



Final report on compound extremes modelling framework

Deliverable 1.3

31st August 2026

Deliverable 1.3 – Compound extremes modelling framework

Title	Final report on compound extremes modelling framework
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Deliverable number	1.3
Work Package	WP1: Characterizing compound extremes in current and future climates
Submission date	31/08/2026

Dissemination Level

PU	Public — fully open (automatically posted online)	X
SEN	Sensitive — limited under the conditions of the Grant Agreement	
CI	EU classified — Restreint-UE/EU-Restricted, Confidential-UE/EU-Confidential, Secret-UE/EU-Secret under Decision 2015/444	

Version History

Date	Version	Contributors	Comments
25/08/2026	0.1	Natalia Aleksandrova (Deltares), Henrique Moreno Dumont Goulart (Deltares), Doris Vertegaal (Deltares), Anaïs Couasnon (Deltares), Paweł Terefenko (University of Szczecin)	First version for internal review
25/08/2026	0.2	Sanne Muis (Deltares)	Internal review
28/08/2026	1.0	Eloise Matthews (Met Office), Anaïs Couasnon (Deltares)	Final review and first finished version
31/08/2026	1.1	Maggie Kossida (SEVEN)	Copy editing

Citation

Aleksandrova, N., Couasnon, A., Terefenko, P., (2026): Final report on compound extremes modelling framework. Horizon Europe project COMPASS. Deliverable D1.3. DOI: 10.5281/zenodo.22125256



Funded by the
European Union

The COMPASS project has received funding from the European Union's HORIZON Research and Innovation Actions Programme under Grant Agreement No. 101135481

Disclaimer

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Executive summary

This deliverable presents the final compound extremes modelling framework developed within the COMPASS project under Work Package 1, supporting the characterisation of compound extremes in current and future climates and contributing to the project's attribution and demonstrator activities. The framework provides a structured, reproducible basis for modelling compound hazards across a range of event types, with particular developments for compound flooding and for heatwave- and drought-related impact assessment. It was designed to support COMPASS Use Cases by combining globally available datasets, open-source tools, automated workflows and case-specific configuration files, while allowing users to adapt the modelling chain to different regions, events and attribution questions.

For compound flooding, the framework links hydrological, coastal hydrodynamic and local inundation modelling components through an automated Snakemake-based workflow. It uses tools such as HydroMT, wflow, Delft3D-FM and SFINCS, together with data catalogs and user-editable configuration files, to set up and run event-based simulations. The workflow supports the integration of key flood drivers, including precipitation, river discharge, storm surge, wind and coastal water levels, and was applied or adapted across several COMPASS Use Cases, including tropical cyclones in Mozambique and Honduras, winter storms in the United Kingdom, and flooding in South Africa. The framework also includes options for counterfactual simulations, enabling users to modify drivers such as precipitation, sea level and wind in order to explore attributable changes in flood extent, depth, volume and, where relevant, impacts such as damages and population exposure.

For heatwaves and droughts, the framework summarises the workflow developed to assess climate-related impacts on agricultural crop yields in Poland. This workflow brings together meteorological datasets from ERA5, ERA5-Land and EMO-1, bias adjustment and statistical downscaling procedures, LISVAP-derived evapotranspiration variables, and ATTRICI-based counterfactual climate datasets. By processing factual and counterfactual climate information consistently within the same modelling chain, the framework enables comparative assessment of how anthropogenic climate change may have influenced hazard conditions and related impacts. While the detailed software documentation for this component is provided in the forthcoming Deliverable D5.3, this report places the workflow within the broader compound extremes modelling framework and explains how it can be adapted for other climate-impact attribution applications.

Overall, the deliverable demonstrates that the COMPASS modelling framework can support transparent, reusable and attribution-oriented analyses of compound extremes, while making clear that its application requires expert judgement. Users need to define appropriate model domains, select suitable input datasets, adapt configuration and data catalog files, ensure that required software is available on the target computing system, and validate results against available observations or reference products. The framework should therefore not be applied as a black-box tool, but as a flexible modelling environment that supports consistent comparison between factual and counterfactual conditions, facilitates learning across Use Cases, and provides a basis for future operational deployment and further methodological development.

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1 Introduction

Compound extremes can result from the interaction of multiple drivers, such as heavy rainfall, river discharge, storm surge, heat or drought conditions. These complex interactions can lead to extreme impacts that cannot be captured using single-hazard approaches. A consistent modelling framework is therefore needed to represent relevant processes, combine different data sources and support comparable analyses across event types and regions.

Deliverable D1.3 provides an overview of the compound extremes modelling framework developed within the COMPASS project. It is part of Work Package 1, *“Characterising compound extremes in current and future climates”*, which aims to develop and validate a modelling framework for characterising compound extremes under current and future climate conditions. Deliverable D1.3 contributes to specific objective SO1.2 by developing a global-to-local modelling framework for computing compound extremes. This deliverable presents the specific developments done under this project for the hazard modelling framework of some compound extremes and is directly linked to milestone M2, the final version of the compound modelling framework, available in the COMPASS GitHub repository. The compound extremes modelling framework was developed to support the Use Cases attribution analyses in Work Package 4, *“Developing actionable climate information for events”*, whose findings are presented in Deliverables D4.1 and D4.2. It also supports Work Package 5, *“Demonstrator with steps towards an operational deployment”*, through its contribution to the online web-based demonstrator.

This deliverable summarises the framework developments and provides users with key information on the automated modelling workflows. Chapter 2 describes the specific developments that have been done in this project in relation to the Use cases, Chapter 3 presents the framework and capabilities for compound flood modelling, while Chapter 4 focuses on heatwaves and droughts. A more detailed description of the latter workflow is described in deliverable D5.3 but is summarised here for consistency.

2 Application of compound extremes modelling framework in COMPASS use cases

This deliverable focuses on the developments supported within the COMPASS project based on the specific needs observed for the Use Cases (UCs) when doing impact attribution. The UCs are testbeds aimed at providing insights on the feasibility of attributing compound extremes and their impacts to climate change. They are spread over two phases, with the first phase completed in August 2025 and documented in D4.1 and the second phase with either extended UCs from phase I or the addition of new UCs.

Table 2-1 presents the UCs, including UCs for phase II with the results to be documented in D4.2 in August 2026. The table shows more specially how the hazard modelling was done, whether new developments have been made and where it is stored, if relevant. The UCs cover a variety of compound extremes, with different spatiotemporal dynamics for the hazard modelling, from multivariate events - for example when considering the tropical cyclone (TC) where multiple drivers (rainfall, storm surge, discharge) are interacting - to consecutive events, such as in the case of TC Eta and Iota. During the COMPASS project, hazard modelling developments were made for the automatic setup of a modelling chain for compound flooding (applied in the UCs for TC Idai, TC Kenneth, TC Freddy and the consecutive TC Eta and Iota, as well as the series of winter storms in the United Kingdom) and as part of the automatic setup of the impact attribution forecast system for the heatwaves and droughts in Poland.

Table 2-1: Overview of the Use Cases phase II and specific hazard developments

Use Case name	Phase	Hazard drivers considered	Spatiotemporal dynamics considered ¹	Hazard modelling	Remarks on modelling

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Storm Xynthia, 2010, France	I	Storm surge amplified by high spring tide	Multivariate	Storm surge modelling with Delft3D combined with external data on wave heights, sea level rise and tidal amplitude, with flood hazard zones computed in LISFLOOD	Model already existing, no further development performed
		Wind		Wind speeds derived from reanalysis (ERA5) and hindcast (HadGEM3A)	No further hazard modelling performed
Compound drought heatwave, summer 2022, United Kingdom	I	Surface air temperature, runway temperature	Multivariate and preconditioned	Linear regression between air temperature and runway temperature	No further hazard modelling performed
Compound drought heatwave, summer 2022, United Kingdom	II	Surface air temperature, radiation	Multivariate and preconditioned	Modelling the impact directly with the Met Office Surface Transport Forecasting-JULES (STF-JULES) impact model	Model already existing, no further development performed
Series of winter storms 2013/14, United Kingdom	I and II	Discharge, local rainfall	Temporally compounding	Modelling of compound flooding using combination of physics-based models (wflow and SFINCS). Climate input from ERA5, CEH-GEAR1hr, UKCP Local and HadGEM3-A	Makes use of the compound-flooding-tropical-cyclones repository developed in COMPASS
Tropical Cyclone Idai, 2019, Mozambique	I and II	Rainfall, wind, storm surge, flooding (pluvial, fluvial and coastal)	Multivariate	Modelling of compound flooding using combination of physics-based models (wflow, Delft3D-FM, Hurriwave, and SFINCS). Climate input from ERA5 and IBTRaCS. In the extended phase Climate DT input data.	Makes use of the compound-flooding-tropical-cyclones repository developed in COMPASS
Tropical Cyclone Kenneth, 2019, Mozambique	I	Rainfall, wind, discharge, storm surge	Multivariate	Modelling of compound flooding using combination of physics-based models (wflow, Delft3D-FM, and SFINCS). Climate input from ERA5 and IBTRaCS.	Makes use of the compound-flooding-tropical-cyclones repository developed in COMPASS
Tropical Cyclone Freddy, 2023, Mozambique	I	Rainfall, wind, discharge, storm surge	Multivariate	Modelling of compound flooding using combination of physics-based models (wflow, Delft3D-FM, and SFINCS).	Makes use of the compound-flooding-tropical-cyclones

				Climate input from ERA5 and IBTRaCS.	repository developed in COMPASS
Tropical Cyclone Eta and Iota, 2022, Honduras	I and II	Local rainfall, discharge	Temporally compounding	Modelling of compound flooding using combination of physics-based models (wflow and SFINCS). Climate input from ERA5.	Makes use of the compound-flooding-tropical-cyclones repository developed in COMPASS
Compound Drought Poland	n/a	Heatwave and droughts	Multivariate	Climate inputs from ERA5, ERA5-Land and EMO-1. Bias adjustment and downscaling of climate inputs.	Makes use of the Integration-of-datasets-and-models repository developed in COMPASS
Durban floods, South Africa	II	Extreme rainfall	Preconditioning	Modelling of compound flooding using SFINCS. Climate input from ClimateDT.	Makes use of the compound-flooding-tropical-cyclones repository developed in COMPASS
Historical Tropical Cyclones, 1996-2024, United States	II	Wind, rainfall, storm surge	Multivariate	Modelled wind fields (Holland 08 model), rain fields (TCR model) and storm surge depths (GeoClaw model) based on IBTRaCS TC track data and partly published as COMPASS D1.4	No compound flooding modelling. No further developments done
Drought Crete, Greece	II	Dry spells, temperature, reduced groundwater recharge	Multivariate	Modelled with a water resources management model was developed in WEAP21 using a node-based architecture developed in EU project TRANSCEND	Model already existing. No further development needed

¹The categories refer to the topology of compound events as defined in Zscheischler et al. (2020)

3 Compound flooding modelling framework

3.1 Introduction

The modelling framework for compound flood hazard is an implementation of the methodology described in Deliverable 1.1.

The framework relies on open-source datasets and software for physics-based modelling of hydrological and hydrodynamic processes. The modelling is to a large extent automated. The modelling framework is hosted in the public [COMPASS GitHub repository](#) for compound flood modelling and is structured as follows:

```
compound-flooding-tropical-cyclones/
├── Workflows/
├── analysis_examples/
├── docs/
├── .gitignore
├── LICENSE
├── README.md
├── pixi.toml
```

The repository brings together the automated workflows for model setup and execution (folder *Workflows*), the configuration and data access files needed to run them, and supporting material for setting up the workflow (folder *docs*) and analyzing the workflow outputs (folder *analysis_examples*). It also contains project-level files, including the README file, license information and Pixi environment definition, which document the repository and support reproducible execution of the workflow.

Figure 3-1 shows the main components of this hazard modelling framework in terms of models and input datasets. It conceptually shows how meteorological, hydrological and coastal inputs are combined and used in the hydrological, coastal hydrodynamic and compound flood hazard models to simulate compound flooding for a selected event and region. In the sections below, the implementation of the framework is described.

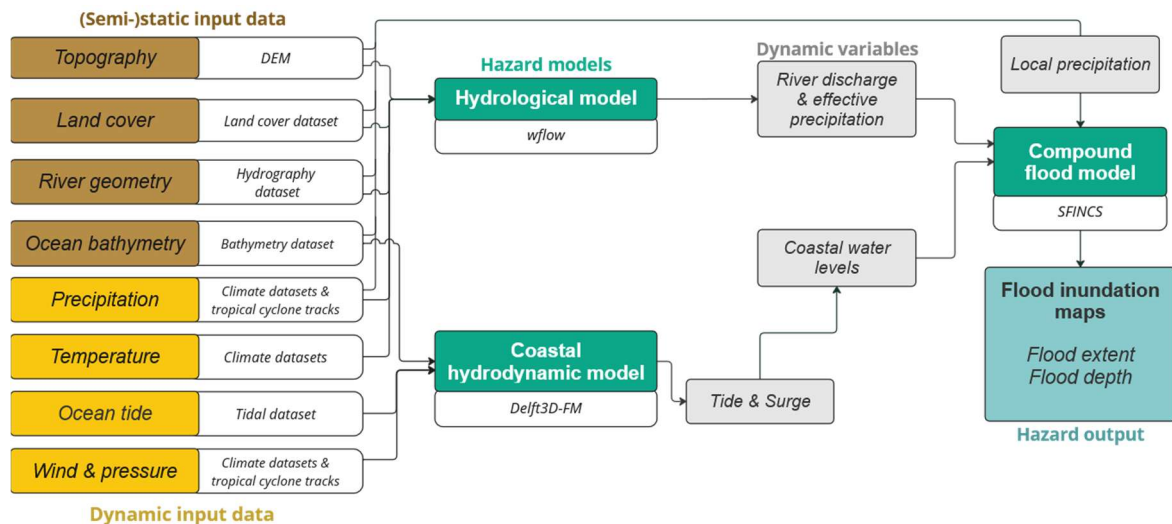


Figure 3-1 The main components of the compound flood hazard modelling framework.

3.2 Automated modelling workflow

3.2.1 Software and models

The workflow is implemented using the workflow manager [Snakemake](#), which orchestrates data pre-processing, model set-up, model execution and post-processing in the correct order. In Snakemake, workflow steps are defined as rules with expected inputs, outputs and commands; Snakemake uses these dependencies between rules to determine which steps need to be executed and in which order. A workflow configuration file is used to prescribe the input information to the workflow manager, including the model set-up and boundary conditions. The structure of this file is described in a later section.

The workflow is designed to be deployed on HPC (Linux-based) systems. The Python environment for executing the workflow is set up using [Pixi](#) with pre-defined environments. Pixi is used to define and reproduce the software environment needed to run the workflow by installing the required Python packages and command-line tools in an isolated project environment, based on the dependency specifications in the repository. This helps ensure that the same workflow dependencies can be recreated when the workflow is run on different systems.

Together, these tools separate the workflow logic from the model-specific implementation. Snakemake controls the order of execution, while Pixi supports a reproducible software environment. Within the workflow, the Python packages HydroMT and dfm_tools support model set-up and data preparation, and the numerical models simulate the hydrological, coastal hydrodynamic and local compound flooding processes. The workflow relies on Delft3D-FM for coastal hydrodynamic modelling, wflow for hydrological modelling of river catchments and SFINCS for compound flood modelling.

[Delft3D-FM](#) is used as the coastal hydrodynamic model in the workflow. It provides coastal water-level boundary conditions (water levels) for the local compound flood model. Its model set-up and related pre-processing are supported by Python scripts using [dfm_tools](#), which is used to prepare the model setup (computational grid, boundary conditions, forcings).

[HydroMT](#) is used to automate model building and input data preparation. In this workflow, HydroMT model builders are used for wflow and SFINCS through the plugins [HydroMT-Wflow](#) and [HydroMT-SFINCS](#). Together with the HydroMT [data catalog approach](#), these tools link the datasets specified in the workflow configuration files to the model set-up scripts.

[wflow](#) is used as the hydrological model for river catchments. Within the workflow, the wflow model is set up for the user-defined region and time period, and is used to calculate river discharge boundary conditions to the local compound flooding model.

[SFINCS](#) is used as the compound flood model. It combines the relevant flood drivers from the hydrological and coastal hydrodynamic model components, as well as local rainfall (rainfall-on-grid) to simulate flooding for the selected region and event. Its set-up is supported by Python scripts making use of HydroMT-SFINCS.

3.2.2 Data catalogs

The workflow makes use of HydroMT data catalogs to provide standardized access to the input datasets required by the model set-up scripts. A data catalog is a YAML file that describes where datasets are stored, how they should be read and which metadata are needed to interpret them correctly. This approach separates the data references from the workflow logic: the Snakemake rules and Python scripts can use dataset names (keywords) instead of having to rely on hard-coded file paths.

In HydroMT, data catalogs provide a common interface to raster, vector and tabular datasets, and can include information such as the data type, driver, coordinate reference system, file path, units and source metadata. They can also be combined, for example by using predefined global catalogs together with project-specific or user-defined catalogs for local datasets.

Within the workflow, the names of the data sources defined in the data catalog act as data handles. These handles are used in the configuration files to specify, for example, which precipitation, topography, land-use, river, coastal or meteorological datasets should be used for a given event and region. The Python scripts then use the HydroMT data catalog functionality to read, subset and pre-process the requested datasets and link them to the appropriate model components.

For a new application, the user should check that the data catalog entries point to accessible data locations on the system where the workflow is executed and that the dataset names match the names used in the workflow configuration file. The repository includes an [example notebook](#) for accessing data through the data catalog, which illustrates how the catalog is used outside the automated workflow. This provides a useful starting point for testing whether data paths and catalog entries are correctly configured before running the full workflow. For more information and examples see the HydroMT [Data Catalog documentation](#).

Examples of data catalogs listing the datasets that were used for the Use Cases modelling can be found in the folder *Workflows/03_data_catalogs/*.

3.2.3 Workflow structure

The core automated workflow is stored in the folder *Workflows*. It is organized by separating the different elements of the workflow in different folders detailed in Table 3-1:

- **Workflow execution scripts.** These scripts provide the operational entry point for running the workflow. They are intended to launch the Snakemake workflow with the correct configuration file, software environment and computing settings. In practice, they connect the repository workflow to the HPC system on which it is executed, by activating the required (Python) environment, selecting the workflow configuration and submitting or starting the Snakemake run. Since job schedulers, paths and software availability differ between systems, these scripts are the part of the workflow most likely to require local adaptation when the workflow is moved to another HPC environment.
- **User-editable configuration files.** These YAML files define the case-specific settings for a workflow application. They specify the region and event to be modelled, the simulation period, the datasets to use, the model components to run and the relevant boundary and forcing settings. Because these files contain the main user choices, they are the primary place to adapt the workflow to a new flood event or study area.
- **Snakemake rules.** The Snakemake rules describe the logical steps of the automated workflow and the dependencies between them. Each rule defines the files it expects as input, the files it produces as output and the command or script used to create those outputs. Based on these file dependencies, Snakemake determines which steps are already complete, which steps need to be rerun and in what order the remaining steps should be executed. This makes the workflow modular and reproducible: individual components such as data preparation, model set-up, model execution and post-processing can be updated without manually rerunning the complete workflow.
- **Data catalogs.** The data catalog files define the input datasets that can be used by the workflow and describe where these datasets are stored and how they should be read. Configuration files link the datasets from the data catalogs by using corresponding handles.
- **Python scripts.** The Python scripts implement the tasks that are called by the Snakemake rules. They prepare input data, build model schematizations, generate boundary and forcing files, run post-processing steps.
- **Model-specific default configuration files.** These files provide default settings for the numerical model components, such as wflow and SFINCS. They contain model parameters and setup options that are reused across applications, while the user-editable workflow configuration files define the case-specific choices. Expert users can adapt these defaults when an application requires more detailed model tuning.

The execution scripts and Snakemake rules serve different but complementary purposes. The execution scripts determine how the workflow is started on a specific computing system, whereas the Snakemake rules determine what the workflow does once it is running. This distinction is important for reuse: a new application may only require changes to the configuration and data catalog files, while deployment on a different HPC system may also require changes to the execution scripts.

This structure allows the same workflow logic to be reused for different flood events and regions by adapting the configuration and catalog files rather than rewriting the workflow itself.

The repository also contains supporting notebooks in *docs*. These notebooks are not used in the automated workflow, but they document and demonstrate important building blocks, including data catalog access and the creation of coastal boundary needed as input for the Delft3D-FM and SFINCS model coupling. They are

therefore useful for understanding, testing or adapting parts of the workflow before running the complete Snakemake workflow.

Figure 3-2 illustrates the Snakemake workflow rules and their interdependencies. The workflow is run using workflow execution (Bash) scripts. The main part of the workflow (hydrological and flood models) is run using a single execution script that follows the model chain from the creation of SFINCS and wflow models to postprocessing the flood maps. The coastal hydrodynamic model (Delft3D-FM) is set up and executed separately – this model requires larger computational capacity and its use is optional in the workflow. The user can specify an alternative source for coastal water levels in the configuration file (e.g. a global timeseries derived from a global hydrodynamic model). In the case that the coastal hydrodynamic model is used, the main flood modelling workflow will expect the coastal hydrodynamic model output to already be available and linked via a handle in the data catalog (specified in the configuration file). Similarly, if the user wants to make use of the bankfull river discharge correction, the 30-year wflow run needs to be set up and executed using a separate execution script.

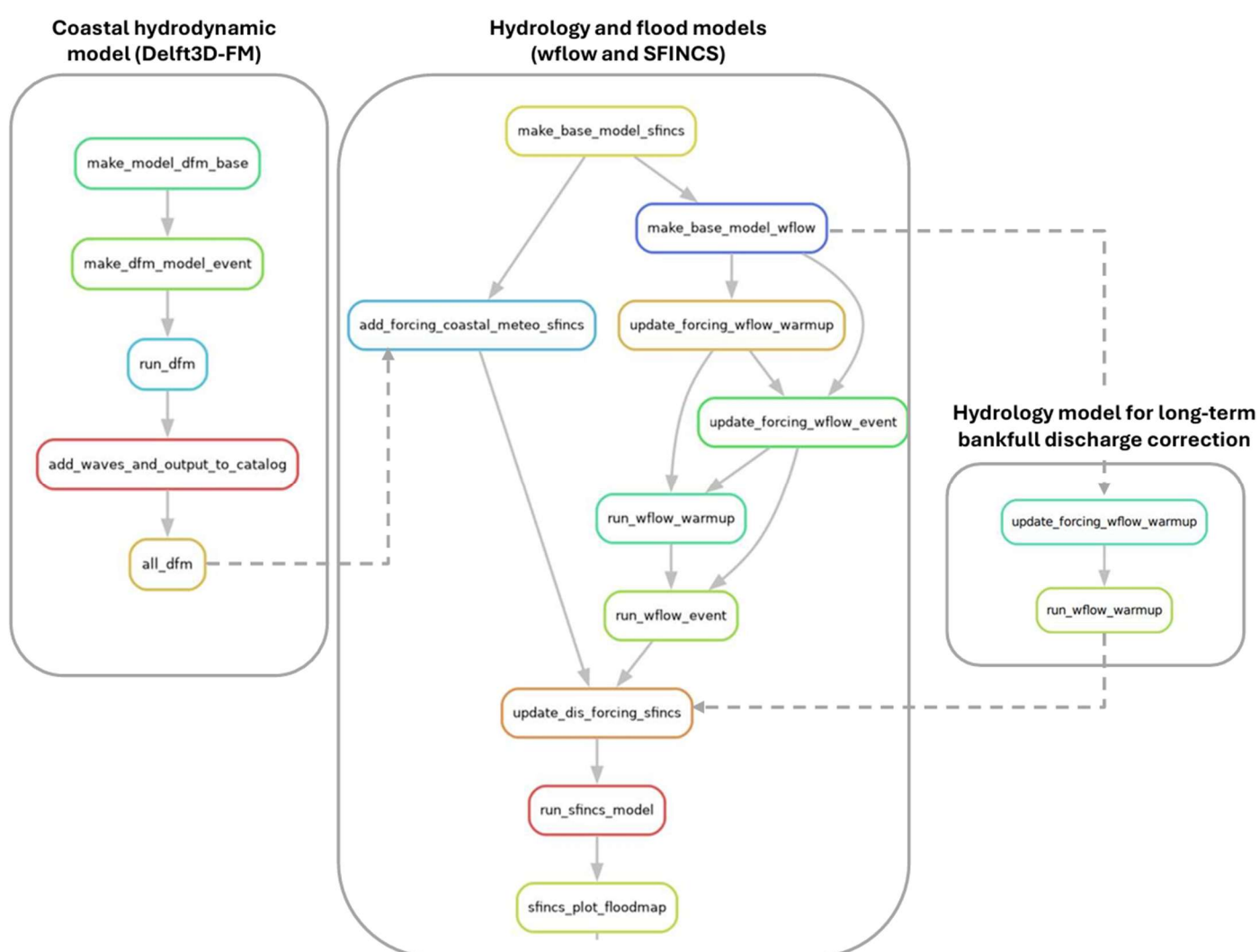


Figure 3-2 Schematic representation of the structure of the Snakemake workflow. Each block corresponds to a Snakemake rule, dependencies between the rules are shown with solid arrows. The dashed arrows indicate optional dependencies.

3.2.4 Configuring the workflow

The workflow configuration files provide the case-specific information needed to run the automated modelling chain. They are YAML files that translate the choices for a particular event and study area into settings that can

be interpreted by the Snakemake workflow and the underlying Python scripts. In the repository, these files are used together with the data catalogs: the configuration files specify which datasets should be used, while the data catalogs define where these datasets are located and how they should be read.

Software

Users need to make sure that the necessary software is available on their HPC and is correctly linked within the workflow. The kernels and executable model files are not provided in the workflow since it is the responsibility of the user to have them installed in accordance with the appropriate license and terms and conditions. The reader is referred to [this](#) page for more information about the specific software installation.

The coastal hydrodynamic model simulation is launched using a Delft3D-FM singularity container. The path to the singularity container is prescribed in the [example Bash script](#) that is used to start the simulation.

Similarly, the compound flooding hydrodynamic model SFINCS is ran using an apptainer. More information on the versions available and how to pull and run the apptainer can be found in the documentation of SFINCS, [here](#).

For the hydrological model wflow, the framework assumes that the model is installed locally using Julia. Instructions on how to install wflow can be found [here](#).

Defining the configuration file

At a high level, the configuration files define the geographical and temporal scope of the workflow. This includes the region of interest, the spatial domain used for each model component and the start and end dates for the relevant simulations. These settings determine how the hydrological, coastal hydrodynamic and local compound flooding models are prepared for the selected application.

The configuration files also specify the model components and forcing data used in the workflow. This can include specific settings for the wflow hydrological model, the Delft3D-FM coastal hydrodynamic model and the SFINCS compound flood model, as well as references to meteorological forcing, topography, bathymetry, land-use, river network, coastal boundary and observation-point datasets.

Before running the workflow for a new application, the user should check that the selected configuration file points to valid data catalog handles, accessible auxiliary files and appropriate model-specific default settings. The execution scripts then use this configuration file to start the Snakemake workflow on the target computing system.

Model domains definition

Based on the user-defined bounding boxes (bbox_dfm and bbox_sfincs in the configuration file), the model domains are defined. The Delft3D-FM model domain is defined as the ocean part of the bounding box, limited by the coastal mask provided by the user. The coastal mask is needed for the coupling between the coastal hydrodynamic model and overland flood model, and it outlines the boundary between the model domains. The repository provides a [supporting notebook](#) that explains how to create the coastal mask and Delft3D-FM output locations files. These files are location-specific and their creation is not automated because they require a relatively smooth boundary at an appropriate water depth (e.g. 5 m water depth), which cannot be reliably automatically generated.

The model domain for the SFINCS flood model is defined as the cluster of local hydrological basins that intersect with the provided bounding box (using the [HydroBASINS Atlas](#), level 12 basins). The wflow model domain is based on the SFINCS flood model domain and is composed of all the upstream catchments of the

ones selected in the SFINCS model with a minimum drainage area prescribed in the configuration file (default value of 30 km²).

Figure 3-3 shows an example of the modelling domains defined based on user input. Based on the provided bounding box coordinates for the flood model, the domains of the wflow and SFINCS models are defined by the automated workflow. The Delft3D-FM model domain is much larger and is defined based on a separate user-defined bounding box, which needs to be large enough to capture the storm surge generation, i.e. the outer offshore boundary of this domain is preferably located well into the deep ocean waters.

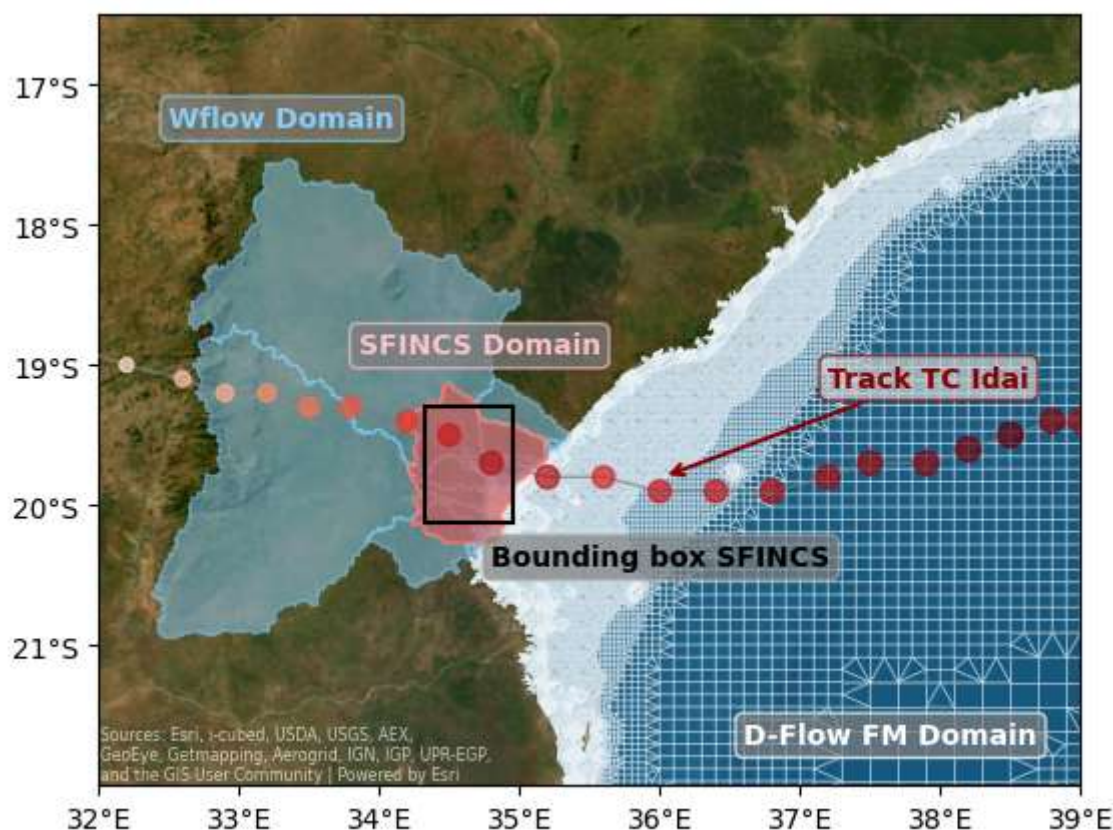


Figure 3-3 Example of modelling domains for TC Idai in Mozambique defined based on user input for the bounding box of the SFINCS flood model in the configuration file.

Meteorological conditions

The workflow supports two alternative ways of providing meteorological forcing, depending on the purpose of the simulation and the available data. The first option is to use gridded meteorological data, such as ERA5, which provides spatially and temporally varying atmospheric forcing fields. These gridded datasets can be used to force the hydrological and hydrodynamic model components with meteorological conditions (rainfall, wind speeds and atmospheric pressure) that are consistent over the full model domain and simulation period.

The second option, relevant for tropical cyclones, is to use schematized *spiderweb* format forcing. In this approach, the wind and pressure fields are represented on a storm-centered polar grid that moves with the cyclone track. For historical events, the cyclone track and intensity parameters can be derived from IBTrACS, after which parametric wind and pressure fields are generated using the Holland-type wind-profile formulation implemented in the *cht_cyclones* Python package. A separate [script example](#) is provided to facilitate the creation of the spiderweb forcing file. The resulting spiderweb forcing can then be used in the coastal hydrodynamic model and the flood model to represent the tropical cyclone wind and pressure forcing. In this case, rainfall data still needs to be provided as a separate gridded dataset.

The choice between gridded forcing and spiderweb forcing is controlled through the workflow configuration file. The configuration should specify which forcing option is used, which data catalog entries provide the required input data, and which simulation period should be extracted.

The meteorological forcing is subsequently passed to the relevant model components. Precipitation is used by the hydrological model and as rainfall-on-grid input for the SFINCS flood model. Wind and atmospheric pressure forcing are used by the coastal hydrodynamic model to simulate storm-surge-driven coastal water levels, which are then coupled to the local compound flood model.

Bankfull correction for river discharges

River bathymetry is often not represented in the topography datasets used in flood models. The lack of river bathymetry in the DEM dataset is problematic since this omits the in-bank river conveyance (Nguyen et al., 2026). In the current workflow, the discharge obtained from the hydrological wflow model represents all incoming inflow from upstream, i.e. both in-bank and out-of-bank discharge. To correct for this, an optional bankfull correction was developed to be applied to the river discharge boundary conditions used by SFINCS. The purpose of this correction is to estimate out-of-bank river conveyance by subtracting the in-bank river conveyance, or bankfull river discharge, based on empirical estimates (Dunne and Leopold, 1978; Liu et al., 2024). The main assumptions here are that the DEM represents the average water surface of the river, presents under-average discharge conditions as estimated by the in-bank discharge, and that only the out-of-bank discharge causes the flooding observed.

The correction is derived outside the event workflow from a separate long-term wflow simulation, namely a 30-year historical run. From this simulation, a representative bankfull discharge is estimated for each relevant river boundary location, using the 2-year return period discharge as an estimate for the bankfull capacity (in-bank river conveyance). This assumption is common in global flood modelling, where a spatially uniform 2-year recurrence interval is often used as a practical approximation of bankfull discharge, although recent work shows that actual bankfull recurrence intervals vary between climates and river systems (Liu et al., 2024). During the event simulation, the estimated bankfull discharge can then be subtracted from the simulated wflow discharge before the corrected discharge is passed to SFINCS.

This step is not fully automated within the event workflow, because the long-term wflow simulation used to estimate the bankfull discharge must be prepared and run separately. The resulting bankfull discharge values should therefore be available before running the event workflow and should be referenced in the workflow configuration. The correction should be used with care, because the 2-year return period discharge is an approximation of bankfull capacity and may not be appropriate for all river systems or model schematizations. Other approaches that estimate river bathymetry, and therefore define river conveyance, more accurately are expected to improve flood modelling results. However, at the moment, those approaches are not globally applicable and are only available for larger rivers or when local data is present.

Counterfactual simulations

The configuration files can also be used to define alternative simulations, including counterfactual scenarios. In such cases, one or more flood drivers or boundary conditions are modified while the rest of the workflow structure is kept unchanged. This makes it possible to compare a factual simulation with alternative scenario in a consistent modelling framework. The possible adjustments in drivers that are incorporated in the framework include a percentage change in precipitation rate and/or wind speed applied uniformly to the whole grid, a sea level rise offset for coastal water levels in meters and a counterfactual land use change scenario. For the factual scenarios, a percentage change value of zero, or the factual land use dataset, is used as entry in the config file.

Scripts to adjust the input files necessary for counterfactual scenarios can be found in the *Workflows/04_scripts/preprocessing/CF_data* folder.

3.3 Custom analysis

In addition, the repository includes analysis material that is kept separate from the automated workflow. These scripts depend on output files generated by the workflow and can be used for further analysis, validation or attribution-oriented post-processing. This separation keeps the automated model-production workflow distinct from case-specific analysis steps.

3.3.1 Validation

The repository also provides supporting validation examples to help users assess whether the model outputs are physically plausible and consistent with independent observations or reference products. These scripts and notebooks are kept separate from the automated Snakemake workflow; they are intended for diagnostic analysis after a model run has been completed, rather than as mandatory workflow steps. Depending on the model region, the amount of available open data for validation can vary considerably.

The validation material includes an [example of flood extent validation](#), illustrating the comparison of simulated flood extent and reference flood maps or satellite-derived inundation products. These comparisons can be used to identify spatial patterns of agreement and disagreement, for example whether the model captures the main flooded areas, misses observed inundation or predicts flooding in locations where it was not observed.

Another example of validation focuses on the evaluation of coastal water levels from the Delft3D-FM simulations, by extracting or plotting modelled water levels at selected locations and comparing it to available tidal gauge measurements. Such checks are useful for evaluating the coastal boundary conditions that are subsequently passed to SFINCS.

Validation of river discharges may also be relevant, for example against gauge observations from the [Global Runoff Data Centre](#) (GRDC, 2025) or the modelled [Global Flood Awareness System](#) (GloFAS) discharge data (Grimaldi et al, 2023; Zsoter et al, 2021; JRC and CEMS, 2020). Note that discharge observations are not always available to compare against modelled results, making validation challenging.

3.3.2 Attribution analysis

Attribution analysis aims to assess the extent to which climate change has influenced the likelihood, intensity or impacts of an event, which requires consistent comparison between the observed factual simulation and alternative simulations, so called “counterfactual” simulations. The modelling framework described here supports this process by enabling these alternative simulations to be configured and analysed within the same workflow.

When comparing a factual scenario against counterfactuals simulations, the comparison between them needs to be done in such a way that changes are isolated, so the results can be informative regarding the role of the changed driver. In this repository, we focus on single event attribution due to climate change, and we set the factual event as the baseline scenario, and the counterfactuals as the pre-industrial versions where no climate change influence exists. Note that the selection of the baseline scenario can vary in the attribution literature, with some studies selecting the pre-industrial versions as the baseline. Different counterfactual scenarios can be intercompared to explore the climate change role at different levels. In the *analysis_examples/climate_attribution/scripts*, the standard approach is to run the attribution analysis based on the type of output produced. That translates to first a hazard level analysis, more specifically comparing the flood maps in terms of volume, extent and depth, between the scenarios, which are based on a combination of DFM, wflow and SFINCS runs. Then, if the experiment includes impact simulation, there are also scripts to compare financial damages (based on Delft-FIAT) and population exposure (based on WorldPop data) between scenarios. This allows an understanding of the role of each driver at different levels, from an initial

meteorological domain (changes in temperature and precipitation) to hydrological and inundation changes, and finally to impact changes. These all contain non-linear elements that can influence the attribution magnitude at different levels of analysis between the same two scenarios. For every metric, the attributable change is reported as a percentage of the factual: $(\text{factual} - \text{counterfactual}) / \text{factual} \times 100$. A positive value means climate change increased that metric. Spatially, attribution is shown as a difference map (factual minus counterfactual) on a diverging colour scale centred at zero.

Across the main counterfactual elements of an event in this repository to be changed for an attribution analysis, we have: 1) precipitation, 2) sea level, and 3) wind. Precipitation is scaled following the Clausius-Clapeyron scaling, which means –8% of precipitation for 1°C of cooling, so the user can provide the temperature difference in Celsius. Sea level is scaled based on a constant absolute value in meters according to user decision. Wind can also be scaled based on user needs as a % value of the factual event. Each combination of variables changed leads to a different counterfactual scenario, so the user can isolate which variable or dynamics they want to explore, including compound effects.

3.4 Framework application

3.4.1 Guidelines for how to get started

Now that the conceptual building blocks of the workflow have been explained, Table 3-1 gives an overview of the workflow structure within the *Workflows* folder. We also indicate where most of the user adjustments are expected.

Table 3-1 Overview of the steps and possible adjustments for the compound flood modelling framework

Folder or file	Objective/ Purpose	Typical user adjustments
<i>README.md</i>	Information about the subfolders, expected input and output	n/a
<i>00_execution_script_examples/</i>	Example bash script to run the workflow on a HPC environment	Environment paths, cluster commands
<i>01_config_snakemake/</i>	Example of configuration files for the snakemake workflows developed	This whole file should be adapted by the user to define the region domain, event time, input/output root paths, specific input datasets and model config files and specific settings, etc.
<i>02_workflow_rules/</i>	snakemake workflows developed	Little to no adjustment needed
<i>03_data_catalogs/</i>	Example of data catalogs that lists and uniformises data ingestion by the different models	The user needs to adjust the data catalogs for the sets of input datasets (meteorological, bathymetry, topography, land cover, etc) to be used in the models
<i>04_scripts/</i>	Sets of scripts called in the snakemake workflows and categorised by model type (e.g. wflow, SFINCS, etc.) or workflow step (e.g. pre-processing)	Little to no adjustment needed
<i>05_config_models/</i>	Example of model configuration files for each model considered in the workflow (except for Delft3DFM)	The user can adjust any further model settings in these files, other than the options available in the main config file (in folder <i>01_config_snakemake</i>).

Therefore, to adjust the workflow, the following steps are recommended:

- Step 1: Review the workflow structure and prerequisites (see *README.md*/)

- Step 2 (optional): Adapt the bash script for execution on a HPC cluster to your specific cluster requirements (see *00_execution_script_examples/*)
- Step 3: Set case-study main configuration file (for e.g. domain, time frame, datasets, etc) (see *01_config_snakemake/*)
- Step 4: Repoint and harmonize datasets by setting up your data catalog (see *Workflows/03_data_catalogs/*)
- Step 5: Tune model settings (*Workflows/05_config_models/*)
- Step 6: Run the workflow by calling the appropriate workflow using Snakemake (*Workflows/02_workflow_rules/*)
- Step 7 (not part of the automated workflow): perform the model validation and impact attribution (*analysis_examples/*)

Annex A shows an example for the resulting main configuration file (step 3) for the Use Case phase II of tropical cyclone Idai (also available at this [link](#)). In this case, we did not use the Delft3DFM model (`use_dfm = False`), nor the wave model (`use_wave = False`) but only the wflow (`use_wflow = True`) and SFINCS models. The configuration files explicitly mention the use of ClimateDT climate data for the rainfall and the wind (stored as “ClimateDT_hist” in the data catalog).

3.4.2 General remarks when applying the framework

The modelling framework provides a structured and reproducible basis for analysing compound flood hazards, including when driven by tropical cyclones. Since it relies largely on globally available datasets, open-source tools and automated workflow components, it can be transferred to different regions and events with limited changes to the workflow logic. This makes it valuable for consistent case-study applications, sensitivity analyses and counterfactual simulations, and for bringing together hydrological, coastal hydrodynamic and local flood processes in one modelling chain.

At the same time, the framework should not be applied as a fully generic black-box system. Experience from applying the framework throughout the use cases’ applications for flooding shows that each application requires local choices and expert judgement, for example in defining model domains, selecting input datasets, and assessing whether default model settings are appropriate. The availability and quality of validation data may also differ strongly between regions, which affects how confidently the model outputs can be interpreted.

The framework therefore requires a certain level of expertise in hydrological and hydrodynamic modelling, workflow configuration and result interpretation. Users are responsible for providing suitable application-specific information, adapting configuration files where needed, checking that the data catalogs and auxiliary files are valid for the selected region, and validating the results against available observations or reference products. When applied with these checks, the framework offers a transparent and reusable approach for compound flood modelling, while making the assumptions and limitations of each application explicit.

4 Heatwaves and droughts framework

4.1 Introduction

The primary objective of this extreme modelling framework is to isolate and quantify the explicit impact of heatwaves and droughts on agricultural crop yields across Poland. To achieve this, a prototype (Terefenko et al., 2026) integrating multiple datasets and processing components was developed as part of D5.1 (Terefenko & Ślodziński, 2025). These datasets and components include meteorological observations from Copernicus Climate Change Service products, climate data processing and bias-adjustment and statistical downscaling (BASD) workflows (Ślodziński et al., 2026), tools for counterfactual simulations generated with the ATTRICI statistics-based counterfactual climate data toolbox (Mengel et al., 2021), and impact assessment workflows based on crop yield prediction models.

We provide here a concise overview of the heatwave and drought workflow within the broader compound extremes modelling framework described in this deliverable. Its purpose is not to duplicate the full technical documentation, but to summarise the main workflow logic, the datasets and tools involved, and the way in which the framework supports attribution-oriented impact assessment. A detailed technical description of the tools developed and integrated within the modelling framework for heatwave- and drought-related impact assessment, including their implementation, configuration, reproducibility procedures, and source code, will be provided in the forthcoming Deliverable D5.3, “Open-source software development”. D5.3 will document the individual software components supporting the processing of factual and counterfactual climate data and their integration within the operational modelling workflow, providing the necessary resources for reproducing, adapting, and further developing the framework for heatwave and drought applications.

4.2 Automated modelling framework

Figure 4-1 illustrates the complete extreme modelling workflow and the interdependencies between the individual processing steps and datasets. The workflow starts with the acquisition of ERA5 and ERA5-Land meteorological data, which are processed into a consistent format before being combined with the EMO-1 observational dataset. The EMO-1 and ERA5-Land datasets are subsequently harmonized over their respective historical periods and prepared for the BASD procedure using Inter-Sectoral Impact Model Intercomparison Project 3 (ISIMIP3) BASD (Lange, 2019). As part of this process, EMO-1 is spatially downscaled to match the ERA5-Land grid, while both datasets undergo the required preprocessing before BASD is applied. The resulting bias-adjusted ERA5-Land data are then reformatted and combined with the processed ERA5 information to produce a continuous, gap-filled meteorological dataset suitable for the subsequent impact-modelling steps.

The processed meteorological data are then used to derive additional climate variables required for the agricultural impact assessment. In particular, the LISVAP model (Van der Knijff, 2006) is used to calculate evaporation and evapotranspiration-related time series. Subsequently, these timeseries are incorporated into the climate dataset used by the crop modelling framework. In parallel, the processed and gap-filled meteorological data provide the input for ATTRICI (Mengel et al., 2021), which generates the counterfactual climate dataset representing conditions in the absence of the historical anthropogenic climate-change signal. The factual and counterfactual climate datasets can therefore be evaluated consistently within the same modelling chain and linked with observed crop-yield measurements in the final stage of the workflow. This allows the framework to quantify differences in crop-yield impacts between the observed climate and the corresponding counterfactual climate conditions.

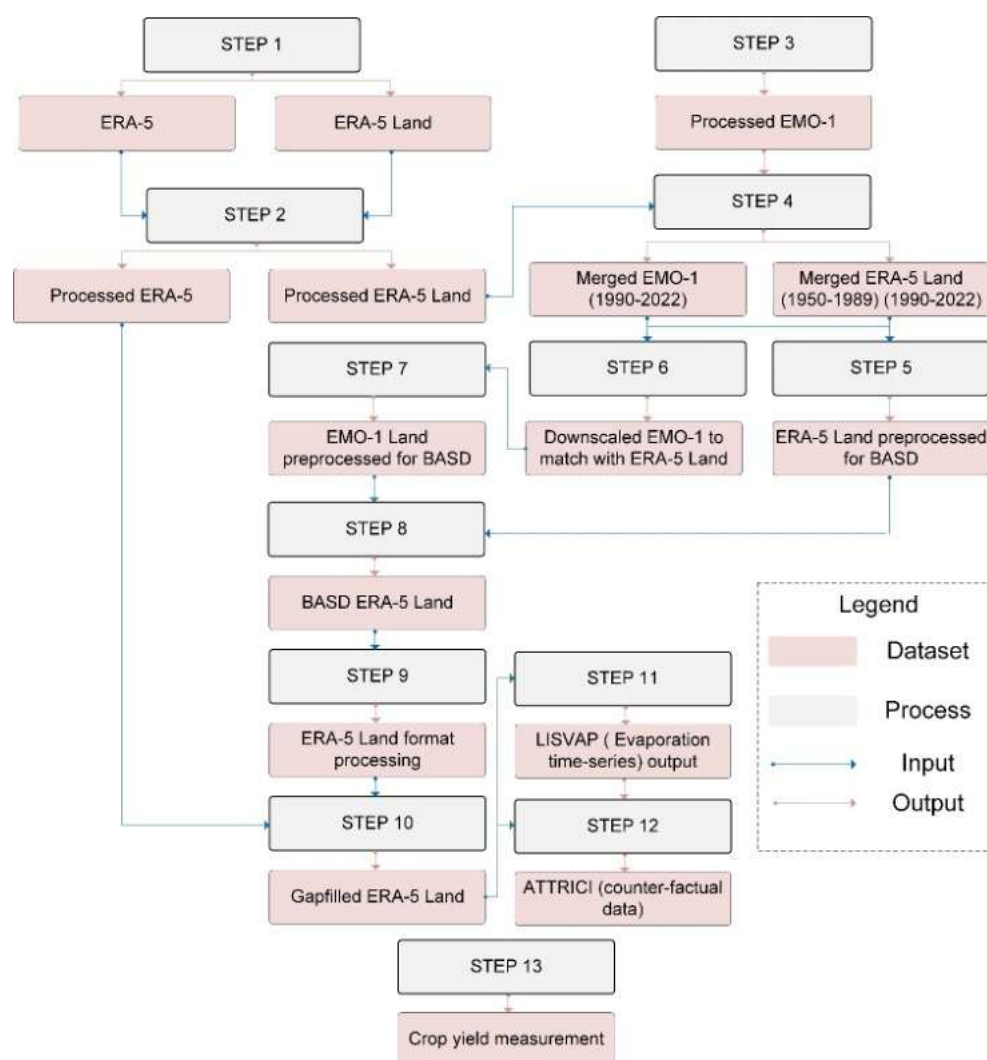


Figure 4-1 Schematic workflow diagram showing complete data collection, processing, merging of factual and counterfactual data

4.3 Framework application

4.3.1 Guidelines for how to get started

The repository includes a [step-by-step guide](#), dedicated processing scripts, environment files and workflow folders that document the main processing chain from data acquisition to the generation of factual and counterfactual datasets.

To adjust the workflow to a specific use case, users can change the following:

- Set their local output/work directories
- Choose the study period
- Change the spatial domain / grid
- Adjust which variables are processed
- Adapt dataset-specific assumptions if they are not using the same ERA5-Land + EMO-1 setup
- Optionally adapt the LISVAP step if they want PET output

Since the workflow is sequential, changes early in the workflow propagate to later steps. Users should first define the scope of the application, including the geographical domain, target period, climate extreme or compound event of interest, required variables and intended impact indicator. These choices determine which parts of the workflow need to be modified. In practice, the main components to adapt are the step-by-step

guide and the corresponding processing scripts in the repository under the */SCRIPTS/* folder (e.g. step 1 refers to script *1_step_1.sh*, step 2 to *2_step_2.sh*, etc.).

Following Figure 4-1, Table 4-1 suggests adjustment that can be made.

Table 4-1: Overview of the steps and possible adjustments for the heatwaves and droughts framework

Step	Objective	Changes possible
1	ERA5/ERA5-Land download	Study period, region, ERA5 variables
2	ERA5 daily processing	Study period, other variables
3	EMO-1 download / preprocessing	Other observational reference dataset
4	Merge datasets	Difference in calibration and observation period
5	ERA5-Land preparation for BASD	Chunk size, different study period, different variables
6	EMO-1 remapping	Different target grid, other remapping method, other variables
7	EMO-1 reference preparation	Variables selected, chunk size, aggregation level
8	BASD setup	Difference in calibration period, other variables, thresholds, distributions, different observational/model pairing changes
9 & 10	- conversion of BASD output back to EMO-1-style format - final post-processing - preparation for downstream hydrological/PET workflows	Naming convention, units based on the variables selected
11	LISVAP	Simulation period and region

Therefore, the following approach is advised:

- Start from *step-by-step-guide.ipynb* and *README.md*
- Set up environment and external tools
- Edit all scripts to use a new shared base directory
- Change Step 1 domain and period
- Verify Step 2 and Step 3 variable/unit assumptions match your datasets
- Update all hard-coded date ranges in Steps 4–8
- Tune BASD options in Step 8 for your variables
- Only then adapt Steps 9–11 if you need hydrology/PET outputs

4.3.2 General remarks when applying the framework

The framework was initially developed for the assessment of heatwave- and drought-related impacts on crop yields, but several components of the workflow are sufficiently valid to support the modelling of other climate extremes. In particular, the automated acquisition and preprocessing of climate datasets, the BASD framework for bias correction and downscaling, the generation of factual and counterfactual climate datasets with ATTRICI, and the spatial and temporal aggregation procedures can be reused or adapted for other applications. Depending on the extreme considered, the hazard-specific indicators and the downstream impact model would need to be modified. For example, the current drought-related indicators and crop yield prediction model could be replaced with extreme precipitation indices and a hydrological or flood-impact model when

assessing flooding, while temperature-based indicators could be adapted for the assessment of cold spells or frost events. This modular structure therefore allows the framework to serve as a broader climate-impact attribution workflow rather than being restricted exclusively to heatwaves and droughts.

The framework is particularly relevant for assessing how anthropogenic climate change has altered the likelihood, intensity, or impacts of climate extremes by consistently comparing outcomes under factual and counterfactual climate conditions. Nevertheless, its application to other extremes requires careful validation and should not be interpreted as universally transferable without modification. BASD can reduce systematic differences between climate-model output and observations, but they cannot correct deficiencies in the underlying physical representation of climate processes or generate information that is absent from the original data (Chandel et al., 2024). Similarly, a method that performs well for temperature or drought-related variables may not necessarily reproduce short-duration, highly localized, or compound extremes with the same level of reliability. The framework should therefore not be used as a substitute for dedicated process-based models where these are required, nor should its outputs be interpreted as deterministic predictions of individual future extreme events. Its results are most appropriately used for comparative attribution and impact assessment, with uncertainties related to the input datasets, downscaling procedure, counterfactual construction, hazard definition, and impact model explicitly considered.

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6 Annex A

We show below the main configuration file for the Use Case phase II of tropical cyclone Idai for the factual simulation from the ClimateDT storylines (also available here: https://github.com/HORIZON-COMPASS/compound-flooding-tropical-cyclones/blob/main/Workflows/01_config_snakemake/config_general_MZB_ClimateDT.yml#L1).

```

1  # Defining parameters to run the snakemake pipeline
2
3  root_dir: 11210471-001-compass # root directory of your project, it is appended to the disk drive name specified in the smk files (e.g. c:/ or p:/)
4  dir_data: 01_Data
5  dir_models: 02_Models # Folder where the base models will be saved (without dynamic forcing data)
6  dir_runs: 03_Runs # Folder where model runs will be saved (with forcing)
7  runname_ids:
8      Idai_ClimateDT_hist: # name of the model run
9      # Settings of the workflow
10     tc_name: Idai # name of the storm. For tropical cyclones, this can be the name of the TC
11     region: sofala # name of the region will be used in naming folders
12     continent: Africa # name of the continent for Delft-FIAT
13     country: Mozambique # name of the country for Delft-FIAT
14     config_fiat_base: fiat_base_build.yml # name of the Delft-FIAT configuration file
15     lulc_mapping_sfincs: vito_mapping_sfincs # land-use -> SFINCS manning mapping table
16     lulc_mapping_wflow: vito_mapping_wflow # land-use -> wflow parameter mapping table
17     wflow_meteo_forcing: era5_hourly_zarr # forcing dataset containing temperature, in- and out-going radiation
18     CF_landuse: [vito] # data catalog handles of land use scenarios
19     sid: 2019063518038 # Storm id from IBTrACS
20
21     # For all model setups
22     start_time: 20190309 000000
23     end_time: 20190325 060000
24     precip_forcing: ClimateDT_hist # forcing dataset for the rainfall data (matching to the DataCatalog handle)
25
26     wind_forcing: ClimateDT_hist # spw_IBTrACS # wind and pressure dataset (used for coastal surge modelling)
27     bathy: 'gebco2024_MZB' # DataCatalog handle for the bathymetry dataset
28     river_upa: 100 # minimum upstream area threshold for the SFINCS and wflow [km2]
29
30     # Models selections
31     use_dfm: False # use the coastal hydrodynamic model D-FM
32     use_wflow: True
33     use_waves: False # use the hydrological model Wflow
34
35     # DFM model user-defined settings
36     bbox_dfm: "[32.3,42.5,-27.4,-9.5]" # Bounding box for the coastal hydrodynamic model in format: [lon_min, lon_max, lat_min, lat_max]
37     dfm_res: '450' # coastal hydrodynamic model maximum (finest) resolution in meters (resolution at the coast)
38     dfm_dxy_base: '0.2' # coastal hydrodynamic model base grid resolution in degrees (this is the width of the largest grid cells)
39     dfm_obs_file: coastal_coupling_DFM_obs_points_MZB # DataCatalog handle for the coastal points used to couple coastal hydro model D-FM and the flood model SFINCS
40     dfm_coastal_mask: coastal_coupling_msk_MZB # DataCatalog handle for the coastal coupling mask
41     dfm_verification_points: dfm_verif_points_MZB # DataCatalog handle for the additional points where D-FM output will be saved for validation purposes
42     tidemodel: 'GTSMv41' # tidal model for boundary conditions as can be read by dfm tools: FES2014, FES2012, EOT20, GTSMv4.1, GTSMv4.1 opendap
43
44     #Wflow model user-defined settings
45     config_wflow_base: wflow_base_build_general.yml # name of the wflow configuration file under 05_config_models/01_wflow (default: wflow_base_build.yml)
46     use_bankfull_corr: True
47     bankfull_corr_lulc: vito # Factual landuse when using bankfull correction from 30 yr wflow run
48
49     # SFINCS model user-defined settings
50     bbox_sfincs: "[34.33,-20.12,34.95,-19.30]" # Bounding box for the flood model in format: [lon_min, lat_min, lon_max, lat_max]
51     config_sfincs_base: sfincs_base_build.yml # name of the SFINCS configuration file (default: sfincs_base_build.yml)
52     sfincs_obs_file: obs_locs_sofala.geojson
53     utmzone: 36s # UTM zone (needed by SFINCS, see https://www.latlong.net/lat-long-utm.html)
54     coastal_ts: dfm_output_event_450_gebco2024_MZB_GTSMv41_CF0_era5_hourly_spw_IBTrACS_CF0_waves # DataCatalog handle for the coastal boundary conditions if D-FM is NOT used
55
56     # Delft-FIAT user-defined settings
57     #continent: Africa # name of the continent for Delft-FIAT
58     #country: Mozambique # name of the country for Delft-FIAT
59     #config_fiat_base: fiat_base_build.yml # name of the Delft-FIAT configuration file (default: fiat_base_build.yml)
60
61     # Counterfactual forcing settings
62     CF_value_rain: [0]
63     CF_value_wind: [0]
64     CF_value_SLR: [0]

```