climate ready regions

Deliverable D2.2 – Report on hazard tools of relevance to the CRA Toolbox

WP2 – Co-design of the supporting toolbox

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HORIZON-MISS-2021-CLIMA-02-01 - Development of climate change risk assessments in European regions and communities based on a transparent and harmonised Climate Risk Assessment approach

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Document Information

Deliverable Title	Report on hazard tools of relevance to the CRA Toolbox
Brief Description	The deliverable describes the hazard datasets used in the CLIMAAX Climate Risk Assessment Toolbox. Each dataset is described and catalogued, including technical specifications. Brief description regarding the uncertainty in the datasets is provided and the need for new datasets to support a more detailed Climate Risk Assessment is discussed.
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Table of Contents

Document Information 2
Table of Contents 4
List of figures 6
List of tables 6
List of abbreviations and acronyms 7
Executive summary 8
1. Introduction 9
2. Concept and assessment methods 10
2.1. Hazards as climate risk drivers 10
2.2. Criteria for hazards' selection 12
3. Database of pan-European hazard data 14
3.1. Data selection and data portals 14
3.1.1. Copernicus Climate Change Service: Climate Data Store 14
3.1.2. Disaster Risk Management Knowledge Centre's Risk Data Hub 15
3.1.3. Other data sources 15
3.2. Data records 15
3.3. Hazard data and tools in the CRA Toolbox 17
3.3.1. Generic data: observations, reanalysis, climate projections 17
3.3.1.1. ERA5 and ERA5-Land global reanalysis 18
3.3.1.2. EURO-CORDEX regional climate model data 18
3.3.1.3. Inter-Sectoral Impact Model Intercomparison Project 19
3.3.1.4. Uncertainties in Ensembles of Regional ReAnalysis 19
3.3.2. Hazard data 19
3.3.2.1. River flood 20
3.3.2.2. Coastal flood 20
3.3.2.3. Flood damage and population exposure 21
3.3.2.4. Multi-risk workflow 21
3.3.2.5. Extreme precipitation 22
3.3.2.6. Relative drought 22
3.3.2.7. Agricultural drought 23
3.3.2.8. Drought exposure 24

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3.3.2.9. Heatwave 25
3.3.2.10. Wildfire 25
3.3.2.11. Windstorm 26
3.3.2.12. Heavy snow and blizzard 27
4. Data limitations 28
4.1. Uncertainties in hazard datasets 28
4.1.1. Generic data 28
4.1.2. Coastal flood 30
4.1.3. River flood 30
4.1.4. Drought 31
4.2. Need for new datasets 31
5. Conclusions 32
6. References 33

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List of figures

Figure 1: Changes in the IPCC Risk Framework 11
Figure 2: The hazards included in the CLIMAAX CRA Toolbox 13
Figure 3: screen shot of the hazard data inventory table 16

List of tables

Table 1. Attributes specified for the hazard datasets and their description. 16

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List of abbreviations and acronyms

Abbreviation / acronym	Description
API	Application Programming Interface
AR	Assessment Report
C3S	Copernicus Climate Change Service
CDI	Combined Drought Indicator
CDS	Climate Data Store
CMIP	Coupled Model Intercomparison Project
CRA	Climate Risk Assessment
DEM	Digital Elevation Model
DRMKC	Disaster Risk Management Knowledge Centre
ECMWF	European Centre for Medium-range Weather Forecasts
EDO	European Drought Observatory
EU	European Union
FAIR	Findable, Accessible, Interoperable and Reusable
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
GCM	Global Climate Model
GRIB	General Regularly distributed Information in Binary form
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
JRC	Joint Research Centre
NetCDF4	Network Common Data Form version 4
NUTS	Nomenclature of Territorial Units for Statistics
RCP	Representative Concentration Pathways
RDLS	Risk Data Library Standard
SSP	Shared Socioeconomic Pathways
UNDRR-ISC	UN Office for Disaster Risk Reduction - International Science Council
WASP	Weighted Anomaly of Standardised Precipitation

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Executive summary

This deliverable D2.2 “Report on hazard tools of relevance to the CRA Toolbox” describes pan-European datasets used in the CLIMAAX Climate Risk Assessment (CRA) Toolbox, which either directly quantify climate hazards, or more generic datasets which are used within the CRA Toolbox to compute the former. It also provides a hazard data inventory table[1], including 40 data entries, with technical specifications of each dataset. Most ready datasets catalogued here are publicly available under the FAIR[2] principle (= Findable, Accessible, Interoperable and Reusable). However, we also catalogue datasets which are computed within the CRA Toolbox and not saved or stored anywhere. In these cases, the codes which produce these datasets are freely available under the Apache 2.0[3] license and thus easily reproducible.

Before presenting the hazard data inventory table, the deliverable first defines climate hazards as drivers of climate risk. We then describe how the hazards, which are currently considered in the CRA Toolbox, were selected. The CRA Toolbox is organised into separate workflows, each of which analyses the risks due to one or several climate hazards. There may also be several workflows analysing risks due to the same hazard. Descriptions of how the respective hazards are assessed are provided in the CLIMAAX deliverable *D2.4 “Report on integrated risk assessment tools of relevance to the CRA Toolbox”*. The hazard data inventory table itself is presented by first describing the criteria used for data selection (FAIR principles) and the data portals used, followed by a description of the data records, as well as a description of the most prominent datasets used in the CRA Toolbox. As pan-European hazard data are subject to a range of limitations, data uncertainties are discussed to create awareness of these issues. Last, needs for new datasets that are currently missing are raised as well.

[1] https://docs.google.com/spreadsheets/d/1esRRDgI_kXyiwai3fR_Q1vz-cUfcyWquGE2CHjqtiCY/edit?usp=sharing
[2] See Deliverable 8.2 “Data Management Plan” for further information on FAIR principles.
[3] http://www.apache.org/licenses/LICENSE-2.0

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1. Introduction

During the pilot phase of the CLIMAAX project, we designed a so-called toolbox for doing the data analysis part of a climate risk assessment (CRA). The CRA Toolbox is composed of a selection of workflows, which are fully executable Python scripts using a set of input datasets to produce climate risk maps which can then be used in CRAs. The CRA Toolbox is part of a wider framework (the CRA Framework), which outlines the steps which need to be taken before and after the data analysis part. The CRA Framework and Toolbox have been published as the CLIMAAX Handbook[4] for regional climate risk assessment.

The data analysis part performed in the CRA Toolbox workflows is based on the Intergovernmental Panel on Climate Change (IPCC) definition of risk (Ara Begum et al., 2023), combining hazard, exposure, and vulnerability data. In this deliverable we concentrate on the hazard datasets which have been used in the CRA Toolbox workflows at the time of the publication of this report. The exposure and vulnerability datasets as well as the risk assessment workflows are described in the CLIMAAX deliverables *D2.3 "Report on pan European vulnerability and exposure projections"* and *D2.4 "Report on integrated risk assessment tools of relevance to the CRA Toolbox"*, respectively. It is noteworthy that some of the workflows are using readily produced hazard data which can be freely downloaded from existing data portals, while other workflows derive the hazard data they need from more generic datasets. This will be outlined in more detail in the sections below. Furthermore, it should be noted that many of the workflows were developed as examples of how a risk analysis may be performed in principle, therefore using freely available datasets with either European or global coverage, so that results could be obtained for any region of Europe. The idea was then for the users to use their own, higher resolution and possibly regional datasets to customise the example workflows to their own special needs.

The CRA Toolbox workflows were tested by the five CLIMAAX pilots, which also included the afore mentioned customisation of the workflows to the special regional needs. Some of the workflows were also designed with already a specific pilot region in mind. Here then, out-of-the-box functionality for any European region may not be guaranteed and may require own data input from the user right away.

This document is organised in the following way: To put the used hazard datasets into context, Section 2 generally introduces the use of hazard data in risk assessment and lays out the criteria/process for hazard selection in the CLIMAAX project. In Section 3, the criteria for selecting the datasets used in the workflows are described and a compiled hazard data inventory table is introduced, followed by a more detailed description of the datasets used and produced within the workflows. In Section 4, the limitations and need for new datasets are discussed, before providing the concluding remarks in Section 5.

[4] https://handbook.climaax.eu/intro.html

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2. Concept and assessment methods

Section 2 is organized as follows. First, the definition and types of hazards as well as their importance in CRA is discussed in Section 2.1. This is followed by a description of the criteria according to which the hazards assessed in the CLIMAAX project were selected in Section 2.2. A more detailed description of the workflows is given in *D2.4 "Report on integrated risk assessment tools of relevance to the CRA Toolbox"*.

2.1. Hazards as climate risk drivers

Climate-related hazards have traditionally been prominently featured in the conceptualization of climate risk, often dominating the discourse. In this context, the IPCC Assessment Reports (ARs) have played a key role in shaping the role of hazard in climate risk conceptualization, as it is essential for understanding the potential intensity, frequency, and spatial distribution of climate risk. Hazard has been defined as *"[t]he potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources*." (IPCC, 2023)[5].

Taking up concepts from the Disaster and Risk Reduction field (such as vulnerability) allowed for a shift of perspective for society from passive respondents to climate hazards towards active sculptors of their climate risk and climate resilience. The fourth IPCC AR (IPCC, 2007) was the first report to consider the multifaceted nature of climate risks by linking risk not only to hazard but also vulnerability. The subsequent evolution of the "Risk Propeller" throughout IPCC's Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation taken up in the fifth and sixth IPCC AR further emphasized the strong role of hazard as a driver of climate risk but also contextualized it within the three other drivers of climate risk, namely, Vulnerability, Exposure and, most recently, Response (Figure 1). This shift in perspective therefore came with additional leverage points that go beyond greenhouse gas mitigation efforts which are relevant for hazard reduction.

[5] WGI uses the term "Climatic Impact Driver" when referring to hazard to avoid positive or negative framing (IPCC, 2021).

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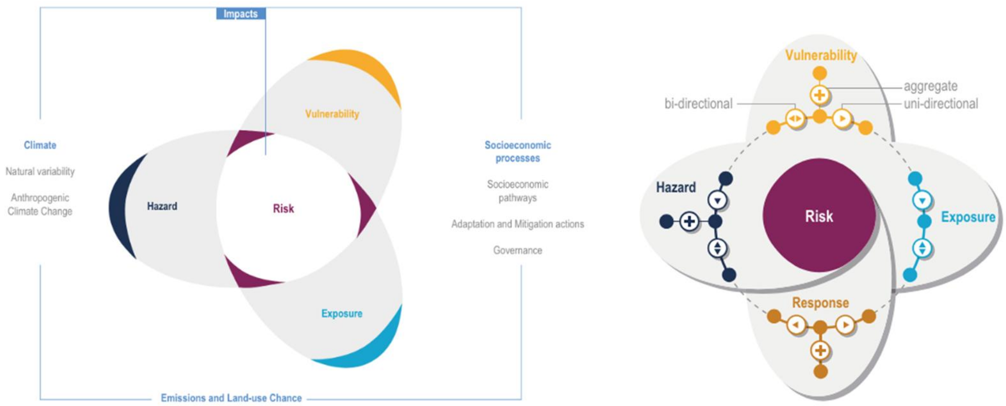

Figure 1: Changes in the IPCC Risk Framework from a) hazard as one of three risk drivers to b) hazard as one of four risk drivers (Ara Begum et al., 2023).

Different approaches have been pursued to develop hazard categorization, which is crucial to systematically assess risk. Some frameworks provide a hazard classification for a specific typology such as floods/precipitation, droughts, heatwaves, cold spells, wind, landslides, coastal hazards, wildfire, water scarcity (Oppenheimer et al., 2014). Another classification method is grouping hazards as intensive or extensive events, where intense events are spatially concentrated, and extensive events refer to more diffused and small-scale events (Lam and Lassa, 2017). This relates to the conceptualization of hazards as sudden- or slow-onset events (UNFCCC, 2012; Seneviratne et al., 2021). While sudden-onset events, such as floods, storms and heatwaves, can generally be characterized by the frequency[6], intensity, and duration of events, slow-onset events, such as desertification or sea level rise, can be assessed based on indicators over time.

Further, multi-hazard approaches are gaining increased attention as the impacts of climate change are felt across multiple dimensions. However, analysing how different hazards coincide, amplify and cascade towards compound risks (Aznar-Siguan and Bresch, 2019, Parker et al., 2019) remains a complex challenge. Multi-hazard events can be studied from two different angles: a) by investigating how they coincide to drive impacts and risks (van den Hurk et al., 2023) and b) by analysing climate hazards and their interrelationships in time and space (e.g., triggering, amplifying, independent or compound; Ward et al., 2022).

[6] Frequency is generally used to derive estimates of return periods (such as for 100-year flood events).

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Examples of compound hazards

Sea level rise may exacerbate impacts of storm surge and coastal floods.

Droughts may increase the risk of wildfire.

Changes in precipitation patterns may lead to floods or water scarcity.

To systematically assess risks, it is crucial to properly characterize hazards. Sudden-onset hazards, such as floods, storms and heatwaves, can generally be characterized by the frequency[7], intensity, and duration of events. On the other hand, slow-onset events, such as drought or sea level rise, can be assessed based on deficits in precipitation over time. Studies have developed hazard metrics and indicators to systematically characterize and rank the severity of climate hazards (Lung et al., 2013, Torresan et al., 2016, Ronco et al., 2017). Hazard maps can spatially represent the location and features of hazards. These may include multi-hazard risk maps (Gallina et al., 2020) or use an impact chain approach for tracing how hazards propagate and aggregate through systems to generate risk conditions (Melo-Aguilar et al., 2022, Menk et al., 2022, Zebisch et al., 2022). Lastly, Machine Learning techniques (Zennaro et al., 2021), Earth Observation imagery (Kotchi et al., 2019), and Big Data approaches (Pollard et al., 2018) have been applied to improve hazard characterization and forecasting by enhancing real-time detection, prediction and monitoring.

2.2. Criteria for hazards' selection

The climate-related hazards included in the CRA Toolbox were defined through a multi-stage process in close collaboration with WP3 and were based on the needs of the pilots. The identification of hazards involved interviews with the pilots, followed by scoping sessions during which the pilots listed the hazards with the highest risk for their region. A detailed description of the results from the interviews, including the hazards identified by the pilots, is presented in *D2.1 "Report on the specifications for the toolbox methods"*. The pilots identified some of the same climate-related hazards. Fluvial or coastal flooding, heavy rainfall, windstorms and heatwaves were identified by all pilots, whereas droughts and forest fires were identified by all pilots except Zilina. Several other meteorological hazards such as heavy snowfall and blizzards, frost, thunderstorms, tornadoes, hail, irregular precipitation, and sea level rise were identified as high impact risks. During the scoping sessions with the pilots, the list of hazards was narrowed down together with the pilots by focusing on the most frequent and high impact risks and hazards and identifying 2-3 hazards for each pilot, considering both the European and local scale. These included floods, temperature-, precipitation- and wind-related hazards, and windstorms. The selected hazards were cross-checked with the climate-related hazards listed in the UN Office for Disaster Risk Reduction - International Science Council (UNDRR-ISC) Hazard Definition and Classification report (Murray et al., 2021). The hazards currently included in the CRA Toolbox are listed in Figure 2.

[7] Frequency is generally used to derive estimates of return periods (such as for 100-year flood events).

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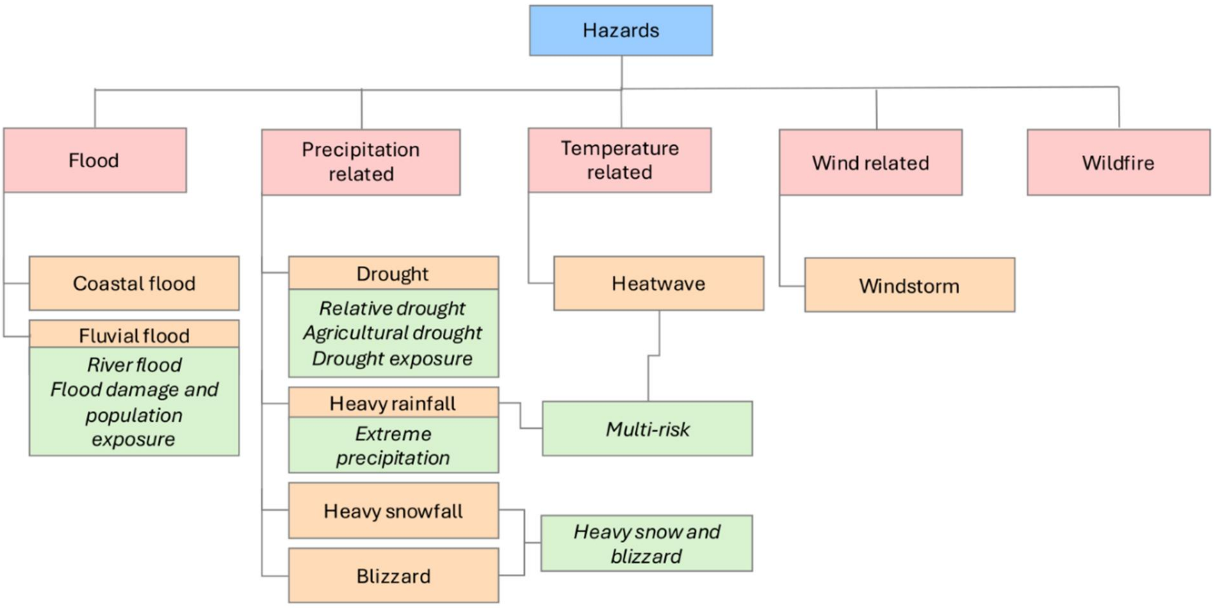

Figure 2: The hazards included in the CLIMAAX CRA Toolbox. The classification of hazards is aligned with the UN Office for Disaster Risk Reduction - International Science Council (UNDRR-ISC) Hazard Definition and Classification report (Murray et al. 2021). The names of the workflows in the CRA Toolbox are highlighted in green if they differ from the hazard name (marked in orange).

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3. Database of pan-European hazard data

The hazard assessment workflows in the CRA Toolbox use a wide range of generic data (i.e. meteorological data from observations, reanalysis or climate projections) and hazard datasets (describes a hazard and is calculated/derived from generic data, e.g. flood maps for different return periods). The data selection and data sources are discussed in Section 3.1. In Section 3.2., a compiled hazard data inventory table that includes the data used and produced in the CRA Toolbox is introduced and described. Last, in Section 3.3., the generic and hazard data used and produced in the hazard assessment workflows of the CRA Toolbox are described.

3.1. Data selection and data portals

In the last decade, a vast amount of climate data has been made available through various data portals, including both generic and hazard datasets. Rather than producing new hazard datasets, the CLIMAAX project aimed to first identify and use existing hazard data (e.g. existing flood maps) for the CRA. Where it is not possible to obtain open, high-resolution datasets needed in the CRA, new datasets are generated through the hazard assessment workflows. Two existing data portals were identified for generic and hazard datasets: the Copernicus Climate Change (C3S) Climate Data Store (CDS)[8] and the Disaster Risk Management Knowledge Centre's (DRMKC) Risk Data Hub[9].

3.1.1. Copernicus Climate Change Service: Climate Data Store

The EU-funded C3S has the aim to provide authoritative, quality-assured information to support adaptation and mitigation policies in a changing climate. At the heart of the C3S infrastructure is the CDS, which provides Essential Climate Variables, climate analyses, reanalyses, projections, and indicators at temporal and spatial scales relevant to adaptation and mitigation strategies for various sectoral and societal benefit areas.

The CDS is designed as a distributed system which provides access to local and remote datasets via a powerful service-oriented architecture. It offers seamless web-based and API-based search and retrieve facilities to access climate data and information. The data provided by the CDS are free and open data, subject to the user agreeing to the relevant dataset licence(s).

At the time of the writing of this deliverable, all the layers of the CDS infrastructure are being modernised: the front-end web interface, the back-end software engine and the underlying cloud infrastructure hosting the service and core data repositories. When the new CDS is launched, the documentation in the CLIMAAX Handbook and all the examples of using the data from the CDS will be updated.

The use of CDS data within the CLIMAAX project is expected to be simplified, as the same European Centre for Medium-range Weather Forecasts (ECMWF) accounts will be used for the work in

[8] https://cds.climate.copernicus.eu/#!/home

[9] https://drmkc.jrc.ec.europa.eu/risk-data-hub/#/

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CLIMAAX, for downloading the hazard data, participating in the user forum[10] and asking for technical support.

3.1.2. Disaster Risk Management Knowledge Centre's Risk Data Hub

The European Commission DRMKC Risk Data Hub offers access to European wide risk data for a range of hazards. The Risk Data Hub allows access to risk data for specific hazards and a data viewer to interactively explore geospatial data of specific hazards (e.g., floods, forest fires and windstorms) overlayed with exposure data (e.g., population and buildings data) at a European level.

3.1.3. Other data sources

In addition to the data available on the platforms discussed above, we have also included hazard datasets available from other portals or from CLIMAAX project partners. The data included in this inventory had to meet the following criteria: the datasets have either European or global spatial coverage, have as high as possible spatial resolution, and must be openly available. Additionally, the data used in the workflows are quality assessed and already comply with the Findable, Accessible, Interoperable and Reusable (FAIR) guiding principles.

In the case that some data sets produced during the project will be published later, this will be done following the four FAIR principles (Wilkinson et al., 2016) as discussed in *D8.2 "Data Management Plan"*: data will be Findable (through standards for identification and rich metadata), Accessible (how data are accessed during and after the project lifetime), Interoperable (defining sharing policy and integration into workflows) and Reusable (including clear licensing and correct formatting of data and metadata).

We note that the hazard data derived/calculated in the CRA Toolbox may not be findable because they may be temporary datasets (i.e. are not saved). Nevertheless, the methodologies and codes used for generating the data are public, making the datasets easily reproduceable.

3.2. Data records

During the development phase, the CLIMAAX partners first performed a review of available pan-European hazard datasets which are potentially useable in the CRA Toolbox. This work resulted in a rather large table of data entries but containing only a few criteria for data categorisation. We here include a link to the table for completeness, but do not describe it further[11]. During the further development of the CRA Toolbox, it became apparent that only some of the datasets listed in the original table would actually be used in the workflows and, more importantly, that many of the hazard data used would have to be calculated from generic data by the workflows. We therefore compiled a second table, called hazard dataset inventory table[12] (see Figure 3 for a screenshot) which includes the hazard datasets available and used and/or produced in each of the CRA Toolbox workflows. A set of 28 attributes is listed for each generic and hazard dataset. The attributes describe the data,

[10] https://forum.ecmwf.int/
[11] https://docs.google.com/spreadsheets/d/1HW1MWW--MWx1HgoXK6ANGrkYdy7-N8D2efcI7QQXRGQ/edit?usp=sharing
[12] https://docs.google.com/spreadsheets/d/1esRRDgI_kXyiwai3fR_Q1vz-cUfcyWquGE2CHjqtiCY/edit?usp=sharing

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the data format, spatial and temporal characteristics, data calculation, provider, and availability (Table 1). The compiled hazard dataset inventory also includes the generic data used in the calculation of newly generated hazard data. A similar set of attributes was used to describe the generic datasets, also specifying the hazards calculated and the variables used in the assessment.

risk_data_type	category	subcategory	title_item
hazard	flood	fluvial flood	River flood extent and water depth
hazard	flood	fluvial flood	River flood extent and water depth
hazard	flood	coastal flood	Deltares Global Flood Maps
hazard	wind-related	windstorm	Wind gust
hazard	wind-related	windstorm	Wind speed of gusts
hazard	precipitation-related	drought	Drought hazard indicator as described in the workflow
hazard	precipitation-related	drought	Crop yield loss from precipitation deficit
hazard	precipitation-related	drought	Combined Drought Indicator
hazard	precipitation-related	blizzard	Blizzard occurrences map
hazard	precipitation-related	heavy snowfall	Heavy snowfall occurrences map
hazard	precipitation-related	heavy rainfall	Precipitation return periods
hazard	precipitation-related	heavy rainfall	Precipitation return periods; Precipitation frequency indicators
hazard	temperature-related	heatwave	Heatwave occurence
hazard	temperature-related	heatwave	Heatwave occurence
hazard	temperature-related	heatwave	Heat wave days
hazard	temperature-related	heatwave	Temperature frequency indicator
hazard	wildfire		Wildfire susceptibility
hazard	wildfire		Wildfire hazard
hazard	wildfire		FWI
hazard	wildfire		FWI

Figure 3: screen shot of the hazard data inventory table

The data attributes specified for each dataset are aligned with the Risk Data Library Standard (RDLS)[13], curated by the Global Facility for Disaster Reduction and Recovery. RDLS offers an open metadata standard for describing hazard, exposure, vulnerability, and loss datasets used in climate and disaster risk assessments.

Table 1. Attributes specified for the hazard datasets and their description.

Attributes	Description
risk_data_type	the types of risk data included in the dataset (i.e. hazard)
category	category of data type (i.e. flood, precipitation-related, temperature-related, wind-related, wildfire)
subcategory	subcategory of data type (i.e. coastal flood, fluvial flood, heavy rainfall, drought, heavy snowfall, blizzard, heatwave, windstorm)
title_item	title of the dataset (item)
description_item	a short description of the dataset

[13] https://riskdatalibrary.org/

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Attributes	Description
title_collection	collection name (if applicable)
short_name_collection	short name of the dataset (if available)
data_type	data type (i.e. gridded, raster, vector, tabular)
data_format	data format (netcdf, GRIB, GRIB2, geotiff, geopackage, shapefile, geodata, csv, excel, ascii)
spatial_scale	geographical area covered by the dataset (i.e. global, regional, national, subnational)
bbox	bounding box coordinates (WGS coordinates)
coordinate_system	numerical code of the coordinate reference system (CRS) (e.g. 4326, 54009); name of CRS if code does not exist (e.g. WGS84, Mollweide)
spatial_resolution	spatial resolution
spatial_resolution_unit	spatial resolution unit (i.e. arc seconds, arc minutes, degrees, meters, kilometers, NUTS1, NUTS2, NUTS3)
reference_period	reference period for which the data are available (i.e. historical, future, historical & future)
temporal_scale	the period of time covered by the data (YYYY-YYYY)
temporal_resolution	size of the time steps used in data (i.e. hourly, daily, monthly, yearly, 5-yearly, 10-yearly, irregular)
scenarios	name of scenarios used (if future period, i.e. RCPs, SSP-RCP, warming level)
data_calculation_type	the method used for data calculation (i.e. inferred, observed, modeled)
underlying_data	data underlying the calculation type and approach (if applicable)
provider	name of data provider
provider_role	role of data provider (i.e. licensor, producer, processor, host)
license	data distribution license
availability_link	link to the website where the data can be accessed
publication_link	link to publication (e.g. doi)
code_link	link to available code (if applicable)
additional_notes	any relevant information for data use
name_contributor	the name of person who added the dataset to the table

3.3. Hazard data and tools in the CRA Toolbox

3.3.1. Generic data: observations, reanalysis, climate projections

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3.3.1.1. ERA5 and ERA5-Land global reanalysis

ERA5[14] and ERA5-Land[15] reanalysis are global atmospheric reanalysis datasets produced by ECMWF. Reanalysis combines model data with observations to form a globally complete and consistent dataset by using the laws of physics. Both datasets are widely used in various applications such as climate research and weather forecasting. The ERA5 and ERA5-Land datasets are also used in some of the workflows included in the CRA Toolbox.

The ERA5 dataset provides a comprehensive view of the Earth's atmosphere, ocean and land-surface quantities on a regular latitude-longitude grid available at 0.25° horizontal resolution globally. Its temporal coverage spans from 1950 to present and it is updated daily with a latency of about 5 days.

The horizontal resolution in ERA5-Land is higher (available at 0.1° degrees resolution) than in ERA5. However, ERA5-Land covers only land areas whereas ERA5 covers both land and water areas. ERA5-Land is also gridded to regular latitude-longitude grid. Like ERA5, ERA5-Land covers the time period from 1950 to present. It is updated monthly with a delay of about three months relative to the actual date.

The output from both ERA5 and ERA5-Land is provided in hourly resolution, enabling the analysis of sub-daily processes, but also monthly averages have been provided as a different dataset. Many atmospheric, ocean-wave, and land-surface quantities from ERA5 and ERA5-Land needed in CRA can be downloaded via the CDS. The full list of variables available from each dataset can be found in the documentations of the respective dataset. Note that the CDS also contains several other datasets derived from ERA5 and ERA5-Land data. Lastly, ERA5 also includes an ensemble component at half the resolution to provide information on the synoptic uncertainty of its products, whereas ERA5-Land parameter uncertainty currently can only be estimated using the equivalent ERA5 fields.

3.3.1.2. EURO-CORDEX regional climate model data

EURO-CORDEX[16] regional climate data provides high-resolution regional climate model simulations covering Europe. The dataset has been produced in collaboration with a consortium of European research institutions. This regional climate information dataset is widely used in climate research, impact assessments, and adaptation planning at the regional level.

The EURO-CORDEX dataset provides both hindcasts and projections of future climate at a regional scale and is available at a resolution of 0.11° (about 12.5 km). The EURO-CORDEX data spans the time period from 1950 to 2100, where the historical time period covers 1950-2005. The CORDEX experiments employ the widely used Representative Concentration Pathway (RCP) 2.6, 4.5 and 8.5 scenarios, which provide different pathways for future climate forcing, and simulations are available for different combinations of global and regional climate models. The full list of variables available for CRA can be found from the documentation of the EURO-CORDEX simulations. Note that the

[14] https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5
[15] https://www.ecmwf.int/en/era5-land
[16] https://www.euro-cordex.net/

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available variables may vary based on which combination of global and regional climate model is used to produce the simulations.

The EURO-CORDEX datasets can be accessed from CDS, where data is provided at different temporal resolutions (3 and 6 hours as well as daily, monthly, and seasonal means), and the list of model variables varies with choice of model combination, RCP scenario, and resolution.

3.3.1.3. Inter-Sectoral Impact Model Intercomparison Project

The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)[17] provides climate and socioeconomic forcing datasets for climate impact modelling to address the question of how climate change affects natural and human systems in the present and future climate. ISIMIP was initiated by the Potsdam Institute for Climate Impact Research and the International Institute for Applied Systems Analysis. The latest simulation round (ISIMIP3) consists of ISIMIP3a and ISIMIP3b. The ISIMIP3a dataset contains historical simulations forced by observed climate, as well as socioeconomic information. The ISIMIP3b provides bias-corrected Coupled Model Intercomparison Project 6 (CMIP6) climate forcing for pre-industrial and historical conditions, as well as future projections based on the Shared Socioeconomic Pathways (SSP) SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5.

3.3.1.4. Uncertainties in Ensembles of Regional ReAnalysis

The Uncertainties in Ensembles of Regional ReAnalysis (UERRA)[18] is a regional reanalysis dataset containing parameters from the surface and near-surface atmosphere. The UERRA dataset covers the European area with a temporal coverage from January 1961 to July 2019. The system provides analyses with a 6-hour time step. Variables describing the climate have been generated with two systems, namely the UERRA-HARMONIE and the MESCAN-SURFEX systems.

The UERRA-HARMONIE is a 3-dimenional system that uses ERA40 global reanalysis data as lateral boundaries for the period 1961-1978, after which the ERA-Interim reanalysis is used. The UERRA-HARMONIE data is available in a 11 km resolution. The MESCAN-SURFEX system, on the other hand, is a complementary surface analysis system that has been produced using the UERRA-HARMONIE system together with MESCAN analyses. It is available in a higher resolution than the UERRA-HARMONIE data, namely, the horizontal resolution is 5.5 km. Moreover, forecasts up to 30 hours initialised from the analyses are available with hourly resolution.

The data files are in GRIB or NetCDF4 format and can be downloaded via CDS. Please see the documentation of the UERRA dataset for a list of variables available for CRA.

In addition to the standard atmospheric variables, the UERRA dataset also provides uncertainty estimates for each variable. These variables can be used to assess the reliability of the data and quantify the level of confidence in any climate-related analysis or decision-making process.

3.3.2. Hazard data

[17] https://data.isimip.org/
[18] https://uerra.eu/

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3.3.2.1. River flood

River flooding occurs when a river overflows its banks, flooding adjacent areas with water. The river flood hazard is assessed in the CRA Toolbox using existing flood maps, that represent the river flood extent and inundation depth, available on either European or global scale. The main source for assessing the river flood hazard is the latest version of “River flood hazard maps for Europe and the Mediterranean Basin region” dataset available on the Joint Research Centre (JRC) portal (Baugh et al., 2024). The values from that dataset indicate water depth in units of m. The flood map dataset covers the extent of Europe at 3 arc-seconds spatial resolution, and they are only available for the present-day climate and no future climate scenarios are available. The flood maps are available for return periods of 10, 20, 30, 40, 50, 75, 100, 200, and 500 years. This dataset has been produced by means of the hydrological model LISFLOOD and the hydrodynamic model LISFLOOD-FP (Dottori et al., 2022).

The second river flood hazard dataset used in the hazard assessment is the "Aqueduct Flood Hazard Maps" dataset which is used to assess the likely impact of climate change on river floods (Ward et al., 2020). The data represents inundation depth in units of m. The coarse-resolution Aqueduct Floods Tool is openly available via the World Resources Institute website, and it has a global coverage and spatial resolution of 30 arc-seconds (300-750 m in Europe depending on latitude). This dataset includes flood maps for extreme flood events in the baseline climate (ca. 1980) and in the future climates (2030, 2050, 2080 for RCP4.5 and RCP8.5 climate scenarios). Extreme events with return periods ranging between 2 and 1000 years are included. The Aqueduct Flood Maps are based on the GLOFRIS model with PCR-GLOBWB hydrological model. Historical meteorological conditions behind this dataset are derived from the EUWATCH dataset and the future climate scenarios are based on the ISIMIP climate model outputs (see Section 3.3.1.3). The dataset's resolution is too coarse to enable a detailed quantification of flood hazard on a regional scale and mainly contains floods in larger river basins, but it allows the user to compare qualitatively the flood maps under different climate change scenarios.

The workflow outputs spatial distribution of potential flood depth and extent maps with different return periods for the region in question.

3.3.2.2. Coastal flood

Coastal flooding is caused by extreme sea levels, which occur during particularly severe sea storms resulting in high storm surge levels, on top of tidal water level fluctuations. The extreme sea levels are further increasing with sea level rise. The coastal flood hazard assessment workflow follows the same principles as those used in the river flood hazard assessment workflow (see Section 3.3.2.1). In the hazard assessment for coastal flood, we use an existing "Deltares Global Flood Maps" dataset, available at the Microsoft Planetary Computer[19]. The Deltares Global Flood Maps dataset includes inundation maps of flood depth based on extreme sea levels with different return periods (extreme events) under the present-day climate and under one scenario with sea level rise (including projected sea level rise for 2050 according to the RCP8.5 scenario). The included return periods are 2, 5, 10, 25, 50, 100, and 250 years. The flood maps have a resolution of 3 arc-seconds.

[19] https://planetarycomputer.microsoft.com/dataset/deltares-floods

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The Deltares Global Flood Maps dataset has been constructed by combining modelled sea level extremes and global topography datasets (Digital Elevation Models, DEMs). The sea level extremes have been derived from the Global Tide and Surge Model (GTSMv3.0, Muis et al., 2020) which was forced with atmospheric conditions from the ERA5 reanalysis (See Section 3.3.1.1). Statistical analysis of the modelled data was used to arrive at extreme water level values for different return periods. These values were then used to calculate flood depths by applying a static inundation modelling routine ("bathtub" method, with a simplified correction for friction over land) over a high-resolution DEM (MERIT-DEM or NASADEM).

As with the river flood workflow (see Section 3.3.2.1), this workflow outputs the spatial distribution of potential flood depth and extent maps for the region in question.

3.3.2.3. Flood damage and population exposure

This workflow estimates the economic damage to buildings and population in those buildings and the number of people displaced or forced to leave their homes resulting from the damage. The hazard component in this workflow requires a flood raster (fluvial, pluvial, coastal, or combined). While the workflow can be customized to use a variety of datasets, including local, the default version provided in the CRA Toolbox uses the same flood maps used in the river flood hazard workflow (see Section 3.3.2.1), namely the "River flood hazard maps for Europe and the Mediterranean Basin region" dataset (Baugh et al., 2024), which gives the inundation extent and depth over a variety of return periods.

3.3.2.4. Multi-risk workflow

The CRA Toolbox also contains a multi-risk assessment workflow that evaluates the impact of individual hazards (e.g., extreme precipitation, heat waves) on various infrastructure components related to airports. The hazard assessment included in this workflow includes calculation of percentiles of daily extreme precipitation and return periods, as well as percentiles of maximum temperatures and extreme heat days. Two generic datasets are used in the workflow, one for the historical time period and one for the future projections.

For the historical period, the UERRA MESCAN-SURFEX (Ridal et al., 2017) regional reanalysis dataset with a spatial resolution of 5.5 km over Europe is used. The UERRA MESCAN-SURFEX dataset has been specifically optimized for the land surface. Please refer to Section 3.3.1.4 for more information regarding the UERRA dataset. Concerning the climate projections, the EURO-CORDEX high-resolution simulation of the regional climate models at 12 km spatial resolution (Hennemuth et al., 2017, Jacob et al., 2020) were used to assess the potential variation of the hazard indicators. Please refer to Section 3.3.1.2 for more information regarding the EURO-CORDEX dataset. For climate models, the RCP2.6, RCP4.5, and RCP8.5 scenarios were considered in this workflow. The use of a set of regional climate models offered the opportunity to evaluate the average (often referred to as "ensemble mean"), obtained starting from the values of the individual models, as well as the dispersion of the single models around this average value (Von Trentini et al., 2019). The dispersion was quantified through the calculation of the standard deviation: a low standard deviation value indicates a high agreement between the climate models of the EURO-CORDEX ensemble, and vice versa (Von Trentini

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et al., 2019). From the UERRA MESCAN-SURFEX and EURO-CORDEX datasets, information regarding near-surface temperature and precipitation were obtained.

The hazard data produced by this workflow contains information about extreme precipitation and heatwaves for the time periods 1981-2010, 2021-2050, 2041-2070, and 2071-2100 with a yearly temporal resolution. For extreme precipitation estimates, the workflow outputs the average recurrence intervals of rainfall events of a specific intensity at a particular location. The information is also computed as frequency indicators of rainfall: The workflow computes the 99th, 99.5th and 99.9th percentile of daily accumulated precipitation, as well as the precipitation amount for return periods of 10, 20, 30, 50, 100, and 150 years. The workflow also calculates frequency indicators for heatwaves derived from near-surface temperature data, namely the 95th and 99.9th percentile and number of days where the maximum temperature exceeds 35°C, 40°C, 45°C. In the case of the climate projections, the hazard data is computed as an anomaly with respect to the historical period.

3.3.2.5. Extreme precipitation

The frequency and magnitude of extreme precipitation events are likely to vary under the premises of climate change scenarios. These projected changes can translate to an increase in the frequency and magnitude of pluvial floods (urban and flash floods) resulting from the precipitation intensity exceeding the critical impact rainfall thresholds of natural and artificial drainage systems capacities. To understand how the current local critical impact-based rainfall thresholds (in terms of magnitude, duration, and frequency) will vary under climate change the extreme precipitation hazard assessment workflow considers two key factors: the rainfall intensity and frequency.

In the extreme precipitation hazard assessment, the non-bias corrected EURO-CORDEX climate projections at a 12 km spatial resolution (see Section 3.3.1.2) of the variable “mean precipitation flux” have been employed to understand how the critical impact-based rainfall thresholds will vary in terms of frequency and magnitude in a European scale. Analysing return periods can help understand the frequency of extreme precipitation events and assess their likelihood of occurrence over time. By applying extreme frequency analysis, the workflow outputs hazard maps of precipitation return periods. The output includes extreme precipitation amounts in units of mm for several durations (3, 6, 12, 24 hours) and return periods (e.g., 2, 5, 10, 25, 50, 100 years). The information is available for Europe at the EURO-CORDEX spatial resolution of 12 km for the following simulations and time periods:

- Global Climate Models (GCM): ICHEC-EC-EARTH, MOHC-HADGEM2-ES
- RCPs: RCP8.5
- Historical timeframes: 1951-1980, 1971-2000, 1976-2005
- Future timeframes: 2011-2040, 2041-2070, 2071-2100 (2070-2099 for MOCH-HADGEM2-ES)

3.3.2.6. Relative drought

The relative drought hazard assessment workflow estimates, in a given region, the drought hazard as the probability of exceeding the median of regional (e.g., EU level) severe precipitation deficits for a historical reference period and future time period. The assessment follows the methodology developed and applied globally by Carrão et al. (2016) and uses the weighted anomaly of standardised precipitation (WASP) index to define the severity of the precipitation deficit. The WASP

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index considers the annual seasonality of the precipitation cycle and is calculated by summing the weighted standardised monthly precipitation anomalies.

To calculate the WASP index required for the relative drought hazard assessment, the total monthly precipitation in a given region (e.g., NUTS3) during the historical reference period and the future time period is needed. In the workflow, climate input data of average monthly precipitation from ISIMIP3 is used, which provides bias-adjusted climate input datasets on a 0.5° x 0.5° global grid and at daily time steps for both the historical period and future projections (see Section 3.3.1.3 for details). For the historical period, atmospheric (precipitation) climate input data from the ISIMIP3a GSWP3-W5E5 obsclim dataset (Lange et al., 2022) was employed, which covers the years 1901-2019 and is based on the observational datasets GSWP3 v1.09 (Kim, 2017) and W5E5 v2.0 (Cucchi et al., 2020, Lange et al., 2021).

The future precipitation projections, on the other hand, took advantage of the ISIMIP3b bias-adjusted atmospheric climate input data available for the years 2015-2100 (Lange and Büchner, 2021). This dataset is available for five CMIP6 global climate models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL) and three different scenarios (SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5).

Both datasets can easily be downloaded from the ISIMIP website provided by the Potsdam Institute for Climate Impact Research. However, it needs to be considered that their gridded horizontal resolution of about 55 km (0.5 x 0.5°) may not be sufficient for local applications at a higher resolution.

The workflow calculates the drought hazard for the time period 1979-2100. The result from the workflow is a list of drought events and their severity for each region (e.g., NUTS3 regions) for the reference period. This can then be compared to the median of severe precipitation deficits for the same period for all regions considered (e.g., EU level) to calculate the probability of each region being affected by a drought event (i.e., exceeding the EU median of severe precipitation deficits).

3.3.2.7. Agricultural drought

The agricultural drought hazard assessment workflow estimates the potential loss in yield for a given crop in the absence of an artificial irrigation system compensating for precipitation scarcity. The agricultural drought workflow quantifies the impact that changing precipitation rates across Europe will have on rainfed agriculture, highlighting the importance of improving water resilience and irrigation infrastructure in agricultural systems. The agricultural drought hazard assessment workflow uses four types of data: historical and future climate data, DEM, soil available water capacity and thermal climate zone.

For the climate dataset, we use the EURO-CORDEX projections at 12 km resolution (see Section 3.3.1.2 for more information regarding the EURO-CORDEX dataset). To calculate the crop standard evapotranspiration potential needed for the workflow, six daily climate variables are needed: "mean precipitation flux", "2 m relative humidity", "2 m surface wind speed", "shortwave solar radiation downward", "maximum temperature" and "minimum temperature". Out of the EURO-CORDEX models, the MPI-ESM (global model) KNMI-RACMO22E (regional model) combination is used as default in the assessment, but four other combinations can be accessed.

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The DEM is sourced from the United States Geophysical Service Global Multi-resolution Terrain Elevation Data 2010 initiative (Danielson & Gesch, 2011). This dataset provides a numeric value that represents a geographic attribute, such as elevation or surface slope, for that unit of space. The dataset used has global spatial coverage at 30 arc-seconds resolution.

The soil available water capacity (in units of mm) is sourced from Hengl & Gupta (2019). The dataset has global spatial coverage at 250 m resolution and provides information about the soil available water from the surface to 2 m depth. The temporal coverage of this dataset is 1950-2017. The available water capacity is derived by calculating the difference between the field capacity and wilting point following the NRCS Soil Survey Laboratory Methods Manual (Soil Survey Staff, 2014) then summing this up for all standard soil layers (0–200 cm). The available water capacity is used to determine the maximum amount of available water for crops' evapotranspiration at any grid-cell of the studied region.

The thermal climate zone dataset is sourced from FAO (Van Velthuizen et al., 2007) and is used to determine the region's thermal climate conditions. It has global spatial coverage at 5 arc-minutes resolution. The thermal climate zones represent a classification of global climates in 8 categories characterised by different annual temperature ranges and rain seasons. This classification is helpful for agricultural modelling as crops have different growing calendars and evapotranspirative responses depending on the temperature and precipitation regimes (Chapagain & Hoekstra, 2004).

The hazard dataset produced by the workflow is a regional map of the crop yield loss (in %) deriving due to the absence of an irrigation system compensating for precipitation shortages. The hazard dataset has the same resolution as the EURO-CORDEX climate projections (0.11° which is about 12 km) and has spatial and temporal extents as defined in the workflow, where these two are limited to Europe and the period 2014 -- 2100, respectively. A spreadsheet file containing the point-by-point values visualised in the map is also produced to allow the user to explore the results in greater detail.

3.3.2.8. Drought exposure

The drought exposure hazard assessment workflow aims to visualise the exposed vulnerable population to drought. The workflow expresses the hazard of drought by using the Combined Drought Indicator (CDI)[20], which is an indicator for drought early warning, specifically designed to monitor agricultural drought. The CDI has been implemented in the European Drought Observatory (EDO), by combining three drought indicators, namely, the Standardized Precipitation Index, Soil Moisture Anomaly and Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) Anomaly. The Standardized Precipitation Index (Edwards & McKee, 1997, McKee et al., 1993) measures the precipitation anomalies at a given location. The Soil Moisture Anomaly is calculated from anomalies of estimated soil moisture (or soil water) content produced by the JRC LISFLOOD hydrological model (de Roo et al. 2000, Laguardia and Niemeyer, 2008). The fAPAR Anomaly is an estimate of the vegetation greenness (Gobron et al., 2005).

The Drought Exposure workflow provides maps of CDI for the region in question in 5 km spatial resolution. The CDI dataset is available for the historical period starting from 2012 to near real time in a monthly temporal resolution. The maps of CDI can be used to identify areas affected by

[20] https://drought.emergency.copernicus.eu/

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agricultural drought, areas where the vegetation has already been affected by drought, and areas in the process of recovery to normal conditions. Accordingly, the CDI classification scheme gives information about the spatial distribution of three primary drought classes (“Watch”, “Warning”, and “Alert”) and three recovery classes (“Temporary Soil Moisture recovery”, “Temporary vegetation recovery”, and “Recovery”).

3.3.2.9. Heatwave

The heatwave hazard workflow employs three distinct methodologies to define heatwaves:

1. the EUROheat project’s definition of a heatwave (Michelozzi et al. 2007, WHO, 2009)
2. the heatwave definition established in PESETA IV (Naumann et al., 2020),
3. the XCLIM methodology that employs the XCLIM Python library[21]

All three methods use the EURO-CORDEX climate model projections (see Section 3.3.1.2) for their analysis.

Method (1) uses pre-calculated data from the "Heat waves and cold spells in Europe derived from climate projections" dataset (Hooyberghs et al., 2019) to calculate the heatwave hazard in Europe. This dataset itself has been computed using daily minimum and maximum 2 m air temperature from the bias-adjusted EURO-CORDEX dataset which developed in the CLIM4ENERGY project[22] for two different climate scenarios, RCP4.5 and RCP8.5. It contains the number of hot and cold spell days using different European-wide and national/regional definitions developed within the C3S European Health service. It covers the years 1986 -- 2085 with a yearly temporal resolution and the same spatial resolution as the underlying EURO-CORDEX dataset (0.11°). Here we used the definition of the EUROheat project.

Methods (2) and (3) compute the heatwave hazard data directly based on generic data from the EURO-CORDEX dataset. Both methods output the number of heatwave occurrences within the historical timeframe of 1971 -- 2100 with a monthly time resolution. The spatial resolution of the data is the same as of the underlying EURO-CORDEX data (0.11°). For further details on the methodologies, please see the description of the workflow in Deliverable 2.4.

3.3.2.10. Wildfire

The wildfire hazard assessment workflow is based on an empirical approach described in Trucchia et al. (2022, 2023) and Tonini et al. (2020). The assessment is conducted using a trained Machine Learning model, and the data used in the workflow includes topographic data, land cover information, climate data, and past fire polygons.

The trained Machine Learning model considers different climate data influencing the ignition and spread of wildfires, across the specified time periods. For the climate data, the ECLIPS-2.0 dataset is used. This dataset leverages on a downscaling of EURO-CORDEX data (Chakraborty et al., 2021). The dataset has a resolution of 30 arcsec, has the temporal coverage of 1961-2100, and it provides the 14 variables needed in model: mean warmest month temperature, annual total precipitation,

[21] https://xclim.readthedocs.io/en/stable/indices.html
[22] https://climate.copernicus.eu/climate-information-energy-sector

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annual mean temperature, continentality, mean summer temperature, mean winter precipitation, annual heat-moisture index, maximum summer temperature, degree-days above 18°C, summer heat-moisture index, mean autumn precipitation, mean spring precipitation, degree-days below 0°C and mean summer precipitation.

The time periods used for training the Machine Learning model were 1991-2020 for the present period, 2021-2040 for the near future, and 2040-2060 for the forthcoming future (note that 2061–2080 and 2081–2100 periods can be studied as well with minor changes to the code). To link geo-climatic predictors of fires and fire occurrences, an algorithm is trained from scratch by the workflow, leveraging on *scikit-learn* Python library[23]. The Machine Learning classifiers produce wildfire susceptibility maps as output, indicating the likelihood of fire occurrence at a pixel level. Using different climatic data, period-specific wildfire susceptibility maps can be produced. Wildfire hazard maps are derived from the integration of the Machine Learning outputs, specifically the susceptibility maps with fuel maps generated by aggregating the Corine Land Cover[24] data and Burned Area polygons. The Corine Land Cover dataset provides information on land cover and land use for the year 2018 in 100 m spatial resolution. The Burned Area polygons can be obtained from the European Forest Fire Information System (EFFIS)[25], which has a 100 m spatial resolution for the years 2008 until present, with a daily time resolution. These data can easily be replaced with local/regional datasets.

The first result from the workflow is a wildfire susceptibility map, that can be used as an indicator describing the likelihood of a certain area to experience wildfire in given time period due to the intrinsic characteristics of the territory. The other result is a hazard classes map which cross likelihood of fire and potential intensity of fire occurrence. The information is available for the time periods of 1991-2020, 2021-2040, 2041-2060, 2061-2080, 2081-2100 and for the climate scenarios RCP4.5 and RCP8.5 at a 100 m spatial resolution.

The workflow used Catalonia as a reference test area, but the analysis can be adapted to other regions if land cover, wildfire database (from national sources or from EFFIS or other open available sources) and DEMs are available.

3.3.2.11. Windstorm

The windstorm hazard workflow assesses the damage to structures caused by windstorms using a simplified version of the methodology from Koks & Haer (2020). The workflow uses data on historical windstorm footprints[26] and synthetic windstorms[27] that are available from the CDS.

The historical windstorm footprints are available for Europe for the period 1979-2021 and are derived from the ERA5 reanalysis dataset (see Section 3.3.1.1 for more information). The historical footprints give, for an identified storm track, the maximum 3 s wind gust at 10 m (in units of m s^{-1})

[23] https://scikit-learn.org/stable/
[24] https://doi.org/10.2909/960998c1-1870-4e82-8051-6485205ebbac
[25] https://forest-fire.emergency.copernicus.eu/
[26] https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.9b4ea013?tab=overview
[27] https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.ce973f02?tab=overview

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over the 72-hour period capturing the storm, crossing Europe. This dataset has a 1 km horizontal resolution and covers the months from October to March.

The CDS also provides plausible yet synthetic windstorms that are physically realistic. This dataset is based on modelled climatic conditions and has been created using the Met Office HadGEM3 model. These synthetic storms create a larger than historical overview of possible events which can affect the area in current-day situations. The synthetic storm dataset provides the maximum 3 s wind gust at 10 m over a 72-hour period along the storm track. The synthetic windstorm events are available for Europe in a 4.4 km horizontal resolution covering the months September to May. This dataset, however, is not designed to reproduce actual historical observations.

The workflow produces hazard maps that present the maximum wind gust of a storm at the resolution of the underlying dataset (1 km and 4.4 km, respectively).

3.3.2.12.Heavy snow and blizzard

Heavy snowfall and blizzards can lead to numerous disruptions and impacts across various sectors. A blizzard is characterized by low temperatures, sustained winds, or frequent wind gusts accompanied by significant precipitation or blowing snow. To effectively evaluate the associated risks of heavy snowfall and blizzard events, the heavy snowfall and blizzard hazard assessments employ the impact indicator defined in Vajda et al. (2014).

In the heavy snow and blizzard workflows, we utilize two generic datasets: For historical data, we employed the ERA5 reanalysis dataset (see Section 3.3.1.1) with a spatial resolution of 0.25°. To examine future changes in heavy and blizzard events, we employed high-resolution simulations from the EURO-CORDEX regional climate models at 0.11° spatial resolution (Jacob et al., 2020, see Section 3.3.1.2). For the future data, we considered the RCP2.6, RCP4.5, and RCP8.5 climate scenarios. The use of multiple model simulations provides the opportunity to evaluate both the ensemble mean and the uncertainty range. In this workflow, we use simulations produced with six different regional climate models produced from EURO-CORDEX (SMHI-RCA4-CanESM2, SMHI-RCA4-NorESM1, SMHI-RCA4-IPSL-CM5A-MR, KNMI-RACMO22E-EC-EARTH, KNMI-RACMO22E-HadGEM2-ES and MPI-CSC-REMO2009-MPI-ESM-LR). For the heavy snow workflow, the variables "snow depth" and "snow density" were obtained from the ERA5 reanalysis and "mean precipitation flux" was obtained from the EURO-CORDEX simulations. The blizzard hazard assessment required additional variables and, in addition to the above-mentioned variables, the variables "2m Temperature" and "10m wind gust" were obtained from the ERA5 dataset and "surface temperature" and "10m wind speed " from the EURO-CORDEX simulations.

Both the heavy snowfall and blizzard workflows calculate the annual probability of occurrence of heavy snow or blizzard events in a given region for the specified time period 2014-2100 in the EURO-CORDEX spatial resolution (0.11°) in a yearly temporal resolution. More specifically, the heavy snowfall hazard assessment presents a heavy snowfall occurrences map that indicates the probability of daily snowfall exceeding 6 cm and 25 cm. The users also have the option to set their own thresholds. The blizzard hazard assessment produces a blizzard occurrences map expressed as a probability. Here blizzard days are defined as days with average temperature (Tmean) ≤ 0°C, snow accumulation (Rs) ≥ 10 cm, and wind gusts (Wg) ≥ 17 m s^{-1}.

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4. Data limitations

In this section, the uncertainties associated with hazard data (see Section 4.1) and hazard datasets unavailable but needed in CRA (see Section 4.2) are discussed briefly.

4.1. Uncertainties in hazard datasets

The workflows of the CRA Toolbox use pre-existing data to first assess the climate hazards themselves and then the risks associated with them. To this end, the workflows either use pre-calculated, freely available hazard datasets, or they use generic datasets such as observational, reanalysis and global and regional climate model data to compute the needed hazard data. Generic climate data come with a range of uncertainties. This includes both reanalysis data and climate projections. We give a short overview over these uncertainties in this section. Pre-calculated hazard datasets have a range of uncertainties as well, which may or may not be documented in the datasets. Where such documentation was given, we give short descriptions in this section. Furthermore, the data computed within the workflows of the CRA Toolbox may be affected by additional uncertainty due to assumptions and approximations included in the assessment methodology.

4.1.1. Generic data

Uncertainties in observational datasets (such as surface weather observations, radar and satellite-derived information) arise mainly from incomplete spatial and temporal coverage. Therefore, there is often a lack of consistent quality-controlled timeseries of meteorological quantities covering long time periods. For example, understanding past trends in extreme precipitation may be difficult due to the highly local nature of those events, which may be hard to capture using observations. Also, measurement techniques or equipment may differ between regions and time periods, making comparisons between different observation time series difficult. At the time of the writing of this document, none of the workflows were using observational data, but the workflows are planned to be extended and one of these future extensions include validation of model data using observations. Furthermore, some of the flood and heatwave workflows intend to use local observations in their analysis.

Reanalysis data give complete and consistent information of meteorological variables covering large areas with an evenly spaced time and spatial resolution. This makes it easier to analyse past climate trends. However, reanalysis datasets can only be considered as a “best estimate”, as they are produced by combining observations and models. Therefore, reanalysis data are affected by limitations associated with observational, global and/or regional weather model data. The uncertainty estimate is complicated even further, as for different time periods the spatial and temporal coverage of the available observational data may vary. At the time of writing this deliverable, the CRA Toolbox workflows used reanalysis data from ERA5, ERA5-land, and UERRA.

For ERA5, provides the results of an ensemble of 10 simulations at half resolution which provides information on the synoptic uncertainty of its products. It is stated that this uncertainty mainly is due to internal variability while systematic errors (mostly) cannot be assessed using this product. Sources of uncertainty in ERA5 apart from internal variability are not explicitly listed. Instead, like with most atmospheric models, the product is evaluated against observations (e.g., Hersbach et al.,

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2020). An up-to-date list of know issues with the product is available on the ECMWF confluence pages[28]. The uncertainties for ERA5-land can be assessed using the ERA5 uncertainty product. For UERRA, detailed documentation and a list of known issues can be found on the CDS[29].

Data from climate model projections introduce a whole range of uncertainties which are not all present in reanalysis data. First off, climate model projections are based on scenarios (e.g., emissions and land use) which are based on assumptions like, e.g., future use of natural resources, societal development, and population increase. Uncertainties also exist regarding the past, especially in terms of natural and anthropogenic aerosol emissions and volcanic eruptions since about the start of the industrial aera. The RCP and SSP scenarios have been developed to span a plausible range of future emission pathways, but there is not absolute ground truth. Therefore, the choice of a certain scenario (e.g., RCP or SSP) will influence the outcome of any climate model simulation (see, e.g., Chen et al. 2021, especially Section 1.4 and the references therein).

Further uncertainties arise because many physical processes (e.g., cloud physics, climate feedback mechanisms) in the atmosphere are still not well enough constrained by observations. Also, many atmospheric processes occur at length scales much smaller than what a global climate model can resolve. Good examples for this are, e.g., convective clouds and thunderstorms. Such processes are parameterised in climate models, which leads to uncertainties as well. Process- and resolution-related uncertainties lead to differences in simulation results between different models, because different models parameterise different processes differently. This means that different climate models may arrive at quite different results even if the underlying scenarios are the same. This is especially true for projections of local changes. On the other hand, exactly these differences in climate models allow us to quantify the underlying uncertainties by analysing so-called ensembles of climate model projections, namely, multiple model runs from a range of climate models. This provides us with a statistical distribution of climate projections, including a best estimate and an uncertainty range (see, e.g., Lee et al., 2021., especially Section 4.2.5 and the references therein for more information).

To increase the spatial resolution of climate models, regional climate models are used in addition to global climate models to produce climate projections. In EURO-CORDEX models (which are used in many of the CRA Toolbox workflows), for instance, the spatial resolution is 12 km as compared to a resolution of the order of 100 km for global climate models. This allows for many physical processes to be resolved and computed explicitly, thereby removing some of the resolution-related uncertainties. However, regional climate models only cover a small part of the globe, which means that they need to be provided with boundary conditions from (or driven by) global climate models. This also means that some of the uncertainties of the driving global climate model are inherited by the regional climate model (Adachi et al., 2018). Also, spatial distribution of some variables of the regional climate model can be quite different than the "original" spatial distribution computed by the driving global climate model in the same modelling domain. Again, using ensembles of regional climate model projections can help to assess the uncertainties of the model results (see, e.g., Von Trentini et al., 2019, Mankin et al., 2020 for a detailed discussion). The users of the workflows may

[28] https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation#ERA5:datadocumentation-Knownissues
[29] https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-uerra-europe-single-levels?tab=doc

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be instructed to test different model combinations (e.g. different EURO-CORDEX models) to understand the variability in the produced hazard data depending on different input data.

Most of the datasets produced by the workflows do not include information about uncertainties. Below we describe the uncertainties for the workflows where sources of uncertainties were listed.

4.1.2. Coastal flood

The coastal flood dataset (see Section 3.3.2.2) from the Microsoft Planetary Computer helps to estimate the flood potential at a given location. The flood modelling in this dataset does not account for man-made coastal protections that may already be in place in populated regions (e.g. dams, and storm barriers). For this reason, this dataset is not reliable for areas with highly managed coastline, such as in the Netherlands. Therefore, it is always important to survey the local circumstances when interpreting the flood maps.

There is a clear advantage to using a global high-resolution dataset, as it allows for consistent methodology across regions. However, it is important to note that in areas with complex bathymetries the performance of the models is likely reduced (e.g. in estuaries or semi-enclosed bays) and the results should be treated with caution. The dataset also does not include land subsidence, which may be of importance in some regions. If this is a known issue in the area of interest, it should be taken into account when interpreting the coastal flood maps.

The current version of the coastal flood map dataset is based on extreme water levels statistically derived from water level timeseries over the period of 1979-2018. There is inherent uncertainty to extreme value analysis performed over a limited duration of time (40 years). Next to that, the uncertainty in topography datasets used in creating this dataset (MERIT-DEM) also leads to uncertainties in the flood maps, as relatively “small” errors in the digital elevation of several decimetres may lead to significant differences in the flood maps. Future development of this dataset may help to reduce such uncertainties significantly as more accurate DEMs and longer timeseries of water levels become available.

4.1.3. River flood

High-resolution JRC river flood hazard maps for Europe (see Section 3.3.2.1) only include river basins that are larger than 150 km^2, and do not account for man-made flood protection measures. In areas where flood risk is caused by smaller river basins and/or the rivers are already highly managed, this dataset may provide less useful information. In other areas it may be an important source of information to facilitate quantitative assessment of flood risk. Still, some uncertainty is associated with the modelling of river flood extents because of the topographic uncertainty and uncertainty associated with the extreme value analysis for river discharges.

The dataset does not provide information on local (urban) flash floods. This can potentially be derived from the heavy rainfall workflow in combination with local high-resolution flood models.

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4.1.4. Drought

For the drought exposure workflow, the CDI dataset from EDO was used (see Section 3.3.2.8). The CDI signal over snow-covered regions comes from a real precipitation deficit combined with a soil moisture deficit (estimated by hydrological simulations). Having snow cover for longer periods, unfortunately, negatively affects the quality of soil moisture estimations. Hydrological models currently in use need to be improved with respect to the snow dynamics.

4.2. Need for new datasets

As mentioned in the Introduction (see Section 1), the workflows of the CRA Toolbox were originally planned to be developed as example workflows which can produce results for all European regions. This meant that the datasets used in the example workflows had to be pan-European at the cost of relatively low resolutions. This, in turn, meant that the results of these example workflows may not provide high enough resolutions to be suitable for a full CRA as is. One such example workflow is the river flood workflow (see Section 3.3.2.1) which uses global flood maps at a resolution of 30 arcseconds and only includes the largest rivers. The idea was therefore for the users to adapt these workflows to their regional context, using higher-resolution and probably local datasets for their analysis. During the second phase of the CLIMAAX project, the funding of the 50+ regions to apply the CRA Toolbox in their regional risk assessments, sufficient time was reserved for finding or generating such additional data.

During the development of the workflows, especially during the collaboration with the project pilots, it turned out to be more feasible for some of the workflows to be developed with a particular pilot region in mind. In these cases, the datasets used may not all be pan-European and hence these workflows may not be operable for all European regions without adjustment of the workflows or further data acquisition. At the time of writing this deliverable, the wildfire workflow (see Section 3.3.2.10 for details) uses regional data which spans only the area of Catalonia, Spain.

Another limiting factor we encountered was that certain, otherwise useful, hazard datasets (e.g., the Canadian fire weather index as indicator for wildfire susceptibility) is only available for some models and some scenarios. This severely limits the reliability of the risk analysis results, especially for regional analyses, as it is very hard to assess the uncertainty in the results. One way around this problem is to calculate the same data for other models within the workflows (at least for the region to be assessed). Another one would be to ask the providers to compute such hazard data for more climate models. Especially for often-used datasets the latter may be the preferrable option.

For the drought exposure workflow, the CDI dataset from EDO was used (see Section 3.3.2.8). The drawback of this dataset is that it is only available for the past, namely, for the period 2012 to near real time. Therefore, a similar parameter derived from regional climate projections would be extremely useful for assessing the population exposed to the droughts in the future. Moreover, this dataset is available only for Europe and on the temporal resolution with 10 days step interval. Looking beyond CLIMAAX, a global dataset with daily temporal resolution would be quite useful for the wider community exposed to droughts.

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5. Conclusions

This deliverable describes datasets either directly describing climate hazards or data used to compute such data. The datasets described here are limited such that they are being used in one of the workflows of the CRA Toolbox which is accessible through the CLIMAAX Handbook. In addition to the descriptions in the text, the datasets have also been catalogued in the hazard data inventory table which is provided as appendix[30] to this deliverable. Within the catalogue, the used datasets are separated into hazard data and generic data, and each dataset is categorised based on a set of 28 attributes. For each dataset, either links to the data sources are provided or the workflow in which the data are computed is named. Altogether the hazard data inventory table includes 18 hazard data entries and 20 generic data entries. The table lists both historical data and future projections. All datasets are subject to limitations which influence the outcomes of the workflows in which they are used. Most of the limitations arise from uncertainties, due to, e.g., model resolution, parameterisations, scenarios, or assumptions. However, some workflows also suffer from other limitations such as temporal resolution or coverage of the data. Therefore, in connection with the data described here, the results of the workflows should be seen as a first estimate. To produce more reliable CRAs, the workflows should be adjusted and complimented with local, higher-resolution data. Such data could be used both directly as replacement for the data described here, or for validation of the same.

Especially for climate projections, many of the hazard estimates are based on only one or a few climate model simulations instead of all the model results available from, e.g. EURO-CORDEX. To get more reliable climate risk analysis results for the future, including uncertainty estimates, it may be necessary to compute the hazard data also for all other models, at least for the region to be assessed. An alternative may be to push for certain hazard datasets to be extended to more models if these hazard datasets prove particularly useful.

[30] https://docs.google.com/spreadsheets/d/1esRRDgI_kXyiwai3fR_Q1vz-cUfcyWquGE2CHjqtiCY/edit?usp=sharing

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