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Climate-related hazard indices for Europe

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1 Introduction

1.1 Objective and scope

This Technical Paper describes the review and selection process for a compact set of 32 climate-related hazard indices for Europe. These activities were carried out by experts from the European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC/CCA) in support of the development of a European Environment Agency (EEA) Report on climate-related hazards in Europe to be published in 2021.

The information provided by the final hazard index set has the following objectives:

1. to provide a European overview on past trends and projected changes in key representative climate-related hazards with adaptation relevance for different sectors and policy themes,
2. to support the development and application of national and regional indices for climate-related hazards with adaptation relevance.

The index review and selection were conducted by the ETC/CCA team under Task 1.4.3.1 of the ETC/CCA Action Plan 2020. They were supported by external experts through an offline consultation and an online workshop.

The final index set covers several climate-related hazards that are relevant for large parts of Europe, considering both acute events (e.g. heatwaves, heavy rain) and slow-onset hazards (e.g. sea level rise, changes in mean temperature and precipitation).

Chapter 2 describes the framework, sources and process that led to the selection of the final index set. Chapter 3 presents the general findings on index definition and data availability deriving from the discussion within the team and the external experts. Chapter 4 presents the specific results on single climate-related hazards and indices from the discussion with the team and external experts. Chapter 5 presents index factsheets for all selected indices, which include data recommendations for their operationalization.

1.2 Policy background

The European Commission (EC) adopted in 2013 the 'EU Strategy on Adaptation to Climate Change' (EC, 2013), aiming to contribute to a more climate-resilient Europe. In 2018, the EC published an evaluation of the EU Adaptation Strategy (EC, 2018). The aim of the evaluation was to examine the implementation and performance of the Strategy, looking at its relevance, effectiveness, efficiency, coherence and added value for the EU. Also, the evaluation included the "adaptation preparedness scoreboard" for measuring Member States' level of readiness based on qualitative, process-based indicators. The evaluation showed that the strategy has delivered on its objectives to promote action by Member States, 'climate-proof' action at the EU level and support better-informed decision-making. Nevertheless, the evaluation outlined how Europe is still vulnerable to climate impacts within and outside its borders and suggests areas of improvements to prepare vulnerable regions and sectors. Informed by the evaluation, DG CLIMA has announced its intention to revise the EU Adaptation Strategy by early 2021. The revised strategy will raise information needs regarding climate change impacts and adaptation at the EU and national levels. In May 2020, the EC has published a blueprint for the new EU Adaptation Strategy and launched an open public consultation (EC, 2020d).

In August 2020, the EC adopted an Implementing Regulation on Member State (MS) reporting under the Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action (EC, 2020b). This Implementing Regulation includes in Annex I a list of observed and future climate-related hazards which countries are asked to report on. The first MS reporting is due by 15 March 2021, and every two years

thereafter. The proposal for a European Climate Law (EC, 2020c) foresees that the EC, with the support of the EEA, regularly assesses MS progress in adapting to climate change, based on MS reporting.
Decision No 1313/2013/EU on a Union Civil Protection Mechanism (UCPM) (EU, 2013) calls EU Member States and other Participating States to develop National Risk Assessments (NRA) periodically and make their summary available to the EC. The EC has stressed that further efforts are needed to improve the coverage of climate change in the next round of NRAs, which is due in December 2021.

The Interim report of the mission board of the Horizon Europe Mission area 'Adaptation to climate change including societal transformation' (EC, 2020a) explicitly recommends *'providing access to fast track climate risk assessments build upon cutting-edge climate and environmental information from the Copernicus Programme, Galileo and other services clearinghouses and data hubs such as the Climate-Adapt and the Disaster Risk Management Knowledge Centre'*.

In response to these policy development and related information needs, the EEA, with support from the ETC/CCA, is developing a set of climate-related hazard indices for Europe that are relevant for adaptation planning at the European and national level. The indices included in this set shall be based on publicly available data, in particular from the Climate Data Store (CDS) of the Copernicus Climate Change Service (C3S)[1]. They will be described in detail in an EEA report scheduled for publication in 2021. Depending on the data availability in the C3S CDS, these indices shall also be made available interactively through the European Climate Data Explorer, a graphical user interface to selected C3S data currently under development on EEA's Climate-ADAPT platform[2].

The C3S CDS was chosen as the reference data source for the indices presented in this Technical Paper, the EEA report that builds on it and the accompanying 'online atlas' because CDS data:

- are the only quality-controlled European data covering past, current and future climate conditions,
- are freely available to all users, and
- can be visualized in the European Climate Data Explorer.

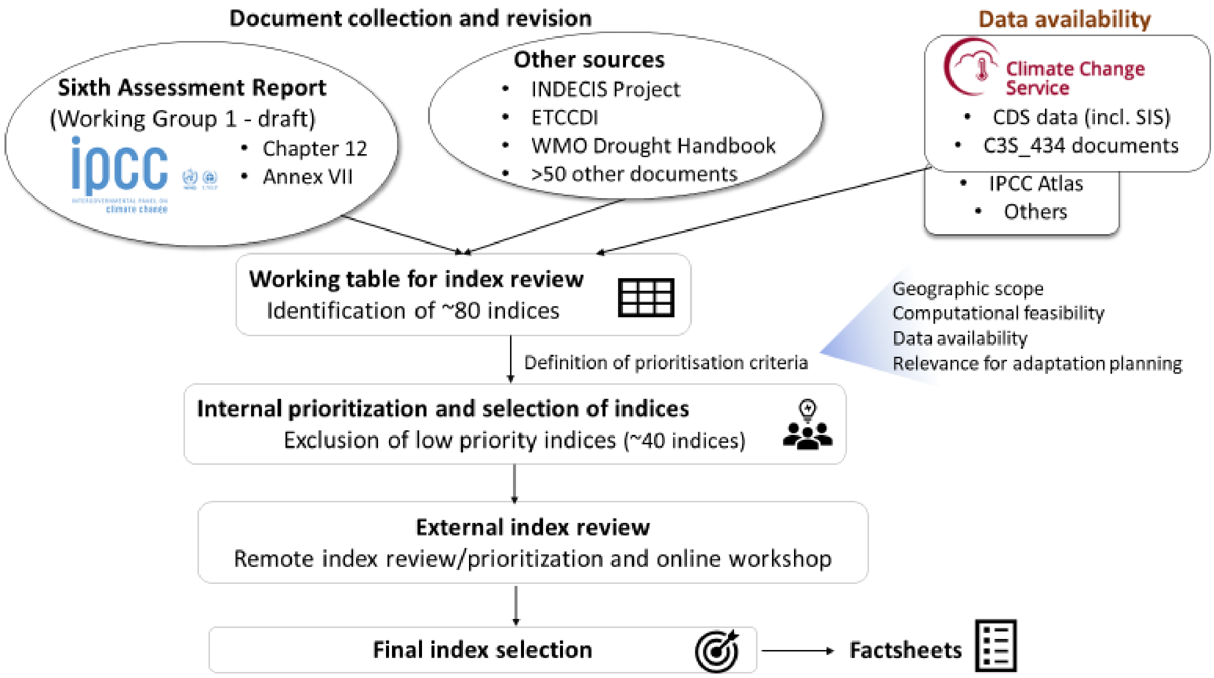
[1] https://cds.climate.copernicus.eu/cdsapp#!/home
[2] https://climate-adapt.eea.europa.eu/

2 Review and selection approach

The identification and selection of a representative set of climate-related hazard indices for Europe was performed in six phases (see Figure 2.1):

1. Review of relevant international and national literature,
2. Definition of structure and criteria for index characterization,
3. Index prioritization and selection by the ETC/CCA task team,
4. Remote index review and prioritization by external experts,
5. Online workshop with external experts,
6. Final index selection by ETC/CCA task team.

Figure 2.1: Workflow for the selection of climate-related hazard indices.



ETCCDI: Expert Team on Climate Change Detection and Indices (27 Climate Change Indices)
WMO: World Meteorological Organisation
C3S: Copernicus Climate Change Service
CDS: C3S Climate Data Store
SIS: C3S Sectoral Information System
C3S_434: C3S contract 'CDS Interface to Climate-ADAPT'

2.1 Literature review of climate-related hazard indices

Information on existing climate-related hazard indices was retrieved from relevant documents from international organizations, European projects, national authorities and the scientific literature. The identified indices were reported in a **working table** including, for each of them, an extensive list of relevant characteristics that would support the following index prioritization and comparison.

The two main international references were Deliverable 4.2 of the INDECIS project (INDECIS project, 2018) and the Second Order Draft of the Working Group I contribution to the IPCC Sixth Assessment Report (AR6, hereafter named **IPCC AR6 draft**). The INDECIS project report is the result of a review process of user-oriented climate indicators for specific sectors at the European level involving relevant stakeholders whereas the IPCC AR6 draft builds on a review of the relevant national and international literature.

The **IPCC AR6 draft** was made available for review in March 2020. According to the governing rules of the IPCC, all drafts are confidential and should not be cited, quoted or distributed. The current work does not use any (confidential) result of the IPCC AR6 draft. However, it used certain structural elements (in particular from its Chapter 12 and Annex VII) as an inspiration for the general framework of climate-related hazard indices in this Technical Paper. In particular, the IPCC AR6 draft introduces the concept of 28 **Climatic Impact Drivers (CIDs)**, which are grouped under **six main categories** (“Heat and cold”, “Wet and dry”, “Wind”, “Snow and ice”, “Coastal”, “Oceanic”). Please note that there are slight differences in the number, categorisation and names of CIDs in different parts of the IPCC AR6 draft. Furthermore, this structure may change in the final IPCC AR6.

The index review was facilitated by a working table that included all indices discussed in the IPCC AR6 draft, structured largely according to CIDs. This table also includes the index names proposed in the IPCC AR6 draft and, if available, their computation (see below for details on the index review table). Relevant indices listed in the **INDECIS report** but not in the IPCC AR6 draft were also considered. Other international references considered were the **ETCCDI** climate change indices (Zhang et al., 2011) available from the **CLIMDEX project** and the existing **EEA indicators**.

In addition to these key documents, a **wide range of sources** on climate-related hazard indices and their application was collected and reviewed by the ETC/CCA task team. More than 50 documents were considered, including scientific papers, project reports, operative web portals and adaptation strategies at European and national scales. Particular attention was paid to existing climate adaptation portals and projects with structured stakeholder involvement.

This literature body was used to identify existing adaptation applications of each index retrieved from the INDECIS report and the IPCC AR6 draft in order to assess the relevance, uncertainty and sectoral relevance of the pre-selected indices. It also allowed to identify those indices the operationalization of which (e.g. threshold values) differed depending on their geographical or sectoral application. In addition, some indices proposed in these documents were added to the working table even if they were mentioned neither in the INDECIS report nor in the IPCC AR6 draft, if they were considered to be relevant for a particular CID and/or sector.

The framework for the index review includes classifications and concepts from the IPCC AR6 draft, the Implementing Regulation and the C3S datasets. It also provides the structure for the **working table** of all identified indices. In particular, the **six main categories** for the CIDs and the **CID**s itself from the **IPCC AR6 draft** were adopted (with some modifications) as the overarching structure of the climate-related hazard indices presented in this Technical Paper. The IPCC AR6 draft also provided information on the main essential climate variables (ECVs) associated with each index and on the sectoral relevance of indices.
Moreover, information on the **climate-related hazard types** was linked to the already existing classification from Annex I of the (at that time, draft) **Implementing Act** cited above. The classification in the Implementing Act splits the climate-related hazards in two main categories: chronic and acute. This classification was not adopted here, because it shows limited flexibility when considering climate variables whose chronic trends could lead to acute hazards (e.g. heat stress is listed as chronic while in some cases it can be considered as an acute hazard).

Index-specific information on **data availability** (distinguished into observations, reanalyses and future projections with or without bias adjustment) and **geographic coverage** was added, with an emphasis on datasets, variables and indices available through the **C3S**. This entry specifies also whether an index was already calculated in a C3S application or whether only its underlying ECVs are available. Where future projections for a specific index or its ECVs were not available within the C3S datasets, the **draft IPCC AR6 online atlas** and other external sources were scrutinized.

Finally, information on **adaptation applications** was extracted from the collected reports and publications on the application of climate-related hazard indices for national adaptation purposes.

2.2 Initial index prioritization

This first selection step aimed at halving the total number of ca. 80 indices that were collected and described in the working table. This initial prioritization was performed by the ETC/CCA task team. Each index was assigned a qualitative priority level (high, medium and low) based on four scoring criteria: geographic relevance, computational feasibility, data availability and relevance for adaptation planning (see Table 2.1 below). These criteria were selected in agreement with the overall objectives of the final index set. Indices representative for large parts of Europe were ranked higher compared to others with more limited applications. Furthermore, already calculated and available in the C3S CDS or those indices requiring a limited number of readily available ECVs were assigned a higher priority. Where suitable C3S datasets were not available, other European or global datasets were also explored. Finally, high priority was assigned to those indices already applied in national adaptation contexts.

Table 2.1: Scoring criteria applied in the first step of the index prioritization and selection.

	Scoring		
Criterion	**High**	**Medium**	**Low**
Geographic relevance	*Relevant for most or all of Europe*	*Relevant for a significant part of Europe (e.g. snow, hail)*	*Relevant for a limited region only (e.g. permafrost)*
Computational feasibility	*Essential climate variable (i.e. already available on C3S) or simple calculation*	*Multiple input variables required*	*Data beyond climate models required (e.g. socio-economic data)*
Data availability (spatial and temporal coverage)	*Complete data coverage over Europe, also for future period*	*Data available for all of Europe (or all regions where the hazard is relevant) but for past period only*	*Data available only for a part of the region where the hazard is relevant (e.g. only one country)*
Relevance for adaptation planning	*Index (widely) applied in national climate change risk assessments and/or for (sectoral) adaptation planning*	*Index proposed in internationally agreed reports and/or in scientific projects with stakeholder involvement*	*Index proposed in individual scientific publications only*

The ETC/CCA experts assigned a score for each of the four criteria as well as an overall priority score to each index; where relevant, they also compared indices belonging to the same CID with each other. The votes from all experts were gathered and discussed in order to converge to an agreement on the overall priority for each index. The indices with high or medium overall priority were retained for the next selection phase, and their definition and uncertainty/robustness were further discussed from a sectoral and adaptation perspective.

Furthermore, each of the 28 CIDs was assessed qualitatively based on similar criteria. As a result, seven CIDs proposed in the IPCC AR6 draft (namely landslide, sand and dust storm, permafrost, lake, river and sea ice, snow avalanche, coastal erosion and salinity) were dropped from further consideration because they were either considered to be of low relevance for adaptation planning in Europe or they go beyond the climate-hazard perspective adopted throughout this Technical Paper. During the external expert review (see Section 2.3), two further CIDs were excluded because of insufficient data availability (namely heavy snow and ice storm, and hail). Finally, three pairs of related CIDs were regrouped to a single hazard type (namely cold spell and frost; ocean mean temperature and marine heatwaves; and ocean and lake acidity and salinity). Hence, the final index set covers 16 hazard types.

2.3 Further index review by external experts

The initial index prioritization by ETC/CCA experts was followed by an external expert consultation, which consisted of an **offline review** of the draft indices list followed by an **online workshop**. This consultation involved 21 European experts in the fields of climate data, climate modelling and climate-change adaptation from C3S, national meteorological services, research institutes, environmental agencies and other organisations. Among them were IPCC AR6 lead authors and representatives of the INDECIS, ISIMIP and CORDEX projects and initiatives. The full list of involved experts is available in the Annex.

For each index retained in the initial prioritization, the external experts were invited to review its priority ranking, to comment on its usefulness in an adaptation context, to suggest specific changes and/or alternative indices. In addition, they were asked to provide information on additional datasets, including observations, reanalyses and projections, that could be used for the index computation. In particular, CS3 experts were invited to point out relevant datasets that are already published in the CDS or under development under C3S Sectoral Information System (SIS) contracts.
The results of the offline review were internally discussed, and all the suggestions received by the external experts were integrated into the index table before the workshop. The preliminary conclusions and the open questions identified during the offline review were then discussed during the online workshop.

EEA organized a full-day online workshop on 16 June 2020, to which all experts participating in the remote index review where invited. This online workshop constituted of two parts. Discussions in the first part addressed general issues regarding climate index selection, quality criteria and data availability. A summary of the general outcomes is available in Chapter 3. In the second part, all retained indices were discussed individually with the external experts. The main outcomes of the online workshop were recorded in a meeting protocol and shared with the participants. Please see Chapter 4 for key discussion points and conclusions for each index.

2.4 Final index selection

The ETC/CCA task team, jointly with EEA experts, used the outcomes of the expert workshop to finalize the set of 32 climate-related hazard indices for Europe recommended for inclusion in the planned EEA report and the related online atlas. C3S experts were further consulted in bilateral meetings in order to understand the current and (where known) planned availability of pan-European data sources for the index computation.
The final set of 32 climate-related hazard indices is presented in **factsheets** in Chapter 5.

3 General considerations regarding climate-related hazard indices

This chapter discusses challenges for the definition of indices describing climate-related hazards (Section 3.1), choices to be made for operationalizing and presenting such indices (Section 3.2) as well as key European datasets (Section 3.3).

3.1 Climate-related hazards and their measurement

Climate change is affecting the occurrence and features of many climate-related hazards. These hazards are generally classified into chronic hazards, which refer to gradual and long-term variations in average conditions (such as a rise in mean temperature) and acute hazards, which refer to extreme episodes occurring on short timescales (e.g. extreme precipitation and windstorms). 'Acute' climate-related hazards can be characterized by their duration, magnitude and severity (WMO, 2018). For this reason, different indices may be required to cover the most relevant properties of a given hazard.

This Technical Paper and the forthcoming EEA report adopt a modified version of the Climatic Impact Driver (CID) categories borrowed from the IPCC AR6 draft instead of a coarser terminology based on chronic and acute hazards. In the IPCC AR6 draft, the term CID essentially replaces the term 'climate hazard' in order to use a more neutral terminology. Considering that this concept has not yet been published or generally adopted, the forthcoming EEA report will continue to use the term 'climate-related hazards', though in a broad sense comparable to the term CID.

In the following, the main aspects to consider and properly define when measuring a climate-related hazard and interpreting related indices are listed and separately discussed.

3.1.1 Fixed vs. percentile-based thresholds

Thresholds defining a value above or below which climatic conditions become 'extreme' can be identified by either fixed or percentile-based values. For instance, 'days with extreme precipitation' can be defined based on a fixed amount (e.g. above 30 mm per day) or based on a percentile (e.g. above 95th percentile of daily precipitation), which is derived from the precipitation values during a baseline period. Both choices show advantages and drawbacks and their use needs to be evaluated according to specific applications and purposes.

The use of thresholds with fixed values allows for easy index interpretation, comparability across different locations and sector-specific needs (e.g. frost days or the growing degree days for specific agricultural crops). However, the choice of a suitable threshold can be challenging due to the high variations among European locations and sector-specific applications (e.g. different agricultural crops). Moreover, whenever fixed thresholds are applied, bias-adjustment of climate model outputs is strongly recommended in order to avoid a significant mismatch between modelled and actual regional conditions.

Percentile-based thresholds partly avoid these drawbacks by applying the same index definition over different locations based on a common baseline period. They provide a more robust representation of projected changes even without bias-adjusted model output. Moreover, a percentile-based threshold allows for a flexible identification of events occurring with different frequency (e.g. moderately rare, rare and very rare events) for regions with different climatic conditions by the application of increasing percentile levels (e.g. 95th, 98th and 99th percentiles). However, the information provided by percentile-based exceedances may be less directly suitable for specific adaptation actions, for which the knowledge of the events exceeding a specific critical level (e.g. wind speed above 40 metres per second threating tree stability) would be more crucial. Finally, the choice of the baseline period for the percentile computation can strongly influence percentile-based thresholds, in particular when the variable of interest has been changing considerably due to anthropogenic climate change or multi-decadal climate variability.

3.1.2 Temporal resolution

The time scale of a specific climate-related hazard determines the required temporal resolution of data needed to assess changes in that hazard. For example, proper assessments of extreme events occurring at short time scales, such as flash floods caused by intense downpours, require sub-daily climate data. However, since sub-daily data are not readily available for many essential climate variables (ECVs), and their future projections are affected by higher model uncertainties, most climate-related hazard indices are based on climate data at daily resolution.

3.1.3 Spatial resolution

Different climate-related hazards have different characteristic spatial scales. Limited availability of high-resolution spatial data can affect the representation of localized climate-related hazards (e.g. extreme precipitation in the Alps or extreme wind speed). Continental-scale climate model outputs is typically available at a spatial resolution of several tens of km (~10-50 km). The mismatch between the effective spatial resolution of computed indices and the scale of their potential application is therefore an intrinsic issue and source of uncertainty. National and regional high-resolution datasets, possibly in combination with dynamical or statistical downscaling approaches, can help bridging the resolution gap between coarse datasets and user requirements, but such techniques are not generally available for C3S datasets. The EEA report on hazard indices will include an overview of national climate services to stress that the EEA products are not in competition, but complementary to national services.

3.1.4 Computational complexity

The definitions of climate-related hazard indices imply different levels of computation complexity. While several indices are based on very simple definitions (e.g. the seasonal total precipitation or the number of days with minimum temperature above 20 °C), others require more complex computation (e.g. the river flow index using runoff based on the results of hydrological model simulations). A complex index can be more difficult to interpret. Furthermore, it may be more difficult to identify a harmonized dataset of all required input parameters for its computation for past and future periods. For instance, the computation of future projections for fire danger-related indices is not straightforward since it requires consistent projections for four ECVs (i.e. daily temperature, precipitation, wind speed and relative humidity). Finally, complex indices are more prone to uncertainties due to an error accumulation and propagation of the various input source.

3.1.5 Robustness

Detailed information on the robustness of a climate-related hazard index is an essential requirement for a proper index interpretation. Sources of uncertainty, such as the choice of the thresholds used in the index definition as well as the uncertainty of the ECVs derived from the climate model data have to be clearly assessed. Further relevant contributions to the index uncertainty derive from the mismatch between the coarser spatial resolution of models and the actual spatial scales of index applications and from the use of not bias-adjusted climate projections. The forthcoming EEA report will include a semi-quantitative robustness assessment of all indices presented therein.

3.2 Operationalization of climate-related hazard indices

In order to properly implement the selected climate-related indices and ease their interpretation, several aspects regarding, e.g. the choice of reference periods, climate scenarios and visualization elements, need to be defined according with the final scopes and end users. The main issues and related recommendations are reported in the following.

3.2.1 Choice of reference period

Ideally, the same reference period should be used for the definitions and presentation of all indices in the online atlas. The reference period is the 30-year interval over which the normal climate conditions are computed and used to quantify the future changes. 1961–1990 is the reference period recommended by WMO representing the baseline for climatological studies, however the use of more recent decades is preferable for practical applications and future adaptation purposes. 1981–2010 is therefore recommended, but the consistency between the future projections and the data for the reference period needs to be preserved. For most currently available model projections (e.g. from CMIP5 and EURO-CORDEX), the historical runs end already in 2005, which implies that the 1981–2010 period is not fully covered. If bias-adjusted projections are used, a full coverage of the reference period can be retrieved from the reanalyses considered for the correction. In other cases, alternative methods need to be implemented to identify a common baseline climate for current conditions and future scenarios.

The same consistency is desirable for the choice of the time horizon and of future time periods. The indices presented here extend until 2100, reflecting the dominant user needs as well as data availability. Extending the future projections after 2100 could be relevant for some large investment decisions, in particular in coastal regions. However, projections for all indices discussed here are restricted until 2100, reflecting the availability of key datasets and the needs of most users.

3.2.2 Choice of emissions scenarios for future projections

The CMIP5 model projections used in the IPCC AR5 and EURO-CORDEX projections are based on 'representative concentration pathways' (RCPs), which can be loosely translated as 'emission pathways'. These RCPs have been complemented by 'shared socio-economic pathways' (SSPs). The CMIP6 modelling exercise currently underway, which will be the foundation of the IPCC AR6, is based on nine global emissions trajectories for the 21st century and beyond that integrates the RCP and SSP concepts (Gidden et al., 2019; Meinshausen et al., 2020).

Most model projections currently available in the C3S Climate Data Store provide simulations for at least two RCPs, typically RCP4.5 (corresponding to a medium emissions scenario) and RCP8.5 (a high emissions scenario). Note that neither of these RCPs is compatible with the goals of the Paris Agreement. Some model projections are also available for RCP2.6, which has a reasonable chance for keeping warming within the range required by the Paris Agreement.

Time series of future projections should be presented for all available RCPs. For map-based projections of the near future (i.e. up to mid-21st century), presentation of a single RCP is generally sufficient. Map-based projections of the far future (e.g. end-21st century) should generally be based on two different RCPs. The interpretation of future projections of climate-related hazard indices can be facilitated by providing the corresponding level of global warming for the respective time period and RCPs as contextual information. This information is (partly) available from the IPCC AR5 (IPCC, 2013) e.g. Table SPM.2.

3.2.3 Aggregation of model ensembles

Climate projections are generally based on an ensemble of simulations from different climate models (multi-model ensemble). Ensembles may further involve variations of model parameters (perturbed parameter ensemble) or slightly different initial conditions (initial condition ensemble).

Most applications of climate indices are interested in certain statistical features of the model ensemble (e.g. 'best guess', uncertainty range or robustness of direction of change) rather than in the individual model projections. Therefore, the results from the individual simulations need to be aggregated by deriving, for instance, the mean, median or other percentiles of the model ensemble. The median is typically used to reflect the 'best guess' projection whereas the 15th and 85th percentiles characterize the 'likely' uncertainty range. The robustness of the direction of change in an index a given location (i.e. decrease or increase) can be expressed by the share of ensemble simulations agreeing on the direction of change.

3.2.4 Visual presentation of indices

The selected indices can be presented as time series covering longer past and/or future periods, as absolute values averaged over a (typically) 30-year period and as differences between two 30-year periods (e.g. recent climate and future period). All these options can provide valuable information for adaptation purposes.

Time series graphs show past and projected changes under different emissions scenarios for a specific location or region (e.g. a country, subnational administrative unit or river basin) in an easily understandable way. They also allow for the depiction of uncertainty intervals, which provide important information on the robustness of the data. Furthermore, time series graphs allow for an easy comparison of past and projected index changes and its interannual variability, which gives information about how exceptional the long-term change is. Finally, time series graphs can be used to compare a limited number of locations or regions. However, they cannot provide a comprehensive picture of the regional climate and its changes.

Maps of 30-year averages show the spatial distribution of an index or of past and projected changes of that index. This allows for an easy identification of particularly affected areas (i.e. hotspots). However, information on the robustness of a given trend considering natural climate variability and the uncertainty of observations or projections is more difficult to visualize. Maps of projected changes based on ensemble simulations need to be interpreted with particular care. Whereas maps displaying low or high percentiles (e.g. 15th and 85th percentile) are accurate in each location, they do not show a geographically consistent picture of possible 'low' and 'high' changes, because the underlying model simulation may differ from location to location.

Independent of its presentation in time series and maps, an index can be defined based on yearly values (e.g. annual precipitation) or seasonal values (e.g. summer precipitation). Monthly values are also possible, but they are typically beyond the scope of this report. The most relevant temporal aggregation depends on the specific index and its application.

3.3 Data availability for climate-related hazard indices

In the interest of consistency, a limited number of input datasets should be used for the computation of all climate-related hazard indices, covering both the past period and future projections. Ideally, a single bias-adjusted dataset based on a common and consistent bias-adjustment scheme would be used for future projections of all or most indices. Furthermore, the bias adjustment would ideally use the same observational or reanalysis dataset underlying past trends of the index. However, these ideal criteria cannot be met by currently available pan-European datasets.

The current availability of climate data in the C3S Climate Data Store, and in particular of climate projections at appropriate resolution and including bias adjustments, was identified as a major limitation for the definition and operationalization of a comprehensive set of climate-related hazard indices for Europe. A comprehensive and detailed overview of current and -where available- planned CDS content is therefore essential to identify the most suitable data sources to implement a given index.

3.3.1 Data availability from the Copernicus Climate Change Service

The C3S Climate Data Store (CDS) is the reference data source for the pan-European indices presented in this Technical Paper. The CDS contains several *general* datasets, such as climate observations (e.g. E-OBS), reanalyses (e.g. ERA5) and projections (e.g. CMIP5). It also includes some *specific index* datasets containing processed data, such as bias-adjusted climate projections, complex climate indices (e.g. Canadian Fire Weather Index) and a limited number of climate impact estimates (combining climatic and socio-economic information). Most processed datasets released in the CDS are the outcomes of C3S contracts to build the Sectoral Information System (SIS). These contracts develop user-oriented products of various climate-sensitive sectors (e.g. energy, biodiversity, water management, human health and tourism). Several SIS contracts are currently ongoing and provide continuous updates to the CDS resources. In addition, CDS offers a workspace, called CDS Toolbox, where users with sufficient technical knowledge can retrieve the data of interest, apply additional calculations and display the results according to their specific needs.

The specific CDS datasets were developed independently for different target applications and sectoral requirements, so they are based on different reference data, timescales and bias-adjustment methods. This heterogeneity prevents using a single homogeneous and harmonized pool of underlying climate data for the computation of all the indices selected and described in Chapter 5. Furthermore, the CDS datasets may contain several versions of an index developed under different contracts, using either the same or different underlying input datasets. The index factsheets in Chapter 5 consider all CDS datasets that include a given index as it is not always possible to recommend one of them over the others. In addition, several datasets or indices have been developed under a C3S contract but are not currently available in the CDS. Some of these datasets are reported in Chapter 4 because they may become available in the CDS following quality control and/or in response to user requests.

The remainder of this section provides further technical insights on relevant general and specific datasets available in the C3S CDS. The key general datasets include both observations, reanalyses and climate projections. They provide the main essential climate variables required for the computation of most indices not covered by any of the specific datasets available in the CDS.

Based on the experiences in this project, EEA has identified several priorities for the future development of the CDS and communicated these recommendations to its C3S counterparts.

3.3.2 Observation and reanalysis datasets available from the C3S CDS

- **E-OBS**: daily gridded observation dataset over Europe
  This European dataset covers the period 1950–present (updates every 6 months), and it is available at two spatial resolutions (0.1° and 0.25°). In the latest versions, the dataset is provided as ensemble mean together with the ensemble spread, which helps in assessing the accuracy of the gridded fields. The main ECVs provided are temperature (daily minimum, mean and maximum), precipitation, sea level pressure and solar radiation.
- **ERA5**: fifth generation ECMWF atmospheric reanalysis of the global climate
  This global reanalysis covers the period 1979–present (daily updates) at hourly temporal resolution and 0.25° resolution. It covers a wide set of climate variables for both land and ocean. An extension of the dataset back to 1950 is planned.
- **ERA5-Land**: enhanced resolution ERA5 for land variables

This global reanalysis covers the period 1981–present (monthly updates) at hourly resolution and 0.1° resolution. It provides the land fields of ERA5 atmospheric variables at finer spatial resolution, thus supporting its applicability in several sectors, such as flood forecast.

- **UERRA**: regional reanalysis of near-surface variables for Europe
  This European reanalysis is generated by UERRA-HARMONIE and MESCAN-SURFEX systems and covers the period 1961–2019 (July), without further planned updates. It spans the whole Europe (both land and ocean) at the surface level and with a horizontal resolution of 5.5 km x 5.5 km or 11 km x 11 km, depending on the variable and underlying data source. For each day, 4 analyses are available each 6 hours. Temperature, precipitation, wind and relative humidity are available at fine resolution, while other variables, including snow and cloud cover, are provided at 11 km grid spacing.

ERA5 and **ERA5-Land** reanalyses have the advantage of providing a global coverage and continuous updates. **UERRA** is specific for the European domain with a finer spatial resolution, but it ends in 2019 and cannot be used as an operational product. **E-OBS** is an operational European dataset based on in-situ observations. It includes a smaller set of ECVs compared to reanalyses and therefore cannot be used to calculate complex climate indices based on multiple input parameters.

3.3.3 Projection datasets available from the C3S CDS

- **CMIP5**: fifth phase of the Coupled Model Inter-comparison Project
  This global dataset includes the simulations of almost 40 GCMs, but some models do not cover all climate variables. The CMIP5 ensemble was used extensively in the IPCC Fifth Assessment Report. The simulations are available globally (land and ocean) at daily resolution with a spatial resolution ranging from 0.125° to 5°, depending on the GCM. The historical runs span the period 1850–2005; projections are available for four different RCPs (2.6, 4.5, 6.0 and 8.5) from 2006 to 2100, with some extensions until 2300. The provided variables are temperature (minimum, mean and maximum), precipitation, wind speed, relative and specific humidity, pressure, solar radiation and snowfall. The inclusion of the new CMIP6 experiments in CDS is foreseen a later stage.
- **CORDEX**: regional climate model data for Europe
  This European dataset was developed in the framework of the Coordinated Regional Climate Downscaling Experiment (CORDEX). It includes RCM simulations for three different RCPs (2.6, 4.6 and 8.5) and for different combinations of 8 GCMs (from CMIP5 experiments) and 10 RCMs. It covers the whole Europe (land and ocean) with a horizontal resolution of 0.11°. The variables are provided at 3-hour or 6-hour time resolution, depending on the variables; daily, monthly and seasonal means are also available. The historical runs span the period 1950–2005 while the projections cover the period 2006–2100. The variables provided include temperature, precipitation, wind, pressure, solar radiation and relative humidity.
- **Essential climate variables for water sector applications derived from climate projections**
  This global dataset provides 4 ECVs derived from downscaled and bias-adjusted simulations of 18 GCMs participating in CMIP5 for two RCPs (4.5 and 8.5). Daily minimum, mean and maximum temperature and precipitation rate are available from 1979 to 2100 at a spatial resolution of 0.5°. The data were bias adjusted by means of the Distribution Based Scaling (DBS) method versus the global reference dataset HydroGFD2.0. The dataset was processed to be mainly suitable for hydrological impact modelling and applications in water the sector. This is the only set of bias-adjusted projections currently available from the C3S CDS.

For European applications, the EURO-CORDEX dataset is generally preferred over CMIP5 because of its finer spatial and temporal resolution and its larger set of variables included in the CDS. However, the global CMIP5 dataset includes a larger model ensemble and longer temporal coverage both in the past (back to 1800) and the future (until 2300).

C3S provides access to a comprehensive range of direct climate model outputs, but a comprehensive dataset of bias-adjusted projections is not currently available in the C3S. C3S also provides access to state-of-the-art tools, such as Climadjust, a Bias-Adjustment service for the Climate Data Store. Climadjust allows to apply different climate-adjustment methods to a wide range of climate projections (including CMIP5, CMIP6 and CORDEX). However, the tool is not currently integrated in the C3S Toolbox and requires separate registration.

Several bias-adjusted ECVs are included in the CDS dataset 'Essential climate variables for water sector applications derived from climate projections' (see above). This dataset was derived by applying a bias-adjustment procedure that responds to the requirements of water sector applications. Furthermore, bias-adjusted climate indices for Europe are available from several C3S-related contracts (see below). However, the different CDS products implement different bias-adjustment methods, which affects the consistency among the climate indices included therein.

The **ISIMIP** project is one of the main current sources of global bias-adjusted climate projections, based on a subset of CMIP6 simulations. Inclusion of this dataset into the CDS is currently under discussion for the next phase of C3S (starting in mid-2021), but it will not be in time for the forthcoming EEA report.

Bias-adjusted projections of selected ECVs based on EURO-CORDEX data are available from the CORDEX-Adjust project and the JRC PESETA IV project (Dosio and Fischer, 2018; Dosio, 2020). These two datasets implement different subsets of GCM-RCM combinations and different bias adjustment methods; neither of them is available through the C3S CDS.

3.3.4 *Key 'index' datasets available from the C3S CDS*

- **Heat waves and cold spells in Europe derived from climate projections**
  This European dataset provides the number of hot and cold spell days considering different heatwave or cold spell definitions. The multiple definitions combined in the dataset allow the comparison of European and national/regional definitions (climatological, health and country related). Data is available for different future time periods and for two RCP scenarios (4.5 and 8.5) from 1986 to 2085 at a spatial resolution of 0.1°x0.1°. The dataset provides statistics for the whole year ad for the winter and summer seasons based on bias-adjusted EURO-CORDEX simulations.
- **Thermal comfort indices derived from ERA5 reanalysis**
  This global dataset includes indices representing human thermal stress and discomfort under different outdoor conditions based on air temperature, humidity, ventilation and radiation. The dataset is based on ERA5 reanalysis from ECMWF covering from 1979 to near real time data.
- **Water quantity indicators for Europe**
  This European dataset provides data on water runoff and wetness, river flow, snow water equivalent and soil water content. Climate model data were used to run three hydrological models at a pan-European level (i.e. E-HYPE, VIC and LisFlood). Data are provided at different resolutions (0.5°, 0.1° and catchment resolution) as averages over 30-year periods for a time coverage spanning from 1971 to 2100.
- **Agroclimatic indicators from 1951 to 2099 derived from climate projections**
  This global dataset provides 26 agro climatic indicators that are relevant for further downstream analysis and as forcing of agricultural impact models. The dataset was computed from ERA-interim and bias-adjusted datasets from the Inter-Sectoral Impact Model Intercomparison (ISIMIP) Project. It covers historical and future time periods from 1951 to 2099 at a spatial resolution of 0.5° and at annual, seasonal or decadal (1 days) temporal resolution.
- **Fire danger indicators for Europe from 1970 to 2098 derived from climate projections**
  This European dataset presents projections of fire danger indicators for Europe based upon the Canadian Fire Weather Index System (FWI). The indicators were computed by the Global ECMWF Fire Forecasting model (GEFF) driven by 6 GCMs for three RCPs (2.6, 4.5 and 8.5). Five indicators,

including daily and seasonal FWI and number of days above a certain fire danger rate, cover Europe at 0.11° spatial resolution at different temporal scales.

- **Mountain tourism meteorological and snow indicators for Europe from 1950 to 2100 derived from reanalysis and climate projections**
  This European dataset provides meteorological indicators as well as indices for natural, groomed and managed snow under past and future climate conditions at NUTS-3 level and at 100-meter elevation steps. The 39 indicators result from the combination of the Crocus snowpack model within the SURFEX land surface model forced with bias adjusted EURO-CORDEX atmospheric fields for three RCPs (RCP2.6, RCP4.5 and RCP8.5). The dataset spans from 1950 to 2100 with either an annual resolution or 20-30 year aggregates.
- **Water level change time series for the European coast from 1977 to 2100 derived from climate projections**
  This European dataset provides time series of water level considering sea level rise, tides and surges for historical and future scenarios. The dataset was created by forcing the Deltares Global Tide and Surge Model (GTSM) version 3.0 with bias-adjusted projections from the HIRHAM5 RCM combined with the EC-EARTH GCM. Spatial resolution varying from 0.1° for coastal grid points to 0.25°, 0.5° and 1° for ocean grid points within 100 km, 500 km and beyond 500 km of the coastline, respectively. Historical temporal coverage ranges from 1977 to 2005 whereas future scenarios cover 2071–2100 for RCP4.5 and 2041–2070 for RCP8.5, at a temporal resolution of 10 min. The dataset also includes indicators for 1979–2017 derived from ERA5 reanalysis.
- **Water level change indicators for the European coast from 1977 to 2100 derived from climate projections**
  This European dataset includes extreme-value indicators for coastal sea levels at 0.1° resolution. The dataset was created by forcing the Deltares Global Tide and Surge Model (GTSM) version 3.0 with bias-adjusted projections from the HIRHAM5 RCM combined with the EC-EARTH GCM. Historical temporal coverage ranges from 1977 to 2005 whereas future scenarios cover 2071–2100 for RCP4.5 and 2041–2070 for RCP8.5. The dataset also includes indicators for 1979–2017 derived from ERA5 reanalysis.
- **Marine biogeochemistry data for the Northwest European Shelf and Mediterranean Sea from 2006 up to 2100 derived from climate projections**
  This European dataset contains indicators for changes in marine physics and biogeochemistry for the Northwest European Shelf and Mediterranean Sea until 2100. The dataset was derived by coupling the models ERSEM v15.06 (European Regional Seas Ecosystem Model), POLCOMS (Proudman Oceanographic Laboratory Coastal Ocean Modelling System) and NEMO (Nucleus for European Modelling of the Ocean) using the FABM (Framework for Aquatic Biogeochemical Models) coupler. The models were driven by CMIP5 at the open ocean boundaries combined with downscaled atmospheric data from the Swedish Meteorological and Hydrological Institute (SMHI) Rossby Centre Regional Atmospheric Model (RCA4). The dataset has a spatial resolution of 0.1° for the POLCOMS-ERSEM and 0.06° for the NEMO-ERSEM coupled models over 43 vertical levels. The dataset includes both physical (e.g. temperature, salinity) and biochemical (dissolved oxygen, nutrients concentrations) parameters simulated under RCP4.5 and RCP8.5. Temporal coverage spans from 2006 to 2050 for NEMO-ERSEM and up to 2100 for POLCOMS-ERSEM with a daily and/or monthly temporal resolution depending on the selected variable.

4 Discussion of climate-related hazards and indices

This chapter documents the outcomes of the discussion with external experts before, during and after the expert workshop on each single climate-related hazard. Further information on each selected index is provided in Chapter 5.

4.1 Heat and cold

4.1.1 Mean temperature

Changes in mean annual and seasonal temperature influence ecosystems and a wide range of human activities.

The selected indices for this hazard comprise a general-purpose index as well as three indices focusing on energy and agriculture.

1. **'Mean temperature'** is a **high-priority index** with a wide range of applications. Changes in annual mean temperature are often used as a headline index in regional climate change assessments whereas changes in seasonal mean temperature are relevant for various sectoral applications. Data are readily available from observations, reanalyses and projections, including with bias adjustments. (Related EEA indicator: Global and European temperature).
2. '**Growing degree days**' is a **high-priority index** for agriculture. This index is readily available from the C3S agro-climatic indicators ('Biologically effective degree days'), which uses 10 °C and 30 °C as lower and upper threshold for daily mean temperature, respectively. National or regional applications may use different temperature thresholds to account for local conditions and crop types.
3. '**Heating degree days**' and
4. '**Cooling degree days**' are two **high-priority indices** for the energy sector. Different implementations of these indices use different underlying data (e.g. daily mean vs. daily minimum and maximum temperature), threshold temperatures, and possible seasonal restrictions (e.g. only pre-defined heating or cooling season). These indices are not currently available from the C3S CDS, but the underlying data are readily available. Past trends and future projections for these indices are shown in the EEA indicator Heating and cooling degree days, based on data provided by the JRC. Information on past trends for both indices is also available from the Eurostat dataset Energy statistics - cooling and heating degree days (nrg_chdd), based on JRC's Agric4Cast dataset Monthly heating and cooling degree days in the European Union, which uses a somewhat different definition.

Further indices considered were 'Growing season length' and 'Onset of growing season'. They were not included in the final index set because of considerable overlap with 'Growing degree days'. Information related to these indices can be found in the EEA indicators Growing season for agricultural crops and Agrophenology, respectively.

4.1.2 Extreme heat

Extreme heat is an important hazard for many sectors and activities, including human health, agriculture, construction, transport and energy, whereby the specific hazardous conditions and thresholds differ widely across systems and climatic zones. Most heat indices are based on daily mean, maximum or minimum temperature only. Heat impacts on human health and wellbeing, however, are better described by indices that combine temperature with other variables, such as relative humidity and solar radiation. Extreme hazard indices can focus on the frequency, duration or magnitude of extreme conditions.

The selected indices include three simple indices based on temperature data only as well as three more complex indices.

5. '**Tropical nights**' (i.e. the number of days with minimum daily temperature above 20 °C) is a **high-priority index** with particular relevance for human health. This index is readily available from the C3S dataset on agro-climatic indicators.
6. '**Hot days**' (i.e. the number of days with maximum daily temperature above a fixed threshold) is a **high-priority index** with a wide range of applications. 30 °C is a suitable threshold for a pan-European index, whereas national and regional assessments in warmer regions may use 35 °C and 40 °C as additional thresholds. This index is not currently available from the C3S CDS, but the underlying data are readily available.
7. '**Warmest three-day period**' (i.e. highest daily mean temperature averaged over a three-day window) is a **high-priority index** for the magnitude of changes in hot temperatures. This index is not currently available from the C3S CDS, but the underlying data are readily available.
8. '**Heatwave days based on apparent temperature**' is a **high-priority index** with relevance for human health. It is the only heatwave index combining temperature and humidity for which data on past trends as well as projections is readily available. The implementation of this index in the C3S dataset on heat waves and cold spells (EuroHEAT definition) considers daily maximum and minimum temperatures over the summer season above a percentile-based threshold.
9. '**Climatological heatwave days**' (i.e. the number of days with temperatures above a given percentile of temperatures during the reference period) is a **medium-priority index** because of its somewhat difficult interpretation. It depicts the change in unusually warm days, independently of the baseline climate. Different implementations of this index use different percentiles (e.g. 90th, 95th or 99th) and reference periods for calculating the threshold (e.g. the whole summer season or a window around the corresponding calendar day). One implementation of this index is available from the C3S dataset on heat waves and cold spells (Climatological EURO-CORDEX definition). (Related EEA indicator: Global and European temperature).
10. '**Days with UTCI above a threshold**' is a **medium-priority index** with relevance for human health. The Universal Thermal Climate Index (UTCI) was developed as a universal heat-related health risk index for Europe based on an energy balance model of the human body (Di Napoli et al., 2018). A UTCI of 26 °C and 32 °C characterises moderate and strong heat stress, respectively, and the latter would be an appropriate threshold for a European index. Hourly UTCI data are available for the past from the C3S dataset on thermal comfort indices, which allow calculation of changes in the number of days with maximum daily UTCI above a threshold (such as 32 °C). UTCI calculation based on climate model projections is not straightforward, and no such dataset is currently available.

A further index considered was 'Changes in days with wet-bulb global temperature above a threshold'. This index was not included in the final index set because of limited data availability and considerable overlap with 'Heatwave days based on apparent temperature'.

4.1.3 Cold spells and frost

Cold spells and frost are relevant hazards for several sectors, including agriculture, construction and transport. Their relevance and impacts largely depends on the affected climate zones and system.
The two selected indices comprise a general-purpose index and an index with specific relevance for agriculture. Both indices account for the frequency of the hazardous conditions.

11. **'Frost days'** (i.e. the number of days with minimum daily temperature below 0 °C) is a **high-priority index** with easy interpretation and wide applicability. This index is readily available from the C3S dataset on agro-climatic indicators.

Further indices considered were 'Cold spell duration', 'Ice days' and 'Zero crossing days'. They were excluded from the final index set due to their limited use at pan-European level.
A particularly intense discussion focussed on indices for assessing the risk of 'late' spring frost (i.e. significant frost events occurring during the vegetation period). Late spring frost is relevant for agriculture, in particular viticulture and fruit cultivation, as well as forestry. However, relevant indices of late frost risk

vary considerably between the specific agricultural or tree species, and they require high-resolution climate data (Leolini et al., 2018; Ma et al., 2019). Therefore, it does not seem feasible to develop such an index at pan-European scale.

4.2 Wet and dry

4.2.1 Mean precipitation

Changes in annual and seasonal precipitation influence ecosystems and a wide range of human activities. One index was selected for this hazard based on a simple and general definition.

12. **'Total precipitation'** is a **high-priority index** with a wide range of applications. Changes in total annual and seasonal precipitation are often used as headline indices in regional climate change assessments and for various sectoral applications. Data are readily available from observations, reanalyses and projections, including with bias adjustments. (Related EEA indicator: Mean Precipitation).

4.2.2 Extreme precipitation (pluvial flooding)

Extreme precipitation is an important hazard for many sectors, including transport and disaster risk management. This hazard is called 'Pluvial flooding' in the CID framework of the IPCC AR6 draft, but the term 'Extreme Precipitation' presents a more general label.

The three selected indices are all based on daily precipitation data because of the paucity of sub-daily precipitation data.

13. **'Maximum consecutive five-day precipitation'** (i.e. the greatest precipitation total over five consecutive days in a year) is a **high-priority index**. It accounts for the magnitude of the event, is of easy interpretability and is widely used in hydrological applications. This index is not currently available from the C3S CDS, but it is expected to become available from two C3S contracts. Furthermore, the underlying data are readily available. (Related EEA indicator: Heavy precipitation in Europe).
14. **'Extreme precipitation total'** (i.e. the sum of precipitation values on all days above a fixed threshold defined over a reference period) is a **high-priority index**. It accounts for the frequency and magnitude of unusual precipitation events identified with respect to the baseline conditions. Different implementations of this index use different percentiles (e.g. 95^{th} or 99^{th}) depending on the level of rarity to be considered. This index is not currently available from the C3S CDS, but the underlying data are readily available. (Related EEA indicator: Heavy Precipitation in Europe).
15. **'Frequency of extreme precipitation'** (i.e. the number of days with precipitation above the threshold defined over a reference period) is a **medium-priority index**. It may be more easily understandable than the previous one but uses less information. Different implementations of this index use different percentiles (e.g. 95^{th} or 99^{th}) depending on the level of rarity to be considered. This index is not currently available from the C3S CDS, but it is expected to become available from a C3S contract. Furthermore, the underlying data are readily available.

4.2.3 River flooding

River flood is an important climate-related hazard for hydrological applications, transport and disaster risk management.

One complex index was selected, which is based on the outcomes of hydrological models.

16. **'River flood index using runoff'** is a **high-priority index** for extreme river floods. It reports the maximum river discharge for a given return period, typically 50 or 100-year period. The index is readily available from the C3S dataset on water quantity indicators for Europe over a pan-

European grid and at catchment level. 'Flood recurrence 50 years Return Period' will be among the indices added soon under the C3S SIS water contract. (Related EEA indicator: River Floods).

4.2.4 Aridity

Changes in the aridity regime represent an important hazard influencing several sectors, including water management, agriculture and energy.

The selected indices include one simple index based on precipitation only and one more complex index based on the combination of precipitation and evapotranspiration.

17. **'Aridity actual'** (i.e. the ratio between annual total precipitation and actual evapotranspiration) is a **high-priority index** where the actual evapotranspiration is derived from hydrological model outputs. The index is readily available from the C3S dataset on water quantity indicators for Europe, in which it is called Aridity 2 and it is derived from three hydrological models. It will be included under 'Aridity Actual' in the operational water contract.
18. **'Consecutive dry days'** (i.e. longest period of consecutive days with precipitation below 1 mm) is a **medium-priority index** accounting for the duration of the dry conditions. It can be easily computed, but it provides limited added value over the other aridity and drought (see below) indices. The index is readily available from the C3S dataset on agro-climatic indicators.

Further indices considered were 'Aridity potential' and 'Climatic water balance'. The former was not included because of the limitations of projections of potential evapotranspiration; the latter is largely interchangeable with the ratio-based aridity index for annual averages (though not for seasonal values).

4.2.5 Drought

Drought is an important climate-related hazard affecting agriculture, forestry, energy sector and water management. There are different types of drought (including meteorological, hydrological and soil moisture droughts) the relevance of which varies across climatic zones and sectors. This has led to the development and use of a wide range of drought-related indices.

Three indices for drought were included in the final list. Two indices for meteorological droughts are based on precipitation only and is most relevant for agriculture. The third index is based on soil moisture with particular relevance for forestry and water management.

19. **'Duration of meteorological droughts'** is a **high-priority index** that reports the total number of months with anomalously low precipitation conditions (for at least two consecutive months) in a given time period, based on the Standardized Precipitation Index (SPI). Different implementations of SPI use different time aggregations and threshold values for precipitation values. The index presented here is based on 3-month aggregated precipitation (SPI-3), which is generally considered suitable for agricultural applications, and a threshold value of -1 for the identification of drought occurrences. Neither SPI nor SPI-based indices are currently available in the C3S CDS, but the underlying precipitation data are readily available. SPI-3 for past and present periods is readily available from C3S dataset on indices based on E-OBS data. Drought conditions based on SPI are also monitored by the JRC EDO platform. (Related EEA indicator: Meteorological and hydrological droughts in Europe).
20. **'Magnitude of meteorological droughts'** is a **medium-priority index** that combines information about the duration and severity of droughts. It is defined as the positive sum of the SPI for all the months within drought events that occurred in a given period. For consistency with 'Duration of meteorological droughts', this index is also based on SPI-3 and a threshold of -1 is used to identify drought occurrences. The medium priority is due to the more complex interpretation of this drought index, compared to the duration index. (Related EEA indicator: Meteorological and hydrological droughts in Europe).

21. **'Duration of soil moisture droughts'** is a **high-priority index** that reports the total number of months with anomalously low soil moisture during a given period. The index applies the definition from the Drought Monitor for Germany, which identifies a drought when soil moisture is lower than the 20th percentile during the reference period. The index is not readily available from the C3S CDS, but soil water content (SWC) in vegetation layers based on hydrological models is provided by the C3S dataset on water quantity indicators for Europe. Soil water content is also available in the C3S from satellite observations, but they cover only the uppermost soil layer. Soil water estimates from climate models (such as the ERA5, ERA5-Land and CMIP5 datasets) are much less reliable than those from hydrological models. Drought conditions based on soil moisture are also monitored by the JRC EDO platform. (Related EEA indicator: Soil moisture).

Drought indices based on the Standardized Evapotranspiration Precipitation Index (SPEI) were also considered, but they were excluded from the final set because of limitations of projections of potential evapotranspiration.

4.2.6 Wildfire

Wildfire is an important hazard for forestry, agriculture, human health and settlements. It can lead to environmental and economic damages and often results in the loss of human lives.

The selected index is based on the Canadian Fire Weather Index (FWI), which combines information on temperature, humidity, precipitation and wind.

22. **'Days with fire danger exceeding a threshold'** is a **high-priority index** that assesses the frequency of dangerous conditions based on weather conditions that affect fuel moisture and fire behaviour. In the fire danger rating of the European Forest Fire System (EFFIS), FWI values above 11.2, 21.3 and 38.0 represent moderate, high and very high fire danger, respectively. Different implementations of this index use different thresholds which define different classes of fire danger. The index is readily available in the C3S from Fire danger indicators for Europe, based on EURO-CORDEX projections and from Fire danger indices historical data based on ERA5 reanalysis. FWI projections for Europe were also developed in the JRC PESETA III project. (Related EEA indicator: Forest Fires).

4.3 Wind

4.3.1 Mean wind speed

Information on mean wind speed and its changes is particularly relevant for the energy sector.
One general-purpose index was selected for this hazard.

23. **'Mean wind speed'** is a **high-priority index** with a wide range of applications. The index presented here shows mean wind speed at 10 m, because this variable is most widely available. Wind speed at 100 meters would be more relevant for wind power, but it is not available from projections.

4.3.2 Severe windstorm

Severe windstorms are an important hazard for a wide range of sectors and activities such as forestry, infrastructure, buildings, energy and transport. However, data availability for this hazard is limited, and there are substantial discrepancies between different data sources (e.g. observations and reanalysis).

The final index set includes one index for this hazard, which is based on daily maximum wind speed.

24. **'Extreme wind speed days'** (i.e. number of days with maximum wind speed above a certain percentile) is a **medium-priority index** owing to the high uncertainty of pan-European windstorm reanalyses and projections. Different implementations use different percentiles defined over a baseline period (e.g. 95th or 98th), depending on the rarity of the event to be considered. The index

is not currently available from the C3S CDS, but it can be computed from hourly reanalyses (e.g. ERA5 and ERA5-Land) and from sub-daily EURO-CORDEX data. Information on historical storm-tracks (based on ERA-Interim and ERA20C) is available from the C3S WISC contract for six European macro-regions, but this information is not suitable for index definition due to its coarse resolution. (Related EEA indicator: Wind storms).

4.4 Snow and ice

4.4.1 Snow and land ice

Changes in snow and ice conditions are important for several sectors, including water management and winter tourism. However, the specific hazardous conditions and thresholds differ widely across systems and climatic zones. The development of snow-related indices is challenged by the strong elevation dependence of snowfall and snow melting. Therefore, high-resolution datasets and analyses are particularly important.

The two selected indices relate to snowfall and snow depth; ice-related indices were not included due to their limited application in Europe.

25. **'Snowfall amount'** (i.e. the cumulative value of snowfall precipitation over the winter season) is a **high-priority index** despite recognized limitations of snowfall projections. This index is readily available from the C3S dataset of Mountain Tourism Meteorological and Snow Indicators for Europe whereby the winter season is defined as the period from November to April.
26. **'Period with snow water equivalent above a threshold'** is a **medium-priority index** due to the limited confidence in models for snow melting driven by climate model projections. Different implementations of the index use alternatively snow water equivalent or snow depth; threshold values may also vary depending on the specific application. This index is readily available from the C3S dataset of Mountain Tourism Meteorological and Snow Indicators for Europe based on the coupling of climate models with dedicated snow accumulation models. (Related EEA indicator: Snow cover).

4.4.2 Heavy snow and ice storms

Heavy snow and ice storms are an important hazard for several sectors, including infrastructure and transport.

The indicator 'Heavy snowfall' (i.e. number of days with snowfall above a certain threshold) was considered, but it was not included in the final index set owing to its limited relevance for sectoral applications and very high uncertainty in climate projections.

4.4.3 Hail

Hail events are among the costliest weather-related extreme events in several European regions, causing substantial damage to crops, vehicles, buildings and other infrastructures. Therefore, information on current and future changes in hail occurrences over Europe can be relevant for a wide range of applications.

The 'Potential hail index', which quantifies the atmospheric potential for hailstorms, was considered but not included. Owing to its high computational complexity and low representativeness in climate models, this index conditions cannot be readily operationalized at European level. (Related EEA indicator: Hail).

4.5 Coastal

4.5.1 Relative sea level

Sea level changes are important for nearly all activities in coastal zones, including urban and regional planning. Sea level change relative to land is most relevant for coastal adaptation purposes. Many of its components (including ocean and ice dynamics as well as glacier isostatic adjustment) can be assessed globally or across Europe scale whereas others (such as local subsidence) are beyond the scope of pan-European datasets. The choice of the components to include in the sea level rise definition therefore depends on the data availability and on the target resolution.

The final index set includes one index reporting relative sea level changes.

27. **'Relative sea level rise'** is a **high-priority index** based on the time-mean sea level. It includes several components that influence sea level change relative to land, except for local land movement effects. The index for present and future scenarios is not readily available from the C3S CDS, but underlying data can be derived from the C3S dataset on water level change time series and indicators. (Related EEA indicator: Global and European sea-level rise).

4.5.2 Coastal flooding

Coastal floods are an important hazard in coastal regions where they can affect buildings, infrastructure, energy and water supply.

The final index set includes one index of extreme sea level, which is a proxy for coastal floods.

28. **'Extreme sea level'** (i.e. the total water level for a certain return period) is a **high-priority index**. Different implementations of the index consider different return periods. A return period of 100 years is often chosen for the planning of coastal protection infrastructures, but different protection levels may be chosen dependent on the population density and other regional characteristics. This index is readily available from the C3S dataset on water level change time series, based on modelled changes in mean sea level, tides, storm surges and waves. This JRC dataset also provides information on the '100-year event total water level' along the global coastline for the present period and the future. (EEA indicator: Global and European sea-level rise).

4.6 Oceanic

4.6.1 Ocean temperature

Information on changes in ocean temperature, including marine heatwaves, is particularly relevant for marine biodiversity, but also for fishery, tourism and human health.

These hazardous conditions are described in the final index set by one general-purpose index and one more complex index, both based on sea surface temperature.

29. **'Sea surface temperature'** is a **high-priority index**. Changes in annual and seasonal mean sea surface temperature are often used as a headline index in global and regional climate-change assessments and various sea-related sectoral applications. The index is readily available at monthly resolution from the CMIP5 dataset in the C3S CDS. Note that the coarse resolution of this dataset limited its accuracy in coastal regions. Furthermore, it can be calculated based on daily observations in a C3S CDS dataset based on satellite measurements or a Copernicus Marine Service dataset from the Operational Sea Surface Temperature and Ice Analysis (OSTIA) system. (Related EEA indicator: Sea surface temperature).

30. **'Duration of marine heatwaves'** (i.e. the total number of days experiencing heatwaves) is a **medium-priority index**. A marine heatwave is generally defined as a period of consecutive days with sea surface temperature above a certain percentile (e.g. 90th, 95th or 99th) computed for the same seasonal window over the baseline period (see Collins et al., 2019, section 6.4). Sea surface temperature projections are currently available at monthly resolution only in the C3S CDS; therefore, only a modified version of the index based on monthly data could be readily computed in the C3S. This index is regarded as having only medium priority due to the computational complexity and the limited confidence in projections of sea surface temperature in coastal regions. (Related EEA indicator: Sea surface temperature).

4.6.2 Marine biochemical properties

Changes in marine biochemical properties can represent a relevant hazard for marine ecosystems and fishery.

31. **'Dissolved oxygen level'** is a **medium-priority index** owing to its limited data availability in the most affected regions**.** Data on recent changes for most European regional seas (except the Black Sea) based on reanalyses are provided by the Copernicus Marine Environment Monitoring Service (CMEMS) in separate datasets for the Baltic sea, the Atlantic-European Northwest shelf, the Atlantic-Iberian Biscay Irish and the Mediterranean Sea. Future projections are available from the CDS dataset on Marine biogeochemistry data. However, this dataset covers neither the Baltic Sea, where oxygen deprivation is most severe, nor the Black Sea. (Related EEA indicator: Oxygen concentrations in European coastal and marine waters).
32. **'Ocean pH level'** is a **medium-priority index** owing to its limited data availability at high resolution. Data on recent changes for most European regional seas (except the Black Sea) based on reanalyses are provided by the Copernicus Marine Environment Monitoring Service (CMEMS) in separate datasets for the Baltic sea, the Atlantic-European Northwest shelf, the Atlantic-Iberian Biscay Irish and the Mediterranean Sea. Future projections are available from the CDS dataset on Marine biogeochemistry data; this dataset does not cover the Baltic Sea and the Black Sea. (EEA indicator: Ocean acidification).

Other indices considered were 'Ocean salinity' and 'Chlorophyll-A level' which were not included in the final index set due to their more limited applicability and weaker links with global climate change.

4.7 Overview of selected climate-related hazard indices

The consultations from the online workshop and the following bilateral meetings with the C3S experts resulted in the 'final' selection of 32 climate-related indices. (Note that this selection is 'final' in the context of this Technical Paper; however, limited changes are possible in the planned EEA report if further relevant data becomes available in the CDS). This set includes 22 high-priority indices and 10 medium-priority indices (Table 4.1). The priority level was assigned according to the relevance for adaptation applications, data availability in the C3S and the robustness of the available data.

Table 4.1 Summary table of the final index set, ordered by hazard types.

Hazard category	Hazard type	Index name	Priority	#
Heat and cold	**Mean temperature**	Mean temperature	High	1.
		Growing degree days	High	2.
		Heating degree days	High	3.
		Cooling degree days	High	4.
	Extreme heat	Tropical nights	High	5.
		Hot days	High	6.
		Warmest three-day period	High	7.
		Heatwave days based on apparent temperature	High	8.
		Climatological heatwave days	Medium	9.
		Days with UTCI above a threshold	Medium	10.
	Cold spells and frost *	Frost days	High	11.
Wet and dry	**Mean precipitation**	Total precipitation	High	12.
	Extreme precipitation *	Maximum consecutive five-day precipitation	High	13.
		Extreme precipitation total	High	14.
		Frequency of extreme precipitation	Medium	15.
	River flooding	River flood index using runoff	High	16.
	Aridity	Aridity actual	High	17.
		Consecutive dry days	Medium	18.
	Drought	Duration of meteorological droughts	High	19.
		Magnitude of meteorological droughts	Medium	20.
		Duration of soil moisture droughts	High	21.
	Wildfire	Days with fire danger exceeding a threshold	High	22.
Wind	**Mean wind speed**	Mean wind speed	High	23.
	Severe windstorm	Extreme wind speed days	Medium	24.
Snow and ice	**Snow and land ice**	Snowfall amount	High	25.
		Period with snow water equivalent above a threshold	Medium	26.
Coastal	**Relative sea level**	Relative sea level rise	High	27.
	Coastal flooding	Extreme sea level	High	28.
Oceanic	**Ocean temperature ***	Sea surface temperature	High	29.
		Duration of marine heatwaves	Medium	30.
	Biochemical ocean properties *	Dissolved oxygen level	Medium	31.
		Ocean pH level	Medium	32.

Note: Hazard categories and types were inspired by the Climatic Impact Drivers (CIDs) in the IPCC AR6 draft report. A star (*) denotes a hazard category that differs from the CID concept in scope or name.

5 Factsheets for the selected climate-related hazard indices

This chapter presents further information for the 32 selected climate-related hazard indices in the form of structured factsheets. The factsheet includes information on available pan-European data sources for each index. Whenever available, they refer to CDS datasets that provide a readily computed version of the index. Otherwise, they refer to the general observation, reanalysis and projection datasets reported in Section 3.3 that cover the specific ECV(s) required for its computation. In the dataset selection, the products providing consistent information for both past, present and future periods were prioritized.

Each index factsheet provides information on:

- index name,
- index acronym,
- index definition,
- main sectors of application,
- overall priority (high or medium),
- the ECVs (and possibly other variables) required for the index computation,
- the physical units,
- specific input datasets from the CDS (if any),
- remarks on input data availability,
- variants of index definition,
- identical or similar index definitions from the INDECIS index set (INDECIS project, 2018) and the ETCCDI index set (Zhang et al., 2011) available through the CLIMDEX project,
- related EEA indicators and
- key references (related to the index definition and/or application, if any).

For each index dataset, the following details are reported:

- CDS dataset name and link,
- Spatial and temporal coverage and resolution,
- Bias-adjustment (yes/no),
- Availability of future climate scenarios (RCPs),
- Underlying dataset (if any; referring to the basic dataset used to derive the index),
- Notes.

5.1 Heat and cold

1. Mean temperature

Mean temperature is a base index representing the temporal pattern of mean temperature over different timescales.
Mean temperature has a wide range of potential application in all sectors.

- Assigned priority: **High**
- Essential climate variables: 2 m daily mean temperature
- Unit: °C

Data availability

- The index can be computed by considering the key observation, reanalysis and projection datasets listed in Section 3.3. The use of CORDEX projections allows a higher spatial resolution. Bias-adjusted projections are generally recommended, but the spatial resolution of bias-adjusted ECVs from CMIP5 is coarser, and the historical period starts in 1978 only. Furthermore, the bias-adjustment of the CMPI5 dataset in the CDS was implemented specifically for water sector applications.

Existing identical or similar index definitions

- INDECIS project: Index 7 – GTG
- EEA indicator: Global and European temperature

2. Growing degree days

The index Growing degree days (GDD) represents the cumulative sum over the year of daily mean temperature exceedances of a reference threshold (e.g. 5 °C or 10 °C). In some cases, an upper temperature limit is applied as well. The simplest version of the index is computed as follows:

$$\mathrm{GDD} = \sum_{i=1}^{365} \mathrm{GDD_i} \;\text{ with } \mathrm{GDD_i} = \begin{cases} \mathrm{T_i} - \mathrm{T_b} \\ 0 \end{cases} \text{if} \begin{cases} \mathrm{T_i} \geq \mathrm{T_b} \\ \mathrm{T_i} < \mathrm{T_b} \end{cases} \; \mathrm{T_b} = 5°\mathrm{C}$$

The GDD index is mainly applied for the agriculture sector as a measure of heat accumulation used to predict plant phenology, insect generation cycles, and pest outbreaks.

- Assigned priority: **High**
- Essential climate variables: 2 m daily mean temperature
- Unit: °C*days

Recommended dataset

Input dataset(s)	Agro climatic indicators from 1951 to 2099 derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-agroclimatic-indicators?tab=overview)
Spatial coverage	Global
Horizontal resolution	0.5° x 0.5°
Temporal coverage	1951–2099
Temporal resolution	10-day
Bias adjustment	Yes
Scenarios	RCPs 2.6, 4.5, 6.0 and 8.5
Underlying dataset	ISIMIP bias-adjusted CMIP5
Notes	Biologically effective degree days is computed as follows: Sum of daily mean temperatures above 10°C and less than 30°C.

Data availability

- If the recommended CDS dataset is not used and the GDD index needs to be computed, the key general CDS datasets listed in Section 3.3 can be used. However, bias-adjusted temperature projections are preferred in order to limit under- or overestimations of temperature exceedances with respect to the fixed base threshold.

Variants of the index

- Variants of GDD are possible. The proposed base temperature thresholds (5 °C and 10 °C) are considered as representative for the main crops in Europe, but the most suitable value varies with the species and plant varieties of interest. Alternative GDD definitions include an upper temperature threshold. The length of the seasonal window for GDD computation could also vary among geographical zones.

Existing identical or similar index definitions

- INDECIS project: Index 35 – GT4 (applying a 4 °C temperature threshold).

References

- Spinoni, J., Vogt, J., Barbosa, P., 2015. European degree-day climatologies and trends for the period 1951–2011. International Journal of Climatology 35, 25–36. https://doi.org/10.1002/joc.3959
- Ruosteenoja, K., Räisänen, J., Venäläinen, A., Kämäräinen, M., 2016. Projections for the duration and degree days of the thermal growing season in Europe derived from CMIP5 model output. International Journal of Climatology 36, 3039–3055. https://doi.org/10.1002/joc.4535

3. Heating degree days

The index Heating degree days (HDD) is a proxy for the energy needed to heat a building. There are different implementations, but the specific variant suggested here is computed as follows:

$$\mathrm{HDD} = \sum_{1}^{182} \mathrm{HDD_i} \ \text{with } \mathrm{HDD_i} = \begin{cases} T_b - T_M \\ \dfrac{T_b - T_N}{2} - \dfrac{T_X - T_b}{4} \\ \dfrac{T_b - T_N}{4} \\ 0 \end{cases} \text{if } \begin{cases} T_b \geq T_X \\ T_M \leq T_b < T_X \\ T_N \leq T_b < T_M \\ T_b \leq T_N \end{cases} \ T_b = 15.5\ ^{\circ}\mathrm{C}$$

The cumulative sum is computed from 1st October to 31st March. The HDD index is most relevant for the energy sector.

- Assigned priority: **High**
- Essential climate variables: 2 m daily mean temperature, 2 m daily minimum temperature, 2 m daily maximum temperature
- Unit: °C*days

Data availability

- The index can be computed from any of the key CDS datasets (Section 3.3). Bias-adjusted temperature projections are preferred in order to limit under- or overestimations of temperature exceedances with respect to the fixed base threshold.

Variants of the index

- Alternative T_b and cumulative time windows can be chosen, according to the local climate and specific applications.

Existing identical or similar index definitions

- INDECIS project: Index 24 – HD17 (defined as the annual cumulative sum of daily mean temperature difference with respect to an upper threshold of 17 °C)
- EEA indicator Heating and cooling degree days

References

- Spinoni, J., Vogt, J. and Barbosa, P. (2015), European degree-day climatologies and trends for the period 1951–2011. Int. J. Climatol., 35: 25-36. https://doi.org/10.1002/joc.3959

4. Cooling degree days

The index Cooling degree days (CDD) is a proxy for the energy needed to cool a building. There are different implementations, but the specific variant suggested here is computed as follows:

$$\mathrm{CDD} = \sum_{1}^{182} \mathrm{CDD_i} \;\; \text{with } \mathrm{CDD_i} = \begin{cases} 0 \\ \dfrac{T_X - T_b}{4} \\ \dfrac{T_X - T_b}{2} - \dfrac{T_b - T_N}{4} \\ T_M - T_b \end{cases} \text{if} \begin{cases} T_b \geq T_X \\ T_M \leq T_b < T_X \\ T_N \leq T_b < T_M \\ T_b \leq T_N \end{cases} \; T_b = 22\,°\mathrm{C}$$

The cumulative sum is computed from 1st April to 30th September. The CDD index is most relevant for the energy sector.

- Assigned priority: **High**
- Essential climate variables: 2 m daily mean temperature, 2 m daily minimum temperature, 2 m daily maximum temperature
- Unit: °C*days

Data availability

- The index can be computed from any of the key CDS datasets (Section 3.3). Bias-adjusted temperature projections are preferred in order to limit under- or overestimations of temperature exceedances with respect to the fixed base threshold.

Variants of the index

- Alternative T_b and cumulative time windows can be chosen, according to the local climate and specific applications.

Existing identical or similar index definitions

- EEA indicator Heating and cooling degree days

References

- Spinoni, J., Vogt, J. and Barbosa, P. (2015), European degree-day climatologies and trends for the period 1951–2011. Int. J. Climatol., 35: 25-36. https://doi.org/10.1002/joc.3959

5. Tropical nights

The index Tropical nights counts the number of days over a certain period with daily minimum temperature exceeding 20 °C.
The index is mainly applied in health-related contexts.

- Assigned priority: **High**
- Essential climate variables: 2-m daily minimum temperature
- Unit: number of days

Recommended dataset

Input dataset(s)	Agro climatic indicators from 1951 to 2099 derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-agroclimatic-indicators?tab=overview)
Spatial coverage	Global
Horizontal resolution	0.5° x 0.5°
Temporal coverage	1951–2099
Temporal resolution	10-day
Bias adjustment	Yes
Scenarios	RCPs 2.6, 4.5, 6.0 and 8.5
Underlying dataset	ISIMIP bias-adjusted CMIP5
Notes	

Variants of the index

- The proposed minimum temperature threshold is considered suitable for a pan-European perspective. However, other thresholds could be considered depending on the local climate.

Existing identical or similar index definitions

- INDECIS project: Index 23 – TN
- CLIMDEX/ETCCDI set: Index 4 – TR

6. Hot days

The index Hot days counts the number of days over a certain time interval with daily maximum temperature above 30°C.
This index is mainly applied in health-related contexts.

- Assigned priority: **High**
- Essential climate variables: 2 m daily maximum temperature
- Unit: number of days

Data availability

- The index can be computed from any of the key CDS datasets (Section 3.3). Bias-adjusted temperature projections are preferred in order to limit under- or overestimations of temperature exceedances with respect to the fixed base threshold.

Variants of the index

- The 30 °C threshold is considered suitable for a pan-European prospective. Other temperature values, for example 35 °C and 40 °C, can be used as additional thresholds for warmer regions.

Existing identical or similar index definitions

- INDECIS project: Index 20 – SUD; Index 39 – D32 (applying 25 °C and 32 °C as maximum temperature thresholds, respectively).
- CLIMDEX/ETCCDI set: Index 2 – SU (with 25 °C threshold).

References

- Fallmann, J., Wagner, S. & Emeis, S. (2017). High resolution climate projections to assess the future vulnerability of European urban areas to climatological extreme events. Theor. Appl. Climatol., 127, 667–683. https://doi.org/10.1007/s00704-015-1658-9

7. Warmest three-day period

The index Warmest three-days period reports the highest daily mean temperature averaged over a three-day window.
The index measures heatwave intensity and is mainly applicable in health-related sectors and agriculture.

- Assigned priority: **High**
- Essential climate variables: 2 m daily mean temperature
- Unit: °C

Data availability

- The index can be computed from any of the key CDS datasets (Section 3.3). Bias-adjusted temperature projections are preferred in order to limit under- or overestimations of extreme temperature values.

Variants of the index

- The length of the time window for computing the moving average of temperature can vary depending on the specific applications.

References

- World Weather Attribution (2017): Euro-Mediterranean heat, summer 2017. https://www.worldweatherattribution.org/euro-mediterranean-heat-summer-2017/

8. Heatwave days based on apparent temperature

The index Heatwave days based on apparent temperature counts the number of days in a year within prolonged periods of extreme humid heat conditions. According to the EuroHEAT definition (Michelozzi et al., 2007; WHO Europe and EC, 2009), heatwaves are defined as periods of at least two consecutive days during the summer months (June, July, August) in which the maximum apparent temperature (T_{app}) and minimum temperature exceed their corresponding 90th percentiles for each month computed over the control period 1979–2008.
The apparent temperature is a measure of relative discomfort due to combined heat and high humidity, based on physiological studies on evaporative skin cooling. It can be calculated at hourly scale as a combination of air and dew point temperature:

$$T_{app} = -2.653 + 0.994T_{air} + 0.0153T_{dew}^2$$

The index is mainly applied in health-related contexts.

- Assigned priority: **High**
- Essential climate variables: 2 m daily minimum temperature, 2 m hourly air temperature and dew-point temperature
- Unit: number of days

Recommended dataset

Input dataset(s)	Heat waves and cold spells in Europe derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-heat-and-cold-spells?tab=overview)
Spatial coverage	European region (Extent: ~ 27N – 72N, ~22W – 45E)
Horizontal resolution	0.1° x 0.1°
Temporal coverage	1986–2085 (30-year moving average)
Temporal resolution	Year
Bias adjustment	Yes
Scenarios	RCPs 4.5 and 8.5
Underlying dataset	bias-adjusted EURO-CORDEX
Notes	Ensemble members average and standard deviation are provided

Variants of the index

- The index is based on one of the possible heatwave definitions. An alternative heatwave definition is also provided in the same recommended CDS dataset (see Factsheet 9). In addition, this dataset also provides heatwave days based on country-specific heatwave definitions.

References

- Michelozzi, P., Kirchmayer, U., Katsouyanni, K., Biggeri, A., McGregor, G., Menne, B., Kassomenos, P., Anderson, H.R., Baccini, M., Accetta, G., Analytis, A., Kosatsky, T., 2007. Assessment and prevention of acute health effects of weather conditions in Europe, the PHEWE project: background, objectives, design. Environmental Health 6, 12. https://doi.org/10.1186/1476-069X-6-12
- WHO Europe, EC, 2009. Improving public health responses to extreme weather/heat-waves: EuroHEAT, Summary for policy-makers. World Health Organization & Regional Office for Europe & European Commission, Copenhagen, Denmark.

9. Climatological heatwave days

The index Climatological heatwave days counts the number of days in a year within prolonged periods of unusually high temperatures. A heatwave is identified accordingly to the climatological EURO-CORDEX definition as a period of at least three consecutive days on which the daily maximal temperature exceeds the 99th percentile of the daily maximum temperatures of the May to September season during the control period 1971–2000.

The index is mainly applied in health-related contexts.

- Assigned priority: **Medium**
- Essential climate variables: 2 m daily maximum temperature
- Unit: number of days

Recommended dataset

Input dataset(s)	Heat waves and cold spells in Europe derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-heat-and-cold-spells?tab=overview)
Spatial coverage	European region (Extent: ~ 27N – 72N, ~22W – 45E)
Horizontal resolution	0.1° x 0.1°
Temporal coverage	1986–2085 (30-year moving average)
Temporal resolution	Year
Bias adjustment	Yes
Scenarios	RCPs 4.5 and 8.5
Underlying dataset	bias-adjusted EURO-CORDEX
Notes	Ensemble members average and standard deviation are provided

Variants of the index

- The recommended CDS datasets includes this index as one of the possible heatwave definitions. The same dataset includes an alternative heatwave definition (see Factsheet 8) as well as heatwave days based on country-specific heatwave definitions.

References

- Jacob, D. , J. Petersen, B. Eggert, A. Alias, O.B. Christensen, L.M. Bouwer, A. Braun, A. Colette et al. (2014): EURO-CORDEX: new high-resolution climate change projections for European impact research, Regional Environmental Change, 14, 563-578. https://doi.org/10.1007/s10113-013-0499-2

10. Days with UTCI above a threshold

The Universal Thermal Climate Index (UTCI) was developed as a universal heat-related health risk index for Europe. The proposed index accounts for the number of days in a certain period with maximum daily UTCI above 32 °C, which corresponds to strong heat stress.
This index is applied in a human health context.

- Assigned priority: **Medium**
- Essential climate variables: 2 m air temperature, relative humidity, 10 m wind speed and radiation fluxes at the Earth's surface.
- Unit: number of days

Recommended dataset

Input dataset	Thermal comfort indices derived from ERA5 reanalysis (https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.553b7518?tab=overview)
Spatial coverage	Global (except for Antarctica)
Horizontal resolution	0.25° x 0.25°
Temporal coverage	1979–present
Temporal resolution	Hourly
Underlying dataset	ERA5
Bias adjustment	No
Scenarios	None
Notes	

Data availability

- The UTCI is not currently available for future projections.

Variants of the index

- The proposed minimum temperature threshold is considered suitable for accounting for strong heat stress in a pan-European prospective; other thresholds could be alternatively considered depending on the local climate.

References

- Di Napoli, C., Pappenberger, F. & Cloke, H.L. (2018). Assessing heat-related health risk in Europe via the Universal Thermal Climate Index (UTCI). Int J Biometeorol 62, 1155–1165. https://doi.org/10.1007/s00484-018-1518-2

11. Frost days

The index Frost days counts the number of days over a certain period with daily minimum temperature below 0 °C.
The index is mainly applied in agriculture to account for frost damages, but it is also relevant for the transport sector.

- Assigned priority: **High**
- Essential climate variables: 2 m daily minimum temperature
- Unit: number of days

Recommended dataset

Input dataset(s)	Agro climatic indicators from 1951 to 2099 derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-agroclimatic-indicators?tab=overview)
Spatial coverage	Global
Horizontal resolution	0.5° x 0.5°
Temporal coverage	1951–2099
Temporal resolution	10-day
Bias adjustment	Yes
Scenarios	RCPs 2.6, 4.5, 6.0 and 8.5
Underlying dataset	ISIMIP bias-adjusted CMIP5
Notes	

Existing identical or similar index definitions

- INDECIS project: Index 13 – FDs
- CLIMDEX/ETCCDI set: Index 1 – FD

5.2 Wet and dry

12. Total precipitation

Total precipitation is a base index representing the amount of precipitation at different timescales (e.g. monthly, seasonal, annual).
This index has a wide range of potential application in all sectors.

- Assigned priority: **High**
- Essential climate variables: daily total precipitation
- Unit: mm

Data availability

- The index can be computed by considering the key observation, reanalysis and projection datasets listed in Section 3.3. The use of CORDEX projections allows a higher spatial resolution. Bias-adjusted projections are generally recommended, but the spatial resolution of bias-adjusted ECVs from CMIP5 is coarser, and the historical period starts in 1978 only.

Existing identical or similar index definitions

- INDECIS project: Index 43 – TP
- EEA indicator Mean Precipitation

13. Maximum consecutive five-day precipitation

The index Maximum consecutive five-day precipitation reports the maximum precipitation sum occurred over 5 consecutive days in a given period.
This index is mainly applicable in agriculture, water management, transport and urban-related sectors.

- Assigned priority: **High**
- Essential climate variables: daily total precipitation
- Unit: mm

Data availability

- This index is not currently available from the C3S CDS, but it is expected to become available soon through two C3S contracts.
- The index can be computed by considering the key observation, reanalysis and projection datasets listed in Section 3.3. The use of CORDEX projections allows a higher spatial resolution. Bias-adjusted projections are generally recommended, but the spatial resolution of bias-adjusted ECVs from CMIP5 is coarser, and the historical period starts in 1978 only.

Existing identical or similar index definitions

- INDECIS project: Index 48 – Rx5day
- CLIMDEX/ETCCDI set: Index 18 – Rx5day
- EEA indicator: Heavy precipitation in Europe

14. Extreme precipitation total

The Extreme precipitation total index represents the total sum of daily precipitation over a certain period exceeding the 99^{th} percentile of the reference interval.
This index is mainly applicable in agriculture, water management, transport and urban-related sectors.

- Assigned priority: **High**
- Essential climate variables: daily total precipitation
- Unit: mm

Data availability

- The index can be computed by considering the key observation, reanalysis and projection datasets listed in Section 3.3. The use of CORDEX projections allows a higher spatial resolution. Bias-adjusted projections are generally recommended, but the spatial resolution of bias-adjusted ECVs from CMIP5 is coarser, and the historical period starts in 1978 only.

Variants of the index

- The percentile used to define the threshold for extreme conditions can vary depending on the rarity of the events to be considered.

Existing identical or similar index definitions

- CLIMDEX/ETCCDI set: Index 26 – R99pTOT

15. Frequency of extreme precipitation

The index Frequency of extreme precipitation reports the number of days over a certain period with daily total precipitation exceeding the 99^{th} percentile of the reference interval.
The index is mainly applicable in agriculture, water management, transport and urban-related sectors.

- Assigned priority: **Medium**
- Essential climate variables: daily total precipitation
- Unit: number of days

Data availability

- This index is not currently available from the C3S CDS, but it is expected to become available soon from one C3S contract.
- The index can be computed by considering the key observation, reanalysis and projection datasets listed in Section 3.3. The use of CORDEX projections allows a higher spatial resolution. Bias-adjusted projections are generally recommended, but the spatial resolution of bias-adjusted ECVs from CMIP5 is coarser, and the historical period starts in 1978 only.

Variants of the index

- The percentile used to define the threshold for extreme conditions can vary depending on the rarity of the events to be considered.

References

- Myhre, G., Alterskjær, K., Stjern, C.W., Hodnebrog, Ø., Marelle, L., Samset, B.H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M., Stohl, A., 2019. Frequency of extreme precipitation increases extensively with event rareness under global warming. Scientific Reports 9, 16063. https://doi.org/10.1038/s41598-019-52277-4

16. River flood index using runoff

The River flood index using runoff accounts for extreme water discharge as it reports the value of daily river flow corresponding to a return period of 100 years.
The index is mainly applicable in water and flood management.

- Assigned priority: **High**
- Essential climate variables: output of hydrological models
- Unit: $m^3\ s^{-1}$

Recommended dataset

Input dataset(s)	Water quantity indicators for Europe (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-quantity-swicca?tab=overview)
Spatial coverage	Europe
Horizontal resolution	0.5° x 0.5°, catchment aggregation
Temporal coverage	1971–2100
Temporal resolution	Statistics over 30-year periods
Bias adjustment	No
Scenarios	RCPs 2.6, 4.5 and 8.5
Underlying dataset	Several RCMs
Notes	The return period values for river flow are calculated using a Gumbel distribution fitted to the yearly maximum river flows for a given 30-year period. The whole dataset is based on three hydrological models.

Variants of the index

- The return period can vary according with the rarity of the events to be considered and the specific applications.

Existing identical or similar index definitions

- EEA indicator: River Floods

References

- Alfieri, L., Burek, P., Feyen, L., Forzieri, G., 2015. Global warming increases the frequency of river floods in Europe. Hydrology and Earth System Sciences 19, 2247–2260. https://doi.org/10.5194/hess-19-2247-2015

17. Aridity actual

The index Aridity actual is the ratio between actual evapotranspiration and total precipitation accumulated over a certain time window. Actual evapotranspiration is retrieved from the outputs of hydrological models.

The index is mainly applicable in agriculture and water management.

- Assigned priority: **High**
- Essential climate variables: daily total precipitation, output of hydrological models
- Unit: dimensionless

Recommended dataset

Input dataset(s)	Water quantity indicators for Europe (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-quantity-swicca?tab=overview)
Spatial coverage	Europe
Horizontal resolution	0.5° x 0.5°, 5km, catchment aggregation
Temporal coverage	1971–2100
Temporal resolution	30-year, month, 10-day averages
Bias adjustment	No
Scenarios	RCPs 2.6, 4.5 and 8.5
Underlying dataset	Several RCMs
Notes	The whole dataset is derived by applying three hydrological models

References

- Dezsi, Ş., Mîndrescu, M., Petrea, D., Rai, P.K., Hamann, A., and Nistor, M.-M. (2018). High-resolution projections of evapotranspiration and water availability for Europe under climate change, Int J Climatol., 38, 3832– 3841. https://doi.org/10.1002/joc.5537

18. Consecutive dry days

The index Consecutive dry days reports the longest dry period over a certain time window with daily precipitation below 1 mm.
The index is mainly applicable in agriculture and water management.

- Assigned priority: **Medium**
- Essential climate variables: daily total precipitation
- Unit: number of days

Recommended dataset

Input dataset(s)	Agro climatic indicators from 1951 to 2099 derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-agroclimatic-indicators?tab=overview)
Spatial coverage	Global
Horizontal resolution	0.5° x 0.5°
Temporal coverage	1951–2099
Temporal resolution	season
Bias adjustment	Yes
Scenarios	RCPs 2.6, 4.5, 6.0 and 8.5
Underlying dataset	ISIMIP bias-adjusted CMIP5
Notes	

References

- Sieck, K., Nam, C., Bouwer, L. M., Rechid, D., and Jacob, D.: Weather extremes over Europe under 1.5 °C and 2.0 °C global warming from HAPPI regional climate ensemble simulations, Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2020-4, in review, 2020.

19. Duration of meteorological droughts

The index Duration of meteorological droughts represents the total number of months in a year that experience drought conditions as determined by anomalously low precipitation values. The index is based on the 3-month Standardized Precipitation Index (SPI-3), which accounts for the deficit (or surplus) of precipitation accumulated over 3 months with respect to the corresponding reference value from a 30-year baseline in the historical period.

The precipitation values over the baseline period are fitted by a Gamma probability distribution, which is then transformed into a normal distribution so that the SPI mean for the period is zero. SPI values are therefore the number of standard deviations from the long-term mean and can be used to compare different geographical locations and timescales. According to the most common definition (Spinoni et al., 2020), a drought event starts when SPI values fall below -1 for at least two consecutive months and ends when the index returns positive.

SPI is the most common index for detecting and characterizing meteorological droughts. It is applicable in a wide range of water-related sectors, especially agriculture, hydrology and water management.

- Assigned priority: **High**
- Essential climate variables: monthly total precipitation
- Unit: number of months

Data availability

- The index can be computed from the general CDS datasets (see Section 3.3).
- SPI data (since 1981) is also available on request from the European Drought Observatory (https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1104).

Variants of the index

- The baseline period to consider for the fit of the underlying distribution can cover a 30-year past period or extend to the entire time window depending on the scope of the analysis. In addition, different accumulation periods are generally considered, each of them referring to different types of drought. Shorter periods (up to 3 months) account for meteorological droughts, medium periods (e.g. 6 months) for agricultural drought and longer periods (e.g. 12 months) for hydrological droughts.
- SPI does not account for the increase in evapotranspiration driven by increasing temperature. Soil moisture-based indices (see Factsheet 21) can complement the provided information.

Existing identical or similar index definitions

- EEA indicator Meteorological and hydrological droughts in Europe (focussing on drought frequency rather than duration).

References

- Spinoni, J., Barbosa, P., Bucchignani, E., Cassano, J., Cavazos, T., Christensen, J.H., Christensen, O.B., Coppola, E., Evans, J., Geyer, B., Giorgi, F., Hadjinicolaou, P., Jacob, D., Katzfey, J., Koenigk, T., Laprise, R., Lennard, C.J., Kurnaz, M.L., Li, D., Llopart, M., McCormick, N., Naumann, G., Nikulin, G., Ozturk, T., Panitz, H.-J., Porfirio da Rocha, R., Rockel, B., Solman, S.A., Syktus, J., Tangang, F., Teichmann, C., Vautard, R., Vogt, J.V., Winger, K., Zittis, G., Dosio, A., 2020. Future Global Meteorological Drought Hot Spots: A Study Based on CORDEX Data. J. Climate 33, 3635–3661. https://doi.org/10.1175/JCLI-D-19-0084.1
- JRC, 2017. European Drought Observatory. http://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000

20. Magnitude of meteorological droughts

The index Magnitude of meteorological droughts represents the cumulated severity of drought events as determined by anomalous low precipitation values. The index is based on the 3-month Standardized Precipitation Index (SPI-3), which accounts for the deficit (or surplus) of precipitation accumulated over 3 months with respect to the corresponding reference value from a 30-year baseline in the historical period. The severity of a drought event is computed as the sum of SPI absolute values in the months included in the drought episode.

The precipitation values over the baseline period are fitted by a Gamma probability distribution, which is then transformed into a normal distribution so that the SPI mean for the period is zero. SPI values are therefore the number of standard deviations from the long-term mean and can be used to compare different geographical locations and timescales. According to the most common definition (Spinoni et al., 2020), a drought event starts when SPI values fall below -1 for at least two consecutive months and ends when the index returns positive.

SPI is the most common index for detecting and characterizing meteorological droughts. It is applicable in a wide range of water-related sectors, especially agriculture, hydrology and water management.

- Assigned priority: **Medium**
- Essential climate variables: monthly total precipitation
- Unit: dimensionless

Data availability

- The index can be computed from the general CDS datasets (see Section 3.3).

Variants of the index

- The baseline period to consider for the fit of the underlying distribution can cover a 30-year past period or extend to the entire time window depending on the scope of the analysis. In addition, different accumulation periods are generally considered, each of them referring to different types of drought. Shorter periods (up to 3 months) account for meteorological droughts, medium periods (e.g. 6 months) for agricultural drought and longer periods (e.g. 12 months) for hydrological droughts.
- SPI does not account for the increase in evapotranspiration driven by increasing temperature, so that other indices. Soil moisture-based indices (see Factsheet 21) can complement the provided information.

Existing identical or similar index definitions

- EEA indicator Meteorological and hydrological droughts in Europe (focussing on drought frequency rather than magnitude).

References

- Spinoni, J., Barbosa, P., Bucchignani, E., Cassano, J., Cavazos, T., Christensen, J.H., Christensen, O.B., Coppola, E., Evans, J., Geyer, B., Giorgi, F., Hadjinicolaou, P., Jacob, D., Katzfey, J., Koenigk, T., Laprise, R., Lennard, C.J., Kurnaz, M.L., Li, D., Llopart, M., McCormick, N., Naumann, G., Nikulin, G., Ozturk, T., Panitz, H.-J., Porfirio da Rocha, R., Rockel, B., Solman, S.A., Syktus, J., Tangang, F., Teichmann, C., Vautard, R., Vogt, J.V., Winger, K., Zittis, G., Dosio, A., 2020. Future Global Meteorological Drought Hot Spots: A Study Based on CORDEX Data. J. Climate 33, 3635–3661. https://doi.org/10.1175/JCLI-D-19-0084.1
- JRC, 2017. European Drought Observatory. http://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000

21. Duration of soil moisture droughts

The index Duration of soil moisture droughts represents the total number of months in a year experiencing soil drought conditions. Soil droughts are defined here as months with a soil moisture content (cumulated over all soil layers) below the corresponding 20th percentile from the 30-year baseline period.
The index is mainly applicable in forestry, water management and, to a lesser degree, in agriculture.

- Assigned priority: **High**
- Essential climate variables: monthly soil moisture
- Unit: number of months

Recommended dataset

Input dataset(s)	Water quantity indicators for Europe [(https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-quantity-swicca?tab=overview)](https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-quantity-swicca?tab=overview)
Spatial coverage	European
Horizontal resolution	0.5° x 0.5°, catchment aggregation
Temporal coverage	1971–2099
Temporal resolution	30-year, month, 10-day averages
Bias adjustment	No
Scenarios	RCPs 2.6, 4.5 and 8.5
Underlying dataset	Several RCMs
Notes	The whole dataset is derived by applying three hydrological models; it provides soil water content (i.e. the volume fraction of soil occupied by water), averaged over those soil layers providing moisture for plant transpiration.

Data availability

- Another dataset including a soil moisture variable was developed within the C3S EDgE project, but it is not currently released in the C3S CDS. It could represent another potential source of data for the index implementation.

Variants of the index

- The percentile used to identify hazardous conditions can vary according to the specific applications and climate zones.

References

- Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E.F., Marx, A., 2018. Anthropogenic warming exacerbates European soil moisture droughts. Nature Climate Change 8, 421–426. https://doi.org/10.1038/s41558-018-0138-5

22. Days with fire danger exceeding a threshold

The index Days with fire danger exceeding a threshold is based on the Canadian Fire Weather Index (FWI). The FWI is a numerical rating of the meteorological forest fire danger that combines assessments of fire ignition and spread. The selected index reports the total number of days in a year with FWI above a threshold. According to the EFFIS classification, FWI thresholds of 21.3 and 38 represent high and very high fire risk, respectively.
This index provides information about fire danger conditions to a wide range of sectors, including forestry, regional planning and disaster risk management.

- Assigned priority: **High**
- Essential climate variables: model output required for the FWI computation
- Unit: number of days

Recommended dataset

Input dataset	Fire danger indicators for Europe from 1970 to 2098 derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-tourism-fire-danger-indicators?tab=overview)
Spatial coverage	Europe
Horizontal resolution	0.11°x0.11°
Temporal coverage	1970–2098
Temporal resolution	Annual
Bias adjustment	No
Scenarios	RCP 2.6, 4.5, 8.5
Underlying dataset	EURO-CORDEX
Notes	Climate model outputs are combined in the Global ECMWF Fire Forecasting model.

Variants of the index

- Different fire danger classes (i.e. FWI-based thresholds) can be considered for accounting for the level of fire risk.

References

- Copernicus Emergency Management Service for the European Forest Fire Information System (EFFIS) [WWW Document], n.d. URL: https://effis.jrc.ec.europa.eu/about-effis/technical-background/fire-danger-forecast/
- De Rigo, D., Libertà, G., Durrant, T.H., Vivancos, T.A., San-Miguel-Ayanz, J., 2017. Forest fire danger extremes in Europe under climate change: variability and uncertainty (JRC Technical Reports No. EUR 28926 EN). Publications Office of the European Union, Luxembourg.

5.3 Wind

23. Mean wind speed

The index Mean wind speed represents the mean horizontal wind speed over a given period.
This index is mainly applied in the energy industry.

- Assigned priority: **High**
- Essential climate variables: 10 m wind speed
- Unit: $m \cdot s^{-1}$

Data availability

- The index can be computed from the general CDS datasets (Section 3.3). CORDEX projections are preferable over CMIP5 projections because of their higher spatial resolution. Currently, no bias-corrected projections are available.

Existing identical or similar index definitions

- INDECIS project: Index 88 – FG

References

- Tobin, I., Jerez, S., Vautard, R., Thais, F., Van Meijgaard, E., Prein, A., Déqué, M., Kotlarski, S., Maule, C.F., Nikulin, G., Noël, T., Teichmann, C., 2016. Climate change impacts on the power generation potential of a European mid-century wind farms scenario. Environ. Res. Lett. 11, 34013. https://doi.org/10.1088/1748-9326/11/3/034013

24. Extreme wind speed days

The Extreme wind speed days index counts the number of days in a year with daily maximum wind speed above the 98th percentile (computed over a reference period).
The index is mainly applied for forest, agriculture, buildings, onshore and offshore infrastructures and energy industry.

- Assigned priority: **Medium**
- Essential climate variables: 10 m wind speed
- Unit: number of days

Data availability

- The index can be computed from the general CDS datasets (Section 3.3). CORDEX projections are preferable over CMIP5 projections because of their higher spatial resolution. Nevertheless, the horizontal resolution of the input dataset may not capture local windstorms. Currently, no bias-corrected projections are available.

Variants of the index

- A different percentile for the identification of the extreme conditions can be adopted depending on the rarity of the events to be considered.

References

- Spinoni, J. Formetta, G., Mentaschi, L., Forzieri, G. and Feyen, L. (2020): Global warming and windstorm impacts in the EU. JRC Technical Report JRC118595. http://doi.org/10.2760/039014

5.4 Snow and ice

25. Snowfall amount

The Snowfall amount index represents cumulative value of snowfall precipitation over the winter season from November to April.
The index is mainly applied in water and tourism sectors.

- Assigned priority: **High**
- Essential climate variables: total snow precipitation
- Unit: kg · m^2

Recommended dataset

Input dataset(s)	Mountain Tourism Meteorology and Snow Indicators (https://climate.copernicus.eu/mountain-tourism-meteorology-and-snow-indicators)
Spatial coverage	European (Extent: ~ 27N – 72N, ~22W – 45E)
Horizontal resolution	NUTS-3 regions
Temporal coverage	1950–2100
Temporal resolution	Annual (from November to April) Climatology: 20-30 year aggregation
Bias adjustment	Yes
Scenarios	RCPs 2.6, 4.5 and 8.5
Underlying dataset	bias-adjusted EURO-CORDEX
Notes	The snow index was generated coupling climate models with the Crocus snowpack model, a multi-layer snowpack model embedded in the land surface model (SURFEX/Crocus).

Existing identical or similar index definitions

- INDECIS project: Index 101 – SS.

References

- Soci, C., Bazile, E., Besson, F.O., Landelius, T., 2016. High-resolution precipitation re-analysis system for climatological purposes. Tellus, Ser. A Dyn. Meteorol. Oceanogr. 68. https://doi.org/10.3402/tellusa.v68.29879

26. Period with snow water equivalent above a threshold

The index Period with snow water equivalent above a threshold counts the number of days (from November to April) where the water equivalent of natural snow is above a given threshold (here: 100 kg m^{-2}).

This index is particularly relevant for the tourism sector, but also for forestry, agriculture and water management.

- Assigned priority: **Medium**
- Essential climate variables: snow water equivalent
- Unit: number of days

Recommended dataset

Input dataset(s)	Mountain tourism meteorological and snow indicators for Europe from 1950 to 2100 derived from reanalysis and climate projections (https://sis-dev.climate.copernicus.eu/cdsapp#!/dataset/sis-tourism-snow-indicators?tab=overview)
Spatial coverage	European (Extent: ~ 27N – 72N, ~22W – 45E)
Horizontal resolution	NUTS-3 regions
Temporal coverage	1950–2100
Temporal resolution	Annual (from November to April) Climatology: 20-30 year aggregation
Bias adjustment	Yes
Scenarios	RCPs 2.6, 4.5 and 8.5
Underlying dataset	Bias-adjusted EURO-CORDEX
Notes	The snow indices were generated coupling climate models with the Crocus snowpack model, a multi-layer snowpack model embedded in the land surface model (SURFEX/Crocus).

Variants of the index

- Different types of snow can be considered for the index definition, i.e. natural, groomed or machine made.
- Different thresholds for snow water equivalent or -alternatively- for snow depth can be adopted according to the application needs.

Existing identical or similar index definitions

- INDECIS project: Index 107 – HSD (based on snow depth with a threshold of 50 cm).

References

- Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le moigne, P., Martin, E., Willemet, J.-M., 2012. The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2. Geosci. Model Dev. 773–791. https://doi.org/10.5194/gmd-5-773-2012

5.5 Coastal

27. Relative sea level rise

The Relative sea level rise index represents the average height of sea water in a given year and region in comparison to a reference period. This index includes geophysical sources that drive its long-term changes, such as ice components, ocean-related components, land water storage and glacial isostatic adjustment, except for local land movement effects (Church et al., 2013).
This index is most relevant for coastal infrastructure, regional and urban planning.

- Assigned priority: **High**
- Essential climate variables: sea level/sea surface height
- Unit: m

Recommended datasets

Input dataset(s)	Water level change time series for the European coast from 1977 to 2100 derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-level-change-timeseries?tab=overview) Water level change indicators for the European coast from 1977 to 2100 derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-level-change-indicators?tab=overview)
Spatial coverage	European (Extent: ~ 27N – 72N, ~22W – 45E)
Horizontal resolution	Coastal grid points: 0.1° Ocean grid points: 0.25°, 0.5°, and 1° within 100 km, 500 km, and >500 km of the coastline, respectively
Temporal coverage	ERA5 reanalysis: from 1979 to 2017 Historical: from 1977 to 2005 RCP8.5: from 2041 to 2070 RCP4.5: from 2071 to 2100
Temporal resolution	10 min
Bias adjustment	Yes
Scenarios	RCPs 4.5 and 8.5
Underlying dataset	Bias-adjusted EURO-CORDEX
Notes	To compute these indices, the Deltares Global Tide and Surge Model (GTSM) version 3.0 is used together with regional climate forcing and sea level rise initial conditions.

Variants of the index

- Variants of relative sea level rise consider different components affecting sea level rise at regional and local scale. More information on established definitions and variants can be found in Gregory et al., 2019.

Existing identical or similar index definitions

- EEA indicator Global and European sea-level rise

References

- Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D., Unnikrishnan, A.S., 2013. Sea-level change, in: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis:

Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

- Gregory, J.M., Griffies, S.M., Hughes, C.W., Lowe, J.A., Church, J.A., Fukimori, I., Gomez, N., Kopp, R.E., Landerer, F., Cozannet, G.L., Ponte, R.M., Stammer, D., Tamisiea, M.E., van de Wal, R.S.W., 2019. Concepts and Terminology for Sea Level: Mean, Variability and Change, Both Local and Global. Surv Geophys 40, 1251–1289. https://doi.org/10.1007/s10712-019-09525-z

28. Extreme sea level

The index Extreme sea level represents the total sea water level in coastal locations for 100-year return period events.
This index is most relevant for coastal infrastructure and ecosystems, regional and urban planning, agriculture and water supply.

- Assigned priority: **High**
- Essential climate variables: total water level
- Unit: m

Recommended dataset

Input dataset(s)	Water level change indicators for the European coast from 1977 to 2100 derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-level-change-indicators?tab=overview)
Spatial coverage	European (Extent: ~ 27N – 72N, ~22W – 45E)
Horizontal resolution	Coastal grid points: 0.1° Ocean grid points: 0.25°, 0.5°, and 1° within 100 km, 500 km, and >500 km of the coastline, respectively
Temporal coverage	Statistics for ERA5 reanalysis: from 1979 to 2017 Statistics for historical: from 1977 to 2005 Statistics for RCP8.5: from 2041 to 2070 Statistics for RCP4.5: from 2071 to 2100
Temporal resolution	No temporal resolution as the indicators are derived from the daily series and represents statistics over the temporal coverage
Bias adjustment	Yes
Scenarios	RCPs 4.5 and 8.5
Underlying dataset	bias-adjusted EURO-CORDEX
Notes	To compute these indices, the Deltares Global Tide and Surge Model (GTSM) version 3.0 is used together with regional climate forcing and sea level rise initial conditions.

Variants of the index

- The return period can vary according with the rarity of the events to be considered and the specific applications.

Existing identical or similar index definitions

- EEA indicator Global and European sea-level rise

References

- Muis, S., Apecechea, M.I., Dullaart, J., de Lima Rego, J., Madsen, K.S., Su, J., Yan, K., Verlaan, M., 2020. A High-Resolution Global Dataset of Extreme Sea Levels, Tides, and Storm Surges, Including Future Projections. Front. Mar. Sci. 7. https://doi.org/10.3389/fmars.2020.00263
- Vousdoukas, M.I., Mentaschi, L., Feyen, L., Voukouvalas, E., 2017. Extreme sea levels on the rise along Europe’s coasts. Earth’s Future. 5, 1–20. https://doi.org/10.1002/eft2.192

5.6 Oceanic

29. Sea surface temperature

The index Sea surface temperature (SST) represents the mean sea surface temperature over different timescales.
This index is most relevant for marine ecosystems and fishery.

- Assigned priority: **High**
- Essential climate variables: sea surface temperature
- Unit: °C

Data availability

- SST data are available in the C3S CDS from satellite observations (daily resolution) and ERA5 reanalysis (monthly resolution). SST projections are available in the C3S CDS from CMIP5 at monthly resolution.

Existing identical or similar index definitions

- EEA indicator Sea surface temperature

References

- Alexander, M.A., Scott, J.D., Friedland, K.D., Mills, K.E., Nye, J.A., Pershing, A.J., Thomas, A.C., 2018. Projected sea surface temperatures over the 21st century: Changes in the mean, variability and extremes for large marine ecosystem regions of Northern Oceans. Elementa 6. https://doi.org/10.1525/elementa.191

30. Duration of marine heatwaves

The index Duration of marine heatwaves represents the total number of days in a year where a marine region experiences unusually warm sea temperature. A marine heatwave is defined as a period of at least 5 consecutive days with sea surface temperature above the 90th percentile computed over a 11-day window centred on the calendar day for a reference period.
The index is most relevant for marine ecosystems and fishery.

- Assigned priority: **Medium**
- Essential climate variables: daily sea surface temperature
- Unit: number of days

Data availability

- The index as defined above requires daily SST as input whereas SST data from CMIP5 is available in the CDS at monthly resolution only.

Variants of the index

- To accommodate limited data availability, the index can alternatively be defined on a monthly timescale.

References

- Frölicher, T.L., Fischer, E.M., Gruber, N., 2018. Marine heatwaves under global warming. Nature 560, 360–364. https://doi.org/10.1038/s41586-018-0383-9

31. Dissolved oxygen level

The index Dissolved oxygen level is defined as the average of mean oxygen concentration over different timescales.
The index is most relevant for marine ecosystems and fishery.

- Assigned priority: **Medium**
- Essential climate variables: dissolved oxygen
- Unit: mol · m^3

Recommended dataset

Input dataset(s)	Marine biogeochemistry data for the Northwest European Shelf and Mediterranean Sea from 2006 up to 2100 derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-marine-properties?tab=overview)
Horizontal coverage	POLCOMS-ERSEM: Northwest European Shelf and Mediterranean Sea (20W to 37E, 11N to 65N) NEMO-ERSEM: Northwest European Shelf (20W to 13E, 40N to 65N)
Horizontal resolution	POLCOMS-ERSEM: 0.1° x 0.1° NEMO-ERSEM: 0.06° x 0.06°
Vertical coverage	0-5500 m below sea level
Vertical resolution	POLCOMS-ERSEM: 43 vertical levels NEMO-ERSEM: 43 vertical levels
Temporal coverage	POLCOMS-ERSEM: 2006 up to 2100 NEMO-ERSEM: 2006 up to 2050
Temporal resolution	Daily and monthly
Bias adjustment	No
Scenarios	RCP 4.5 and 8.5
Underlying dataset	CMIP5 + several RCMs
Notes	

Data availability

- The recommended dataset covers only parts of European regional seas. Furthermore, it does not include data for the historical period. Observations of dissolved oxygen concentrations are also available from the European Marine Observation and Data Network (EMODnet).

Existing identical or similar index definitions

- EEA indicator Oxygen concentrations in European coastal and marine waters

References

- Wakelin, S.L., Artioli, Y., Holt, J.T., Butenschön, M., Blackford, J., 2020. Controls on near-bed oxygen concentration on the Northwest European Continental Shelf under a potential future climate scenario. Progr. Oceanogr., 187, 102400. https://doi.org/10.1016/j.pocean.2020.102400

32. Ocean pH level

The index Ocean pH level is defined as the mean rate of ocean acidification over different timescales. The index is most relevant for marine ecosystems.

- Assigned priority: **Medium**
- Essential climate variables: sea water pH
- Unit: dimensionless

Recommended dataset

Input dataset(s)	Marine biogeochemistry data for the Northwest European Shelf and Mediterranean Sea from 2006 up to 2100 derived from climate projections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-marine-properties?tab=overview)
Horizontal coverage	POLCOMS-ERSEM: Northwest European Shelf and Mediterranean Sea (20W to 37E, 11N to 65N) NEMO-ERSEM: Northwest European Shelf (20W to 13E, 40N to 65N)
Horizontal resolution	POLCOMS-ERSEM: 0.1° x 0.1° NEMO-ERSEM: 0.06° x 0.06°
Vertical coverage	0-5500 m below sea level
Vertical resolution	POLCOMS-ERSEM: 43 vertical levels NEMO-ERSEM: 43 vertical levels
Temporal coverage	POLCOMS-ERSEM: 2006 up to 2100 NEMO-ERSEM: 2006 up to 2050
Temporal resolution	Monthly
Bias adjustment	No
Scenarios	RCP 4.5 and 8.5
Underlying dataset	CMIP5 + several RCMs
Notes	

Data availability

- The recommended dataset covers only parts of European regional seas. Furthermore, it does not include data for the historical period. Observations of global mean sea water pH are available from the Copernicus Marine Service.

Existing identical or similar index definitions

- EEA indicator Ocean acidification

References

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