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The new TSMP2 coupled Earth system model

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Abstract. The Terrestrial Systems Modeling Platform (TSMP, github.com/HPSCTerrSys/TSMP2) is a scale-consistent, highly modular, physics-based, massively parallel, and fully integrated coupled groundwater-vegetation-atmosphere modeling system for regional Earth system modeling. TSMP is composed of the atmospheric models ICON or COSMO, the land surface model Community Land Model (CLM), and the ParFlow subsurface-surface hydrological model, linked to each other through the OASIS3-MCT coupler. TSMP is used across a wide range of spatio-temporal scales, ranging from individual field plots, large eddy simulations to continental scale climate mode runs in a variety of applied research topics, such as water resources, land-atmosphere coupling, or climate change projections. In version 2, or short TSMP2, we have comprehensively modernized the coupled model system. One of the main changes from version 1 is the replacement of component models with their current state-of-the-art successors for the atmosphere and the land surface, and a modified coupling design to improve the mass and energy balances between the compartments. TSMP2 now relies entirely on a CMake build-system, which enhances the system's portability across different computer infrastructures. Through a Git-based framework TSMP2 includes auxiliary tools for model setup, a workflow engine and case study simulation experiments to meet reproducibility, research software engineering, and FAIR data best practices. The TSMP2 coupled model system and all its components are free open-source software. Aside from a description of the TSMP2 infrastructure, we present the impact of coupling approaches between the compartments on model states in TSMP2, and outline our development strategy along with technical and performance aspects arising from the coupling.

1. Introduction

This model description paper presents version 2.0 of the Terrestrial Systems Modelling Platform (hereafter TSMP2), a regional earth system model (RESM) with a focus on terrestrial hydrology. The TSMP2 is the next-generation reimplementation of the TSMP1 software platform and concept, first introduced by Shrestha et al. (2014).

With an intensifying water cycle and an increase in (projected) hydrometeorological extremes, such as heavy precipitation or droughts, accurately representing and closing the coupled terrestrial water and energy cycles is vital for understanding the climate system (Huntington, 2006; Mbabazi et al., 2025; Trenberth, 2011). Many relevant feedback processes, such as soil moisture temperature or soil moisture precipitation feedback loops, are linked to and influenced by mass, energy and momentum transfers between the subsurface, including groundwater, land surface, vegetation, and atmosphere, across a wide range of spatial and temporal scales (Heinze et al., 2019). The interactions between these compartments play a critical role in regulating the Earth's climate (Avissar and Pielke, 1989) and need to be explicitly simulated to improve predictions of climate variability, water resources availability, and ecosystem responses under changing environmental conditions. Despite this complexity, regional climate models (RCMs) often have a simplified representation of hydrological processes, where only a 1D vertical subsurface water flow and free drainage at the lower boundary are combined with runoff generation at the land surface without a lateral redistribution of surface and subsurface water. A simplified representation leads to a resolution-dependent impact on flux partitioning at the land surface, land-atmosphere coupling, and affects the land water balance and hydrometeorology (e.g. Barlage et al., 2021; Poshyvailo-Strube et al., 2024). To overcome these limitations, the TSMP was developed as a coupled regional climate system model applicable across a wide range of scales and for various purposes (from weather forecasting to climate change projections) enabling a physically consistent simulation of the hydrological cycle and terrestrial system feedbacks (Shrestha et al., 2014).

Aside from TSMP, recent years have seen a number of developments that aim to improve model structure, towards a more realistic process representation, and uses of coupled regional Earth system models. Examples for RESMs with a coupled ocean and simulation of river include the CNRM-RCSM4 over the Mediterranean (Sevault et al., 2014), the recent implementation of the ICON-CLM atmospheric model coupled to the GCOST-AHOI ocean, and the HD hydrological discharge model by Ho-Hagemann et al. (2024) with a similar coupling approach as used in TSMP2 for the North Sea and the Baltic. Primo et al. (2019) use COSMO RCM coupled to different versions of NEMO, covering all European marginal seas. With respect to terrestrial hydrology, the WRF-Hydro (Lahmers et al., 2019) is a widespread model system that can simulate overland flow and river discharge, but does not explicitly simulate 3D groundwater flow. Recent applications of WRF-Hydro include Arnault et al. (2025), who investigate the sensitivity to soil hydraulic properties, or Zhang et al. (2025), who showed that a lake-reservoir improved the simulation of streamflow. The groundwater capability was added with WRF-ParFlow coupling by Williams III et al. (2013). The lateral subsurface flow alters the flux partitioning in a landscape between convergence zones in river valleys and ridges. To account for it, less code-intrusive and computationally more efficient approaches that modify the groundwater parametrization in existing land surface models (LSM) also exist. Barlage et al. (2021) use the 3D groundwater scheme of Miguez-Macho et al. (2007) within the Noah-MP LSM to reduce the warm bias in WRF continental US simulations, and to demonstrate an increased impact of groundwater on hydroclimate going towards convection-permitting km-scale simulations. Schlemmer et al. (2018) implemented a topography-driven groundwater runoff formulation into the TERRA LSM in the COSMO RCM that also reduces air temperature biases. The

RCSM modeling approaches are meanwhile mature enough to be included as so-called increased complexity models in the current Coordinated Regional Downscaling Experiment (CORDEX) dynamical downscaling regional climate change ensemble (Katragkou et al., 2024).

The TSMP version 1 (TSMP1, previously also abbreviated as TerrSysMP) was developed by Shrestha et al. (2014) with later-on performance improvements by Gasper et al. (2014). TSMP is a fully integrated, physics-based soil-vegetation-atmosphere RCSM where an atmospheric model, a land surface model, and an integrated hydrologic model are linked with each other through an external coupler for flux exchange along compartmental interfaces - the land surface, following the same coupling paradigm as most RCSMs from above, as opposed to process-based coupling (e.g., Jöckel et al., 2010). An outstanding feature of TSMP is the incorporation of hydrologic processes through 3D soil and groundwater hydrodynamics, solved in a continuum approach with 2D overland flow, linking groundwater with atmospheric processes through the land surface. Hence, TSMP enables physically consistent, two-way exchanges of water, energy, and carbon in the terrestrial system. This combination of an atmospheric, land surface and hydrological model allows for a more holistic understanding of terrestrial feedbacks and interactions, such as how precipitation is partitioned into evapotranspiration and runoff, how soil moisture dynamics affect atmospheric boundary layers, or how groundwater-surface water interactions influence land-climate feedbacks. Such model systems help to integrate traditionally separate modelling realms into a coherent terrestrial system perspective (Fersch et al., 2020).

The TSMP1 concept's usefulness and applicability have been shown in several studies. TSMP1 has been run temporally and spatially from local domains over a few hours (Zhang et al., 2023) to regional domains over several years (Sulis et al., 2010) to climate projections on a pan-European scale (Furusho-Percot et al., 2019) and for short- to medium-range weather forecasts (Kollet et al., 2018). The modelling system was also used to show the relationship between the groundwater representation and the evolution of hydrometeorological extremes, such as the August 2003 European heat wave (Keune et al., 2016). With its groundwater-to-atmosphere feedbacks, TSMP can reproduce heatwave statistics in CORDEX ERA5 driven evaluation runs (Furusho-Percot et al., 2019) in comparison to RCMs with a more simplified hydrology representation more accurately (Furusho-Percot et al., 2022). In a water resources study (Hartick et al., 2021) could show the effect of groundwater dynamics on the long-term persistence of subsurface water storage anomalies. Keune et al. (2018) investigated human interventions with the water cycle and water resources by groundwater abstraction and irrigation. Zipper et al. (2019) studied the effect of remote land-atmosphere feedbacks due to land use and land cover change that lead to widespread changes of energy and water balances, e.g., through substantial increases in cloud cover, while shallow groundwater mitigates those heterogeneous impacts. Similarly, Hartick et al. (2022) described a feedback loop based on a coupled TSMP1 evaluation simulation, where groundwater droughts systematically increase net solar incoming radiation through a cloud feedback mechanism, which amplifies the drought. Using a new diagnostic, Zhang et al. (2024) analyse the relationship between evapotranspiration and cloud water dynamics, which can spatially be associated with water- and energy-limited coupling regimes.

Although TSMP1 has proven its versatility in these studies, there are some technical shortcomings, which led to the TSMP2 development. TSMP1 uses the COSMO v5.01 (COnsortium for Small-scale MOdeling; Baldauf et al., 2011) atmospheric model and the CLM v3.5 (Community Land Model; Oleson et al., 2004). Both of these component models are no longer

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updated and receive increasingly less community support. New features, such as transient aerosols, or greenhouse gas concentration pathways for COSMO need to be backported. Parallel I/O, necessary for large, km-scale model domains, is not available. The CLM3.5 land surface model does not offer dynamic vegetation, and features only a simplified urban representation, which is also highly relevant for km-scale simulations. Additionally, the coupling of CLM3.5 was limited to vegetation landunits.

TSMP2 builds on the foundations of TSMP1 and past experience and constitutes a comprehensive redesign of the model system. With TSMP2, the model system has been significantly updated, offering enhanced capabilities for simulating and analyzing interactions within terrestrial systems, including human interventions, dynamic vegetation, biogeochemical cycles, or urban areas. TSMP2 has all new component models, or latest versions thereof, a redesigned coupling interface, complemented by a new CMake build infrastructure, runtime environment and model setup scripts. Furthermore, TSMP2 retains the possibility to run component models standalone or in various coupling configurations. Component models may be upgraded to their latest versions to stay up-to-date with new features. With TSMP2, the COSMO atmospheric model has been replaced by one of the latest ICON versions (Pham et al., 2021; Zängl et al., 2015), the Community Land Model v3.5 by the encore Community Land Model, a fork of the land surface model CLM5 (Lawrence et al., 2019) for standalone and coupled CLM use. Terrestrial hydrology is still simulated with the integrated hydrologic model ParFlow (Ashby and Falgout, 1996; Kollet and Maxwell, 2006; Kuffour et al., 2020) in one of the latest versions. Technically, model coupling is via the external OASIS3-MCT coupler (Craig et al., 2017), albeit using a revised coupling approach.

Here we introduce the new TSMP2 RESM with the aim to give a detailed description of the model system, explain the coupling approaches implemented, show-case its basic functionality, and briefly present a typical intended application example. Beyond the coupled model system itself, TSMP2 provides a comprehensive platform that includes a build-infrastructure, supporting software tools for model setup, run-control, and post-processing, along with complete example experiments. This makes TSMP2 readily accessible on GitHub for community use and further development.

This model descriptor study is organized as follows: Section 2 introduces the TSMP2 component models. Section 3 explains the coupling interface and the component model communication. Section 4 provides evidence of the functioning of the coupling with an idealized test case, including performance considerations. In Section 5, TSMP2 is applied with a real data case for regional climate scenario simulations in line with the CORDEX-CMIP6 dynamical downscaling experiment protocol. Section 6 deals with TSMP2 computational efficiency, while Section 7 provides a short overview on the TSMP2 platform functionalities and tools. Last, Section 8 concludes this model overview with open aspects and an outlook to upcoming developments.

2. TSMP2 model structure and component models

The TSMP model system consists of an atmospheric model, a land surface model and an integrated hydrological model coupled via an external coupler.

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2.1 Atmospheric model – ICON

The Icosahedral Nonhydrostatic (ICON, Zängl et al., 2015) model is a unified state of the art numerical weather prediction and climate modeling system that solves the fully compressible non-hydrostatic Navier-Stokes equations on the sphere. A set of physical parameterisations is included, which accounts for the effect of motions that fall below a chosen horizontal mesh size. Depending on its application, ICON is able to run on two different physical packages: Atmosphere Earth System (AES) physics and Numerical Weather Prediction (NWP) physics. ICON-NWP is used for global and regional weather forecasting by the German weather service (DWD) and regional climate modelling (Pham et al., 2021). For small-scale application there is also a large eddy model (ICON-LEM, Dipankar et al., 2015), which uses a planetary boundary layer (PBL) scheme based on Smagorinsky (1963) available for the NWP physics package.

In contrast to the predecessor COSMO (Baldauf et al., 2011), the ICON is a multi-scale modelling framework designed to run in global, regional (limited-area), convection-permitting and large-eddy simulation configurations, all with consistent dynamical cores. ICON utilizes a icosahedral (triangular) grid system that guarantees consistent resolution worldwide, thereby circumventing the pole singularities typically associated with latitude-longitude grids. The parameterisations of the NWP physics package were selected from various sources, in particular from the COSMO model and the IFS model. Compared to its predecessor, the physical parameterisations have been enhanced, resulting in better prediction quality (Pham et al., 2021; Zängl et al., 2015).

ICON is jointly developed by the ICON partnership consisting of the German Meteorological Service (DWD), the Max Planck Institute for Meteorology (MPI-M), German Climate Computing Center (DKRZ), Karlsruhe Institute of Technology (KIT) and the Center for Climate Systems Modeling (C2SM). The ICON model can run on CPU and GPU infrastructure (Herten et al., 2024). The ICON component is open source and under the 3-clause BSD license. More information and source code can be found at https://icon-model.org and https://github.com/HPSCTerrSys/icon-model_coup-oas.

2.2 Land surface model – eCLM

The newly integrated land surface model eCLM is based on the Community Land Model (CLM; Lawrence et al., 2019) that has been developed to simulate land surface processes and interactions with the atmosphere by the National Center for Atmospheric Research (NCAR). CLM v5.0 incorporates intricate representations of land surface processes, such as photosynthesis, various biogeochemical cycles, energy exchange, and hydrology. The model allows for the examination of different land management practices and their impacts on ecosystems, making it a valuable tool for studying climate change, land use change, and natural resource management.

eCLM is a fork of Community Land Model v5.0 for standalone usage removing the dependencies to the Community Earth System Model (CESM) and developed with minimal dependencies maintained within the Research Centre Jülich. CLM code functionalities remain unmodified besides additional features implemented in the TSMP context. More information and source code is available at https://github.com/HPSCTerrSys/eCLM.

Compared to its predecessor CLM3.5 used in TSMP1, eCLM introduces dynamic land unit transitions, a more detailed hydrology and snow system, and mechanistic plant hydraulics incorporating hydraulic redistribution. The biogeochemistry

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module features modernised nitrogen (N) cycling and leaf physiology with flexible stoichiometry and N optimisation, while a prognostic crop model adds realistic irrigation and fertilisation dynamics. Compared to the native LSMs of the ICON model used as default LSM model of ICON, JSBach and TERRA-ML, the eCLM model includes a more sophisticated soil hydrology representation, an interactive crop model incorporating fertilisation and irrigation, and the ability to depict transient land cover change and dynamic vegetation.

2.3 Subsurface hydrological model – ParFlow

ParFlow is a parallel, integrated hydrology model (IHM), see (Kuffour et al., 2020) for extensive introduction and overview. With the means of Parflow, dynamic two-way groundwater surface water interactions and intermittency in streamflow can be simulated in a continuum approach. ParFlow solves 2D dynamic surface and 3D subsurface flow by the usage of simplified shallow water equations, implicitly coupled to Richards' equation. The Richards equation is discretized in space and time, respectively, using a cell-centered finite-difference scheme and an implicit Eulerian scheme. It is able to simulate a stretched vertical resolution, allowing for shallow vertical layers close to the surface and deep confined and unconfined aquifers.

The model is exascale-ready and can be run on CPUs and GPUs (Burstedde et al., 2018; Herten et al., 2024; Hokkanen et al., 2021). The ParFlow model is an open-source code under LGPL license available at https://github.com/parflow/parflow, where more information can be found.

2.4 Coupler infrastructure – OASIS3-MCT

The OASIS coupler (Craig et al., 2017; Valcke, 2013) allows the synchronized exchange of coupling information between the component models and is developed by the Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS) and the Centre National de la Recherche Scientifique - Institut Pierre Simon Laplace (CNRS-IPSL). The fully parallel implementation of coupling field regridding and exchange is provided by OASIS3-MCT, which is the OASIS coupler interfaced with the Model Coupling Toolkit (MCT, Larson et al., 2005) from the Argonne National Laboratory. OASIS3-MCT is widely used for Earth system modelling e.g. in EC-Earth model, CNRM-CM or GCOAST-AHOI (Döscher et al., 2022; Ho-Hagemann et al., 2024; Voldoire et al., 2019). The software is open source and licensed under the GNU Lesser General Public License (LGPL). Its source code is available at https://gitlab.com/cerfacs/oasis3-mct

3. Coupling between component models

TSMP2 adopts a multiple program multiple data (MPMD) architecture (Gropp et al., 1999), in which different executables run concurrently on separate processors and exchange information via in-memory MPI-communication during runtime. This design is most suitable for independently developed code such as the TSMP component models involved, and it follows the design of the previous TSMP version. There is a high modularization of TSMP between the component models for different component configurations, allowing for interaction between just two components (ICON-eCLM, eCLM-ParFlow) or all three components (ICON-eCLM-ParFlow), and ICON, eCLM, or ParFlow can even be compiled and run as stand-alone independent models within the TSMP framework (Figure 1). In a coupled mode states and fluxes are passed between the

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component models, i.e., the coupled component models in this case replace the default inputs along the coupling interfaces. For example, upper boundary conditions in eCLM may be prescribed without feedback in standalone mode, or provided by ICON in a coupled configuration.

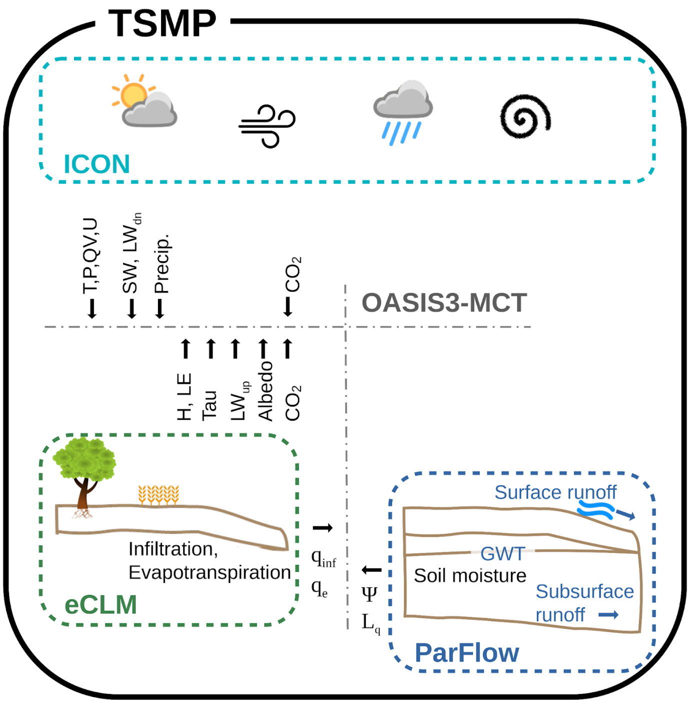

Figure 1: Schematic of the TSMP2 coupled model system. The component models for the atmosphere (ICON), the land surface (eCLM), and the subsurface (ParFlow) are coupled via the external coupler and driver OASIS3-MCT. The following quantities are sent from ICON to eCLM: Temperature at lowermost model level (T), pressure at lowermost model level (P), specific humidity at lowermost model level (QV), horizontal wind speed at lowermost model level (V,U), incident shortwave radiation at surface (SW), longwave downward radiation at the surface (LW), precipitation rate (Precipitation, rain and snow), carbon dioxide (CO2, optional). From eCLM to ICON: Sensible heat flux (H), latent heat flux (LE), momentum flux (Tau), longwave upward radiation at surface (LW), albedo and carbon dioxide (CO_2, optional). From eCLM to ParFlow: Infiltration flux (q_{inf}). From ParFlow to eCLM: Liquid water content (L_q) and the pressure head (Φ).

TSMP2 is open-source under MIT license and the code is available at https://github.com/HPSCTerrSys/TSMP2. The model system itself as well as its components are open-source. ParFlow and ICON have GPU capabilities, so that heterogeneous applications or even the usage of modular supercomputing infrastructure (MSA) is possible.

3.1 Flux coupling

The primary purpose of OASIS3-MCT (Craig et al., 2017) is the ability to interpolate and exchange the coupling fields between components in memory to form a coupled system. OASIS3-MCT is a coupling library that is compiled and linked to the component models. OASIS3-MCT governs the overall execution and is managed by its own namelist called namcouple. The underlying communication is done via the Model Coupling Toolkit (MCT; Larson et al., 2005). MCT

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handles the parallel communication and mapping details, thus communication between processors is only activated when needed via a communication scheduler and allows for rank to rank communication. Thus, OASIS3-MCT leads to an efficient exchange of fields with big model domains. Only the overlapping patches exchange information in memory; MPI_Allgather operations are not required. Each component model has its own MPI communicator and a distinct set of processors. We are using the version 5.0 of OASIS3-MCT available at https://gitlab.com/cerfacs/oasis3-mct.

3.2 Atmosphere – land surface interface

The atmospheric model ICON contains a default land surface model, TERRA-ML (Schrodin and Heise, 2001; Schulz and Vogel, 2020) to provide the lower boundary condition for the atmosphere. TERRA-ML has a rather simplistic representation of the land surface (Pitman, 2003). Depending on user needs, a more process-based representation of vegetation is needed including human land management, ecological models and biogeophysical and biogeochemical processes. In TSMP2, the eCLM LSM replaces the built-in default subroutine-coupled LSM of ICON.

The atmospheric state of the atmospheric model ICON at its lowest level and current time step is used as the forcing term for eCLM. eCLM then computes the surface energy fluxes, momentum fluxes, albedo, outgoing longwave radiation, and carbon dioxide, which are used as lower boundary conditions in ICON. The coupling between the component models is explicit in time. Sending and receiving of exchanged quantities is done in the component model time loop. The processing of coupled quantities is done in the physics modules of ICON and eCLM (see figure 2 a).

With TSMP three atmosphere-landsurface coupling approaches are implemented and tested extensively; the default is the fixed flux coupling approach. Flux calculation with ICON-eCLM is determined by the following equations:

$$H_0 = -\rho\, c_p\, |v_h|\, C_\theta\, (\theta_{ke} - \theta_s)$$
$$LE_0 = -\rho\, L_v\, |v_h|\, C_q\, (q_{v,ke} - q_{v,s})$$
$$M_{i,0} = -\rho\, C_M\, |v_h|\, u_{i,ke}$$

(1)

where H_0 and LE_0 are the sensible and latent heat flux. M_0 is the momentum flux. ρ is the air density. L_v is the latent heat for evaporation, c_p is the specific gas constant for constant pressure, v_h is the horizontal wind speed, C_θ, C_q, and C_M are the exchange coefficients for heat, moisture and momentum, $q_{v,ke}$ is the specific humidity at the lowermost atmospheric level and $u_{i,ke}$ is the wind speed at the lowermost atmospheric level, while $q_{v,s}$ and $\theta_{v,s}$ are specific humidity and temperature at the surface.

In the original coupling approach proposed, TSMP1 uses the flux inversion approach; where the surface energy and momentum fluxes are coupled (H_0, LE_0, M_0 in Eq. 1), and based on these fluxes the surface exchange coefficients are used (C_θ, C_q, C_M in Eq. 1), which are in turn used to update the atmospheric states of the lowermost layer (Shrestha et al., 2014). This flux coupling was also originally used with TSMP1. But this coupling approach, namely flux inversion

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approach, shows weaknesses during transition phases around sunrise and sunset with large changes in energy flux densities, because of unbounded exchange coefficients.

Hence, a new coupling scheme was implemented in TSMP1 to ensure numerical stability, where the exchange coefficients are directly coupled instead of the surface energy and momentum fluxes. The direct coupling of exchange coefficients has the advantage of being stable by design but has some drawbacks in the energy and mass conservation between the components.

Therefore, a third approach was implemented and is now the default in TSMP2. With the fixed flux coupling approach, the surface energy and momentum fluxes between the atmosphere and land surface are coupled directly and kept constant between the coupling time steps. The fixed flux coupling approach is energy and mass conservative by design, but not necessarily numerically stable. However, coupling time steps below 1 hour generally shows numerical stability (see section 4.3).

ICON can be applied in Large Eddy Model (LEM) for high-resolution simulations and a numerical weather prediction (NWP) mode for climate simulations. Both modes of ICON can be used coupled with eCLM within TSMP2. However, the update of the ICON atmospheric states depends on the used mode and connected Planetary Boundary Layer (PBL) and transfer schemes.

In LEM mode, the Smagorinsky PBL scheme is a LES scheme (Dipankar et al., 2015). The Smagorinsky PBL scheme uses Dirichlet boundary conditions at the top and bottom boundaries. Thus, the update of the temperature, humidity, and wind speed state of the lowermost half level of ICON is done by directly using the surface energy and momentum fluxes. The transfer scheme based on Louis (1979) is switched off.

In the NWP mode, the turbdiff PBL scheme is a Turbulent Kinetic Energy (TKE) based scheme based on the level 2.5 of Mellor and Yamada (1982) (Raschendorfer, 2001). The Turbdiff PBL scheme uses in its core von-Neumann boundary conditions for the bottom boundary conditions. The update of temperature, humidity and wind is done based on the lowermost full level of ICON. The surface energy and momentum fluxes need to be transferred to the lowermost half level state variables. The transfer scheme (turbtran) is TKE based, similar to the turbdiff.

In addition to the surface energy and momentum fluxes, the land surface temperature, specific humidity of the land surface, direct and diffuse albedo as well as outgoing longwave radiation are transferred from eCLM to ICON. In turn, eCLM receives from ICON the lowermost air temperature, wind speed, specific humidity, rain and snow precipitation rate, surface pressure and incoming shortwave and longwave radiation, and measurement height.

The exchanged variables are passed between the component models at grid cell level. The subgrid hierarchy at patch level in the land surface component is aggregated to grid scale before coupling with the atmosphere or the integrated hydrological model. It is assumed in the coupling of the compartments that every compartment acts on the same topography. The lateral boundary points In the limited area mode of ICON are excluded from the coupling with the land surface model.

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Compared to TSMP1, additional updates include the exchanged quantities to improve the energy and mass conservation between the two compartments. Snow and rain precipitation are coupled separately in TSMP2, so that eCLM can treat each type of precipitation separately.

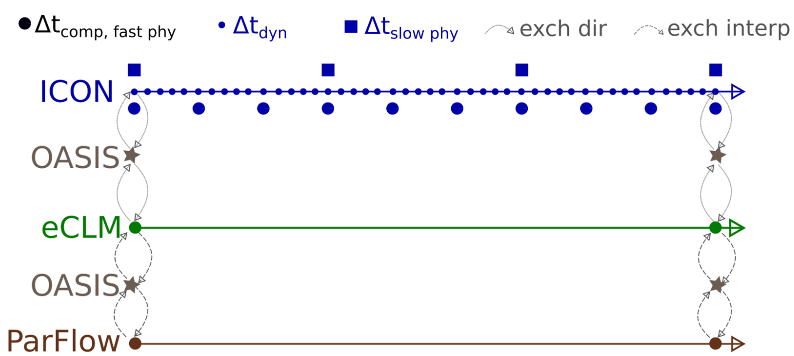
3.3 Land surface – subsurface interface

Most of the land surface models, including eCLM only act in the vertical dimension. By taking into account the lateral flow of the surface and subsurface hydrological flow, the model can capture the complete terrestrial hydrological cycle. To achieve this coupling, the infiltration flux and root water uptake flux are passed from eCLM to ParFlow, and accounted as sink/source terms of the Richards equation. The pressure potential is passed from ParFlow to eCLM and replaces the 1D Richards solver in eCLM. ParFlow typically has more vertical layers, as it reaches deeper than eCLM. The vertical discretisation for those vertical levels that overlap between eCLM and ParFlow is enforced to be the same for both models, as no vertical interpolation is applied. Note, soil freezing and thawing processes are currently ignored in the interface and will be incorporated in an ensuing development step.

3.4 Component model communication

TSMP2 employs the OASIS3-MCT coupler to orchestrate the exchange of data fields between components at user-defined coupling intervals, ensuring temporal synchronization and consistent boundary conditions across component models. Each component operates as a separate executable, often on distinct subsets of computing units (e.g., processors), enabling concurrent execution and scalability and each component performs its individual I/O operations. This Multiple Program Multiple Data (MPMD) approach enables efficient resource allocation and concurrent execution, enhancing scalability on distributed-memory systems. Communication between models occurs via parallel, MPI-based field exchanges, configured through coupling metadata that defines variable mappings, interpolation methods, and coupling frequencies via the coupler, which also governs the execution.

(a)



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(b)

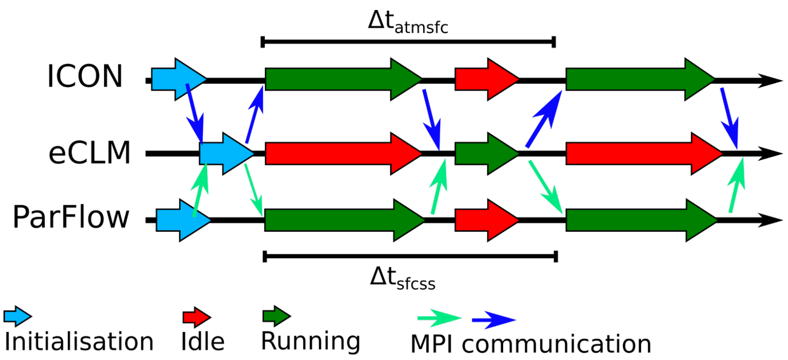

Figure 2: (a) Schematic of time sequence of computations and coupling processes in TSMP2, showing one coupling cycle. Lines represent the simulation timeline. (b) Schematic of the synchronization and communication structure. Black lines represent wallclock timelines. While ICON and ParFlow initialize, eCLM is waiting. eCLM receives variables first from ICON and then from ParFlow. While eCLM is running, ICON and ParFlow are idle and vice versa. eCLM sends first to ICON before sending to ParFlow.

When synchronising component models in externally coupled systems, such as TSMP2, governance of the overall execution is required as each component model operates with its own numerical schemes and methods. To ensure that the information is consistent across the component models, there are both asynchronous and sequential coupling elements. Figure 2 shows the coupling frequency synchronization and communication structure within TSMP2. While the initialisation between the atmospheric and hydrological component is independently performed, the land surface component is initialized using the input from the other components. After initialization, the exchanged fields are sent to ICON and ParFlow. Each coupling time step is performed to run ICON and ParFlow asynchronously, while eCLM is run sequentially. After ICON and ParFlow complete their respective time steps while eCLM remains idle, both models send their state variables to eCLM, which then carries out its time step, completing a full coupling time step. The sequential coupling approach ensures the time synchronisation across all component models.

The coupling time step can interfere with the parameterisation, especially the radiation calculation in ICON. These parameterisations, not performing every time step, are called slow physics and their calling frequency can be set by the ICON namelist. The coupling sequence remains unchanged when performing simulations with two component models. If there is only one, standalone component model, the external coupler is not used.

4. Proof of coupling concept via idealized test case

To explore TSMP2's coupling behavior under simplified, controlled conditions we use an idealized test case. With this test case we can demonstrate TSMP2 functionalities and its usefulness to investigate complex subsurface-surface-atmosphere interactions.

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4.1 Experimental design

The simulation setup uses horizontally homogeneous initial conditions. The simulation time is 24 hours. A periodic boundary condition is used in the X and Y direction for ICON, while a flat terrain is set for ParFlow, so there is no gravity-driven lateral flow. ICON and eCLM operate on the same icosahedral grid while ParFlow operates on a cartesian grid. The horizontal grid spacing is 2 km for all component models and covers an area of 140 x 140 km². In ICON, the vertical grid spacing is staggered from the surface up to a height of 22 km with 50 layers. eCLM's subsurface model grid extends to a depth of 8.5 m with 20 hydrological active layers, and 30 layers for ParFlow to a depth of 30 m, respectively. Figure 3 summarizes the domain setup. The model time step of ICON is 10 seconds, the coupling time step is 600 seconds, which is also the model time step of eCLM and ParFlow.

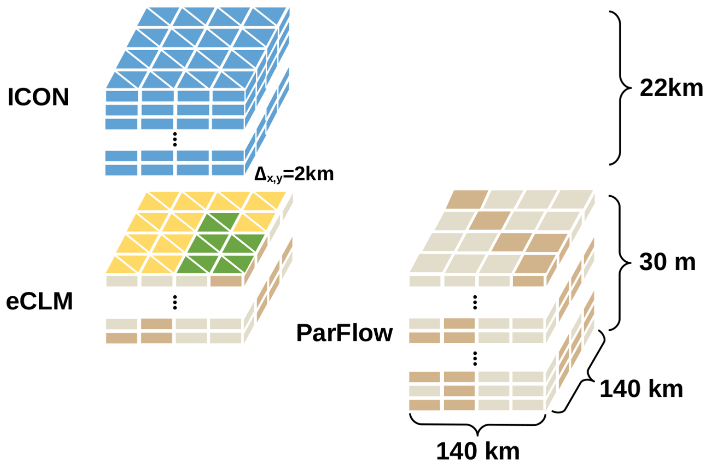

Figure 3: Setup of TSMP2 component models for the idealised domain. ICON and eCLM run on the same triangular horizontal grid, while ParFlow covers the same area on a rectangular grid, resulting in half of the horizontal grid elements compared to ICON and eCLM.

The atmosphere is initialized with an idealized vertical profile with a constant lapse rate of 0.6K/100m. Surface, vegetation, and atmospheric temperature at the lowermost model level are initialized at 290 K everywhere. The solar insolation follows the diurnal cycle at 50°N on the 1st of July. We run an ensemble with four members: The volumetric soil moisture is either set to θs=0.11 or θs=0.3 and the land cover is either all grass or forest.

4.2 Proof of functionality

A functionality test between the compartment models within TSMP2 is a critical step to ensure the integrity and reliability of the coupled system. The modular architecture of TSMP2 allows for an independent execution and a flexible coupling configuration of the atmospheric, land surface, and hydrological models; therefore it is essential to verify that data exchange, temporal synchronization, and physical feedback between the component models operate as intended. Such a test confirms that variables are correctly passed, remapped, and conserved across interfaces and to identify potential communication errors, unit mismatches or unintended time lags between the compartments. As we use a fixed flux coupling

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approach, any difference between the exchanged fluxes should only originate from the remapping (see Section 3.2 and 3.3). The energy and mass budgets between the coupled compartments is consistent.

Figure 4 shows a comparison of the exchanged fluxes and states of the compartment models using the output from each component model. The surface energy and water balances are central to the interactions between the atmosphere and the land surface. The surface energy fluxes of ICON and eCLM in Figure 4a illustrate that variables pass the coupler interface between ICON and eCLM unmodified, as expected. The flux partitioning reflects the diurnal cycle. The liquid water content (Figure 4b) in the soil layer between 0.02-0.06m of eCLM and ParFlow match as well. Please note that the lines exactly overlap. The decrease is due to the evapotranspiration. Because two grid elements of eCLM exactly match one ParFlow grid element (see Figure 3) this also demonstrates the consistent interpolation between the eCLM and ParFlow grids.

(a) (b)

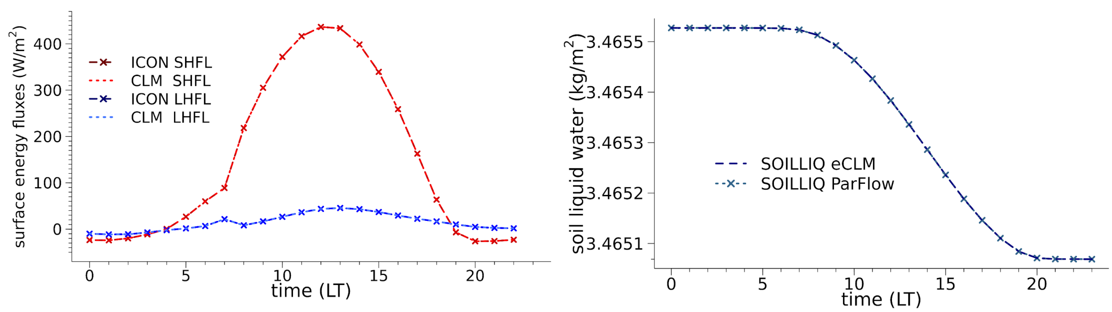

Figure 4: Comparison of model domain average fluxes (a) and states (b) passed between the TSMP2 compartment models. (a) ICON (long dashes) and CLM (short dashes) sensible (SHFL) and latent (LHFL) heat flux at the surface [W m^{-2}]. (b) eCLM (long dashes) and ParFlow (short dashes) liquid water content between 0.02-0.06m depth [kg m^{2}]. Please note the lines overlap exactly. Shown is the experiment ensemble member land cover for grass, clay loam soil texture, and an initial soil moisture of θs =0.11.

(a) (b)

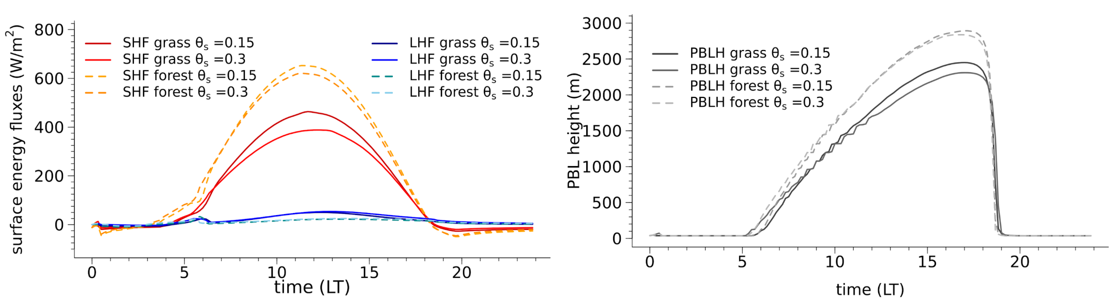

Figure 5: As in Figure 4, for land cover grass and Needleleaf temperature evergreen tree (forest) and initial soil moisture of θs =0.11 and θs =0.3, and in (b) planetary boundary height identified via the Richardson number.

Figures 5a and 5b are also from the same ensemble of test simulations, as described above. Here we present the domain averaged surface energy fluxes and planetary boundary layer (PBL) height, respectively, the latter serving as an indicator of

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the intensity and extent of turbulent mixing and thermodynamic processes occurring within the PBL. Lower soil moisture of ParFlow propagates via eCLM into a smaller sensible heat flux, which results in less buoyancy and thus to a lowering of the PBL height.

4.3 Sensitivity to coupling time step

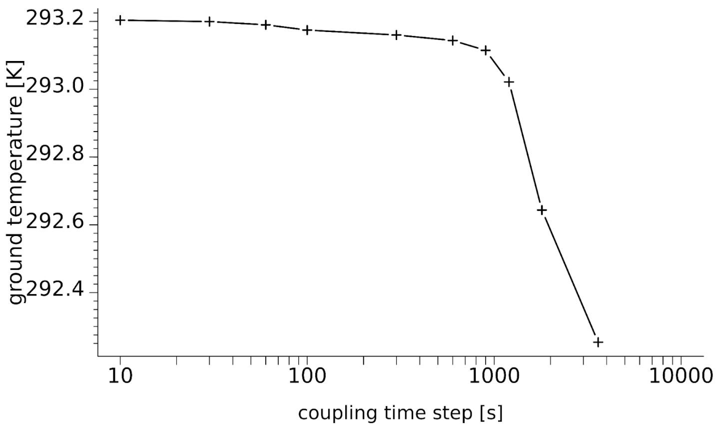

Figure 6: Ground temperature at the end of the simulation period for different coupling time steps for the idealized test case (Section 4.1) with ICON-eCLM-ParFlow and land cover for grass, clay loam soil texture, and an initial soil moisture of θ =0.3.

Based on the same idealized test case of section 4.1, additional tests were designed to explore how different coupling interval time steps affect the representation of land-atmosphere interactions in terms of energy fluxes and near-surface air temperature. For all experiments, the model time step for all component models was fixed at 10 seconds, while the coupling time step was modified as indicated in Figure 6. Prior studies (Beljaars et al., 2017; Gross et al., 2018) have shown that large coupling time steps can lead to inaccuracies due to the asynchronous exchange of fast-evolving variables or processes. Our simulations confirm this sensitivity. Longer coupling intervals result in a lowering of temperature compared to shorter coupling time steps (Figure 6).

Specifically, the analysis reveals that the optimal coupling time step aligns with the radiation time step, typically on the order of 15 to 30 minutes, depending on model configuration. Coupling intervals longer than one hour lead to a noticeable deterioration in physical consistency, highlighting the importance of tight coupling for realistic representation of non-linear exchange processes. This effect of linearization introduced by operator splitting across component models becomes evident in the model response when the coupling time step is increased and is dependent on the involved processes, which in turn depend on the grid spacing of the model.. These simulations inherently require fine temporal resolution, making sub-hourly coupling both necessary and practical. Therefore, coupling time steps exceeding one hour are not planned for regular use within the platform.

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5. Real test case - CORDEX EUR-12

The real case test case shows the ability of the coupled model system to perform as a regional Earth system model. The model domain encompasses the Pan-European continent (Figure 6) and operates at a horizontal resolution of 0.11° (approximately 12.5 km), referred to as the “EUR-12” grid, as part of the COordinated Regional Downscaling EXperiment (CORDEX) project (Gutowski Jr. et al., 2016; Jacob et al., 2020).

5.1 Experiment design

The ICON model follows the so-called “recommended configuration” of the Climate Limited area Modelling COMmunity (CLMcom) with 50 vertical layers. In this configuration, the eCLM model includes 20 soil layers with a combined depth of 8.5 meters. These layers align with the top 20 layers in ParFlow, which extends further with 10 additional layers of increasing thickness toward the base of the model domain, reaching a total depth of 60 meters. ParFlow and eCLM use a time step of 15 minutes, which is also the coupling time step between the compartments, while ICON is running on a 100 second time step.

The external static parameter fields are shared between the component models. The topography data are based on the ASTER dataset. Globcover is used as a land cover data set and mapped to the 17 plant functional type classes of eCLM. ParFlow's hydraulic conductivity parameters are estimated based on soil texture data from the SoilGrids database. Fifteen distinct soil types are used to define permeability, porosity and soil hydraulic conductivity. Figure 7 shows examples of prominent static input data.

The simulation period is July 2017, during which much of Europe experienced a heatwave, and below-average precipitation in some regions. The eCLM is spun-up for 10 years. ParFlow IHM is initialized with a spatially homogeneous water table depth of 2m. The atmospheric boundary conditions for the land surface model spin-up, as well as the initial and lateral boundary conditions, prescribed sea surface temperatures for the atmospheric model, were derived from the ECMWF ERA5 reanalysis (Hersbach et al., 2020).

The modular structure of TSMP2 enables a robust validation strategy for its component models by allowing them to be run in standalone, atmosphere-land, land-hydrology, or fully coupled atmosphere-land-hydrology configurations. This flexibility facilitates a targeted evaluation of model system interactions and ensures that there are no coupling-induced artifacts. This stepwise comparison ensures that coupling processes preserve the physical integrity of the individual models and gives confidence in the validity of the fully coupled system. Also, this type of comparison shows the impact of the coupling, i.e., differing results are expected. Since the standalone versions of the component models - such as the ICON atmospheric, eCLM land surface, and ParFlow hydrologic modules - have been in use in a large number of applications and have been independently validated against observational data, their established reliability provides a frame of reference for comparison (e.g., Belleflamme et al., 2023; Lawrence et al., 2019; Pham et al., 2021).

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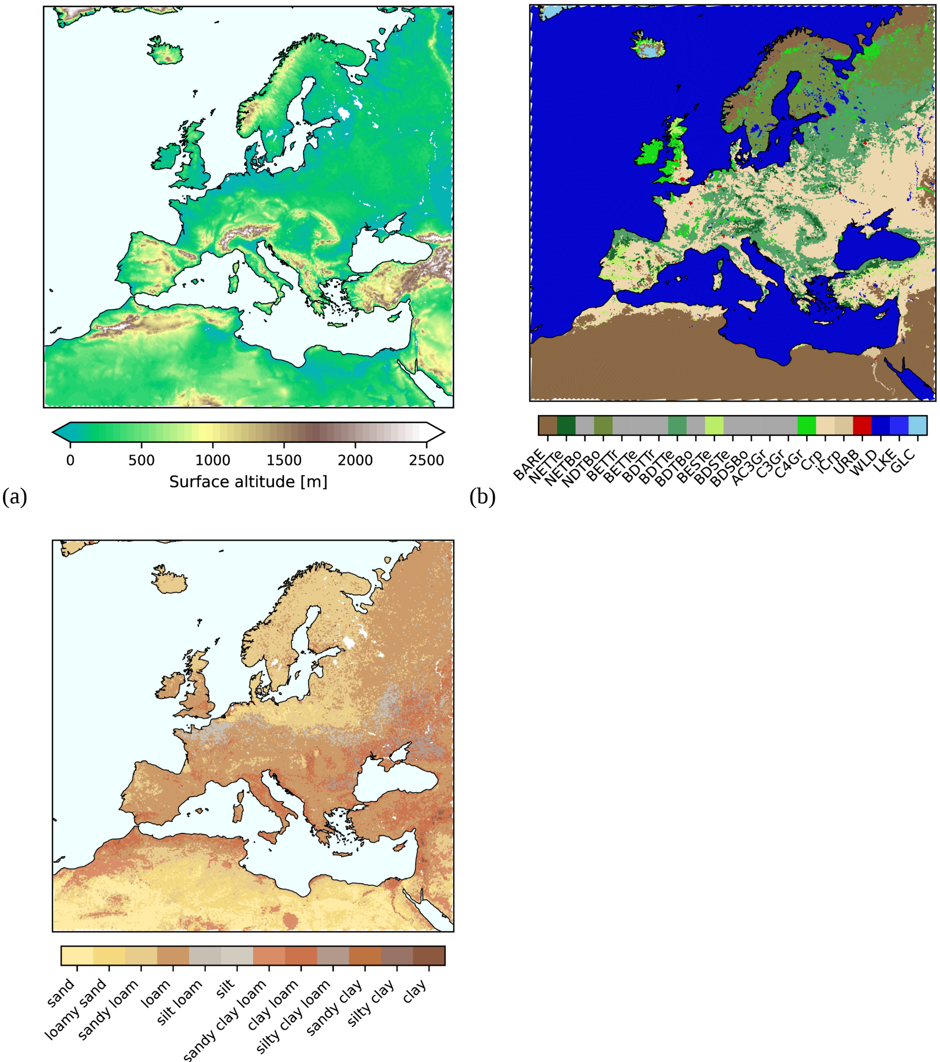

Figure 7: External parameters for CORDEX EUR-12 domain: (a) topography based on ASTER database, (b) dominant land cover based on Globecover2009, and (c) soil texture classes in 0.02-0.06m depth based on SoilGrids dataset.

5.2 Results

This real data case simulation serves as a proof-of-concept, that TSMP2 can be used for such (climate mode) simulations. An analysis of the temporal evolution of 2-m air temperature across all model configurations - standalone, two-model coupling, and fully coupled - reveals a generally consistent behavior in terms of variability and diurnal patterns (Figure 8a). Simulations that incorporate the atmosphere-land surface coupling show systematically lower daily temperatures compared to the other simulations. Furthermore, the fully coupled ICON-eCLM-ParFlow and ICON-eCLM configurations show similar temperature behavior, while the eCLM-ParFlow simulation closely aligns with the standalone eCLM run. This indicates that the inclusion of ParFlow exerts only a modest influence on near-surface temperature relative to the impact of

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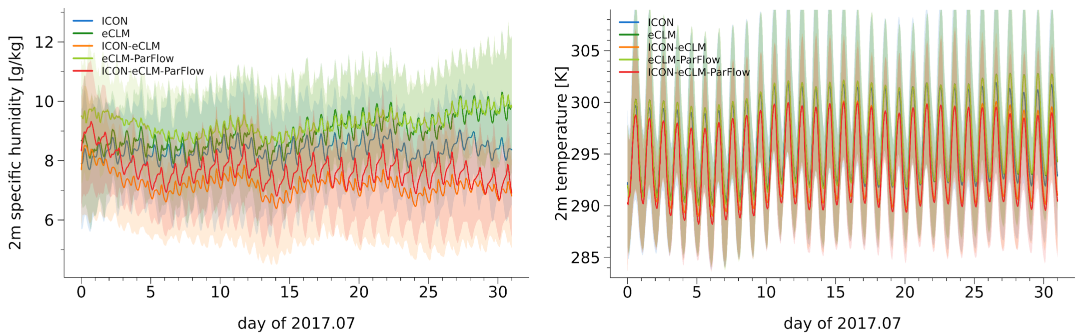
the land-surface model. For 2 m specific humidity, higher values are observed at the start of the month due to the inclusion of ParFlow. This effect evens out over the course of the month (Figure 8b).

The time of the 2m maximum temperature changes with the used LSM. While the 2m maximum temperature with the eCLM LSM is at 14UTC, with ICON and the TERRA-ML LSM it is 1-2 hours earlier, depending on the region (Figure 8b). While the inclusion of ParFlow in the Prudence region of Scandinavia (SC) has no effect, low temperatures are reached in the Iberian Peninsula (IP) and Mediterranean (MD) when the ParFlow IHM component is included. In return, the inclusion of ParFlow results in a more humid atmosphere compared to runs without the IHM component. However, the greatest effect on the 2m specific humidity is observed in an active atmosphere. The daily cycle of 2m specific humidity is driest in the coupled ICON-eCLM simulations, while the simulations with offline atmospheric forcings are wettest (Figure 8b).

(a)



(b)

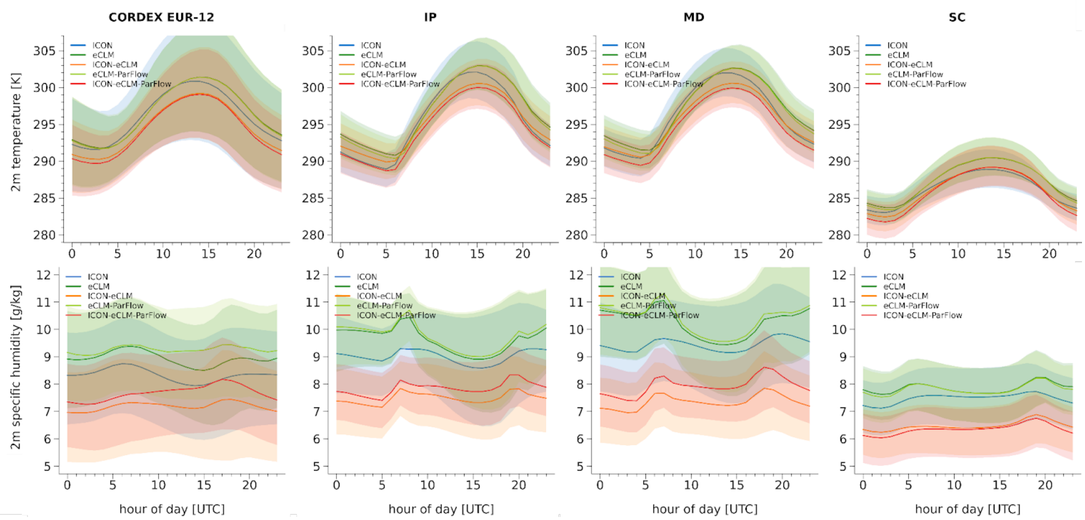


Figure 8: Domain averages (lines) and 25/75% quantiles (shaded area) of the 2m air temperature (a, left column), 2m specific humidity (a, right column) of EURO-CORDEX EUR-12 domain over land for ICON, eCLM, ParFlow, ICON-eCLM, eCLM-ParFlow and ICON-eCLM-ParFlow for July 2017. (b): same as (a) for the diurnal cycle for EURO-CORDEX EUR-12

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domain over land and Prudence regions Iberian Peninsula (IP), Meditarianien (MD) and Scandinavien (SC) after Christensen and Christensen (2007).

The evaporation fraction (EF) is used as an indicator for characterising atmosphere-land-groundwater coupling (Keune et al., 2016). Figure 9 shows how water and energy fluxes at the surface are clearly affected by the coupling. The ICON-eCLM-ParFlow simulation is used as a reference. As expected, the lowest EF is seen on the African continent, while the highest is seen in Eastern Europe. All simulations show a higher EF over Central Europe compared to the fully coupled reference simulation. Over the Iberian Peninsula, the inclusion of the ParFlow in the coupling leads to a higher EF. ParFlow's impact is still somewhat limited in this simulation, due to the relatively short spinup of the subsurface; ICON-eCLM shows the smallest difference to the reference, also eCLM vs eCLM-ParFlow are very similar. What seems to have the largest impact here on flux partitioning is the inclusion of eCLM that differs strongly from the TERRA in the ICON standalone TSMP2 variant. The LSMs differ for example with respect to their transfer schemes, which is TKE-based in TERRA vs Monin-Obukhov similarity theory-based in eCLM.

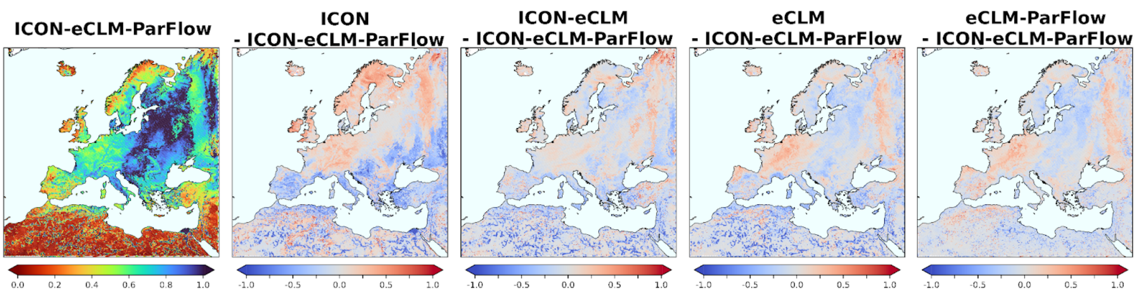

Figure 9: Evaporative fraction (ratio between latent heat flux and available energy at the land surface) between 06-18 UTC, of EURO-CORDEX EUR-12 domain over land for ICON-eCLM-ParFlow (reference) and ICON, eCLM, ParFlow, ICON-eCLM, eCLM-ParFlow minus reference (from left to right) for 31th July 2017.

6. Performance and portability

6.1 Portability

A key strength of TSMP2 lies in its high degree of portability across computational environments. The model system is implemented with a modular and standardized infrastructure using a CMake-based build system. CMake enables a standardized and flexible mechanism for configuring, compiling and linking its modular components, ensuring compatibility with a wide range of compilers, libraries and architectures. As a result, TSMP2 can be deployed seamlessly on platforms ranging from local workstations (Linux-based) to high-performance computing (HPC, Tier 0-3) clusters and emerging exascale architectures.

Different environments are stored in dedicated environment files, each loading the corresponding software environment and compiler settings. These settings can be found in the TSMP2 env directory and can be expanded to any computational

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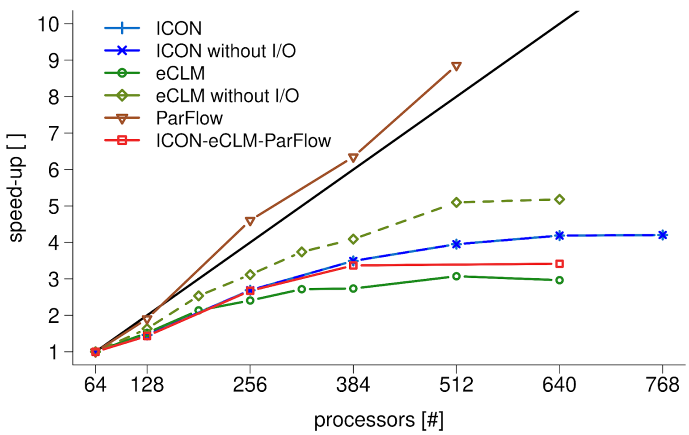
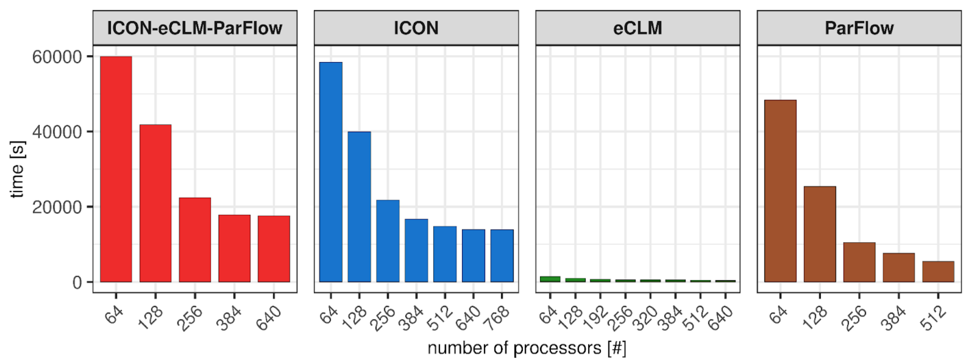
environments which are not supported by default. The required dependencies can vary, depending on the installed component model combination.

6.2 Scalability

The scalability of the system is constrained by the scalability of the component models. A strong scaling study is performed on the JURECA-DC HPC system at the Juelich Supercomputing Centre in Germany, with hybrid MPI-OpenMP parallelization and O2 optimization. JURECA-DC features two AMD EPYC 7742 CPUs per node (128 cores), and InfiniBand HDR100 using an Intel toolchain with a ParaStation MPI implementation (Jülich Supercomputing Centre, 2021). The strong scaling test is based on the EURO-CORDEX EUR-12 climate simulation experiment setup (Section 5.1), including I/O. The target simulation time for such simulations is usually one Simulated Year Per real Day (SYPD). Performance optimisation and scaling studies with a fully coupled system may be complicated (Gasper et al., 2014), and depend on a combination of HPC System, compile time optimisation, model configuration, I/O, model timesteps, coupling time steps, domain or problem size, and grid spacing.



(a)



(b)

Figure 10: Strong scaling for EURO-CORDEX EUR-12 test case for individual component models ICON, eCLM, ParFlow and for the coupled system ICON-eCLM-ParFlow for a simulation time of one month. (a) Speed-up curves of component models and

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the fully coupled system, black line is ideal speed-up. (b) Bar charts of wallclock times for the fully coupled system (red), ICON only (blue, I/O: turquoise), eCLM only (green, I/O: olive), and ParFlow only (brown).

Here we apply a simplified scaling experiment where in a first step the optimum scaling of one of the TSMP2 component models, here ICON, is determined; this defines then the wallclock runtime performance envelope for eCLM and ParFlow. In a subsequent step ParFlow is scaled until the ICON runtime stays the same. eCLM scaling follows, according to the same principle. In effect, no component model needs to wait for the others. Thus, for ICON-eCLM-ParFlow, the number of processors specified by ICON remains the same for eCLM and ParFlow at 384 processors.

ICON shows a moderate strong scaling up to 512 processors. Due to the asynchronous output of ICON (io_proc_num=3), the I/O only adds up 10-40 seconds to the total simulation time (20k-60k seconds). Thus, the I/O is not a limiting factor for the scaling of ICON. Whereas, for the eCLM strong scaling, the I/O is a limiting factor, occupying up to 50% of the total runtime for 640 processors. The speed-up of ParFlow follows the optimum line.

The simulation time is highest for ICON, which is due to its comprehensive physical parameterisations and fine spatial resolution, which increase the computational effort. ParFlow has less demanding computational requirements (Figure 10b). In contrast, eCLM has significantly faster run times, with simulation times that are orders of magnitude shorter than those of ICON and ParFlow.

For the coupled system, the number of processors for ParFlow and eCLM is fixed to 384 cores, respectively. The scaling of the coupled system follows the one of the ICON model (Figure 10 a), indicating that this is the limiting component model for the scalability of the system. The simulation time of the coupled model system is larger than the combined simulation times of ICON and eCLM (Figure 2) by 2-5%, which could be attributed to the exchange of fields and load balancing between the three compartments. The reader should keep in mind that in the coupled system, ICON and ParFlow run (partially) concurrently, whereas eCLM runs sequentially before/after ICON and ParFlow. It is therefore expected that the ICON runtime and scalability properties dominate the TSMP2 coupled runtime and scalability.

6.3 Computational overhead of the coupled model

The runtime overhead introduced by the coupled system in TSMP2 amounts to approximately 2–10% compared to the standalone execution of individual component models (Figure 10), if one ignores the increase in computational resources needed. This overhead primarily arises from the coordination and data exchange managed by the coupler, including synchronization at defined coupling intervals. This interpolation step adds computational complexity and communication load beyond the baseline coupling overhead. However, increasing the number of coupled fields, i.e., the volume of exchanged variables, does not have a significant impact on run-time performance, indicating that the communication infrastructure is efficient and not a bottleneck in typical use cases. Overall, TSMP2 maintains strong performance while enabling comprehensive process coupling. In future, a reduction of the runtime overhead could be achieved through the parallel execution of the component models (see Figure 2) and the optimisation of the eCLM output. The I/O of eCLM is the most limiting part in the total runtime of this compartment. Performing output of eCLM after sending the exchanged quantities would be an optimisation for the total runtime of the coupled system. The parallel execution would result in the

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exchanged quantities having a time shift. However, Marti et al., (2021) showed that using an atmosphere-first approach in parallel execution only resulted in a slight degradation of the simulation results.

7. TSMP2 framework

In order to run simulations, simply providing the coupled model and the build script is not enough. It is also necessary to have static or external parameter fields (topography, land cover, etc.), forcing data, i.e., time-varying boundary conditions, initial conditions, as well as a model configuration, i.e., namelists, and a workflow engine for simulation and data handling, based on a properly installed and maintained runtime environment. In order to handle the authors' own simulation experiments efficiently, aid the development of TSMP2 and support training activities, all of the aforementioned components that make up the TSMP2 framework are provided via public Git repositories. To ensure modularity, which aids in a flexible use and maintenance of the system, each component of the framework has its own Git repository. Together, these components constitute the TSMP2 framework, offering an end-to-end solution that facilitates reproducible workflows, lowers barriers to adoption, and enhances the usability of TSMP for both research and operational applications.

An overview of the software tools can be found at https://github.com/HPSCTerrSys/.github/blob/main/profile/README.md. The workflow engine provides a summary of the functionalities around simulation experiments by using Git submodule functionality to manage the respective parts to perform a specific simulation (https://github.com/HPSCTerrSys/TSMP2_workflow-engine).

8. Conclusions and outlook

In this model descriptor study, we present the fully modernized free open-source Earth system model, TSMP v2.0.0 (TSMP2). In TSMP2 the state of the art atmospheric model ICON (v2024.07), the land surface model eCLM (v0.4) and the integrated hydrologic model ParFlow (v3.14) are coupled via the OASIS3-MCT coupler (v5.0). TSMP2 can be used for a wide range of simulation experiments across a range of spatial and temporal scales. With its focus on a sophisticated terrestrial hydrology representation and explicit treatment of 3D hydrodynamics and groundwater processes and its flexible modular structure, TSMP2 is a valuable tool for studying atmosphere-land-subsurface interactions, water resources questions, and for climate simulations as part of a new class of “increased complexity” model systems, as used in the CORDEX experiment.

The first version of TSMP (TSMP1) has been in use for over a decade, with a focus on land-atmosphere interaction and water cycle research. TSMP2 enables an even more accurate simulation of the energy and water cycles through the use of new coupling strategies. The state-of-the-art modelling components makes it possible to have a more complete process representation. In this study, the basic coupling functionality of TSMP2 is demonstrated through idealised experiments that also highlight the interconnectivity between groundwater and the atmosphere. A correlation between coupling time step and model parameterisations such as the radiation subroutine calls was found. A real data case simulation over the CORDEX EUR-12 pan European model domain illustrates TSMP2’s readiness for regional Earth system modelling.

As part of the ongoing development TSMP2, a 20-year simulation period is planned for the EUR-12 region at spatial resolutions of 12 km and convection-permitting 3 km. This extended simulation will enable comprehensive evaluation of model performance. The 12 km simulations will provide a robust baseline for regional climate processes forced with ERA5 reanalysis data, while the high-resolution 3 km runs will allow for detailed analysis of fine-scale phenomena such as convective precipitation and land-atmosphere feedbacks. Evaluation will be conducted using a suite of observational datasets and reanalyses, ensuring rigorous assessment of atmospheric, land surface, and hydrological components.

eCLM supports the simulation of bio-geochemical cycles, dynamic vegetation, and a sophisticated representation of urban areas; these features are implemented but not subject to this introduction. In this study, we focused on the hydrological cycle above and below land. To limit complexity and computational demand, we did not include an interactive ocean component, instead prescribed sea-surface temperatures are used. However, achieving a fully integrated Earth system model will require adding an explicit ocean model to TSMP. Oceans contribute to climate regulation through heat storage, carbon sequestration, and biogeochemical cycling, and their coupling with land and atmosphere processes can improve feedback representation, such as carbon exchange and coastal runoff (Heinze et al., 2019).

The MPI-based parallelization paradigm also allows for the usage of heterogeneous supercomputers combining CPUs and GPUs, either through Modular Supercomputer Architecture (MSA) execution modes, or the tightly integrated CPU-GPU architecture of superchips such as Grace-Hopper (Caviedes-Voullième et al., 2025). GPUs can be utilized for tasks that require a high level of computation, such as those related to atmospheric and hydrological components. While keeping memory demanding applications, such as the land component, on the CPU.

Coupling and synchronisation within terrestrial systems is critical to accurately represent the complex interactions between the atmosphere, land surface and hydrological processes. These components operate on different spatial and temporal scales, necessitating a robust coupling framework that ensures consistent exchange of energy, mass and momentum across compartment interfaces. Previous studies, such as Marti et al. (2021), have shown how coupling synchronisation can influence simulation outcomes and how this influence can be measured using the Schwarz iterative. We plan to adjust the model synchronisation in the future to concurrent coupling by performing an atmosphere- and hydrology-first sequence. This will make a higher frequency between atmosphere and land surface coupling possible.

This initial presentation of TSMP2 has not yet addressed its capability to operate at the global scale. The ICON atmospheric model is run in many climate and NWP applications globally and eCLM - by original design also the land surface component model of CESM2 (Danabasoglu et al., 2020) - likewise supports global deployment. The hydrologic model ParFlow has recently proven to work globally. Together, these components provide a strong foundation for extending TSMP2 toward fully global Earth system simulations.

All component models of TSMP2 are under active development, and the modular design of TSMP2 makes such updates easily possible. TSMP2 will continue to be actively developed as a free and open source (regional) Earth system model and in conjunction with a modular framework of auxiliary software tools will be a platform for collaborative research on terrestrial system processes.

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Code and data availability

The TSMP2 coupled system can be downloaded from GitHub under this URL: https://github.com/HPSCTerrSys/TSMP2. The HPSC-TerrSys competence center GitHub account with all relevant auxiliary tools for TSMP2 is under this URL: https://github.com/HPSCTerrSys.
The complete idealized simulation experiment (initial fields, external parameter fields, model configuration files) from Section 4 is available under this URL:
https://github.com/HPSCTerrSys/simexp_ideal_fs-idealnwp_icon-eclm-parflow_wfe-case.
The complete real case simulation experiment from Section 5 is available under this URL:
https://github.com/HPSCTerrSys/TSMP2_workflow-engine/.
The ERA5 reanalysis data used as boundary conditions for the real data case in Section 5.2 can be downloaded via the Copernicus Climate Change Service, Climate Data Store https://cds.climate.copernicus.eu/datasets.

Author contribution

TSMP2 conceptualization was done by SK with the support of KG and DCV. SP, PR and SB developed the model code, HTMHH supported. SP performed the simulations. CH and MvH supported in performing the simulation. AGN and JK supported in the framework. KG, DCV and HJHF supported in the design of the experiments. SP prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

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