 11 different RCMs downscaling simulation output from 10 different GCMs, resulting in a total number of 88 simulations being composed into 49 simulations of a "business as usual" emission scenario (RCP8.5), 18 simulations of a "medium" scenario (RCP4.5) and 21 simulations of a "climate protection" scenario (RCP2.6).

## DATA AND METHODS

The following nine meteorological variables were processed: average, maximum and minimum near-surface air temperature, precipitation, surface air pressure, near-surface specific humidity, surface downwelling longwave and shortwave radiation.

The bias adjustment methodology used within the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) phase 3, named ISIMIP3BASD, is used for bias adjustment. This method is based on a parametric quantile mapping approach and is meant to be "approximately trend-preserving in all quantiles" (Lange 2019), thus, featuring a comprehensive trend preservation and (more) robust adjustment of biases in extreme quantiles. Bias-adjustment was conducted on daily average, minimum and maximum near-surface air temperature and precipitation. Observation-based reference data sets for the bias-adjustments are based on interpolated DWD station data (inside Germany, Deutscher Wetterdienst, 2019) and E-OBS v20.0e gridded observational data (outside Germany; Cornes et al. 2018).

Subsequent to the bias adjustment, the simulation data have been spatially disaggregated to a spatial resolution of 1.2 km² applying the external drift kriging methodology developed and provided by UFZ (EDK, Samaniego et al. 2011, Zink et al. 2017) and further adapted for this project to suitable disaggregation methods for all meteorological variables. The variogram parameters were estimated by fitting to an empirical variogram (Zink et al. 2017). In case interpolated observational data was missing, variogram parameters were substituted or taken from literature values. For temperature variables and precipitation variogram parameters were estimated using E-OBS observational data. Parameters for wind speed and relative humidity are based on Berndt and Haberlandt (2018). Variogram parameters from average temperature were used for surface pressure. Parameters for shortwave and longwave radiation were used from average temperature and sill from Rehman and Ghori (2000).

The temperature variables, precipitation, wind speed and surface pressure were disaggregated using elevation as external drift. Shortwave and longwave radiation were disaggregated using terrain aspect as drift assuming an increase of radiation of southwards directed slopes. Specific humidity was disaggregated in a three step procedure by (1) transforming relative humidity (hurs) from specific humidity (huss) on input resolution using surface pressure and average temperature fields (2) disaggregating hurs with EDK (dem as drift) (3) re-computing huss from relative humidity on output resolution using disaggregated surface pressure and average temperature fields. The transformations of humidity are following the equations of Buck (1981).

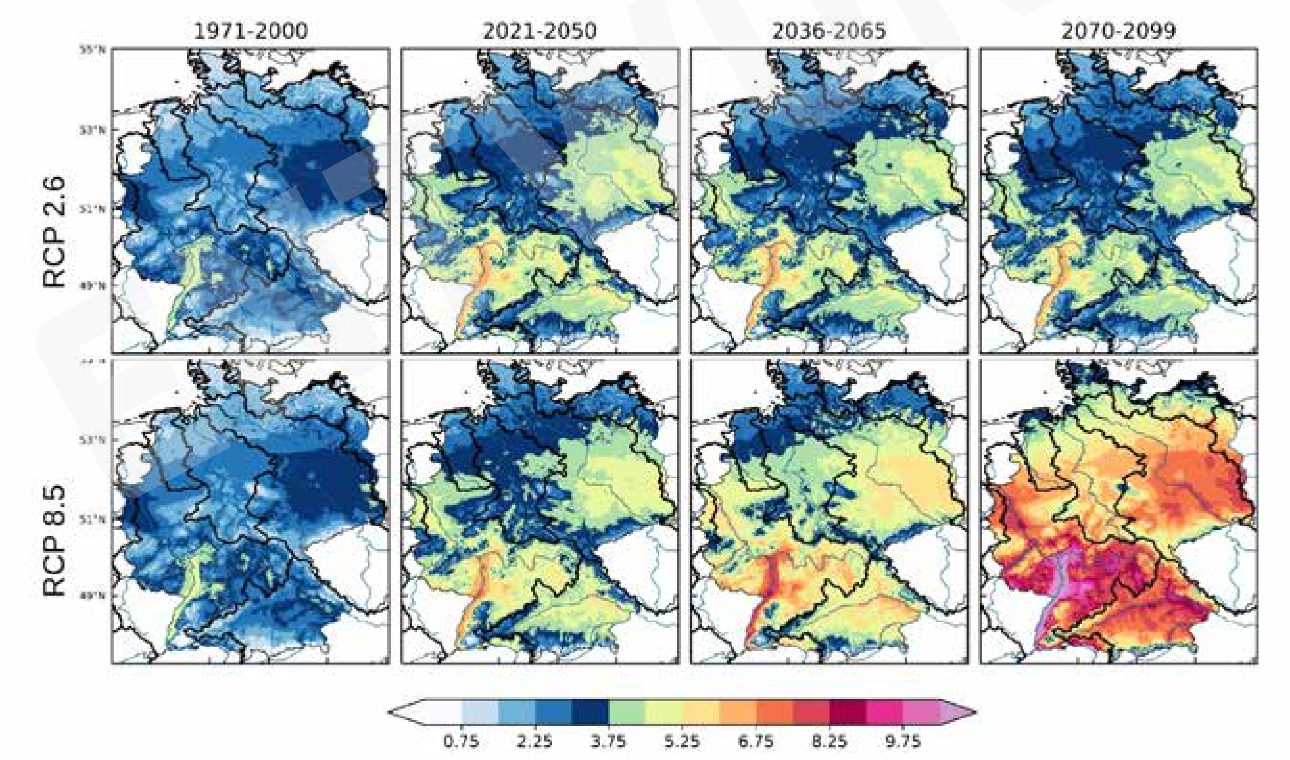


**Figure 1**. Ensemble Median of average yearly number of consecutive heat days (daily maximum temperature > 30°C) of 21 RCP 2.6 and 49 RCP 8.5 Simulations in the historic reference period (1971-2000) and three future 30 year periods (2021-2050, 2036-2065 and 2070-2099).

## RESULTS

The disaggregation and bias-adjustment resulted in a dataset of 88 climate ensemble members at daily temporal and 0.015625° (~1.2x1.2 km²) horizontal spatial resolution for Germany and headwaters (including Danube, Oder, Elbe and Meuse). The data is projected in World Geodetic coordinate System (EPSG:4326) and covers the timespan 1971 - 2099 (2098). Additionally, a European dataset was generated at 0.03125° (~3 km) horizontal resolution. The datasets are available up-on request.

Based on the meteorological variables, climate indices were calculated for impact assessments within HI-CAM and follow-up studies. Exemplarily, Figure 1 shows spatial maps of number of consecutive heatdays in historic and future 30-year periods under for RCP 2.6 and RCP 8.5 climate scenarios.

## ACKNOWLEDGEMENTS

The EURO-CORDEX initiative (***https://euro-cordex.net***) is a voluntary effort of many of the leading and most active institutions in the field of regional climate research in Europe. We acknowledge the EURO-CORDEX community for making their RCM simulation results publicly available. We also acknowledge the ReKliEs-De project (***http://reklies.hlnug.de***), funded by BMBF, for making their RCM simulation results publicly available. We would like to thank Akash Koppa for his support in data collection and preparation.

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# Towards high-resolution multi-model climate-hydrology indicators for Germany

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## INTRODUCTION

Global climate change is already manifesting itself in more frequent, more severe, and longer-lasting heat waves and droughts with significantly below-average precipitation combined with increased evaporation. In the last 20 years, Central Europe has been affected by summer heat waves and droughts six times. 2018 and 2019 were exceptionally drought and heat years, characterised by extreme low water discharges, falling groundwater levels and severe soil drought.

While climate indicators on the basis of large ensembles for states or continents have become standard, studies of climate impacts on the water cycle focus usually on the regional scale and specific variables of interest. Therefore, we utilize the 88 climate simulations of the HI-CAM work package "High-resolution bias-adjusted and disaggregated climate simulation ensemble" to drive the state-of-the-art hydrological models mHM and provide a high-resolution multi-model climate-hydrology ensemble for Germany. Variables such as streamflow, actual evapotranspiration, groundwater recharge or soil moisture are available under three Representative Concentration Pathways (RCPs 2.6, 4.5, and 8.5) at the kilometer scale. A set of national hydrological impact indicators has been generated to support the adaptation process in Germany.

## DATA AND METHODS

Within the framework of the Helmholtz Climate Initiative, a high-resolution reference climate data set has been developed in the past two years (Samaniego et al., this report). For this purpose, 88 climate simulations from the EURO-CORDEX and ReKliES-DE projects (Hübner et al. 2017) were disaggregated to a horizontal resolution of 1.2x1.2 km² for Germany and the surrounding catchments. The directional error of the climate simulations was adjusted with a trend-preserving method as in Hempel et al. (2013). Climate impacts on the water balance were estimated with the hydrologic model system mHM (Samaniego et al. 2010, Kumar et al. 2013) on the model grid identical to the climate simulations. The environmental model can mathe-matically describe dominant ecosystem processes at the landscape scale and provides e.g. surface runoff, interception, actual evaporation, soil water components or groundwater recharge. The model was driven by all 88 climate simulations on the one-kilometer scale for Germany. I a first step, the hydrological model was set-up and calibrated for the domain shown in Fig.2. The soil physical properties on texture (sand and clay fraction) and mineral bulk density are derived from the SoilGrids database (Hengl et al. 2017). The soil maps aim to represent the local soil composition by identifying patterns of similar soils. Soil depths in mHM are discretized into 6 soil layers: 0–5, 5–15, 15–30, 30–60, 60–100, and 100–200 cm). Land use is based on GLOBCOVER (ESA, 2009), and hydrogeological input data was derived from the GLIM database (Hartmann and Moosdorf 2012). The digital elevation model and its derivatives (flow direction, flow accumulation, slope and aspect) were derived from USGS (2017).

The unknown parameters of the mHM model setup were calibrated against observed discharge using the Kling-Gupta efficiency (KGE; Gupta et al., 2009) as the objective function. 200 parameter sets were obtained using a multi-basin/domain-wide joint basin calibration strategy, in which a subset of 6 basins was randomly selected (out of 201 total number of basins) and then jointly calibrated during a common period of 1990-2005. In a second step, all 200 parameter sets were evaluated against the full ensemble of the 201 basins during an extended period of 1986–2005 (with a spin-up period of 5 years). The single unique parameter set with the best performance in terms of the median daily KGE over 201 basins was selected and used for the consequent analysis. The model performance of the best cross-evaluated parameters based on daily streamflow from 201 catchments in Germany yielded a median performance of 0.76 KGE (**see Fig. 1**).

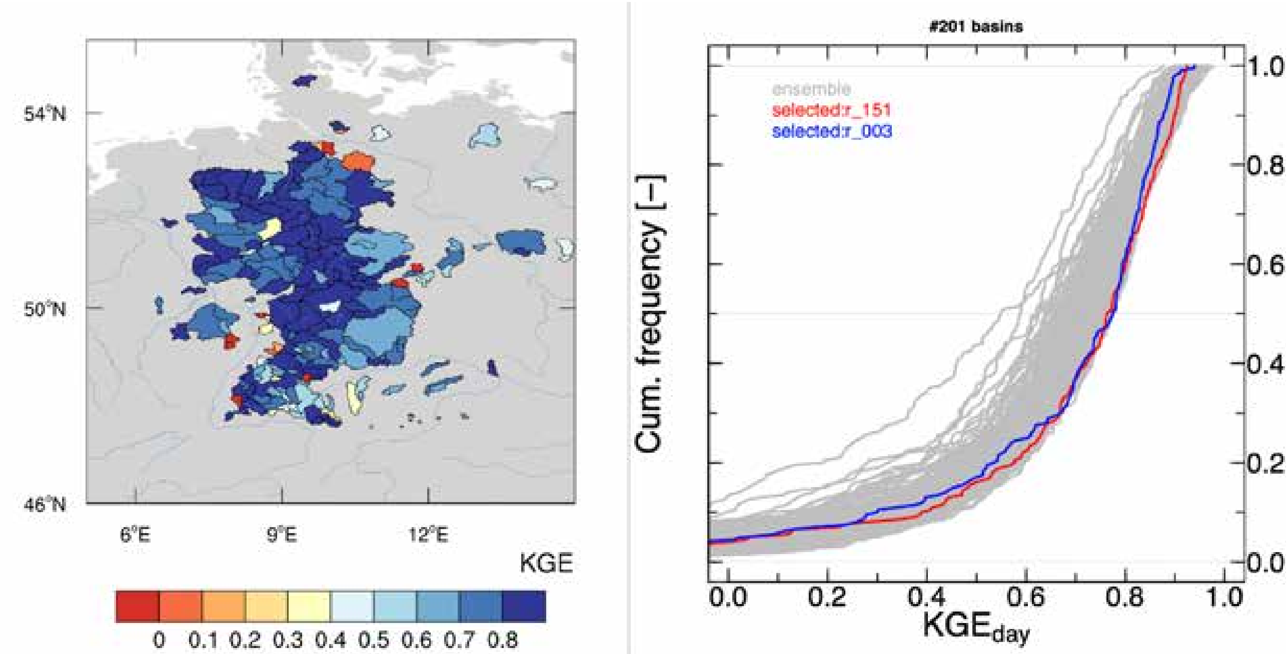


**Figure 1**. Results of mHM multbasin model calibration based on streamflow data from 201 catchments. Left: spatial map of KGE for each basin. Right: KGE Cumulative density function of setup 200 parameter sets, generated by random sampling of the basins. Bold red marks the selected parameter set ID 151.

## RESULTS AND DATA/INFORMATION AVAILABILITY

Based on the 88 model runs, hydrological and agricultural climate indicators such as the climate induced changes in soil moisture drought days have been calculated (**see Fig. 2**) based on the soil moisture index (SMI, Samaniego, 2013). The results have been used for the subsequent impact models employed in other projects and raised large interest from stakeholders.

Data and information from the HI-CAM high-resolution multi-model climate-hydrology ensemble have been used e.g. in a project for the regional Leipzig Water Supply (LWW) to estimate climate impacts on future water demand and availability. Furthermore, we currently assess climate impacts on water availability on the national scale for the DVGW (competence network for all questions related to gas and water supply).

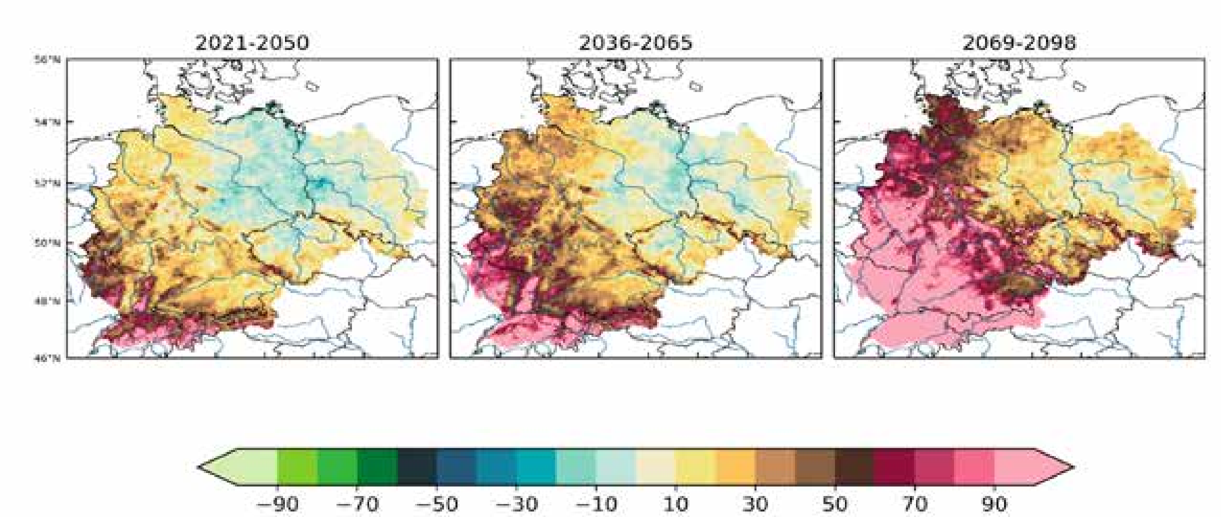


**Figure 2**. Relative change in the number of annual drought days, soil layer 0-30cm, in the vegetative active period II (July-September), simulated with the hydrological model mHM and compared to 1971-2000. The results show the median change over 49 climate-hydrology simulations under RCP 8.5.

The Helmholtz association funded the knowledge transfer platform WIS-D (water resources information system for Germany, UFZ 2022). The project, started in 2021 and running until 2025, will provide stakeholder-defined climate impact indicators and data via an online platform. It is planned to make available large parts of the HI-CAM based indices and indicators as well as the underlying spatial data via this platform. Besides the technical platform, a dialogue platform has been established to support or enable non-scientists in using climate impact data and information.

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# Groundwater in Terrestrial Systems Modelling over Europe: New Heat Events Climatology for Historical Time Span and Projections

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## INTRODUCTION

The number of extreme hydroclimatic events (e.g., droughts, heat waves, heavy precipitation) increased during the recent years, and will likely occur even more often in the future (e.g., Hari et al. 2020; Molina et al. 2020; IPCC, 2021), resulting in multiple socio-economic impacts. In order to develop useful adaptation strategies consistent, high-resolution climate data are needed. The groundwater (GW) representation in most regional climate models (RCMs) is generally oversimplified or absent, as well as its interaction with soil moisture and atmosphere, leading to biases in simulation of extreme heat events. In fact, many RCMs overestimate the heat waves frequency, duration and intensity (e.g., Vautard et al. 2013; Lhotka et al. 2018).

In this project, we explicitly simulate full 3D soil and GW dynamics, closing the terrestrial water cycle from GW across the land surface into the atmosphere, by utilizing the Terrestrial Systems Modelling Platform (TSMP) over the EURO-CORDEX domain. We obtained all terrestrial essential climate variables and indices for historical time span and the climate change projections with the Representative Concentration Pathways (RCP) 2.6 and RCP 8.5 (a rise in global temperature by 1.5 °C and 4 °C by 2100 respectively). Our analysis focused on the assessment of the effects of GW on the evolution of heat waves by investigating its frequency, duration and intensity.

## DATA AND METHODS

TSMP is a scale-consistent, highly modular, fully integrated soil-vegetation-atmosphere numerical modeling system (e.g., Shrestha et al. 2014). In the applied setup, TSMP is comprised of three component models: an atmospheric model – the COnsortium for Small Scale Modeling model system (COSMO) version 5.01 (e.g., Baldauf et al. 2011), the Community Land Model (CLM) version 3.5, responsible for the land-surface modeling (e.g., Oleson et al., 2004), and hydrological model ParFlow version 3.2 (e.g., Kollet and Maxwell, 2006). The independent component models are externally coupled via the Ocean Atmosphere Sea Ice Soil (OASIS, version 3.0) Model Coupling Toolkit (MCT) coupler (e.g., Valcke, 2013).

The TSMP simulations were set up over the EURO-CORDEX domain, using a rotated latitude-longitude grid with a horizontal resolution of 0.11° or approximately 12.5 km (EUR-11) (e.g., Jacob et al. 2020). The simulations were performed for the historical time period from December 1949 until the end of 2005, and further for the RCP2.6 and RCP8.5 projections until 2100 (Figure 1). The TSMP land surface, subsurface hydrology, and energy states were initialized by the conditions of 1st of December 2011, from the evaluation run driven by ERA-Interim reanalysis (Furusho-Percot et al., 2019). In the TSMP setup used, COSMO has a vertical range of

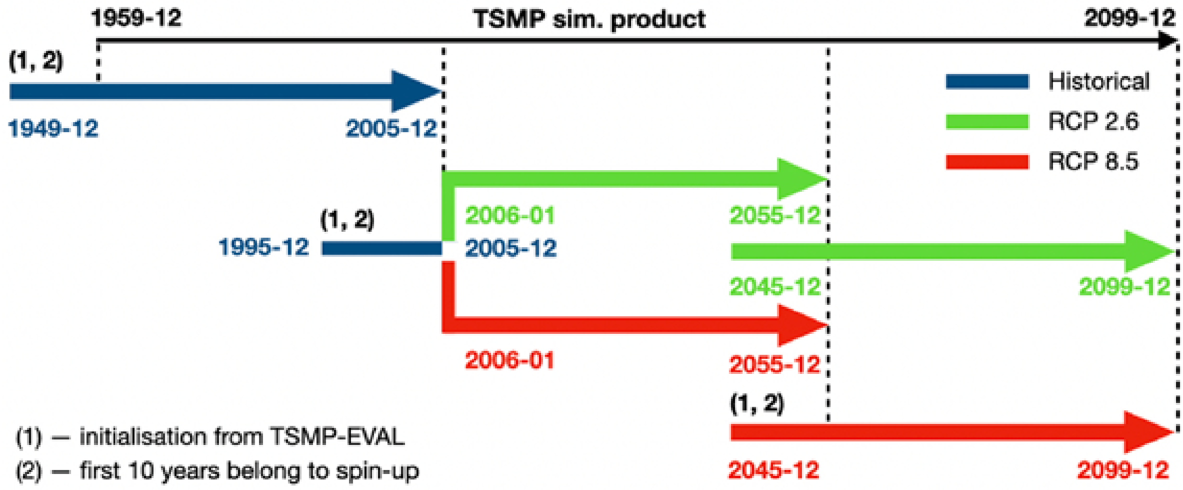


Figure 1. Schematic of the TSMP experiment with different MPI-ESM-LR forcing data: historical, RCP 2.6, and RCP 8.5. Each arrow represents a sub-period of simultaneous TSMP simulations.

22 km, CLM has a total depth of 3m, and ParFlow reaches a total depth of 57 m providing information of the 3D subsurface moisture distribution to CLM. The TSMP output contains all terrestrial essential climate variables at 3h time step including variables of the subsurface, such as moisture, groundwater storage, and recharge. The forcing data for the TSMP atmospheric component model is provided by the GCM of Max-Plank Institute, MPI-ESM-LR r1i1p1 T63L47 (e.g., Giorgetta et al. 2013).

In order to study the evolution of future heat waves in Europe, firstly we investigate in this work the past heat events by assessing the modelled climate statistics in the EURO-CORDEX ensemble of RCMs driven by GCMs. We analyze the frequency, duration and intensity of heat events between 1976 and 2005. The calculations are based on the simulated 2m air temperature, with respect to the reference period of 1961-1990. From the comparison of the heat wave characteristics obtained from TSMP and other RCMs lacking GW, we assess the effects of GW on the evolution of European heat waves. Note that a heat wave is defined as an event with a minimum of 6 consecutive days, with mean temperatures exceeding the 90th percentile of the reference period (Fischer and Schär, 2010). The 90th percentile is calculated from a consecutive 5-day moving window, centered on each calendar day of the reference period. The analysis is based on the work of Vautard et al. (2013).

## RESULTS

Our results show that the effect of GW coupling on the heat events frequency depends on the considered time span and region. Importantly, GW coupling has a systematic impact on the duration and intensities: heat events of long duration and high intensity appear less often in TSMP than in the other RCMs. Note, the duration of a heat event is defined as the number of days when the heat event lasts, the intensity of a heat wave is a maximum difference between the absolute temperature and the 90th percentile of the reference period within one heat wave event.

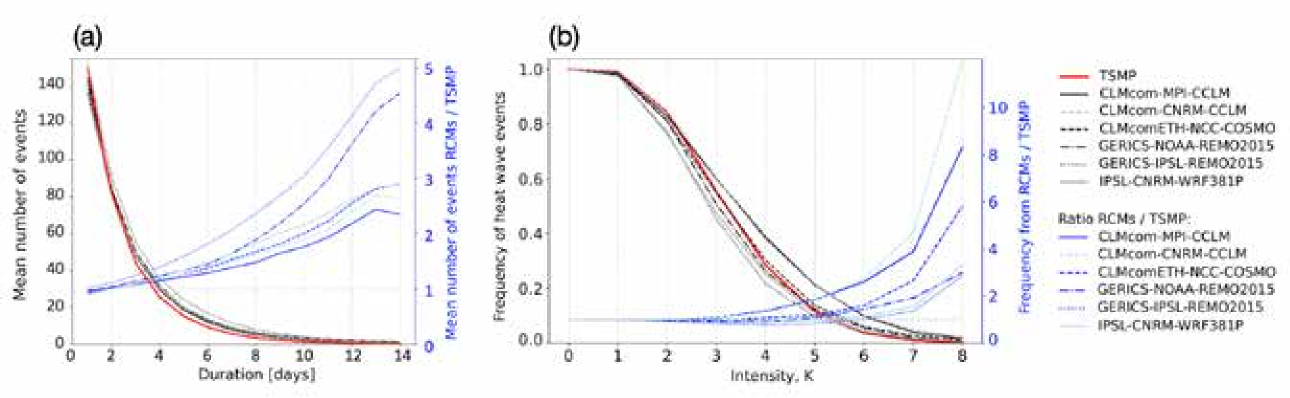


**Figure 2**. (a) Averaged number of heat events of duration larger or equal than a given number of days (shown on X-axis), as a function of this number of days; the averaging is performed over all land pixels of EURO-CORDEX domain in each RCM. (b) Frequency of heat waves in EURO-CORDEX domain with intensity larger than a given number of days (shown on X-axis) as a function of this number of days; a frequency of heat wave with fixed intensity is a number of such heat wave events divided by a total number of heat wave events. Data are taken for 1976-2005 with respect to the reference 1961-1990 period in each considered RCM.

Long heat events, so-called heat waves (duration > 6days), are, on average, over the EURO-CORDEX domain less frequent in TSMP in comparison to the other RCMs, by a factor of 1.3-5 (Figure 2a). The frequency of heat waves with high intensities (exceeding 90th temperature percentile by 5K or more) is lower by a factor of 2 in TSMP than in the other RCMs, while the frequency of heat waves with intensities < 2K is slightly higher (Figure 2b).

## CONCLUSIONS

Within the HI-CAM project, we have produced a new RCM dataset utilizing the TSMP over EURO-CORDEX domain, forced by MPI-ESM-LR GCM. In TSMP, the full 3D soil and GW dynamics were explicitly represented, closing the terrestrial water cycle from the GW across the land surface into the atmosphere. The simulations have been performed for historical time span and climate change projections with RCP2.6 and RCP 8.5. As GW representation is oversimplified or absent in most RCMs, we provide novel information about how future atmospheric extreme events may unfold within a full terrestrial water cycle. From the analysis of the evolution of heat waves (namely, its frequency, duration and intensity) for the historical period, we conclude that the inclusion of GW coupling in RCMs may lead to weaker simulated heat events in Europe. The results emphasize the importance of GW in RCMs, and consequently, in the heat waves evolution in climate projections.

### Data Availability (or) Available Information

The results obtained within HI-CAM project, are currently in preparation for publishing. Detailed information on TSMP is available at ***https://www.terrsysmp.org/***. The TSMP version (v1.2.2) used in this project can be found at ***https://github.com/HPSCTerrSys/TSMP***. At the moment, the TSMP simulated data is available upon request.

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# CLUSTER II:
# HI-CAM-ADAPTATION
## Urban systems

**Centers involved:**

UFZ HELMHOLTZ Zentrum für Umweltforschung
GFZ Helmholtz-Zentrum Potsdam
DLR
HZDR Helmholtz Zentrum Dresden Rossendorf
Helmholtz-Zentrum hereon
KIT Karlsruher Institut für Technologie

# Urban systems

Successful climate adaptation essentially depends on the transformative power of cities since the majority of the World's population, the economic performance and assets are concentrated in urban areas. The urban system is very complex. Research needs to be focused at the local scale to understand driving processes and foster the transformation to resilient and livable cities. Subsequently, local results are up-scaled to city-scale or to other cities. Because regional and urban climate trends superimpose each other, the adaptation to extremes is a pressing current and future threat for the cities. Adaptation involves a series of scientific fields (**see Fig. 1**) such as urban planning, mobility and transport, remote sensing, urban climate modelling, wind forecasting, nature conservation in cities, urban green, air quality, as well as public health.

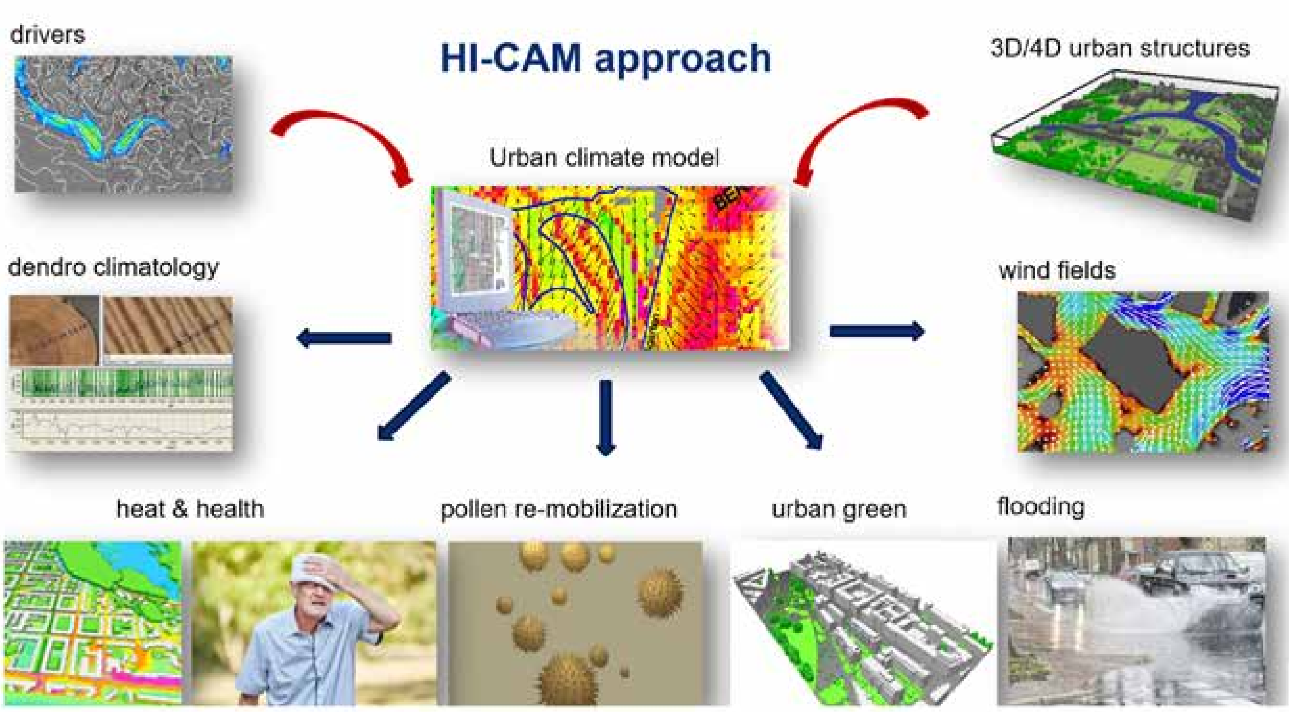


**Figure 1**: Multi-disciplinary concept to study and suggest measures for urban climate adaptation

The potential impact of climate change on mobility in passenger and freight transport as well as in urban spaces in particular was investigated. For this purpose, the relationship between weather conditions and mobility behaviour was analysed on the basis of transport models. Different scenarios were modelled to shed light on the impact of future weather conditions that can be expected due to climate change on the overall mileage of the transport system and on peoples' mobility. In addition, it was analysed how alternative fuels and drivetrains could contribute to lower emissions in the transport sector. Different diffusion rates of battery electric vehicles and plug-in hybrids in the passenger vehicle fleet were considered. This allowed for modeling the impact of these technologies on the emissions caused by the transport sector in different climate change scenarios. In particular, the effect of rising temperatures on energy consumption of internal combustion engines and battery electric vehicles was investigated.

Over recent years, the frequency and intensity of heavy rainfall has substantially increased in most parts of Germany. Furthermore, episodes with an exceptional high number of quasistationary thunderstorms related to atmospheric blocking, causing locally extreme precipitation accumulations, have been observed in recent years (cf. May/June 2016 and 2018). At the same time the frequency and duration of dry weather and low water discharge periods increases which changes the dilution and transport capacities of entire river networks. Consequently, urban flash floods and related damage to buildings / infrastructures and water pollution from untreated sewage discharges have increased significantly, making appropriate adaptation strategies indispensable. The entire effect chain has been investigated: from extreme rainfall scenarios including expected changes and temporal clustering through inundation and flooding to resulting household/infrastructure damage to the effect of rainwater overflow to the impacts on water quality and ecology.

Inter- and transdisciplinarity is key to urban adaptation. Therefore, different contributions are bundled in this chapter:

- Provision and utilization of urban data from different sources for urban modelling (DLR)
- Refinement and application of numerical urban climate models at high spatial resolution for urban heat island assessment in larger urban regions (UFZ)
- Investigation of the impact of hot and dry situations to healthy living conditions, especially the remobilization of airborne particulate matter affecting respiratory health (HZDR)
- Assessment of species-specific climate sensitivities of vegetation (potential for both adaptation and mitigation); recommendation of suitable species for climate-adapted cities (GFZ), including the quantification of the effects of tree species on local climate parameters (UFZ)
- Determining the impact of climate change on mobility behavior and investigation how the energy consumption of different vehicle drivetrains will be influenced by climate change (DLR)
- Development of the adaptation tool ‘storm monitor’ (HEREON)
- Assessment of extreme rainfall (KIT)
- Pluvial flood modelling and forecasting (GFZ)
- Assessing waste water treatment plants at risk (UFZ)

The achieved results are finally combined to e.g. develop recommendations on the cooling and shadowing effects of urban vegetation, on data provision (remote data, tree inventories), on storm protection and preparedness, on mobility behavior, on the aerosol distribution, and on measures for the prevention of adverse health effects.

# Urban climate modeling

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## INTRODUCTION

Coping with urban heat adaptation requires high-resolution maps for the contributing biophysical processes (radiation, convection, evapotranspiration, heat storage and anthropogenic heat) to local urban warming (urban – rural temperature difference; Hertel & Schlink, 2019). In particular, heat storage can be a dominant driver but still little attention is given to that process. During the HI-CAM project we closed this knowledge gap in order to support locally tailored adaptation measures. In a next step, upscaling from local to city level (exemplified with Leipzig) was established. For this purpose and together with the DLR we produced a high-resolution dataset (buildings, streets, vegetation, etc.) for Leipzig as input for the latest micro-meteorological model PALM-4U and made first simulations on the high performance computing cluster at the UFZ.

## DATA AND METHODS

The attribution of urban temperatures to biophysical processes (Zhao et al. 2014; Ridgen & Li 2017, Li et al. 2019) improves the understanding of the urban heat island (UHI) phenomenon. Traditionally UHI studies are based on satellite observations, which are limited in their spatial resolution. Little is known about the composition and interaction of the biophysical contributions at micro-scale (some meters). Therefore, we suggest an entropy concept for the heat storage cycle, reducing the complexity of the system and improving the understanding of hysteresis phenomena. The entropy framework was applied to different surface types based on micrometeorological simulations (ENVI-met, 3 m × 3 m horizontal resolution) that are validated by an airborne thermal scan (Hertel & Schlink, 2022). The visualization, entropy calculation and analysis (see Fig. 1) were done with programs developed in R.

In an effort to upscale our local findings we implemented PALM-4U on the EVE computing cluster at UFZ and prepared, together with the German Aerospace Center (DLR), a high-resolution dataset that covers the total area of Leipzig. This dataset comprises bridge height, bridge ID, bridge pavement type, bridge street type, building height, building ID, building type, terrain height, object height, pavement type, street type, tree height, tree species, tree plant year, water type, water ID and soil type – each with a horizontal resolution of 1m, 2m, 3m, 5m and 10m. The street tree parameters were processed with PALM-4U's canopy generator that produces 3D objects that are considered in the plant-canopy model. In order to construct leaf density profiles for each tree species several parameters such as tree shapes, trunk diameters or crown diameters need to be defined. Since often this information was not available, default values from the PALM-4U model system were used and extended by additional tree species that were missing (originally the default values were derived for street trees in Berlin). From the DLR data, some tree species were doubled and not fitting to the default values so that corrections for the classification were necessary. Typically, soil types within urban areas and with a high resolution are difficult to gather. Therefore, we used the BÜK200 (Bodenübersichtskarte Deutschland, BÜK200), clipped and resampled the data for Leipzig and, finally, reclassified the soil types for PALM-4U standard. Further, data gaps and inconsistencies were corrected.

## RESULTS

**1. Entropy metrics for urban heat storage (Hertel & Schlink, 2022):**

In addition to the effects of reduced convection and evapotranspiration we found that heat storage can make a very dominant contribution locally. It proceeds in entropy loops, where steep slopes and maximally symmetrically closed loop areas are optimal for achieving a balance between heat storage and release. The characteristics of the entropy cycles help suggest new and optimized strategies to attenuate urban heat episodes and we present a stepwise procedure (workflow) for the application of this method (Hertel & Schlink, 2022). Fig. 1 shows the respective entropy loop properties for each surface type at the daily heat storage maximum (11:00). The slope characterizes the phase shift and, thus, how fast the warming/cooling of a surface takes place. The enclosed loop area represents the amount of energy that is transferred during a daily heat storage cycle. In that interpretation slope is the temporal and enclosed loop area the spatial dimension. The colored lines represent the heat storage contribution to UHI (ΔTstor). The surface types can be clustered into 4 groups (see Fig. 1). It turns out that the sealed surfaces cool during day because they are located within a residential area where a lot of shadow is provided. Because of the daily heating, heat is transferred from surface into soil so that ΔTstor is negative compared to rural situation although the surface itself can be very hot because of absorption of shortwave radiation. During night (not displayed) the situation will be opposite. For the unsealed surface types this effect is not so strong but can be even reversed resulting in a slight warming effect. Obviously, the local infrastructure (buildings, vegetation, etc.) has a huge impact on these results and differs depending on the site of interest or even the city. For that reason, Fig. 1 generalizes the UHI contribution of an arbitrary surface type which can be directly read off.

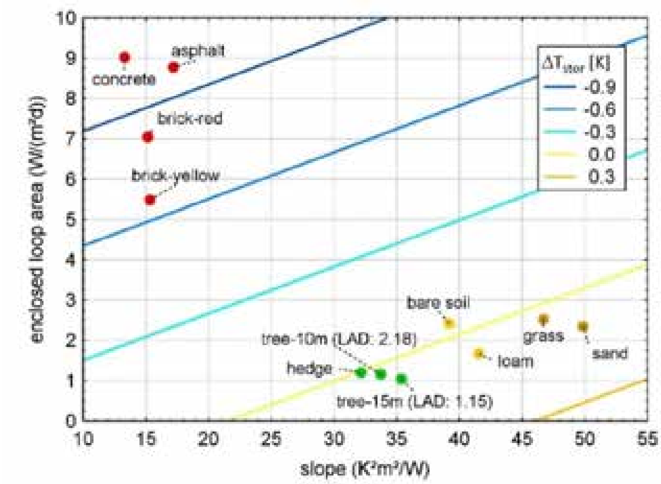


**Figure 1**: Entropy loop properties clustered into 4 groups (red = sealed surfaces, green = un-sealed with high vegetation, light yellow = unsealed for open land and loam, dark yellow = grass and sand); LAD = leaf area density. Colored lines represent linear interpolations of the UHI contributions from heat storage (ΔTstor) at the daily maximum (11:00) (Hertel & Schlink, 2022).

**2. Urban climate modelling with PALM-4U:**

Fig. 2 presents an example simulation for the 'Bayerischer Bahnhof' area in Leipzig. The channeling effects between buildings and street canyons are well represented as well as the fine turbulent structure of the airflow. This is an advantage against ENVI-met where the turbulence resolution is not that high and, consequently, the channeling effects are less pronounced. Additional simulations for a 10x10 km area, which covers the complete city core and large portions of the total Leipzig area, are prepared and currently running on the computing cluster. The input dataset which was used for the urban climate simulations in section 1 for the 'Bayerischer Bahnhof' area (a subset of the spatial extent of Fig. 1 – 675x675 m) was shared with: Re-mobilization of particles (details see respective subsection Banari et al.).

## CONCLUSIONS

According to Hertel & Schlink (2022), we conclude subsequent findings: The entropy approach (Fig. 1) can be used by practitioners for urban heat management and an assessment of the feasibility of adaptation measures related to heat storage. Fig. 1 reveals that only the combination of both properties helps to assess which surface type is superior. If one analyses this for each hour of the day it allows for finding suitable surface covers mitigating heat accumulation. Without these 2 properties it seems to be impossible to select the best ones. For example, sand and vegetation have a similar ΔTstor at noon (around 0, see Fig. 1), they only differ in their slopes. It is important at which time and location during day which effect occurs. Therefore, we highly recommend that practitioners not only consider spatial temperature characteristics (enclosed loop area) but also incorporate the temperature dynamics (slope). For climate adaptation, surface types within cities should be as close as possible to the top right corner of Fig.1, because they can store a large amount of heat (and provide cooling during daytime) but, after sunset, can release it very quickly, avoiding heat accumulation during night. Our framework is site-independent with an easy transferability to other urban locations or cities worldwide.

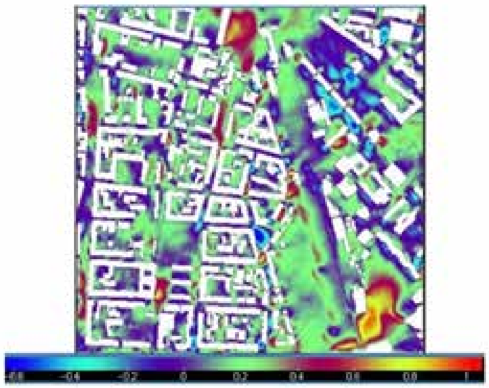

**Figure 2:** Modelled horizontal wind velocity (v-component, m/s) in 10 m height at 12:00 (23 September, 2010) for the 'Bayerischer Bahnhof' area in Leipzig (1050x1050 m, 3 m horizontal resolution).

The **PALM-4U** system is a very powerful micrometeorological model. Because of the performance optimized and strongly parallelized code it can be used for upscaling the results of the entropy approach or the UHI decomposition algorithm. Currently, the necessary input data is prepared, the model implemented at the UFZ computing cluster, and several test runs for different area sizes and resolutions are performed. Next steps achieving the upscaling goal will be a nested setup for whole Leipzig with a 10 m resolution and selected quarters with 1 or 2 m as well as establishing cooperation for application and further model development.

### Data Availability (or) Available Information

Data is available upon request. The results for the entropy metric are published in the Urban Climate journal (https://doi.org/10.1016/j.uclim.2022.101129).

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# Remobilization of pollen particles

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## INTRODUCTION

Pollen outbreaks are the main cause of asthma and allergy in the world. From 2001 to 2011, the number of people with asthma grew by 28 percent. The main reason for this was the urban heat Island (UHI) which causes heat waves which lead to increase of airborne pollens. One solution for preventing the asthma or allergy attacks is that the sensitive people avoid going to the high risk area of the city. For doing that a map of urban area with high possibility of pollen remobilization in high wind conditions is needed. In our task, a fast numerical tool for simulating the fluid flow and propagation of pollen particles in the urban area has been developed.

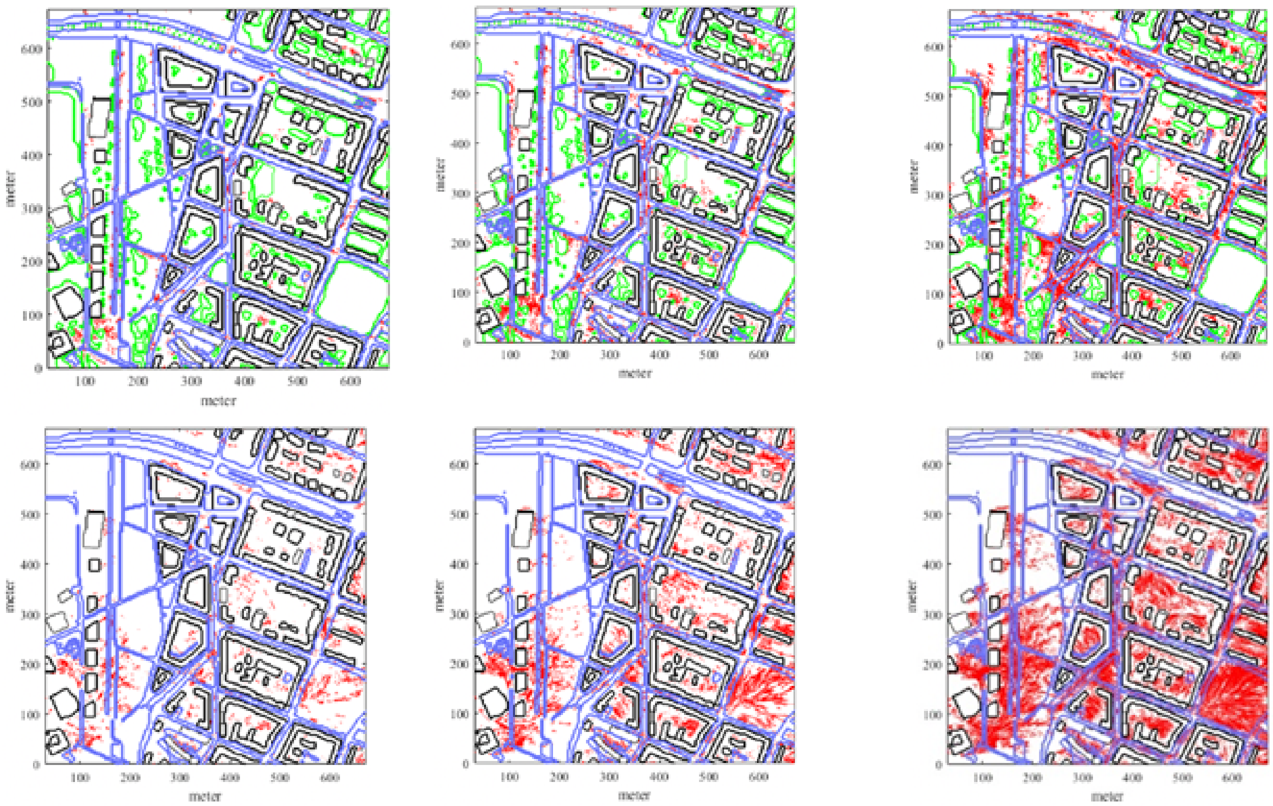
Laboratory experiments usually fail to study urban flow due to the complexity of the buildings and high cost. In the recent years, the progress in hardware and computational resources made the CFD more popular for studying the urban flow. Most of the works about the pollutant dispersion in urban area are limited to small non-realistic subsection of city. There are some limited CFD data on simulation of large city section. This limitation mainly is due to do high computational cost of flow simulation for a big data.

In this work package we carried out a numerical simulation to study the urban flow and pollen dispersion. We focus on developing a forecast map which shows the risk area with high pollen concentration for sensitive people. In the first step of this work, the area “Bayerischer Bahnhof” in Leipzig, Germany is chosen for testing the capability of our numerical tool. Additionally, this area is selected as joint work with “Urban climate modeling” (Hertel & Schlink, this report) for the urban green infrastructures (GI) design. Our project partner at UFZ studied the decomposition of urban warming ΔTand applied it to the same city section of the current work. They studied the placement of GI for reducing the UHI. If GI is placed at an unfavorable location where airflow is trapped, it can hamper vertical exchange of heat. As a result, the total UHI might be even higher and air pollution accumulates.

## DATA AND METHODS

This fast simulation has been achieved by using an efficient lattice Boltzmann method. The lattice Boltzmann method has several advantages with respect to classical Eulerian/Navier-Stokes solvers. It benefits from a straightforward implementation and does not need pressure correction. The locality of the operators allows to take full advantage of recent advances in parallel General Purpose Graphical Processing Units (GPGPU) for fast Calculation. For tracking the pollen particles, a Lagrangian approach is used. The resuspension of the particles happens when the shear velocity $u^*$ exceeds the threshold pick up velocity $u_{cr}^*$ of a specific surface. Computing the shear velocity at the wall from the numerical velocity profile is not a wise decision. Mainly because the grid is too coarse to calculate the velocity gradient by finite difference and the numerical error is too high. Instead of the finite difference, the shear velocity is found from the log wind profile which is alternative and more accurate wind profile close the ground.

Three different object types are activated in the numerical domain. Green surfaces (grass, bush ...), asphalt roads and  building. It must be mentioned that the resuspension process is a very complicated phenomena and the critical friction velocity for the particle resuspension depends on various parameters. In previous experimental works, various particles in different size (1-100 µm), shapes and material (glass, alumina, iron, polymer ...) on various  substrates with different material (glass, steel,..) and roughness are studied for finding the critical shear velocity.  By scanning those shear velocity, it can be concluded that the resuspension happens in the range of 0.2 m/s< ucr*<1.5 m/s when the surface is solid (not vegetated). For vegetated surfaces the data are more limited and also more construable.




(a) uwind=4m/s (b) uwind=5m/s (c) uwind=7m/s

**Fig. 1**. Resuspended particle path with (top) , without (bottom) green surfaces.

We extrapolated the Giess et al. data and found that  ucr*=2.35 m/s for f=50 % resuspension. It can be concluded qualitatively that for the vegetated surfaces the resuspension rate drop up to 70% to 100% for grass swards compare to non-vegetated one. In this work, the numerical size is 671m*671m and the height is 131 m. The initial satellite data set of the city has resolution of Δx=3 m. This date is interpolated to Δx=1.3 for a finer resolution. This gives the grid number of 498×498×98. 40000 particles with different pick up velocity initially were distributed randomly but homogeneously on city surface.

We did a numerical simulation of the resuspension and the propagation of the particles on west wind scenario for different wind speeds. Fig. 2 illustrates the path of the particles which were resuspended from the ground up to 3 meter above the surface. This 3-meter height is chosen as possible zone that particles can be inhaled by human and is risky for the health. The particles that travel to the upper layers and eventually into the atmosphere are not considered dangerous and the zones with good ventilation also can be checked by this approach. As it can be seen in Fig. 1 for the uwind=4 m/s there are few particles that start to move. By increasing the wind speed to uwind=5 m/s some high risk zones with high particle path concentration can be ob-served. It is recommended that sensitive people avoid this zone in this wind conditions. But for higher wind speed u=7 m/s, almost all roads and streets are considered to be red zones and it is highly recommended to not to walk or stay in the city at this wind conditions.

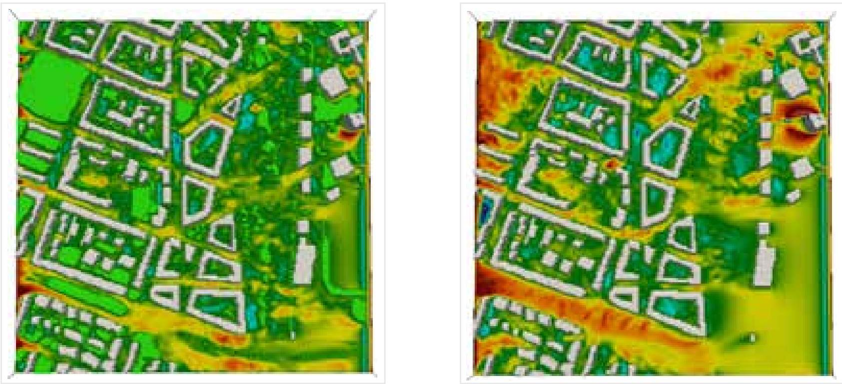


**Fig. 2**. Flow field with (left) and without (right) green structures.

The effect of the vegetated surfaces on particle detachment also is investigated. In this scenario all green areas are replaces with solid ones and the particles resuspension are compared. The bottom panel of Fig. 1 shows the particle path near the surface when the green surfaces are neglected. By comparison to top panel, as it is expected the vegetated surfaces play important role to keep the particles on the ground and by eliminating the green areas, particle detachment increases up to 400%. Fig. 2 shows the flow field 1 meter above the surface for wind speed of the u=7 m/s. The high-velocity zone where the most of particle resuspension occurs.

The dense green areas, such as trees and tall bushes can also change the flow field and direction. Although the vegetated surfaces are desirable by increasing the adhesion of particles, but the flow filed alternation could be harmful in some cases if it causes high-velocity zones. In designing and placement of the green infrastructures the flow field must be checked to avoid the high velocity areas near the surface. For example, the change in flow field with and without vegetation can be seen by comparison Fig. 2 left and right snapshots. Additionally, it is recommended with a joint work with our project partner, both urban “high-velocity zones” and UHI be checked prior to GI placement.

## CONCLUSIONS

A very fast numerical tool is developed which is able to successfully and extremely quickly simulate the particle laden flow to find the high risk areas map in a district of a city.  This numerical tool can almost in real time simulated the urban flow and pollutant dispersion. This tool can be later used for developing a smartphone application which is able to show the high risk area zone. Besides showing the high pollen concentration area, the effect of green surfaces (bush, grass, etc.) for decreasing the particle resuspension is studied. This capability of the current work can be used for designing the city infrastructures to avoid high-velocity urban areas.

### Data Availability (or) Available Information

The data and numerical cod for this work is available upon request.

### Literature

P. Giess, A.J.H. Goddard, G. Shaw, Factors affecting particle resuspension from grass swards, Journal of Aerosol Science, Volume 28, Issue 7,1997, Pages 1331-1349,ISSN 0021-8502,

# Tree growth sensitivity to excess heat and urban conditions from Berlin's open inventory and data

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## INTRODUCTION

Excess urban heat can exacerbate adverse conditions (e.g., drought), yet higher temperatures may also increase growth rates for urban compared to rural conspecifics (Pretzsch et al., 2017). Indeed, recent literature reports heat-driven modulation of growth ranging from negative to beneficial (Zhao et al., 2016; Dahlhausen et al., 2018). Differences between and within species are typically established by detailed assessments of (intra) annual growth, physiological responses, and dynamics of larger-scale, remotely sensed indices. This implies either low spatial/tree coverage due to logistical limitations or lack of detailed local information, and may explain at least in part the differences and/or contrasting patterns observed for temperature. This project aimed to overcome these limitations by leveraging comprehensive urban tree inventories and high-resolution environmental data, capturing a broad range of growing conditions, species and demographics. Berlin - as the city with Germany's strongest urban heat island (Fenner et al. 2014) - was used as a case study, where we applied spatially explicit statistical models to infer the impact of excess heat as well as the urban fabric on tree growth using data that is or will be widely available, including tree inventories and environmental observations.

## DATA AND METHODS

We modelled the stem diameter of Berlin's ten most abundant species (contingent to ancillary data availability) in relationship to their location, age, a measure of excess heat (UrbClim by de Ridder et al. 2015; Berlin Environmental Atlas models; LandSat-derived surface urban heat island by Chakraborty et al. 2019), and additional environmental covariates with generalized additive models (GAMs). Berlin's open data provided tree inventories (species, age, location, diameter which were processed with a bespoke software datacleanr by Hurley et al., submitted), planting bed area, estimates of soil nutrient availability, and adjacent building height. With WUDAPT local climate zones (Demuzere et al. 2019), these were used to determine trees' growing conditions (locally, or within a radius of 150m/300m).

## RESULTS

We tested several (excess) heat data products in models with different covariates, and identified day-time LandSat surface urban heat (Figure 1A) and local climate zone 6 (representing open to mid-rise urbanization at 150 m) to reproduce age and location-specific growth patterns satisfac-torily (Radj2 = 0.79; Figure 1B), with more open urban areas allowing for higher growth on average (Figure 1C). The sign of temperature effects shifted from positive (enhancing) for younger trees (age 30-35) to negative (detrimental) for older trees (Figure 2A), with clear differences between species, where Tilia spp. and cultivars, Quercus robur and Aesculum hippocastanum fared better at higher ages (Figure 2B). The considerably greater sensitivity of Platanus acerifolia (Figure 2B; age 60-65) may be due to bias in the data/model. Most trees are planted under intermediate to high excess heat conditions (distributions in Figure 2A), which implies decreased growth potential in the future.

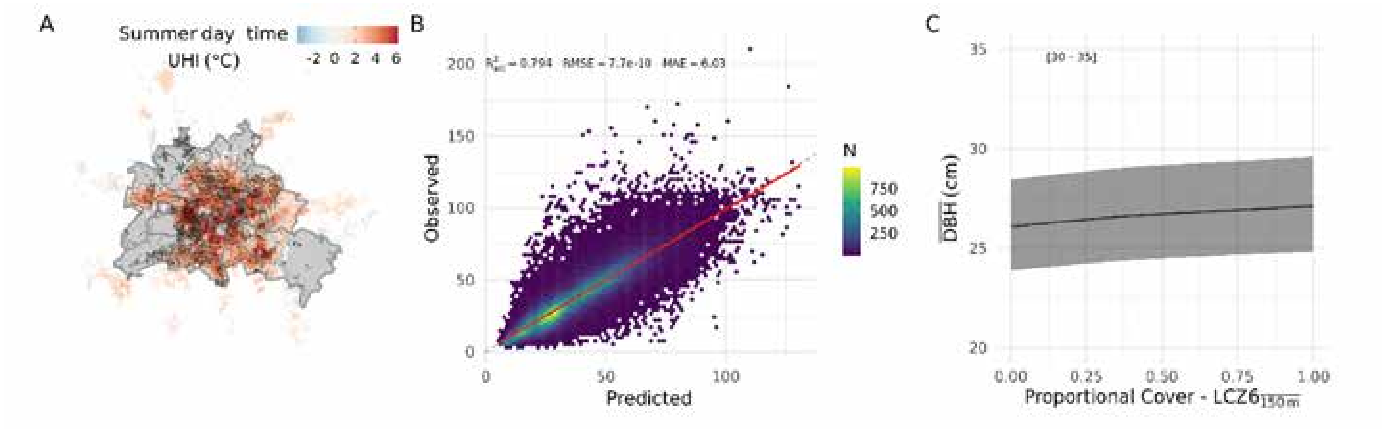


**Figure 1**: Heat measure (LandSat surface urban heat island; A), predictive performance (B), and relationship with environmental covariate (local climate zone 6; C) for the best GAM model of tree diameter for ages 30 - 35. Dots in A are tree locations.

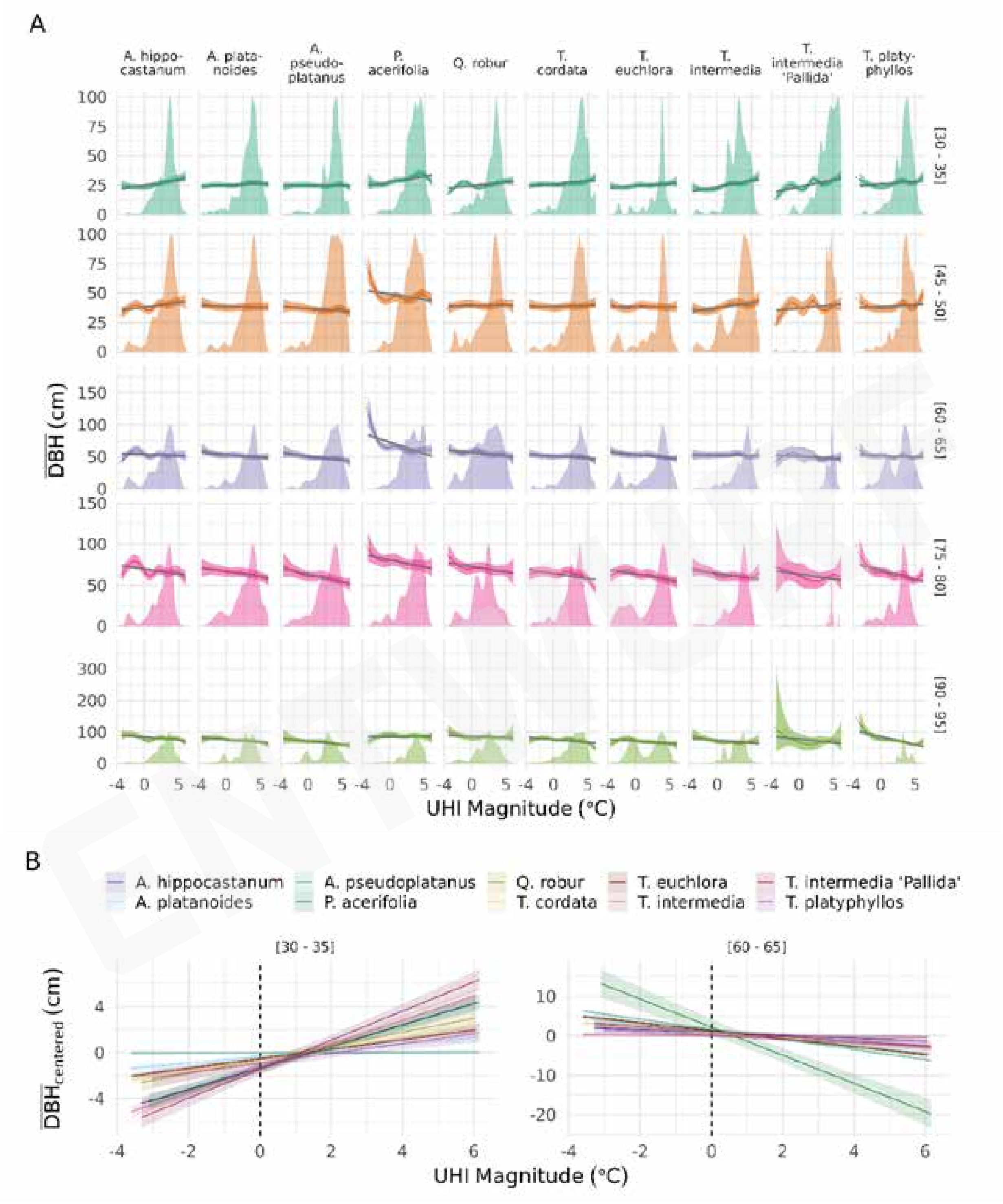


**Figure 2**: Average diameter growth of 10 most abundant species modelled with best GAM from Figure 1.

**A:** Distributions highlight planting locations along the excess heat gradient and colored lines/ribbons are GAM estimates averaged for each age group (rows), while grey lines are fit to these as interpretative aids (AI).

**B:** Best fit lines (AI) for GAM estimates, highlighting the contrasting species-specific sensitivities across two age groups.

## CONCLUSIONS

The tested models satisfactorily reproduced growth patterns, and highlighted species and age specific sensitivity to excess urban heat. This approach shows great promise to better inform adaptation through tree planting and managing efforts for urban areas as the required data is becoming increasingly available, or in many cases is already accessible, through open data policies. The reliability and effectiveness of the approach can be increased by combining it with other frameworks, such as the species-climate matrix (Roloff et al. 2009). Yet we urge local authorities to ensure frequent and comprehensive inventories of their urban forests to (1) enable this approach per se and (2) ensure the greatest possible confidence for statistical inferences and subsequent interpretations.

### Data and Software Availability

Processed data and results are available upon request. Software datacleanr is published under GPL-3 license at ***https://github.com/the-Hull/datacleanr***.

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# 3D/4D Characterization of the Built Environment

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## INTRODUCTION

A continuous and reliable monitoring of urbanization is of key importance to accurately estimate the distribution of the expanding human population, and to evaluate its effects on the use of resources, infrastructure needs, socioeconomic development, etc. In recent years, the increased availability of EO data, along with the development of sophisticated machine learning algorithms has facilitated this task, by allowing the production of geospatial datasets that describe the extent and distribution of human settlements at local, regional and global scales. However, while many built-area datasets are openly available and intensively used by governments and institutions around the world, only a few of these datasets outline the distribution of the settlements over time, or provide additional information on the built-up environment, such as density and vertical information. In other words, many existing products are mostly binary datasets available for one, or just a few time steps, restricting the implementation of more detailed, multi-temporal analyses, needed to establish sustainable planning strategies. In this context, to improve the understanding of trends in urbanisation, we have developed and improved the World Settlement Footprint (WSF) suite, a collection of novel datasets aiming at providing accurate, reliable and frequent information on the location, extent, density and 3D-morphology of human settlements. On the one hand, the WSF-Evolution, together with the WSF-Imperviousness dataset provide yearly binary/density maps of all built-up areas at a 30m resolution starting from 1985 and currently reaching up to 2015, which allow analysing settlement expansion and city densification over three decades. The WSF 3D, on the other hand, gives insights into the volumetric properties of the built environment, allowing for more accurate analyses at the local scale.

## DATA AND METHODS

**1. WSF-Evolution**: To create a consistent long-term mapping of settlements, our approach is solely based on 30m resolution satellite data from the Landsat constellation with its long-time archive starting from 1984. In an initial step yearly temporal statistics of spectral indices are calculated. These indices include the widely used normalised difference vegetation index - NDVI, the normalised difference built-up index - NDBI and the modified normalised difference water index - MNDWI. In the second step we iteratively classify the settlement extend for each year going back in time using a supervised random Forest approach with training data for settlement and non-settlement areas derived from the previously classified year. This iterative approach assumes urban growth restricting prior years to the extent of later years and can therefore not address the in comparison minor phenomenon of settlement shrinkage.

**2. WSF-Imperviousness:** In addition to the yearly settlement maps information on the imperviousness and thus the building density inside the settlements is very important. Therefore, we further derive the percentage of impervious surface inside the settlements from the yearly intermediate temporal statistics, especially utilizing the inverse relationship between the phenological peak vegetation signal and the impervious surfaces.

**3. WSF-3D:** Besides a proper delineation of the extent of human settlements, precise information on the building heights is of key importance for better estimating the distribution of the resident population, energy consumption, greenhouse gas emissions, and urban heat island. To date no layer exists which provides a 3D map of the built-up areas globally. Therefore, we estimate the built-up height by jointly exploiting the 12m TanDEM-X digital elevation model combined with WSF Imperviousness and OSM data. The approach first detects vertical edges in the TDX-DEM data and then combines the information about settlements extend and imperviousness as well as OSM data to remove Trees and hedges from the vertical edges and create a building mask. To compensate for layover effects of higher buildings in the DEM and misregistration of the different datasets the data is aggregated to 90m to calculate the average building fraction, height and volume.

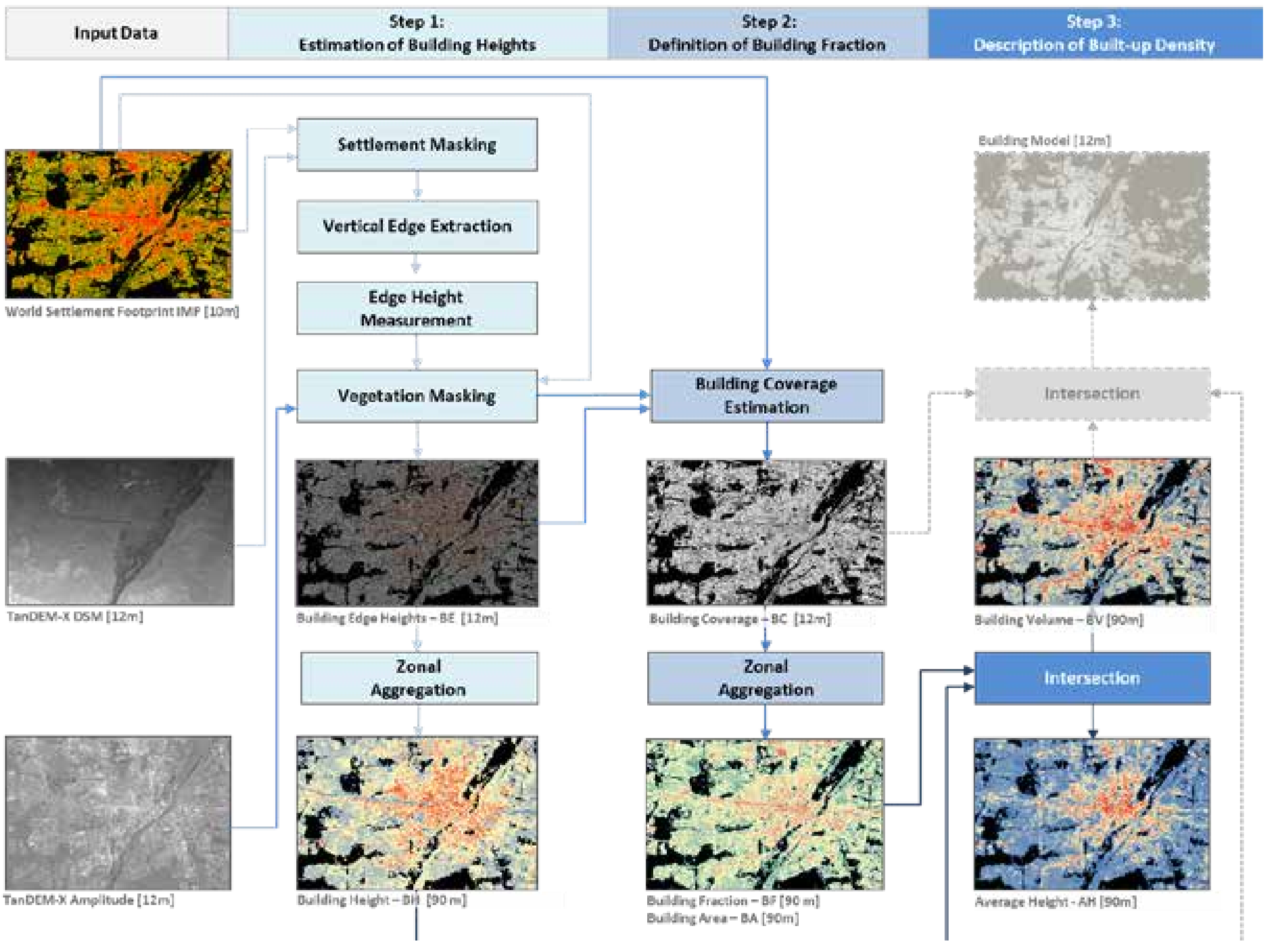


**Figure 1**: Schematic view of the WSF 3D work-flow.

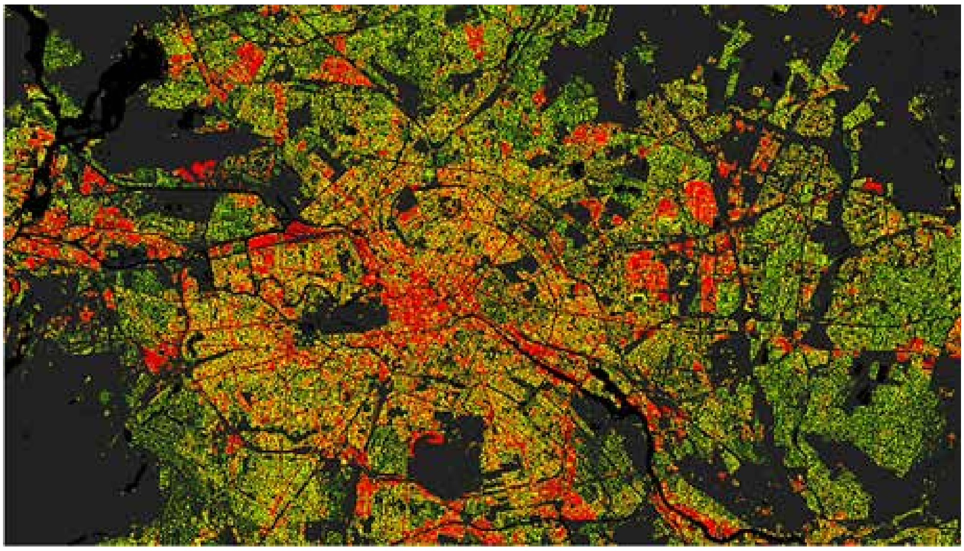

**Figure 2:** Imperviousness classification Berlin.

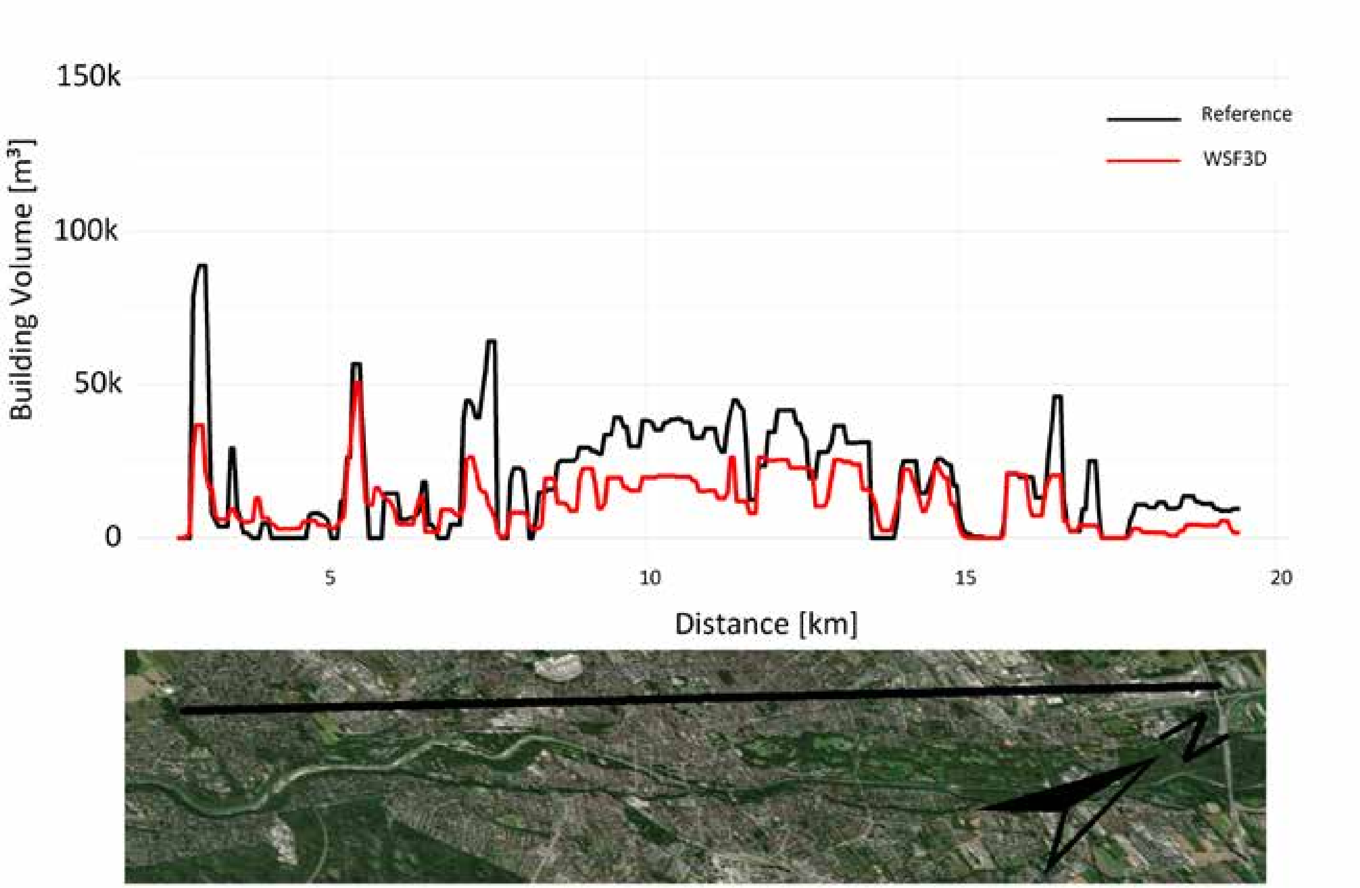


**Figure 3:** Transect of Munich comparing building volume and reference data. Results show overall underestimation, especially for high rises.

## RESULTS

The entire classification process for the WSF-Evolution/Imp. was performed on the Google Earth Engine (GEE) platform. To quantitatively assess the accuracy of the dataset an extensive campaign based on crowdsourcing photointerpretation of very high-resolution airborne and satellite Google Earth imagery is currently ongoing and shows accuracies of 83 - 89 % (Kappa 0.55 - 0.78).

The precision of the building height estimation was validated by comparing the WSF 3D building height with the average building heights from reference data to the identical 90 m. The results show a mean error (ME) ranging from -13.14 to 0.98 m and indicate an overall underestimation of the height which increases systematically with rising building heights.

## CONCLUSIONS

The WSF suite opens up new opportunities for scientific research, but also for the practice of planners, decision makers and political leaders. This applies, in particular, to the fields of spatial planning, sustainable development, urban climate, urban economics, disaster and risk management, but also to the modelling of population distribution, air pollution and emissions, or assessments of carbon footprint, energy demand, and traffic patterns. Here, the WSF 3D layers (and knowledge gained from them) might help answering key questions and addressing future challenges related to a sustainable and resilient development of the built environment.

### Data Availability (or) Available Information

The World Settlement Footprint (WSF) Evolution can be visualized and downloaded globally from the DLR/EOC Geoservice. As soon as the validation of the WSF imperviousness datasets are finalized and published they will also be published here. For the WSF 3D we also pursuing an open and free data policy. However due to the underlying TerraSAR DEM data, the dataset is subject to German data distribution regulations (SatDSiG) and the approval process for its release is still ongoing. As soon as this approval is granted the data will also be made available from the DLR/EOC Geoservice. Until then WSF 3D and WSF imperviousness data is provided on request (contact: *guf@dlr.de*)

*https://geoservice.dlr.de/web/maps/eoc:wsfevolution*
*https://geoservice.dlr.de/web/maps/eoc:wsf*
*https://geoservice.dlr.de/web/maps/eoc:wsf2019*

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# Predicting the cooling potential of street trees by species' functional traits

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## INTRODUCTION

The ongoing climate change has a vast influence especially on urban areas (Revi et al. 2014). Due to highly sealed surfaces, building structures etc., urban areas show much higher air temperatures in comparison to their surrounding countryside (so-called urban heat island effect) (Taha et al. 1988). An increase in extreme weather events such as droughts and heat waves exacerbate the situation in urban areas, and thus in places where the majority of the world's human population lives (United Nations, 2008). To mitigate those effects and to adapt cities to future climate beams the focus towards the already existing as well as possible future urban green infrastructure. In particular, urban trees play a major role in this context. Beside the quite effective regulation of temperature by transpiration and shade, they provide diverse ecosystem services including recreational and aesthetic effects, sequestering of carbon, filtering of air pollutants, etc. (Armson et al. 2012; Gillner et al. 2014).

In this context, we investigate the potential of plant functional traits as indicators for the cooling effect (Grote et al. 2016) of street trees. Functional traits reflect the adaptation of species towards their environment (e.g. thicker leaves in arid areas) and can be linked to ecosystem services (Lavorel & Grigulis 2012). Developing trait-based indicators of cooling potential is of high importance in the face of climate change and the predicted consequences for urban areas. When implemented in urban climate modelling – such as with the model developed by Hertel & Schlink within "Urban System"– for the green infrastructure traits can provide a helpful instrument for urban planners. Therefore, we measured differences in air temperature and air humidity between spaces beneath tree crowns vs. spaces not covered by tree crowns as well as several physiological and morphological traits of tree species (e.g. leaf water potential (predawn/midday), specific leaf area, stomata per $mm^2$ etc.) across six tree species/cultivars at nine sites in the city of Leipzig, Germany.

## DATA AND METHODS

The field campaign started in August and ended in September 2020. Every measurement series (two in total) took ten days, equaling one day per site. The tree species Fraxinus excelsior 'Westhof's Glorie' ,Pyrus calleryana 'Chanticleer',Robinia pseudoacacia, Robinia pseudoacacia 'Monophylla' ,Tilia cordata 'Rancho' , Tilia x vulgaris 'Pallida' were chosen for further analysis. For getting an impression of the tree characteristics diameter at breast height (DBH), height (h), height of crown base (hbase), leaf area index/density (LAI/LAD) and visual assessments were determined once. This was equally done for the samples for tree and leaf trait measurements (taken for sun and shade crown). To get an idea of trees' effects on cooling at different points in time and a related range of physiological adjustments, sampling for leaf water potential ($\Psi$min, $\Psi$max) and climatic variables occurred twice.

To analyze whether the microclimate (air temperature, relative humidity) at midday is influenced by the chosen traits, we applied two linear mixed effect models using the 'nlme' package for R (Pinheiro et al., 2021) with a significance level of 0.1. We analyzed the influence of height of crown base (hbase), crown volume (Vcrown), specific leaf area (sun leaves; SLAsun), leaf dry matter content (sun leaves; LDMCsun), stomatal density (sun leaves; SDsun), leaf area index and density (LAI/LAD), range of water potential (ΔΨ) and leaf water potential at turgor loss point (ΔΨTlp) as fixed factors on the increase or decrease of the range of air temperature and relative humidity at midday (ΔTair, midday; ΔRHmidday). The measurement series nested in tree species and tree species nested in site were included as random factors.

## RESULTS

The minimal adequate model explaning ΔTair, midday shows a significant effect of leaf area index (LAI; estimate=0.169), height of crown base (hbase; estimate= -0.140) and range of leaf water potential (Δψ; estimate= 0,171). According to that an increase of hbase results in higher temperatures beneath the crown. Whereas an increase of LAI and range of Δψ lower temperature (Figure 1). No significance was shown for Vcrown, SLAsun, LDMCsun, SDsun, LAD and ψTlp; these variables were excluded during model simplification.

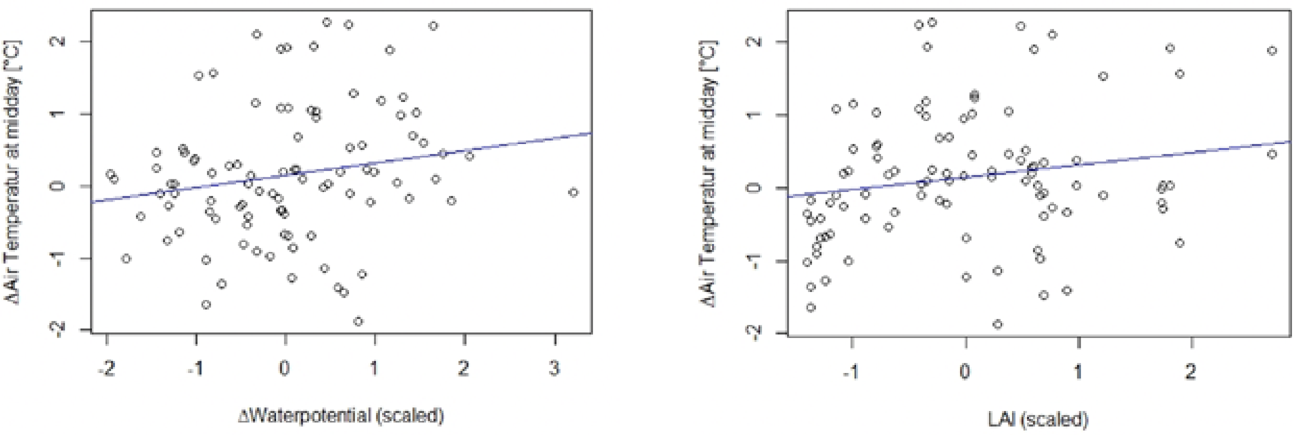


**Figure 1** Effect of range of water potential (ΔWaterpotential; left picture) and leaf area index (LAI; right picture) on range of air temperature (ΔAir Temperature). Positive values of air temperature mean lower temperatures beneath the tree crown.

Almost the same predictors show a significant influence on relative humidity at midday. Leaf area density is a further predictor on what relative humidity seems to relate to. Therefore, trees with a dense crown show less relative humidity beneath.

## CONCLUSIONS

Based on our results we can conclude that the traits hbase, LAI and Δψ have the biggest effect on mitigation of air temperature and increase of relative humidity beneath a tree. LAD has an additional effect on relative humidity. Based on the traits recommendations could be to:

- Keep height of crown base low, where it's possible under given circumstances
- Plant trees with a high LAI and low LAD.

Further, we can see that trees which can cope with a high variance of leaf water potential seem to provide better cooling as temperature seems lower and relative humidity higher beneath the crown. As we did not measure over a longer period, this latter result has to be interpreted with care. More measurements would be required to clarify effects of Δψ.

### Data Availability (or) Available Information

Data is available upon request.

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# Mobility in a changed climate

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## INTRODUCTION

The mobility project investigated the potential impact of climate change on the transport sector. For this purpose, the relationship between weather conditions and mobility behaviour was analysed on the basis of transport demand models. In addition, it was analysed how climate change will impact the energy consumption of different drivetrain systems. In particular, the effect of rising temperatures on energy consumption of internal combustion engines and battery electric vehicles was investigated.

Based on the results of the project, policy recommendations were derived that aim at both adapting the transport sector to climate change but also reducing the transport sector's impact on global warming.

## DATA AND METHODS

The B3 local data set of the survey "Mobility in Germany 2017" constitutes the most important source of data used in the project. Altogether around 316,000 people from 156,000 households contributed their travel information including trip origins and destinations that were spatially located in the Inspire grid system of the European Union. Based on the grid cells and the date and time of the trip starts, information from the measurement stations of the German Weather Service and regional climate models from the drivers project were added to the mobility data set.

The resulting data set allowed to include the specific information on weather conditions in transport demand models in addition to the usual mobility-related factors such as car ownership, driving license, age, household composition, etc. The models were first trained on the basis of the measured weather conditions. Then they were used to model the mobility behaviour under the weather conditions that are expected to be in place if the global warming levels of 1.5, 2.0, 3.0, and 4.0°C are reached. In order to extract the specific impact of climate change, all other relevant factors such as car ownership, public transport infrastructure etc. were kept constant in the analyses.

To analyse how climate change will affect energy consumption of passenger vehicles a model to calculate the change in energy consumption based on exemplary mobility data in different climate zones worldwide as well as actual German mobility data with respect to multiple global warming levels was set up.

## RESULTS

One of the main results of the analyses is that the choice of means of transport is much less affected by weather conditions than by other factors such as car ownership, public transport availability and cost, trip purpose etc. Indeed, there are no clear-cut impacts of air temperature, precipitation or wind speed on the usage of the car, public transport or walking. However, bicycle usage is an exception and the impact of air temperature on bicycle usage is almost linear as illustrated by Figure 1:

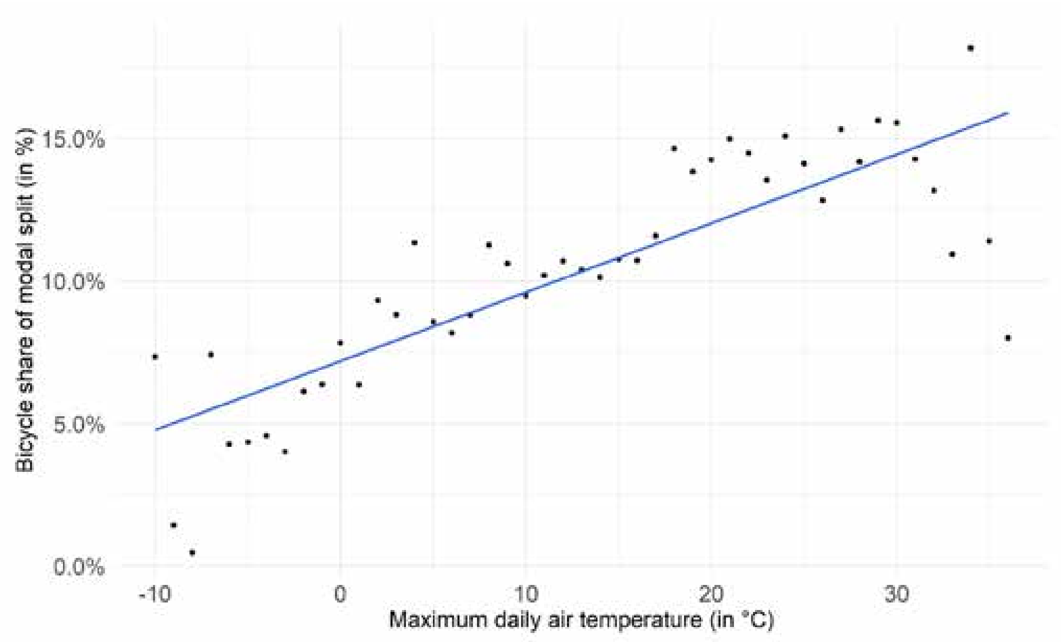


**Figure 1**. Bicycle share in the modal split for Germany by maximum daily air temperature. Source: Mobility in Germany 2017 for the mobility data and German Weather Service for the weather data.

In fact, the correlation between the share of the bicycle in the modal split and the maximum daily air temperature shows a remarkably high value of 0.83 Pearson's r. Also the adjusted $R^2$ is with 0.68 rather high. An increase in the maximum daily air temperature results in a rise of 0.24% of the bicycle share in the modal split for Germany. Against this background further analyses were conducted for the city of Berlin on the basis of bicycle count station data of the years 2017–2019 and the outputs of regional climate models. The results show that climate change will lead to an overall annual increase in bicycle traffic of 1–4% in the city of Berlin if all other factors such as infrastructure etc. are kept constant.

In addition, climate change will likely lead to an increased energy consumption of vehicles with an internal combustion engine due to the increase in cabin climatization caused by the higher ambient temperatures. At a global warming level of 4.0°C the calculated energy consumption on average is 2,1% higher than without taking the climate change related changes in temperature into account which would lead to nearly 2 million additional tons of $CO_2$ released. In contrast, battery electric vehicles are expected to have a lower overall energy consumption due to the lower heating needs during winter caused by global warming. At a global warming level of 4.0°C the calculated energy consumption is on average 2,4% lower than without taking the climate change related changes in temperature into account.

## CONCLUSIONS

The results show that above all bicycle usage will be positively affected by climate change. This development should be supported by an improvement and an extension of the existing bicycle infrastructure. This would both adapt the transport sector to the impact of climate change and at the same time help to reduce the transport system's contribution to climate change.

Furthermore, the results outline that the speed of the distribution of battery electric vehicles should be increased. Battery electric vehicles emit considerably less greenhouse gas emissions than cars with an internal combustion engine. In addition, climate change is expected to lead to a lower energy consumption of battery electric vehicles, while it will likely increase the energy consumption of vehicles with an internal combustion engine.

### Data Availability

The "Mobility in Germany 2017" dataset is available upon request at ***https://daten.clearingstelle-verkehr.de/279/***. The weather data used can be accessed via the open data portal of the German Weather Service ***https://www.dwd.de/DE/klimaumwelt/cdc/cdc_node.html***. The climate change data was provided by the drivers project.

### Literature

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# A storm monitor for northern and central Germany

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## INTRODUCTION

Storms are one of the major natural hazards affecting northern and central Germany. Due to the associated high wind speeds and heavy precipitation, storms can cause substantial damages and have severe impacts on infrastructure, population, etc. Along the coasts, storms may trigger secondary events such as storm surges and high waves, which in combination may lead to flooding with corresponding impacts and/or increase coastal erosion. Because of the existing risk and expected future developments, information on long-term changes in storm activity is important for decision-making (e.g. Kodeih 2018). In the aftermath of a storm and within the context of climate change, public discussions frequently debate whether the event was still "normal" or already showed imprints from anthropogenic climate change. Commonly, analyses for such assessments are not readily available but are typically published with some time delay. To address this gap, near-real-time automated analyzes within a detection and attribution framework (e.g. Hergerl et al. 2010) are needed.

In this study, a tool was developed that automatically integrates real-time measurements with long-term statistics and puts ongoing extremes and the course of the ongoing storm season into a climatological context in near-real-time. The tool, here referred to as storm monitor, was implemented for the northern and central parts of Germany and makes such information publicly available.

## DATA AND METHODS

To assess ongoing extremes in a historical context two types of data are needed. First, homogeneous long-term data are needed from which long-term statistics describing the present or recent state of the climate system concerning storms can be inferred. Second, real-time data need to be available to measure and describe the characteristics of ongoing events and seasons. Wind speed measurements, which would represent a natural choice to describe storm duration or intensity, are unfortunately often not homogeneous, as station relocations, vegetation changes, or the construction of buildings in the surrounding of a station can systematically bias the measurements. The latter becomes particularly problematic when long-term statistics and trends need to be assessed. A detailed discussion along with examples can be found e.g. in Weisse and von Storch (2010).

To address the issue, pressure-based proxies for storm activity were developed (Schmidt and von Storch 1993) and successfully implemented for the North Atlantic (e.g. Krueger et al. 2019) or the German Bight (Krieger et al. 2020) as pressure measurements are substantially less affected by inhomogeneities. For the storm monitor, the approach described in Krieger et al. (2020) was extended to cover northern and central Germany to derive statistics describing the historical storm activity in the different regions. An example is shown in Fig. 1 for the German Bight, illustrating pronounced interannual and decadal variability. Apart from that, there is presently no long-term trend in storm activity.

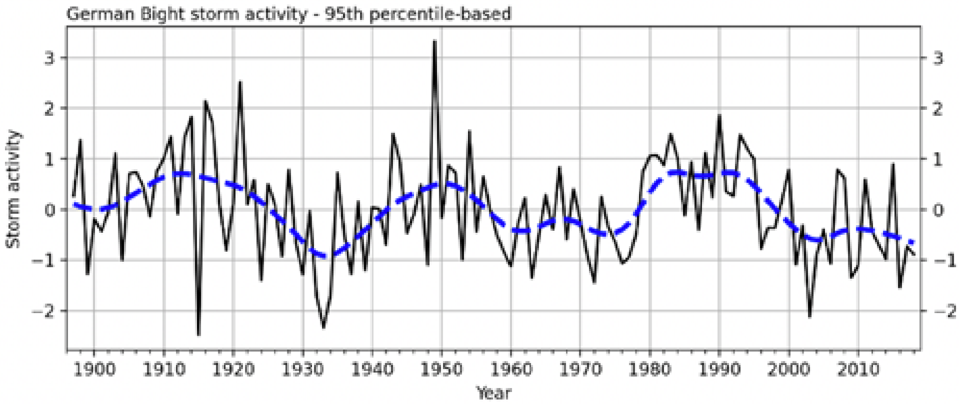


**Fig. 1**: Storm index for the German Bight 1897-2018 based on standardized annual 95thpercentiles of geostrophic winds over the German Bight (black) together with Gaussian low-pass filtered data (with parameter σ = 3) (blue) (adopted from Krieger et al. 2020).

Historic pressure data to derive long-term storm statistics were available from various sources that are described in detail in Krieger et al. (2020) and on the storm monitor website. Real-time pressure data are automatically fetched daily from the archives of the National German Weather Service. Based on that several storm statistics are automatically computed in near-real-time and put into perspective of long-term changes. The storm monitor is automatically updated daily such that near-real-time assessment of ongoing extremes and the ongoing storm season become possible.

## RESULTS

Fig. 2 exemplarily demonstrates some of the capabilities of the storm monitor for northeast Germany. In this region, between 01.07.2021-03.11.2021 a total of three storms was detected all of which were rather typical for the region with return periods of less than 2 years (Fig. 2, left). So far, the course of the current season is well within the observed range as the cumulative number of storms closely follows the long-term median (Fig. 2, right, top). The number of storms in October is above the long-term monthly average but well below the historical maximum (Fig 2, right, bottom).

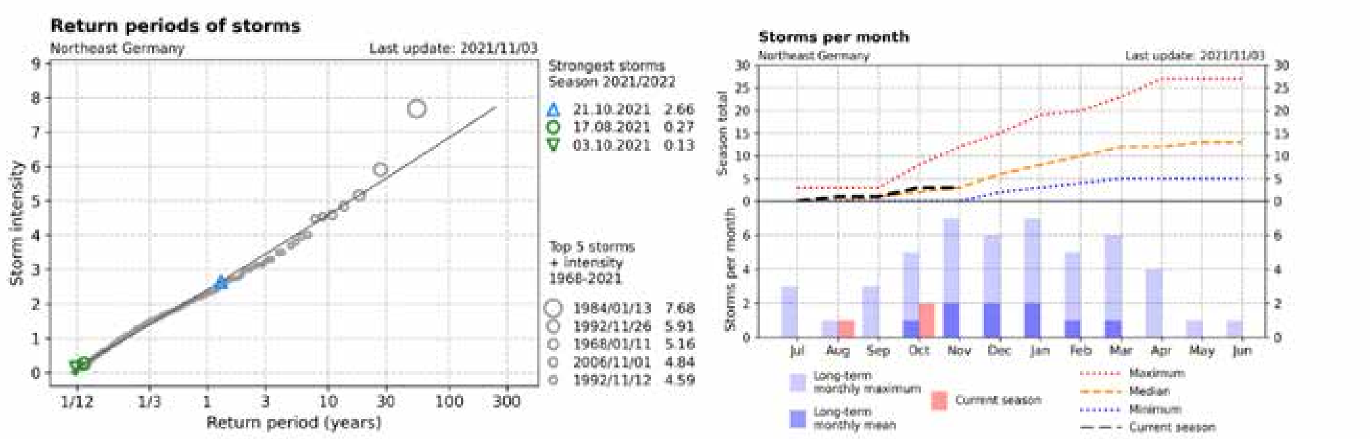


**Fig. 2**: Example snapshots of the storm monitor for northeast Germany as of 03.11.2021. Left: Return period of events in the ongoing storm season (colored symbols) against the historical background (grey). Right: (Top) Course of the ongoing storm season (black, dashed) against the historical distributions (red-maximum, orange-median, blue-minimum); (Bottom) Number of storms per month in the current season (red) and historical mean and maximum values (blue).

## CONCLUSIONS

The storm monitor implemented detects ongoing extremes in real-time and immediately puts them into a climatological context. This way, not only an assessment of the ongoing storm is achieved but also the development over the past is documented. The tool aims at providing easily accessible information to the public, science, and stakeholders supporting the evaluation of ongoing extremes. Measures to assess long-term changes can also be inferred from the monitor.

In particular, the monitor was found to be useful to the media, since it fits their needs to focus on actual threats and to contextualize them within a scientific frame. This is supported by numerous interview requests that were served after launching the monitor. We argue that the storm monitor can further serve educational purposes and can also be useful to researchers providing auxiliary information. We reckon that the tool has the potential to be developed into a larger suite of tools including, for example, other regions and/or other (coastal) hazards.

### Data Availability (or) Available Information

The monitor and the statistics are freely available online at ***https://storm-monitor.eu/***.

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# Assessment of Extreme Rainfall for risk modelling in Urban areas (ExRain)

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## INTRODUCTION

In recent years, the frequency and intensity of heavy convective precipitation has substantially increased in Germany. The rain increase is proportional to the increase in humidity at higher temperatures, as determined by the Clausius-Clapeyron scaling. Furthermore, in recent years, several episodes of atmospheric blocking, lasting several days to weeks, with an exceptionally high number of quasi-stationary thunderstorms – that locally produced extreme precipitation and triggered urban flooding – have been observed (e.g., May/June 2016 and 2018; Mohr et al. 2020). Consequently, urban flash floods and their related infrastructure damage, and water pollution from untreated sewage discharges have increase significantly. As such, it is pertinent that appropriate adaptation strategies are adopted. HI-CAM's project "Urban flash floods and sewerage", conducted in cooperation between KIT, GFZ, and UFZ, aims to simulate and assess the entire effect chain including extreme rainfall scenarios and their expected changes and temporal clustering, inundation and flooding, infrastructure damage, the effect of rainwater overflow, and the impacts on water quality and ecology.

The sub-project, ExRain, analyzes and assesses the frequency and intensity of extreme convective rainfall in Dresden, the urban test area, over past decades. Hourly extreme rainfall scenarios are simulated by spatially shifting observed extreme rainfall patterns to the region of interest. This method allows the estimation of convective extremes upper bounds. Probabilistic precipitation changes for future decades are quantified from an ensemble of high-resolution regional climate models (RCM). To better understand the temporal variability of the local-scale extremes, we also investigated their relation to large-scale dynamics in terms of atmospheric blocking (Mohr et al., 2019) or teleconnections (Piper and Kunz 2017), influencing serial clustering over periods of days to weeks.

## DATA AND METHODS

Extreme convective rainfall events were drawn from the RADOLAN v.2 data (Radar-Online-Aneichung; a merger of radar precipitation scans with station observations) from the German Weather Service (DWD) on a 1 x 1 km$^2$ grid with a temporal resolution of 5 minutes or 1 hour for the period 2001-2019. Future precipitation changes for the test area were quantified as anomalies from an ensemble of RCM simulations for temperature increases of 1.5 K (42 members), 2K (same), and 3K (38 members). The ensemble considered 4 global climate models (GCMs), 3 representative concentration pathways (RCPs 2.6, 4.5, 8.5), and 6 RCMs (CCLM, REMO, RACMO, RCA, HIRHAM, RCA). All ensemble members were provided by the HI-CAM consortium (UFZ).

Convective events were filtered from the sample of all extreme precipitation events by considering the spatial gradients of hourly precipitation totals (2-hours to include also events that spread over two time stamps) for 720 km² (720 grid points) areas, comparable to the area of Dresden. Based on this event set, rain totals for several return periods (T= 2, 5, 10, 20, 50, 100 years) were estimated at each grid point based on Peak-over-threshold with the Generalized Pareto distribution (GPD). The temporal clustering of extreme events was assessed using the "Dispersion-Index".

Because the 20-year period of the RADOLAN data is too short to produce reliable extreme estimates, we developed a method that artificially extent the time horizon of the data by identifying the most extreme events that have occurred elsewhere in Germany. The method virtually shifts the external extreme events to the test area. This method allows us to estimate upper bounds for the extremes.

Based on an ensemble of different RCMs for three different temperature scenarios (+1.5, +2, +3 K), we estimated how the frequency and intensity of convective extremes will change in the future. These datasets are processed in accordance to the present day data.

## RESULTS

According to the applied dispersion statistics (Pinto et al. 2016), the convection-filtered events selected for the catalogue shows a significant serial clustering. The considerable deviation from a Poisson process is due to the connection between the events and large-scale atmospheric circulation patterns, namely a blocking regime with the high pressure center over Poland and the Baltic Sea (Fig 1, left). This correlation between the most intense rainfall events and atmospheric blocking is evident for both the test area of Dresden and for other areas such as Hamburg (Fig. 1, right). Convective storms are propagating very slowly, or even become stationary, with the consequence of high precipitation accumulations on local areas (usually only a few RADO LAN grid points). The near-stationary behavior of convective storms is due to its relation to low geo-potential gradient blocking.

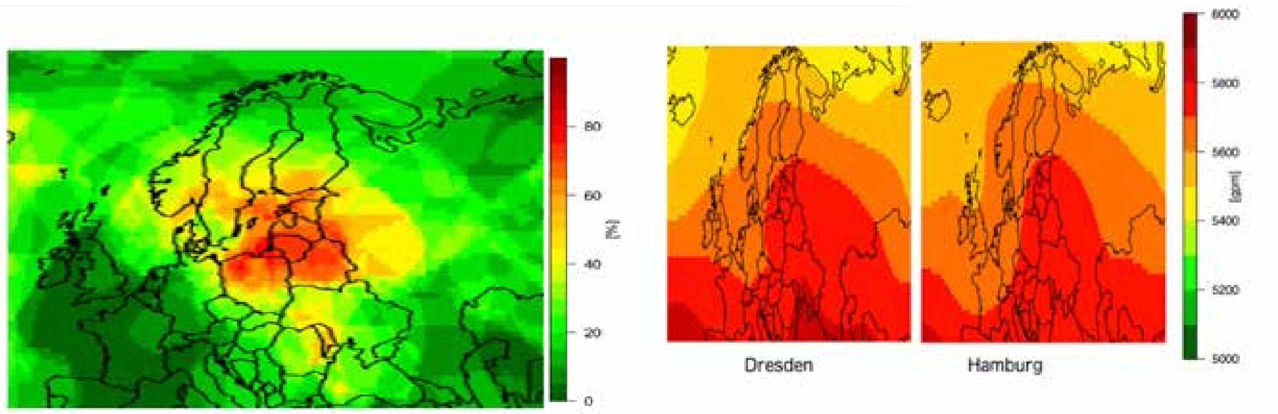


**Figure 1**: Percentage of the events associated with atmospheric blocking (left) and mean geopotential height at 500 hPa of the most extreme rain events according to RADOLAN (right).

In the last twenty years, the intensity of the most extreme events observed in Dresden was far below than what is expected for events that trigger urban flash floods (e.g., maximum areal precipitation of about 30 mm / 2 hours; 100-year return values between 60 and 80 mm). The underestimation of extreme events is attributed to the limited time period of the RADOLAN data. Simulating extreme events in the test area was conducted by the artificial shifting of said events to areas with similar characteristics and comparable elevation as the test region (between 100 and 300 m above sea level where Dresden is approx. at 113 m). The simulation extends our event catalogue to 2.7 million events, with mean areal totals approximately 2.5x greater than those of the original event catalogue. Both the new and original event catalogues were used as input for GFZ's hydraulic model, RIM2D (see Final Report "RIM2D – A generalized and fast GPU-based model for urban pluvial flood risk modelling and forecasting").

To estimate how climate change modifies convective precipitation totals – and with that increases the risk of urban flash floods and sewer system failures – we quantified relative changes of hourly precipitation based on an ensemble of RCMs for the Dresden area. For the event selection, we applied the same methods as the present-day data, including filtering of convective events. In the ensemble, all three temperature scenarios (+1.5, 2, 3 K temperature increases) show a considerable increase in summer precipitation, both for the area precipitation and at the respective grid points. The drawn correlation is the higher the percentiles, i.e. the more intense the precipitation totals are, the stronger are the changes (Fig. 2). Whereas the differences between the +1.5 and 2 K scenario are similar, the 3 K scenario show the strongest rain increase.

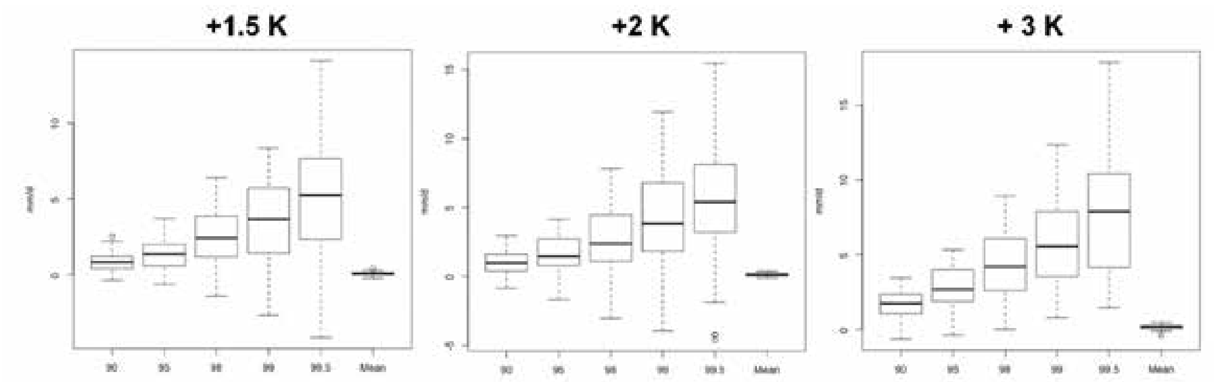


**Figure 2**: Changes of different percentiles of hourly rain totals from an ensemble of different RCMs for +1.5, +2, and +3 K temperature increase for the area of Dresden.

## CONCLUSIONS

We have developed a method that enables us to estimate upper bounds of convective extreme precipitation. The background of the method is the finding that heavy rain events can occur practically everywhere in Germany with approximately the same probability. This method was derived and applied to the test region of Dresden, but can be transferred to any region in Germany to estimate upper bounds of precipitation extremes. Together with the partners involved in the HI-CAM project "Urban flash floods and sewerage", the heavy rain fields can be used to identify urban areas highest exposed to risk, such as the Ahr valley with the devastating flood in July 2021 (Schäfer et al. 2021).

## Data Availability

The event set of extreme convective precipitation for Dresden test region (5 min, hourly, 2-hours; 2001-2019) and extreme precipitation estimates for different return periods (1,-10-, 100-year return period) are available upon request.

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# RIM2D – A generalized and fast GPU-based model for urban pluvial flood risk modelling and forecasting

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## INTRODUCTION

Urban flash floods caused by heavy convective precipitation pose an increasing threat to communes worldwide due to the increasing intensity and frequency of convective precipitation in a changing climate. Thus, flood risk management plans adapted to the current flood risk but also capable of managing future risks are of high importance to mitigate flood damages and risks. These plans necessarily need model based pluvial flood risk simulations in order to plan and implement appropriate and cost-effective flood risk management strategies. In an urban environment these simulations have to have a high spatial and temporal resolution in order to implement street and even block-specific management solutions, but also to be capable of simulating the flooding caused by spatially and temporal highly variable rainfall. Moreover, the effect of the sewer systems has to be included to achieve realistic inundation simulations, but also to assess the effectiveness of the sewer system and its fitness to future changes of the pluvial hazard. The setup of these models, however, typically requires a large amount of input data, a high degree of modelling expertise, a long time for setting up the model, and to finally run the simulations. Because of high costs associated with classical detailed urban hydrodynamic models, not all communes can afford such engineering services. Also, many consultancies cannot offer scalable solutions for large scales. This calls for a hydraulic model and a modelling approach, that is time efficient in both model setup and simulation runtimes, and that can be easily transferred to all communes in Germany. The hydraulic model RIM2D was developed within HI-CAM to fulfil these requirements.

## DATA AND METHODS

RIM2D is a 2D regular grid based hydraulic model for the simulation of inundation dynamics in urban areas considering the urban texture (streets and buildings) and the effect of the sewer system and infiltration on the inundation. RIM2D solves the inertial formulation of the shallow water equations with an explicit numerical scheme including an adaptive time stepping mechanism (Bates et al. 2010), and numerical diffusion for additional numeric stability (Almeida et al. 2012). RIM2D is coded in FORTRAN90, with the hydraulic kernel coded in FORTRAN CUDA for massive parallelization on NVIDIA Graphic Processor Units (GPUs). Conceptually, in an urban set-ting the sewer system and infiltration on non-sealed surfaces need to be considered in order to simulate realistic inundation dynamics. RIM2D achieves this by applying a capacity-based approach for both the sewer system and infiltration. Infiltration and sewer capacities are defined in terms of mm/h. Rain falling on the pervious and sealed surfaces is reduced by this capacity. The remaining rainfall amount defines the water ponding on each grid cell, which is then routed by the hydraulic model.

RIM2D is designed as a parsimonious model, using in most cases open data sets with a complete spatial coverage over Germany and beyond. The minimum data set for model setup includes:

- **1.** a high resolution DEM (≤ 5 m)
- **2.** a map of building footprints (e.g. by Open Street Maps)
- **3.** a land use map (e.g. CORINE land use maps)

The buildings are defined as blocking objects in the hydraulic routing, whereas the land use map serves for deriving the hydraulic roughness and the sealed/non-sealed surface areas. With this minimum amount of information RIM2D models can be setup for practically every commune in Germany, with a high degree of automatization. Within HI-CAM a RIM2D model was setup for a part of the city of Dresden, the Lockwitzbach catchment. The simulation domain covers an area of 26 $km^2$, with a total of about 1 million grid cells at 5 m resolution.

## RESULTS

The Lockwitzbach model was used to simulate several intensive rainfall events of the past two decades, driven by spatially distributed rainfall obtained from the RADOLAN rainfall radar product of the German Weather Service (DWD) in a temporal resolution of 5 minutes. The model runtimes were less than 1% of the simulated time, i.e. a rainfall event of 12 hours was simulated in a total of 350 seconds including the writing of output grid files.

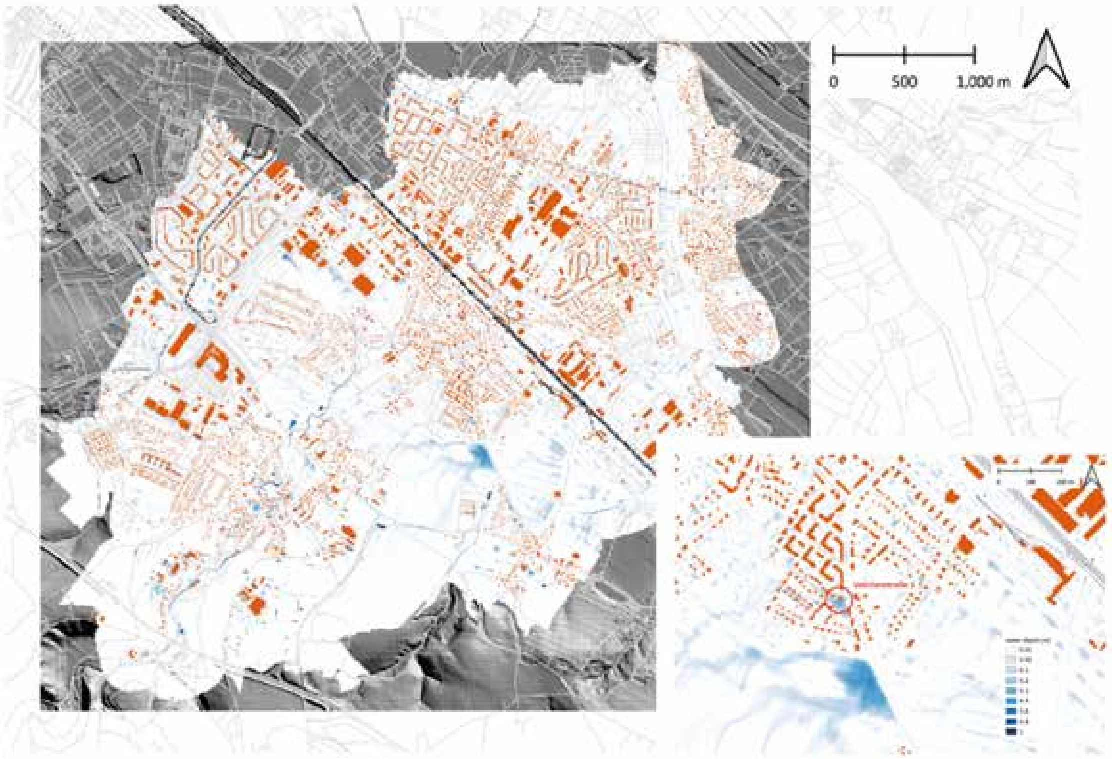
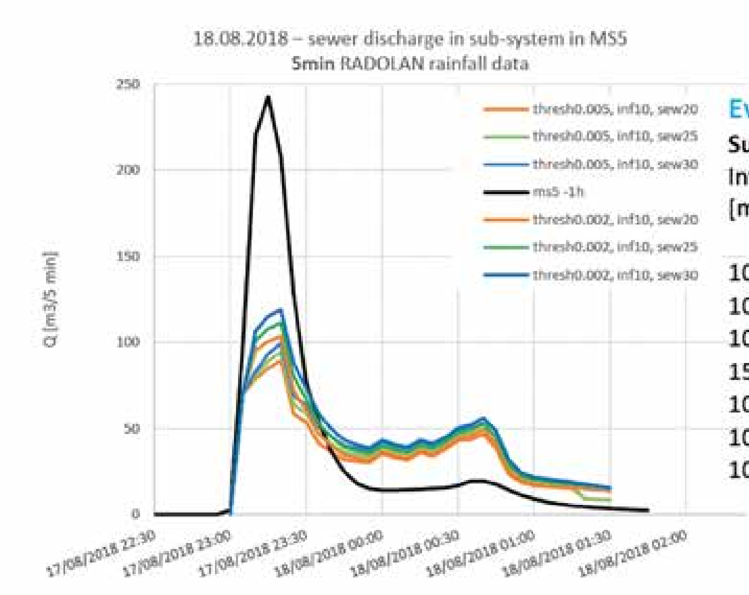



**Figure 1**: Simulated maximum surface inundation for the heavy precipitation event of 27th May, 2014 in the Lockwitzbach area of Dresden. The inset shows a plausibility check, comparing a reported basement inundation of a building (red circle) with the simulated inundation.

The surface inundation modelling was checked for plausibility by comparing maximum simulated inundation depth with reported surface inundation. The reports are, however, only qualitative, thus a quantitative assessment of the surface inundation modelling was not possible. **Figure 1** shows the simulation result of the rainfall event of May 27th, 2014, and the matching simulated and reported inundation of a basement.

Additionally, the important sewer stormwater discharge simulated by the model was checked with insewer discharge measurement undertaken by the Technical University of Dresden. The comparison of the measured and simulated sewer discharge is shown in **Figure 2**. The general dynamics of the sewer discharge is well reproduced by the model. However, the dynamics of the sewer discharge is underestimated. This has to be attributed to the simplified representation of the sewer system in the model, which neglects the dynamics of the water flow in the sewer channel and pipe network. The underestimation of the peak discharge can also be caused by a likely underestimation of the rainfall peak by the RADOLAN rainfall product. But more importantly, the overall sewer discharge volume can be well matched depending on the parameterization of the sewer capacity. The difference of only a few percent between modelled and measured sewer volume shows, that the implemented simplified approach of sewer system modelling can be used for reliable urban inundation modelling, if the model is parameterized with appropriate sewer system capacities. In order to obtain a generally applicable rule for estimating the best performing sewer capacity over all simulated events of 25 mm/h was compared to the KOSTRA rainfall statistics provided by the DWD. Following the rules of the German Water Association (DWA) for calculating the effective sewer loading from rainfall events, the determined sewer capacity corresponds to a high intensity rainfall event of a return period of 2 years and a duration of 15 minutes. As these rainfall events are typically chosen as design storms for the sewer systems in Germany, the KOSTRA data set can be used to derive sewer capacities in communes in Germany, where the actual sewer capacity is unknown.




**Event 2018-08-18**
**Subsystem MS5**

| Inf. Rate [mm/h] | sewercap. [mm/h] | threshold [m] | Volume - difference 23:00 - 01:30 |
|---|---|---|---|
| 10 | 20 | 0.005 | -4.02% |
| 10 | 25 | 0.005 | 4.30% |
| 10 | 30 | 0.005 | 11.69% |
| 15 | 30 | 0.005 | 1.85% |
| 10 | 20 | 0.002 | 4.94% |
| 10 | 25 | 0.002 | 14.42% |
| 10 | 30 | 0.002 | 10.90% |

**Figure 2**: Modelled and measured sewer discharge in the sewer subsystem M”5 of the Lockwitzbach area with different infiltration rates, sewer system capacities and thresholds for activation of the model sewer system.
The threshold indicates the surface inundation water depth, above which surface water is subtracted from the inundation according to the sewer capacity. The black curve indicates the measured sewer discharge.

## CONCLUSIONS

The development of RIM2D brought significant improvements in the simulation speed of high-resolution urban inundation modelling, while at the same time realistic simulations of both the surface inundation and sewer discharge volume were obtained. This enables the use of the model in probabilistic urban flood risk simulations, requiring numerous inundation simulations. Moreover, due to the minimal data requirements, which can be fulfilled with readily available and mostly public data sets, RIM2D can be implemented for practically every commune in Germany. This opens the door for pluvial flood risk assessments and thus an adapted flood risk management even in communes with limited resources. In order to facilitate the use of RIM2D in practice, the model will be made available to users under license.

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# A new, systematic and generic framework for assessing wastewater treatment plants at risk of causing adverse impacts on the aquatic ecosystem under climate change

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## INTRODUCTION

Security of freshwater resources and aquatic ecosystems is threatened by global challenges including population growth, urbanization, and climate change (UNEP, 2016). An increasing fraction of urban residents indicates greater amounts of households' wastewaters and therein pollutants over the upcoming decades (UN, 2019). Moreover, extreme hydrological conditions are expected to be more frequent under changing climate conditions (Stott, 2016; Hari et al. 2020). Given circumstances, Municipal wastewater treatment plants (WWTPs) will play more important role in ensuring water quantity and quality of receiving rivers water bodies. Thus the effects of their effluents on river bodies should be evaluated basin-wide to prevent water problems in the future (WWAP, 2017). Nonetheless, a systematic assessment framework has been missed with a holistic approach from end-of-pipe to the impacts of WWTP-effluents on receiving rivers. Therefore, based on data-model synthesis, this project aimed to develop a new, systematic, and transferable framework to assess WWTPs at risk of causing water security problems across river basins in any climate zone.

## DATA AND METHODS

Three large Central European rivers (Rhine, Elbe and Weser; ~185K, ~144K, and ~46K km$^2$) were selected as study areas. We used freely available EU Hydro dataset to indicate network layouts of the three rivers (EEA 2020a). The structural hierarchy of the river networks is represented by the Horton-Strahler stream-orders $\omega$ (Horton 1945) in the EU Hydro dataset. We employed EU-scale publically available WWTP-data reported to the European Environmental Agency (EEA 2019). Geospatial coordination of WWTP-discharge locations and the magnitude of population equivalent (PE; a proxy of people served by a WWTP) are included in the dataset. All WWTPs analyzed here were classified as five class-sizes k following German regulations based on the PE magnitude. We used daily river discharge simulated over the entire Europe using GFDL-ESM2M/RCP8.5 (Global Circulation Model/Representative Concentration Pathway) and the 3K warming level (Marx et al. 2018) with a spatial resolution of 5km based on the mesoscale hydrological model (mHM) (Samaniego et al. 2010; Kumar et al. 2013). The simulated river discharge for the first 30-year period crossing the warming level of 3K (the years 2067-2096 – far future scenario) was compared to the reference period (the years 1971–2000 – historical scenario).

Pressures of the treated wastewater from WWTPs to their receiving streams were quantified as the urban discharge fraction (UDF, 0~100 %). UDF is defined as the ratio between the discharged water from WWTPs and the total water flux in their corresponding receiving river (Yang et al. 2019). A higher UDF indicates a lower dilution capacity of the receiving river. To estimate the effects of WWTP-effluents on ecological risks at local-scale, we focused on two types of nutrients discharged from WWTPs, total phosphorous (P) and ammonium-nitrogen (NH4N). Assuming zero background concentrations for the nutrients in receiving river, the local mixing concentration (CP, CNH4N) was calculated based on the mass-balance principle. Nutrient loads in the WWTP-effluents were estimated as the product between PE and per-capita daily loads. We applied a binary classification of 'At risk' or 'Not at risk' to assess the WWTP-effluents (i.e., WWTPR or WWTPNR) for each of the three environmental indicators (UDF, P, and NH4N). In this project, WWTPR for a given indicator is assigned when 50% is below the probability to exceed the thresholds required for Good-Ecological-Status, i.e., UDF* = 3.1% (Büttner et al., 2020), CP* = 0.1 mgP/L (Heidecke et al. 2015), and CNH4N* = 0.1 mgN/L (BMUB/UBA, 2014).

## RESULTS AND IMPLICATIONS

For the three catchments, the NH4N indicator had the highest number of $WWTP_R$ in the far future scenario, whereas the TP indicator had the lowest (e.g., Fig. 1A). WWTPR for NH4N, UDF, and P indicators consisted of respectively 40~50%, 35~45% and 25~33% of total WWTPs in each catchment. The Weser River showed the lowest fraction for all indicators compared tothe Rhine and Elbe Rivers. This finding reflected a few distinct characters regarding the WWTPs' distribution in the Weser: less fraction of WWTPs in smaller streams, and more spread people served by a WWTP. All three indicators (NH4N, UDF, and P) showed non-uniform distributions of $WWTP_R$ over the entire ranges of WWTP class-size (k) and stream-order (ω) in the three rivers (e.g., Fig. 1B). Specifically, $WWTP_R$ for each indicator were grouped in lower-order streams ($\omega < 3$) and spanned across almost all class-sizes. For a given k-ω combination, the fraction of $WWTP_R$ out of total number of WWTPs was generally higher for greater k and lower ω. The results indicate that smaller receiving streams are highly vulnerable to direct effluents of WWTPs, which are related to the degradation of water quality and the loss of aquatic ecosystems integrity. We estimated the differences in the fraction of $WWTP_R$ for individual indicators between the two periods, to identify how climate-induced dynamics of streamflow would affect WWTPR, (e.g., Fig. 1C). For three basins, lower-order streams receiving discharges of middle-size WWTPs (i.e., $\omega < 4$, k = 2~4) showed the most differences. The pattern revealed that the lower-order streams were already deteriorated by the largest WWTPs during the wetter historical scenario due to insufficient dilution capacity.

The systematic and transferrable risk-assessment framework presented here can be flexibly applied to larger spatial scales. Extension of the framework to continental- or global-scales will facilitate appraising the environmental policies on WWTP-discharges or evaluating progress to fulfill international commitments to water quality protection in a consistent way. For example, the European Urban Waste Water Treatment Directive (UWWTD) provides concentration thresholds for WWTP-effluents categorized by the WWTP-sizes and treatment levels. The most stringent regulations in the UWWTD are applied to WWTPs with the most advanced tertiary treatments regarding nutrient concentrations in WWTP-effluents. Nonetheless, as this project revealed, even WWTP-effluents satisfying the most stringent regulations are expected to cause environmental risks especially to smaller streams. Thus, our results underpin the necessity to amend the regulations towards more consideration of the receiving river perspective, e.g. by using the strem-order. Adverse effects highlighted here may be more prominent in other European catchments with lower connection of people to tertiary-level treatment. Further analyses at EU-scale are required to support or contradict this hypothesis.

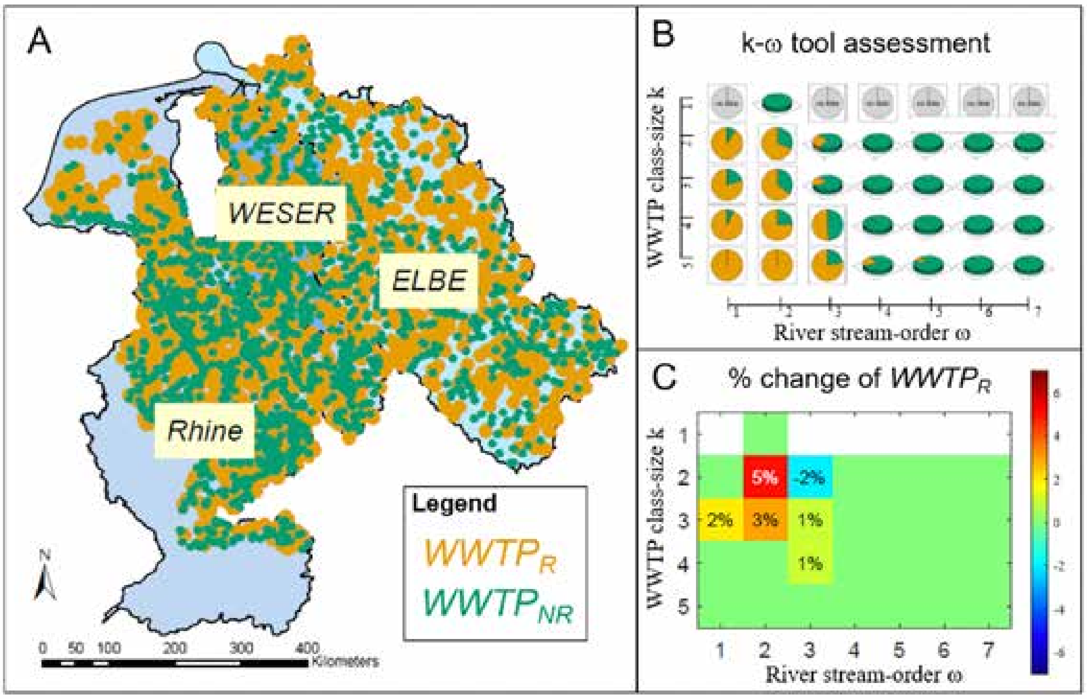


**Figure 1**. Selected key results of this project. (**A**) For the studied three river basins, the risk-assessments for NH4N concentrations at the local-scale in the far future are visualized for $WWT_{PR}$ in orange and $WWTPN_R$ in green. (**B**) For the Rhine River, the result shown in (**A**) is de-picted by following the k-ω tool frame with the same color-codes of two status. (**C**) The k-ω rep-resentation for the changed % of $WWT_{PR}$ from historical to the far future scenario regarding the NH4N indicator over the Rhine river basin.

## CONCLUSIONS

This project developed a new systematic and transferable framework to assess $WWTP_R$ across any river basin in any climate zone. It consists of a factorial combination between the number of connected population (WWTP class-size k) and the WWTP-effluent location in a river network (River stream-order ω). As case studies, we evaluated the environmental risks of WWTP-effluents releasing to three large river basins in Central Europe (Rhine, Elbe, Weser) under the most extreme scenario of projected climate in the far future. Under climate change, for the three indicators examined (UDF, P, NH4N), $WWTP_R$ is expected to be more evident in lower-ω streams across almost all-k. Higher k results in more $WWTP_R$. The presented framework can be used to plan catchment- and/or indicator-specific actions for WWTP-technology adaptation to climate change. Furthermore, it can play a key role in assessing progress towards the achievement of long-term international commitments to freshwater security for humans and ecosystems. Note that the presented results will be published soon in Earth's Future (Yang et al., 2022).

### Data Availability

Dataset of the EU Hydro and the EEA WWTPs are publically available. The daily streamflow data simulated using the mHM is available upon request.

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# CLUSTER II:
# HI-CAM-ADAPTATION
## Climate change, public health impacts and adaptation

**Centers involved:**

HelmholtzZentrum münchen
Deutsches Forschungszentrum für Gesundheit und Umwelt

HZI HELMHOLTZ
Zentrum für Infektionsforschung

UFZ HELMHOLTZ
Zentrum für Umweltforschung

dkfz.
DEUTSCHES KREBSFORSCHUNGSZENTRUM IN DER HELMHOLTZ-GEMEINSCHAFT

MDC MAX-DELBRÜCK-CENTRUM FÜR MOLEKULARE MEDIZIN IN DER HELMHOLTZ-GEMEINSCHAFT

DZNE

# Climate change, public health impacts, and adaptation

Climate change presents an unacceptably high risk for the current and future health of populations worldwide (Watts et al. 2019). In Germany, harm to health is directly caused by extreme weather events, particularly by high ambient temperatures during heatwaves (Breitner et al. 2014, Brachat-Schwarz et al. 2017, an der Heiden et al. 2019a, an der Heiden et al. 2019b). Further, climate change also affects human health through changes in ecosystems. Changing environmental conditions might result in modification of occurrence, density or activity of vectors (mosquitoes and ticks) of infectious diseases. This includes vectors of infectious diseases that are already present in Germany, such as Lyme disease (Borreliosis) (Lotto-Batista et al. 2021). Rising temperatures also alter the allergenic pollen biology by extending the seasonal duration and pollen load of plants, such as ragweed (Ambrosia artemisiifolia), thereby increasing the burden of asthma and airborne allergic reactions (Ziska et al. 2019).

Most at risk to the effects of high air temperatures are the elderly, infants, patients with chronic diseases such as cardiovascular, metabolic, and kidney disease (Schneider et al. 2017, Matthies et al. 2008). Due to its aging population, high rates of urbanization, and high prevalence of cardio-metabolic diseases, the European and specifically the German population is highly vulnerable (Watts et al. 2019). Increased temperatures are associated with increased acute mortality both in Germany and worldwide. The summers of 2003, 2006, and 2015 claimed high numbers of deaths attributable to heat exposure (an der Heiden et al. 2019a).

The HI-CAM subproject “Health” focused on biomarkers, physiological patterns, mechanistic pathways, and association of diseases with climate variables that are influenced by ambient temperatures. For this purpose, novel temperature data using satellite-based, spatiotemporal models were generated at HMGU and linked with NAKO data. At the DZNE, data from the Rhineland study were also linked to the novel temperature data, and relationships between air temperature and physiological parameters (including metabolomics data) were investigated. In addition, HMGU incorporated results from a study on the association of temperature with cause-specific mortality in the 15 largest cities in Germany into the project. The preparation of NAKO data on cardio-metabolic diseases and the assessment of the reliability of questions were performed at the MDC. At DKFZ, the joint impact of temperature and UV radiation on infectious disease antibodies was explored to monitor exacerbations and impact on cancer risk. Allergy research at HMGU has developed a basic model with relevant weather and pollution parameters in order to be able to map the effects of climate change on the triggers of allergies. In addition to developing a risk score for thunderstorm-related asthma and improving the database of pollen and fungal spores, HI-CAM was also able to develop a statistical model for predicting allergic reactions.

Understanding disease dynamics of climate sensitive infectious diseases, such as borreliosis, is key for predicting potential modifications resulting from a changing climate. The research team at HZI approached this system from two perspectives. On the one hand, they looked for serological evidence of Borrelia burgdorferi in a single-centre cohort together with the DZNE, known as the Rhineland Study, and later extended this serosurvey to NAKO participants coming from four study centres. On the other hand, HZI developed a probabilistic model to detect and quantify sensitivity to climate in Lyme disease, i.e. borreliosis cases captured by the national surveillance system.

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# Model-based projection of one health risks from Ixodes ricinus ticks under climate change

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## INTRODUCTION

The castor bean tick Ixodes ricinus, is the most widespread tick species in Europe and especially in Germany (Rubel et al. 2021). It is an important vector of pathogens causing Lyme borreliosis and tickborne encephalitis. The population dynamics depend on complex interacting biotic and abiotic factors which complicates the prediction of the future abundance and activity of I. ricinus and the associated health risk for humans (Brugger et al. 2018). The objective of this HI-CAM health sub-project was to combine ecological-epidemiological models with high-resolution climate projection data to extrapolate I. ricinus tick abundance and activity patterns into the distant future. For this purpose, we developed a spatially-explicit population model to simulate I. ricinus on the local scale. This model was linked to high-resolution climate projection data to make statements about future shifts in temporal activity of tick nymphs that pose the highest risk of contact to humans. In a further step (07/2021-11/2021), we added a borreliosis infection module to the population model to make nuanced statements about the exposure risk in future landscapes. We produced a Germany-wide map to predict changes in the occurrence of I. ricinus nymphs for different climate scenarios to better assess the health hazard of vector contact under climate change.

## DATA AND METHODS

**Data**: For model input we used EURO-CORDEX projection data of temperature, precipitation, and relative humidity for the period between 1971 and 2099 from 15 different climate models covering Germany with a horizontal grid resolution of 0.11 degree (~12.5 km). This data was provided by The Climate Service Center Germany. In addition, we used data of temperature and relative humidity for the period between 1949 and 2020 from the German Weather Service (2021).

**Product 1 (Local tick population model):** Tick activity was addressed with a newly developed climate-driven cohort-based and spatially-explicit tick population model. We simulated the seasonal population dynamics of I. ricinus using climate forecasts between 1971 and 2099 and recorded weather data since 1949 at a specific location in southern Germany. We evaluated different qualitative descriptors of tick ecology, e.g. the maximum questing activity of the nymphal stage, the questing activity of the nymphal stage in the seasons of a year and the minimum questing activity of the nymphal stage in summer.

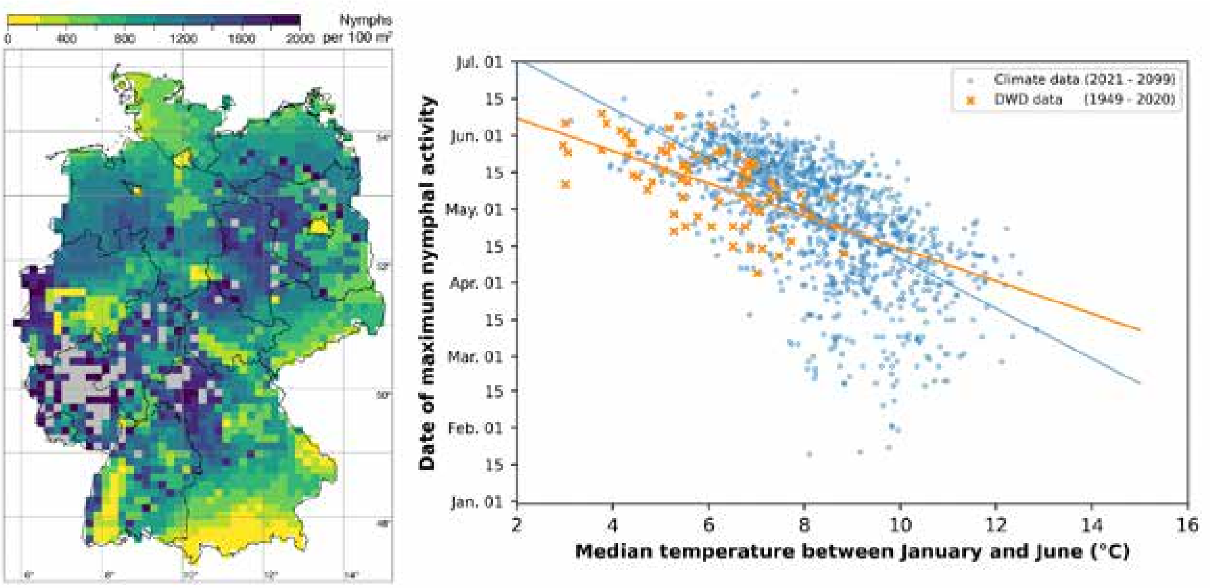


**Figure 1 (left)**: Germany map of nymphal Ixodes ricinus density anomalies depicting the change between the reference period (1971–2000) and the long-term scenario (2070–2099). If the density exceeds the threshold of 2,000 nymphs/ 100 m2, the grid cells are indicated in grey.
**Figure 1** (**right**): Relationship of the median temperature between January and June (x-axis) and the date of maximum nymphal peak activity (y-axis). Each data point corresponds to a simulation of a given year. Orange crosses represent IRIS simulations with weather data from the German Weather Service (DWD, 1949–2020). Blue circles represent IRIS simulations with input data from 15 different climate models for future years (2021–2099).

**Product 2 (German-wide tick density projection):** We used the negative binomial regression model introduced by Brugger et al. (2016) to predict changes in spatial nymph densities of I. ricinus across Germany. The nymphal density was estimated using mean annual temperature, mean temperature of driest quarter, annual precipitation, mean annual relative humidity, land cover/use, and geographical latitude. For comparison with the reference period (1971–2000) four climate scenarios were considered: the near-term scenario (1.5K, 2012–2041), the mid-term scenario (3K, 2050–2079), and the long-term scenario (4K, 2070–2099). We applied the technique of ensemble projections to estimate the most likely prediction considering the 15 climate models. We estimated the I. ricinus nymphal density for each simulation. The 30a-reference period and three 30a-scenarios provides us with the range of the projected future nymphal tick density. An ensemble mean was calculated for each scenario and anomalies be-tween the scenarios and the reference depicted.

## RESULTS

We found (Nolzen et al., 2022) that the peak of nymphal questing activity would shift towards early seasons of the year, from end of June to early April the further the climate projection data went into future (**Figure 1, right**). Interestingly, the principle trends of the climate projection for future years could be seen already from data of the climate history. With regard to the German-wide tick density projection, we found high spatial heterogeneity of predicted tick abundance across Germany, with hot spots of up to 2000 nymphs per 100 m$^2$, as well as cold spots without density changes (**Figure 1, left**).

## CONCLUSIONS

We successfully combined two ecological-epidemiological models with high-resolution climate projection data to extrapolate I. ricinus tick abundance and activity patterns into the climatic future. This allowed us to estimate the expected spatial and temporal risk of tick vector contact from outdoor activities under given climatic conditions. Linking our models with climate simulation data facilitated the prediction of plausible changes in health hazards in the distant future.

### Data Availability

The tick population model (IRIS) and its documentation according to the ODD protocol is available online under: *https://git.ufz.de/ecoepi/iris*.

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# Quantification of the influence of climate on Lyme disease cases reported to the German surveillance system

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## INTRODUCTION

Lyme disease, also known as borreliosis, is the most common arthropod-borne disease in Europe (Semenza and Menne 2009). Borrelia spirochetes causing the disease are transmitted by ticks of the genus Ixodes sp. Socio-demographic characteristics such as age, sex, occupation and type of recreational activities have been widely associated with seropositivity or occurrence of disease (Wilking and Stark 2014; Wilking et al. 2015, Enkelmann et al. 2018). On the other hand, it is possible to identify optimal environmental conditions for tick development and outdoor activities (Ehrmann et al. 2017). Tickborne diseases belong to a wide group of infectious diseases known for their sensitivity to climate. Ticks' activity is influenced by humidity and temperature and is indirectly affected by modifications in the environment (Ostfeld and Brunner 2015). In a world undergoing climate change, it is important to quantify the influence that these factors have on occurrence of disease.

## DATA AND METHODS

In this project, we used monthly case counts, stratified by region (NUTS-2), age and sex, reported to the German surveillance system and publicly available at the Survstat@RKI 2.1 platform (RKI-Ratgeber). We used land cover data derived from the CORINE project, climate reanalysis products from ERA5-land and tick density generated by colleagues at the Helmholtz Centre for Environmental Research (UFZ). Here, we established partnerships with Friedrich Boeing and Hans-Herman Thulke from UFZ in Leipzig, and Thomas Remke from the Helmholtz Centre Hereon, Climate Service Centre Germany (GERICS) in Hamburg.

We started by exploring correlations between variables to prevent collinearity. Correlation analysis allowed us to reduce the set of variables to include in candidate models. We then proceeded to use a Bayesian probabilistic modelling framework to quantify the effect of each of the selected variables on the number of cases reported to the surveillance system. We tested models of increasing complexity and evaluated their performance using a combination of goodness of fit statistics such as the deviance information criteria (DIC) and R2.

## RESULTS AND CONCLUSIONS

Overall, our final model fits data with high accuracy, reflected in a DIC decrease of 385 compared to the reference model, as illustrated by the exemplary time series from Brandenburg (Figure 1). When looking at effect sizes, we found that some climate and environment variables had a marginal yet significant on occurrence of Lyme disease, as observed with temperature and soil water (Figure 2). Additionally, model outputs showed that land type is a strong driver of disease occurrence and that the risk is higher in areas with high vegetation coverage, coinciding with the literature (Ostfeld and Brunner 2015; Ehrmann et al. 2017). Finally, from a demographic perspective, risk of disease was higher in females and people above 50 years old. These results resemble those reported by Enkelmann and colleagues in 2018 (Enkelmann et al. 2018). We did not detect a meaningful effect of tick density on the number of cases reported to the surveillance system.

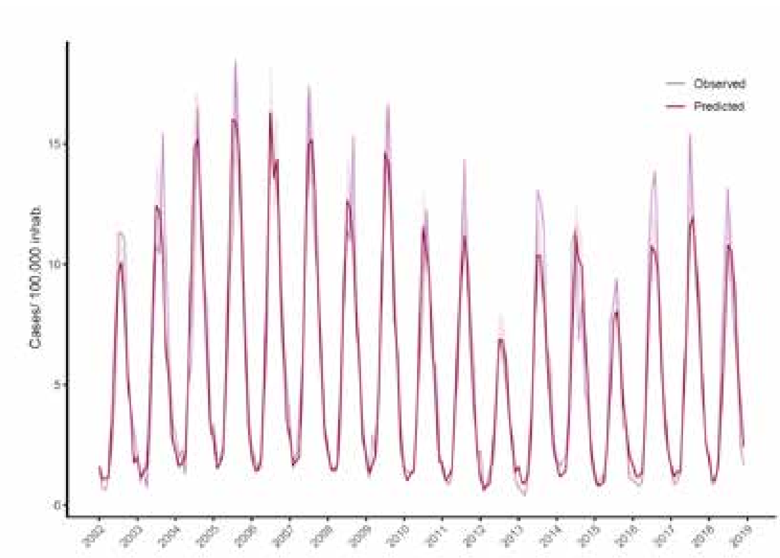


**Figure 1**. Observed versus fitted incidence with 95% credible intervals in Brandenburg between 2002 and 2018.

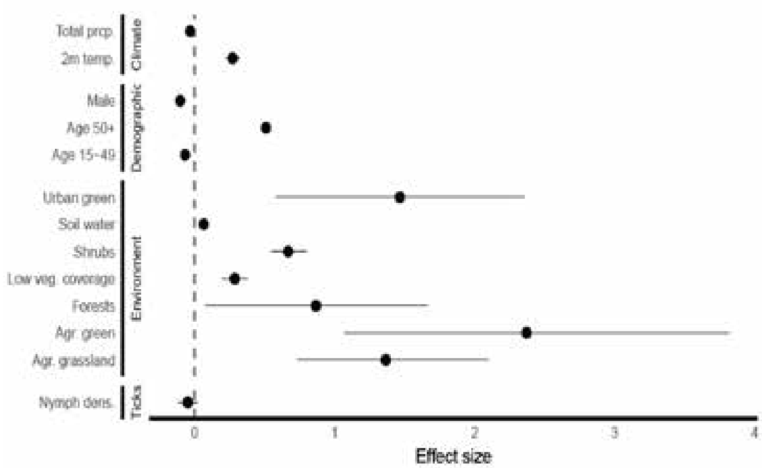


**Figure 2**. Effect size with 95% credible intervals of environmental, demographic and climatic variables on cases reported to the German surveillance system.

Although the effect sizes seem to be small, it is possible to capture the indirect influence of climatic processes in the number of cases reported to the surveillance system. Furthermore, these results imply that it might be possible to predict the number of cases of Lyme disease in upcoming decades with scenario-specific climate data. In order to achieve this, our next steps involve testing and validating our model for performing predictions.

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# Effects of air temperature on health & seroprevalence of Lyme borreliosis in the Rhineland Study population

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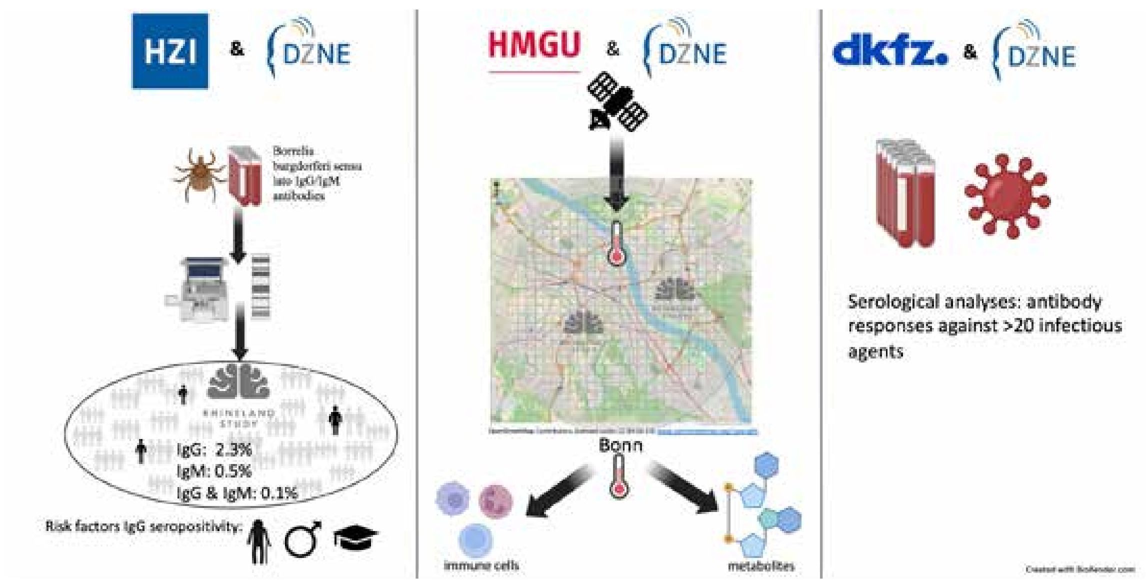
## INTRODUCTION

Since the pre-industrial era, there has been a rise in the global average temperature of 1.1°C (Deutsches Klima-Konsortium et al., 2021). Climate change bears considerable risks for human health via both direct and indirect mechanisms (Watts et al., 2015). Direct effects of climate change are for example prolonged heat periods that lead to heat stress (Watts et al., 2015). Ex-amples of indirect mechanisms are air pollution or decreased water quality (Watts et al., 2015). Further, a rise in the average air temperature likely increases the exposure risk to vector-borne diseases such as Lyme borreliosis (Dautel et al., 2008; Gray et al., 2009), which is the most prevalent tick-borne disease in Europe (Dehnert et al., 2012).

The overarching aim of this project was to investigate how climate affects health across a wide age range in the population-based Rhineland Study cohort. For this, we conduct 3 subprojects:

1. In collaboration with colleagues from the HZI, we examined the seropositivity and risk factors for Borrelia burgdorferi sensu lato in the Rhineland Study population.
2. In collaboration with colleagues from the HMGU, we are analyzing the relation between fluctuations in air temperature and immune markers and metabolomics profiles.
3. In collaboration with colleagues from the DKFZ, we conduct serological analyses to quantify antibody responses against more than 20 infectious agents, and how they change over time.

**work completed** | **work in progress** | **work in progress**



## DATA AND METHODS

We used data from the participants of the Rhineland Study, which is a population-based cohort study in Bonn. All inhabitants of two geographically defined areas in Bonn who are at least 30 years old and have sufficient command of the German language to provide written informed consent can participate upon invitation. Study eligibility is irrespective of health status. All participants undergo an 8-hour in-depth multi-domain phenotypic assessment including blood withdrawal.

The population-level profiling of immunoglobulin G (IgG) and immunoglobulin M (IgM) antibodies for Borrelia burgdorferi sensu lato in participants of the Rhineland Study was conducted by our collaboration partners of the HZI. The serostatus was determined using a two-step approach that includes an initial screening ELISA and subsequent analyses of all borderline and positive results with a line blot. We then associated the data on the serostatus with possible determinants of Lyme borreliosis, i.e. age, sex and socioeconomic status.

For subproject 2, our collaboration partners from the HMGU in Munich provided satellite-based spatiotemporal resolved air temperature data for Bonn for the years 2016 to 2019. To map the air temperature data to the residential addresses, we first placed a 1km*1km grid over Bonn and aligned each address to the center of the corresponding grid square. This prevents conclusions on exact residential addresses. We then aligned the air temperature data to the residential addresses by using spatial coordinates. This was the prerequisite to start the analyses on the associations between air temperature data and metabolites profiles and immune markers.

For subproject 3, together with our collaboration partners from the German Cancer Research Center (DKFZ), we decided which viruses should be tested for in participants of the Rhineland Study for subsequent analyses.

## RESULTS

Antibodies for Borrelia burgdorferi sensu lato were present in 2.9% of the Rhineland Study population. Risk factors for IgG seropositivity were old age, male sex and high educational status. More detailed results on the serosurvey can be found in the final report entitled “Lyme Borreliosis antibodies in a German population-based cohort (Rhineland Study)”. We jointly prepared the manuscript with the HZI. It is currently under review.

The satellite-based spatiotemporal resolved air temperature data could successfully be matched to the residential addresses of the participants of the Rhineland Study that had their examinations between 2016 and 2019. Data for more recent years are planned to follow and analysis is ongoing.

The samples for subproject 3 have been sent to our collaboration partners at the DKFZ in Heidelberg and analyzed by them. Analysis of this data at our group is ongoing.

## CONCLUSIONS

We could confirm that old age and male sex represent risk factors for IgG seropositivity. The seropositivity for Borrelia burgdorferi sensu lato was similar in the Rhineland Study population compared to previous nationwide serosurveys. Further work within this project is required to assess antibody responses in the Rhineland Study population against other infectious agents. Results on subprojects 2 and 3 are still pending.

### Data Availability (or) Available Information

The datasets are not publicly available because of data protection regulations. Access to data can be provided to scientists in accordance with the Rhineland Study's Data Use and Access Policy. Requests to access the datasets should be directed to Dr Monique Breteler, *RS-DUAC@dzne.de*.

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# Lyme Borreliosis antibodies in a German population-based cohort (Rhineland Study)

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[*] Monique M.B. Breteler and Stefanie Castell contributed equally to this work.

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## INTRODUCTION

Lyme borreliosis (LB) is the most common tick-borne disease in Europe [1,2]. Furthermore, due to climate change, cases are expected to increase over time [3]. However, Lyme borreliosis is a notifiable disease in nine of 16 German states, excluding North-Rhine Westphalia (NRW), and the literature offers no recent serosurveys for this region. Therefore, little is known concerning the disease frequency [4] or seroprevalence of Borrelia burgdorferi sensu lato (B. burgdorferi s.l.) antibodies. For regions without an infectious disease notification system, serosurveys may pro-vide estimates for infection risk. In the literature, several risk factors for sero-positivity have been identified and partially remain under discussion. For example, people with increased age among adults or male sex may have a higher risk for seropositivity [5]. In contrast, the role of socioeconomic status and its interplay with outdoor exposure remains debatable [6-8]. Conse-quently, our overall aim was to assess B. burgdorferi s.l. seropositivity and its risk factors in NRW. The German Center for Neurodegenerative Diseases (DZNE) and Helmholtz Centre for Infection Research (HZI) started collaborative work on the aforementioned research question within HI-CAM. The results can then inform modelling activities that project potential developments of LB under various climate scenarios.

## DATA AND METHODS

DZNE and HZI jointly organized a seroepidemiological investigation of B. burgdorferi s.l. antibodies among subjects of the Rhineland study (Bonn area). Blood samples were assessed using enzyme-linked Immunosorbent assay-tests (ELISA) and Line immunoblots for the presence of immunoglobulin G (IgG) and immunoglobulin M (IgM) antibodies for B. burgdorferi s.l. For further analysis of risk factors, data on demographics and socioeconomics were available. We calculated the odds for IgG- or IgM seropositivity using regression models while adjusting for demographics and socioeconomics. In sensitivity analysis, we considered the raw ELISA quantitative scale and also positive, borderline and negative immunoblot results (IgG and IgM) as the outcome.

## RESULTS

In the Rhineland serosurvey, we detected IgG and IgM antibodies for B. burgdorferi s.l.in our study sample. In addition, we found increased odds for IgG seropositivity for differing demographics and socioeconomics. However, we found no statistical link between any of our in-cluded variables and IgM seropositivity.

## CONCLUSIONS

The serosurvey for IgG and IgM antibodies for B. burgdorferi s.l. in the Rhineland Study offers new insights and complements dated serosurveys in Germany and Lyme borreliosis incidence from the notification system which do not cover NRW. Future investigations are still required for further insights on seropositivity and risk factor assessment, including weather variables. HZI initiated a similar seroepidemiological survey for local study subjects from the German National Cohort Study (NAKO) in Hannover, Münster, Berlin and Augsburg. These pending serosurveys enable us to map potential geographical variation in seropositivity and investigate additional potential risk factors (e.g. smoking status, BMI, seasonality and dependency on weather, tick density (Hannover)).

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# Impact of environmental factors on asthma-related emergencies: Thunderstorm asthma in southern Germany

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## INTRODUCTION

Allergic reactions and diseases are of high social relevance as they already affect 40 percent of the European population and the trend is strongly rising. With regard to climate change and the resulting changes of vegetation zones, highly allergenic pollen like Ambrosia are going to disperse into new territories in Europe increasing the health risk for allergic individuals (Ludwig et al. 2021, Traidl-Hoffmann et al. 2014, Rasmussen et al. 2017). Asthma, a noncommunicable and chronic disease characterized by recurrent attacks of breathlessness and wheezing, can be triggered by allergic reaction due to aeroallergens (pollen and fungal spores) in the outside air.

In the year 1999 the phenomenon of thunderstorm asthma was first discovered, describing the increase of asthma-related emergencies during a thunderstorm event (Packe and Ayres 1985). The severest and also most prominent thunderstorm asthma event with epidemic proportions occurred in Melbourne, Australia in November 2016 with more than 3500 patients searching for emergency health services due to respiratory distress and also ten deaths according to this epidemic stroke were detected (Hew et al. 2019). The pathogenic mechanisms of thunderstorm asthma are not fully understood yet. In general, it is assumed that the cooccurrence of aerosols like air pollutants, pollen and fungal spores are broken into smaller particles due to osmotic shock and mechanical breakup within the thunderstorm cell. These smaller particles are able to infiltrate deeper into the respiratory tract and intensify the allergic reactions. Also, strong downdraft and winds can cause a higher concentration of aeroallergens on the ground level (Taylor and Jonsson 2004; D'Amato et al. 2017). In Europe, southern Germany belongs to the regions with highest activity of lightnings. With regard to climate change, it is assumed that this activity will further increase due to more extreme weather conditions (Rädler et al. 2019; Raupach et al. 2021). For this reason, the phenomenon of thunderstorm asthma was investigated for southern Germany (Bavaria) in cooperation with the University of Augsburg, Institute for Geography, Physical Geography and Climate Science, the Department of Pediatric Pneumonology and Allergology, Children's University Hospital Augsburg, the Bavarian State Ministry of the Environment and Consumer Protection (StMUV) and the Bavarian State Ministry of Health and Care (StMGP) (Straub et al. 2021). With this retrospective study, the impact of the cooccurrence of thunderstorm and aeroallergens on asthma-related emergencies is investigated. The overall goal of our studies is the implementation of a real-time forecasting model, providing quantified risk factors according to environmental conditions in order develop clear recommendation for action like medication for affected individuals.

## DATA AND METHODS

Asthma-related emergencies were provided by the Bavarian Association of Health Insurance Doctors (KVB) with a regional resolution for 5-digit postal code areas (see Figure 1). Data from the BLIDS (Blitz Informationsdienst Siemens) lightning detection network were provided by Sie-mens AG for southern Germany (47–51°N; 6–14°E) and contains position, time and time of the lightning (Siemens 2019). The pollen and fungal spore data were provided by the electronic Pollen Information Network (ePIN), carried out by the Center of Allergy and Environment (ZAUM, TUM), the chair of Ecoclimatology of the technical university of Munich (TUM) and our own data from the Institute of Environmental Medicine (Augsburg). In total pollen and fungal spore counts of 20 locations across Bavaria were available for the year 2015 including the following aeroallergens: Alnus, Artemisia, Ambrosia, Betula, Fraxinus, Poaceae, Populus, Taxus, Carpinus and Alternaria. Since the Bavarian aeroallergen data is only available for the year 2015 only this year could be analysed. Furthermore, the study concentrates on the summer months (JJA) with the highest occurrence of thunderstorms in Bavaria.

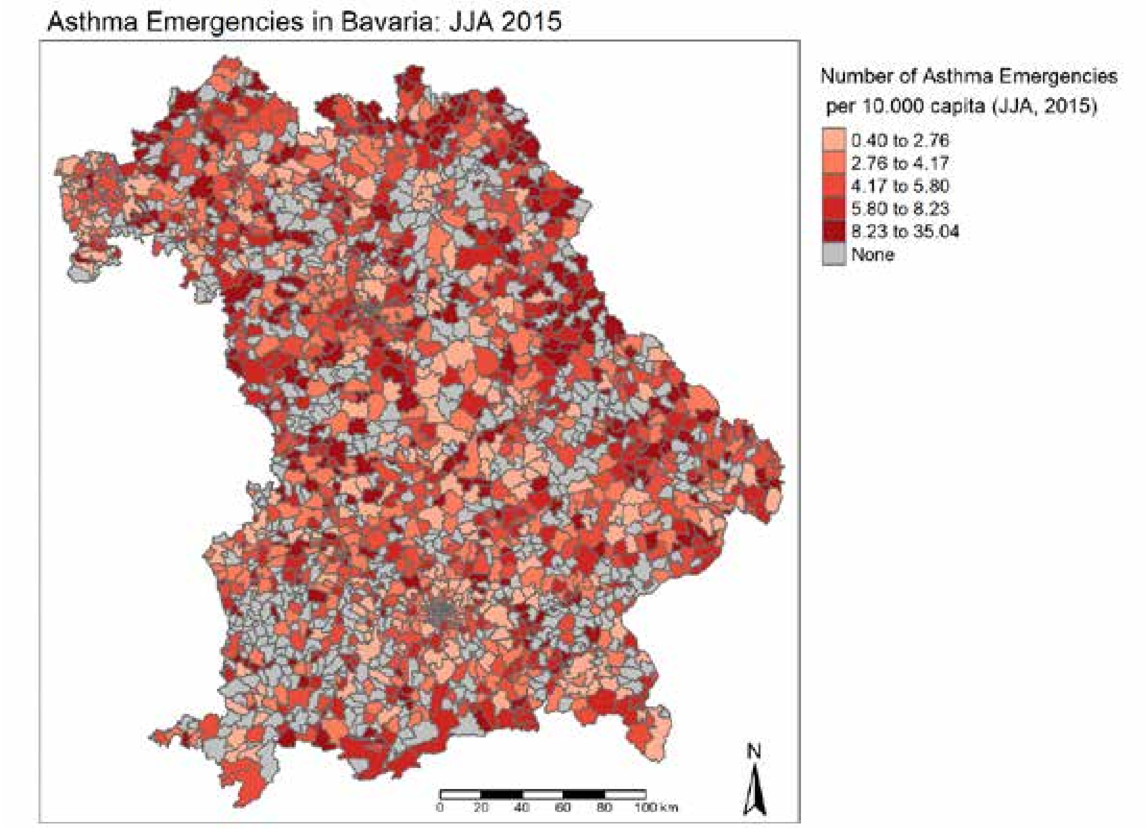


Figure 1 Number of all asthma-related emergencies per 10.000 capita in Bavaria and 5-digit postal code for the summer months (JJA), 2015.

Around each aeroallergen measuring station four investigation regions were defined with a radius of 5, 10, 15, 20 kilometres. Within these regions the asthma-related emergency cases were aggregated by postal codes and the number of lightnings by coordinates on a daily basis. In order to investigate the combined effect of aeroallergen abundances all possible combinations of aeroallergens were applied by using the binomial coefficients resulting in 1023 possible combinations. A hierarchical cluster analysis was performed on the asthma-related emergencies (see Figure 2) and the lightnings using Ward's method. All locations and clusters were then applied to a log-linear regression model in order to find significant ($p<0.05$ and $p<0.1$) odds ratio (OR) which quantify the interaction between the variables (Faraway 2006).

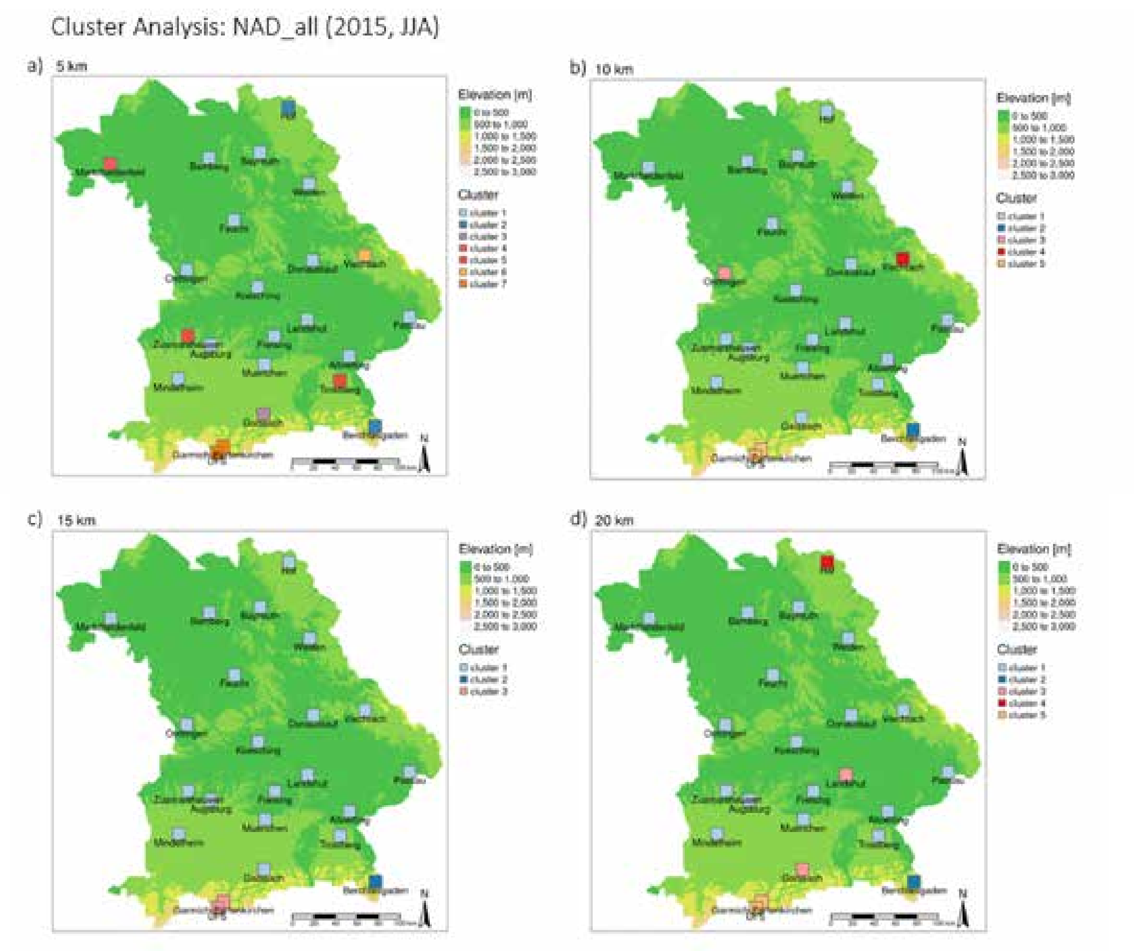


Figure 2 Cluster Analysis of all ICD-Codes (NAD_all) for the summer months (JJA) in the year 2015 and four study areas: a) 5 km, b) 10 km, c) 15 km and d) 20 km.

## RESULTS

Considering all available asthma-related emergencies significant interactions of asthma caused by thunderstorms and aeroallergens were found in Hof (OR: 4.6), Berchtesgaden (OR: 3.0 – 4.7), Augsburg (OR: 6.2), Cluster-2 (NAD_all, 5 km: Hof and Berchtesgaden, OR: 2.2) and Cluster-3 (TS, 15 km) which contains the same location as Cluster-2 (TS, 20km): Munich, Donaustauf, Viechtach, Freising (OR: 1.7 – 9.8). Odd ratios higher than four were found for Hof, Berchtesgaden and Augsburg. Therefore, at these locations the risk of asthma-related emergencies is at least four times higher on days with thunderstorm and the occurrence of aeroallergens. For the thunderstorm-cluster including Munich, Donaustauf, Viechtach, Freising the highest OR with up to 9.8 was found. With regards to the classification of the asthma-related emergencies, Berchtesgaden was found to be specific since it builds a cluster by its own within the study regions with a radial area of 10, 15, 20 kilometres. Furthermore, in regards to the combined effect of aeroallergens the most relevant taxa are mainly Poaceae and Alternaria in co-occurrence with Artemisia and Ambrosia both having pronounced seasonality and high allergenic potential.

## CONCLUSIONS

This retrospective study proofs that the phenomenon of thunderstorm asthma occurs in southern Germany (Bavaria) with moderate but also high odds ratio. Further researches have to be carried out in order to investigate also the important influence of pollutants to asthma-related emergencies during thunderstorm events in order to implement health-risk forecasts for affected individuals.

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# Spatiotemporal modeling of air temperature and relative humidity for Germany and air temperature impacts on cause-specific mortality in Germany's 15 largest cities

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## INTRODUCTION

Extreme temperatures increase the risk of cardiovascular (CVD) and respiratory (RD) disease mortality (Zanobetti and Schwartz 2008; Breitner et al. 2014). Existing evidence reflects that the temperature-mortality association is complex and could potentially change over time, with the population possibly getting adapted or even more susceptible to both heat and cold in the future. Exploring the temporal variation of this association would hence provide a solid basis to develop effective climate change adaptation strategies and increase the population's resilience. However, evidence in this field is still scarce, especially for Germany. We, therefore, investigated the short-term effects of air temperature (Ta) on CVD and RD mortality and its temporal variation across Germany's 15 largest cities.

The commonly used weather station observations are inefficient in representing spatial variability leading to exposure misclassification (Zhang et al. 2011) and possibly underestimation of Ta health effects (Hutcheon et al. 2010; Lee et al. 2016). We, therefore, aimed to improve the spatiotemporal coverage of historical minimum, mean, and maximum Ta data in Germany. Moreover, as there is a lack of spatially resolved relative humidity (RH) data, we also mapped German-wide daily mean RH using a robust machine learning approach.

## DATA AND METHODS

(1) Our mortality analysis was conducted in the 15 largest German cities. We analyzed the data of the whole study period but also divided the study period into two parts: 1993-2004 and 2005-2016, excluding 2003, the so far most prominent heatwave. Location-specific confounder-adjusted Poisson regressions with distributed lag non-linear models were carried out for each of the different periods. Multivariate meta-analysis was applied to pool the location-specific estimates. We also performed age- and sex-stratified analysis.

(2) Daily minimum, mean, and maximum Ta over 2000-2020 were estimated using a 3-stage regression-based modeling process with satellite Land Surface Temperature (LST) as the main predictor. LST, observed meteorological, spatial and spatiotemporal land use data were combined in mixed-effects regression models to estimate Ta with a $1km^2$ resolution. For each day, random intercepts and slopes for LST were estimated to capture the day-to-day temporal variability of the Ta-LST relationship. We estimated daily mean RH at $1km^2$ resolution over 2000-2021 using a hybrid random forest model with our modeled mean Ta as main predictor.

We internally validated our models by out of sample 10-fold cross validation (CV) and externally in the Augsburg metropolitan area with data from the REKLIM monitoring network. We also validated our Ta predictions across Germany with the DWD Project TRY dataset (Krähenmann et al. 2016).

## RESULTS

(1) For the overall period 1993-2016, heat showed significantly larger effects on RD than cold (Fig. 1). For heat, the age groups > 65y and > 85y showed stronger effects for RD and CVD, respectively. Cold effects on CVD were higher in males than in females.

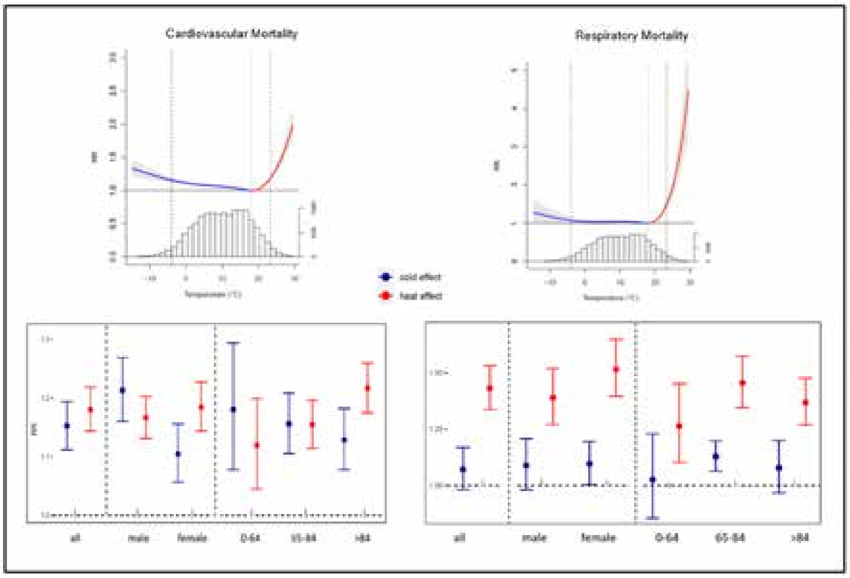


**Figure 1**: Exposure-response relationship between temperature and mortality with age- and sex-stratified heat- and cold-effect estimates.

(Dotted line= Minimum Mortality Temperature [MMT], dashed line=2.5th & 97.5th percentile of the temperature distribution.
Heat effect: Relative Risk [RR] at 97.5th temperature percentile (23.3°C) relative to the MMT (18.2°C for CVD and 17.4°C for RD). Cold effect: RR at 2.5th temperature percentile (-3.8°C) relative to the MMT).

Regarding potential temporal variations, results showed that the population was getting more susceptible to both heat and cold over time (Fig. 2). The heat susceptibility was seen to be more prominent for RD mortality with higher risk during the second period (2005-2016) [RR of 1.20 (95% CI 1.16, 1.24)] compared to the first period (1993-2004) [1.11 (1.05, 1.18)]. Similarly, the cold susceptibility was more prominent for CVD mortality during the second period than during the first period (Fig. 2).

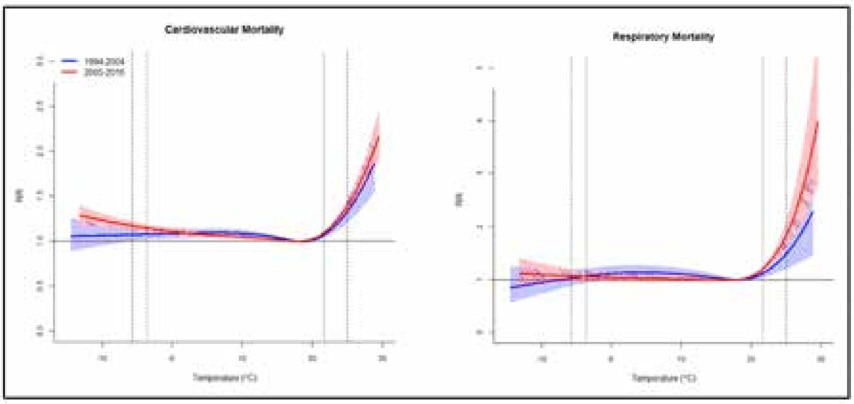


**Figure 2**: Temporal variation in the temperature-mortality association.

(Dashed line= 2.5th and 97.5th percentile of the temperature distribution, dotted line= 1st and the 99th percentile of the temperature distribution).

(2) Over the period 2000-2020, the hottest years in Germany were 2014 (10.28°C), 2018 (10.45°C), 2019 (10.22°C) and 2020 (10.44°C). All models showed excellent performance. We found the mean Ta model's 21-year overall mean $R^2$=0.96 and CV-R2=0.98 in the 1st and the 3rd stage, respectively. Overall mean CV-RMSE was 1.416°C for the 1st stage and 0.997°C for the 3rd stage. Regressing our mean Ta model predictions against the REKLIM observations during 2016-2018 resulted in $R^2$=0.99 and RMSE=1.066°C, while the crude large-scale model comparison gave an $R^2$=0.99 and an RMSE=0.904°C, being robust to various sensitivity analyses. For minimum and maximum Ta models, the findings were similar. Regarding the mean RH model, we found the 5-year overall mean CV-$R^2$=0.80 and CV-RMSE=5.515%. As for the external validation in the Augsburg metropolitan area, the percentage of explained variance remained high ($R^2$=0.81) and the error quite low (RMSE=7.051%).

## CONCLUSIONS

We observed an increased risk of CVD and RD mortality with both high and low temperatures. Pronounced higher heat than cold effects were seen for RD. Results also showed a higher susceptibility of the population to both heat and cold over time. Heat-susceptibility was seen to be comparatively prominent for RD and cold-susceptibility for CVD mortality.

Our results for the applied hybrid regression- and ML-based models indicate that they are suitable for estimating historical minimum, mean, and maximum Ta and mean RH, respectively, at high spatiotemporal resolution for Germany. Hence, our products contribute to improved exposure classification in German health cohorts such as the German National Cohort (2014). Moreover, we plan to repeat the German cities analysis using these products instead of data from DWD measurement stations.

### Data Availability

Daily minimum, mean, and maximum Ta as well as daily mean RH prediction datasets have been produced at 1km$^2$ resolution across Germany over the periods 2000-2020 and 2000-2021, respectively. The datasets are available upon request.

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# Short-term effects of exposure to air temperature on blood pressure, pulse pressure, heart rate and biomarkers of cardiovascular disease

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## INTRODUCTION

The association between outdoor air temperature and risk of cardiovascular disease (CVD) is potentially mediated by blood pressure (Yu et al. 2020). Blood pressure exhibits seasonal variation with lower levels at higher air temperatures and higher at lower temperatures (Stergiou et al. 2020). In treated hypertensive patients, it may result in excessive blood pressure decline during summer period, or rise in winter period, possibly deserving treatment modification. In Germany, decreases in air temperature have been associated with an increase in systolic blood pressure (SBP), diastolic blood pressure (DBP) and pulse pressure (PP) in a small sample size study with diabetes mellitus of Augsburg (Lanzinger et al. 2014). On the other side, increases in daytime air temperature precede increased nocturnal blood pressure levels, suggesting that under certain circumstances; even brief changes in air temperature might alter blood pressure in differing ways (Brook et al. 2011). In addition, several inflammatory biomarkers have been studied as potential intermediate phenotypes for the association between air temperature and CVD in study participants with cardio-metabolic conditions (Schauble et al. 2012; Schneider et al. 2008). However, the potential for short-term exposure to air temperature to affect the low-grade systemic inflammation in apparently healthy individuals has scarcely been studied. We aim to investigate the association of short-term exposure to air temperature with levels of blood pressure, heart rate and inflammatory biomarkers and biomarkers of kidney function in participants from the NAKO Gesundheitsstudie (German National Cohort) baseline assessment, with the final scope to identify the impact of climate on health in the study population.

## DATA AND METHODS

Our study population comprises the Midterm Baseline Dataset of the first 101,806 NAKO study participants. The joint NAKO data application was done with the HMGU and the data usage agreement was approved in 2021. For the exposure, we would make use of the data generated by HMGU.

The preparation of NAKO data on cardiovascular and metabolic diseases has been performed by our group as well as the assessment of the reliability of questions on CVD (Jaeschke et al. 2020). Blood biomarker data quality assurance in the NAKO study is still in process. We have, therefore, analyzed the laboratory data of NAKO participants enrolled at the Berlin-North study center. Harmonization of blood biomarker data analysis between MDC and HMGU is being carried out.

A cross-sectional analysis will be performed and analyzed using distributed lag non-linear models in order to model both the non-linear association of air temperature and response variables and the air temperature's common delayed effects.

## RESULTS

Overall, 41.6% of men and 34.3% of women reported at least one diagnosis of CVD in the base-line assessment ((Jaeschke et al. 2020)). Arterial hypertension was the most frequent CVD reported in the study population (Table 1). In addition, we analyzed the frequency of self-reported CVD in the complete dataset of the NAKO study (n=205,184), resulting in comparable estimates (frequency of hypertension was 27.4 %) (8) . We found a good reliability of questions on CVD over a period of 1 year (Jaeschke  et al. 2021).

| | **MEN (n=47,266)** | | **WOMEN (n=54,540)** | |
|---|---|---|---|---|
| | n | % | n | % |
| Myocardial infarction | 1,631 | 3.5 | 415 | 0.8 |
| Number of events | | | | |
| 1 | 1,344 | 82.4 | 364 | 87.7 |
| 2 | 205 | 12.6 | 38 | 9.2 |
| >2 | 79 | 4.8 | 9 | 2.2 |
| Angina pectoris | 2,269 | 4.8 | 836 | 1.5 |
| Heart failure | 1,671 | 3.5 | 1,339 | 2.5 |
| Cardiac arrythmias | 4,754 | 10.1 | 5,649 | 10.4 |
| Claudicatio intermittens | 1,282 | 2.7 | 968 | 1.8 |
| Arterial hypertension | 16,355 | 34.6 | 14,736 | 27.0 |

Table 1. Frequency of self-reported cardiovascular diseases in the NAKO study.

Similarly, we finalized a report on the analysis of the completeness and plausibility of biomarkers of study participants enrolled at the Berlin-North study center, and assessed the intra and inter-individual variability over one-year (Moreno Velásquez et al. 2021). Overall, the distribution of biomarkers concentrations measured at the Berlin-North study center was comparable to the distribution of biomarkers reported by other centers. In addition, in a subset of individuals from the NAKO-pretest, we have conducted a study using a dynamic measurement of blood pressure (postural changes in systolic blood pressure) under similar indoor temperatures and its relation to obesity, with the potential of implementing this novel assessment in the future examination of the NAKO study.

## CONCLUSIONS

Once the linkage between exposure and health data in the NAKO study is completed, we will analyze the short-term effects of exposure to air temperature on SBP, DBP, PP and heart rate as well as on biomarkers. We will also examine whether subpopulations may be more susceptible for higher or lower levels of cardiovascular related outcomes due to heat and cold exposure by conducting subgroup analyses by age, sex, ethnicity, socioeconomic status and comorbidities.

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# Impact of cutaneous human papillomavirus infections on non-melanoma skin cancer incidence in the German National Cohort (NAKO) and Rhineland study

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## INTRODUCTION

Non-melanoma skin cancer (NMSC) is by far the most common cancer in the fair-skinned population of Germany. UV light is known to be its most important factor, and indeed NMSC incidence is much higher in countries with high UV exposure (e.g. Australia). In addition, diverse mechanistic and seroepidemiological studies suggest the involvement of cutaneous human papillomaviruses (cHPV) infecting the skin rather than the mucosa. In recent years, functional model systems have been used to demonstrate in vitro and in vivo their role as important co-factors in this process (Hasche et al. 2017, 2018; Viarisio et al. 2018).

Because the antibody response to infections persists even after pathogen elimination, serological measurements are an excellent way to detect previous infections with cHPV. Furthermore, antibody titers against cHPV correlate with the risk of developing NMSC (Andersson et al. 2012, 2008). Recently, it has been shown for Australia that higher long-term UV exposure leads to increased antibody titers against cHPV (Kricker et al. 2019). Globally, however, little is known to date about the relationship between UV exposure, cHPV prevalence, and the incidence of NMSC. This is also true for the German population, since NMSC is not registered in the federal German cancer registry. In a recent study, the influence of socioeconomic and geographic factors on the incidence of NMSC among people with statutory health insurance was investigated for Germany, and showed an increase of NMSC incidence of 53% between 2009 and 2015 (Augustin et al. 2018), and more than 500,000 new cases in 2019 (Hautkrebsreport 2019).

Due to the increase in cumulative UV exposure in the German population associated with cli-mate change, further increases in NMSC incidence and associated mortality, treatment morbidity, and treatment costs are expected. There are different UV exposures within Germany, mainly with a strong north-south gradient. Using UV exposure, cHPV infection, weather data of the German Meteorological Service (Deutscher Wetterdienst, DWD), NMSC incidence data of the cancer registries of the German states, and serum samples of the NAKO and Rhineland Study, the complex picture of NMSC incidence and its drivers will be investigated in an ecological study design.

## DATA AND METHODS

In total, 5000 serum samples from the Rhineland Study (DZNE), and 6250 samples from the German national Cohort (NAKO; each 2500 from the study centers Münster and Augsburg, and 1250 from Berlin Nord), totaling 11,250 serum samples, will be analyzed simultaneously by multiplex serology for antibodies to common cHPV types (Waterboer et al. 2009, 2005). High-throughput multiplex serology for simultaneous measurement of serum antibodies against multiple antigens is a long-established methodology at DKFZ and has been used in more than 300 published international epidemiological studies over the past 15 years (Andersson et al. 2012; Kricker et al. 2019, 2020).

Antibody measurements will be analyzed in conjunction with demographic data (age, sex, preva-lent diseases, environmental factors, and others), as well as UV data and NMSC incidence. In addition to the data collected in the NAKO and the Rhineland Study, data sets from the Climate Data Center (CDC) of the DWD will be used to determine regional UV exposure in Germany. These were generated with a Germany-wide network of measuring stations (pyranometers) for the measurement of global radiation as well as satellite measurements and contain information about the last three decades. With these data sets (geographical resolution of 1x1 km) a UV exposure index in the catchment area of Bonn (Rhineland Study) and the respective NAKO study centers will be calculated. Since NMSC is not registered in the federal German cancer registry, data from the individual state cancer registries will be used. Demographic risk factors (e.g. age, sex, environmental factors) for seropositivity or level of cHPV antibody response will be deter-mined using multivariable regression models. A UV exposure index will be calculated for each subject using CDC UV radiation data and geographic and demographic information of the study sites and participants. Cancer registry data for NMSC, the UV exposure index and its geographic change will be used additionally for this purpose. The obtained metadata (ecological data) allows the descriptive analysis and corresponding correlation analyses stratified by study center.

## RESULTS

For both NAKO and the Rhineland study, complex project proposals, research collaborations, contractual arrangements, and sample retrieval processes had to be put in place. The Rhineland study samples were shipped to DKFZ in October 2021, and the NAKO samples are expected in December 2021. The Rhineland study samples are currently being analyzed at DKFZ, and analysis of the NAKO samples is planned for early 2022. Retrieval of UV exposure data from DWD is ongoing and will be completed by March 2022.

## CONCLUSIONS

A possible association of UV exposure, cumulative cHPV infection, and NMSC incidence could serve as a rationale for the use of cross-protective vaccines against cHPV that are in develop-ment (Huber et al. 2017; Seitz et al. 2015). In addition, the results may highlight the importance of regular skin cancer screening programs among the general population. These are known to only about 50% of those with public health insurance as a health insurance benefit, and are only used by about 20% of the insurants per year (Eissing et al. 2017).

### Data Availability (or) Available Information

Data is available upon request.

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# CLUSTER II:
# HI-CAM-ADAPTATION
## Rural systems

**Centers involved:**

UFZ HELMHOLTZ Zentrum für Umweltforschung

DLR

# Rural systems and renewables

Climate change affects agricultural, aquatic and forest ecosystems. Frequent and prolonged periods of drought have diverse and far-reaching impacts: Aquatic systems face challenges from declining water quality including enhanced eutrophication risk. Agricultural yields and the potential of soils to provide marketable yields are at risk and forest systems may turn from carbon sinks to carbon sources. This could facilitate climate change as both soils and forest systems usually represent a potential carbon sink and thus the ability to compensate to some extend for unavoidable emissions from other economic sectors. And finally, all in all, a significant change from conventional energies to renewable energies is required to reduce anthropogenic emissions. However, renewable energies are subject to climate-related fluctuations. In this context, the respective projects P7 'Agricultural and aquatic systems', P8 'Forest systems', and P9 'Renewable energies' addressed the following challenges.

In project P7 necessary Germany-wide data bases were created in order to (1) evaluate the site-specific vulnerability of agricultural crops and soils to drought events, (2) analyse the specific effects of the drought events on agricultural crops and yields as well as on water quality, and (3) to predict future deficits in the soil water balance and to estimate eutrophication in rivers under specific climate scenarios. Nation-wide continuous soil information on the storage capacity for plant available water was generated by pedometric modelling (P7.1 'Pedometric modelling of the plant available soil water capacity at national scale'). Germany-wide datasets on the distribution of arable crops and on anomalies in plant development were created employing remote sensing time series (P7.2 'Satellite Earth Observation based products for monitoring and assessing agriculture in Germany'). Furthermore, the nationwide river database was strongly upgraded to enable a comprehensive large scale assessment of climate-driven changes in river ecosystems and their consequence for water quality (P7.3 'Towards a large scale assessment of climate change-driven changes in river ecosystems.').

In project P8 Forests are analysed, an important ecosystem of the German biosphere. At DLR, forest height and 3D forest structure parameters could be determined for the first time by combining remote sensing data from different satellite missions for large regions (Thuringia). These parameters play an important role in determining the condition of forest stands and can be used to characterize the effects of extreme events, such as prolonged droughts, on the state of the forest. Such information is critical for initializing or validating simulations with forest models. At the UFZ, the $CO_2$ fixation rate of all trees in the national forest inventory - 1.6 million trees from ca. 72.000 forest stands - was simulated using digital twins of these trees under different climate scenarios (RCP 2.6, 4.5 and 8.5) of six different climate models and weather data. Climate data were delivered by GERICS whereas soil data were delivered by the CHS of the UFZ. Forest productivity decreases by about 50% under a 4°C global temperature increase (RCP 8.5) if forest structure and species composition will not change in the future. A decrease of 20% was simulated under the climate change scenario RCP 2.6 and about 30% under RCP 4.5. Spruce monocultures are much more at risk than mixed deciduous forests with a moderate tree size mixture. If the proportion of such deciduous forests increases in the coming decades and the Paris Agreement will adhere to, the $CO_2$ fixation rate of native forests would remain stable.

In project P9 the effects of climate change and weather extremes on the German renewable power provision have been analysed. For this purpose, spatiotemporal simulation models for the electricity generation from variable renewables (i.e., wind power and photovoltaics) were developed and used with detailed plant and weather data. The impact of climate change and extreme weather events on the electricity generation was investigated by employing climate scenario data (RCP 2.6, 4.5 and 8.5) as weather information in these simulations. Such climate change scenarios, which were created using past weather data with different climate change signals in climate models, were delivered by GERICS for meteorologically typical years, the wind rich 2008 and the low wind year 2010. It could be clearly shown that the impact of climate change and extreme weather events can be investigated for variable renewables with the help of numerical simulations. Due to the limited sensitivity of the employed weather models for the climate change scenarios, the effects on the power generation from wind turbines were not very strong but showed ideas for improvements in climate scenario data for GERICS. Furthermore, the nationwide wind power simulation database was upgraded and the onshore wind turbine dataset with the corresponding wind power generation was handed over to DLR for integration into future modeling of the entire German energy system.

# Satellite Earth observation based data products for monitoring and assessing agriculture under climate change

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## INTRODUCTION

In recent years, heavy droughts, heat waves and floods have uncovered the vulnerability of German agriculture to climate change and climate extremes. In years of such extreme events, yields have considerably declined and fodder production was threatened. As a consequence, enormous amounts of emergency aid had to be paid to farmers – around 300 Mio. € only in 2018. Furthermore, the past has shown that there are clear geographical differences in how Germany's agricultural landscapes are affected by climate extremes. The development of adequate adaptation strategies thus has to be tailored also to these regional differences.

Satellite Earth observation has the capability to quantify the state and dynamics of agriculture for large areas which allows a uniform assessment of all of Germany, and can reveal regional and local discrepancies. Particularly the European Copernicus Program with its time series sensors Sentinel-1 (radar) and Sentinel-2 (multispectral) allows for a detailed assessment of the state and phenology of agriculture at 10-20m spatial resolution. But likewise, longer satellite time series reaching back more than 20 years deliver important information when assessing agriculture in climatically relevant time frames. Here the spatially coarser (250m) data of the sensor MODIS can contribute crucial information.

In HI-CAM, we created a data basis for assessing first important aspects of state and dynamics of agriculture in Germany. This data can be directly explored in scientific analyses, but it can also be used as input for modeling and for the development of adaptation practices for Germany's agriculture under climate change. The data basis contains information on the spatial extent of agricultural areas (grassland, cropland), as well as on crop type distribution. Furthermore, time series information on long-term vegetation anomalies of cropland and grassland areas as well as spatially detailed information of crop-specific anomalies under drought conditions have been generated.

## DATA AND METHODS

For generating maps of agricultural areas and crop types, Sentinel-1 (S1) and Sentinel-2 (S2) time series data were classified with machine learning techniques (random forest). S2 L1C A/B MSI (Multi-Spectral Instrument) data for February to October 2018 was atmospherically corrected to L2A using the PACO algorithm (de Los Reyes et al. 2020). Based on 10 S2 bands plus a vegetation index (NDVI) and 17 temporal intervals, spatial-temporal features were calculated and used as input to the classification. All available S1 A/B ground range detected (GRD) datasets in descending mode for 2018 were preprocessed using ESA's Sentinel-1 Toolbox (ESA 2021), including orbit metadata updates, thermal noise removal, radiometric calibration, border noise removal, speckle filtering, terrain correction, and conversion to dB. As input data for classification, spatial-temporal features were calculated based on the resulting S1 backscatter data (VV and VH) and monthly temporal intervals. As reference data, LUCAS (Land Use and Coverage Area frame Survey) (EUROSTAT 2021) and LPIS data for all German Bundesländer (except for North Rhine-Westphalia and cities) were available for DLR's research purposes in the HI-CAM project.

Anomalies of grassland and cropland for all of Germany were calculated using 250m MODIS Enhanced Vegetation Index (EVI) time series (MOD13Q1) for the years 2000-2021, based on an approach adapted after Reinermann et al. (2019). Monthly deviances of EVI were calculated for grassland and cropland areas separately where land cover was distinguished based on the CORINE land cover (CLC) and CORINE land cover change layers (EEA 2012). In addition, an anomaly analyses at high spatial resolution was conducted based on 10m Sentinel-2 vegetation index time series and multi-annual LPIS data for Brandenburg for 2016-2020 (GDI-BB 2021).In this approach, the multi-annual mean (as a basis for the anomaly detection) was calculated for each crop type individually by considering that crop types are cultivated on different fields every year.

## RESULTS

Next to the general spatial distribution of cropland and grassland, 18 crop types could be mapped all over Germany (Fig. 1). An overall accuracy of 82% was achieved, with class-specific F1-scores ranging between more than 0.9 (for sugar beet, winter rapeseed, hops, vineyards) and around 0.7 for more challenging classes such as summer oats, spring wheat and winter triticale. The combination of multispectral (Sentinel-2) and radar (Sentinel-1) data led to a clear increase of overall accuracies by more than 10%.

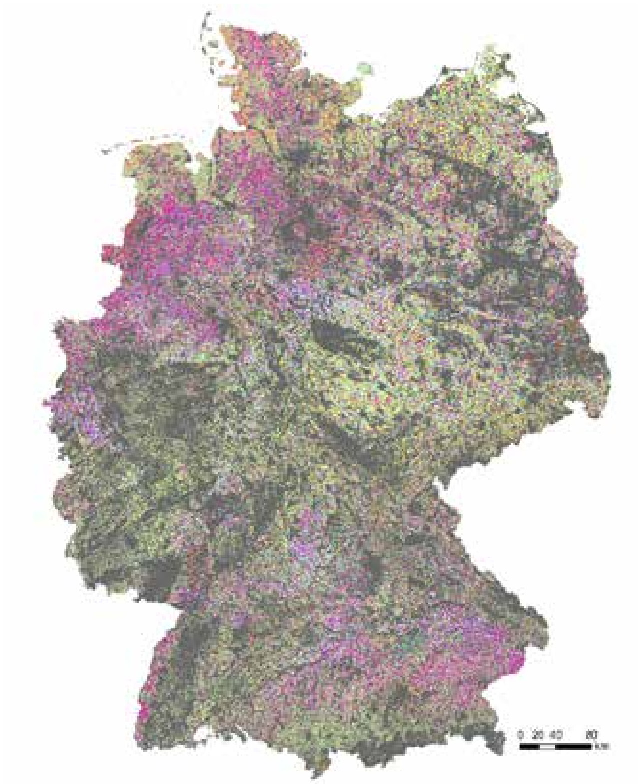

**Figure 1**: Crop Type Map of Germany 2018 based on satellite time series of the instruments Sentinel-1 and Sentinel-2.

From our 21-year satellite-based anomaly detection, Figure 2 exemplarily depicts the results for cropland and the drought year 2018. The MODIS analyses were conducted for Germanys cropland and grassland and for all years between 2000 and 2021 at a monthly basis. The pixel-based results were used to calculate Germany-wide maps of monthly cropland vegetation anomalies per Landkreis (Figure 2, top row). The maps show that e.g. in 2018, Germany's cropland showed below-normal vegetation activity particularly from June-September where regional dif-ferences become clearly apparent. By additionally using high resolution (10m) time series of Sentinel-2, deviations of crop type development compared to medium-term (2016-2020) behavior could be assessed for Brandenburg (Figure 2, bottom row). This analysis allows to quantify temporal profiles of anomalies that are characteristic for each crop type. Figure 2 (bottom row) illustrates for example strong negative anomalies of maize (red colored fields) in September 2018.

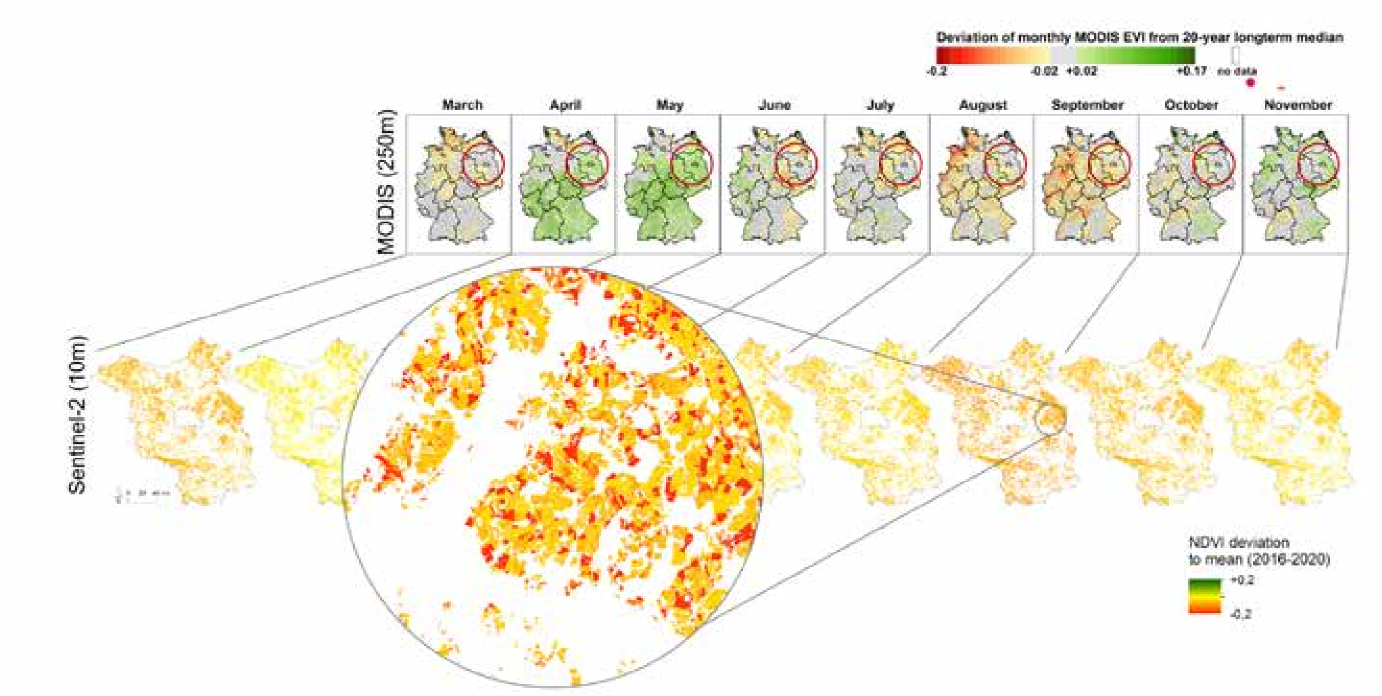


**Figure 2**: Cropland (top row) and crop-specific (bottom row) anomalies of vegetation activity as extracted from an up to 21-year satellite-based anomaly detection of croplands in Germany.

## CONCLUSIONS

The presented data basis includes maps of crop types and agricultural anomalies. It forms an important basis for a direct monitoring and assessment of the state and dynamics of German agriculture under climate change and extreme weather events. The data will be jointly used in combination with high resolution soil information of the HI-CAM project to assess drought- and soil-related vegetation anomalies as a basis for developing adaptation practices. Furthermore, crop type maps are an essential input for different kind of climate-change related modeling activities, e.g. for crop models (yield prediction), environmental health models (crop-related allergens) and biodiversity-related models (agrobiodiversity).

## Data Availability (or) Available Information

Crop type data is available upon request after its publication (Asam et al., submitted).
Vegetation anomaly data is available upon request.

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# Pedometric modelling of the plant available soil water capacity at national scale

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## INTRODUCTION

Frequent and prolonged drought periods challenge the soils' potential to provide marketable yields. The insufficient availability of water due to empty soil water stores during important crop development stages is of major concern. Soils differ in their capacity to store plant available water; crops differ in the amount of water they require and their vulnerability to drought during their respective development stages. Accordingly, the provision of nation-wide soil information at the resolution of individual agricultural fields is important to evaluate the site-specific vulnerability and to develop adequate climate adaptation strategies.

The soil distribution throughout a particular landscape is the product of the interaction of the soil forming factors climate, organisms, relief, and parent material through long periods of time. Pedometric modelling can be applied to understand this functional relation, and to project soil profile data into space to generate the required nation-wide soil information at high resolution. It is an empirical modelling approach that integrates soil system knowledge with applied statistics, mathematics and geoinformatics.

To provide the means to develop site-specific agricultural adaptation strategies, we have generated nation-wide soil information of the agricultural soils' storage capacity for plant available water (top 100 cm) at 100 m resolution by means of pedometric modelling.

## DATA AND METHODS

Pedometric modelling relies on the availability of a large nation-wide soil profile database and the generation of multivariate gridded parameter fields to approximate the soil forming factors. The former was provided by the German agricultural soil inventory (Poeplau et al. 2020), the latter were derived from remote sensing data products and vector maps. Data from 2979 soil profiles were included to evaluate the profile-wise plant available water capacity to a depth of 100 cm or till bedrock, respectively. Concerning the gridded proxies for the soil forming factors, 61 parameters were included consisting of 15 for climate, 13 for organisms (vegetation/landuse), 29 for relief, and 2 for parent material. Additionally the explicit geographic position was also included. For more details on the parameters see Gebauer et al. (2021).

Measurements of the soil water retention that would allow for the direct extraction of the soil horizon-wise storage capacity of plant available water are hardly available. The determination is rather time consuming. Consequently, it is common place to estimate it from other soil properties by means of so-called pedotransfer functions. These are empirical equations linking fast and economically measurable properties such as soil texture, bulk density and organic carbon to labor intensive soil properties like the soil storage capacity for plant available water. From the available pedotransfer functions we have compared the guidelines of the German Soil Survey System (Ad-hoc AG Boden 2005) with two further pedotransfer functions. They were selected according to (1) the involved number of soil profile sites and samples used for their fitting, (2) the required soil characteristics, and (3) the respective soil-landscapes and geophysical context they were developed for. Machine learning with the random forest algorithm was used to extract the soil landscape relationship and to project the profile-wise plant available water capacity into continuous national space. A nested 5-fold cross-validation approach was applied for model training, tuning and evaluation. Balancing between the required spatial resolution to provide estimates at individual agricultural fields and computation time, we have addressed a final target resolution of 100 m.

## RESULTS

Figure 1 shows the plant available soil water capacity predictions. The maps display the 1st, 2nd and 3rd quartile of 25 model runs on behalf of different data subsets from 5 repetitions of the 5-fold cross validation scheme. The underlying pedotransfer function is the one from the German soil survey system. The maps clearly indicate high capacity values in regions dominated by soils with high silt contents that originated from loess deposits, and low capacity values for the sandy soils in northern Germany. It is the latter that are particularly vulnerable to periods of drought. Due to the German climate being guided by an increase in continental climatic character from west to east and the corresponding higher summer temperatures and lower precipitation, in north-eastern Germany, this soil-bound vulnerability is intensified by a climate-bound vulnerability.

Variable importance in the respective machine learning models confirmed the high affinity with the parent material map of Germany. Predictive model performance amounts to an RMSE of 36 mm.

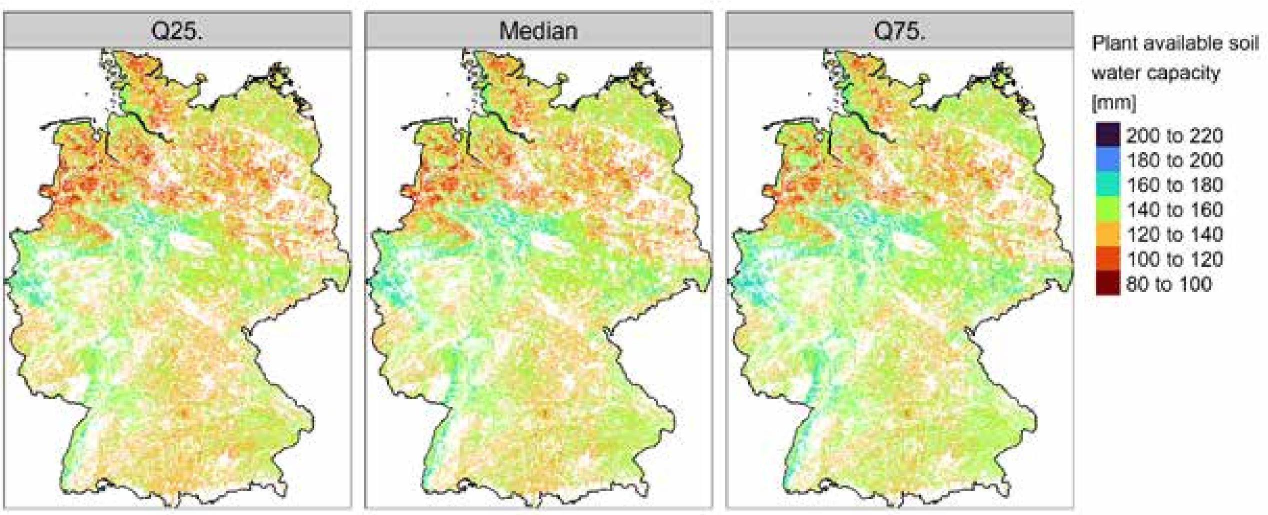


**Figure 1**: Median, 1st and 3rd quartile of the predicted plant available water capacity to a depth of 100 cm. Non-agricultural areas are masked.

## CONCLUSIONS

We succeeded in modelling the storage capacity for plant available water on agricultural soils throughout Germany. The developed data product will be used in further analysis involving regional crop portfolios and their water requirements during the respective development stages. Together with the maps of crop types and agricultural anomalies developed in this HI-CAM project, the nation-wide spatial soil information on the root-zone plant available water capacity will then form the basis to develop site-specific climate adaptation strategies for agricultural management while considering even more extreme climatic scenarios.

### Data Availability (or) Available Information

Data is available upon request.

### Literature

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# Forest Height and Structure by means of SAR Measurements

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## INTRODUCTION

The ability of microwaves to penetrate into and through forest canopies while being sensitive to the geometric and dielectric properties of vegetation elements makes multiangular Synthetic Aperture Radar (SAR) configurations, from today's perspective, the only remote sensing technique that can provide high-resolution measurements of 3D forest structure on large scales. Radar scattering and propagation strongly depends on the size, shape and orientation distribution of the vegetation elements in the forest volume, which leads to a strong dependency on the frequency (e.g., wavelength) and polarization with which the SAR configuration is operated. A new generation of interferomeric and/or tomographic SAR configurations, allows today 3D reflectivity measurements globaly with high spatial (on the order of 10m) and adequate temporal resolution (on the order of weeks to months). This dramatically improves our ability to monitor the 3D structure of global forests and its change in time and to assess their current condition and - in combination with a dynamic forest model - to predict the future development of forest stands under different environmental conditions.

At the same time, the water content of the canopy determines its dielectric properties (since water has a high relative dielectric constant, while the other plant components are rather poor conductors), and thus defines the propagation of microwaves trough and their ability to penetrate it. In this way, the water content of the treetops strongly influences the propagation of microwaves through the canopy and allows a direct estimation of effects caused by changes in water content.

## DATA AND METHODS

**TanDEM-X:** The German TanDEM-X mission is the first bistatic SAR configuration consisting of two nearly identical X-band SAR satellites flying in a close formation (Hancock et al. 2019). While the primary mission objective was to generate a highly accurate global digital elevation model, the flexible configuration allowed the demonstration of new SAR techniques and applications, especially in the vegetation and forest domain. The mission was launched in 2010 and is expected to operate until 2023.

**GEDI:** NASA's Global Ecosystem Dynamics Investigation (GEDI) mission is a waveform lidar instrument optimised to measure vegetation structure that operates since April 2019 aboard the International Space Station (Krieger et al. 2013). GEDI, whose nominal mission duration has just been extended to 2023 allows an unprecedented density (~4% of the Earth's land surface between 51.6° N and 51.6° S) of measurement points. However, since GEDI is not a continuous imaging instrument and gaps occur between the ground tracks and over cloudy areas. These are particularly severe in tropical regions, leaving large parts (~96%) of the land surface unmapped to date.

For the generation of the forest height maps, a novel approach was developed and implemented based on the derivation of a "mean" vertical reflectivity profile from the discrete GEDI wave-forms which is then used to invert forest heights from simple polarimetric standard DEM mode TanDEM-X data (Guliaev et al. 2021). The forest structure parameter has been derived from the variance of the interferometric phase center height estimated at a scale of 10m from the TanDEM-X data (Choi et al. 2021).

## RESULTS

Large scale forest height and 3D forest structure maps with a spatial resolution of 100m x 100m as in the example of Thuringia shown in Figure 1 have been generated and validated. These parameters play an important role in determining the actual condition of forest stands and, when combined with an forest model able to simulate the growth of forests as the Foremind model developed at UFZ to characterize the effect of extreme environmental events, such as prolonged droughts, on the state of the forest.

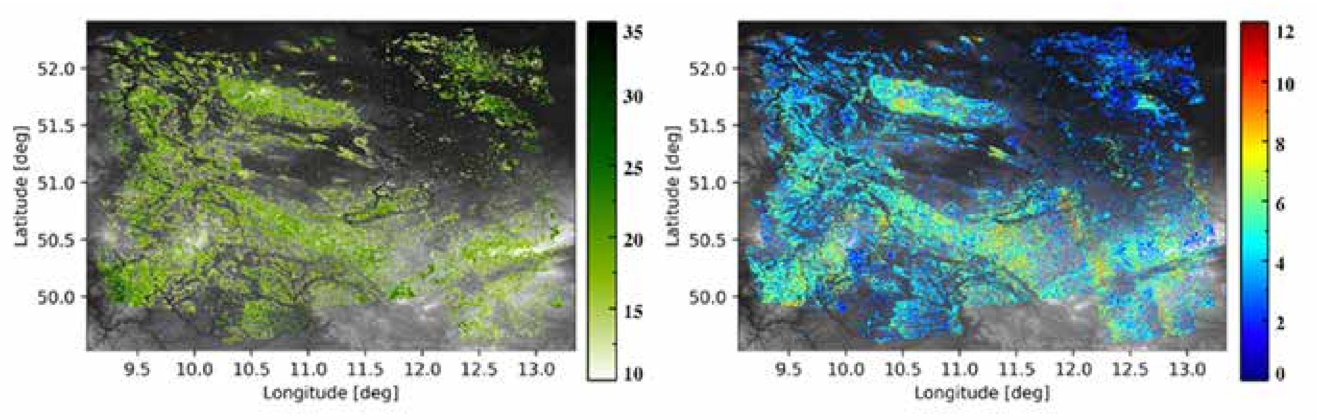


**Figure 1:** TanDEM-X and GEDI derived forest height (left in [m]) & forest structure maps (right in rel. units) of Thuringia, size 300km x 300km, resolution 100m x 100m.

In **Figure 2** an example of a direct estimation of the effect of reduced canopy water content is shown for a peat-swamp forest in Kalimantan, Indonesia. In a time series of forest height maps the height estimates at the end of the dry season are underestimated by 2-3m as the result of the reduced water content. The lack of similar appropriate time series over Germany (caused by severe data request conflicts) does not allow a similar demonstration. However, the example demonstrates the unique sensitivity of multi-angular SAR measurements for detecting changes in the water content of vegetation.

## CONCLUSIONS

Interferomeric and/or tomographic SAR configurations allow high-resolution measurements of 3D forest structure parameters on large scales. This is critical as it allows to assess the current state of forests worldwide and to initialize forest models for predicting the future development of forest stands under different environmental conditions. At the same time the unique sensitivity to the canopy water content allows a direct estimation of its temporal variation triggered by variable environmental conditions.

### Data Availability (or) Available Information

Data are available upon request.

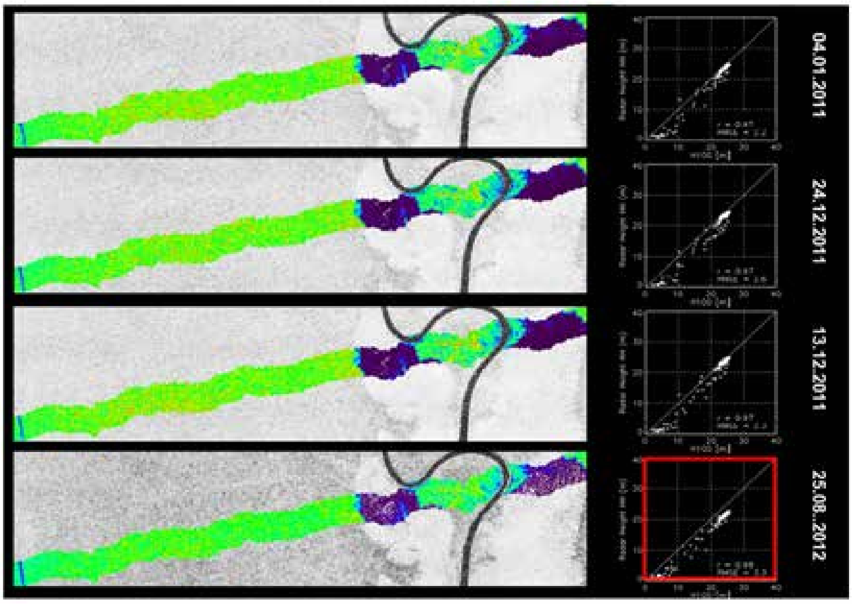


**Figure 2**: Time series of forest height maps over a peat-swamp forest in Kalimantan, Indonesia the height estimates at the end of the dry season (25.08) are underestimated by 2-3m.

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# Carbon sequestration of future forests as a result of climate change

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## INTRODUCTION

Forests are an important ecosystem of the temperate zone and the German biosphere. They cover 30% of the land area in Germany, provide important resources, like timber, and play an important role in the carbon and water cycle. In recent decades, carbon sequestration by forests suffers during droughts in Europe (e.g. Ciais et al. 2005). In 2018/19, 2.5% of German forests (285,000 ha) died due to drought and pest-outbreak in monocultures, with spruce being the most affected (Thünen 2020). In total, more than 160 million m³ of low-quality fallen timber threatened the timber market, resulting in an emergency aid of 800 million euros from the German government (Thünen 2020, BMBF 2019).

Hence, the responses of temperate forests to future climate change and the fate of the dominant carbon sink in Germany remains one of the big questions in ecology. Individual based forests models allow the analysis of future forests, as recent technical developments enable the application the individual based approaches to larger spatial scales and to assess the productivity of forests by taking into account species composition and tree size structure (Maréchaux et al. 2021).

In this project we developed a model framework which simulates each stand of the German forests inventory in order to evaluate carbon fixation under different future climate scenarios.

## DATA AND METHODS

For the simulation of the carbon fixation rate of German forests, we initialized the temperate version of the process-based forest model FORMIND (Bohn et al. 2014) with the 2012 German forest inventory data (Thünen Institute, n.d.). Soil data for Germany were derived from the mHM model (Kumar et al. 2013; Samaniego et al. 2010). Available irradiance due to shading, air temperature, and available soil water controls each tree's photosynthesis, respiration, and carbon fixation. The different species in the simulation respond differently to their environment depending on their drought and heat tolerance, successional niche, or tree type (coniferous or deciduous). For the simulations, each plot of the German forest inventory (72,424 plots, 1.6 million trees) was simulated six times within each scenario to average stochastic processes.

To simulate climate change, we use time series from EURO-CORDEX up to the year 2099 (Jacob et al. 2014), which were statistically downscaled to a 1x1-km grid and bias adjusted. We used time series from RCP 8.5, RCP 4.5, and RCP 2.6 and assumed that forest structure and species composition in German forests do not change in the future.

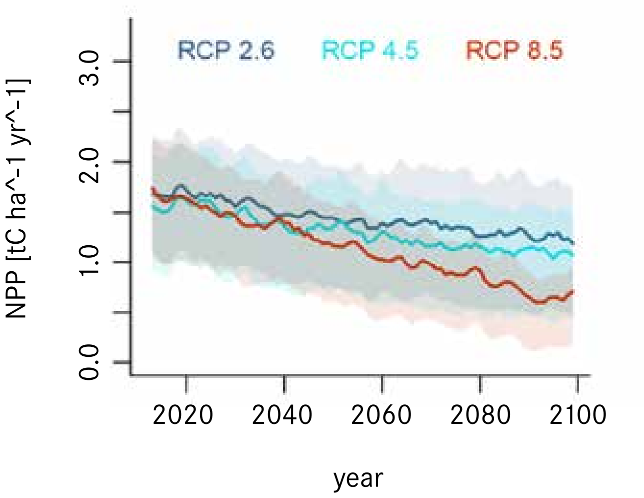


**Figure 1**: Mean carbon fixation rate as net primary production (NPP) of the German forests (as lines) under three different climate scenarios (colour). Coloured bands show the IQR of all forest stands.

We further analyse the behaviour of the different forest types. Only deciduous forests consisting of more than 80 % deciduous tree species have the same average fixation rate at the end of the century in the RCP 2.6 scenario as today's forests (Fig. 2). Coniferous forests in contrast, which consist of more than 80% coniferous species, are the most affected in all scenarios (especially spruce forests). Note that a decrease in carbon sequestration increases the likelihood that trees will be attacked by insects or pathogens.

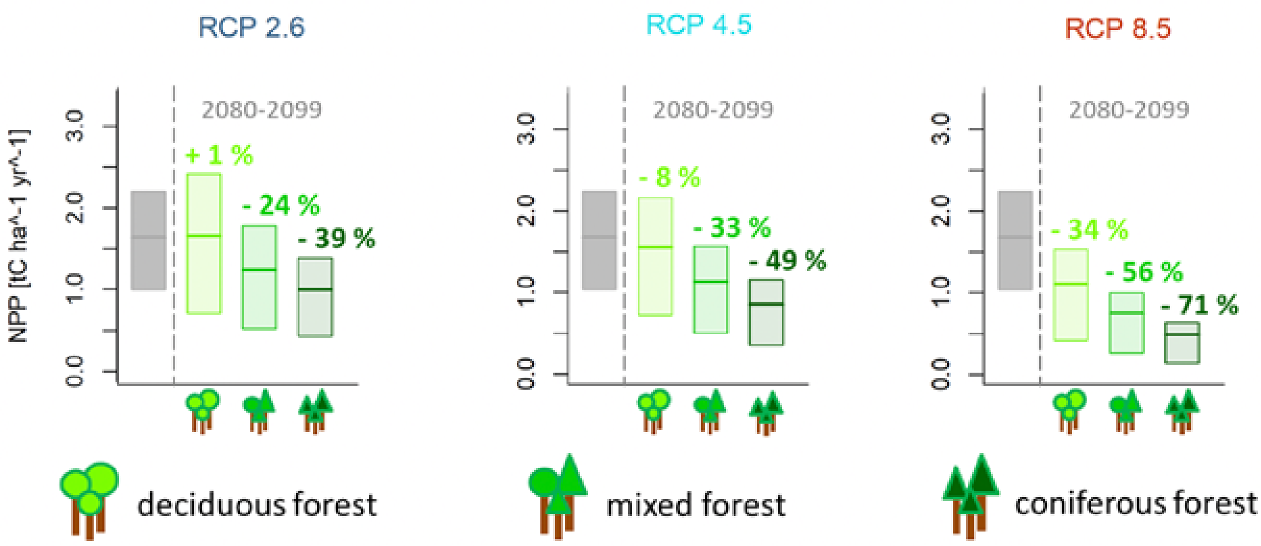


**Figure 2**: Comparison of current carbon fixation rate as net primary productivity (NPP) of all German forests (grey) and carbon fixation rate of three forest types in RCP 2.6, RCP 4.5 and RCP 8.5 at the end of the century (green). Boxes represent the IQR range of all stands within the forest type, whereas the line indicates the mean rate of the forest type.

## CONCLUSIONS

In this project, we were able to show that regardless of the climate scenario, deciduous forests will sequester more $CO_2$ in the future than coniferous forests. In order to maintain the current $CO_2$ fixation rate of temperate forests, foresters should continue and intensify forest restructuring to replace harvested coniferous forests (especially spruce) with deciduous forests in most cases and limit the global temperature increase to less than 2°C.

### Data Availability (or) Available Information

Various ecosystem variables (e.g. photosynthesis, evapotranspiration, autotrophic respiration, carbon fixation rate, biomass, etc.) are produced for each year until 2099. Each time series is available for 72.000 forests stands and six climate models and three scenarios RCP 2.6, RCP 4.5 and RCP 8.5. Data is available upon request.

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# Towards a large scale assessment of climate change-driven changes in river ecosystems

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## INTRODUCTION

River ecosystems are an important component of the water cycle, and their integrity is essential to sustain water quality and quantity. However, river ecosystems are intensively used by humans resulting in a multitude of pressures, including the input of nutrients from point and non-point sources, extensive morphological changes, and water abstraction (Lemm et al. 2020). Thus, the stress due to climate change and climate extremes need to be understood in the framework of a complex stressor-ecosystem landscape. While experiments allow painting detailed pictures of causal relationships at case study sites, they cannot cover the complexity of driver combinations and river ecosystem variability in space and time in the context of their network and terrestrial environment. To bridge this gap, a large scale river ecology perspective is needed to elucidate systematic differences in dominant processes, stressor combinations, and determine relevant scales. Large scale river ecology needs to be grounded on long-term monitoring data in space and time. However, even so for Germany intensive monitoring programs for river water quality and quantity exist, the wealth of data is distributed over different federal and federal state authorities, and thus not readily available for scientific large scale assessment of climate change effects on river ecosystems. For this reason, we have updated a German-wide data set and expanded it considerably in terms of the included measuring stations, period and parameters. The data are used in river water temperature trend assessment and analysis of climate change impacts on eutrophication and provide a unique basis for many detailed further analyses in ongoing and future projects.

## DATA AND METHODS

The data was collected from various federal states and federal authorities. The different file and data formats were harmonized into one water quality and one water quantity data set with accompanying metadata sets. For the coupling of quality and quantity monitoring sites, which are mostly not locally coinciding, we associated the monitoring stations with the EU-Hydro river network[1]. Based on this network total upstream river length for each station was determined as a proxy for the catchment area needed for scaling. We used ERA 5 reanalysis data[2] to associate meteorological parameters to each station location. For trend analysis, monthly water temperature data were selected for the period from 1987–2016 and filtered according to various missing values quality criteria. Missing data were conservatively imputed by randomly drawing from the station-wise monthly interquartile ranges using an equal distribution. Interannual trends were estimated using the non-parametric Theil-Sen estimator on annually averaged data. The potential influence of abrupt changes on trends was assessed using segmented regression.

[1] https://land.copernicus.eu/imagery-in-situ/eu-hydro/eu-hydro-river-network-database
[2] https://climate.copernicus.eu/climate-reanalysis?q=products/climate-reanalysis

## RESULTS

The data set currently encompasses 31 parameters on water quantity and quality from around 21,800 monitoring sites from approximately 3000 different streams and rivers, including nutrients, minerals, physical-chemical parameters, parameters describing underwater light climate, hydrological parameters and biological parameters. Available parameter and temporal coverage vary widely between stations. While some parameters like oxygen and total phosphate have very high coverage, this is comparatively reduced for others like total nitrogen, silicate and Chl-a. Data availability considerably improves from 1980 onwards. Trend analysis has particular high demands on data quality; from the 10896 stations with available water temperature information, 664 stations covered a time range from at least 30 years. From this set, 275 time-series with sufficient quality were available in the period 1987-2016, distributed over Strahler orders 1 to 8 (Fig. 1). According to the Theil-Sen estimator, 64% of the time-series showed a significant positive trend 8% a significant negative trend, were 19 positive and 3 negative trends were excluded, since they were likely inflicted by abrupt changes. The estimated median temperature increase for the significant positive trends is 0.35 °C/decade (0.21-0.51, median 95% confidence intervals) and vary between 0.04 and 0.83 °C/decade. The median temperature increase for the significant negative trends is -0.368 °C/decade (between -0.6 and -0.15, median 95% confidence intervals) and vary between -0.96 and -0.1 °C/decade.

## CONCLUSIONS

The established dataset provides a milestone for an in-depth analysis of climate change effects on water quality across Germany. It now allows upscaling climate change effects detected in local observations and experiments and provides a unique basis for the parametrisation of nationwide models. We chose the parameter temperature in the exemplary analysis since it is the master variable for various fundamental aquatic processes. Shifts to higher mean temperatures influence river ecosystems on all scales reaching from oxygen dissolution, metabolic rates to the determination of ecological niches. Our trend assessment confirms the vulnerability of river ecosystems to temperature changes (Markovic et al., 2013, Seyedhashemi et al. 2021) and demonstrates the potential of the dataset to identify vulnerable ecosystems and regions. Further analysis will increase the spatial coverage by including varying periods and differentiate in space and time the physical drivers. The detailed and ecosystem-type-specific warming trends can then be used in ecological models to specify scenarios for effects on biodiversity and ecosystem state. The large-scale assessment of ecosystems is a prerequisite for fully understanding multiple stress effects in space and time and deriving integrated management perspectives. However, the availability of comprehensive and up-to-date data sets is a critical factor for meta-analyses and large-scale studies. Collecting data from distributed and often insufficiently documented sources takes a lot of resources and time. The compilation of a Germany-wide river dataset and its expansion with meteorological and spatial parameters thus forms an important basis for addressing climate change effects on river ecosystems on a large scale. Furthermore, the extensive dataset enables testing new, often data-hungry analysis techniques such as machine learning for understanding and predicting river ecosystems and opens up the possibility to closely connecting data analysis and modelling approaches in the rapidly developing field of knowledge-guided machine learning.

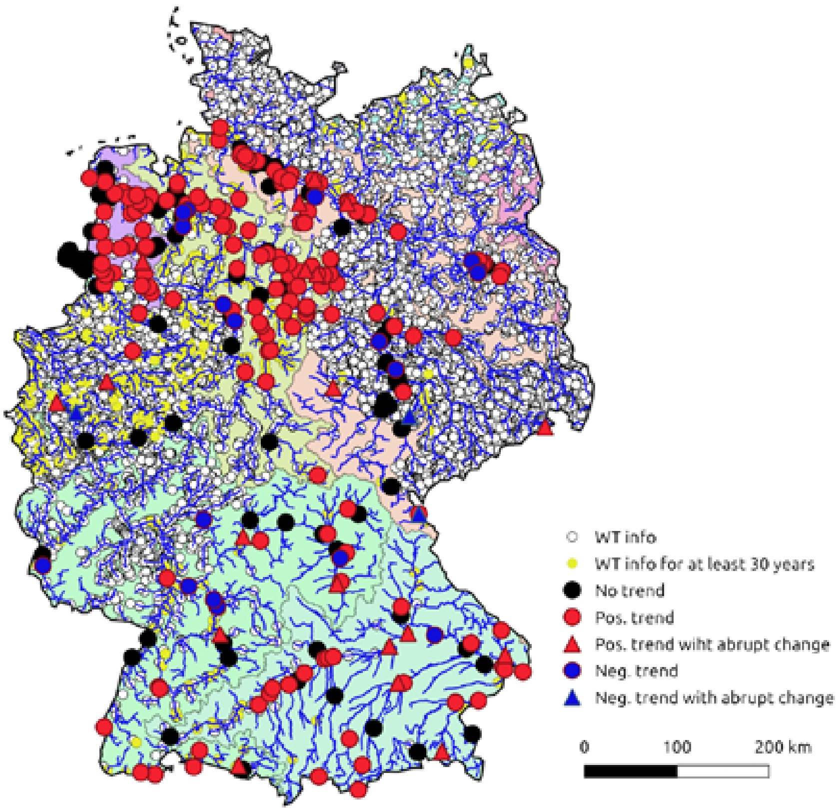


**Figure 1**: River basin (WISE WFD reference spatial data sets) and network (EU-Hydro river network) map with water temperature measuring stations and water temperature trend analysis results. Small dots indicate measuring station with available temperature information (white) and temperature information with at least 30-year coverage (yellow). Large dotes or triangles indicate stations used for water temperature trend assessment for the period 1987-2016 (black dots: no significant trend, red dots: significant positive trend, blue dots: significant negative trends, red triangles: significant positive trend and blue triangles: significant negative trends, potential inflicted by abrupt changes).

## Data Availability (or) Available Information

Data was provided by LUBW, LfU BY, SENUVK BE, LfU BB, HLNUG, LUNG MV, NLWKN, LANUV NW, LfU RP, LUA SL, LfULG SN, LHW ST, LLUR SH, TLUBN and BfG. They are jointly available in the German data set 2.0 compilation of the UFZ. Interested users should contact the authors, as some data owners only agreed on limited use.

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# Power Generation from Variable Renewable Energies (VRE)

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## INTRODUCTION

Climate change and extreme weather events may be associated with strong impacts on the electricity generation from VRE, i.e., wind power and photovoltaics, in the future (Griffin et al. 2020, Bieritz 2015, Jerez et al. 2015, Pryor and Barthelmie 2010). This climate change will alter regional and local weather conditions leading to more and also more intense weather extremes and, therefore, changing the spatiotemporal availability of VRE. Especially for countries with a high share of wind and photovoltaic (PV) power generation like Germany, the overarching questions are, how climate change will affect the electricity production from variable renewables and how strong may be this impact for different climate scenarios (McCollum et al. 2020). In order to investigate these questions, detailed datasets of onshore wind turbines and PV systems were created and used with simulation models developed in this project to simulate the power generation with a high spatial and temporal resolution. Additionally to the simulations of the electricity production from these variable renewables for all of Germany using past weather data, the influence of climate change on selected wind turbine sites was estimated with the help of climate scenario data.

## DATA AND METHODS

The spatiotemporal electricity generation from variable renewable power plants, e.g., onshore wind turbines and PV systems, can be determined with numerical simulations using detailed plant and weather data (Lehneis et al. 2020a, 2020b, 2021, 2022). Moreover, by employing climate scenario data in these simulations, the impact of different climate change scenarios can be estimated for the electricity generation as well. Such climate scenario data, which were created using past weather data with different climate change signals in climate models, were delivered by GERICS for meteorologically typical years, the wind rich 2008 and the low wind year 2010. Figure 1 gives an overview of the involved data and shows the information flow for the performed simulations.

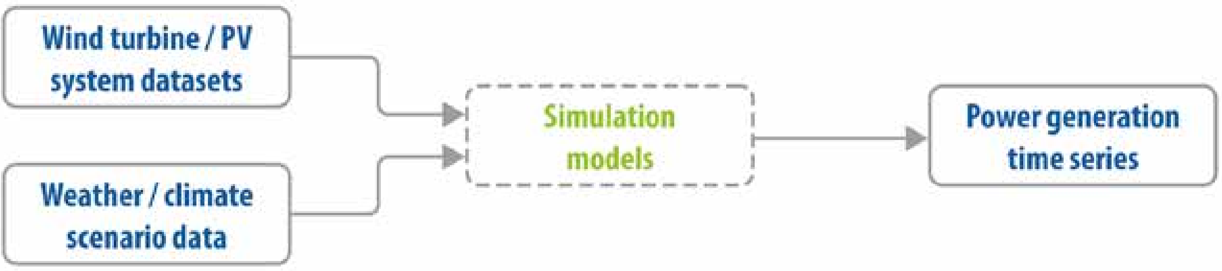


**Figure 1**. Flowchart of the numerical simulations showing the involved data and the information flow.

The calculation steps, the underlying physical laws and the specific properties of the used simulation models, i.e., the wind power and PV models, are described in (Lehneis et al. 2020b, 2021). In order to have also the opportunity to investigate the influence of extreme weather events, e.g., heavy storms, on the electricity generation from onshore turbines, an additional storm control functionality was included in the wind power model. After creation of the plant datasets and finishing the validation of the simulation models, the numerical simulations were carried out for nearly 1.64 million variable renewable power plants in Germany for the year 2016. Furthermore, for selected 22 onshore turbines of different power classes sited in the region from Emden to Husum in the German Bight, the power generation was simulated with actual weather data as reference (REF) and three different climate change scenarios (RCP 2.6, 4.5 and 8.5) for the years 2008 and 2010.

## RESULTS

The following Figure 2 shows the simulated electricity generation from almost 26 thousand onshore wind turbines and over 1.61 million PV systems in Germany for 2016 at county (NUTS-3) level.

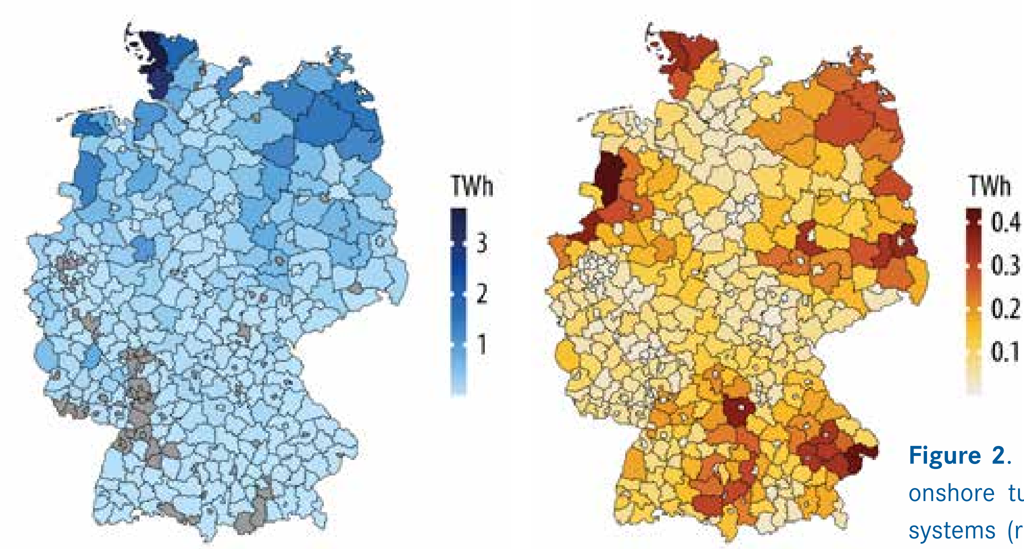


**Figure 2**. Electricity generation from onshore turbines (left map) and PV systems (right map) at NUTS-3 level in Germany for 2016.

It is clear that most of the electricity from onshore turbines is generated in the north of Germany, whereas the power production from PV systems takes mainly place in the northwestern, eastern and southern parts of Germany. Accordingly, these regions are expected to experience the biggest impact of changing weather conditions on the electricity generation from VRE.

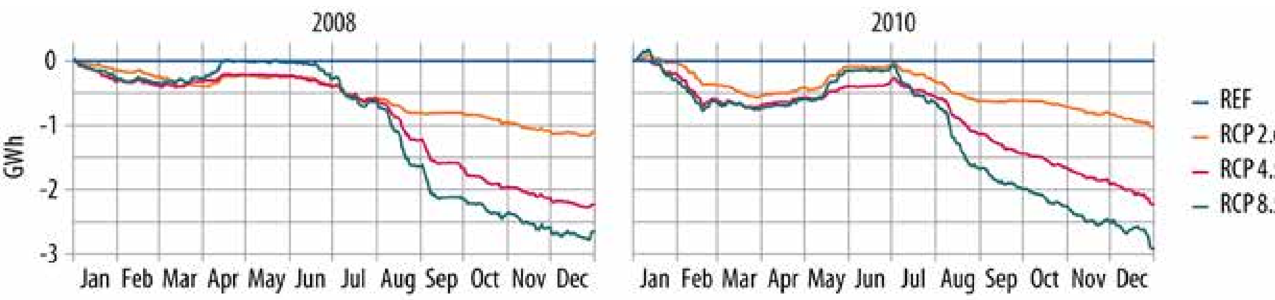


**Figure 3**. Cumulated deviations of the electricity generation from the selected onshore wind turbines for three different climate scenarios compared to the reference values of the years 2008 and 2010.

Figure 3 depicts the cumulated deviations of the electricity production from the selected 22 onshore turbines in the German Bight for the climate change scenarios (RCP 2.6, 4.5 and 8.5) compared to the reference values (REF) of the years 2008 and 2010. It becomes clear that there is hardly any difference in the power generation between these climate scenarios and the actual weather data of the investigated years. The reason for this is that the data provided by GERICS for the different climate scenarios hardly differ from each other. This is due to the inability of current climate models to offer scenario-based data with the spatial and temporal sensitivity required for the presented approach. Further efforts must therefore be made to provide climate scenario data with a high resolution in order to indicate regional and local impacts.

## CONCLUSIONS

It could be clearly shown that the impacts of climate change and weather extremes can be investigated for VRE with the help of numerical simulations using detailed plant and weather data. Caused by the limited sensitivity of the delivered climate scenario data, the effects on the power generation from wind turbines are not as strong as one might assume. In a further step, it is planned to include the electricity production from flexible renewables, e.g., biogas power plants, to enable a more holistic approach. Moreover, within the framework of the project cooperation with DLR, both the dataset of onshore wind turbines and the corresponding wind power generation could be handed over for studies on future energy systems considering the effects of climate change for variable renewables.

### Data Availability

The underlying plant datasets of onshore wind turbines and PV systems are also available for download at *https://www.ufz.de/record/dmp/archive/5467/de/*.

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# Climate change impact on variable renewable power generation in Europe

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## INTRODUCTION

The aim of DLR in this sub-project was to understand the impact of climate change on the variability of wind and solar power generation and of power demand. Variable renewable energy (VRE) generation potentials are calculated with DLR's Energy Data Analysis Tool "EnDAT" (Scholz 2012, Stetter 2014). EnDAT uses weather data and applies area suitability criteria and power plant models. The weather data can either be reanalysis data from weather forecasting models or scenario results from climate models. The time series of potential hourly power output that EnDAT generates can be searched e.g. for changes in the duration of wind calms and, if suitable load scenarios are available, of cold dark calms.

## DATA AND METHODS

Wind speed, solar irradiance, temperature and surface roughness data were provided by the project partner GERICS (Helmholtz Center HEREON) for the European EURO-CORDEX-Domain in an hourly resolution, which is crucial for data for power systems analyses. As the standard temporal resolution of EURO-CORDEX-data is only three-hourly, the choice of scenarios (combinations of global climate model results downscaled by regional climate models) was reduced to 18 scenarios (8 for the representative concentration pathway (RCP)2.6, 2 for RCP4.5 and 8 for RCP8.5) that were downscaled with the regional climate model REMO from GERICS in hourly resolution. Each scenario comprises 150 years. The scenarios are comparable with each other and with rea-nalysis weather data from weather forecasting models only on a 30-year time scale. They cannot be compared concerning individual hours or years. Therefore, 30-year time periods were used to analyze the development of the variability of power generation from VRE.

## RESULTS

**Figure 1** shows the long-term development of annual wind power capacity factors (cf) onshore and offshore and the difference in their seasonal distribution between 2020 and 2085 based on an individual climate scenario (MPI-ESM-LR r3i1p1 / REMO, provided by GERICS) for selected countries. The long-term annual development shows slight trends in several of the selected countries. It becomes visible that trends can be opposing in different countries and that trend reversions are possible in the course of the century. The seasonal analysis shows that for wind onshore, an increase of monthly cf is rather likely in winter months while in the summer, a cf decrease of up to 3% (in absolute cf units) can occur (Great Britain). This reduction is even more pronounced for wind offshore, where it reaches around 6% (in absolute cf units).

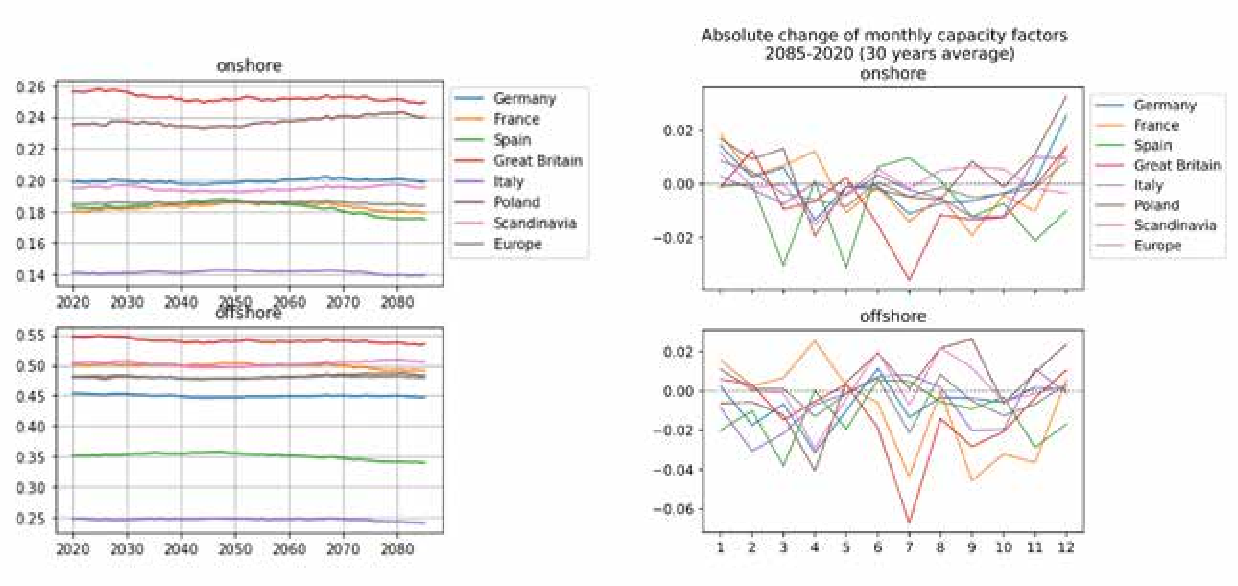


**Figure 1**: Long term development of wind capacity factors (cf) onshore and offshore in selected countries and Europe as a whole. Left: sliding 30-year average of annual cf. Right: change of sliding 30-year average of monthly cf between 2020 and 2085.

**Figure 2** shows the maximum duration of 5% wind calms in selected countries, i.e. the maximum duration of periods with a wind power production lower than 5% of the installed capacity. The graphs show that the longest durations of 5% onshore wind calms of around 200h occur in Poland, Spain and France. As it is hard to identify long term trends from this diagram, additionally the sliding 30-year average is displayed on the right-hand side of Figure 2. It shows that in some countries, the duration of 5% wind calms is rather stable in the long run, while for example in France it increases by around 15h in the second half of the century.

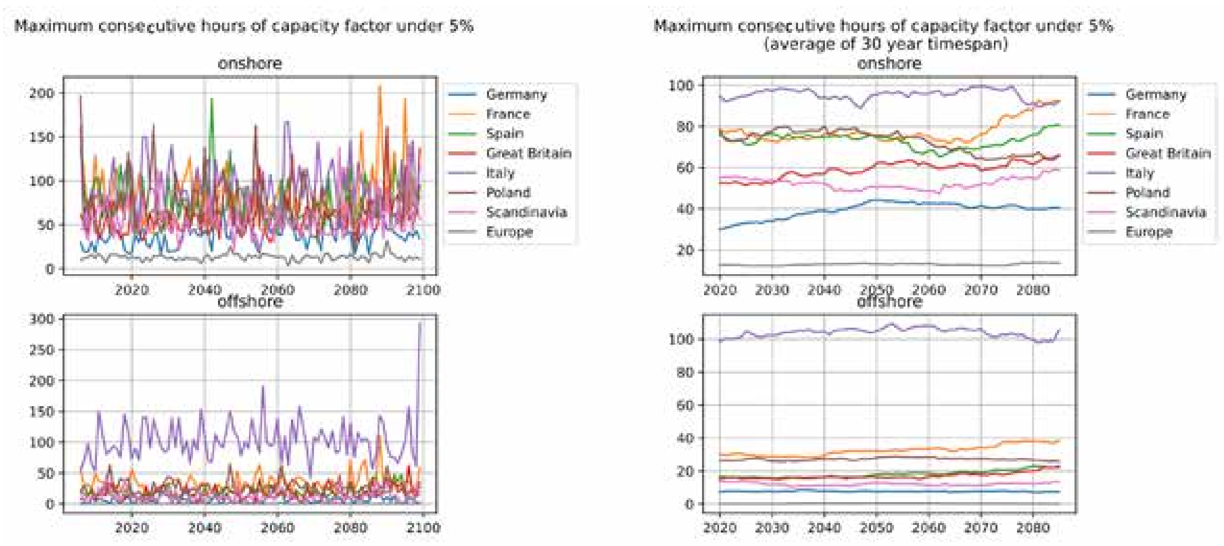


**Figure 2**: Long term development of 5%-wind calms onshore and offshore in selected countries and Europe as a whole. Left: Annual maximum duration of 5%-wind calms. Right: Sliding 30-year average of annual maximum duration of 5%-wind calms.

## CONCLUSIONS

Our analysis shows notable trends of VRE capacity factors and of wind calms in Europe in the course of the 21st century, which can vary between countries and seasons. As of now, the data base consists of only one climate scenario. To enable general conclusions, we will extent the analysis to an ensemble of scenarios. Further, we will include photovoltaic power generation and electric load. Together with a European energy system scenario, these data sets will enable the analysis of residual load and subsequently of cold dark calms, i.e. times with simultaneous high demand and low supply.

### Data Availability (or) Available Information

It is planned to make our results available via the open energy platform OEP.

### Literature

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HELMHOLTZ
CLIMATE INITIATIVE


# CLUSTER III

# CLUSTER III:
# COMMUNICATION

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## INTRODUCTION

The Climate Initiative of the Helmholtz Association started on July 1, 2019, with its scientific part. From the beginning, the initiative was to be accompanied by a communication cluster. During the planning phase, the first ideas workshop on March 13 and 14, 2019, took into account the communicative aspects of systemic climate research. On this basis, in the months that followed, communicators from all six research fields and from the head office worked with researchers to develop ideas for a communication plan. After an external evaluation in May 2019, the Steering Committee decided on June 18, 2019, that a “Helmholtz Information Hub” should be implemented.

The Communication Cluster of the Helmholtz Climate Initiative has been building up this new Helmholtz Information Hub in Berlin since January 1, 2020. The hub has the strategic goal of centrally communicating systemic climate research from all six research areas and the 15 centers involved in the initiative. Its aim is to facilitate topic communication across research areas and centers. The information hub is thus a comprehensive Helmholtz-wide information, communication and expertise platform. This is in line with the mission of the Helmholtz Association to address major societal challenges with a systemic approach.

The following four points were named by the Steering Committee as priority tasks for the communication cluster:

- Establishment of an expert database of about 100 Helmholtz climate researchers who act as direct contacts for politicians, the media and the public
- Creation of fact sheets on current climate-relevant issues, especially for political communication
- Creation of the first social media formats (e.g. YouTube clips featuring selected experts)
- Continuation of discussions with external partners via common communication formats

The existing institutions or initiatives (e.g. GERICS, climate offices, REKLIM, ESKP, etc.) were to be involved in this task.

The primary interaction groups were defined as the media, the (young) public, decision-makers in politics and business, and young scientists.

## KEY MESSAGES

The following six statements were defined as the core messages of climate communication:

1. Climate change is REAL and CONCRETE. It’s happening NOW and it affects YOU.
2. Something has to change – NOW.
3. The necessary changes must be seen as an OPPORTUNITY for our economic and social development. However, the risks of failing to act should not be concealed.
4. Helmholtz is active in the field of climate research as a network that can proactively and reactively provide important fact-based contributions and competent experts.
5. Thanks to its six research areas, the research community has a high level of system expertise.
6. Thanks to its systems expertise, Helmholtz offers solutions for major societal challenges such as climate change.

## SPECIAL FRAMEWORK CONDITIONS

A first inventory in 2019 showed that the Helmholtz Association already had a great deal of potential in climate research and "system expertise" (REKLIM, Helmholtz Climate Offices, GERICS, TERENO, MOSES, Earth System Modeling, Digital Earth, Earth System Knowledge Platform, school laboratories, and "SynCom" as a future networking platform of the Helmholtz research area Earth and Environment, etc.). The inventory also showed that there were a large number of established external climate research and climate communication structures. These had to be taken into account in order to avoid duplication and parallel processes in the communication of climate issues. The new Helmholtz climate communication should not simply be “more of the same.” Rather, the aim was to use synergies that already existed within the Helmholtz Association, but also with other research organizations such as Leibniz, Max-Planck and Fraunhofer as well as universities.

Right from the start of the Climate Initiative, there was thus an opportunity to process and use existing climate knowledge at Helmholtz for communication, especially in the research areas of adaptation and mitigation. In the course of the initiative, the results of the 13 new research projects would then gradually flow into the communication individually and based on their progress.

In principle, the following applied: not only quick and reactive but also proactive communication is required, as can be seen in the often shortened political and media debate. The short initial funding period of 24 months also presented the communication with the challenge of establishing measures that could be implemented quickly and were not just a “flash in the pan” but offered a long-term connection option.

At the end of 2021, it was clear that the communication of the Helmholtz Climate Initiative should be continued in the medium to long term. All communication formats developed up to this point could therefore be continued and improved from the beginning of 2022.

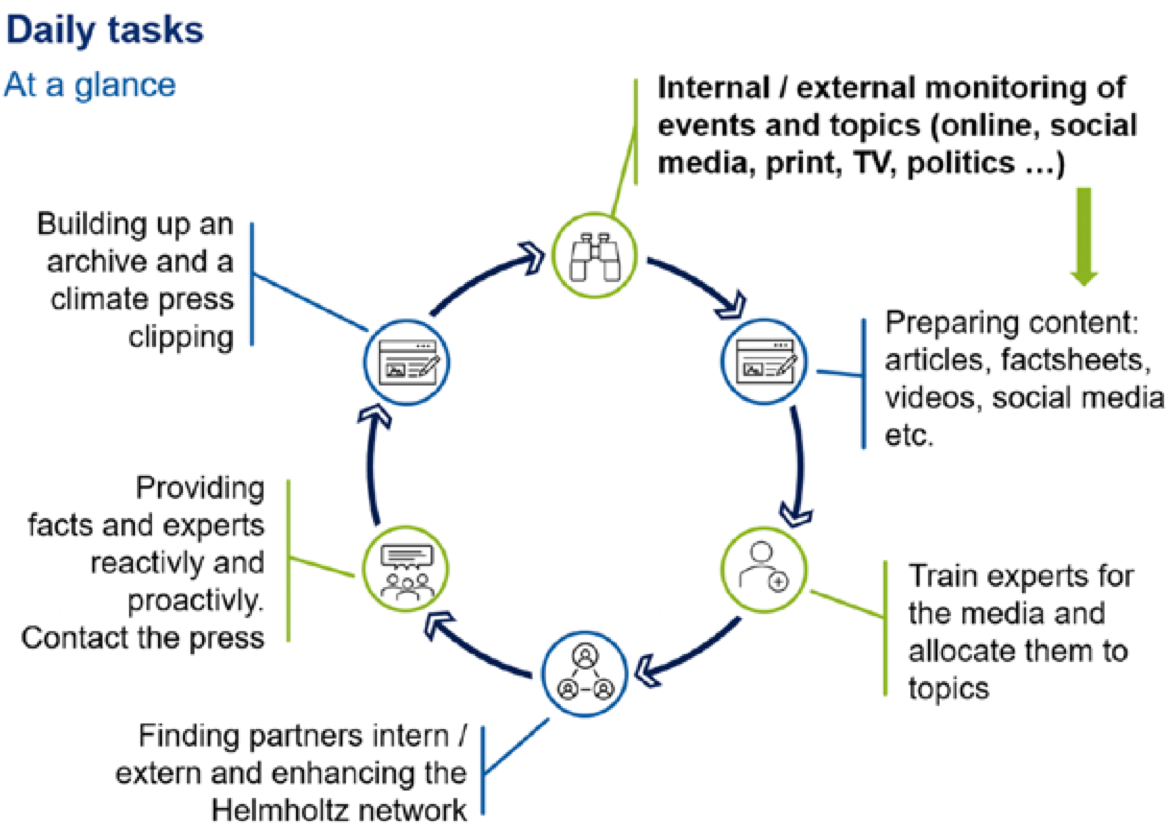
## WHAT IS THE UNDERLYING COMMUNICATION CONCEPT?

In the digital age, communication takes place as a media and political "24/7 business". In print, online, TV, radio and social media, we not only experience an incessant multimedia flow of information, but also a cross-media flow. This means that the different media formats recur and complement each other. This also poses special challenges for climate communication On the one hand, the relevant information must be continuously monitored. On the other hand, it is important to participate proactively and reactively to be able to speak as quickly as possible. More and more media organizations and companies rely on the newsroom model, which involves monitoring current information flows on various channels (also on target group-specific channels) and interacting with them directly and as promptly as possible.

The breadth of Helmholtz's research expertise in the field of climate research makes it possible for the communication concept of the Helmholtz Information Hub to be operationally based on the model of such modern media newsrooms: daily monitoring of current or upcoming climate-relevant topics and debates in public, media, politics and business. At the same time, it is possible to continuously check which results of Helmholtz climate research are available or are to be expected. These results can be processed as required for various communication channels, for example with online articles, social media posts, fact sheets, background papers, graphics and explanatory videos. Ideally, Helmholtz scientists can also be positioned as topic experts. In-house media training can be offered to them for this purpose. Networking with other partner organizations in climate science extends the range of our own actions. In this way, current interests of the target groups are addressed and Helmholtz expertise is brought into the corresponding debates.

Some of the Helmholtz topics are also suitable for starting our own debates. This enables the Helmholtz Climate Initiative to act not only reactively but also proactively. We also had to determine whether the Helmholtz newsroom could serve as a best-practice example in the long term for the communication of other interdisciplinary Helmholtz topics going beyond the Climate Initiative.

Against this backdrop, the media newsroom was chosen as a model for the design of the work processes in the Helmholtz Information Hub.



## ESTABLISHING A NEW OFFICE IN BERLIN

Communication with politics and the media thrives on personal meetings and discussions. That is why the team has set up its office in Berlin-Mitte, close to the capital city's media and federal politics.

With the first pandemic lockdown in March 2020, new working conditions arose unexpectedly. In-person meetings with scientists, politicians and journalists were limited to a minimum. Communications work was mainly done in home offices, and meetings and discussions were held via video conference. Nonetheless, the planned schedule was adhered to – with essential support from communication colleagues in the centers and administration of the UFZ. By summer 2020, an adequate communication infrastructure had been set up, employees were hired and moved into the new offices, and external services were tendered and commissioned.

Initially, 3 employees were hired (1 FTE assistant from April 1, 2020, and 2 FTE science editors from March 15, 2020, and July 1, 2020). At Markgrafenstraße 22, 10117 Berlin, we moved into two office rooms (approx. 25 square meters each). Service providers were hired for the following: website design and programming, graphics, video films, media training for scientists, translations.

## MONITORING

Daily media and topic monitoring takes place using these services: Press Relations (via the Berlin office), Echobot (via Hereon), Science Information Service (idw), dpa-Agenda, Tagesspiegel-Background.

## ESTABLISHING A WEB PRESENCE (GERMAN AND ENGLISH)

On July 8, 2020, the central communication platform of the Helmholtz Climate Initiative went online with the website *www.helmholtz-klima.de*. Further operational communication work began around this central platform, including social media, networking, events, expert placement, media library, press portal, and climate FAQ. The core elements of the website are:

- Current articles and interviews with HI-CAM scientists (about 90 articles published as of March 2022)
- A database of experts with around 120 entries (as of March 2022) of Helmholtz climate scientists. Visitors can also find selected experts on current topics (e.g. IPCC status reports) directly on the website's homepage, where they can also make inquiries about their own concerns.
- Media library with videos, fact sheets and infographics (about 8,000 downloads as of March 2022)
- Press portal with press releases from the Helmholtz Association on climate issues, press contacts (including contacts in the centers), and a media library with a download area
- Climate FAQs with answers to relevant, frequently asked questions about climate change; fact checks on false statements about climate change were also published on the website of the climate initiative in cooperation with klimafakten.de
- Presentation of the 13 research projects of the Helmholtz Climate Initiative and the publications that were created in the projects
- Climate calendar with upcoming climate-related events (conferences, decisions, discussion panels, publications by the IPCC, etc.)
- Visualization of further Helmholtz climate research and the 15 participating centers

- Two interactive story-telling formats: "Our CO2 budget" and "City of the future"
- Since July 2020, the Helmholtz Climate Initiative websites (as of March 2022) have been clicked about 200,000 times by some 90,000 visitors.


## DEVELOPMENT OF SOCIAL MEDIA CHANNELS

The Helmholtz Climate Initiative is mainly active on the following social media channels: Twitter, Instagram, Facebook. In order to have the work on these channels professionally assessed, the social media agency Dajana Hoffmann was commissioned in August 2021 to evaluate the work and make suggestions for improvement. The agency came to the following conclusions:

“For the very short development period, the social media channels of the Helmholtz Climate Initiative have very good outreach, although the outreach on Twitter leaves all other channels far behind. The very good interaction with the posts shows that they are viewed as high-quality and relevant by the target groups.

**Twitter**
With around 1,800 followers (more than 2,400 as of March 2022), Twitter is the social media presence of the Helmholtz Climate Initiative with the greatest outreach. This is because the Twitter account is actively operated, but also because of the content and the target group of the specialist audience. In 2021 you can see a significant increase in impressions per day, which proves that the Twitter account of the Climate Initiative is perceived as a source of relevant and high-quality information. This channel has further growth potential. In

June there was a peak of up to 180,000 impressions, which of course also testifies to an enormous range. Since there is a large audience of professionals on Twitter, it can be assumed that the account is clearly perceived as a partner for dialogue and relevant information.

**Instagram**

The Instagram account shows that the content is met with great interest. Approximately 1,100 subscribers (more than 1,500 as of March 2022) read the articles, like or comment on them, and mark their content in order to read it again later. Interaction with the articles has increased significantly over the period; the trend is clearly positive. Particularly noteworthy are the saved articles: 58 articles were saved 186 times, which confirms both the relevance of the information and its high quality. In contrast to the Facebook page, the users here are 25 years and older and therefore tend to be a bit older. The gender distribution is also slightly different: 56% female, 44% male.

**Facebook**

The reach of the Facebook page developed very well in 2021. With a very small number of 340 subscribers, the initiative reached an average of 3,600 people a month; in June it was almost 10,000 people. The number of subscribers is also continuously increasing, especially with increasing reach. This year the initiative has succeeded in realizing particularly large reach with special content. Topics such as the climate outlook for Germany, climate change, global warming, the updated fact sheet on climate change (over 5,000 people reached), and a healthy lifestyle are particularly successful. Contrary to the trend, the subscribers to the Facebook page are rather younger. The number of female and male subscribers is almost equal."

### YouTube

So far, 9 videos have been published on the YouTube channel. The front-runner is the video with UFZ researcher Andreas Marx on the drought monitor, with more than 12,000 views. Other topics that have already been published are:

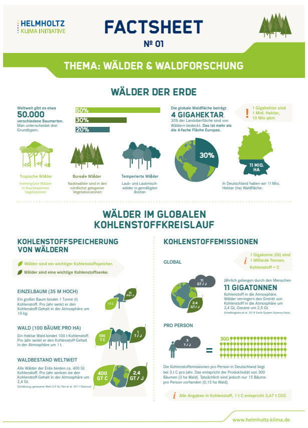
"This is how hot our future could get"
"This man calculates the forest of the future"
"How climate change is affecting our health"
"Climate protection in everyday life: what influence do we have?"
"Seagrass meadows as carbon stores"
"Water and Urban Green: City of the Future"
"Image film: We are the climate initiative"
"Recording of the 2021 Dialogue Conference"
"NET zero technologies"

## CREATION OF FACT SHEETS ON CURRENT TOPICS

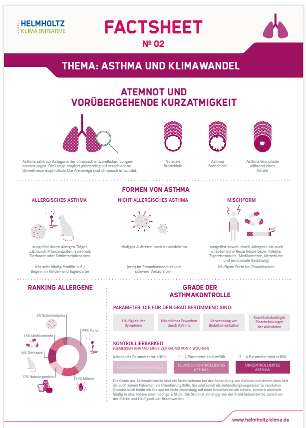
Climate knowledge brought to the point graphically – that is the idea behind the two-page fact sheets of the Helmholtz Climate Initiative. They present individual climate issues in a clear, easy-to-understand and graphically appealing way. The fact sheets close by showing the area in which Helmholtz is researching the relevant topic. The following eight topics have been implemented so far:

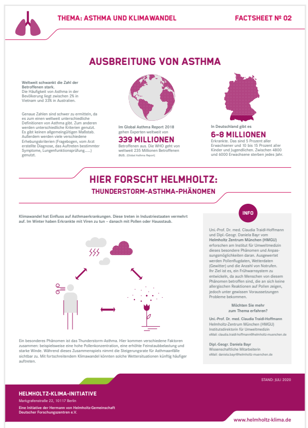
- Forests and forest research
- Asthma and climate change
- Oceans
- Direct air capture
- Photovoltaics
- Soil and soil research
- Air quality and pollutants
- Hydrogen
- Ticks and borreliosis

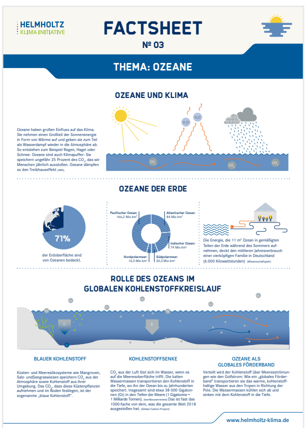
*https://www.helmholtz-klima.de/presse/mediathek?category[8]=8*



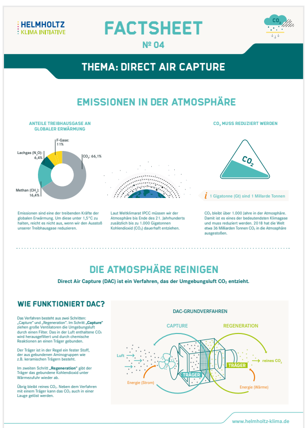


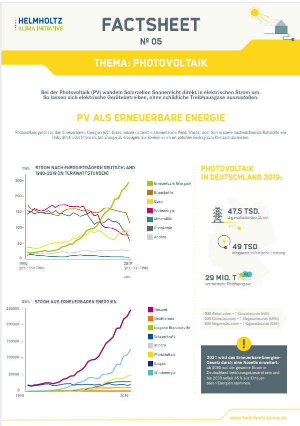




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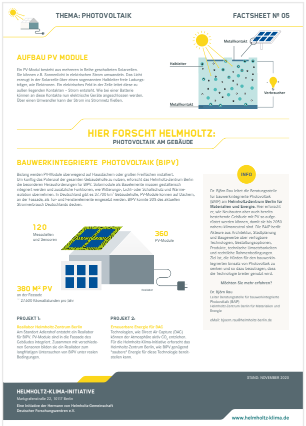
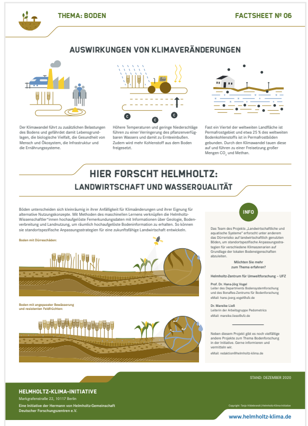

THEMA: PHOTOVOLTAIK
FACTSHEET Nº 05
AUFBAU PV MODULE
HIER FORSCHT HELMHOLTZ:
PHOTOVOLTAIK AM GEBÄUDE
BAUWERKINTEGRIERTE PHOTOVOLTAIK (BIPV)


FACTSHEET
Nº 06
THEMA: BODEN UND BODENFORSCHUNG
BÖDEN DER ERDE
DIE WICHTIGSTEN BODENFUNKTIONEN
ROLLE DER BÖDEN IM GLOBALEN KOHLENSTOFFKREISLAUF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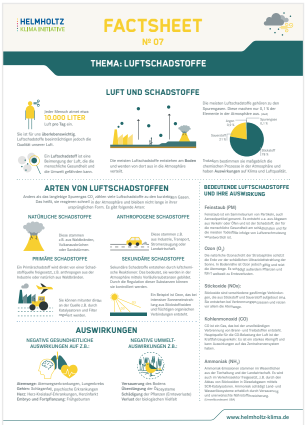
AUSWIRKUNGEN VON KLIMAVERÄNDERUNGEN
HIER FORSCHT HELMHOLTZ:
LANDWIRTSCHAFT UND WASSERQUALITÄT


FACTSHEET
Nº 07
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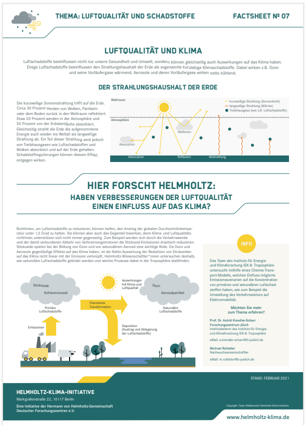
LUFT UND SCHADSTOFFE
ARTEN VON LUFTSCHADSTOFFEN
AUSWIRKUNGEN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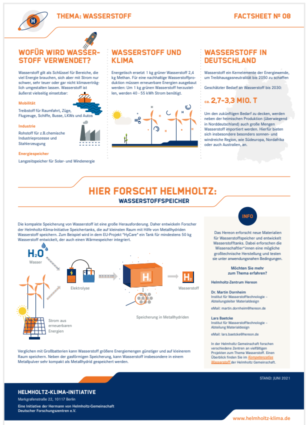
FACTSHEET Nº 07
LUFTQUALITÄT UND KLIMA
DER STRAHLUNGSHAUSHALT DER ERDE
HIER FORSCHT HELMHOLTZ:
HABEN VERBESSERUNGEN DER LUFTQUALITÄT EINEN EINFLUSS AUF DAS KLIMA?


FACTSHEET
Nº 08
THEMA: WASSERSTOFF
WAS IST WASSERSTOFF?
FARBENLEHRE WASSERSTOFF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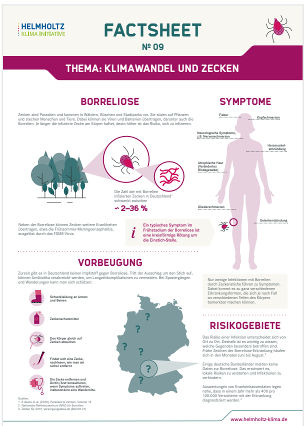
FACTSHEET Nº 08
WOFÜR WIRD WASSERSTOFF VERWENDET?
WASSERSTOFF UND KLIMA
WASSERSTOFF IN DEUTSCHLAND
HIER FORSCHT HELMHOLTZ:
WASSERSTOFFSPEICHER


FACTSHEET
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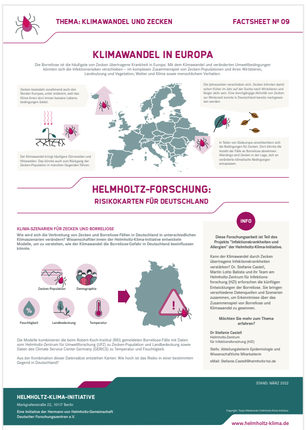
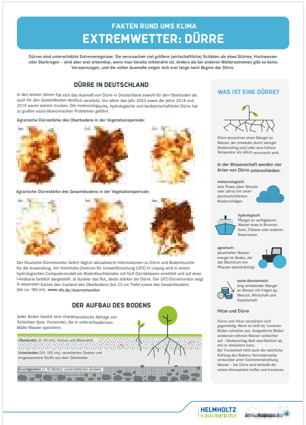
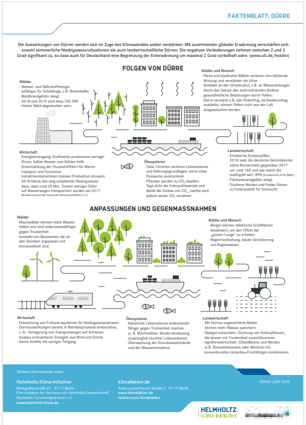
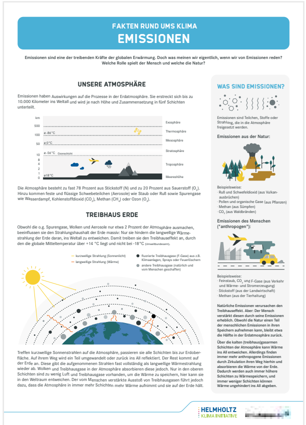
BORRELIOSE
SYMPTOME
VORBEUGUNG
RISIKOGEBIETE

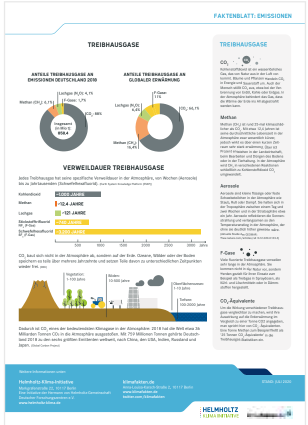

THEMA: KLIMAWANDEL UND ZECKEN
FACTSHEET Nº 09
KLIMAWANDEL IN EUROPA
HELMHOLTZ-FORSCHUNG:
RISIKOKARTEN FÜR DEUTSCHLAND

In cooperation with *klimafakten.de*, two further fact sheets on the topics of drought and emissions were created. In addition to the fact sheets, the climate initiative also makes the individual graphics of the fact sheets available in the media library.










In addition, the 26-page fact sheet "What we know about the climate today – basic facts about climate change" (almost 6,000 website visits) was created in cooperation with the German Climate Consortium, the German Meteorological Society, the German Weather Service, the Extreme Weather Congress and klimafakten.de.

## ACTIVE NETWORKING WITH OTHER CLIMATE COMMUNICATION STAKEHOLDERS

With the co-editors of the fact paper "What we know about the climate today – basic facts about climate change" (German Climate Consortium, German Meteorological Society, German Weather Service, Extreme Weather Congress and klimafakten.de), an active network was built up, including representatives of Max-Planck, UBA, Leopoldina, IPCC, Science Media Center (SMC) and many Heads of Communication from the Helmholtz research field “Earth and Environment.” In this network, regular meetings take place (about once a month) to discuss and plan common communication topics. For example, 10 climate cards were created for politicians, which were distributed to all members of the Bundestag and the state offices of the parties at the beginning of September 2021. On each of the 10 cards in postcard format, a fact about climate change was graphically displayed and explained in an easily understandable manner with two or three key explanations.

Since climate issues play a very important role in the Earth and Environment research area with its “Changing Earth – Sustaining our Future” program, there is also a regular exchange with the heads of communication from the 7 Earth-Environment Centers. As one result, the interactive storytelling on “$CO_2$ Budget" was created. Further important and useful interfaces are currently being developed to SynCom and DAM in the immediate vicinity of the office.

On the BMBF website ***www.wissenschaftsjahr.de*** there are regular articles about researchers from the Climate Initiative and their projects under the heading “Heads of Change”.

For the National Institute for Science Communication (NaWik), the communication cluster has been active on the advisory board for the development of a new e-learning course since December 2021.

## PRESS RELATIONS

Classic press relations show how important it is to work closely with colleagues in the communication departments of the centers and the office. The structures established there are still primarily used by journalists. The communicative offer of the climate initiative is above all a complementary one: the cluster communication is the first point of contact for journalists who need orientation or help finding contacts or if climate issues need to be answered across centers and research areas. In addition, the climate initiative offers media representatives direct contact and active exchange.

A newly established press distribution list now includes some 160 contacts. These are of particularly high quality, since only journalists register themselves there. So, they have a strong interest in the content of the Helmholtz Climate Initiative. Press inquiries are received regularly. They will be answered in close cooperation with the press offices of the centers. For example, Helmholtz scientists are referred to newspapers, magazines, radio or TV-stations for interviews or expert discussions. So far, the front-runners in media coverage have been the climate outlooks by Gerics / Hereon (July 2021) with around 50 contributions in regional and national media.

An important communication topic was COP 26, which took place in Glasgow in November 2021. All Helmholtz activities were bundled and published on a dedicated landing page (***https://www.helmholtz-klima.de/klima-konferenz-cop26-glasgow***). In addition, the COP was actively supported on social media. Reports and podcasts from Glasgow have been published. Scientists from the Helmholtz Climate Initiative were represented in four side events of the EU pavilion.

## POLITICAL COMMUNICATION

In political communication, contacts are continuously being established. A dedicated editor's position was set up to focus on political communication in April 2021. This will use the upcoming phase after the federal election to build up a resilient network with climate politicians. The political transition period was used for initial contacts. Meetings were held with the environmental and climate policy speakers from five parliamentary groups. Afterwards, the speakers received fact sheets specifically compiled for them explaining the research of the Helmholtz Centers relevant to environmental and climate policy, as well as invitations to events.

The Helmholtz Climate Initiative has also created tailor-made distribution lists with contacts from government and administration as well as economic, social and environmental associations. These can be used, for example, to send invitations to various climate policy events.

As far as possible, the Communication Cluster takes on the monitoring of political initiatives and events in Berlin for the centers. A comparison of the climate policy positions of the election programs of the six parties represented in the Bundestag and some summaries of the parties' current position papers were drawn up. In particular, announcements about research funding and repositioning of our research topics were worked out. Scientists from the initiative could be referred for several media inquiries to compare the election programs. The centers' press offices were also briefed on current political developments, e.g. on the subject of CCS.

## MEDIA TRAINING FOR HELMHOLTZ CLIMATE SCIENTISTS

The Communication Cluster offers three different types of media training for the scientists of the Climate Initiative:

- Two-day media training
- Two-day moderation training
- Personal media training lasting several hours

On the one hand, the training prepares the scientists for contact with media representatives. On the other hand, it builds up and/or improves their media skills. A total of 15 media training courses, in which 77 scientists took part, were held in cooperation with the external service provider.

## A NEWSLETTER PROVIDES THE LATEST INFORMATION ON CLIMATE RESEARCH

The Helmholtz Climate Initiative's newsletter is published once a month and now has around 600 subscribers. It summarizes the most important topics from the current reports about Helmholtz climate research from the last four weeks. Interesting offers from partner organizations and relevant events are also announced.

## EVENTS

Numerous events in 2020 and 2021 were canceled due to the pandemic. Nevertheless, the Helmholtz Climate Initiative participated in various online events:

- 4 research breakfasts for members of the Bundestag and their staff in close cooperation with the DKK
- Environment week at the German president's summer meeting
- Series of webinars with Vattenfall
- Science Communication Forum
- Press working group of the Zuse community
- Teatime lecture by the British Embassy
- Online symposium with the German Climate Change and Health Alliance (KLUG)
- Presentation of HI-CAM at Green Talents
- Presentation of HI-CAM at the Citizen Science Think Camp
- Online panel discussion "What can we achieve in climate policy?" with "Wissenschaft im Dialog"
- METKOM2021, panel discussion "Dealing with climate deniers – where facts don't help"
- 4 side events at COP26 in Glasgow in the EU pavilion

The dialogue conference of the Helmholtz Climate Initiative took place on November 17, 2021. It was entitled "One climate – many disciplines". This conference in Berlin-Mitte was the central event for the presentation of the research results achieved by the Helmholtz Climate Initiative up to that point.

The aim of the conference was to offer an interactive, lively event offering more than just a few specialist lectures. Rather, the presentations were to be kept short and generally understandable in order to be able to enter into a direct dialogue with guests from business, politics, associations and the public. The audience at the AXICA Congress Center also had the opportunity to participate in the discussion.

The presentations came in equal parts from the two scientific clusters Mitigation and Adaptation. They showed what Helmholtz is currently researching systemically in the areas of mitigation and adaptation, what results have emerged in the past two years as part of the climate initiative, and what can be developed from them in the future. The aspect of the transfer of Helmholtz research was also in focus. In this way, local stakeholders could be shown what Helmholtz is researching for them.

The conference was accompanied by a program with artists: the photo artist Horst Wackerbarth photographed and interviewed the guests on his well-known "Red Couch". There was a poetic and a graphic recording of the event. The aim of these activities was to loosen the classic science conference character and instead give it the character of a happening, an "adventure day" for all participants.

Although only a very small audience could be received at this hybrid event due to the pandemic restrictions (80 attendants on site), a lively atmosphere was created with many conversations among the participants. At the same time, more than 900 viewers took part in the livestream. The guests were on site from 9:30 am to 10 pm.

Probably the most prominent stage guest was Eckart von Hirschhausen, who moderated the talk on climate communication and also performed an exclusive one-hour performance for the guests in the evening program.

Media partners were Der Tagesspiegel and RadioEins. RadioEins, in particular, was very committed: On the Saturday before the event (November 13, 2021) there was a three-hour broadcast by the professionals from the HZB, in which five scientists from the Climate Initiative were guests (Rutger Schlatmann, HZB; Roland Dittmeyer, KIT; Claudia Traidl-Hoffmann, HMGU; Thomas Jung, AWI; Friedrich Bohn, UFZ). The event on November 17 was then streamed in full on the RadioEins website.

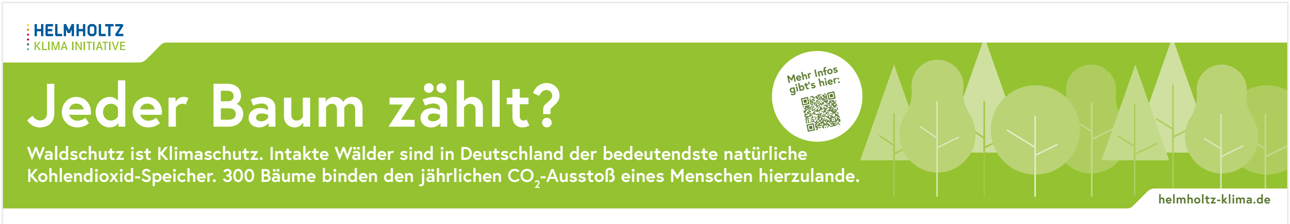
## MARKETING OF THE PARTICIPATING CENTERS AND FURTHER HELMHOLTZ CLIMATE RESEARCH

The website of the Climate Initiative and press activities give visibility to all 15 centers involved in the Climate Initiative as well as the Helmholtz office via corresponding websites, graphics and overviews in presentations. Short portraits of further initiatives by Helmholtz climate research are presented and linked in a central position on the website. Reference is also made there to the press offices of the centers and their media libraries. When it comes to press inquiries and expert recruitment, the HI-CAM communication cluster is in regular, close contact with colleagues in the press offices.

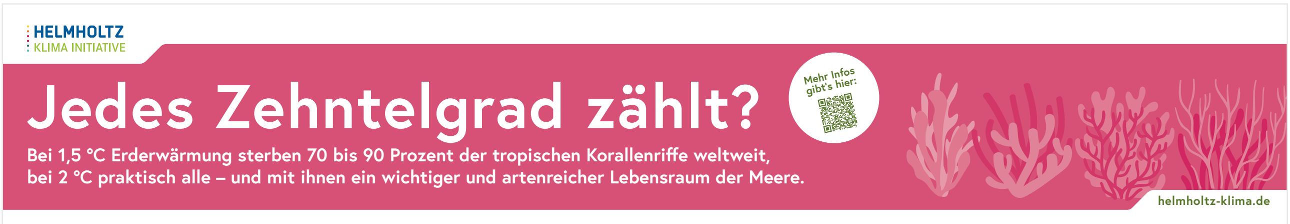
Together with the colleagues in the centers and the head office, the communication cluster of the Helmholtz Climate Initiative forms a communication network with complementary strengths: daily topic monitoring, communicative synthesis of Helmholtz climate knowledge from 15 centers, networking with stakeholders, training and communication of experts, etc. This creates further visibility for the centers on the newly created channels. In addition, the communication cluster provides services in the communication of and research on climate issues.

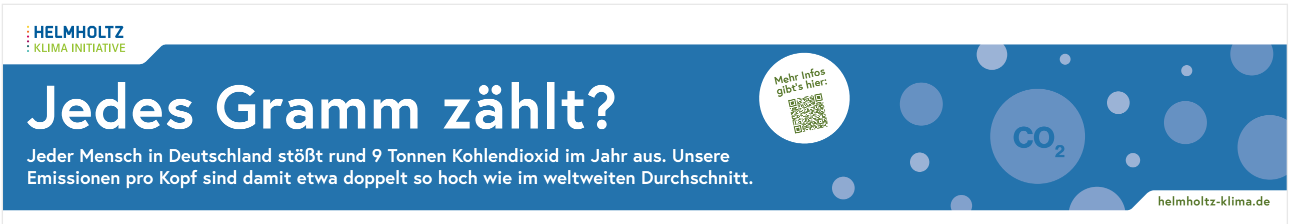
## POSTER CAMPAIGN NATIONWIDE AND AT TRAIN STATIONS IN BERLIN

In the period from October to December 2021, a poster campaign took place in cars of the Berlin S-Bahn, at selected central train stations in Berlin, and in some ICE trains. It had a total of four different motifs on four topics of Helmholtz climate research. The aim of this poster campaign was to draw the general public's attention to the Helmholtz Association's communication offerings in the field of climate knowledge and to encourage an active exchange.







## BUDGET

The total budget from the IVF for the communication cluster in 2020 and 2021 was 1,433,128 euros (+ 286,626 euros overhead). In 2022 the work is to be continued with an annual budget of 700,000 euros: For the months of January, February and March 2022, residual IVF funds were used. From April till December 2022, the budget comes from funding by the 15 centers involved in the initiative. This enables the funding of 5 FTEs + office + material resources.

## CONCLUSION AND OUTLOOK

With the communication of the Helmholtz Climate Initiative, a dynamically growing information hub was set up in 2020 and 2021, which after a short time is showing rapidly increasing growth rates on all channels. The four goals requested by the Steering Committee have been achieved. In addition, there has been a strong interest in the communication offerings of the Helmholtz Climate Initiative in all targeted interaction groups (media, the general public, decision-makers in politics and business, young scientists).

After the decision to continue the communication of the Helmholtz Climate Initiative at the end of 2021, this offer is now to be consistently expanded from the beginning of 2022. As an information, communication and expertise platform, the information hub will provide significant support in making Helmholtz contributions to climate research widely visible.

In addition to the consistent expansion of the existing, established formats, the following expansions for Phase II of the communication of the Helmholtz Climate Initiative would be worthwhile:

- Expansion of the network with the newly elected politicians at federal level
- Creation of further political event formats
- Expansion of cooperation with national media
- Expand cooperation with schools, libraries and other educational institutions

As soon as the pandemic situation allows the organization of and attendance at face-to-face events (more regularly), this should also be done more intensively. Overall, it is to be expected that the visibility of the Helmholtz contributions in climate research will increase significantly as a result of this commitment, especially among the stakeholders in Berlin.