UniFHy v0.1.1: A community modelling framework for the terrestrial water cycle in Python

Thibault Hallouin[1,2,a], Richard J. Ellis[3], Douglas B. Clark[3], Simon J. Dadson[3,4], Andrew G. Hughes[5], Bryan N. Lawrence[1,2,6], Grenville M. S. Lister[1,2], and Jan Polcher[7]

[1]National Centre for Atmospheric Science, UK
[2]Department of Meteorology, University of Reading, UK
[3]UK Centre for Ecology & Hydrology, UK
[4]School of Geography and the Environment, University of Oxford, UK
[5]British Geological Survey, UK
[6]Department of Computer Science, University of Reading, UK
[7]Laboratoire de Météorologie Dynamique, IPSL, CNRS, France
[a]now at: HYCAR Research Unit, INRAE, Université Paris-Saclay, France

Correspondence: Thibault Hallouin (th.thibault.hallouin@gmail.com)

Abstract. The land surface, hydrological, and groundwater modelling communities all have expertise in simulating the hydrological processes at play in the terrestrial component of the Earth system. However, these communities, and the wider Earth system modelling community, have largely remained distinct with limited collaboration between disciplines, hindering progress in the representation of hydrological processes in the land component of Earth system models. In order to address key societal questions regarding the future availability of water resources and the intensity of extreme events such as floods and droughts in a changing climate, these communities must come together and build on the strengths of one another to produce next-generation land system models able to adequately simulate the terrestrial water cycle under change. The development of a common modelling infrastructure can contribute to stimulating cross-fertilisation by structuring and standardising the interactions. This paper presents such an infrastructure, a land system framework, which targets an intermediate level of complexity and constrains interfaces between components (and communities) and, in doing so, aims to facilitate an easier pipeline between the development of (sub-)community models and their integration, both for standalone use and for use in Earth system models. This manuscript first outlines the conceptual design and technical capabilities of the framework, before its usage and useful characteristics are demonstrated through case studies. The main innovations presented here are (1) the interfacing constraints themselves; (2) the implementation in Python (the Unified Framework for Hydrology, `unifhy`); and (3) the demonstration of standalone use cases using the framework. The existing framework does not yet meet all our goals, in particular, of directly supporting integration into larger Earth system models, so we conclude with the remaining limitations of the current framework and necessary future developments.

1 Introduction

The Earth's atmosphere and land surface are highly interconnected systems with significant interactions and feedback (Betts
et al., 1996). Given this, hydrological knowledge is as critical to atmospheric scientists as meteorological knowledge is to hy-
drologists. These interactions have long been represented in Land Surface Models (LSMs) (Blyth et al., 2021). However, they
have historically been developed as a lower boundary condition and intimately connected into atmospheric models which, to
this day, partially explains the shortcomings in the representation of hydrological processes in LSMs. In particular, the resolu-
tion of the land system coupled with the atmosphere has typically been too coarse to adequately represent the spatial structures
of the dominant hydrological processes (Fisher and Koven, 2020), while the focus on vertical exchanges between the land and
the atmosphere has limited the development of the critical lateral redistribution of water on and below the ground (Clark et al.,
2015a). To overcome these limitations, a modular representation of the terrestrial water cycle using interconnected modelling
components would provide the flexibility required in the spatial discretisation of the land system while preserving the exist-
ing coupling approaches with atmospheric models. In turn, such modularity would facilitate the contributions from distinct
modelling communities with expertise in the terrestrial water cycle, that are the land surface, hydrological, and groundwater
modellers, so long as the interfaces between the modular elements are clearly specified. In particular, introducing this modu-
larity would allow the testing of models of varying complexity to determine its impact on simulations. However, such modular
framework does not exist yet for LSMs, despite a variety of existing frameworks developed within the distinct communities
with expertise in simulating the terrestrial water cycle.

The land surface modelling community has developed highly configurable models such as the Joint UK Land Environment
Simulator (JULES) (Best et al., 2011; Clark et al., 2011), the Organising Carbon and Hydrology In Dynamic Ecosystems
(ORCHIDEE) model (Krinner et al., 2005), and the Community Land Model (Lawrence et al., 2019). However, these models
do not allow different parts of the land system to be simulated at different explicit resolutions (except for the runoff routing), nor
do they make it possible to substitute part of one model with another part from another model, which are crucial requirements
to advance land surface modelling (Blyth et al., 2021).

The Earth surface dynamics modelling community has developed coupling frameworks for the land system, e.g. Landlab
(Hobley et al., 2017; Barnhart et al., 2020) can be used to develop modelling components complying with the Basic Model
Interface (BMI) (Peckham et al., 2013; Hutton et al., 2020) that can be coupled using the Python Modelling Toolkit (PyMT)
(Hutton et al., 2021). However, these frameworks are primarily developed to address requirements of geomorphologists, there-
fore they do not consider the essential need for LSMs to be coupled with external models, e.g. atmospheric models, where the
handling of time advancement and memory allocation of the land model need to be delegated to an external model.

The hydrological modelling community has also been developing frameworks of varying granularity to compare differ-
ent physical processes and/or conceptualisations of the hydrological behaviour of a hydrological system. For example, FUSE
(Clark et al., 2008) and SUPERFLEX (Fenicia et al., 2011) provide bucket-style building blocks to develop integrated catch-
ment models, while CMF (Kraft et al., 2011), SUMMA (Clark et al., 2015b), and Raven (Craig et al., 2020) allow the con-
struction of physically-explicit hydrological models by providing finer building blocks in the form of the process equation

themselves. However, given the large number of processes included in LSMs, our experience reveals that refactoring existing models using these frameworks is not trivial, and an intermediate level of granularity is required to simplify their refactoring. The Open Modelling Interface (OpenMI) has been developed to provide an international standard to link hydrological and hydraulic models as components. It has been implemented as a flexible approach for allowing models as components to be linked at runtime (Harpham et al., 2019). However, despite its flexibility, there is no standardised interface for linking OpenMI compliant components which reduces their compatibility and continued reusability over time.

The Earth system modelling community has also developed frameworks with intermediate modularity, where atmosphere, ocean, and land components together simulate the dynamics of the Earth system. The technologies used to combine such modelling components range from integrated coupling frameworks such as ESMF (Collins et al., 2005) or CPL7 (Craig et al., 2012), where existing modelling components require code refactoring to comply with a set of organising and interfacing requirements, to couplers such as OASIS-MCT (Valcke, 2013; Craig et al., 2017), or YAC (Hanke et al., 2016), where existing modelling components require minimal additions to expose their variables to the coupler. While these two families of frameworks vary in the level of intrusiveness into the existing code, they both offer access to essential functionalities such as I/O, parallelism, flexible spatial discretisation, remapping, and so on. In addition, the community has developed standardised interfaces between the components (see e.g. Polcher et al., 1998; Best et al., 2004). While this experience and these technologies ought to be exploited to build modular land system models, these frameworks do not consider the specific challenges in the land system and the hydrological cycle. In particular, linear interpolation applicable in the remapping in continua such as those of the atmosphere and of the ocean is problematic for the land continuum because of strong discontinuities on and below the ground. In addition, the spatial discretisations typically used in Earth System modelling frameworks lack meaning for the hydrological cycle. This is why a modular framework specific to the land system is required.

The increasing complexity of LSMs renders the monolithic structure they have today untenable for future development. However, the LSM community contributing to Earth System Models (ESMs) cannot adopt the coupling frameworks of the Earth surface dynamics community as they are not compatible with the complexity, parallelisation, and optimisation needs of ESMs; nor can it adopt highly modular hydrological modelling frameworks because their granularity is too fine for practical implementations with LSMs. An intermediate approach is thus needed for land system models where sub-components of the land system are defined with clear interfaces which can be implemented with current ESM couplers. This should introduce a granularity within LSMs similar to the one of current ESMs with only a few components (i.e. atmosphere, ocean, land, cryosphere, etc.).

In this manuscript, a standardised sub-division of the water cycle in the land system is introduced, and a framework implementing it is described. It follows an integrated coupling philosophy featuring three framework components interconnected through standardised interfaces. The current state of development does not yet meet all goals to be embedded in ESMs, but there is enough functionality for standalone use cases. The remainder of the manuscript is structured as follows: section 2 expands on its design principles and implementation details, section 3 showcases usage of the framework, section 4 details how to contribute to the framework with new science components, section 5 demonstrates the capabilities of the existing framework

on case studies, and finally section 6 provides some conclusions including the development directions which will be necessary to meet the goals of integration in Earth system models.

2 Description of the framework

2.1 Modular water cycle blueprint

90 Given the dominant spatial structures and temporal scales of the processes involved in the terrestrial water cycle, and the interconnected nature of the land system with the atmosphere and the ocean, a modular blueprint featuring three framework components is chosen (see Figure 1): a surface layer component encapsulating the dynamics of moisture and energy exchanges between the atmosphere and the Earth's surface, which are amongst the fastest processes in the terrestrial water cycle and predominantly uni-directional (i.e. vertical); a subsurface component to address the movement of water through the soil down to

95 the bedrock, which in comparison tends to be slower and truly tri-directional (i.e. lateral redistribution according to topographic and hydraulic head gradients, and vertical percolation/capillary rise/vegetation uptake); and an open water component for the movement of free water in contact with the atmosphere which is of intermediate speed and predominantly bi-directional along the surface of the Earth towards the seas and oceans. Despite this modularity, each component must be conservative with respect to the quantities in the continuity equations so that these are also conserved across the entire land system.

100 For existing modelling components to be coupled, outputs from one need to be mapped onto inputs for another: this requires a common bank of defined variables, i.e. an ontology, to guarantee that the output of one is semantically equivalent to the input of the other. Moreover, to maximise the chances of finding compatible models, this calls for a common interface between components that skilfully yet pragmatically subdivides the terrestrial water cycle continuum. Indeed, a compromise must be found between allowing flexibility in model construction and maximising the potential for existing models to be incorporated

105 in the framework. This is why the degrees of freedom offered to the user are intentionally limited and a standard interface between the components of the framework is formulated. This interface is a set of prescribed transfers of information between each pair of components in the blueprint. For instance, the open water component is receiving (i.e. inward transfers) 'direct throughfall flux', 'water evaporation flux from open water', 'surface runoff flux delivered to rivers', and 'net subsurface flux to rivers', while it is sending (i.e. outward transfers) 'open water area fraction' and 'open water surface height' (see Figure 1

110 and Table 1). These interfaces define the relationship between the framework components. They were designed considering the existing structure of land surface models, namely JULES (Best et al., 2011; Clark et al., 2011) and ORCHIDEE (Krinner et al., 2005), and are the fruit of considerable consultation. The information transferred through the interface includes the fluxes necessary to fulfil the continuity equations across the entire land system, as well as the diagnostic quantities characterising the state of components which necessarily condition fluxes in other components.
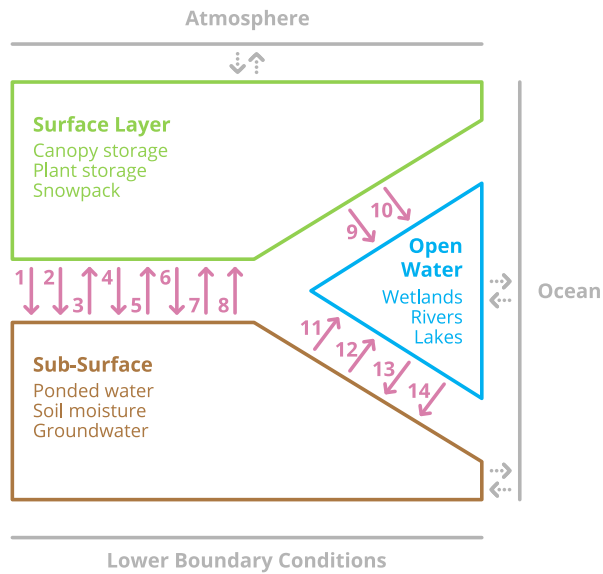
Figure 1. Schematic blueprint of the terrestrial water cycle featuring the three components 'Surface Layer', 'Sub-Surface', and 'Open Water', their transfers of information as numbered arrows (see Table 1), and their relationships with external models (atmosphere and ocean).

2.2   Integrated coupling approach

A first implementation of this blueprint is developed in Python (Hallouin and Ellis, 2021) as an integrated coupling framework following an object oriented approach (see Figure 2 for a visual overview of the software architecture using the Unified Modelling Language (UML)). Object oriented programming is ideally suited to efficiently implement such modular software: the inheritance of the core functionalities of a framework component allows for code reuse in the constitution of the various subdivisions of the water cycle, and ultimately the development of community-based component contributions. In this framework, three `Component` objects are coupled together by a `Model` object and executed concurrently, so that the order in which the components are called does not impact on the outcome of the simulation. The `Model` is responsible for the exchange of information between components, including their potential temporal accumulation and aggregation and/or their potential spatial remapping (using an `Exchanger` object), and is responsible for the time advancement of all components (using a `Clock` object).

The `Component` object provides infrastructure to support the science component; e.g. reading input (using `DataSet` objects), writing output (using `Record` and `RecordStream` objects), and state memory allocation (using `State` objects). The `Component` class itself is subclassed into the actual framework components represented by the `SurfaceLayerComponent`, `SubSurfaceComponent`, and `OpenWaterComponent` classes, which are used to enforce inward and outward transfers corresponding to the framework interfaces. Each accommodates the description of the physical processes of a given part of the terrestrial water cycle (i.e. the science component) following an initialise-run-finalise paradigm. `DataComponent` and

Table 1. Prescribed interface variables defining what must be transferred between the framework components.

#	Name	Unit
1	canopy_liquid_throughfall_and_snow_melt_flux	$\mathrm{kg\,m^{-2}\,s^{-1}}$
2	transpiration_flux_from_root_uptake	$\mathrm{kg\,m^{-2}\,s^{-1}}$
3	soil_water_stress_for_transpiration	1
4	direct_water_evaporation_flux_from_soil	$\mathrm{kg\,m^{-2}\,s^{-1}}$
5	soil_water_stress_for_direct_soil_evaporation	1
6	water_evaporation_flux_from_standing_water	$\mathrm{kg\,m^{-2}\,s^{-1}}$
7	standing_water_area_fraction[*]	1
8	total_water_area_fraction[*]	1
9	water_evaporation_flux_from_open_water	$\mathrm{kg\,m^{-2}\,s^{-1}}$
10	direct_throughfall_flux	$\mathrm{kg\,m^{-2}\,s^{-1}}$
11	surface_runoff_flux_delivered_to_rivers	$\mathrm{kg\,m^{-2}\,s^{-1}}$
12	net_groundwater_flux_to_rivers	$\mathrm{kg\,m^{-2}\,s^{-1}}$
13	open_water_area_fraction[*]	1
14	open_water_surface_height	m

[*] Standing and open water both refer to the water on the land surface in direct contact with the atmosphere, but the former corresponds to the ephemeral water on the land surface, while the latter corresponds to the water in rivers and lakes. Total water refers to the combination of standing and open water, taking into account any overlap between the two.

NullComponent classes are also provided as a convenience to allow any of the three framework components to be either replaced with appropriate data or removed. In both cases the replacement generates outward data transfers, in the former case, from data, in the latter case, zeros. Attempted inward data transfers are quietly ignored.

2.3 Flexible discretisation

The framework modularity makes it possible to resolve the processes in each science component at their own temporal and spatial resolutions. Each Component is discretised individually with its own instances of the TimeDomain and SpaceDomain classes defining their temporal and spatial discretisations, respectively.

In the framework, the TimeDomain class limits instances to temporal discretisations that are regularly-spaced. While each component could theoretically run on any temporal resolution independent of the resolution of the other components, it is essential to make sure that restarting times exist across the simulation period in case of unexpected interruption of the execution. In order to achieve this, the Clock object makes sure that the temporal resolutions are constrained such that, across the three components, the component temporal resolutions are required to be integer multiples of each other, and the component temporal extents to span the same simulation period. These temporal discretisations act as contracts signed between
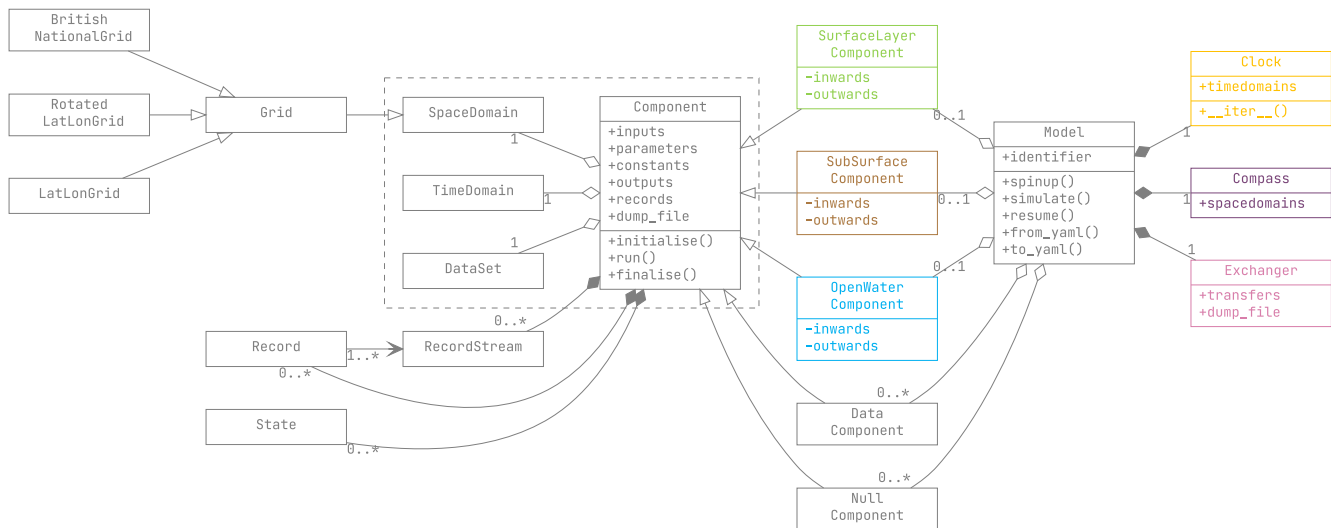
Figure 2. UML class diagram of the `unifhy` Python package.

145 the components and the framework to guarantee that the latter can orchestrate the simulation, but this does not need to preclude components from employing sub-time steps or adaptive time stepping schemes internally.

In the framework, the `SpaceDomain` class is subclassed into a `Grid`, intended to encompass all structured gridded spatial discretisations. The distinction between `SpaceDomain` and `Grid` is done in anticipation of additional subclasses to be created in the future (e.g. unstructured grids). The `Grid` class itself currently features three subclasses corresponding to

150 two discretisations on spherical coordinate systems (latitude-longitude and rotated-pole latitude-longitude) as well as one discretisation on a Cartesian (projected) coordinate system (the British national grid), but additional subclasses can easily be developed. Internal spatial remapping between differing component discretisations relies on the remapping functionality provided by ESMF (Collins et al., 2005). If components are to be resolved on different spatial discretisations, not only the components must conserve the quantities in the continuity equations, but the remapping operation must also be conservative.

155 Discontinuities being intrinsic to the land system, e.g. in land cover or soil properties, it appears unrealistic to directly apply traditional interpolation methods for the remapping since they assume continuity, whereas supermeshing techniques (Farrell et al., 2009), where a supermesh is the union of the components meshes, offer solutions to remain conservative in the remapping without the need for a continuity assumption. Since the current implementation of the framework does not yet feature an explicit supermeshing technique across the three components, the `Compass` object makes sure that components are discretised using

160 space domains of the same class (i.e. in the same coordinate system), that they span the same region, and that their spatial resolutions are encapsulated in one another, which effectively guarantees that for each pair of coupled components, one is the supermesh for both of them.

2.4 Open science library

Alongside the framework infrastructure itself, an initial library of open source science components complying with the standard framework interface is available. This allows users to explore alternative combination of components as alternative solutions to simulate the terrestrial water cycle.

Additional components can be exploited by the framework so long as they comply, or can be made to comply, with the framework interface via a particular Python class template (see Script 7).

Land system and hydrological modellers are encouraged to become contributors to the framework by sharing their science components with the rest of the community. These contributions can be implemented purely in Python, but can also rely on Fortran, C, or C++ programs called by interface middleware. Contributors need not handle basic functionalities such as memory allocation nor input/output operations, as these are handled by the framework. Ideally, the use of the framework will simplify model development allowing framework contributors to focus on scientific development (see section 4).

2.5 Meaningful data

The interface specification is effectively a data specification. To guarantee the unambiguous specification of that interface, as well as to bring to the framework and to users alike a full awareness of the physical meaning and spatio-temporal context of input and output data, the NetCDF Climate and Forecast (CF) Metadata Conventions (Eaton et al., 2020) are exploited in the framework. These conventions provide a robust guide for describing, processing, and sharing geophysical data files. They are used in a variety of applications, including for global model inter-comparison efforts such as CMIPs (e.g. Eyring et al., 2016). In particular, the CF standard names list provides the main ontology followed for the naming of the fields in the framework interfaces, although given it does not include some concepts relevant specifically for hydrology, some digression from this ontology exists in the framework until these concepts are submitted for inclusion in the CF standard names list.

The `DataSet` class responsible for providing each `Component` with input data relies on reading CF-NetCDF files. This enables the framework to check the compatibility between the data and the configured component, both physically and spatio-temporally. In addition, all record files and dump files are generated as CF-NetCDF files. Such CF-NetCDF files are processed with the package cf-python (Hassell et al., 2017; Hassell and Bartholomew, 2020).

3 Usage of the framework

This section describes a typical step-by-step user workflow through an example setup. The workflow can be sub-divided into a configuration stage and a simulation stage as illustrated on Figure 3. Each stage is described step-by-step in the two following sub-sections.
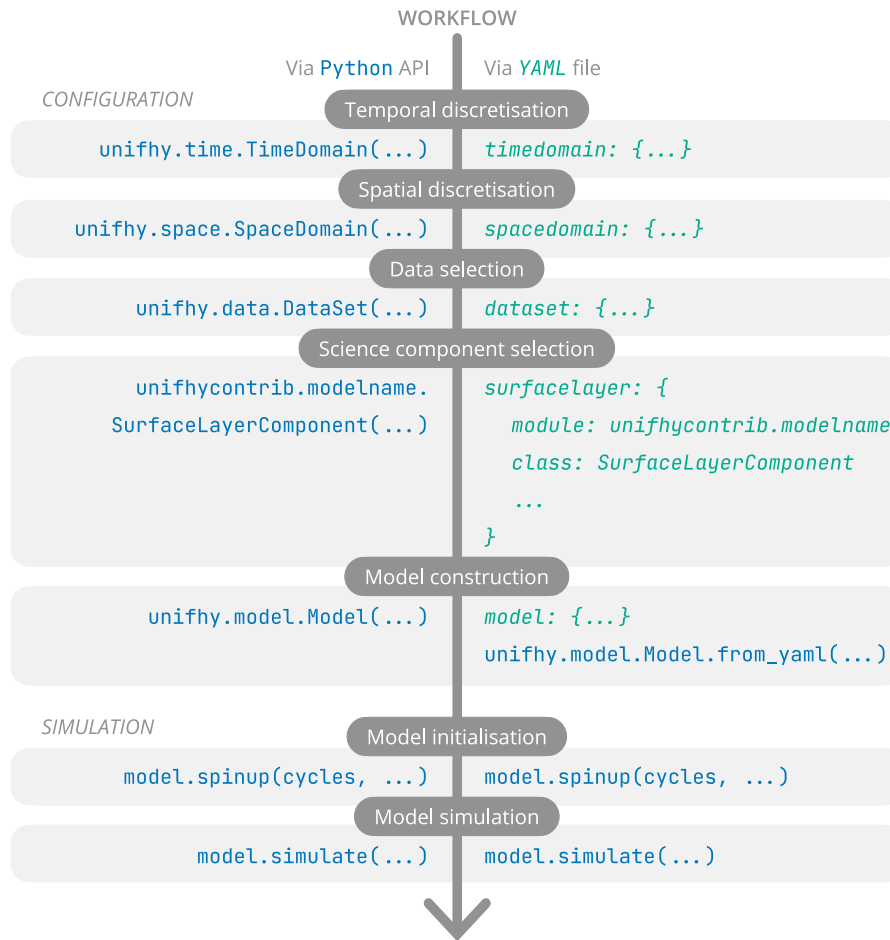
Figure 3. Workflow to follow to configure and use the modelling framework, exclusively via the Python API on the left-hand side, and via the use of a YAML file for configuration on the right-hand side.

3.1 Configuration

In this sub-section, the framework configuration workflow is presented. The user can configure the framework either using the Application Programming Interface (API) directly, or using an intermediate YAML (Yet Another Markup Language) configuration file (summarised on the right-hand side and on the left-hand side of Figure 3, respectively). These two configuration alternatives are presented in turn below.

3.1.1 Application Programming Interface

The first step in this workflow is to define the temporal and spatial discretisations. The user has to instantiate `TimeDomain` and `SpaceDomain` objects. The framework comes with a variety of constructor methods for these two objects, including

195

using existing CF-compliant data structures, e.g. `from_field`, or using the limits and spacing of the discretisation, e.g.
200 `from_start_end_step` for `TimeDomain` and `from_extent_and_resolution` for `SpaceDomain`. Examples
using the latter are presented in Script 1.

```
1   from unifhy.time import TimeDomain
2   from datetime import datetime, timedelta
3   from unifhy.space import LatLonGrid
4
5   td = TimeDomain.from_start_end_step(
6       start=datetime(2007, 1, 1, 0, 0, 0),
7       end=datetime(2017, 1, 1, 0, 0, 0),
8       step=timedelta(hours=1)
9   )
10
11  sd = LatLonGrid.from_extent_and_resolution(
12      latitude_extent=(49, 55),
13      latitude_resolution=0.5,
14      longitude_extent=(-11, 3),
15      longitude_resolution=0.5
16  )
```

Script 1. Example of temporal discretisation (to generate hourly timestepping), and spatial discretisation (to generate a regular 0.5° latitude-longitude grid) using the framework's API.

The second step consists in selecting the NetCDF files containing the input data. To do so, the user has to instantiate a
`DataSet` object (Script 2). These files must comply with the CF-conventions (subsection 2.5).

```
1   from unifhy.data import DataSet
2
3   ds = DataSet(
4       files=['file.nc'],
5       select='flow_accumulation'
6   )
```

Script 2. Example of data specification using the framework's API: selecting the "flow accumulation" variable from a CF-NetCDF file.

The third step, which completes the configuration of a `Component`, is to select a science component and to provide these three objects to it alongside values with units for the component parameters and constants (e.g. lines 3-12 in Script 3). Additionally, the user can select the variables to record for this component, whether component outward transfers and/or component outputs and/or component states with customisable temporal resolutions (multiples of its `TimeDomain` resolution) and summary statistics (mean, minimum, maximum, instantaneous) (e.g. lines 13-14 in Script 3). For example, in Script 3, the open water science component RFM, based on the RFM model (Bell et al., 2007; Dadson et al., 2011), is used and configured (note that the science components do not come with the framework and need to be installed separately). Instantiating a `Component` will be successful only if all the inputs, parameters, and constants required by the science component are provided and compatible in names, units, time and space dimensions with the component and its time and space domains.

```python
1  from unifhycontrib.rfm import OpenWaterComponent
2
3  ow = OpenWaterComponent(
4      timedomain=td,
5      spacedomain=sd,
6      dataset=ds,
7      saving_directory='.',
8      parameters={'c_land': [0.20, 'm s-1'], 'cb_land': [0.10, 'm s-1'],
9                  'c_river': [0.62, 'm s-1'], 'cb_river': [0.15, 'm s-1'],
10                 'ret_l': [0.20, '1'], 'ret_r': [0.10, '1'],
11                 'routing_length': [50000, 'm']},
12     constants={'a_thres': [1, '1']},
13     records={'outgoing_water_volume_transport_'
14              'along_river_channel': {timedelta(days=1): ['mean']}
15  )
```

Script 3. Example of component configuration using the framework's API: an open water component based on the RFM model is chosen; it is given the temporal and spatial discretisations instantiated before, as well as seven parameter values, one constant value; and it is requested to record one mean daily output.

The fourth and last step in the configuration workflow is to gather three components, one of each of the three types `SurfaceLayerComponent`, `SubSurfaceComponent`, and `OpenWaterComponent` to form a model. For example, in Script 4, the variables 'sl', 'ss', and 'ow' are instances of each, respectively, configured similarly to the example in Script 3. Note, the three components forming the model need to comply with the temporal and spatial discretisation constraints formulated in subsection 2.3 for the instantiation of a `Model` to be successful.

```
1   from unifhy.model import Model
2
3   md = Model(
4       identifier='example_run',
5       config_directory='.',
6       saving_directory='.',
7       surfacelayer=sl,
8       subsurface=ss,
9       openwater=ow
10  )
```

Script 4. Example of model configuration using the framework's API: a model is instantiated by combining three components previously configured (i.e. `sl`, `ss`, and `ow`; by giving it a unique identifier, and by specifying paths to configuration and saving directories.

3.1.2 Configuration file

An alternative to the API is the use of a configuration file written using the human-readable serialisation language YAML. This
220   provides both a more accessible configuration approach for users less comfortable with programming and a way to easily share configurations with other users. The complete configuration workflow presented above using the API can be formulated in a single YAML file. For reasons of brevity, only an equivalent for the third step above, i.e. configuring one component (Script 3), is presented in Configuration 1. Entire configuration files can be found in the Supplement.

Configuration files can then be loaded using the API to instantiate the `Model` directly (Script 5). Note, after the successful
225   instantiation of a `Model` using the API (i.e. Script 4), such a YAML file is automatically created in the configuration directory.

```
1   from unifhy.model import Model
2
3   md = Model.from_yaml('example_run.yml')
```

Script 5. Example using the framework's API to instantiate a Model from a YAML configuration file.

3.2 Simulation

A configured `Model` can then be used to start model spin-up cycle(s) and/or to start a simulation run over the entire simulation period specified in the time domains of the components (Script 6). The spin-up period can either be within or outside of the simulation period, so long as the datasets given to the components contain data for it.

```
1   openwater:
2     module: unifhycontrib.rfm
3     class: OpenWaterComponent
4     saving_directory: .
5     timedomain:
6       start: 2007-01-01 00:00:00
7       end: 2017-01-01 00:00:00
8       step: timedelta(hours=1)
9     spacedomain:
10      class: LatLonGrid
11      latitude_extent: [49, 55]
12      latitude_resolution: 0.5
13      longitude_extent: [-11, 3]
14      longitude_resolution: 0.5
15    dataset:
16      flow_accumulation:
17        files: [file.nc]
18        select: flow_accumulation
19    parameters:
20      c_land: [0.20, 'm s-1']
21      cb_land: [0.10, 'm s-1']
22      c_river: [0.62, 'm s-1']
23      cb_river: [0.15, 'm s-1']
24      ret_l: [0.20, '1']
25      ret_r: [0.10, '1']
26      routing_length: [50000, 'm']
27    constants:
28      a_thres: [1, '1']
29    records:
30      outgoing_water_volume_transport_along_river_channel:
31        timedelta(days=1): [mean]
```

Configuration 1. Excerpt from YAML configuration file semantically strictly equivalent to Script 3.

```
1   from datetime import datetime, timedelta
2
3   md.spin_up(start=datetime(2007, 1, 1, 0, 0, 0),
4              end=datetime(2008, 1, 1, 0, 0, 0),
5              cycles=3)
6
7   md.simulate(dumping_frequency=timedelta(days=100))
```

Script 6. Example using the framework's API to start simulations with a Model.

230   Both spin-up and simulation runs can produce dump files, i.e. files containing intermediate snapshots in the simulation period with all the information required to resume the simulation in case of an unexpected interruption. The user can specify a dumping frequency to choose how often such snapshots should be saved. Once the `Model` is re-instantiated using its configuration file created through Script 4, the simulation can be resumed using any snapshot in these dump files. Moreover, these files can be used to provide initial conditions for the component states in replacement or in addition to the spin-up cycles.

235   Note, detailed documentation is available online and accessible at unifhy-org.github.io/unifhy.

4   Contribution to the framework

If the science components already available in the open science library (subsection 2.4) are not sufficient or suitable for the needs of users, they have the opportunity to create their own. New science components for use in the framework must be developed as Python subclasses of the framework's internal `SurfaceLayerComponent`, `SubSurfaceComponent`, and

240   `OpenWaterComponent` classes.

    The approach to developing a science component is designed to require minimal development effort, and can be divided into five steps. The first step is to declare a Python class whose base class is one of the `SurfaceLayerComponent`, `SubSurfaceComponent`, or `OpenWaterComponent` classes (e.g. lines 1-3 in Script 7). The second step is to provide a description for the component using the docstring of the class (e.g. line 4 in Script 7). The third step is to declare the

245   component interface, i.e. to indicate which transfers in the standard interface are used and produced (e.g. lines 7-8 in Script 7). The fourth step is to define the component characteristics, including its inputs, parameters, constants, states, and outputs in their corresponding class attributes (e.g. lines 9-23 in Script 7). The fifth and last step is to implement the three class methods `initialise`, `run`, and `finalise` (e.g. lines 26-34 in Script 7, where the `pass` statements should be replaced by the actual implementation of these methods). This initialise-run-finalise (IRF) paradigm is based on the interfacing standards BMI

250   (Peckham et al., 2013; Hutton et al., 2020) and OpenMI (Harpham et al., 2019).

Thanks to their base class, they inherit the functionality that make them readily usable in the framework, as described in section 3, such that instances of newly created `Component` classes can then be directly created (following the same approach as in Script 4).

It is possible that, for existing models, the contributor may need to perform some refactoring of their source code, namely to comply with the framework interfaces and to comply with the initialise-run-finalise paradigm. While, the creation of a Python class is a requirement for use in the framework, the `initialise`, `run`, and `finalise` methods can call software which can be interfaced with Python, such as existing Fortran, C, or C++ programs. Contributors interested in interfacing C/C++ or Fortran methods are invited to take a look at the components used in the unit tests of the framework to get started.

Note that on a scientific level, there is no a priori restriction on the degree of complexity models must meet to be refactored into science components, only their compatibility with the framework standardised interface is expected. Nonetheless, Blyth et al. (2021) provides a good overview of the class of models primarily targeted.

A blank template is available on GitHub at unifhy-org/unifhycontrib-template to provide a starting point for contributors to package their new or existing models into framework compatible Python libraries, and contributors are invited to follow the step-by-step description on component contributions available in the online documentation.

5   Case studies using the framework

This section introduces case studies as demonstration and illustration material of the capabilities of the framework detailed above, i.e. allowing users to choose and configure various modelling components to simulate the terrestrial water cycle. The selected science components, their configurations in the framework, and the study catchments are presented before some outputs obtained with the framework are briefly presented and evaluated.

5.1   Selected science components

A selection of existing models have already been refactored into science components compatible with the framework. These include the Artemis (Dadson et al., 2021), RFM (Lewis and Hallouin, 2021), and SMART (Hallouin et al., 2021) models.

The Artemis model provides a simple runoff production model designed to be comparable with the runoff-production models typically embedded within climate models, which combines Penman-Monteith evaporation (Monteith, 1965) with Rutter-Gash canopy interception (Gash, 1979), TOPMODEL runoff production (Clark and Gedney, 2008), and a degree-day-based snow accumulation and melting model (Moore et al., 1999; Hock, 2003; Beven, 2012). The River Flow Model (RFM) is a runoff routing model based on a discrete approximation of the one-directional kinematic wave with lateral inflow (Bell et al., 2007; Dadson et al., 2011). The Soil Moisture Accounting and Routing for Transport (SMART) model is a bucket-style rainfall-runoff model based on the soil layers concept (Mockler et al., 2016).

Note, the Artemis and RFM model parameters are not optimised, while the SMART model parameters are optimised for each catchment separately using a standalone version of the model (Hallouin et al., 2019) and selecting the best performing parameter set from a Latin Hypercube Sampling (McKay et al., 2000) of 10^6 parameter sets, using a subset for the period

```python
1    import unifhy
2
3    class SurfaceLayerComponent(unifhy.component.SurfaceLayerComponent):
4        """Component description"""
5
6        # Component definition
7        _inwards = {'inward_name'}
8        _outwards = {'outward_name'}
9        _inputs_info = {
10           'input_name': {'units' : '',  'kind': ''}
11       }
12       _parameters_info = {
13           'parameter_name': {'units' : '', 'valid_range': [0., 1.]}
14       }
15       _constants_info = {
16           'constant_name': {'units' : '',  'default_value': 1.}
17       }
18       _states_info = {
19           'state_name': {'units' : ''}
20       }
21       _outputs_info = {
22           'output_name': {'units' : ''}
23       }
24
25       # Component implementation
26       def initialise(self, input_name, parameter_name, constant_name, state_name, **kwargs):
27           pass
28
29       def run(self, inward_name, input_name, parameter_name,
30               constant_name, state_name, **kwargs):
31           pass
32
33       def finalise(self, parameter_name, constant_name, state_name, **kwargs):
34           pass
```

Script 7. Template to follow to develop a new science component contribution presented through an example with a fictional surface layer component whose definition and implementation are kept intentionally generic and trivial, respectively.

1998-2007 of the driving and observational data used by Smith et al. (2019), and the modified Kling-Gupta Efficiency (Kling et al., 2012) as objective function.

5.2 Selected configurations

The capabilities of the framework are demonstrated through three different configurations summarised in Table 2.

The first configuration puts the Artemis and the RFM models together to form a simple land system model. It demonstrates the flexibility in the temporal and the spatial resolutions of the various components. Indeed, the surface layer and the subsurface components are taken from the Artemis model and configured to run at an hourly timestep on a 0.5 degree resolution latitude-longitude grid, while the open water component from RFM is used and configured to run at 15-minute intervals on a 0.5/60 (~0.008) degree resolution on a latitude-longitude grid.

The second configuration demonstrates the possibility to replace science components with datasets. To do so, the surface and subsurface runoff outputs from the JULES model (Best et al., 2011; Clark et al., 2011) available in the CHESS-land dataset (Martínez-de la Torre et al., 2018) are put together as a `DataComponent` and used in place of the subsurface component, which is then coupled with the open water component of the RFM model, both on a 1 kilometre resolution on the British National grid. The surface layer component is removed by setting it as a `NullComponent`.

The third and last configuration puts together the Artemis and SMART models. It demonstrates the possibility to substitute parts of an existing model (i.e. SMART) with parts from another model (i.e. Artemis) and explore the impacts on the model performance. The SMART model is a rainfall-runoff model for application to hydrologically meaningful spatial elements (e.g. catchments, sub-basins), for which the existing gridded space domains are irrelevant. However, the model can be run on a single spatial element assumed to represent the whole catchment until more complex geometries are supported in the framework.

Note, the details of the three configurations are available as YAML configuration files in the Supplement.

5.3 Selected study catchments

The three configurations are applied to three British catchments, selected to explore the capabilities of the framework: the upper Severn catchment predominantly located in Wales, the Ouse catchment located in North East England, and the Tay catchment located in East Scotland (see Figure 4). These three catchments cover a range of climatological, topographical and geological settings. Their base flow indices (BFI) are 0.53, 0.39, and 0.64, respectively (Boorman et al., 1995). The three configurations applied to these three study catchments form nine case studies. The simulation period considered is 2008-2017.

5.4 Results

Figure 5 showcases the river discharge simulated with the three framework configurations described above, focussing on the river discharge at the catchment outlet in the line plots (a, c, e), and the spatial distribution of river discharge at the end of the simulation in the gridded plots (b, d). For reasons of brevity, only the Tay catchment is shown in the main text, figures for the other two study catchments are available in Appendix B. These figures confirm qualitatively the plausibility of the

Table 2. Framework configurations.

Framework Component	Science Component	TimeDomain	SpaceDomain	DataSet[1]
Configuration 1: running a simple land system model				
SurfaceLayerComponent	Artemis	Hourly	WGS84 0.5 degree	ERA5
SubSurfaceComponent	Artemis	Hourly	WGS84 0.5 degree	ERA5
OpenWaterComponent	RFM	15 minutes	WGS84 ~0.008 degree	HydroSHEDS
Configuration 2: routing previously simulated runoff				
SurfaceLayerComponent	NullComponent	–	–	–
SubSurfaceComponent	DataComponent	Daily	OSGB 1 km	CHESS-land
OpenWaterComponent	RFM	15 minutes	OSGB 1 km	CHESS-land
Configuration 3: adding explicit surface evaporation processes in a rainfall-runoff model				
SurfaceLayerComponent	Artemis	Hourly	WGS84 0.5 degree	ERA5
SubSurfaceComponent	SMART	Hourly	Catchment (one grid cell)	–
OpenWaterComponent	SMART	Hourly	Catchment (one grid cell)	–

[1] See Appendix A for more details on data sources.

framework simulations. Indeed, the overlaid hydrographs suggest that the overall observed discharge pattern is captured by the simulations, while the spatial distributions of river discharge sketch a realistic picture of the catchment river network.

In addition, a quantitative evaluation of the performance of the framework simulations is done with respect to the river discharge at the catchment outlet where observed and simulated time series are compared using the non-parametric Kling-Gupta efficiency (R_{NP}). This is a composite metric made of three equally-weighted components r_S, α_{NP}, and β, assessing the agreement in the dynamics (i.e. correlation), the variability, and the volume (i.e. bias) of the discharge time series, respectively (Pool et al., 2018). Table 3 features these metric components computed for the three configurations and the three study catchments using the Python package `hydroeval` (Hallouin, 2021).

The comparative performance of the three configurations for each catchment in turn informs the most suitable combination of components for a given temporal and geographical context. For instance, the third configuration appears to be the most suitable in the Tay catchment, if one is solely interested in simulating the river discharge accurately (R_{NP} of 0.766), while the second configuration would be preferred for the Ouse and Severn catchments (R_{NP} of 0.674 and 0.706, respectively). However, these conclusions are metric-dependent and the analysis of the components of the composite metric can reveal the strengths and weaknesses of a given configuration, e.g. while the third configuration performs highest on the composite metric in the Tay catchment, its ranking on capturing the flow variability is the lowest of the three configurations (α_{NP} of 0.940).
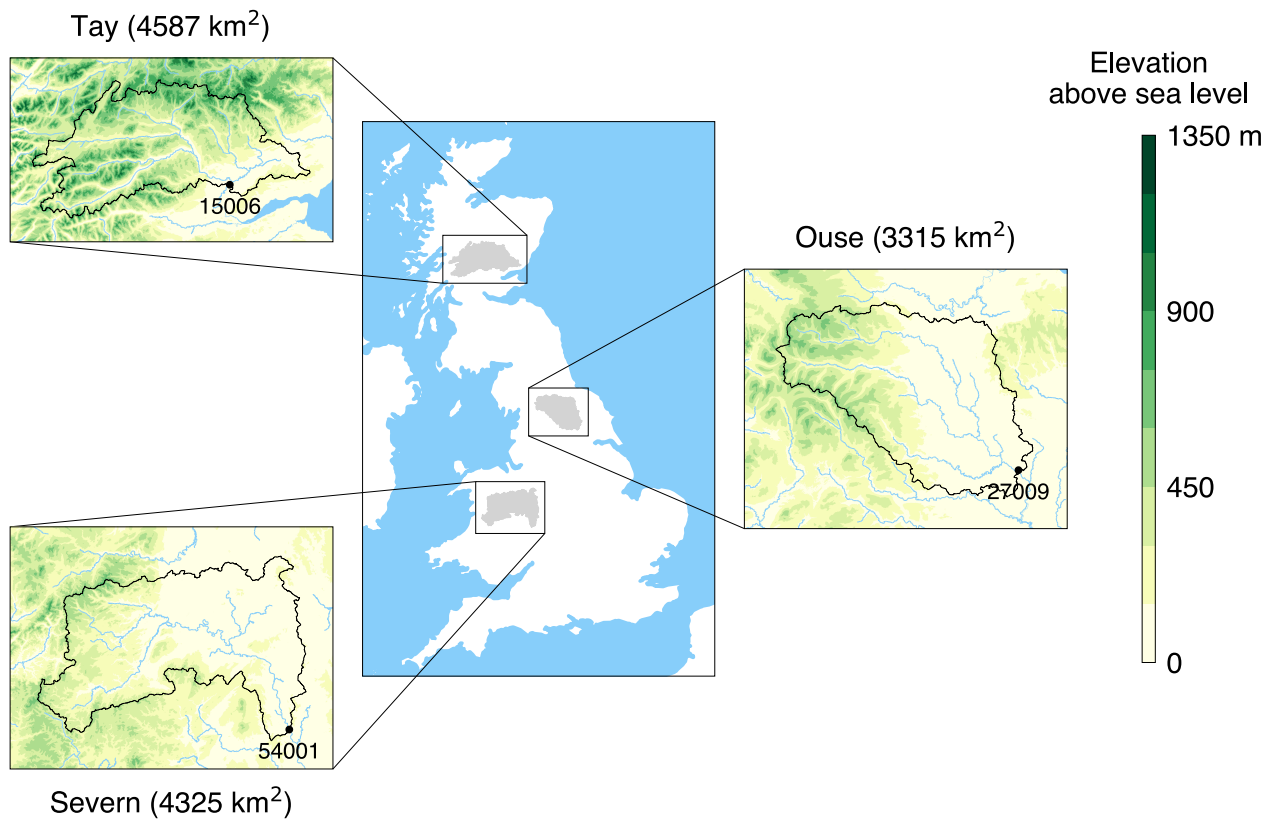
Figure 4. Location of the three study catchments in Great Britain. In the zoomed-in panels, the dots correspond to the outlets of the catchments and their adjoining five-digit labels correspond to the number of the National River Flow Archive (NRFA) hydrometric stations at these outlets. The elevation is based on digital spatial data licensed from the UK Centre for Ecology & Hydrology, ©UKCEH (Morris and Flavin, 1990, 1994).

Some caveats in this comparison are that the third configuration used a calibrated model unlike the first and second configurations, and the second configuration used data from a model constrained to conserve mass and energy, unlike the other configurations that only conserve mass. This likely skews the comparison.

This brief analysis of the results is used to demonstrate the potential of the framework to compare alternative combinations of components to simulate the hydrological behaviour for a given region and a given objective; it is not to draw definitive conclusions as to which combinations should be used for the catchments selected here, and more components than those presented in this manuscript can be developed and used in the framework. Moreover, this analysis focuses on one hydrological variable, the river discharge, but other hydrological variables such as e.g. soil moisture or evaporation could also be considered.
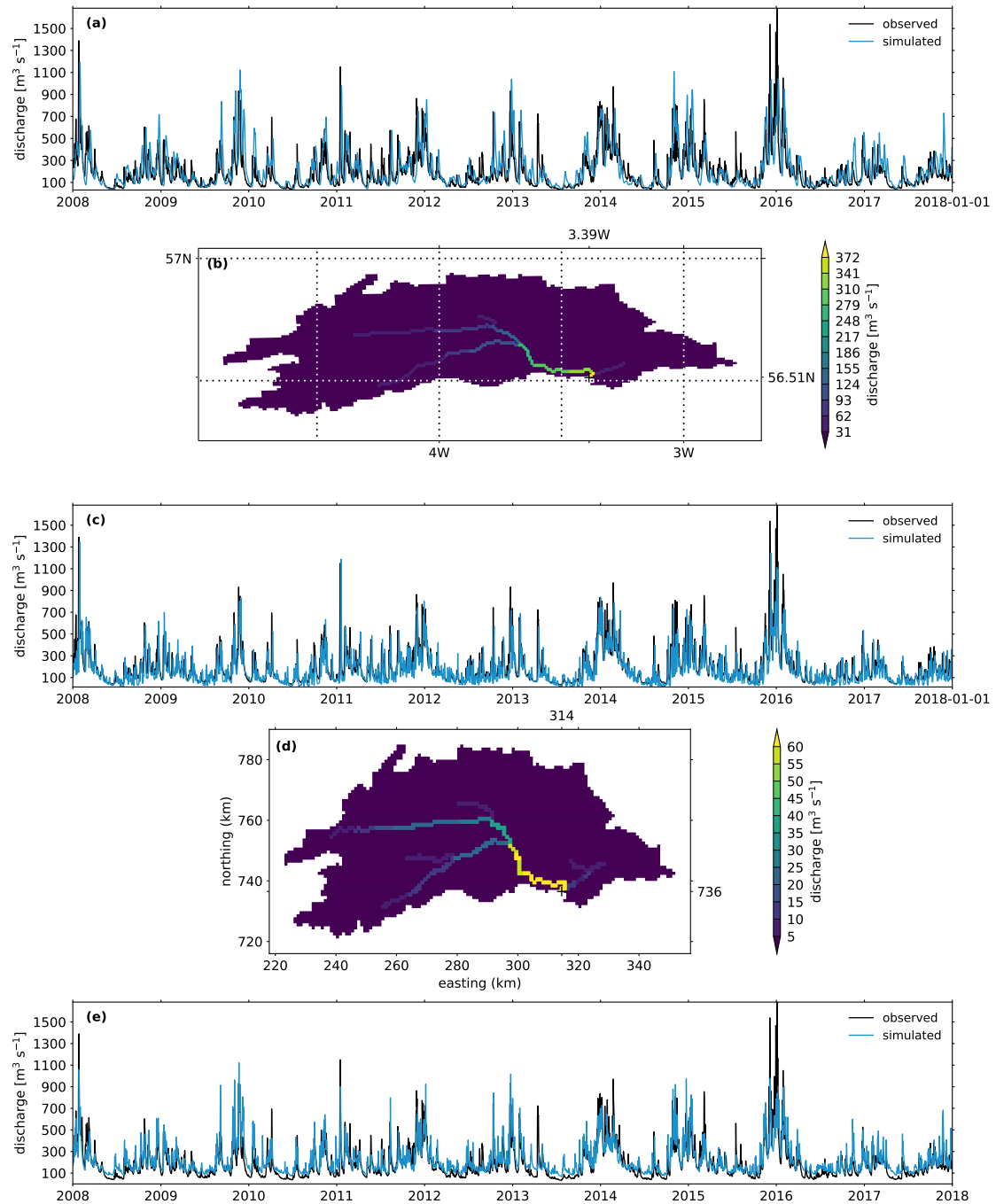
Figure 5. Simulation of the river discharge with the three configurations for the Tay catchment: **(a)** observed and simulated hydrographs with configuration 1 at the catchment outlet [3.39 °W, 56.51 °N], **(b)** gridded simulated discharge with configuration 1 for the last simulation step [2018-01-01], **(c)** observed and simulated hydrographs with configuration 2 at the catchment outlet [314, 736], **(d)** gridded simulated discharge with configuration 2 for the last simulation step [2018-01-01], **(e)** observed and simulated hydrographs with configuration 3 at the catchment outlet.

Table 3. Quantitative comparison of the three configurations for the three study catchments.

Catchment	Configuration	Performance metrics			
		R_{NP}	r_S	α_{NP}	β
Tay	1	0.667	0.692	0.981	1.126
	2	0.743	0.773	0.979	0.881
	3	0.766	0.821	0.940	1.139
Ouse	1	0.456	0.614	0.870	1.361
	2	0.674	0.705	0.945	0.875
	3	0.493	0.790	0.882	1.447
Severn	1	0.495	0.721	0.909	1.411
	2	0.706	0.719	0.946	0.933
	3	0.218	0.840	0.926	1.762

6 Conclusions

The framework presented in this manuscript, UniFHy, represents the first implementation of a new modular blueprint to model the terrestrial water cycle. It is open source and comes with extended online documentation. By design, this Python package is intended to be easy to use, with a low entry bar for people with little programming experience. Indeed, installing a Python package is straightforward and only a few steps in a Python script are needed to set up and run a complete model in a Jupyter notebook, which is likely to prove useful for teaching and training activities alike. It is also intended to be easily customisable, through choosing from a library of compatible science components those most suitable for a given modelling context. Finally, it is intended to be easily extensible by creating new components, which should streamline the development and sharing of new science for the terrestrial water cycle.

In comparison to other hydrological and land surface modelling frameworks, this framework consciously reduces the degrees of freedom offered to the model developers in view to maximise the potential for reusability of their contributions with the other interested modelling communities. Indeed, unlike highly granular frameworks such as SUMMA or Raven, UniFHy prescribes the level of granularity to three modelling components, much like in Earth System modelling frameworks such as ESMF or OASIS-MCT. In addition, unlike other component-based modelling frameworks such as PyMT or LandLab, UniFHy prescribes the information to be exchanged between modelling components through its standardised interfaces. In addition, it controls the time advancement and the state memory allocation for the user which will be a crucial advantage when it is coupled in Earth System models. Nonetheless, UniFHy should directly be able to benefit from existing modelling environments such as LandLab, FUSE, or SUPERFLEX to develop modelling components.

In order to become the future of land components and improve the coarse-grained concurrency of Earth system models (Balaji et al., 2016; Lawrence et al., 2018), later versions of the framework will technically require the implementation of additional functionalities including: implicit spatial heterogeneity such as tiling schemes (see e.g. nine surface types in JULES

(Best et al., 2011; Clark et al., 2011)) and hydrologically connected units (see e.g. flow matrix of TOPMODEL (Beven and Freer, 2001) in use in HydroBlocks (Chaney et al., 2016), intra-hillslope configuration in CLM (Swenson et al., 2019), unit-to-

360 unit routing in ORCHIDEE (Nguyen-Quang et al., 2018)); unstructured spatial meshes already in use in atmospheric models (see e.g. reduced grids in ECMWF's IFS model (Hortal and Simmons, 1991)), icosahedral grids as in DWD's ICON model (Zängl et al., 2015) or IPSL's DYNAMICO core (Dubos et al., 2015), or cubed spheres as in UK Met Office's LFRic model (Adams et al., 2019), or NOAA's FV3 model (Putman and Lin, 2007)); task and domain decomposition for parallel execution (such as in ESMF (Collins et al., 2005), OASIS-MCT (Valcke, 2013; Craig et al., 2017), or CPL7 (Craig et al., 2012)); and

365 expose interfaces for coupling with external models (atmosphere and ocean). In addition, later versions of the framework will scientifically require to extend the blueprint to include other biogeochemical cycles (e.g. carbon, nitrogen, phosphorus) as well as anthropogenic influences.

In the meantime, we hope that the science library will grow with new contributions from the land, hydrology, and groundwater modelling communities, and stimulate collaborations between them.

370 *Code availability.* The framework is open source and available on Zenodo (Hallouin and Ellis, 2021). The science components are also open source and available on Zenodo, i.e. Artemis (Dadson et al., 2021), RFM (Lewis and Hallouin, 2021), and SMART (Hallouin et al., 2021). The online documentation is accessible at https://unifhy-org.github.io/unifhy.

Data availability. The input data used in the case studies is publicly available using the references provided in Appendix A. The observed river flow data is publicly available from NRFA (http://nrfa.ceh.ac.uk/, last access: 10 October 2021). The framework output data is available

375 upon request from the corresponding author.

Appendix A: Data sources

Table A1. Sources for data used in configuration 1.

Variable name	Dataset name	Data DOI	Related publications
precipitation flux	ERA5	10.24381/cds.20d54e34	Cucchi et al. (2020)
specific humidity			
surface downwelling shortwave flux in air			
surface downwelling longwave flux in air			
air temperature			
wind speed			
surface albedo[1]	–	–	–
vegetation height	GLAS	–	Los et al. (2012)
leaf area index	MOD15A2H	10.5067/MODIS/ MOD15A2H.006	–
topmodel saturation capacity	HWSD	–	Nachtergaele et al. (2012)
saturated hydraulic conductivity			
topographic index	–	–	Marthews et al. (2015)
flow direction	HydroSHEDS	–	Lehner et al. (2008);
flow accumulation			Lehner and Grill (2013)

[1] Produced using suite u-ag343 accessible at https://code.metoffice.gov.uk/trac/roses-u.

Table A2. Sources for data used in configuration 2.

Variable name	Dataset name	Data DOI	Related publications
surface runoff flux delivered to rivers	CHESS-land	10.5285/c76096d6-45d4-4a69-a310-4c67f8dcf096	Martínez-de la Torre et al. (2018)
net groundwater flux to rivers			
flow direction	–	–	Davies and Bell (2009);
flow accumulation			Martínez-de la Torre et al. (2019)

Table A3. Sources for data used in configuration 3.

Variable name	Dataset name	Data DOI	Related publications
precipitation flux	ERA5	10.24381/cds.20d54e34	Cucchi et al. (2020)
specific humidity			
surface downwelling shortwave flux in air			
surface downwelling longwave flux in air			
air temperature			
wind speed			
surface albedo[1]	–	–	–
vegetation height	GLAS	–	Los et al. (2012)
leaf area index	MOD15A2H	10.5067/MODIS/ MOD15A2H.006	–

[1] Produced using suite u-ag343 accessible at https://code.metoffice.gov.uk/trac/roses-u.

Appendix B: Additional results

Author contributions. All co-authors designed the blueprint for the framework. TH and RJE developed the framework implementation in Python. TH performed the simulations. TH and RJE processed the simulation outputs. TH prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interests.

Acknowledgements. This work was funded by the Natural Environment Research Council (NERC) as part of the Hydro-JULES programme (NE/S017380/1). AGH publishes with the permission of the Executive Director, British Geological Survey.

The authors would like to thank the developers of `cf-python`, David Hassell and Sadie Bartholomew, for implementing the requested features required by the framework, and Andy Heaps for the `cf-plot` support. They would also like to thank Katie Facer-Childs for providing the rainfall and potential evapotranspiration data used to calibrate the SMART model, Helen Davies for providing the HydroSHEDS dataset, and Huw Lewis for providing a Python version of RFM used to create an open water component for use in the framework.

The authors also thank the editor and the reviewers for their valuable comments and suggestions that contributed to improving the manuscript.
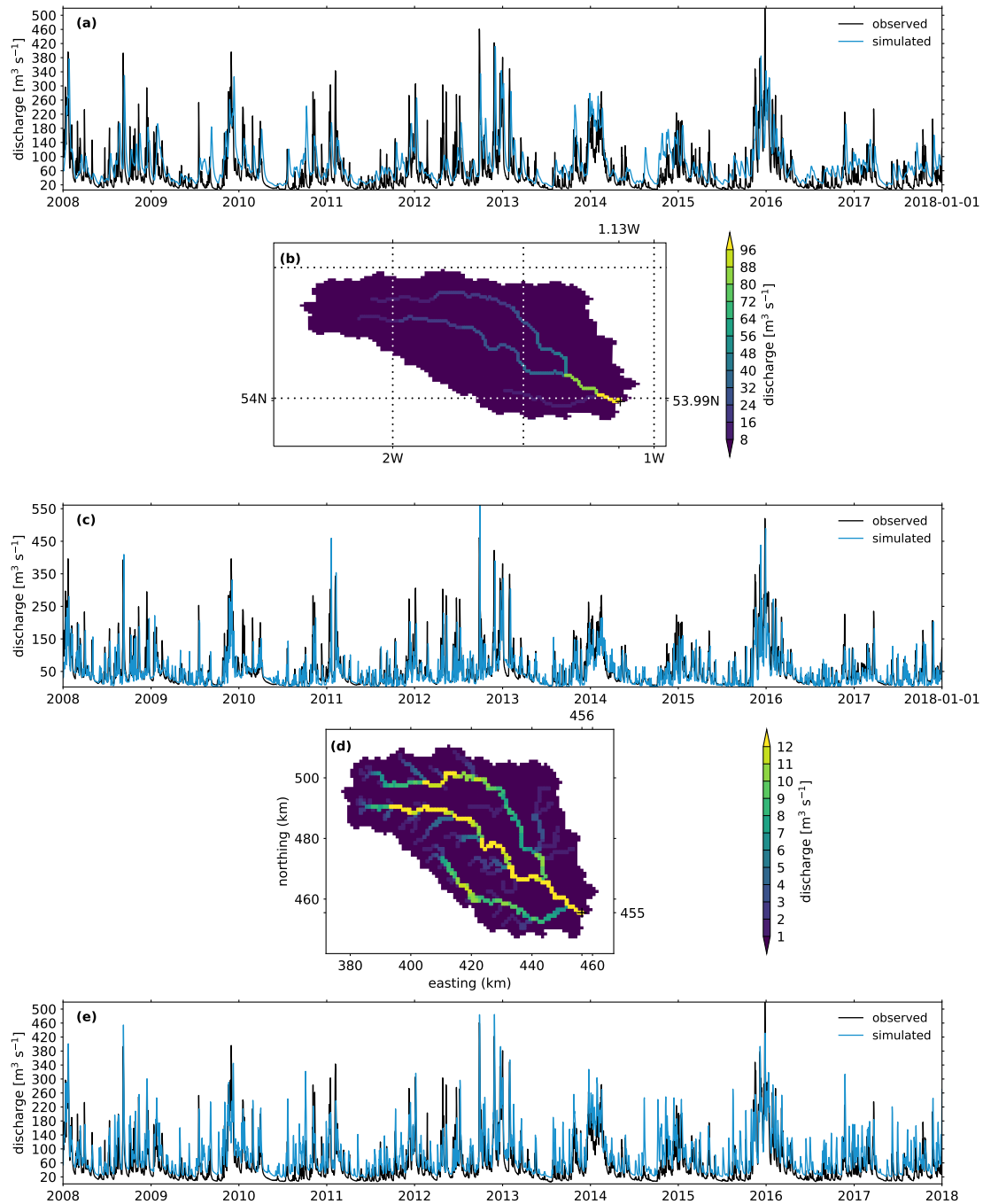
Figure B1. Simulation of the river discharge with the three configurations for the Ouse catchment: **(a)** observed and simulated hydrographs with configuration 1 at the catchment outlet [1.13 °W, 53.99 °N], **(b)** gridded simulated discharge with configuration 1 for the last simulation step [2018-01-01], **(c)** observed and simulated hydrographs with configuration 2 at the catchment outlet [456, 455], **(d)** gridded simulated discharge with configuration 2 for the last simulation step [2018-01-01], **(e)** observed and simulated hydrographs with configuration 3 at the catchment outlet.
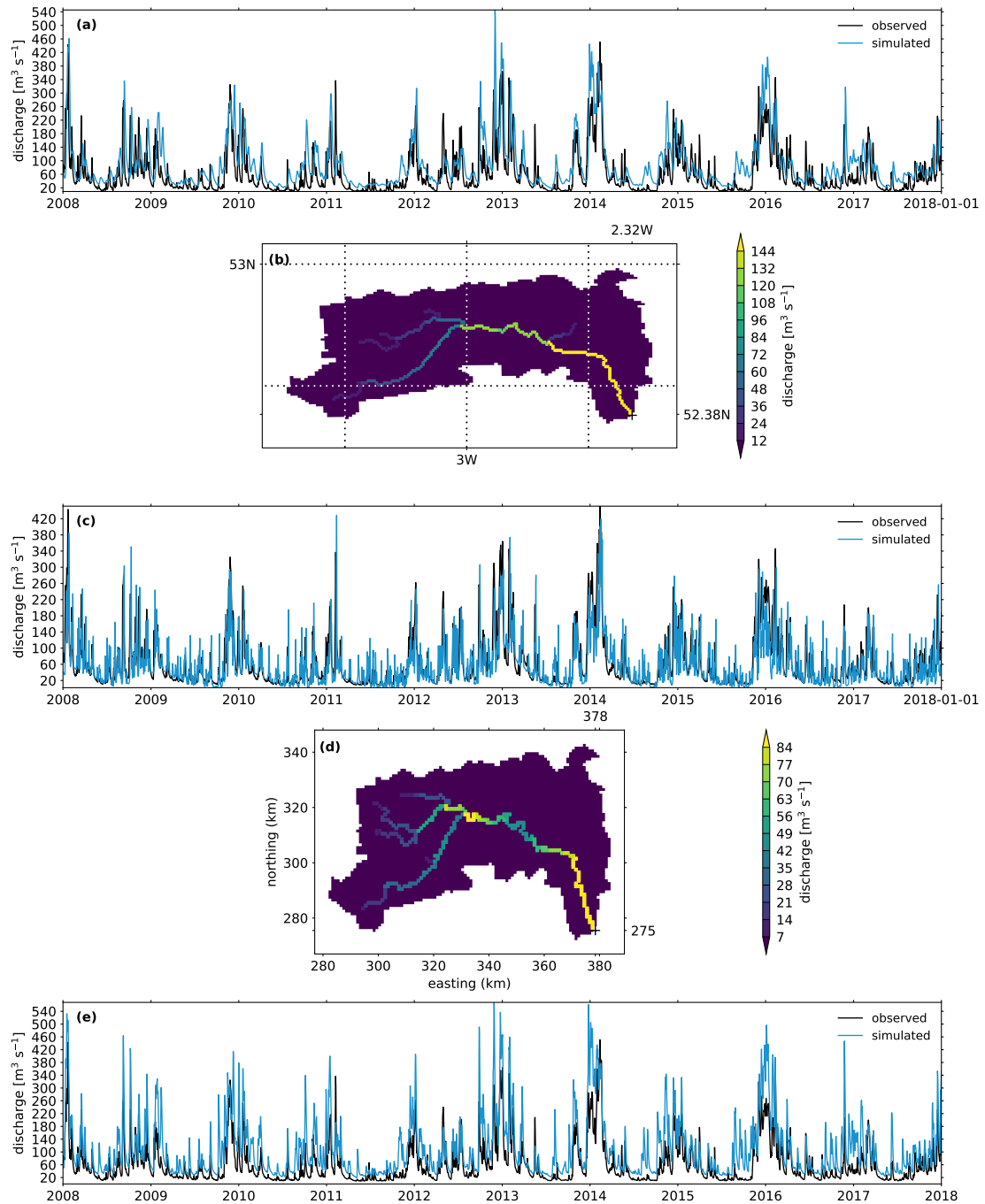
Figure B2. Simulation of the river discharge with the three configurations for the Severn catchment: **(a)** observed and simulated hydrographs with configuration 1 at the catchment outlet [2.32 °W, 52.38 °N], **(b)** gridded simulated discharge with configuration 1 for the last simulation step [2018-01-01], **(c)** observed and simulated hydrographs with configuration 2 at the catchment outlet [378, 275], **(d)** gridded simulated discharge with configuration 2 for the last simulation step [2018-01-01], **(e)** observed and simulated hydrographs with configuration 3 at the catchment outlet.

References

Adams, S., Ford, R., Hambley, M., Hobson, J., Kavčič, I., Maynard, C., Melvin, T., Müller, E., Mullerworth, S., Porter, A., Rezny, M., Shipway, B., and Wong, R.: LFRic: Meeting the challenges of scalability and performance portability in Weather and Climate models, Journal of Parallel and Distributed Computing, 132, 383–396, https://doi.org/https://doi.org/10.1016/j.jpdc.2019.02.007, 2019.

Balaji, V., Benson, R., Wyman, B., and Held, I.: Coarse-grained component concurrency in Earth system modeling: parallelizing atmospheric radiative transfer in the GFDL AM3 model using the Flexible Modeling System coupling framework, Geoscientific Model Development, 9, 3605–3616, https://doi.org/10.5194/gmd-9-3605-2016, 2016.

Barnhart, K. R., Hutton, E. W. H., Tucker, G. E., Gasparini, N. M., Istanbulluoglu, E., Hobley, D. E. J., Lyons, N. J., Mouchene, M., Nudurupati, S. S., Adams, J. M., and Bandaragoda, C.: Short communication: Landlab v2.0: a software package for Earth surface dynamics, Earth Surface Dynamics, 8, 379–397, https://doi.org/10.5194/esurf-8-379-2020, 2020.

Bell, V. A., Kay, A. L., Jones, R. G., and Moore, R. J.: Development of a high resolution grid-based river flow model for use with regional climate model output, Hydrology and Earth System Sciences, 11, 532–549, https://doi.org/10.5194/hess-11-532-2007, 2007.

Best, M. J., Beljaars, A., Polcher, J., and Viterbo, P.: A Proposed Structure for Coupling Tiled Surfaces with the Planetary Boundary Layer, Journal of Hydrometeorology, 5, 1271 – 1278, https://doi.org/10.1175/JHM-382.1, 2004.

Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., Essery, R. L. H., Ménard, C. B., Edwards, J. M., Hendry, M. A., Porson, A., Gedney, N., Mercado, L. M., Sitch, S., Blyth, E., Boucher, O., Cox, P. M., Grimmond, C. S. B., and Harding, R. J.: The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes, Geoscientific Model Development, 4, 677–699, https://doi.org/10.5194/gmd-4-677-2011, 2011.

Betts, A. K., Ball, J. H., Beljaars, A. C. M., Miller, M. J., and Viterbo, P. A.: The land surface-atmosphere interaction: A review based on observational and global modeling perspectives, Journal of Geophysical Research: Atmospheres, 101, 7209–7225, https://doi.org/10.1029/95JD02135, 1996.

Beven, K.: Rainfall-Runoff Modelling: The Primer, vol. 3204, Wiley-Blackwell, 2nd ed. edn., https://doi.org/10.1002/9781119951001, 2012.

Beven, K. and Freer, J.: A dynamic TOPMODEL, Hydrological Processes, 15, 1993–2011, https://doi.org/10.1002/hyp.252, 2001.

Blyth, E. M., Arora, V. K., Clark, D. B., Dadson, S. J., De Kauwe, M. G., Lawrence, D. M., Melton, J. R., Pongratz, J., Turton, R. H., Yoshimura, K., and Yuan, H.: Advances in Land Surface Modelling, Current Climate Change Reports, 7, 45–71, https://doi.org/10.1007/s40641-021-00171-5, 2021.

Boorman, D. B., Hollis, J. M., and Lilly, A.: Hydrology of soil types: a hydrologically-based classification of the soils of United Kingdom, Institute of Hydrology, Wallingford, 1995.

Chaney, N. W., Metcalfe, P., and Wood, E. F.: HydroBlocks: a field-scale resolving land surface model for application over continental extents, Hydrological Processes, 30, 3543–3559, https://doi.org/10.1002/hyp.10891, 2016.

Clark, D. B. and Gedney, N.: Representing the effects of subgrid variability of soil moisture on runoff generation in a land surface model, Journal of Geophysical Research: Atmospheres, 113, https://doi.org/10.1029/2007JD008940, 2008.

Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., Pryor, M., Rooney, G. G., Essery, R. L. H., Blyth, E., Boucher, O., Harding, R. J., Huntingford, C., and Cox, P. M.: The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics, Geoscientific Model Development, 4, 701–722, https://doi.org/10.5194/gmd-4-701-2011, 2011.

425   Clark, M. P., Slater, A. G., Rupp, D. E., Woods, R. A., Vrugt, J. A., Gupta, H. V., Wagener, T., and Hay, L. E.: Framework for Understanding Structural Errors (FUSE): A modular framework to diagnose differences between hydrological models, Water Resources Research, 44, https://doi.org/10.1029/2007WR006735, 2008.

Clark, M. P., Fan, Y., Lawrence, D. M., Adam, J. C., Bolster, D., Gochis, D. J., Hooper, R. P., Kumar, M., Leung, L. R., Mackay, D. S., Maxwell, R. M., Shen, C., Swenson, S. C., and Zeng, X.: Improving the representation of hydrologic processes in Earth System Models,
430   Water Resources Research, 51, 5929–5956, https://doi.org/10.1002/2015WR017096, 2015a.

Clark, M. P., Nijssen, B., Lundquist, J. D., Kavetski, D., Rupp, D. E., Woods, R. A., Freer, J. E., Gutmann, E. D., Wood, A. W., Brekke, L. D., Arnold, J. R., Gochis, D. J., and Rasmussen, R. M.: A unified approach for process-based hydrologic modeling: 1. Modeling concept, Water Resources Research, 51, 2498–2514, https://doi.org/10.1002/2015WR017198, 2015b.

Collins, N., Theurich, G., DeLuca, C., Suarez, M., Trayanov, A., Balaji, V., Li, P., Yang, W., Hill, C., and da Silva, A.: Design and Implemen-
435   tation of Components in the Earth System Modeling Framework, The International Journal of High Performance Computing Applications, 19, 341–350, https://doi.org/10.1177/1094342005056120, 2005.

Craig, A., Valcke, S., and Coquart, L.: Development and performance of a new version of the OASIS coupler, OASIS3-MCT_3.0, Geoscientific Model Development, 10, 3297–3308, https://doi.org/10.5194/gmd-10-3297-2017, 2017.

Craig, A. P., Vertenstein, M., and Jacob, R.: A new flexible coupler for earth system modeling developed for CCSM4 and CESM1, The
440   International Journal of High Performance Computing Applications, 26, 31–42, https://doi.org/10.1177/1094342011428141, 2012.

Craig, J. R., Brown, G., Chlumsky, R., Jenkinson, R. W., Jost, G., Lee, K., Mai, J., Serrer, M., Sgro, N., Shafii, M., Snowdon, A. P., and Tolson, B. A.: Flexible watershed simulation with the Raven hydrological modelling framework, Environmental Modelling & Software, 129, 104 728, https://doi.org/10.1016/j.envsoft.2020.104728, 2020.

Cucchi, M., Weedon, G. P., Amici, A., Bellouin, N., Lange, S., Müller Schmied, H., Hersbach, H., and Buontempo, C.: WFDE5: bias-adjusted
445   ERA5 reanalysis data for impact studies, Earth System Science Data, 12, 2097–2120, https://doi.org/10.5194/essd-12-2097-2020, 2020.

Dadson, S., Bell, V., and Jones, R.: Evaluation of a grid-based river flow model configured for use in a regional climate model, Journal of Hydrology, 411, 238–250, https://doi.org/10.1016/j.jhydrol.2011.10.002, 2011.

Dadson, S. J., Hallouin, T., and Ellis, R.: unifhycontrib-artemis, https://doi.org/10.5281/zenodo.6560408, 2021.

Davies, H. N. and Bell, V. A.: Assessment of methods for extracting low-resolution river networks from high-resolution digital data, Hydro-
450   logical Sciences Journal, 54, 17–28, https://doi.org/10.1623/hysj.54.1.17, 2009.

Dubos, T., Dubey, S., Tort, M., Mittal, R., Meurdesoif, Y., and Hourdin, F.: DYNAMICO-1.0, an icosahedral hydrostatic dynamical core designed for consistency and versatility, Geoscientific Model Development, 8, 3131–3150, https://doi.org/10.5194/gmd-8-3131-2015, 2015.

Eaton, B., Gregory, J., Drach, B., Taylor, K., Hankin, S., Blower, J., Caron, J., Signell, R., Bentley, P., Rappa, G., Höck, H., Pamment, A.,
455   Juckes, M., Raspaud, M., Horne, R., Whiteaker, T., Blodgett, D., Zender, C., and Lee, D.: NetCDF Climate and Forecast (CF) Metadata Conventions, http://cfconventions.org/Data/cf-conventions/cf-conventions-1.8/cf-conventions.html, 2020.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geoscientific Model Development, 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016.

460   Farrell, P., Piggott, M., Pain, C., Gorman, G., and Wilson, C.: Conservative interpolation between unstructured meshes via supermesh construction, Computer Methods in Applied Mechanics and Engineering, 198, 2632–2642, https://doi.org/10.1016/j.cma.2009.03.004, 2009.

Fenicia, F., Kavetski, D., and Savenije, H. H. G.: Elements of a flexible approach for conceptual hydrological modeling: 1. Motivation and theoretical development, Water Resources Research, 47, https://doi.org/10.1029/2010WR010174, 2011.

Fisher, R. A. and Koven, C. D.: Perspectives on the Future of Land Surface Models and the Challenges of Representing Complex Terrestrial

465   Systems, Journal of Advances in Modeling Earth Systems, 12, e2018MS001 453, https://doi.org/10.1029/2018MS001453, 2020.

Gash, J. H. C.: An analytical model of rainfall interception by forests, Quarterly Journal of the Royal Meteorological Society, 105, 43–55, https://doi.org/10.1002/qj.49710544304, 1979.

Hallouin, T.: hydroeval: an evaluator for streamflow time series in Python, https://doi.org/10.5281/zenodo.4709652, 2021.

Hallouin, T. and Ellis, R. J.: unifhy, https://doi.org/10.5281/zenodo.6466215, Funded by the Natural Environment Research Council (NERC)

470   Hydro-JULES programme (NE/S017380/1)., 2021.

Hallouin, T., Mockler, E., and Bruen, M.: SMARTpy: Conceptual Rainfall-Runoff Model, https://doi.org/10.5281/zenodo.3376589, 2019.

Hallouin, T., Mockler, E. M., and Bruen, M.: unifhycontrib-smart, https://doi.org/10.5281/zenodo.6466276, 2021.

Hanke, M., Redler, R., Holfeld, T., and Yastremsky, M.: YAC 1.2.0: new aspects for coupling software in Earth system modelling, Geoscientific Model Development, 9, 2755–2769, https://doi.org/10.5194/gmd-9-2755-2016, 2016.

475   Harpham, Q., Hughes, A., and Moore, R.: Introductory overview: The OpenMI 2.0 standard for integrating numerical models, Environmental Modelling & Software, 122, 104 549, https://doi.org/10.1016/j.envsoft.2019.104549, 2019.

Hassell, D. and Bartholomew, S. L.: cfdm: A Python reference implementation of the CF data model, Journal of Open Source Software, 5, 2717, https://doi.org/10.21105/joss.02717, 2020.

Hassell, D., Gregory, J., Blower, J., Lawrence, B. N., and Taylor, K. E.: A data model of the Climate and Forecast metadata conventions (CF-

480   1.6) with a software implementation (cf-python v2.1), Geoscientific Model Development, 10, 4619–4646, https://doi.org/10.5194/gmd-10-4619-2017, 2017.

Hobley, D. E. J., Adams, J. M., Nudurupati, S. S., Hutton, E. W. H., Gasparini, N. M., Istanbulluoglu, E., and Tucker, G. E.: Creative computing with Landlab: an open-source toolkit for building, coupling, and exploring two-dimensional numerical models of Earth-surface dynamics, Earth Surface Dynamics, 5, 21–46, https://doi.org/10.5194/esurf-5-21-2017, 2017.

485   Hock, R.: Temperature index melt modelling in mountain areas, Journal of Hydrology, 282, 104–115, https://doi.org/10.1016/S0022-1694(03)00257-9, mountain Hydrology and Water Resources, 2003.

Hortal, M. and Simmons, A. J.: Use of Reduced Gaussian Grids in Spectral Models, Monthly Weather Review, 119, 1057–1074, https://doi.org/10.1175/1520-0493(1991)119<1057:UORGGI>2.0.CO;2, 1991.

Hutton, E., Piper, M., Drost, N., Gan, T., Kettner, A., Overeem, I., Stewart, S., and Wang, K.: The Python Modeling Toolkit (PyMT),

490   https://doi.org/10.5281/zenodo.4985222, 2021.

Hutton, E. W., Piper, M. D., and Tucker, G. E.: The Basic Model Interface 2.0: A standard interface for coupling numerical models in the geosciences, Journal of Open Source Software, 5, 2317, https://doi.org/10.21105/joss.02317, 2020.

Kling, H., Fuchs, M., and Paulin, M.: Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios, Journal of Hydrology, 424-425, 264–277, https://doi.org/10.1016/j.jhydrol.2012.01.011, 2012.

495   Kraft, P., Vaché, K. B., Frede, H.-G., and Breuer, L.: CMF: A Hydrological Programming Language Extension For Integrated Catchment Models, Environmental Modelling & Software, 26, 828–830, https://doi.org/10.1016/j.envsoft.2010.12.009, 2011.

Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochemical Cycles, 19, https://doi.org/10.1029/2003GB002199, 2005.

Lawrence, B. N., Rezny, M., Budich, R., Bauer, P., Behrens, J., Carter, M., Deconinck, W., Ford, R., Maynard, C., Mullerworth, S., Osuna, C., Porter, A., Serradell, K., Valcke, S., Wedi, N., and Wilson, S.: Crossing the chasm: how to develop weather and climate models for next generation computers?, Geoscientific Model Development, 11, 1799–1821, https://doi.org/10.5194/gmd-11-1799-2018, 2018.

Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., Collier, N., Ghimire, B., van Kampenhout, L., Kennedy, D., Kluzek, E., Lawrence, P. J., Li, F., Li, H., Lombardozzi, D., Riley, W. J., Sacks, W. J., Shi, M., Vertenstein, M., Wieder, W. R., Xu, C., Ali, A. A., Badger, A. M., Bisht, G., van den Broeke, M., Brunke, M. A., Burns, S. P., Buzan, J., Clark, M., Craig, A., Dahlin, K., Drewniak, B., Fisher, J. B., Flanner, M., Fox, A. M., Gentine, P., Hoffman, F., Keppel-Aleks, G., Knox, R., Kumar, S., Lenaerts, J., Leung, L. R., Lipscomb, W. H., Lu, Y., Pandey, A., Pelletier, J. D., Perket, J., Randerson, J. T., Ricciuto, D. M., Sanderson, B. M., Slater, A., Subin, Z. M., Tang, J., Thomas, R. Q., Val Martin, M., and Zeng, X.: The Community Land Model Version 5: Description of New Features, Benchmarking, and Impact of Forcing Uncertainty, Journal of Advances in Modeling Earth Systems, 11, 4245–4287, https://doi.org/10.1029/2018MS001583, 2019.

Lehner, B. and Grill, G.: Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems, Hydrological Processes, 27, 2171–2186, https://doi.org/10.1002/hyp.9740, 2013.

Lehner, B., Verdin, K., and Jarvis, A.: New Global Hydrography Derived From Spaceborne Elevation Data, Eos, Transactions American Geophysical Union, 89, 93–94, https://doi.org/10.1029/2008EO100001, 2008.

Lewis, H. and Hallouin, T.: unifhycontrib-rfm, https://doi.org/10.5281/zenodo.6466270, 2021.

Los, S. O., Rosette, J. A. B., Kljun, N., North, P. R. J., Chasmer, L., Suárez, J. C., Hopkinson, C., Hill, R. A., van Gorsel, E., Mahoney, C., and Berni, J. A. J.: Vegetation height and cover fraction between 60° S and 60° N from ICESat GLAS data, Geoscientific Model Development, 5, 413–432, https://doi.org/10.5194/gmd-5-413-2012, 2012.

Marthews, T. R., Dadson, S. J., Lehner, B., Abele, S., and Gedney, N.: High-resolution global topographic index values for use in large-scale hydrological modelling, Hydrology and Earth System Sciences, 19, 91–104, https://doi.org/10.5194/hess-19-91-2015, 2015.

Martínez-de la Torre, A., Blyth, E., and Robinson, E.: Water, carbon and energy fluxes simulation for Great Britain using the JULES Land Surface Model and the Climate Hydrology and Ecology research Support System meteorology dataset (1961-2015) [CHESS-land], https://doi.org/10.5285/c76096d6-45d4-4a69-a310-4c67f8dcf096, 2018.

Martínez-de la Torre, A., Blyth, E. M., and Weedon, G. P.: Using observed river flow data to improve the hydrological functioning of the JULES land surface model (vn4.3) used for regional coupled modelling in Great Britain (UKC2), Geoscientific Model Development, 12, 765–784, https://doi.org/10.5194/gmd-12-765-2019, 2019.

McKay, M. D., Beckman, R. J., and Conover, W. J.: A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output From a Computer Code, Technometrics, 42, 55–61, https://doi.org/10.1080/00401706.2000.10485979, 2000.

Mockler, E. M., O'Loughlin, F. E., and Bruen, M.: Understanding hydrological flow paths in conceptual catchment models using uncertainty and sensitivity analysis, Computers & Geosciences, 90, 66–77, https://doi.org/10.1016/j.cageo.2015.08.015, uncertainty and Sensitivity in Surface Dynamics Modeling, 2016.

Monteith, J. L.: Evaporation and environment, Symposia of the Society for Experimental Biology, 19, 205–234, https://repository.rothamsted.ac.uk/item/8v5v7, 1965.

Moore, R. J., Bell, V. A., Austin, R. M., and Harding, R. J.: Methods for snowmelt forecasting in upland Britain, Hydrology and Earth System Sciences, 3, 233–246, https://doi.org/10.5194/hess-3-233-1999, 1999.

Morris, D. G. and Flavin, R. W.: A digital terrain model for hydrology, in: Proc. 4th International Symposium on Spatial Data Handling, edited by Brassel, K. and H., K., vol. 1, pp. 250–262, Zurich, 1990.

Morris, D. G. and Flavin, R. W.: Sub-set of UK 50 m by 50 m hydrological digital terrain model grids, NERC, Institute of Hydrology, Wallingford, 1994.

540 Nachtergaele, F., van Velthuizen, H., Verelst, L., Wiberg, D., Batjes, N., Dijkshoorn, J., van Engelen, V., Fischer, G., Jones, A., Montanarella, L., Petri, M., Prieler, S., Teixeira, E., and Shi, X.: Harmonized World Soil Database (version 1.2), Food and Agriculture Organization of the UN, International Institute for Applied Systems Analysis, ISRIC - World Soil Information, Institute of Soil Science - Chinese Academy of Sciences, Joint Research Centre of the EC, 2012.

Nguyen-Quang, T., Polcher, J., Ducharne, A., Arsouze, T., Zhou, X., Schneider, A., and Fita, L.: ORCHIDEE-ROUTING: revis-
545 ing the river routing scheme using a high-resolution hydrological database, Geoscientific Model Development, 11, 4965–4985, https://doi.org/10.5194/gmd-11-4965-2018, 2018.

Peckham, S. D., Hutton, E. W., and Norris, B.: A component-based approach to integrated modeling in the geosciences: The design of CSDMS, Computers & Geosciences, 53, 3–12, https://doi.org/10.1016/j.cageo.2012.04.002, modeling for Environmental Change, 2013.

Polcher, J., McAvaney, B., Viterbo, P., Gaertner, M.-A., Hahmann, A., Mahfouf, J.-F., Noilhan, J., Phillips, T., Pitman, A., Schlosser, C.,
550 Schulz, J.-P., Timbal, B., Verseghy, D., and Xue, Y.: A proposal for a general interface between land surface schemes and general circula-
tion models, Global and Planetary Change, 19, 261–276, https://doi.org/10.1016/S0921-8181(98)00052-6, 1998.

Pool, S., Vis, M., and Seibert, J.: Evaluating model performance: towards a non-parametric variant of the Kling-Gupta efficiency, Hydrolog-
ical Sciences Journal, 63, 1941–1953, https://doi.org/10.1080/02626667.2018.1552002, 2018.

Putman, W. M. and Lin, S.-J.: Finite-volume transport on various cubed-sphere grids, Journal of Computational Physics, 227, 55–78,
555 https://doi.org/https://doi.org/10.1016/j.jcp.2007.07.022, 2007.

Smith, K. A., Barker, L. J., Tanguy, M., Parry, S., Harrigan, S., Legg, T. P., Prudhomme, C., and Hannaford, J.: A multi-objective ensemble approach to hydrological modelling in the UK: an application to historic drought reconstruction, Hydrology and Earth System Sciences, 23, 3247–3268, https://doi.org/10.5194/hess-23-3247-2019, 2019.

Swenson, S. C., Clark, M., Fan, Y., Lawrence, D. M., and Perket, J.: Representing Intrahillslope Lateral Subsurface Flow in the Community
560 Land Model, Journal of Advances in Modeling Earth Systems, 11, 4044–4065, https://doi.org/10.1029/2019MS001833, 2019.

Valcke, S.: The OASIS3 coupler: a European climate modelling community software, Geoscientific Model Development, 6, 373–388, https://doi.org/10.5194/gmd-6-373-2013, 2013.

Zängl, G., Reinert, D., Rípodas, P., and Baldauf, M.: The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD and MPI-M: Description of the non-hydrostatic dynamical core, Quarterly Journal of the Royal Meteorological Society, 141, 563–579,
565 https://doi.org/10.1002/qj.2378, 2015.