WarmWorld Joint Project Proposal: *Better*

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Participating institutions

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Prof. Dr. J.P. Mellado	University of Hamburg	Bundesstr. 55, 20146 Hamburg
Prof. Dr. C. Hoose	Karlsruher Institut für Technologie (KIT)	Kaiserstr. 12, 76131 Karlsruhe
Prof. Dr. J. Quaas	Leipzig University	Stephanstr. 3, 04103 Leipzig
Prof. Dr. S. Kollet	Forschungszentrum Jülich GmbH	Wilhelm-Johnen-Straße, 52428 Jülich
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Overview of total costs

Institution	Personnel Costs (including overheads)	Travel	Others	Total
AWI	709.606 € (29 %)	8.081 €	–	717.687 €
MPI-M	942.810 € (10 %)	33.912 €	160.250 €	1.136.972 €
UHH	235.698 € (20 %)	6.144 €	–	241.842 €
KIT	299.686 € (20 %)	7.302 €	–	306.988 €
LIM	295.754 € (20 %)	14.176 €	–	309.930 €
FZJ	691.876 € (20 %)	14.583 €	–	706.459 €
DWD	282.245 € (16 %)	16.784 €	–	299.029 €
ECMWF	98.438 € (25 %)	5.000 €	–	103.438 €
				3.822.345 €

1 Goals of *Better* and how they relate to *WarmWorld*

Better, is one of three *WarmWorld* 'Verbundprojekte'. It mostly encapsulates the activities of *WarmWorld*'s Module 1, whose motivation and goals are described in the Umbrella Proposal. *Better* thus assumes primary responsibility for *WarmWorld*'s first global objective (**GO1**), which is to deliver:

> *An ICON based coupled model configuration capable of being run, with an acceptable simulation quality, on km scale (*2.5 km *global grids or finer), with a throughput of* >0.5 SYPD *(simulated years per day) at the start of Phase 2 (planned 2026)*

Whereas achieving the desired throughput is the task of Module 2 *Faster*, *Better* will contribute to meeting this global objective by:

- delivering the configuration of the SR-ESM (coupled, sub 2.5 km scale, > 0.5 SYPD) for Phase 2, denoted Φ_2;
- seed critical second phase development projects and link to applications.

For the reasons discussed in the umbrella document, and elaborated upon further below, in delivering the Φ_2 configuration of the SR-ESM, focus is placed on an optimal configuration of cloud-microphysical, turbulent mixing, and land surface processes. Practically this means that *Better* assumes responsibility for fine-tuning these processes to best represent the vertical structure of the atmosphere, capture land-atmosphere interactions, and establish a balanced energy budget to support long-term applications. For the atmospheric process representations *Better* will build on and extend efforts within NextGEMS to the two-fold higher (2.5 km) resolution targeted by *WarmWorld*, and to structure ICON's physical processes within *WarmWorld*'s overall software concept, for instance by developing test cases for use in the process calibration of the component physics.

Simulations ghosts are a component of the *WarmWorld* strategy, both to support uncertainty quantification, and to develop workflows that are model agnostic. For this purpose *Better* will also support the development of IFS-FESOM as a simulation ghost.

In anticipation of Φ_2 applications within *Better* a new infrastructure development will be initiated, which will be to develop the computational framework for an exa-scale particle model.

In addition, and for the administrative reasons detailed in the umbrella proposal, *Better* also assumes some responsibility for overall project coordination, in particular to:

(1) ensure the smooth functioning and coordination of *WarmWorld* across its different modules and phases;
(2) implement outreach (e.g., summer schools) and communication activities, to extend those planned for NextGEMS and to better highlight *WarmWorld*'s activities in the international context.

These coordination activities will be jointly managed with *WarmWorld*'s Chief Technologist, who is hosted within *Faster*.

2 State of the Art

Coupled global storm resolving models, designed to run for years, are just beginning to be developed, with efforts around ICON being at the forefront of activities worldwide. With the DYAMOND project many groups highlighted an ability to simulate at storm resolving (2.5 km to 5.0 km grids) scales globally. For instance, in the initial DYAMOND project nine groups submitted simulations, two years later this expanded to twelve groups, but of these only four (GEOS, ICON, NICAM and IFS) were committed to providing coupled simulations. Noteworthy in this respect is that two of these are European models, and both form cornerstones of *WarmWorld*. ICON has been running multiannual coupled simulations at 5 km since 2020, with small ensembles of simulations of annual cycles being used to explore the properties of the coupled modelling system. Presently an annual cycle on a 2.5 km grid is being simulated. Experience with this modelling system, also as part of the NextGEMS project, has demonstrated that the energy budget is relatively straightforward to constrain with short simulations. At the same time the simulations helped identify long-standing bugs in the representation of turbulent mixing processes, hydrological discharge, microphysical processes, and air-sea coupling. Based on these experiences, and preliminary results from the simulations, we are confident in our ability to simulate the coupled system, but have learned the value of developing robust tests for the atmospheric physics, and the benefits of expertise related to the representation of physical processes.

Looking forward, candidates for developments to the code-base of storm-resolving earth system models can already be identified. Efforts to improve the representation of cloud microphysical processes could benefit from particle methods, either for superdroplet microphysical representations or for the treatment of aerosols, advanced methods of turbulent mixing, for instance through the inclusion of Leonard terms or the effects of non-stationarity, merit experimentation, and better treatments of the land surface are required to improve the treatment of hydrology and landscale scale processes. This view further guides the choice of projects, expanding our consideration of the land-surface model and including support for the development of an exa-scale particle method capability.

To support the workflow concept, aid in uncertainty quantification, and help identify process sensitivities *WarmWorld* will support simulation ghosts. These will be simulations with IFS-FESOM that mirror those to be performed by ICON. Doing so will also help maintain strong links to other projects based on these models, notably NextGEMS and eventually a DestinE project tentatively entitled Luminous.

2.1 Related Expertise of AG members, by institution

i) MPI-M – Stevens, Klocke, Mieslinger, and Schnur

The MPI-M has been the lead developer of ICON for exascale applications. Together with the University of Tokyo group it initiated and led the first phase of the DYAMOND project – the first ever intercomparision of global storm resolving models – and is initiating and leading the second phase, which includes coupled models. B. Stevens, and increasingly C. Hohenegger and D. Klocke are leaders of these efforts. B. Stevens' main interests are in the role of atmospheric water in structuring the climate system, with expertise related to cloud and turbulence modelling, cloud microphysical processes and climate dynamics, he has been leading the development of the global storm-resolving modelling system. Stevens and MPI-M bring considerable expertise in coordinating large projects, both at the national and European level. Currently T. Mieslinger, who during her PhD helped initiate new coordinated analysis concepts in support of large field campaigns, is the scientific coordinator for the NextGEMS project – filling in for H. Konow who is on maternity leave. She will take over the *WarmWorld* scientific coordination for *WarmWorld* upon Konow's return, equipped with relevant expertise and a strong link to NextGEMS and its scientific community. D. Klocke brings considerable expertise at the nexus of climate modelling and technical development of climate models. He has expertise related to data assimilation, studies of convective systems, and of the ITCZ more broadly. His study of the Atlantic doldrums was the first to show the capability of large-domain storm-resolving models to represent important climate features that the institutes existing models struggled to represent. As the leader of the MPI-M Computational Infrastructure and Model Development group his interests, expertise, and position are centered at the core of *WarmWorld*'s objectives. MPI-M will also contribute longstanding expertise in land modelling, through the support of R. Schnur, who is the lead developer of ICON-Land, and will be supported by institute matching funds to work on *WarmWorld*. Complementary interests of C. Hohenegger, an expert in atmospheric convection and land atmosphere interactions, and the ocean modelling groups, will also help ensure that MPI-M's contributions to *Better* are successful.

ii) UHH – Mellado

J.P. Mellado's research focuses on small-scale atmospheric processes and their interaction with the large scale dynamics. Particularly relevant to his contribution to *Better* is his work on the modeling and simulation of turbulence and its interaction with boundary-layer clouds and surface processes. The importance of stratocumulus clouds to the global energy budget, and the challenge it will be to represent them at storm-resolving (km) scales makes this expertise particularly valuable for devising remedial measures in the case a poor representation of stratocumulus imperils the overall simulation quality. His work has also provided explicit parametrizations of boundary-layer properties in terms of generic environmental conditions such as surface fluxes and tropospheric values of temperature, moisture and wind. This includes parametrizations of boundary-layer depth, mean values, and fluctuations intensities in convective boundary layers [1]. This work has also shed light onto the small scales near the surface and at the boundary-layer top, which helps to rationalize resolution requirements and the effect of turbulence parametrizations. This is particularly relevant for stable boundary layers [2] and cloud-top boundary layers [3], two of the boundary-layer regimes whose representation in global climate models are more problematic. J.P. Mellado also leads the code development for high-resolution simulations of boundary-layer processes[1], and his has been one of the leading groups in Germany in the application of high performance computing for environmental applications during the last decade[2]. He is also a PI on the NextGEMS project, helping to ensure continuity with these efforts.

iii) KIT – Hoose

KIT is one of the four core ICON development partners. C. Hoose's research focuses on the representation of ice microphysical processes in numerical models on different scales. In particular, her team has developed parameterizations (some as part of the HD(CP)^2 project) for heterogeneous ice nucleation [4, 5] and has extensively studied the impact of aerosols on mixed-phase and ice clouds [6, 7]. Further topics of her research are secondary ice formation [8] and the interaction of clouds with large-scale dynamics. She has contributed improvements to the ICON double-moment cloud scheme [9, 10] and has substantial experience with different idealized and semi-idealized test case setups for the evaluation of cloud simulations.

iv) LIM – Quaas

The team of J. Quaas at the Leipzig Institute for Meteorology (LIM) at Leipzig University focuses on the role of clouds in climate change. Key topics are the effective radiative forcing by aerosol cloud interactions [11–13]. Key tools are the ICON model in its different variants in combination with satellite data analysis. The team actively contributed to the development of the high-resolution ICON model in the HD(CP)^2 project by managing the evaluation effort [14] and developing ICON into a tool to study cloud responses to aerosol perturbations [15, 16]. Regional science foci for evaluating clouds in the ICON model are the Arctic [17] and the North Atlantic ocean [18]. The team actively contributes to BMBF's efforts to make data openly available for science [19, 20]. J. Quaas served as lead author for the new 6th assessment report by the Intergovernmental Panel on Climate Change [21].

v) FZJ – Kollet and Riese

The Research Centre Jülich (FZJ) has extensive experience the development of Earth System Model (ESM) capacities and the application of ESMs from the regional to the global scale. In particular, in recent years, significant advances have been made in the realm of terrestrial and atmospheric chemistry modeling – these advances will be an important contribution to *Better*. S. Kollet has extensive experience in the development and application of integrated terrestrial models that simulate the terrestrial water and energy cycle from groundwater across the land surface into the atmosphere. Application range from the watershed scale and event time scales to the continental and the climate time scale. Important studies include demonstration of the connection of groundwater with the land surface water and energy balance; impact of human water and land use on the atmospheric circulation and regional climate over Europe; the implementation of a regional and continental terrestrial forecasting system. With colleagues he developed the first terrestrial climatology from groundwater to the top of the atmosphere, which also led to a novel probabilistic water resources assessment method. In addition, S. Kollet is strongly involved in the application of data assimilation technologies in terrestrial monitoring. Martin Riese is director of the Institute of Energy and Climate Research, Stratosphere (IEK-7) at FZJ and has a wide expertise in atmospheric physics. His particular research focus concerns dynamical and chemical processes ranging from the upper troposphere to the middle atmosphere and their effects on global climate [22]. For that purpose, the Chemical Lagrangian Model of the Stratosphere (CLaMS) has been developed and applied at IEK-7 over more than two decades. The core of CLaMS transport is a particle (Lagrangian) transport.

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[1] `https://github.com/turbulencia/tlab`

[2] gauss-center.eu link

CLaMS is the only Lagrangian chemistry model world-wide with a physical parameterization of atmospheric turbulent small-scale mixing and a sophisticated stratospheric chemistry module and has been coupled also into the climate model EMAC in recent years. Important model applications concern transport of pollutants by the Asian monsoon circulation, variability and changes in the stratospheric water vapour budget and related radiative effects, as well as variations and long-term trends in stratospheric circulation and ozone.

vi) DWD – Schlemmer

The German Weather Service (DWD) develops and operates a global-to-regional chain of numerical weather prediction systems with data assimilation and model based forecasting. With its new ICON modeling framework (ICON global, EU, D2) and its ensemble data assimilation systems, numerical weather prediction at DWD is part of the internationally leading group of weather and climate modeling centers. The coupling between different components of the earth system thereby plays a central role, and DWD's contribution within *Better* will be key to further develop the coupled system. L. Schlemmer will thereby contribute to the development with her expertise in the influence of the state of the surface onto the atmosphere on the one hand [23], and with her know-how on hydrological sub-surface processes and their representation in land-surface models on the other hand [24, 25].

vii) AWI – Jung

The Alfred Wegener Institute (AWI) has been at the forefront of high-resolution climate modelling for the last few years. This includes the development and extensive use of FESOM, the first mature next-generation sea ice-ocean model formulated on unstructured meshes [26]. Due to its multi-resolution capabilities, FESOM allows to enhance resolution in dynamically active regions. It also demonstrates highly competitive throughput in massively parallel applications [27]. FESOM also has been extensively used for coupled climate modelling. Prominent application include contributions to CMIP6 [28] along with some of the first HiResMIP simulations, employing an eddying ocean, which point toward the importance of eddies in the Southern Ocean for explaining the Antarctic sea ice paradox [29]. AWI will contribute to *WarmWorld* through the simulation ghost IFS-FESOM, especially within *Better*. The exascale modelling activities at AWI are led by T. Jung, who has played a pivotal role in a number of high-resolution projects, including Project Athena [30]. He is also a PI in the NextGEMS project, and has extensive experience in coordinating large-scale modelling projects (e.g., EU H2020 project and ESM project within the Helmholtz Association).

viii) ECMWF – Deconinck

The European Centre for Medium-Range Weather Forecasts (ECMWF) is an international organization supported by 34 States, including Germany. ECMWF is both a research institute and a 24/7 operational centre, producing and disseminating medium- and extended-range weather forecasts to its member states and worldwide commercial customers. ECMWF has significant experience in producing world-leading global forecasts on daily to seasonal timescales in a time-critical HPC environment. ECMWF is one of three entrusted entities tasked with delivering the first phase of the Destination Earth programme by 2024. ECMWF is also responsible for delivering the first two high-priority digital twins. The Digital Twin on Weather-Induced and Geophysical Extremes (based on the IFS), will provide capabilities for the assessment and prediction of environmental extremes. In the past 8 years, ECMWF's invested in a "Scalability Programme" with the aim of modernising its forecast models and product chain for the era of exascale computing. Furthermore, ECMWF is one of the key partners in NextGEMS. W. Deconinck is a Senior Scientist in the Earth System Modelling section, researching and maintaining the dynamical core of the Integrated Forecasting System (IFS). He has expertise in solving partial differential equations (PDE's) using unstructured meshes with high-order discontinuous schemes. At ECMWF, he managed the scalability sub-project specific to the IFS. His work involves the management and development of Atlas to be used as foundation for new developments at ECMWF and the wider NWP and climate community.

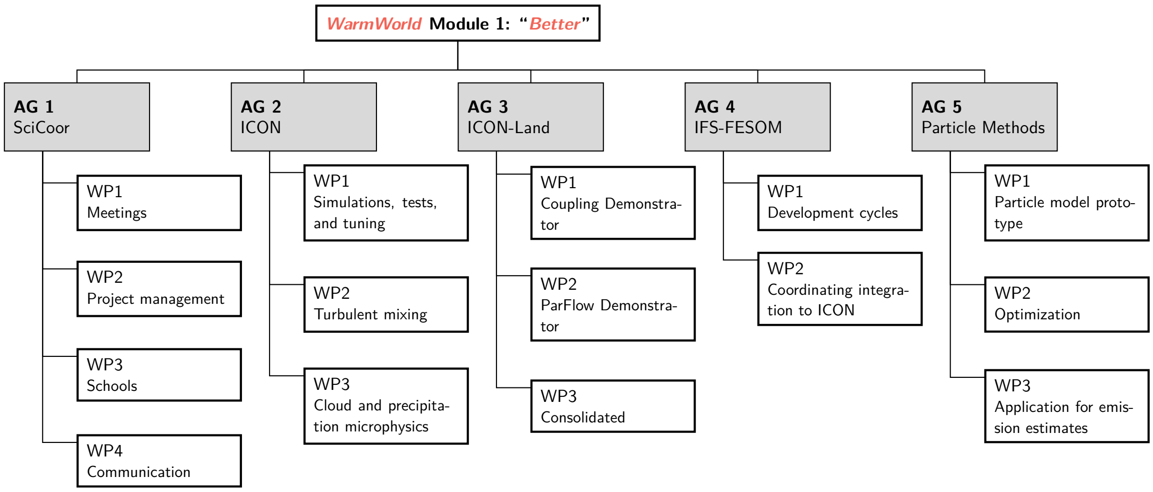
3 Implementation

Better is responsible for defining and testing the model configurations (ICON and IFS-FESOM) to be used in the Φ_2. Activities involve the development and fine-tuning of critical ICON model components to provide balanced km scale decadal simulations in the second phase, and preparing IFS-FESOM for use as a simulation ghost. Novel methods for supporting possible ICON improvements in Φ_2 will be prototyped in Module 1. *Better* also assumes responsibility for guiding and integrating activities in *Faster* and *Easier* and provide links to related external projects, especially NextGEMS.

The specific objectives of Mod1 are to

- Deliver an operational SR-ESM (coupled, sub 2.5 km scale, $>$ 0.5 SYPD) configuration for Φ_2.
- Seed Φ_2 development projects and link to applications.

Better is comprised of five Activity Groups, dubbed “AG:SciCoor”, “AG: ICON”, “AG: ICON-Land”, “AG: IFS-FESOM”, and “AG: Particle Methods”. It will achieve its objectives by managing the overall ICON and IFS-FESOM development processes, and to do so will build upon and extend the NextGEMS development cycle to evaluate longer and finer (1 km to 2 km) simulations. The five AGs are illustrated in the following tree structure and further described in turn below.



3.1 AG1: Scientific Coordination

The scientific coordinator, Dr Theresa Mieslinger, will be responsible for organizing all hands meetings, for helping the module PIs to coordinate activities within and across the modules, she will serve as a liaison with the funding agency and be responsible for organizing project reports. She will organize the formation of the Scientific and User Advisory Groups (in coordination with the funding agency representatives and the Science Board) at the outset of the project, and manage the project and the science outreach and communication strategy. The scientific coordinator will work with the Chief Technologist to organize input from the *WarmWorld* science team to guide the open-funding call for Mod4 projects, to organize the summer schools, and to monitor the risks and implement mitigation strategies.

3.1.a Work packages

WP1 – Meetings: Three cross projects meetings are planned, one to kick off the project in Bonn in late 2022, another for the mid-term review in Bremerhaven in late 2024, and the third as the final Φ_1 project meeting in Hamburg in 2026. *WarmWorld* will be the lead sponsor of the planned summit on next generation climate modelling planned for 2023 (as discussed in umbrella proposal), either in Hamburg or Berlin, and the scientific coordinator will form and lead the organization team for this meeting. *WarmWorld* will also sponsor a Hackathon to continue the NextGEMS sequence of hackathons after that project ends (in 2025)

WP2 – Project management: This work package is responsible for coordination with the funding agency representatives throughout the project, organizing the mid-term review, and putting in place the project science and user advisory groups.

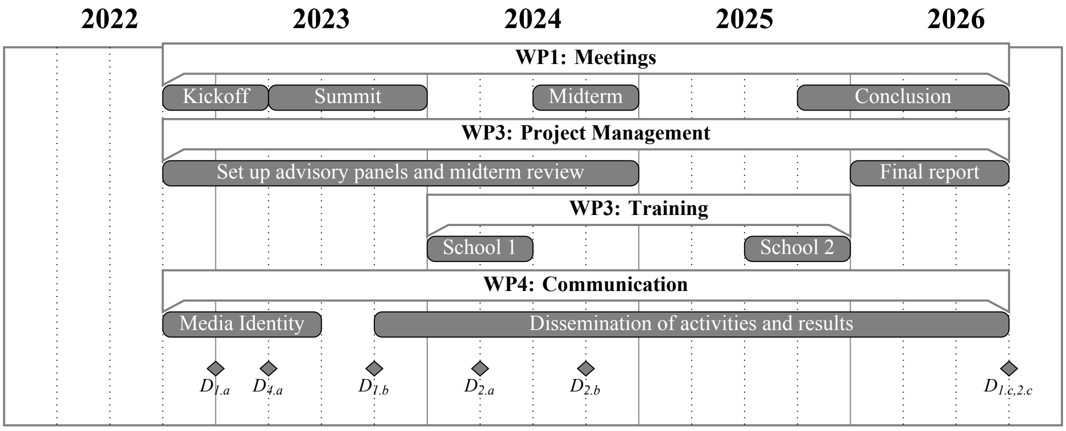
WP3 – Training: The scientific coordinator will work with the Chief Technologist to organize two summer schools designed to provide opportunities for Early Career Scientists and especially attract more female scientists to opportunities in Earth-system informatics.

WP4 – Communication: The major communication tasks will be to define the projects media identity, which includes a visual identity through a web page, a social media presence, and a communication network in partnership with the communication teams of the partner institutes. The different communication channels will be used for the dissemination of project findings and the advertisement of project events and job openings.

3.1.b Milestones & Deliverables

Label	Short Description	Institution
D1.a	Kickoff meeting	MPI-M
D1.b	World Climate Modeling Summit	”
D1.c	Final Project Meeting	”
D2.a	Formation of Advisory Groups	”
D2.b	Midterm Review and General Assembly Meeting	”
D2.c	Final Report	”
D4.a	Media Identity in Place	”

3.1.c Gantt Chart



3.1.d Staffing and Resources

AG1 will be lead by MPI-M. The scientific coordinator position constitutes the main staff contribution, for which 48 person months are budgeted, one quarter of which will come from in-kind institutional contributions by the MPI-M. Additional funding will support her more extensive travel, meetings. To ensure *WarmWorld*’s leadership (and German hosting) of the planned second World Climate Modelling Summit, 80 k€ is budgeted. In addition, MPI-M will support the project communication from in-kind contributions.

3.2 AG2: ICON

The AG will define the configuration of ICON for the start of Φ_2. It spans three workpackages: WP1 is responsible for the ICON development cycles to fix the configuration for Φ_2. Close collaboration with *Faster* will help sync scientific model configuration (physical complexity) with technical progress (performance goals). WP2 & WP3 are responsible for defining adequate representations of the unresolved physical processes – turbulent mixing and cloud-/precipitation-microphysics – influencing the quality of the coupled simulations.

3.2.a Work packages

WP1 – Simulations, tests, and tuning: is responsible for ICON simulations and their evaluation in close collaboration with *Faster* and *Easier*, with the IFS-FESOM AG, and with related activities within the NextGEMS project. Tasks include developing torus test (unit tests, idealized cases, and campaigns, e.g., RCE-MIP, DYCOMS, EUREC^{4}A, EC-TOOC), some of which involves evaluation of field campaign data; evaluating the atmospheric physics as a whole; rationalizing and defining a configuration and appropriate spin-up for the ocean model, in particular the specification of the ocean physics; organizing and extending the *WarmWorld* development cycles, first as contributions to NextGEMS, including proposed DYAMOND3 EC-TOOC coupled simulations; and ultimately, integrating all improvements coming from Modules 2 and 3 into the model system to define the Φ_1-release of ICON and demonstrate its readiness for use in Φ_2.

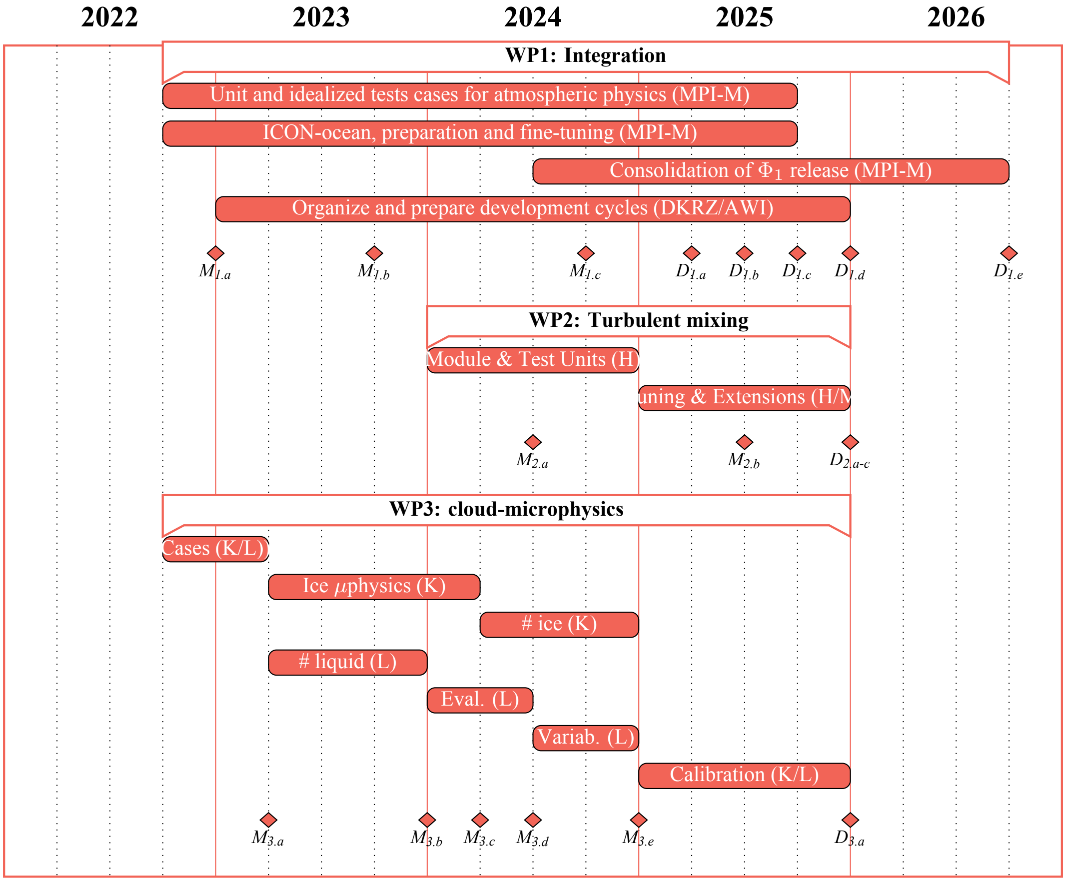
WP2 – Turbulent mixing: will extend and complement efforts in NextGEMS, and thus only starts in Q3 of Y2. The focus will remain on optimizing the turbulent mixing representation to improve the surface energy budget over land, near surface wind profiles, and boundary layer clouds for the atmospheric energy budget – also at coarser (5 km to 10 km) grid spacings for use in ensemble systems. Concepts, in particular the possibility of including Leonard terms in the representation of subgrid fluxes, will be articulated as possible Φ_2 improvements.

WP3 – Cloud and precipitation microphysics: will be responsible for fine-tuning the representation of cloud and precipitation microphysical processes to better represent Earth's energy budget both at the top of the atmosphere and the surface. Efforts will be on pragmatic calibration to match TOA energy budgets. These are complemented by systematic improvements of the ICON model based on experience by the team. This includes a more realistic representation of particle number concentrations, but also more elaborate advances such as determining the appropriate level of microphysical complexity for Φ_2 (i.e., ice categories, number of moments, aerosol interactions) or consideration of subgrid-scale variability. For the evaluation of clouds and precipitation, collaboration with *Easier* (U Cologne/PI Schemann) is foreseen. Calibration will be linked to physics test cases in WP1.

3.2.b Milestones & Deliverables

Label	Short Description	Institution
M1.a	Document describing torus test-case design.	MPI-M
M1.b	Torus test-case β-release.	”
M1.c	Mid-term report of Φ_1-release status.	DKRZ/MPI-M
D1.a	EC-TOOC coupled simulations (40d R2B11, coupled).	DKRZ/AWI
D1.b	Definition of EUREC^{4}A and EC-TOOC test cases.	”
D1.c	Report on ocean spin-up and parameter choices.	”
D1.d	Scientific documentation of torus test cases for Φ_1-release.	”
D1.e	The Φ_1-release with scientific documentation.	DKRZ/MPI-M/AWI
M2.a	Turbulent-mixing contribution to torus test-case	UHH
M2.b	Tuned parameterization of turbulent mixing	”
D2.a	Optimal parameter choice for Φ_1-release	”
D2.b	Test unit with off-line validation of turbulent mixing	”
D2.c	Scientific doc. w/outlook for turbulent mixing in ICON.	UHH/MPI-M
M3.a	Ref. simulations for test cases accomplished.	KIT/LIM
M3.b	Realistic particle concentrations for test cases implemented	LIM
M3.c	Cloud microphysics schemes compared	KIT
M3.d	Evaluation	LIM
M3.e	Metric for test case evaluation with ice	KIT/LIM
D3.a	Optimal parameter choice for test cases demonstrated.	KIT/LIM

3.2.c Gantt Chart(s)



3.2.d Staffing and Resources

AG2 will be lead by MPI-M. The scientist positions constitute the main staff contributions for which 84 person months are budgeted for MPI-M with 6 person months of in kind support. For UHH 24 person months are budgeted, for LIM and for KIT, 40 PM each. The person months for AWI, including in kind parts, are budgeted in AG4. Additional funding will support travel.

3.3 AG3: ICON-Land

This AG will lead the development of ICON-Land into a self-contained Community Land Model embedded in the ICON software ecosystem. Exascale simulation technologies will be developed to reliably represent the energy and water balance in km-scale global coupled simulations from weather to climate time scales with improved prediction quality. AG3 has the following specific objectives:

- Realistic representation of the turbulent exchange of water, energy, momentum and matter between the land surface and the atmosphere, and the vertical transport through the boundary layer and up. A well-designed, flexible interface to the atmosphere will be key for the integration into *WarmWorld* and beyond.
- Realistic representation of the hydrological processes, including the partitioning of precipitation into surface runoff and infiltration, the percolation of water and its transport, and drainage and the regeneration of groundwater. The integration of ParFlow into ICON-Land will give ICON-Land an advanced hydrological capability, opening it to a wide range of applications. This activity will leverage ParFlow's in-situ capabilities (e.g., using data-driven integration approaches) to provide *WarmWorld* with a working, portable and exascale-ready land model early in the project.

An adequate simulation of these processes in a storm-resolving model represents substantial technological challenges to the software architecture, memory layout and numerics, as well as to the parallel performance on heterogeneous HPC architectures. Performance analysis will go along the tasks to help define detailed requirements to adequately represent land surface-atmosphere interactions at km-scales. Fine-tuning of ICON-Land will benefit from the operational NWP validation framework performed at DWD, such that the evaluation of results from short- and longer-term simulations will be pursued in a synergistic way. To achieve these objectives AG3 will be closely collaborating with *Faster* (esp. AG3) to fulfill the technological requirements regarding e.g. code infrastructure (modularization, interfaces), performance portability, coupling and optimization.

3.3.a Work packages

AG3 is composed of three work packages, where the first two work packages will develop "demonstrators" in order to get something cleanly structured albeit simple that can already be used early on in the project for testing and further development. All partners in this AG will be collaborating in all work packages.

WP1 - Coupling Demonstrator: is tasked with the development of a prototype package for vertical diffusion and land/atmosphere coupling. This starts with the design and implementation of modular software structures and interfaces for the coupling between ICON-Land and the atmospheric boundary layer physics that, in addition, allow a clean separation of the physical turbulence and transfer schemes and the numerical solvers for vertical diffusion. Performance will be tested by implementing an OpenACC port for GPUs and by using 32-bit precision in this package and ICON-Land.

WP2 - ParFlow Demonstrator: will develop the demonstrator version of ParFlow integrated with ICON-Land, which affords high-resolution simulations of the coupled water and energy balance including 3D variably saturated groundwater and surface water flow. The integration will explore various coupling options, which afford an efficient, spatially distributed coupling of ParFlow ranging from e.g. continental watersheds to full global coverage. A focus of WP2 is to provide software infrastructure in ICON-Land for performance portability for the next-generation heterogeneous HPC hardware. The infrastructure will be built in cooperation with *Faster* based on concepts of modularization and separation of concerns [31]. The infrastructure will be analyzed for performance resulting in first recommendations for optimization. The demonstrator will be applied in a use case at kilometer-scale resolution including proof-of-concept simulations. The challenges and successes of WP2 will be collected in a lessons-learned report, which will serve as a basis for the design of WP3.

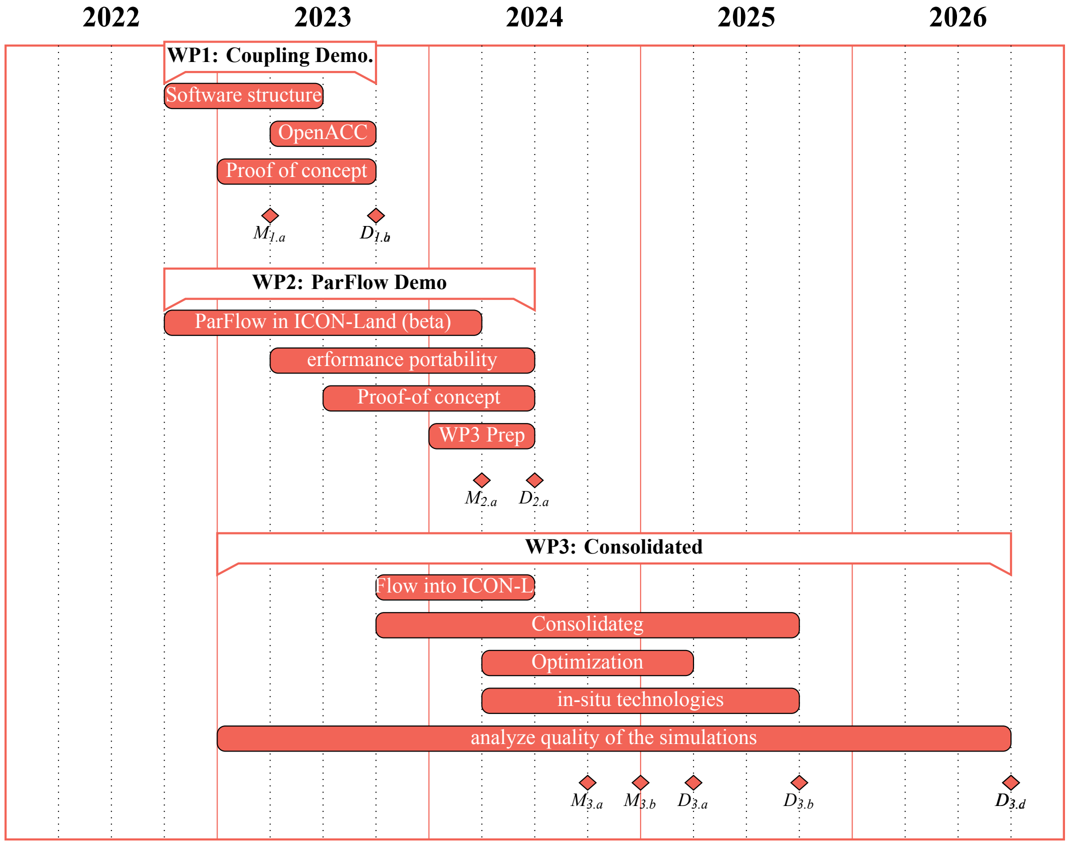
WP3 - Consolidated: Based on WP1 and WP2 in cooperation with *Faster*, Ignition, the integration of ParFlow in ICON-Land resp. the coupling interfaces will be recast or potentially refined and optimized. In WP3, the performance portability will be analyzed comprehensively on various hardware architectures ranging from the existing booster technology to the (pre-)exascale systems. At this stage strategies will be realized for concurrent coupling of ParFlow to ICON-Land and ICON-Land to the vertical diffusion in the atmosphere in cooperation with *Faster*. In the consolidated ICON-Land, initial in-situ technologies will be provided to facilitate user interactive data analytics and impact modeling. For the vertical diffusion, the simple prototype implementations of the physical schemes and the solver from WP1 will be refined or extended for realistic applications. Throughout the entire development phase the simulation results on both the weather and climate time scale will be quality checked based on the use cases established in WP1 and WP2.

3.3.b Milestones & Deliverables

Label	Short Description	Institution
M3.1.a	First experimental version of coupling demonstrator without optimizations	DWD
D3.1.a	Coupling demonstrator ready for WP3 including proof-of-concept simulations of regional to global use cases	DWD

D3.1.b	Lessons learned report	DWD
M3.2.a	First experimental integration of ParFlow in ICON-Land	FZJ
D3.2.a	Demonstrator of ParFlow in ICON-Land including proof-of-concept simulations of regional to global use cases	FZJ
D3.2.b	Lessons learned report	FZJ
M3.3.a	Optimized integration of ParFlow in ICON-Land	FZJ
D3.3a	Fully functional and optimized land/atmosphere coupling and vertical diffusion	DWD
M3.3b	First exploration of in-situ capabilities with ParFlow	FZJ
D3.3b	Fully functional and optimized coupling of ParFlow to ICON-Land	FZJ
D3.3c	Quality assessment of simulations on weather and climate time scales	DWD
D3.3d	Consolidated ICON-Land (full ParFlow implementation and coupling/integration into the ICON software ecosystem	DWD, FZJ

3.3.c Gantt Charts



3.3.d Staffing and Resources

AG3 will be lead by DWD and FZJ. The scientist positions constitute the main staff contributions for which 37 person months are budgeted for DWD, 58 person months are budgeted for FZJ including 28 person months from in-kind institutional contributions, and 27 persons months are budgeted for MPI-M from in-kind institutional contributions. Additional funding will support travel.

3.4 AG4: IFS-FESOM

In this AG, AWI and ECMWF team up to advance the readiness of IFS-FESOM as a simulation ghost for Φ_2, shadowing ICON simulations and thereby increasing the trustworthiness of climate change projections with structurally different climate models.

AG4 in *Better* has the following specific objectives:

- Integrate and test critical developments of IFS-FESOM that improve its exascale-readiness and realism at km-scale resolutions.
- Carry out technical readiness evaluations, including the readiness of IFS-FESOM as a simulation ghost for Φ_2.
- Accelerate progress (i.e., exploit synergies and increase critical mass) through coordination within *WarmWorld* and with strategic partner projects such as NextGEMS and Destination Earth.

3.4.a Work packages

To achieve these objectives AG4 is composed of the following two work packages:

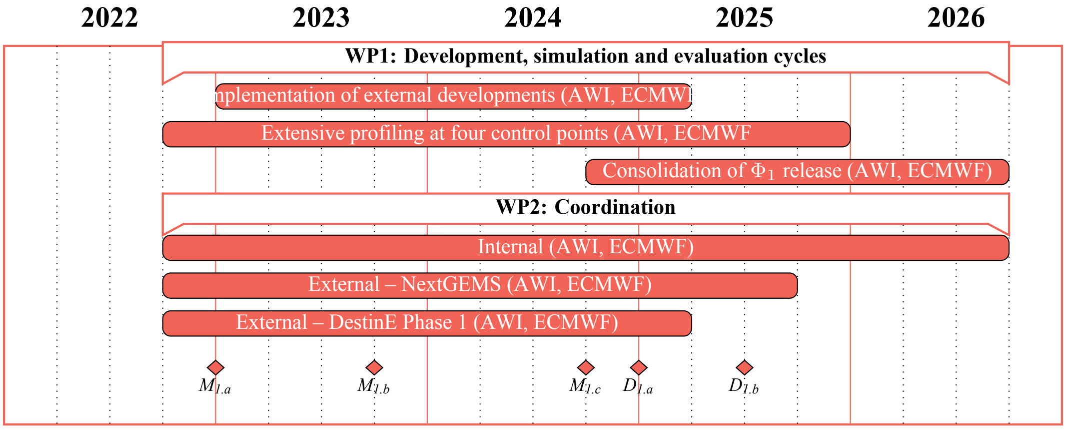
WP1 – Development, simulation and evaluation cycles: is tasked with delivering effective model development, simulation and evaluation cycles. This includes integration and testing of critical developments of the IFS and FESOM that improve its exascale-readiness and realism at km-scale resolutions for the simulation ghost IFS-FESOM, both within and outside of *WarmWorld*. Prominent examples include the implementation of IFS developments for the Extremes Digital Twin of the Destination Earth initiative and FESOM developments as part of program-oriented research in the Helmholtz Association. WP1 also involves running IFS-FESOM simulations at km-scale resolutions and evaluating the results in terms of key diagnostics and processes. This task also includes eradicating long-standing model issues that emerge only at high resolutions as well as fine-tuning model setting at km-scale resolutions. This WP will also play a pivotal role in carrying out the four technical readiness evaluations of IFS-FESOM, which will lead to the final configuration of the simulation ghost as a basis for Φ_2.

WP2 – Coordination: is tasked with coordination to ensure that the impact of different investments, including *WarmWorld*, is maximized. Within *WarmWorld* coordination concentrates on linking evaluation and integration activities to ICON. More generally, cooperating with the teams in *Faster* and *Easier* to ensure the development of common code structure, where possible, will be a key priority. Regarding external initiatives, effective coordination with NextGEMS and DestinE will be central.

3.4.b Milestones & Deliverables

Label	Short Description	Institution
M1.a	First review of the present status of the IFS-FESOM development	AWI
M1.b	IFS-FESOM status report for next release candidate	AWI/ECMWF
M1.c	Mid-term report of IFS-FESAOM Φ_1-release status.	”
D1.a	IFS-FESOM post NextGEMS β-release.	”
D1.b	IFS-FESOM Φ_1-release with scientific documentation.	”

3.4.c Gantt Chart



3.4.d Staffing and Resources

AG4 will be lead by AWI. The scientist positions constitute the main staff contributions for which 75 person months are budgeted for AWI with 78 person months of in kind support. For ECMWF 7 person months are budgeted with additional 2 person months from in-kind institutional contributions. Additional funding will support travel.

3.5 AG5: Particle Methods

This AG of the module *Better* will develop a consolidated software-stack that allows the movement of particles (trajectories) to be computed at storm-resolving scales in ICON based on information provided by its dynamical core. The particle module will be based on the Lagrangian concept [32] developed for the Chemical Lagrangian Model of the Stratosphere (CLaMS), but will be extended to a much wider field of applications. It will also imply writing new code for new architectures. The concept involves a trajectory module that computes the path of particles (winds in the case of the atmosphere), with a strong emphasis on computational efficiency, both regarding parallelization and GPU usage. Exascale readiness will be the guideline here.

Pollution transport by the Asian Monsoon is a very important application for such a trajectory model [33, 34] and will be investigated in a case study. The development of the particle methods in this module is to prototype developments for Φ_2 to support the use of such methods to treat ocean biogeochemistry, ecology models, atmospheric dynamics studies, atmospheric chemistry and also cloud microphysics.

AG5 has the following specific objectives:

- Development of a prototype particle model for ICON.
- Integration of the particle model for ICON into the model core.
- Optimization of the ICON particle model for future exascale-supercomputers.
- Realization of first applications within a high-resolution ICON simulations.

3.5.a Work packages

To achieve these objectives AG5 is composed of the following five work packages:

WP1 – Particle model prototype: The first work package aims at developing the particle model code from scratch to represent different geophysical processes; in particular advection and turbulent mixing. The new modules will make use of modern shared memory concepts and will be integrated into a software library. The particle module will be integrated in the model structure of ICON. Here the particular requirements caused by the ICON grid structure will need to be addressed. (24 PMs for FZJ).

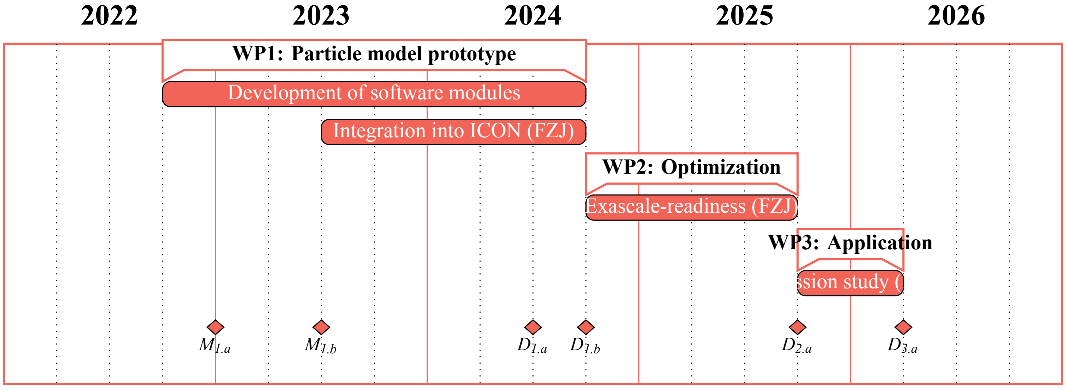
WP2 – Optimization: Performance tests will be defined and carried out to detect bottlenecks in efficiency. A particular focus will be the efficient use of (different) GPU booster systems. First test simulations on km-scale will be carried out. (10 PMs for FZJ).

WP3 – Application for emission estimates: Particle methods are ideal for diagnosing the origin of airmasses, in particular in strongly convective regions. The application within the ICON framework offers an optimal access to the question in how far results are affected by the spatial resolution. (6 PMs for FZJ).

3.5.b Milestones & Deliverables

Label	Short Description	Institution
M1.a	First review of the state of existing particle model	FZJ
M1.b	Particle model workshop (atmos/ocean/conv)	”
D1.a	Interim report on prototype code	”
D1.b	Particle model open source β-release for Φ_2	”
D2.a	Report on exascale readiness of ICON particle model	”
D3.a	Resolution study on pollution emissions in Asian Monsoon	”

3.5.c Gantt Chart



AG5 will be lead by FZJ. The scientist positions constitute the main staff contributions for which 40 person months are budgeted Additional funding will support travel.

4 Exploitation and further use of project results

On a general level *WarmWorld* will make substantial contributions to the development of a state-of-the-art open research infrastructure for Earth system modelling in Germany and Europe. *Better* will develop free and open source software components related to the representation of atmosphere, ocean and land physics, opening these components to algorithmic improvements, also in support open calls with in *WarmWorld* Mod4. The modularity of development, and the software engineering principles that they will adhere to will greatly increase the ability of others to reuse major parts of the *WarmWorld* software infrastructure for other purposes.

4.1 Outlook for Φ_2

Projects within Φ_1 were designed to support three types of Φ_2 activities: (i) the use of the *WarmWorld* modelling system to address scientific and societal questions (AG2, WP1, AG4); (ii) open the code base to improvements in algorithmic improvements (AG2), as for instance anticipated from *Smarter* (Module 4); (iii) open the code base to add functionality (AG5), and a software architecture to guide the exploration of new types of questions (AG3, AG4)).

Development in Φ_2 will be guided by specific scientific questions. For instance possible catastrophic sea-level rise on the centennial scale, which could be addressed by using the resolution of km scale models to explicitly resolve ice-sheet dynamics, perhaps nested to hm scales. The introduction of particle methods could be developed further to study questions of ocean pollution (microplastics) or ecology. A refactored ICON-land would support studies of soil processes, including the hydrology of permafrost regions, estimates of emerging heat-waves, or the influence of the urban canopy. At km-scales microphysical improvements will allow studies of severe storms, addressing questions such as flash-flooding and hail damage. Improvements in turbulence modelling will support better representations of urban and natural canopies, and pollution dispersion. These ideas help illustrate how *Better* creates a platform for addressing some of the most pressing problems in climate change. Which and how many of these questions can be developed in Φ_2 depends on how successful the prototyping is in Φ_1, but hopefully illustrates how work in Φ_1 is opeening the doors to new science and novel applications.

5 Cooperation

WarmWorld is an unusual project as it is designed to serve as a catalyst to synthesize parallel activities that are supported through base funding on a national level – through both institutional and project (e.g., EXCLAIM in Switzerland) funding – and from international projects such as DestinE and NextGEMS. At the same time, as a contribution to the German national modelling strategy it strives to tap a greater range of national (German) expertise in the development and application of next generation Earth system models.

These design principles guided project and partner selection.

Better has developed a meeting strategy that enables efficient collaboration. Key elements of this strategy are:

- *WarmWorld* wide meeting for kick-off (end of 2022), and a project wide General Assembly with invited external guests every other year (mid of 2024 and 2026),
- once per year in Sep one 2-day Module meeting (in 2022 attached to Kick-off, in 2023 and 2024 attached to the NextGEMS hackathons, DWD/KIT in 2025, and LIM in 2026),
- coordination/cooperation with other projects (NextGEMS, Luminous, EXCLAIM, etc.) at least for the chief technologist and main developers to keep developments in line,
- coordination/cooperation with annual ICON-dev meeting, and
- smaller scrums (two per AG/working package and year).

We expect *Smarter* projects to be affiliated with one or more of the core *WarmWorld* Modules (*Better*, *Faster*, *Easier*) and for those affiliated with *Easier* to attend the *Easier* module meetings, thereby helping to maintain bandwidth between *Easier* and *Smarter*.

Hence, in *Better* meetings and exchanges are chosen to support the main form of cooperation among the partner institutes of Verbundprojekt, which will be supported by the scrums. The test environments and software infrastructure implies close cooperation with *Faster* and with the ETH-funded EXCLAIM project, and calibration activities link strongly to activities within *Faster* and to the NextGEMS project. These are supported by the three planned crossed project meetings. The harmonizing of Verbundprojekt meetings with the NextGEMS Hackathons during the first three years of the project, and the continuation of these Hackathons in the final year of the project aims to harmonize activities within NextGEMS and *WarmWorld*. These hackathons/module meetings will also serve to strengthen links to the EXCLAIM project.

A detailed table of all travel costs is given in the appendix. We seek to have the following structure of cooperative exchange within and external to *WarmWorld*

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