MARKET SCOPING REPORT

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1. Aim of the market scoping exercise

This report describes the work undertaken in the BRIGAID market scoping exercise at the European scale (Task 6.1). Its aim is to help the BRIGAID innovators to identify those regions within Europe where potential business opportunities could emerge based on an analysis of the current and expected impacts of climate change and the current adaptive capacity at the regional level. The market scoping should facilitate the identification of markets that have a high potential of adopting innovative climate change adaptation measures whilst also differentiating between the specific hazards that BRIGAID innovations address.

The aim is to perform a high-level assessment that supports innovators in the application of the MAF+ framework being developed under BRIGAID. Related to this, we aim to compare the exposure of European regions current and expected impacts from climatic events and how these regions are currently prepared to deal with these impacts. This analysis will be informed by existing data and indicators generated by European and national public institutions.

The workflow for the market scoping exercise is defined within the Description of Actions (DoA) document in a series of steps:

1. *"The first step will be to segment the market for adaptation measures in Europe considering the different regions' i) exposure to changes in climate and their ii) sensitivity to these changes. This step will use available indicators for climate change vulnerability developed by the European Environment Agency and combine them with selected outcomes from Task 5.1*[1] *(specifically the small-scale projections of the effects of climate change for floods, droughts, and extreme weather).*

2. *In a subsequent step, the resulting market segments will be examined on the basis of their adaptive capacity and willingness to implement innovative adaptation measures. This analysis will combine preliminary outcomes of Task 5.2*[2] *(specifically the analysis to predict acceptance of innovations by end-users) and a review of the EU and National Adaptation Strategies.*

3. *The output will be an assessment of the different geographical regions within Europe on the basis of their vulnerability to climate change and the willingness of their societies to implement (innovative) adaptation measures. This information will feed into the analysis of target markets in Task 6.3."*

The description of the task has been respected although its scope has been enlarged and the work plan has been further developed in some aspects as a consequence of:

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[1] *The contribution from Task 5.1 has focused on the preparation of indicators on hazard potential. See Appendix 3 for a complete description of the work.*

[2] *These preliminary outcomes were not available at the time of production of this document. This was detected some months in advance and it was decided to make an effort in measuring adaptive capacity based on official data sources. This allows a better comparison across countries regions and facilitates a potential update of the calculations in the future, as statistical data from official sources is updated periodically. This was considered as a relevant issue since adaptive capacity is a variable component with a could exhibit greater variance within short periods of time (e.g. based on changes in government administrations, policy priorities, and economic conditions) than hazard potential within countries that inter countries and dependent on the role of institutions. The Task 5.2 responsible partner provided guidance to this process.*

- the findings during our literature review on available data and information,
- the need to coordinate with other project tasks, and
- a further consideration of current risk to natural disasters.

As for the last point, most of the indicators for climate change vulnerability are estimated as relative measures, e.g. percentage of change from the current situation, rather than absolute measures. This implies that a robust characterisation of current impacts is required in order to estimate the expected intensity of future climate change impacts. In addition, the identification of current market opportunities is a key factor for innovators (even if these opportunities may not have been produced as a consequence of climatic changes) and thus, has been considered as a starting point for our analysis, completed and strengthened with the estimation of the expected increase in market opportunities as a consequence of changes in climatic factors.

2. Conceptual framework

2.1. Background and context

The nature of the BRIGAID project, structured around natural hazards and with strong links to climate change science, sets it at the interface between the climate change and the disaster risk communities. This has important implications for the work undertaken in the project, as the range of available concepts and methodologies to incorporate into its research is wider, but the results achieved should be communicated to the different disciplines. In the specific case of this market scoping report, whose target audience are the BRIGAID innovators, the crux lies at the choice of methodologies for the assessment.

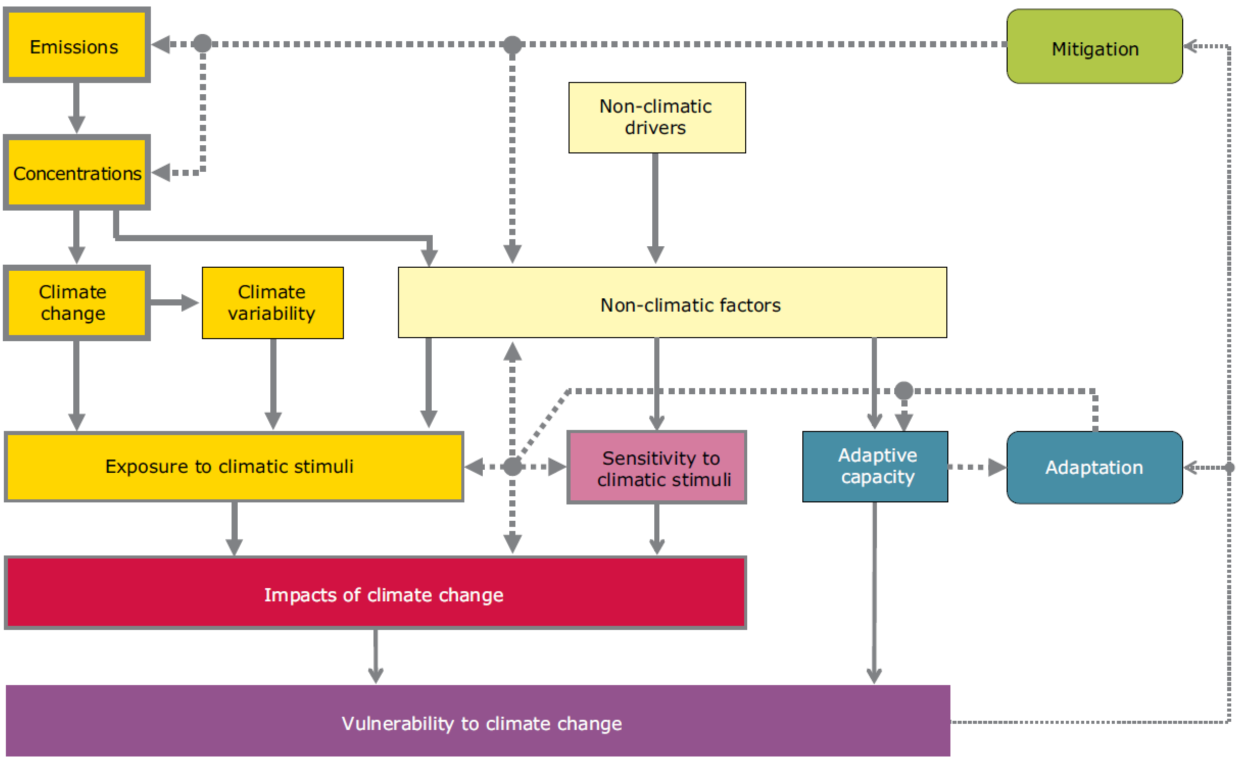
As stated by the European Environment Agency (EEA) in its reports on climate change, impacts and vulnerability in Europe, the use and interpretation of the terms **vulnerability** and **risk**, both significantly relevant to this market scoping report, often vary between the climate change and disaster risk communities (see Box 1). While such discrepancies may have limited influence in generic contexts, this becomes noteworthy when the concepts are used as a basis for quantitative assessments (EEA, 2012; EEA, 2017). Given the mentioned position of BRIGAID and the aspiration of this market scoping exercise to quantify the different elements influencing market potential, the need for an approach that carefully addressed these issues, in addition to considering both the current impacts of natural disasters and the expected future changes in these impacts driven by climate change, was clear.

Box 1. Excerpt on frameworks for assessing vulnerability and risk (EEA, 2017)

The terms 'vulnerability' and 'risk' are often used to describe the potential (adverse) effects of climate change on environmental, social and economic factors, as well as on systems. These terms are attractive, as they are intuitively understood by a large audience and rooted in the scientific communities that contribute to climate change assessments.

The term 'vulnerable' is also used by the UNFCCC (UN, 1992) in the context of '(developing) countries [that] are particularly vulnerable to the adverse effects of climate change'. In general, use of these terms is unproblematic if they are applied in a rather generic, intuitive sense. However, conceptual models of vulnerability differ between scientific communities and are also changing over time. <u>The resulting range of definitions can make the interpretation of certain statements difficult, in particular if the terms have been used quantitatively, and it may reduce the comparability across studies from different sources.</u>

Therefore, this study aims to consider as a reference the most commonly used risk-hazard and climate change frameworks in order to achieve a better understanding of the main criteria to be considered. The general framework employed for the purpose of this study attempts to build upon the work carried out by the European Environment Agency (EEA, 2012; EEA, 2017) as well as previous initiatives aimed at the appraisal of vulnerability to climate change and disaster risk assessment. Specifically, these are the IPCC vulnerability assessment framework (Füssel and Klein, 2006) and the Risk-Hazard framework (UNDHA, 1993) (shown in Figures 1 and 2, respectively).



Source: Adapted from Füssel and Klein, 2006.

Figure 1. *IPCC vulnerability assessment framework (extracted from Greiving et al, 2011)*

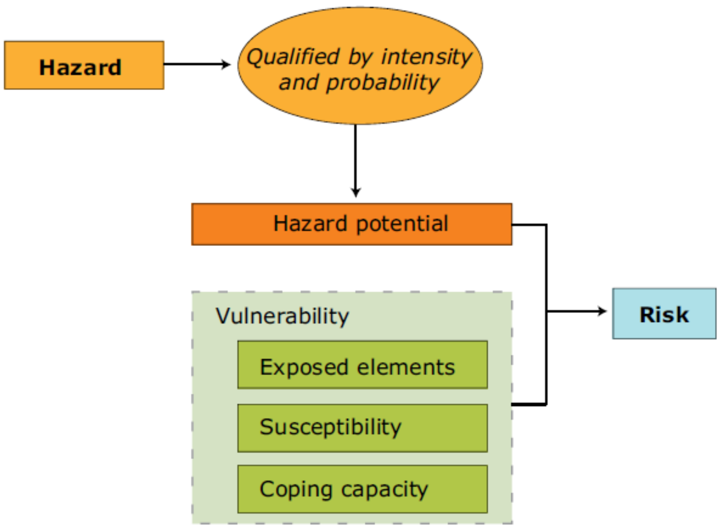


Figure 2. *Risk-Hazard Framework. Extracted from (EEA, 2012), based on (UNDHA, 1993)*

As explained in (EEA, 2012) the main difference between the two frameworks relates to the temporal horizon of application: "*Standard applications of disaster risk assessment are primarily concerned with short-term (discrete) natural hazards, assuming known hazards and present (fixed) vulnerability (Downing et al, 1999). In contrast, key characteristics of anthropogenic climate change are that it is long term and dynamical, it is global but spatially heterogeneous, and it involves multiple climatic hazards associated with large uncertainties. In a nutshell, the hazard events considered in disaster risk assessment are limited in time and space and rather well known (even though their probability may be very uncertain) whereas anthropogenic climate change is a continuous stressor of global extent that involves unprecedented climate conditions*."

Further, our approach takes on board elements of the work of the ESPON Climate program, which has previously produced an estimation of the possible scenario of vulnerability in Europe applying the assessment framework of the IPCC (see Appendix 1). However, some of the terms used in the ESPON-Climate framework are defined as a function of climate change, e.g. sensitivity - which depends on climatic stimuli, whereas the terms used in the risk-hazard framework (figure 2) are more directly applicable for the evaluation or quantification of the existing current risk or the average current damages provoked by different hazards. This situation reflects the differences in how some terms are utilised by the Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA) communities and illustrates the differences identified in (EEA, 2012) between both reference frameworks.

This issue on the difficulties for the operational use of this kind of descriptive assessment frameworks has been previously brought forward by other authors. The Drought-RSPI project (De Stefano et al, 2015) provides a sound analysis on this situation and proposes some specific conditions that should ease the consideration and uptake of final results by the target audiences:

- Comparability of the results, which is a key issue for decision makers and users of the final information. The analysis should aim to provide metrics that allow this comparison among the different geographical regions.
- Transparency: Since the assessment involves a certain level of subjectivity, there is a need to be explicit on which subjective decisions are throughout the assessment process.

- The selection of indicators is one of the most crucial steps in the design and implementation of the assessment. The selection criteria for the indicators must be clear and adapted to the specific aims and context of the analysis. Although data availability tend to be a relevant factor behind the selection of indicators, this should not condition the procedure beforehand.
- Similarly, the selection of the weighing scheme is also pivotal in the process. Several methods can be applied, i.e. arbitrary choice, statistical analysis, expert judgment, etc., but in any case, the scheme should be described.

The analysis framework for the BRIGAID market scoping analysis is a hybrid of the two mentioned approaches. The section 2.2.2 defines all the terms we are using. Also, in that section we try to identify how these terms relate to the ones used in the two general reference frameworks. In order to facilitate the production of operational results, our analysis aims to comply with the conditions described by De Stefano et al.

2.2. Description of the BRIGAID framework for the market scoping exercise

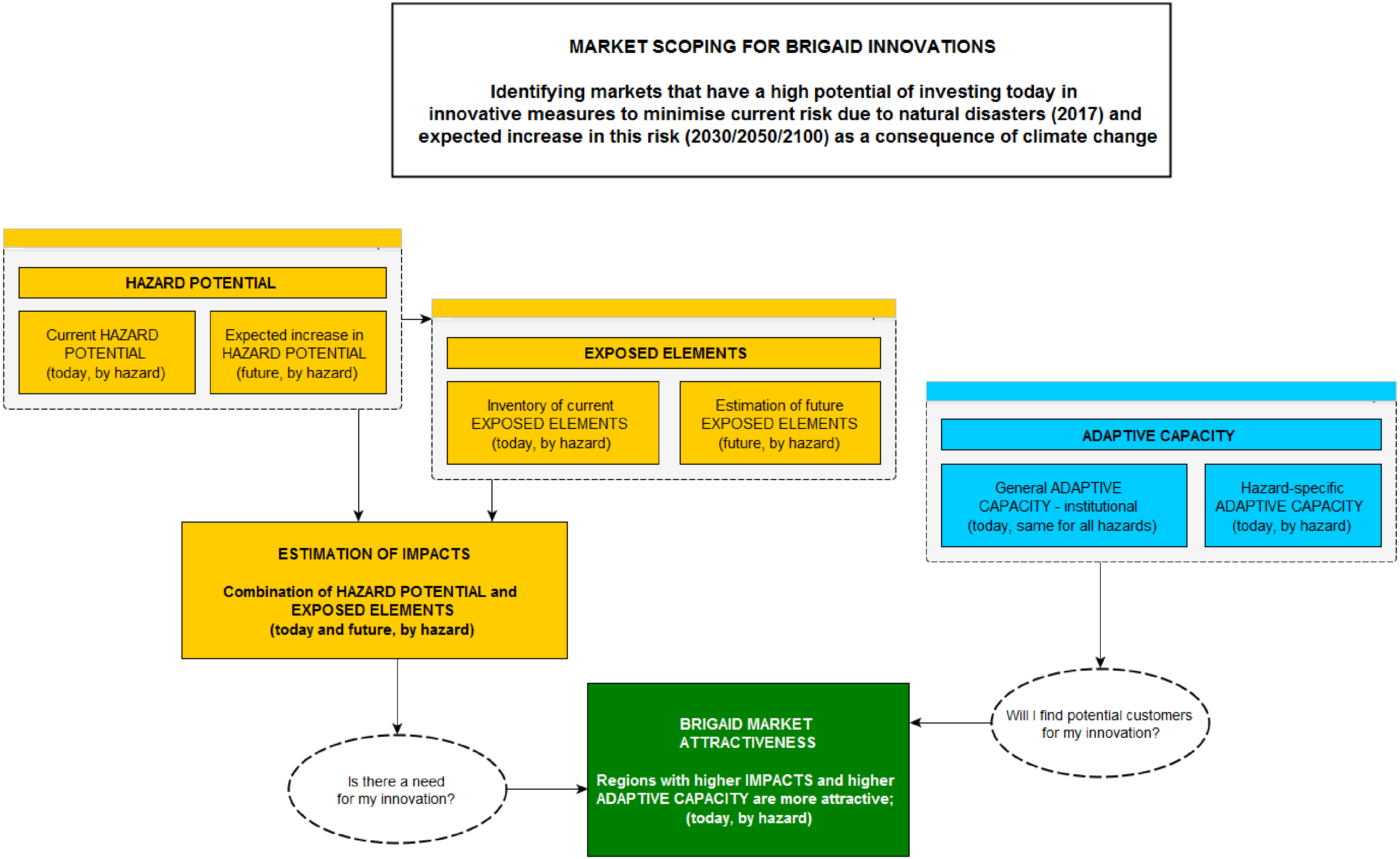
2.2.1. General framework

The goal of the BRIGAID market scoping exercise is to identify different geographical regions within Europe on the basis of their expected climate change impacts and the willingness and ability of their societies to implement (innovative) adaptation measures. That is, we want to identify those regions where market opportunities may be higher for innovations facing each of the considered hazards. One remark is that our scope for adaptation solutions focuses on protecting against climatic disaster events rather than adaptation measures for slow trend changes. Therefore, in this report we focus on hazards potentially provoking these kind of extreme events (see section 3.1.1 for a breakdown of the hazards considered in this study).

The market opportunities will be measured with a score of BRIGAID MARKET ATTRACTIVENESS using two interrelated scales related to "CURRENT AND EXPECTED IMPACTS" and "ADAPTIVE CAPACITY". Both current and expected impacts, together with the adaptive capacity give an indication of market potential at the time when the assessment is conducted. Hazard potential (current and expected) is combined with the exposed elements to estimate the current and expected impacts. The identification of exposed elements is mainly based on current data although projections for future time horizons are used when reliable information is available. A high hazard potential and high exposed elements rank result in a high impact. In contrast to the vulnerability concept, which is higher when high impacts combine with low adaptive capacity, the market attractiveness concept studied in this report is higher when high impacts combine with high adaptive capacity. This is due to the fact that higher rankings in the elements included in the adaptive capacity measure (e.g. citizen awareness, political will, economic capacity) are expected to correlate with higher probabilities of innovative climate change adaptation measures being implemented. Our final aim is to build an ordinal scale to rank the level of market attractiveness based on the different combinations of the factors for each hazard type.

The figure in the next page depicts the flow chart for the combination of a number of criteria for the generation of these two scales measuring current and expected impacts and adaptive capacity.

For each hazard and for each criterion, specific indicators providing values within the spatial frame of our analysis shall be generated. These indicators will be combined into the market attractiveness map, showing spatial variation of our key variables and final scale.


MARKET SCOPING FOR BRIGAID INNOVATIONS
Identifying markets that have a high potential of investing today in innovative measures to minimise current risk due to natural disasters (2017) and expected increase in this risk (2030/2050/2100) as a consequence of climate change
HAZARD POTENTIAL
Current HAZARD POTENTIAL (today, by hazard)
Expected increase in HAZARD POTENTIAL (future, by hazard)
EXPOSED ELEMENTS
Inventory of current EXPOSED ELEMENTS (today, by hazard)
Estimation of future EXPOSED ELEMENTS (future, by hazard)
ADAPTIVE CAPACITY
General ADAPTIVE CAPACITY - institutional (today, same for all hazards)
Hazard-specific ADAPTIVE CAPACITY (today, by hazard)
ESTIMATION OF IMPACTS
Combination of HAZARD POTENTIAL and EXPOSED ELEMENTS (today and future, by hazard)
Is there a need for my innovation?
Will I find potential customers for my innovation?
BRIGAID MARKET ATTRACTIVENESS
Regions with higher IMPACTS and higher ADAPTIVE CAPACITY are more attractive; (today, by hazard)

The innovators will be presented with different maps showing the distribution of scores in market attractiveness per hazard separately. These outputs will inform innovators on how they can elaborate their decisions/strategy on this basis.

2.2.2. Definition of the elements making up the BRIGAID market attractiveness scale

As pointed out earlier, some of the project tasks and outputs can be expected to draw from and touch upon concepts relevant to both the climate change and the disaster risk communities at once. Hence in the case of this report, a first key issue is the definition of the selected criteria for the BRIGAID market scoping framework.

A) Estimation of current and expected impacts

Hazard potential

The hazard potential is defined as the probability of occurrence of a climate-related physical event. Therefore, the hazard potential depends on the intensity and probability of the hazard.

This definition builds on the hazard concept as defined by (IPCC, 2014) and considers intensity and probability as key variables for the specification of the hazard potential, as described by the Risk-Hazard framework (see Appendix 1).

Expected hazard potential is defined as the degree to which a system is expected to be affected by a natural disaster (hazard) given expected climatic variations. The expected hazard potential will often be expressed as a percentage increase or decrease of current hazard potential.

This definition is based on the concept of exposure, as defined in the vulnerability assessment framework (figure 1). The climate change hazard potential exposure indicators to be provided by WP5 will be the key input for the calculation of this criterion.

Exposed elements

Current exposed elements refer to the inventory of elements in an area to which hazard events may occur under current conditions of intensity of a potential extreme event associated to that hazard and considering existing protection against the hazard.

This definition is based on the concept of vulnerability as considered by the Risk-Hazard framework (figure 2), and particularly builds on the exposure concept, also partially considering coping capacity and susceptibility.

The estimation of future exposed elements will be produced by considering the potential increase in the intensity of the hazard as given by the climate change hazard potential indicators produced by WP5. The exposed elements will increase due to the extension of the area potentially affected by the hazard, or due to an increase in terms of population or assets being at risk.

Current / expected impacts

Impacts are defined as the consequences of natural disasters on natural and human systems, which in many cases are expected to increase due to climatic variations. This definition is extracted from the Vulnerability Assessment framework. These consequences could be measured using:

- Quantitative data based on economic valuation of current and expected impacts on human or natural assets (by hazard)
- Quantitative data based on impact on population (e.g. number of affected people or deaths)
- Qualitative scale, only if no quantitative measurements are possible.

This indicator will be calculated as a combination of the indicators of exposed elements and hazard potential. Some specific information already calculated by other studies, i.e. economic valuation of projected climate change impacts will be incorporated to complement this approach and as a means for validation.

B) Estimation of adaptive capacity

Adaptive capacity

Adaptive capacity is defined as “The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.” (IPCC 2014).

The “Adaptive Capacity” component will be split in two groups of indicators.

1. “General Adaptive capacity” is referring to the adaptive capacity indicators which are equally relevant for all hazards analysed in BRIGAID. It includes, e.g. economic resources (e.g. GDP), general access to information (internet use), institutions (e.g. government effectiveness, as well as state of National adaptation strategies), risk perceptions (e.g. Attitudes towards climate change: results from Eurobarometer survey) (see e.g. Greiving et al, 2011; Adger, 2004).

2. “Hazard-specific Adaptive capacity” is defined as adaptive capacity which is only relevant for a single hazard. It could include e.g. recent flood events which increase the awareness for flood protection. These indicators would only be used for the relevant hazard.

Both components are referring to the current situation as adaptive capacity today is influencing the investment decisions for climate adaptation products in the next years.

3. METHODOLOGICAL APPROACH

The methodological approach for the calculation of the market attractiveness is based on the use of indicators.

These indicators have been considered as variables which are measurable and provide a reliable representation of an associated factor that is non-measurable or more difficult to measure. Each one of the elements integrated in our market scoping framework, e.g. hazard potential, exposed elements and adaptive capacity, consists of different categories or factors which may be hazard-specific or remain general for all hazards. Each of the considered categories has been approximated through one or more indicators (see section 3.4) which have been produced under a set of common framing conditions (see section 3.1) and have been integrated through a common methodological approach (see section 3.2). However, each of the main elements present some methodological specificities which are described in more detail as part of section 3.3.

3.1. Framing conditions for indicators

The assessment of the criteria, selected as part of our market scoping framework, has been conducted through indicators produced as maps covering the full geographical domain of analysis. These indicators have been normalised so as to ensure an appropriate integration and allow a reliable comparison among different areas across Europe.

This section describes the thematic, geographical and temporal domain of the indicators as well as the geographical scales considered, which are dependent on the thematic domain.

3.1.1. Thematic domain: list of hazards considered

The market scoping analysis has been conducted separately for different kind of hazards since innovations in BRIGAID are often addressing the risk linked to a specific type of potential disaster. Thus, a specific market scoping is required for each main hazard. The hazard list for market scoping is based on the list of hazards included in BRIGAID (see Table 1.1 of the DoA) which considers: River floods, Coastal floods, Droughts, Heavy precipitation, Storms, Hail, Heatwaves and Wildfires.

Based on this list, the following hazards have been taken into consideration[3]:

- **River floods**: A river flood is the temporary covering by water of land not normally covered by water, caused by high discharge in a river. High discharge may occur due to extreme precipitation and/or snow melt in areas located upstream, that have sufficient intensity and duration, in combination with soil saturation. Rivers include also mountain torrents and Mediterranean ephemeral water courses (European Union, 2007), however only river sections with catchments bigger than 100 km^2 are included in this study. Moreover, cases of flooding caused by ice jams are also not included. Urban floods, caused by insufficient sewage system capacity, and flash floods, caused by very short yet intense rainfall over a small area, are considered under “heavy precipitation”.

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[3] *The definitions of these hazards are based on the document ‘Pan-european climate change indicators and loading conditions’, which is an input to WP5 and WP6 and is included as Appendix 3 to this deliverable.*

- **Coastal floods**: A coastal flood is the temporary covering by water of land not normally covered by water, caused by high water levels in the sea. High water level may occur due to strong winds blowing sufficiently long over an adequately large area, especially toward the coast, causing a large water run-up at the coast. Unfavourable bathymetric conditions and high astronomical tide further increase the run-up. Coastal floods include floods in estuaries and coastal lakes, caused by influx of seawater into those systems. Changes in storminess, sea level rise and glacial isostatic adjustment are considered, but not local effects such as ground subsidence, coastal erosion and accumulation or changes in tide-surge interactions (Paprotny et al, 2016). It should be also noted that high water levels caused by seiches or geophysical events are not considered here.
- **Heavy precipitation and hail, pluvial floods and storms**: Extreme precipitation induced hazards such as pluvial floods, flash floods, landslides, mudflows, etc. are the result of short-duration rainfall intensities when they exceed a given threshold, e.g. the threshold above which a flood initiates. This threshold corresponds to the criteria used for infrastructure design in different European countries and regions. Infrastructure such as land-based transportation and emergency services are especially vulnerable to extreme precipitation events, as they can lead to the flooding of tunnels and can damage streets, railway lines and bridges. Also electricity and telecommunication networks can be affected by heavy precipitation.
- **Wind storms**: Storms (atmospheric disturbances) are defined by strong sustained winds, which are mostly accompanied by heavy precipitation and lightning and in some case also by hail. European storms range from localized to continental events. Effects of storms tend to affect to urban areas in a higher degree.
- **Droughts**: Droughts are the result of a period of consecutive dry days or days with very low rainfall. According to the World Meteorological Organization (WMO), ‘drought means a sustained, extended deficiency in precipitation.’ In terms of operational definitions of droughts, these can be classified into four categories: meteorological, hydrological, agricultural and socio-economical (classification of the American Meteorological Society), depending on the types of impacts.
- **Heatwaves**: These phenomena consists in several consecutive days with very warm days. Based on the WMO definition, heatwaves are defined as periods of more than 5 consecutive days with daily maximum temperature exceeding the mean maximum temperature of the May to September season for the control period (1971–2000) by at least 5°C (Jacob et al., 2014). Alexander and Herold (2016) defined heatwaves (HWs) using different approaches, e.g. amplitude, magnitude, number, duration and frequency.
- **Wildfires**: Fires in forested and highly vegetated areas. Global warming affects the sparking of wildfires. In fact, warmer temperatures enable fuels to ignite and burn faster, resulting in faster wildfire expansion. Wind can help the wildfire expansion, while precipitation can decrease the chances of a wildfire igniting.

Hail[4] has not been considered because of two main reasons: i) none of the BRIGAID innovations so far is related to hail, and ii) hail is not available as a direct output from climate models and therefore it has not been possible to produce the required hazard potential maps.

[4] This clarification is provided because according to the DoA, hail is within the list of hazards to be considered by BRIGAID.

3.1.2. Geographic domain: list of countries considered

Our aim has been to derive indicators for the territory of European Union and main associated countries. However, comprehensive and spatially-consistent data, both on the loading conditions and the socio-economic environment, do not cover the entire geographical extent of the continent and differ between EU Member States and other countries, including some where BRIGAID innovators are located. Thus, there are data gaps, lack of data homogeneity or a reduction in data quality among European countries with a high potential interest for BRIGAID innovators. As a consequence, the market attractiveness has been calculated for the EU28 countries whereas some of the indicators have been produced for other countries providing that base data are available. The geographic domains considered (see figure 3) are:

- Main domain: All 28 European Union (EU) members, but without their dependencies, both in Europe and overseas[5], and also without outlying regions of Portugal and Spain: Azores, Madeira, Canary Islands, Ceuta and Melilla;
- All 4 European Free Trade Agreement (EFTA) members (Iceland, Liechtenstein, Norway, Switzerland).

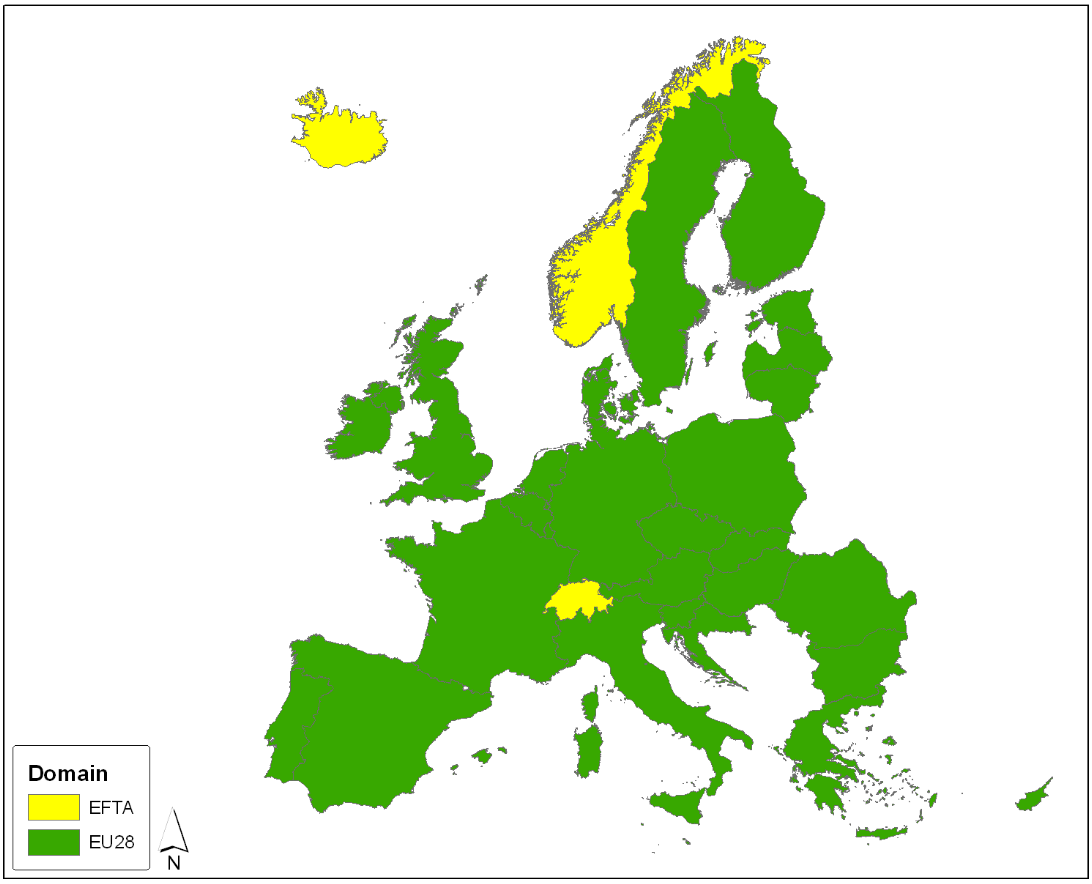

Figure 3. ***Geographical scope of the study***

[5] This exclusion covers all dependent territories of Denmark (Faroe Islands and Greenland), France (overseas departments and other possessions outside Europe), Norway (Svalbard and other polar territories), the Netherlands (territories located in the Caribbean) and the United Kingdom (Guernsey, Isle of Man, Jersey and all British Overseas Territories).

3.1.3. Temporal domain: time horizons considered

We assume that the investment decision is influenced by both current and expected climate change impacts, as well as the level of adaptive capacity.

The current adaptive capacity dictates whether the decision-makers are willing to invest in an innovative solution in the short term, which is expectedly the main interest of the innovators.

Thus, the expected climate change impacts should look at a relative short time-span, ideally 2030-2050. This is the range that innovators and decision-makers are likely to consider in terms of increasing resilience to climate disasters. However, BRIGAID addresses innovations which may focus on the short-term, e.g. software or high-technology innovations but also considers structural innovations with a much longer lifetime, e.g. water infrastructure. Due to this reason, a more extended time horizon, i.e. 2070-2100 is also relevant. These three time horizons are coherent with periods considered in the estimation of climate change effects through climatic models.

The hazard indicators have been produced for 2030, 2050 and 2070-2100 time horizons. The 2050 horizon has been considered as the generic time horizon in the market scoping exercise. The main reason is because the perspective of changes in potential impacts in this period complements well the analysis of the distribution of current impacts and is relevant for the majority of BRIGAID innovations.

3.1.4. Spatial scale of the final outcomes

The literature and data availability review has shown a wide variability in the application scale and accuracy of several available data sources and studies.

We decided to use a broader scale (NUTS 2 level)[6] focusing on identifying the 'hotspots' in terms of market opportunities for innovations dealing with different type of hazards. Here, our idea is that a hotspot is analogue to an area where market opportunities are more likely to emerge.

One particular issue raised after elaboration of preliminary results of the market attractiveness for some hazards very dependent on the density of urban areas, i.e. heavy precipitation or wind storms. Due to the lack of a homogeneous set of criteria for the definition of NUTS areas in the different countries, the way in which these areas are defined at NUTS2 level is producing a bas in the results. In some countries, specific NUTS2 areas are defined as the limit of the metropolitan areas of the capital or main cities, whereas many of the larger city areas are included into NUTS with a broader extension also including rural or intermediate areas.

To ensure consistency, the results included in this report (see section 4) have all been calculated at NUTS2 level. However, in order to deal with the limitation posed by the variability in the definition of NUTS areas, a different version of the maps for heavy precipitation and wind storm has been produced. In this version, the smaller NUTS2 areas just encompassing a city area have been merged with the neighbouring areas that form part of the same NUTS1 area.

[6] NUTS stands for Nomenclature of Territorial units for Statistics. These units were set up by Eurostat set as a single, coherent system for dividing up the EU's territory in order to produce regional statistics for the Community. NUTS are defined into 4 levels, i.e. NUTS0, NUTS1, NUTS2 and NUTS3.

3.2. General methodology for calculation of indicators

The elements under the market scoping framework are very diverse and therefore, the indicators to be considered for the estimation of their variability across European regions cover separate thematic areas and are related to a broad range of disciplines. As a consequence, these indicators are calculated through different processes and methods, and therefore some specificities need to be considered for the set of indicators related to each main element.

For example, the hazard potential indicators are mainly derived from climatic models and are not expected to require changes or updates unless a there is a sudden change in the model conditions. The exposed elements also are in general quite static, and not significant changes are expected within the lifetime of BRIGAID. Finally, the adaptive capacity indicators aim to capture political or socio-economic factors. These indicators are derived from statistical data sources and assessment reports and thus, are more subject to change.

We have combined the numerous factors that determine the BRIGAID Market attractiveness for climate adaptation measures into a single quantitative scale. Good composite indicators are fit for purpose (that is, they convey the information intended), are transparently constructed, and are justified to maximise their dependability and reliability (Nardo et al., 2005). To ensure that the BRIGAID Market attractiveness indicator meets this standard, this section justifies and describes the indicators included in the index, and the index's construction. We follow the OECD/EU Joint Research Centre guidance on composite indicator construction (Nardo et al., 2005) and the examples of Notre Dame Global Adaptation Initiative Country Index (ND-GAIN) (Chen et al., 2015)[7] and ESPON Climate (Greiving et al, 2011).

However, some processes are common and shared in the calculation of all indicators which is a pre-condition required to allow their integration. Thus, a common methodology has been defined for the final calculation of indicators, to be applied through a series of subsequent steps which is described within this section, composed by:

1. Definition and justification of indicators
2. Calculation of indicators
3. Analysis of limitations, data gaps and imputation of missing data
4. Normalisation of data
5. Weighting different indicators
6. Grouping and presentation of results

[7] See also http://index.gain.org/

3.2.1. Definition and justification of indicators

The indicators aim to represent the variability, i.e. regional differences, in factors related to the market attractiveness of innovations to be supported under the BRIGAID project, e.g. innovations increasing resilience to natural hazards.

The hazard potential has been assessed from climate model simulations (see Appendix 3), and thus the indicators describing the variations in the level of intensity expected for the different hazards have been produced through the downscaling of variables estimated through climatic models. In this case, a sole indicator for each type of hazard has been defined to characterise the current and projected hazard potential (see table 1).

HAZARD	*INDICATOR OF HAZARD POTENTIAL*
River floods	*Extreme river water levels with a 100-year return period*
Coastal floods	*Extreme storm surges with a 100-year return period*
Pluvial floods	*The daily precipitation intensity (RX1day) for a specific return period of 5 years*
Wind Storms	*The 99th percentile of daily wind speed corresponding to a stronger storm*
Droughts	*Annual CDD expressed as the maximum number of Consecutive Dry Days (CDD) when precipitation is less than 1 mm*
Heatwaves	*Number of heatwaves over a period of 30 years*
Wildfires	*Forest Fire Danger Index (FFDI)*

Table 1. **List of indicators for hazard potential**

The indicators on exposed elements are directly dependent on the hazard potential indicators for some hazards, e.g. site-specific hazards such as river floods and coastal floods, whereas remain independent for the other hazards. These indicators (see table 2) are produced through spatial analysis procedures or collected from official statistical data sources but in all cases are hazard-specific.

HAZARD	*INDICATOR OF EXPOSED ELEMENTS*
River floods	*(1) Land use inside the boundaries of the 100-year return period river flow*
Coastal floods	*(1) Land use inside the boundaries of the 100-year return period coastal flow*
Pluvial floods	*(1) Population density; (2) Constructions density; (3) Households living in houses (non-apartments) in urban areas; and (4) Number of Vehicles*
Wind Storms	*(1) Population density; (2) Constructions density*
Droughts	*(1) Total irrigated area; (2) Total irrigated area of intensive crops; and (3) index of water exploitation*
Heatwaves	*(1) Urban population; (2) Number and percentage of elderly living in cities; (3) Percentage of households inhabited by a lone pensioner; (4) Purchasing power standards; and (5) Number of touristic beds per 1000 inhabitants*
Wildfires	*(1) Total forested area; (2) Forested area within natural protected areas; and (3) Forested area close to urban areas*

Table 2. **List of indicators for exposed elements**

The estimation of adaptive capacity is based on three different components, namely awareness, action and ability. Knowledge and **awareness** play an important role in terms of identifying vulnerabilities in relation to climate change and enable the identification of adaptation options. To move from awareness to action, **ability** is necessary, which consists of technical and scientific capacity to understand issues and prepare assessments and studies (social, economical, ecological)[8]. Finally, the ability to achieve **action** is supported by economic resources and institutions that enable a society to carry out the adaptation measures that have been defined.

Each one of these three components is characterized through a broad set of indicators (see chapter 3.4 and Appendix II).

The rationale behind the selection of all the hazard potential, exposed elements and adaptive capacity indicators is provided in section 3.3. Regarding this, the most relevant issue affecting the selection has been data availability and quality which has been checked by considering the criteria shown in Table 3.

Selection criteria	*Objective*
Data quality	*Limited data gaps*
Frequency of collection	*Regular update of data collection is preferable*
Data scale	*Data sources which deliver NUTS2 data are preferable*
Data format (especially relevant for data on regional level)	*Data formats which can directly imported and used is preferable to e.g. pdf-documents*

Table 3. **Criteria for data selection**

3.2.2. Calculation of indicators

The calculation of indicators based on best available data has been carried out through different methodological approaches.

The hazard potential indicators are derived from climatic model scenarios following a complex methodology described in a specific internal report (see Appendix 3). All these indicators have been produced for the 3 time horizons specified in section 3.1.3.

The indicators for exposed elements are mainly produced through spatial analysis procedures through the combination and aggregation of georeferenced data. Some of the indicators are directly collected from statistical data sources.

The indicators on potential impacts are developed through the integration of hazard potential and exposed elements indicators. However, a literature review has been conducted under the aim of identifying those initiatives and projects operating at European scale and providing high quality quantitative data on historical and projected damages caused by natural hazards. Even though these data are not usually available for the conditions considered in this study, some relevant data

[8] As BRIGAID is preparing (technological) options for climate adaptations, the development & research on adaptation options does not need to be emphasized in ability. However, the developed options need to be taken up in regions/communities where knowledge on assessments, e.g. vulnerability assessments, is developed and processes (natural, social, economical) are understood.

information at lower scale, i.e. country level is available. This kind of information complements our own indicators and in some cases has proven particularly useful to undertake a validation of the applied methodology.

Finally, the indicators for adaptive capacity have been gathered from official statistical databases and specific studies. The data availability for the indicators has been screened in an extended web-search. European institutions managing data are especially emphasized e.g. Eurostat, EEA, or portals such as Climate-ADAPT. If data sources were not directly available, contact persons were approached.

3.2.3. Analysis of limitations, data gaps and imputation of missing data

While we minimised missing data by screening indicators for coverage, some data gaps remained. Where NUTS 2 regional data was missing but NUTS 1 or national data was available, we used these. Where a region or country was lacking data entirely, we used average EU data to fill this gap. All of our indicators are scaled to the size of the country/region (for example, in per capita or percentage terms), making the average data appropriate for imputing national data to regions different regions. Data gaps are listed in the indicator description table (See Appendix 2).

3.2.4. Normalisation of data

To enable comparison of like with like, we have normalised the different scales of the index's different indicators. The first step was to identify relevant reference points on which to base the scaling. To ensure consistency across all indicators and to increase their descriptive power, we used the maximum and minimum responses as the reference points for all indicators (regardless of their initial form e.g. Likert scale, percentage, €, etc...). The presence of outliers was analysed and these values were discarded, if present. We then used these reference points to normalise each data point for every indicator to a 100 point scale using the following equation:

$$\text{Indexed result}_i = \left(\frac{X_i - X_{refrence\ point\ min}}{X_{reference\ point\ max} - X_{reference\ point\ min}}\right) x100$$

3.2.5. Weighting different indicators

When it is necessary to combine the normalised indicators we give each a weighting, which implicitly gives the relative importance of each indicator as a determinant of one of the factors. The selection of the weights is a subjective procedure although some reasoning based on available information and literature review has been used to limit this subjectivity, i.e. use of weights decided by an experts' Delphi survey in ESPON climate initiative.

3.2.6. Grouping and presentation of results

The final General Adaptive Capacity and Potential Impacts indicators result is a single score between 0 and 100 for each region. These results were then grouped by quintiles into five categories: high values (regions with a score that falls in the top 20%), upper values (regions with scores in the 80-60% range), medium values (60-40%), lower values (40-20%), and low values (bottom 20%).

3.3. Specific methodologies and processes

This section provides more detail on how the common methodological approach has been applied for each one of the main elements included in the BRIGAID market scoping framework.

3.3.1 Hazard potential

The description of these indicators has been extracted from the document ‘Pan-European climate change indicators and loading conditions’ (see Appendix 3 to this deliverable). This document provides further detail on the selection criteria and calculation methods for this set of indicators.

River floods:

The proposed indicator is **extreme river water levels with a 100-year return period, relative to water levels with a 10-year return period under historical climate**. The 10-year return period was chosen as an approximation of the lowest flood protection standards that can be found throughout Europe (see e.g. Scussolini et al. 2016).

Modelling of river floods consisted of two steps. Firstly, extreme river discharges with given return periods were calculated using a Bayesian Network-based hydrological model, under present and future climate. Secondly, selected river discharge scenarios were used to obtain water levels through a one-dimensional hydrodynamic model.

In terms of results, the regions with the highest average water levels are concentrated around large rivers, as outlines of Danube, Elbe, Loire, Po, Rhine or Vistula rivers could be clearly seen. Elevated values of the indicator could be found in more mountainous areas (Norway, Portugal, Spain, Switzerland). It is projected that, in general, extreme river water levels will be higher in the future. An average 100-year surge at local or regional level will be about 10 cm higher in 2071–2100 compared to 1971–2000. Negative trends will mostly occur in northern Europe due to substantially reduced snowfall, which in turn would cause less severe snowmelt. In most of other locations, including large parts central and southern Europe, more cases of extreme rainfall are expected, resulting in higher frequency of extreme river flow occurrences.

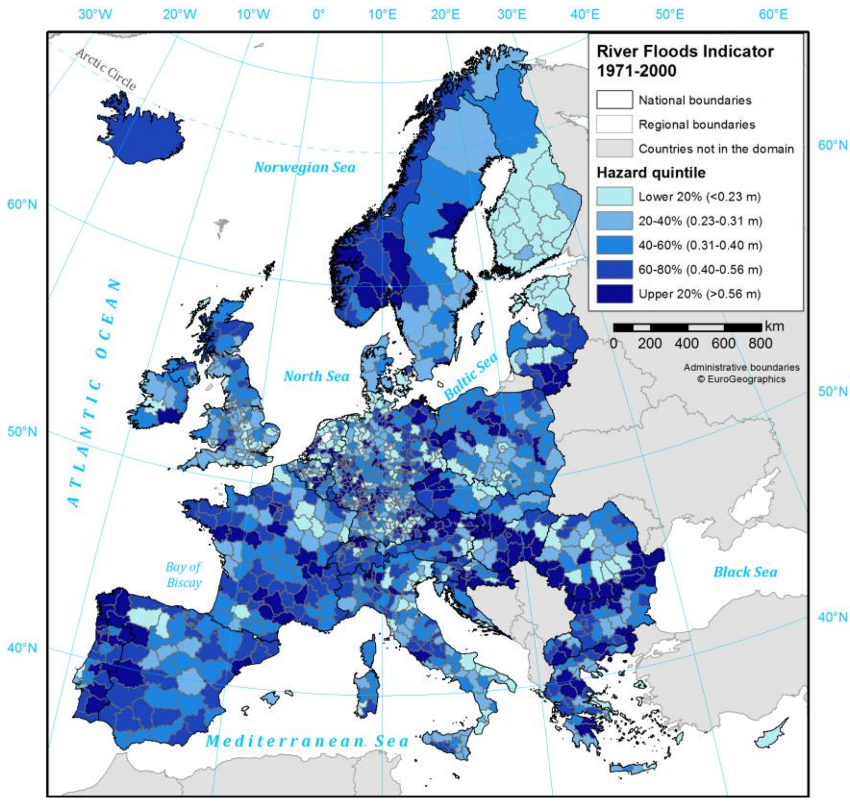

Figure 4. *Quantiles of normalized river flood hazard indicator (100-year water level in a given scenario minus 10-year water level in the historical scenario) at regional level for historical scenario*

Coastal floods:

The proposed indicator is the **extreme water levels from storm surges with a 100-year return period, relative to water levels with a 10-year return period under historical climate**.

The data used to calculate the indicator of coastal flood hazard are obtained from a publicly available dataset (Paprotny and Morales-Nápoles, 2016) produced in the project RAIN.

The analysis includes several sources of uncertainties. One is related with input data. Storm surge heights are derived through a hydrodynamic model, whose performance for individual stations is very diverse. Methodologically, several components that could locally influence surge heights are omitted, such as tide-surge interaction, the impact of sea level rise on tides or ground motion. Those effects could be locally very significant as these are very local factors with a number of causes, and no large-scale datasets are available.

In terms of results, the overall values of the indicator in the historical scenario (1971–2000) are rather low, and range from 7 to 94 cm at local level. In approx. 80% of local units the value of the indicator is below 40 cm. In the Mediterranean or Black seas, surges are mostly no larger than half a metre, therefore the flood hazard indicator does not exceed 20 cm in most of southern European countries. Only in the northern part of the Adriatic Sea, surges could be larger, with Venice being one of the endangered locations in that area. Highest surge are observed in the southern coasts of the North Sea, i.e. in Belgium, Denmark, Germany, the Netherlands and the UK. High surges are also present in the entire Baltic Sea, especially in its southern and eastern coasts, from Germany through Poland, Lithuania, Latvia, Estonia up to Finland. Those patterns are the result of the distribution of paths of extra-tropical cyclones. It is projected that, in general, storm surges will become more intense in the future. An average 100-year surge at local or regional level will be 30–50 cm higher in 2071–2100 compared to 1971–2000.

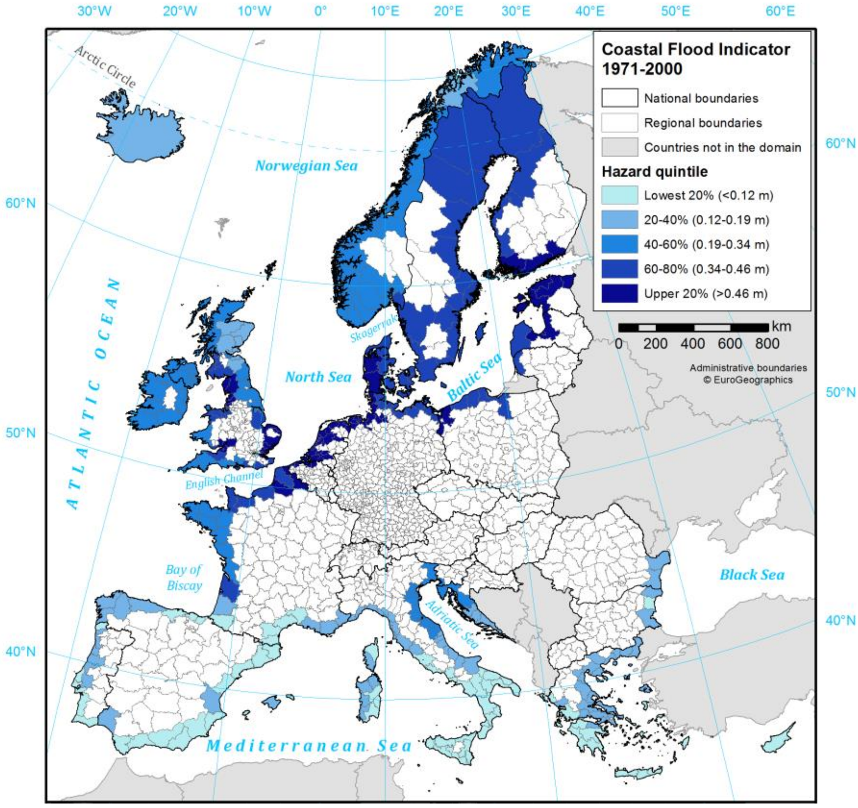

Figure 5. Quantiles of normalized coastal flood hazard indicator (100-year storm surge in a given scenario minus 10-year storm surge in the historical scenario) at regional level for historical scenario

Pluvial floods:

The proposed indicator is the **daily precipitation intensity (RX1day) for a specific return period of 5 years**.

For future conditions, IPCC, in addition to other indicators (i.e. Simple daily intensity index -SDII- index and Precipitation from very wet days -R95p- index), also considers the changes in the 2081–2100 return period (RP) for rare daily precipitation values, RX1day, that have a 20-year return period during historical period 1986–2005. Similar indicators are used by the European Environment Agency. This indicator was selected for BRIGAID project because most urban drainage systems are designed for return periods between 2 and 20 years. Although this indicator was also computed separately for the summer and winter seasons, annual values were finally selected for further use.

The benefit of this indicator is that it is based on direct meteorological outputs of the climate models. There are, however, some limitations:

- Daily precipitation may not be fully representative for pluvial flooding such as flooding as a consequence of sewer surcharge. Many urban drainage systems have response times smaller than 1 day, which means that sub-daily precipitation may be more appropriate.
- This first volume of rainfall will be stored in the underground sewer network, hence does not contribute to the urban flooding. A threshold could be applied to the extreme precipitation intensities or the exceedance above this threshold considered but this threshold strongly depends on the specific system properties.
- For the impact analysis on pluvial flooding, an urban drainage and surface inundation model would be required. Such models are very detailed and should be considered for local impact analysis.

The heavy precipitation hazard indicator based on the daily precipitation intensity for a return period of 5 years, is provided for any location in Europe. This does, however, not mean that pluvial floods and other heavy precipitation induced disasters can happen at any location. The pluvial flood hazard, for instance, depends on the local conditions in terms of topography, land use and drainage system properties.

Heavy precipitation is variable across Europe with higher intensities over elevated areas such as the Alps because of the orographic lifting. Also some other areas show higher precipitation extremes such as the western Norwegian Coast, due to the passage of mid-latitude cyclones directed from west to east, and regions bordering the coasts in the Mediterranean region due to coastal cyclones that transport humid air masses. At the national level, Slovenia, Switzerland and Italy show the highest intensities. The extreme precipitation intensities are projected to increase over entire Europe, with increases between 5 mm and more than 9 mm.

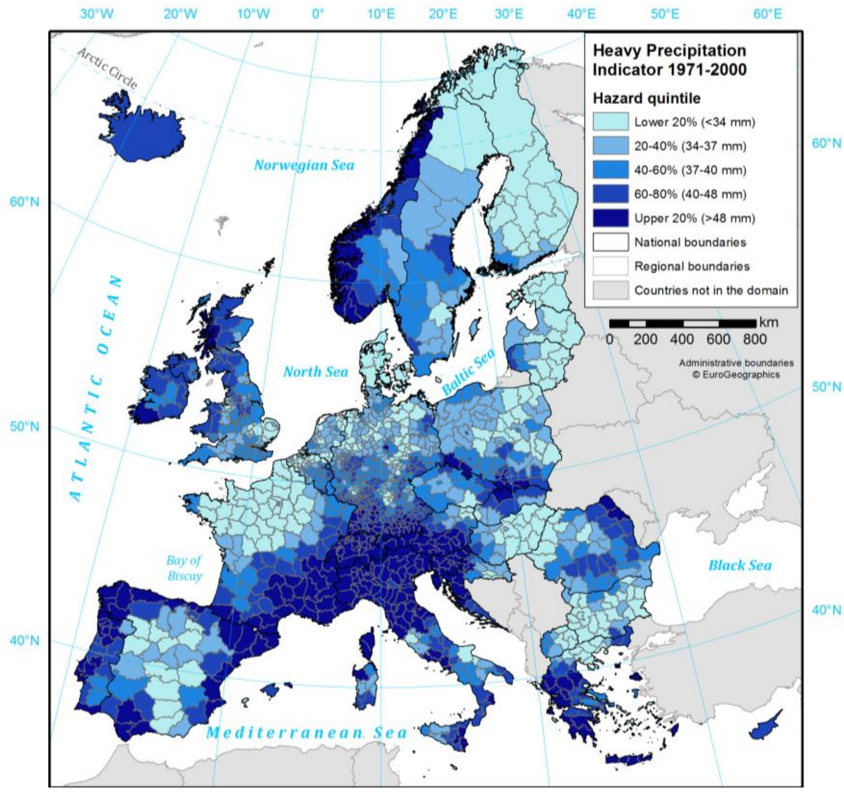

Figure 6. *Quantiles of normalized heavy precipitation hazard indicator (daily precipitation intensity for a return period of 5 years) at regional level for historical scenario*

Wind storms:

The proposed indicator is the **99th percentile of daily wind speed corresponding to a stronger storm.** The European Environment Agency (EEA) considers changes in the 98th percentile of daily maximum wind speed as an indicator of wind storms. However, in our analysis, the 99th percentile was selected as to consider extreme wind storms.

As a limitation, the specific impact of extreme wind storms may depend on the types of buildings and other local conditions, which need to be considered in a more specific / detailed impact analysis.

There are strong regional differences with both negative and positive changes. Bigger increases are expected for Iceland, the UK and the coastal areas of north-western Europe and Norway. For the RCP4.5 scenario, the 99th percentile of daily wind speed decreases to more than 0.12 m/s in comparison with the historical climatic conditions. For the RCP8.5 scenario, this percentile increases up to more than 0.10 m/s. Hence, the range of extreme wind speed values remains almost the same. The same applies to the values at the regional and national levels.

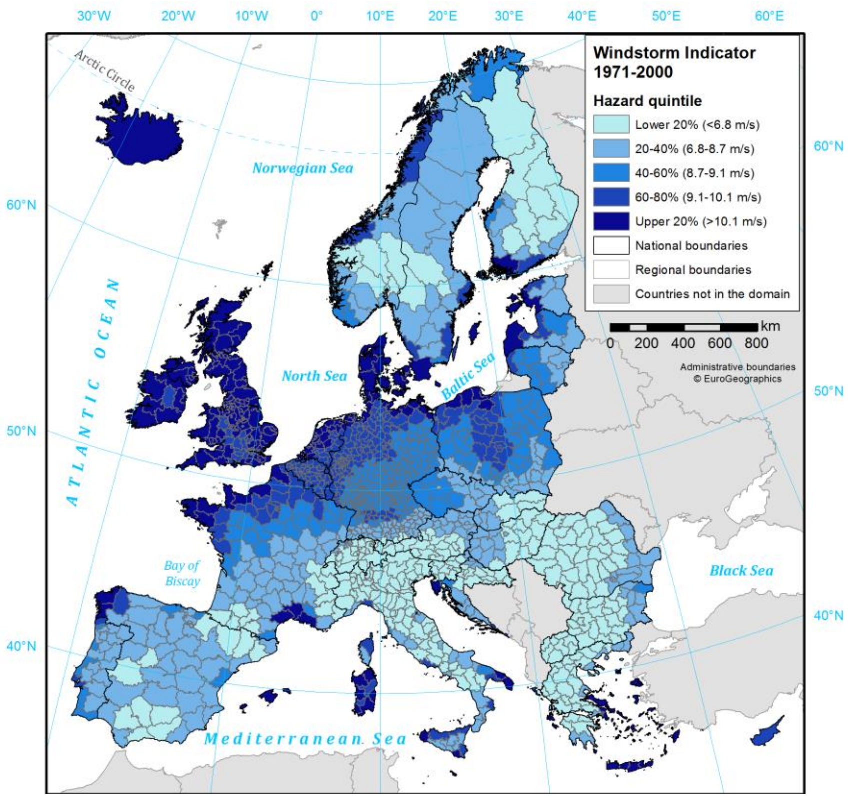

Figure 7. *Quantiles of normalized wind storms (99th percentile of daily maximum wind speed) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios*

Droughts:

The proposed indicator is the **annual Consecutive Dry Days (CDD)** expressed as the **maximum number of consecutive dry days when precipitation is less than 1 mm and considering the largest CDD in the 30-years period.** Therefore, the CDD value considered on the basis of the indicator has an empirical return period of 30 years. This approach is consistent with the IPCC.

The indicator is computed directly from meteorological variables available in the climate model outputs, which is a direct benefit. There are, however, some limitations:

- Next to the number of successive days with no or little rainfall days, there are many more properties of the temporal rainfall variability that are of importance for impact analysis of droughts, such as the cumulative rainfall amounts, the temperature and evaporation amounts, the impacts on soil moisture, low river flows, etc.
- Different types of drought related impacts exist. Quantification of such impacts would require a very specific type of local impact model.

The droughts' hazard indicator shows strong regional differences. There is a clear north-south variation in the number of CDDs with much higher drought hazard conditions in Southern Europe. At the national level, the Southern European countries Cyprus, Spain, Portugal, Greece and Italy have the highest CDD indicator days. They are projected to increase all over Europe, with increases from 8 to 18 CDDs. The changes are strongest for the more dry countries of Southern Europe.

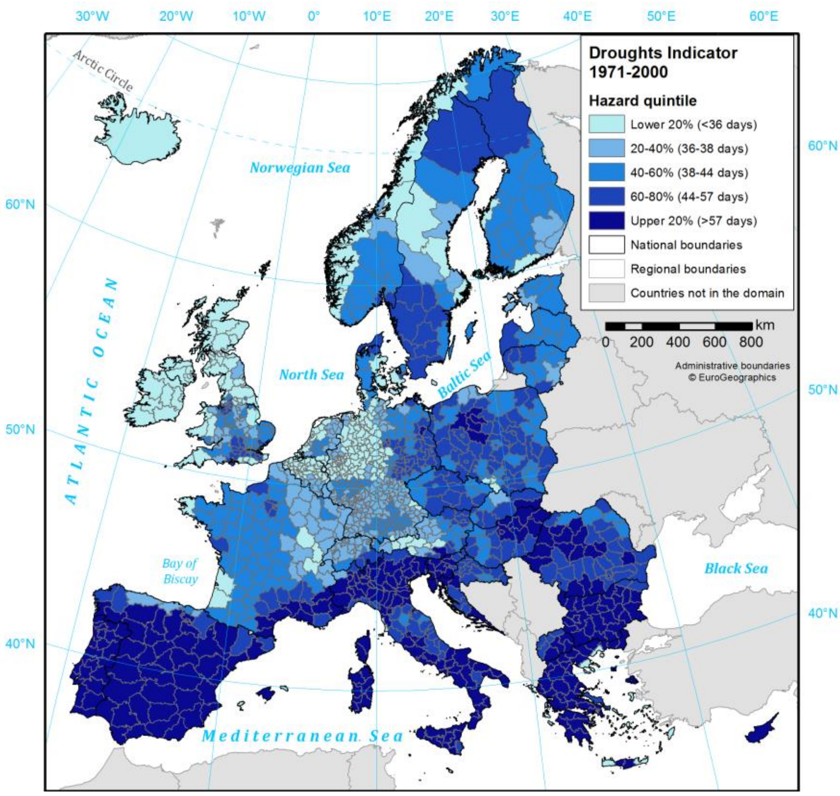

Figure 8. ***Quantiles of normalized drought hazard indicator (maximum number of consecutive dry days when precipitation is less than 1 mm) at regional level for historical scenario***

Heatwaves:

The proposed indicator is the **number of heat waves over a period of 30 years.** This indicator follows the WMO definition of heat waves (see section 3.1).

It is calculated from meteorological outputs of the climate models. There are, however, some limitations:

- Next to the number of heat waves, the intensity and duration of the heat waves may be important as well.
- Just one potential definition of heatwaves was considered whereas many more definitions exist, or information on the full temporal variability of temperature values may be useful for specific types of heat wave related impacts.
- Different types of heat wave related impacts exist. Quantification of such impacts would require a very specific type of local impact model.

The heatwaves indicator shows a higher number of heat waves for the inland areas of Southern Europe. At the national level, Spain and Portugal have the highest number of heat waves. In the historical climate (1971-2000), the 5 and 95 percentiles of total number of heat waves in 30 years across Europe are 9 and 57. They are projected to increase quite strongly over entire Europe, with increases between 60 and 80 heatwaves in 30 years. The maximum number of heat waves at the national level increases from 80 (historical climate) to a range between 150 and 181 in 30 years.

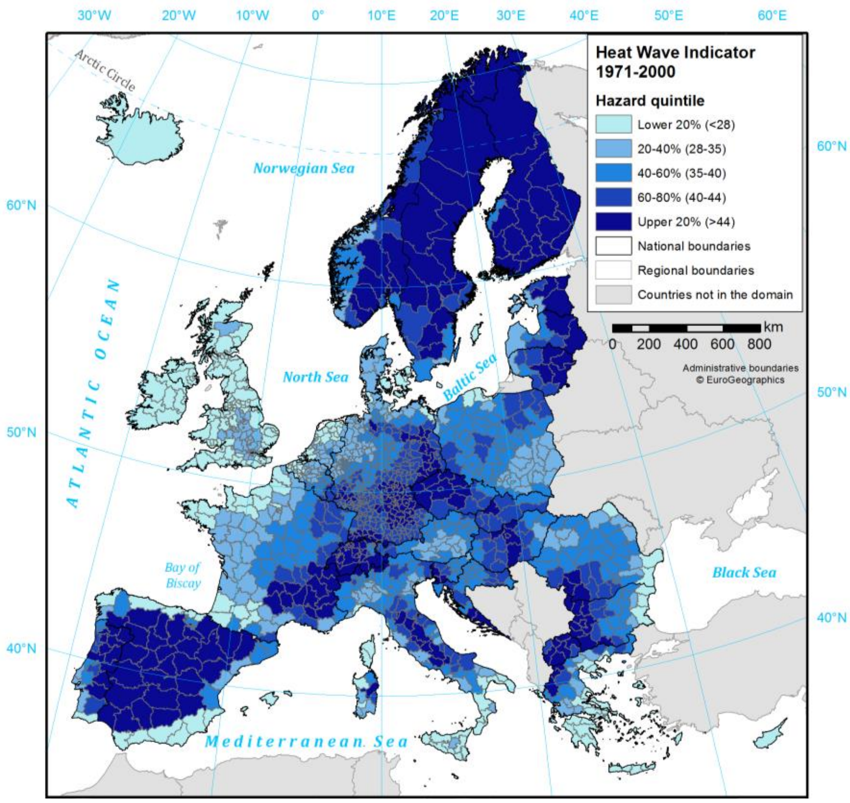

Figure 9. *Quantiles of normalized heat waves hazard indicator (number of heat waves over a period of 30 years) at regional level for historical scenario*

Wildfires:

The proposed indicator is the **Forest Fire Danger Index (FFDI)** defined by (Nobel et al., 1980) as:

$$FFDI = 2exp(0.987logD - 0.45 + 0.0338T + 0.0234V - 0.0345H)$$

where H is the relative humidity from 0-100%,
T is the air temperature in degree Celsius,
V is the average wind speed 10 meters above ground, in meter per second and
D is the drought factor in range 0-10 (Sharples et al., 2009).

This formula is frequently used and can be computed directly from meteorological variables available in the climate model outputs. The calculation was done for each day of the time series and the final index computed by averaging the FFDI for all days of the 30-year time series.

In terms of limitations, wildfires are in different regions of Europe induced by other meteorological and hydrological conditions. Hence, different indicators may need to be considered.

The wildfire hazard indicator shows strong regional differences, as was also the case for the drought and heatwave indicators. There is a strong north-south variation in the FFDI with much higher wild fire hazard conditions in the drier countries of Southern Europe. At the national level, the Southern European countries Cyprus, Spain, Portugal and Greece have the highest FFDI values. They are projected to increase all over Europe but the changes are strongest for the more dry countries of Southern Europe.

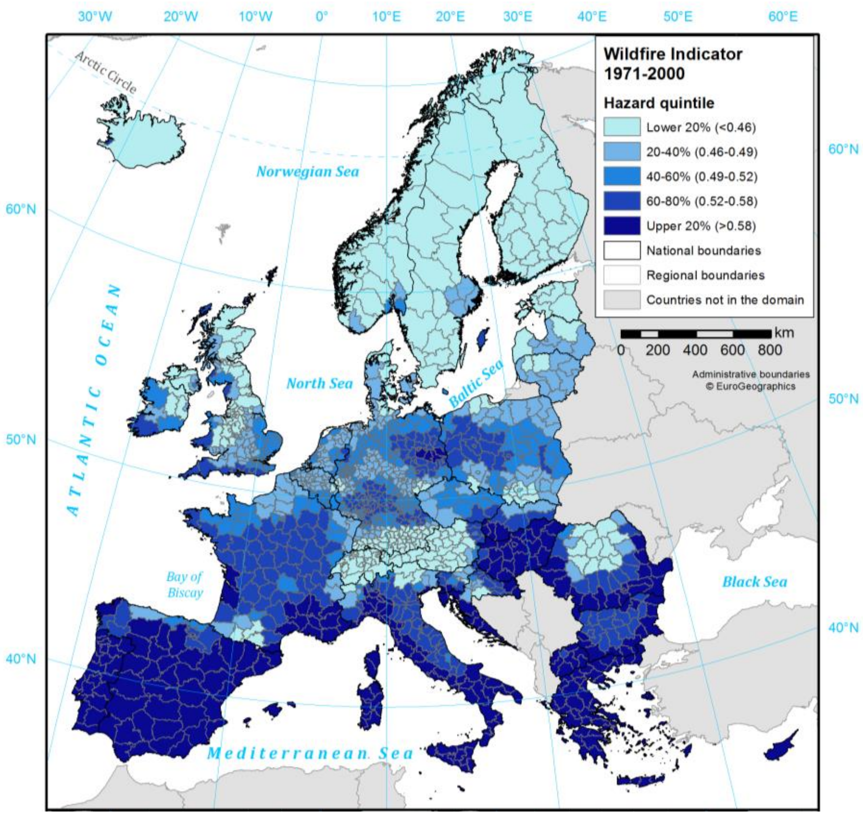

Figure 10. *Quantiles of normalized wild fires hazard indicator (Forest Fire Danger Index) at regional level for historical scenario*

3.3.2 *Exposed elements*

The indicators for exposed elements are hazard-specific and have been generated through different approaches dependent on the hazard.

River floods and coastal floods:

The Floods Directive (European Union, 2007) requires Member States *"to approach flood risk management in a three stage process whereby: 1) Member States will undertake a preliminary flood risk assessment; 2) develop flood hazard maps and flood risk maps in areas with a medium likely hood of flooding (at least a 1 in 100 year event); and 3) draw up flood risk management plans for these zones."* This flood return period of 100 years is the only one specifically mentioned in the Directive and has been considered as reference for our analysis.

The considered exposed elements are population and assets affected by a *100-year return period flooding.* The ancillary data identified for the calculation of this reference information are the CORINE land cover map, which classifies land uses across Europe, and the population density grid generated by the European Environmental Agency (Gallego, 2010). The exposed assets have been finally chosen as the key target indicator, since both types of impact are closely related.

A specific study conducted by the JRC follows a similar approach (Alfieri et al, 2016). These authors also propose to characterise spatial variability of land uses in flooding areas by considering the CORINE map. In this study, high resolution inundation maps are calculated which is considered "*of utmost importance to achieve a meaningful mapping of the flood risk",* due to the strong spatial variability of the impacts of these events.

The trend in past decades has been a rapid increase in exposure due to land occupation in hazardous areas. However, as a consequence of the transposition of the Floods Directive to EU28 National laws, a more strict regulation is being enforced in European countries. The land uses within areas under flood risk are monitored and specifically permitted. As a consequence, the evolution in exposure is expected to follow a different trend even in regions with a strong socio-economic growth. The changes in potential impacts may be more linked to changes in the pattern of flooding than by socio-economic expansion and occupation of flood-prone areas.

Pluvial floods (heavy rain) and wind storms:

These two hazards have been grouped because the exposure to their effects share a similar pattern, both depending on the density of population and existing constructions and the characteristics of households, constructions and infrastructures.

The exposure to these hazards is very dependent on local conditions, and thus more detailed analysis may be required going beyond the more general scale provided by this market scoping at European scale. At the general level, four indicators are considered:

(1) Population density

(2) Density of constructions, including continuous and discontinuous urban fabric, industrial areas and other infrastructures.

(3) Households living in houses (non-apartments) in urban areas

(4) Number of Vehicles

The first indicator characterise the number of people affected. The other three indicators provide information on the private goods potentially most affected by the considered hazards.

The indicators (1), (3) and (4) have been derived from Eurostat data. The density of built-up area is extracted from the CORINE land cover map and aggregated at NUTS2 and NUTS3 levels.

For the estimation of exposed elements in the future, a projection of population in 2050 at NUTS2 level produced by Eurostat is used. In terms of density of built-up area, the category of 'construction sites' under the 2012 land use maps is added.

For heavy precipitation, we will use the four general indicators. The population and urban density are considered as direct indicator of the impact from pluvial or flash floods. The number of houses allow o consider the differential impact due to predominant urban typologies. These impacts are expected to increase in residential areas of small houses in comparison to blocks of apartments. The number of vehicles complements the evaluation of potentially damaged private goods.

The respective weights for the 4 indicators are 0.35; 0.35; 0.24 and 0.06, respectively for the indicators (1) – (4).

For wind storms, we will only use the indicators on population and urban fabric density, applying equal weights to both.

Droughts:

At European scale, droughts have important effects on different sectors, in particular on agriculture, energy and industry, public water supply and water quality (Blauhut and Stahl, 2015).

In our analysis, the effects of droughts will be assessed with a clear focus on the agriculture sector due to two main reasons. Agricultural sector is the largest water consumer in drought-prone European areas, which in addition tend to be affected by water scarcity, and most of innovators interested in engaging into BRIGAID activities and dealing with drought-related problems are focusing on agriculture.

In addition, according to European water legislation, water use for population has always a higher priority than water use in agriculture, so in cases of official declaration of a drought period, there is no competence between these two uses and drinking water is guaranteed over agricultural uses.

A number of three indicators is proposed:

(1) total irrigated area

(2) total irrigated area of intensive crops

(3) index of current water exploitation

The indicators on irrigated areas are provided by Eurostat, as part of the set of Agri-environmental indicators. The total irrigated area is relevant because it can be used to estimate the regular water demand for agricultural use. A reduction in the water availability in case of a prolonged drought period will cause direct socio-economic consequences to the sector. Building on this idea, the extent of intensive crops is also considered. These crops include high value-added crops, i.e. fruit trees, berries, horticultural crops, citrus, vineyards, olive trees and those produced in greenhouses.

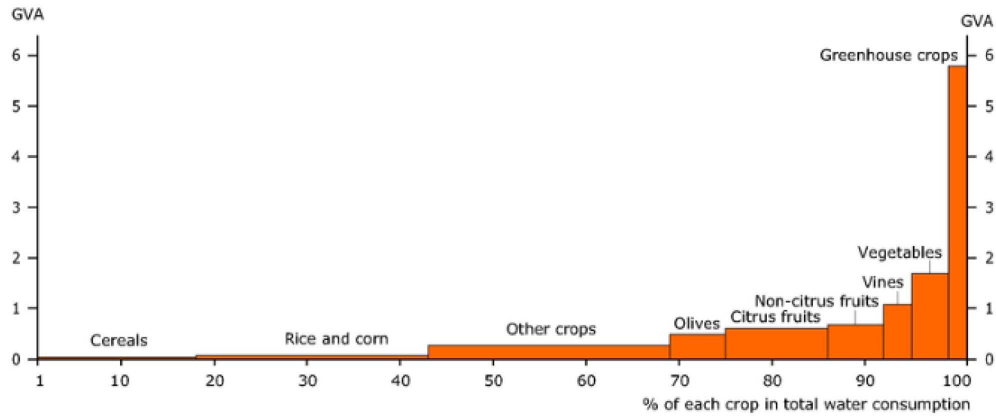

Figure 11. ***Gross Value Added (GVA) per unit of water consumed of the main irrigated crops for Spain (Source: EEA)***

It also must be noted that many of these crops are non-annual crops which may even not survive without irrigation to harsh summer climatic conditions in Southern Europe.

The index of water exploitation is provided by the EEA, and provides additional information on current affection of water scarcity at river basin level. It is defined as "*the mean annual total demand for freshwater divided by the long-term average freshwater resources, and gives an indication of how the total water demand puts pressure on the water resource*."

According to FAO estimations (Bruinsma, 2012) the irrigable area (defined as area equipped for irrigation) in the European Union is expected to remain approximately the same by 2050.

However, the annual irrigation area is expected to increase in Central and Northern Europe areas. Areas equipped (i.e. areas with sprinkler irrigation) are often only irrigated in these regions in dry and hot summers. Currently, the difference between annual irrigated area and irrigable area is quite larger in Southern Europe countries than in the remaining EU areas. However, by 2050 this difference is expected to decrease significantly. Therefore, for calculation of the exposed elements in 2050, the irrigated land will be substituted by irrigable land. The latter is characterized through Eurostat data.

The respective weights for the three indicators are 0.5; 0.4; and 0.1.

This is based on a subjective assessment. The extension of irrigated areas indicates the overall exposed elements and is given half of the total weight. The intensive crops extension provides additional information on the most valuable areas in economic terms, and therefore are given a high weight. Finally, the exploitation index is a complementary information which indicates the level of pressure for the overall water resources and is assigned a much reduced weight.

Heatwaves:

Heatwaves pose a risk to the health of individuals and have been the weather-related hazard which has caused a highest number of human fatalities in Europe over the last decades. The most vulnerable groups are elderly population, the very young and the chronically ill (Loughnan et al, 2013). In addition, heatwaves also has significant impacts on health and on population well-being.

In particular, the effects of heatwaves tend to be more important on urban areas because of the so-called "heat island" effect which produces an increase in day-temperature and also in nighttemperature, being the former usually more pronounced. As an example, the heatwave of 2003 caused over 70,000 deaths most of them in urbanized areas (Hoag, 2015).

The CLIMATE-ADAPT platform provides a valuable reference on the factors influencing vulnerability to urban heatwaves by identifying the "multiple factors influence the exposure of heat and the sensitivity to it". This information has been considered for the selection of indicators for the characterization of exposed elements. Building on this list, a review of factors more often considered in literature, and data availability, the following indicators have been selected:

- Urban population
- Number of elderly living in cities
- Percentage of households inhabited by a lone pensioner
- Purchasing power standards of urban population / share of low-income households
- Number of touristic beds per 1,000 inhabitants

All the data required for the calculation of these indicators is provided by Eurostat, in particular by the series on "statistics of European cities" (see http://ec.europa.eu/eurostat/statistics-explained/index.php/Statistics_on_European_cities). Based on this data source, we are considering as urban population to the inhabitants of cities (consisting of "*one or more local administrative unit (LAU) where the majority of the population lives in an urban centre of at least 50,000 inhabitants*") and greater cities ("*an approximation of the urban centre when this stretches beyond the administrative city boundaries (previously referred to as the kernel*").

The inhabitants of cities form the group of population which tend to be most affected by heatwaves. The share of people over 65 years old living in cities is an indicator of the importance of this vulnerable group, which is even more vulnerable for the case of households only inhabited by pensioners. The economic capacity is another indicator of vulnerability, because population with lower incomes has a much reduced capacity to protect from heatwaves effect. As an example, in Spain although being one of the European countries most affected by heatwaves, only a 35.5% of the households have installed an air-conditioning units. In most of the cases, elder population and lower-income households are part of those population not benefitting from refrigeration systems.

An additional indicator relates to the importance of tourism since this is a key economic activity in many of the European countries most affected by heatwaves that can be quite impacted by this phenomena. This can be a catalyst for the adoption of new solutions aiming to reduce the impact in the most relevant cultural and commercial areas in touristic cities. The selected indicator is the number of touristic beds per 1,000 inhabitants in urban areas, and is also provided by Eurostat.

For the calculation of the 2050 overall indicator, the projections in population and people over 65 years old produced by Eurostat are used.

The weights assigned to the indicators are not equal. The total number of inhabitants of urban cities is given a 0.5. The group of indicators related to vulnerable population are given a 0.45, distributed equally. The indicator on tourism is assigned a 0.05 weight.

Wildfires:

The basic data source for this analysis is the forest map or Europe produced by the European Forest Institute[9]. After contacting this organisation, they have allowed the use of this map within the scope of this project. This is a comprehensive and complete European map on forest area at 1 x 1 kilometre resolution. (see http://www.efi.int/portal/virtual_library/information_services/mapping_services/forest_map_of_europe).

This map has been aggregated at NUTS2-level to quantify the forest areas potentially affected by wildfires.

In order to take into account the higher importance of some forest areas in terms of environmental value as well as in terms of population potentially affected by wildfires, two other indicators have been calculated:

- The forested area within natural protected areas
- The forested area close to highly populated areas and other populated areas

These two cases indicate areas of a higher priority in terms of protection against wildfires.

The information on protected areas is provided by the European Environmental Agency (EEA). In this study, we have used the European inventory of nationally designated areas which "holds information about protected areas and the national legislative instruments, which directly or indirectly create protected areas" (see http://www.eea.europa.eu/data-and-maps/data/nationally-designated-areas-national-cdda-11#tab-gis-data) and the map of areas designated as part of the Natura 2000 network (see http://www.eea.europa.eu/data-and-maps/data/natura-7#tab-gis-data), covering the 2015 version in both cases.

The map of urban areas has been provided by the Urban Atlas initiative from the EEA. The extent of forest areas within a buffer of 25 kilometres of urban areas have been quantified. In addition, a buffer area of 3 kilometres have been considered for the remaining urban areas in Europe. These have been extracted from the 2012 CORINE land use map.

Both indicators have been also aggregated at NUTS2 level after their calculation.

According to data from UNECE and FAO, the forest area in Europe is growing at a very slow pace (lower than a 0.08% per year). Thus, in our analysis the exposed elements by 2050 are considered to remain the same as today.

A weight of 0.6 is assigned to the total forested area whereas equal weights of 0.2 are given to the other two indicators.

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[9] *For further reference see (Kempeneers et al, 2011); (Päivinen et al, 2001) and (Schuck et al, 2002)*

3.3.3 *Potential Impacts*

The potential impact score is calculated through a combination of hazard and exposed elements indicators. This combination is informed by other ancillary data, i.e. economical valuations of historical and projected impacts caused by a specific kind of hazard, which are used as support and a means of validation for the selection of weights.

As a general rule, the overall indicators for current and future hazard potential and exposed elements are first calculated. These overall indicators are then combined using specific weights for each hazard. The combination methodology is described hereafter for each specific hazard.

River floods

For the determination of current impact of river floods in Europe we have decided to use the data provided by (Alfieri et al, 2016) at NUTS2 level in terms of annual damage per the period 1990-2013. After analysis of this information and the procedure followed, this is considered as fully coherent with our methodological framework.

The potential damage is characterised through the application of specific flood damage functions directly dependent on the flood depth, which is our indicator for hazard potential. These functions are applied for the exposed elements determined by measuring the CORINE land use map elements within the flooded areas in the 1990-2013 period. A sound effort is done for the estimation of potential damage, by using the country specific depth damage functions defined by Huizinga (2007) for different land uses, and introducing several adjustments for the different contexts.

For our analysis, we have selected the damage evaluation done by the integral method. This "*estimates the average annual impact of floods by computing a piece-wise integral of the damage-probability curve for a selected range of return periods. The integral sum is truncated at the return period of the protection level of the corresponding location, assuming that no impact occurs for events of lower magnitude. In this step, we used the European flood protection map derived by Jongman et al. (2014).*" The results at country scale are shown in figure 12.

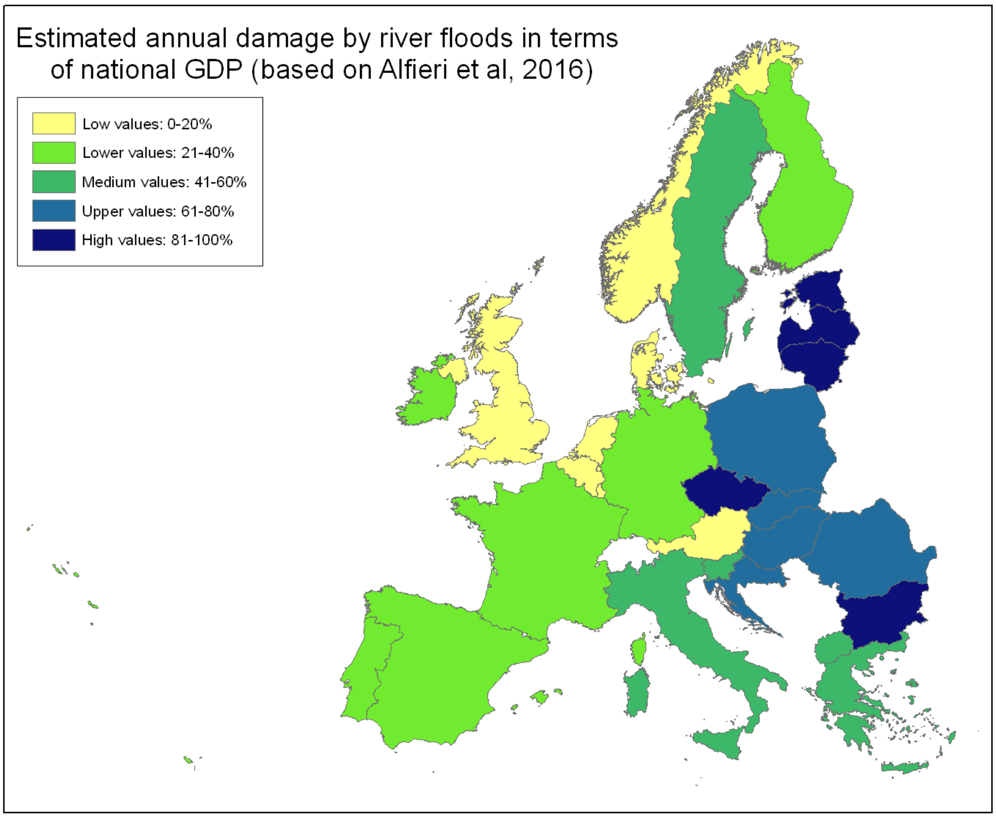

Figure 12. ***Annual expected damage by river floods per country in terms of the national GDP for the period 1990-2013 (based on Alfieri et al, 2016)***

The estimation of expected impacts by 2050 is using the results generate by the ClimateCost project, which have been incorporated into the JRC's PESETA II project.

The methodology applied is described as follows (Feyen et al, 2011): "*the hydrological model calculates the changes in flood frequency and water level statistics, which provide an assessment of the expected changes in flood hazard. The model expresses these as a change in the discharge of a flood with a certain (e.g. 100 years) return period (change in intensity) or a change in the return period of a certain event (change in recurrence) under a changed climate. The high resolution digital elevation data can allow this information to be translated into flooded areas and flood (inundation) water depths. The analysis then uses water-depth damage functions and land-use classifications from CORINE datasets to estimate the direct damage from each flood event, by land-use class. Losses are then accumulated over the frequency distributions to get an overall estimate of the changes in losses.*"

The model was run for the period 1960-2100 using different climatic regional models. The main indicator used for damage evaluation is again the estimation of the flood water levels. As done by Alfieri et al, the ClimateCost project uses water damage functions and the CORINE land cover as main data source for characterisation of exposed elements. As a result, a variation of the expected damage is provided, which is coherent with the results used for estimating the current impact as well as with our analysis framework. Taking this into account, these results have been also incorporated into our analysis for the estimation of expected impacts by 2050 at NUTS2 level.

Coastal floods:

The integration of the different components for the estimation of impact has been carried out through the combination of the hazard indicator, i.e. flood levels for a 100 year return-period with a digital elevation model and the CORINE land cover map. As a result, we have identified the exposed elements to coastal flooding under two time horizons: actual time period and 2070-2100. The consideration of a more extended time horizon instead of 2050 is based on the larger expected lifetime of hydraulic solutions dealing with protection against coastal flooding.

The digital elevation model (EU-DEM) is provided by the EEA (http://www.eea.europa.eu/data-and-maps/data/eu-dem).

Similarly to the case of river floods, the results from the ClimateCost project (Brown et al, 2011) have been considered as a basis for the integration of results since these provide monetised units of current and expected impacts at country level. These results have been disaggregated at NUTS2 level using our indicator for exposed elements, which is dependent on the hazard potential indicator.

Heavy precipitation

For the case of pluvial floods caused by heavy rain, Bhattarai et al (2016) provide an accurate statistical model for the assessment of economic damages. This was developed for Japan for the period 1993-2009 using valuations of damage on private properties for tuning up and validating the model. The main factors influencing the 'damage occurrence probability' are the intensity of precipitation and the slope whereas the population density and the GDP are also considered for the estimation of damage cost.

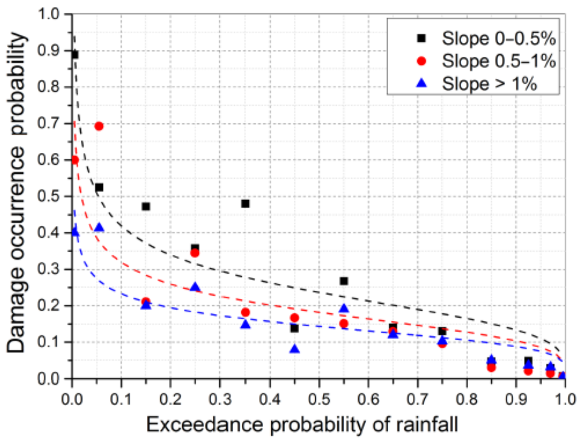

Figure 13. ***Relationship between slope and damage occurrence (Bhattarai et al, 2016)***

For pluvial floods, the impact is expected to be much higher in flat areas due to bigger difficulties in the drainage of water (see figure 13).

On the other hand, under heavy precipitation we are also considering flash floods and landslides, with a higher expected impact for urban areas in high slope.

In order to consider the differences in average slope in urban areas, the map of constructed areas has been segmented into 4 categories, corresponding to:

- slopes under 0.25% (category 1),
- slopes between 0,25 and 0,5% (category 2)
- slopes between 0,5 and 5% (category 3)
- slopes over 5% (category 4).

The information of slopes has been extracted from a map produced by ESDAC (European Soil Data Centre from European Commission)[10]. This map measures for the EU the LS-factor which integrates slope length and steepness factor, with a spatial resolution of 100 metres.

The maps of exposed elements have been recalibrated considering a factor of 1.4 for category 1; a factor of 1.2 for categories 2 and 4; and a factor of 1 for intermediate slopes. Then, these maps have been combined with the hazard potential indicators.

Wind storms:

In the case of wind storms, equal weights have been applied to the overall hazard potential and exposed elements indicators. No specific information on the relationship between the general factors affecting the damages produced by these events and applicable to our geographic scale has been found.

Droughts:

The PESETA II project (Ciscar et al, 2014) estimates the impact on agriculture by projecting to the 2080 horizon the extension of cropland affected by droughts in different European regions (see figure 14).

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	96	8	8	22	31	27
Reference	710	2	61	25	217	405
change (%)	637	-77	627	16	601	1,407

Units: Thousand km^2/year

Figure 14. ***Expected extension of cropland affected by drought (extracted from Ciscar et al, 2014)***

This approximation considers hazard intensity and the extension of agricultural area. By putting the focus on irrigated agriculture, we are also including into the analysis the differences in gross value added of the water use as well as the bigger impact of a lack in water availability on these high-value irrigated crops. This is explained by the crop water production functions. These metrics estimate the relationship between yield and relative evapotranspiration for different type of crops and show relevant differences between drought-tolerant (usually rain-fed crops) and drought-sensitive crops, i.e. irrigated crops (see figure 15).

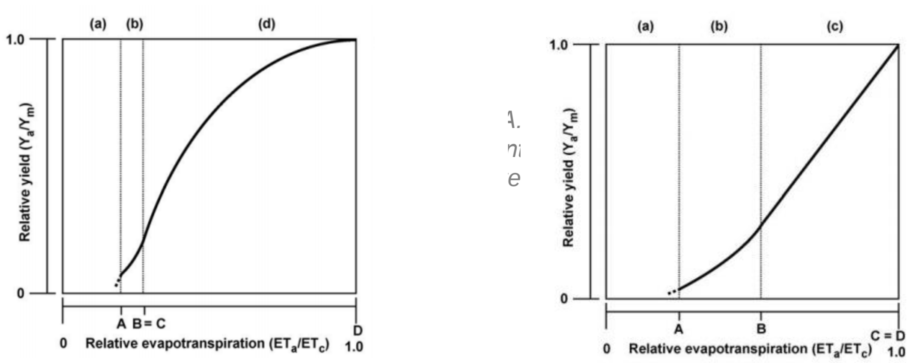

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Figure 15. *General shape of the crop water production function for drought-tolerant crops (left graph) and drought-sensitive crops (right graph). Extracted from (Geerts and Raes, 2009)*

Thus, in this case we have combined the hazard potential and exposed elements by applying equal weights.

Heatwaves:

The consideration of the number of expected heatwaves as indicator of hazard potential facilitates the integration with the exposed elements indicators. The combination of current and expected elements has been weighted by the number of years considered in each case and then summed up.

Wildfires:

For the case of wildfires, the sectorial results from the PESETA II project[11] (Camia et al, 2017) have been considered. This report includes a section on the impact assessment from wildfires which estimates burned area as a function of fire danger indices. In this exercise, the Canadian Fire Weather Index (FWI) system is used instead of the FFDI. The data on burned areas from 2000 on are collected from the European Forest Fire Information System (EFFIS) same as in our study. The FWI has been projected to time horizon 2071-2100 using information from climatic models simulations; and the projected burned area has been modelled through MARS (Multivariate Adaptive Regression Spline) techniques.

The results show a very relevant conclusion for our study: there is an exponential relationship between the increases in burned area as compared to changes in the Forest Fire danger index.

An additionally important remark comes from the limitation of the analysis to Southern European countries (i.e. Portugal, Spain, Italy and Greece) and Southern France, i.e. the European regions by far most affected by forest fires (85% of the current total EU burned area). The analysis is not reported for other EU regions because neither the current or projected effect of wildfires is considered significant enough in comparison to the selected countries.

As a first step, the exponential relationship between the burned area and the FFDI index has been also confirmed using our data (see figure 16). More specifically, the burned area has been calculated as the average of forest-burned area at national level within the period 2000-2015 expressed as a percentage of the forested area. The average FFDI has been aggregated per country scale for the same period.

[11] Specific report on 'Modeling the impacts of climate change on forest fire danger in Europe'

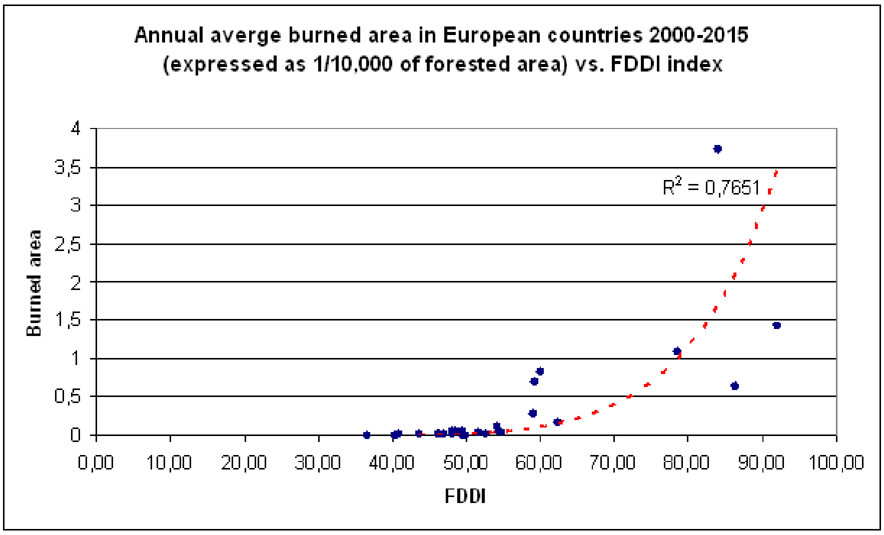

Figure 16. *Exponential relationship between extent of burned area and FFDI index*

The existence of an exponential relationship has been considered for the calculation of combined impact index. This relationship is partly explained by the criteria used for the construction of the FFDI. Although the FFDI is a dimensionless index, it was adjusted to measure the degree of danger of fire in Australian forests using low-intensity fires and historic data of high-impact wildfires (see figure 17). Therefore, the changes in this index are expected to imply relevant and non-lineal variations in impact, e.g. burned area, from wildfires.

Category	Forest Fire Danger Index	Grassland Fire Danger Index
Catastrophic (Code Red)	100 +	150 +
Extreme	75 – 99	100 - 149
Severe	50 – 74	50 – 99
Very high	25 - 49	25 - 49
High	12 – 24	12 – 24
Low to moderate	0 - 11	0 - 11

Figure 17. *Australia's National Fire Danger Ratings (since September 2009)*

Based on this analysis, the following information has been combined into the potential impact index for wildfires:

1. The annual average burned area in the historic period (2000-2015) expressed as a percentage of the total area. The FFDI values in this period have been utilised for disaggregating the data from country level into NUTS3 level. *[Current impact]*

2. An estimation of potential burned area *[Expected impact]* calculated as a combination of:

   - the exposed elements indicator expressed in terms of potentially affected area; and

   - the variations in projected hazard, i.e. potential burned areas, considering the projected FFDI values for 2050 time horizon (average of RCP4.5 and RCP8.5 estimations).

An equal weight has been given to the current and expected impacts, because both are considered as very relevant in terms of investment decisions.

3.4.4 Adaptive capacity

Categories and sub-categories for adaptive capacity

In the last years several studies provided more in-depth analysis of adaptive capacity and have developed factors and indicators to estimate the capacities of EU countries regarding climate change adaptation. Some are concentrating on adaptive capacity, while others have a broader view and also capture vulnerability. Table 4 shows the different components of adaptive capacity under each of the developed approaches.

Source	Components of adaptive capacity
IPCC (2001), Impacts, Adaptation, and Vulnerability	• The range of **available technological options** for adaptation, • The **availability of resources** and their distribution across the population, • The **structure of critical institutions**, the derivative allocation of decision-making authority, and the decision criteria that would be employed. • The stock of **human capital** including education and personal security. • The stock of **social capital** including the definition of property rights. • The system's **access to risk spreading processes**. • The ability of decision-makers to **manage information**, the processes by which these decision-makers determine which information is credible. *The **public perception** to local exposure.*
DG Regio (2009), Regions 2020	• **Information:** Information on the nature and evolution of the climate hazards faced by a society and information on socio-economic systems is important. • **Resources:** Including financial capital, social capital (e.g., strong institutions, transparent decision-making systems), human resources (e.g., labour, skills, knowledge and expertise) and natural resources (e.g., land, water, biodiversity). ***Ability:** The ability of a society to act collectively, and to resolve conflicts between its members, which is heavily influenced by governance, key actors accepting responsibility for adaptation.*
Greiving et al (2011), ESPON-Report	• **Knowledge and awareness:** Knowledge and awareness play an important role in terms of identifying vulnerabilities in relation to climate change and enable the identification of adaptation options • **Ability (Technology, Infrastructure):** To move from awareness to action, ability is necessary, which consists of technology and infrastructure. ***Action (Institutions, Economic resources):** The ability to achieve action is supported by economic resources and institutions that enable a society to carry out the adaptation measures that have been defined.*
Adger et al (2004), New indicators of vulnerability and adaptive capacity	• **Economic well-being:** Proxy for political priorities: poorer countries have other priorities than long-term climate adaptation. • **Education:** Literacy will play an important role in determining access to information regarding the necessity for adaptation and the available of assistance from government to help people pursue adaptation strategies. • **Governance related factors:** Ability to act collectively. ***Technical capacity:** Commitment to and resources for research as well as capacity to undertake research and understand issues.*

Jung et al (2011), RESPONSES-project	• **Financial capital:** Indicators that measure the economic wealth of EU regions and thus their economic ability to cope with threats from climate change. • **Human capital:** Considering the level of education as well as provision of health services and infrastructures. ***Technical capital:*** *Brings together indicators that measure the technical capacity to cope with new challenges posed by climate change.*
Hjerp et al (2012), Climate Proofing of CAP and Cohesion Policy	• **Published climate information (Awareness):** Illustrates the availability of an online information platform that informs of future climate change impacts, scenarios and need for action. • **Technological resources (Ability)**: Ability of a Member State to develop the necessary technologies for adaptation. • **Economic resources (Ability):** Ability of a Member State to provide the necessary funds for adaptation funding. • **National Adaptation Strategy (Action):** This indicator illustrates the state of the National Adaptation Strategy. ***Government effectiveness (Action):*** *This indicator illustrates the efficiency of government and national decision-making.*

Table 4. **Components of adaptive capacity**

The literature screening makes clear that different approaches have been used to assess adaptive capacity of a region or Member State. Concerning the selection of useful indicators for the BRIGAID study, the following two conclusions can be drawn: (1) The studies developed especially for the EU are a good basis for an assessment of BRIGAID market attractiveness (Greiving et al 2011, Jung et al 2011, DG REGIO 2009, Hjerp et al 2012); (2) the broad approach covering all three categories of awareness, ability and action is suitable. For BRIGAID we adjusted the definitions given by Greiving et al (2011). Relevant general indicators and hazard specific indicators are combined. For each category of awareness ability and action, sub-categories were developed based on the literature review.

Awareness:

Knowledge and awareness play an important role in terms of identifying vulnerabilities in relation to climate change and enable the identification of adaptation options.

Based on the approach described by different literature sources, we used following sub-categories to describe awareness:

(1) Public awareness, risk perception, attitudes towards climate change (e.g. mentioned and used by IPCC 2001, Greiving et al 2011)
(2) Willingness to adapt by authorities/institutions (e.g. IPCC 2001)
(3) Frequency/recurrence or proximity of the latest event(s) (see discussion of hazard specific indicators below)
(4) Available information on climate impacts (e.g. information services, platforms) (e.g. DG Regio 2009, Greiving et al 2011, Hjerp et al 2012)
(5) Education level (e.g. Greiving et al 2011, IPCC 2001, DG Regio 2009, Adger et al 2004, Jung et al 2011)
(6) Internet use to reach information (e.g. Greiving et al 2011)

Ability:

To move from awareness to action, ability is necessary, which consists of technical and scientific capacity to understand issues and prepare assessments and studies (social, economical, ecological). A region's governing institutes and their staff members need to have a certain knowledge to frame and implement assessments to be ready to implement the adaptation measures which BRIGAID offers.

The following sub-categories are used:

(1) Technical and scientific capacity to undertake assessments and studies, e.g. vulnerability assessments (e.g. Greiving et al 2011, Adger et al 2004)

Action:

The ability to achieve action is supported by economic resources and institutions that enable a society to carry out the adaptation measures that have been defined.

Following sub-categories are combined for Action:

(1) National Adaptation Policy / Strategies (e.g. IPCC 2001, DG Regio 2009, Greiving et al 2011, Adger et al 2004, Hjerp et al 2012)
(2) Government effectiveness (e.g. IPCC 2001, DG Regio 2009, Greiving et al 2011, Adger et al 2004, Hjerp et al 2012)
(3) Economic resources (e.g. GDP/capita) (e.g. IPCC 2001, DG Regio 2009, Greiving et al 2011, Adger et al 2004, Jung et al 2011, Hjerp et al 2012)
(4) Funding sources for adaptation measures, e.g. by EU Commission (e.g. Greiving et al 2011, Hjerp et al 2012)
(5) Adaptation measures already implemented, e.g. restoration projects (e.g. Hjerp et al 2012)

Hazard specific indicators:

The literature suggests that the occurrence of climate change impacts or hazard events is a significant indicator of awareness of climate change and the need for adaptation to specific hazards (Lee et al., 2015). Unlike the rest of the indicators discussed above, these are hazard-specific indicators. Following computation of a general level of adaptive capacity, we also create a hazard-specific adaptive capacity which is tailored to each of the hazard groups in the BRIGAID project. Given that the occurrence of a hazard event increases awareness (as indicated above in the discussion of awareness sub-categories), to generate the hazard-specific adaptive capacity, we have included an indicator capturing recent occurrence of a hazard event indicator in the "awareness" category by giving it an equal weight to each of the other awareness indicators:[12]

[12] The overall weight of the awareness category does not change from the 30% weighting reported in Figure 18 below, though each indicator's weight decreases from 6% to 5% following the inclusion of this sixth indicator.

- River floods:

Past flood events are linked with increased awareness for flood protection and can be used as an indication of hazard-specific awareness of river floods. We use:

  - Number of European past floods per 10,000 km^2 (2006-2015, national) delivered by EEA (floods); Eurostat, World Bank Country Profiles (country area)

- Coastal Floods:

An increased awareness for coastal flood protection is linked to the number of storm surge events during the last years. We use:

  - Number of storm surges (1991-2016, national) delivered by eSurge-project Database

- Urban flash floods:

Urban flash floods are one main extreme event which causes damages in urban areas. The occurrence of flash floods is an indication on the awareness of urban flood disasters. We use:

  - Number of Flash floods (2006-2016, NUTS II) delivered by EM-DAT International Disaster Database

- Droughts:

Months of drought experienced in region as indicated by a combined drought indicator capturing hydrological drought, which will be linked with an increase in drought awareness in affected countries. We use:

  - Past drought events (1991-2010, country groups)

- Storms:

Insurance damages from major European windstorms are indicative of media coverage and awareness. We use:

  - Insurance damages from major windstorms (1998-2013, national)

- Wildfires:

The hectares of land burnt per country, adjusted by country size, is an indicator of the relative occurrence of wildfires in a country, which in turn is an indicator of the specific awareness of this hazard. We use:

  - Proportion of country burnt by wildfires (%, 2011-2015, national) delivered by European Forest Fire Information System (ha burnt); Eurostat (country size)

Composition of adaptive capacity indicator

We follow the general methodology for calculation of indicators described in 3.2 in the construction of the adaptive capacity index. Steps specific to the construction of the adaptive capacity index are described here. A description of the specific indicators used in the adaptive capacity index can be found in appendix 3.

Weighting

After selecting and normalising indicators in line with the general methodology we give each a weighting, which implicitly gives the relative importance of each indicator as a determinant of a region's general adaptive capacity. In general, we apply equal weighting within each adaptive capacity category of awareness, ability, and action[13], and then follow ESPON Climate weightings to combine these different categories into one overall General Adaptive Capacity score per region.

The ESPON Climate weights were decided by Delphi survey of experts, who applied weightings to different components considered important to the adaptive capacity of the ESPON Climate vulnerability index (Greiving et al, 2011). Only four of these components are relevant to our General Adaptive Capacity index (knowledge and awareness, infrastructure, institutions, economic resources). We do not include technology in our adaptive capacity measure, while ESPON included the existence of technology in a region as an indicator of their ability to adapt to climate change. The BRIGAID project aims to provide technologies to all regions, so the presence of local technologies is less relevant. We have adjusted the relative weights of the components we use in our indicator to reflect this, as shown in Figure 18. The equal weighting we give each indicator within the category of awareness, ability, and action implies that all indicators are equally important determinants of each category.

ESPON					**Our approach**			
Knowledge and awarer	23%	Awareness	23%		Knowledge and awaren	23%	Awareness	30%
Technology	23%	Ability	39%		Technology	0%		
Infrastructure	16%				Infrastructure	16%	Ability	21%
Institutions	17%	Action	38%		Institutions	17%		
Economic resources	21%				Economic resources	21%	Action	49%

Figure 18. ***Weighting of categories - ESPON Climate and our approach***

3.4.5 Market attractiveness

As a final result, the market attractiveness is calculated through the combination of the final scores for impacts from natural hazards and adaptive capacity.

The three main components of the analysis are given an equal weight of 0.333. This has been considered as the most adequate integration of the analysis framework. Also, other initiatives for the production of vulnerability maps at European level, e.g. ESPON and ND-GAIN[14] project have opted for a similar weighting, and thus it has been decided that the use of equal weights may facilitate the comparability of our results.

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[13] The only exception is the ability indicator "adaptation measures", which due to the lower certainty of the data, we give only a 10% weighting, with the other ability indicators having an equal 22.5% weighting.

[14] See http://index.nd-gain.org:8080/documents/nd-gain_technical_document_2015.pdf

3.4. Overview of the indicators considered

This section summarises the list of indicators considered in the analysis. This information is further developed in appendix 2.

HAZARD INDICATORS (hazard-specific)			
Hazard	**Indicator**	**Frame conditions**	**Source**
River floods	Extreme river water levels with a 100-year return period, relative to water levels with a 10-year return period under historical climate	Provided for 4 time horizons (historical, 2030, 2050 and 2070-2100) and the 2 geographic domains (EU28 + EFTA countries)	Own calculation based on climatic models and results from RAIN project
Coastal floods	Extreme storm surges with a 100-year return period, relative to water levels with a 10-year return period under historical climate		Own calculation based on climatic models and results from RAIN project
Pluvial floods	The daily precipitation intensity (RX1day) for a specific return period of 5 years		Own calculation based on climatic models and results from RAIN project
Wind Storms	The 99th percentile of daily wind speed corresponding to a stronger storm		Own calculation based on climatic models and results from RAIN project
Droughts	Annual CDD expressed as the maximum number of Consecutive Dry Days (CDD) when precipitation is less than 1 mm and considering the largest CDD in the 30-years period		Own calculation based on meteorological outputs from climatic models
Heatwaves	Number of heatwaves over a period of 30 years		Own calculation based on meteorological outputs from climatic models
Wildfires	Forest Fire Danger Index (FFDI)		Own calculation based on meteorological outputs from climatic models

EXPOSED ELEMENTS INDICATORS (hazard-specific)			
Hazard	**Indicator**	**Frame conditions**	**Source**
River and coastal floods	Affected assets: Land use inside the boundaries of the 100-year return period river flow	Current conditions. Aggregated at NUTS-2 level. Estimations for some indicators for 2050 time horizon	Own calculation using CORINE land cover maps from 2012 (EEA)
	Affected population: Population directly affected by a 100-year return period river flow		Own calculation using a population density grid (EEA)
Pluvial floods (heavy precipitation) and Wind Storms	Affected population: population density		Eurostat
	Affected assets: density of constructions (urban and industrial areas; infrastructures,…)		CORINE land use map (2012)
	Affected assets: Households living in houses (non-apartments) in urban areas		Eurostat
	Affected assets: Number of Vehicles		Eurostat
Droughts	Affected assets: Total irrigated area		Eurostat
	Affected assets: Total irrigated area of non-annual crops		Eurostat
	Affected population: Index of water exploitation at river basin level		EEA
Heatwaves	Affected population: Urban population		Eurostat
	Affected population: Share of elderly living in cities (population over 65)		Eurostat
	Affected population: Percentage of households inhabited by a lone pensioner;		Eurostat
	Affected population: Purchasing power standards of urban population / share of low-income households		Eurostat
	Affected assets: Number of touristic beds per 1000 inhabitants		Eurostat
Wildfires	Affected assets: Total forested area		Map produced by European Forest Institute
	Affected assets: Forested area within natural protected areas		Map of protected areas under national legislation and in NATURA2000 (EEA)
	Affected population: Forested area close to urban areas		Urban Atlas (EEA)

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ADAPTIVE CAPACITY INDICATORS (non hazard-specific)			
Category	**Indicator**	**Frame conditions**	**Source**
Awareness	Education: Percentage aged 25-64 with tertiary education	(%, 2015, NUTS II)	Eurostat
	Internet: Percentage of 16-74 year-olds who use the internet at least once per week	(%, 2016, NUTS II)	Eurostat
	Adaptation platform: Existence of a national online climate change and adaptation web portal	(2017, national)	Climate-ADAPT
	Public climate change perceptions: Seriousness of climate change as a problem; relative importance of climate change as a problem	(2015, national)	Eurobarometer
	Government awareness: National willingness to develop policies and take adaptation action	(2014, national)	EEA self-assessment survey of the climate adaptation policy process
Hazard-specific	Wildfires: Proportion of country burnt by wildfires	(%, 2011-2015, national)	European Forest Fire Information System (ha burnt); Eurostat (country size)
	River floods: Number of European past floods per 10,000 km^2	(2006-2015, national)	River floods: EEA; Country area: Eurostat, World Bank Country Profiles
	Coastal floods: Number of storm surges	(1991-2016, national)	e-surge project data
	Wind storms: Insurance damages from major wind storms	(1988-2013, national)	European Wind Storm catalogue
	Droughts: Number of droughts	(1991-2010, country groups)	Spinioni et al (2013)
	Urban Flash Floods: Number of Flash floods	(2006-2016, NUTS II)	EM-DAT International Disaster Database
Ability	Scientists/engineers: Percentage of scientists and engineers in population	(%, 2015, NUTS II)	Eurostat
	R&D expenditure: Research and development expenditure per capita	(€ per cap, 2014, national)	Eurostat
Action	National Adaptation Policy: Status of National Adaptation Strategy	(2017, national)	Climate-ADAPT
	National Adaptation Policy: Status of Action Plans	(2017, national)	Climate-ADAPT
	National Adaptation Policy: Status of Impacts, vulnerability and adaptation assessments	(2017, national)	Climate-ADAPT
	National Adaptation Policy: Level at which risk and vulnerability assessments are available	(2014, national)	EEA Self-assessment survey of the adaptation policy process

National Adaptation Policy: Assessment of national level vertical integration mechanisms	(2014, national)	EEA Self-assessment survey of the adaptation policy process
National Adaptation Policy: Assessment of national horizontal integration mechanisms	(2014, national)	EEA Self-assessment survey of the adaptation policy process
National Adaptation Policy: Prioritisation of adaptation options implemented	(2014, national)	EEA Self-assessment survey of the adaptation policy process
National Adaptation Policy: Number of stakeholder groups involved in development, implementation, and monitoring & evaluation phase of national adaptation strategy	(2014, national)	EEA Self-assessment survey of the adaptation policy process
Government effectiveness: World Economic Forum Global Competitiveness (Basic Requirements)	(2016, national)	World Economic Forum
Economic resources: GDP per capita	(Euro, 2013, NUTS II)	Eurostat
Funding possibilities: Planned ESIF funding related to Climate adaptation and risk prevention	(Euro, 2014-2020, national)	EU Commission
Adaptation measures: Number of Case studies in Climate-ADAPT platform	(2016, national)	Climate-ADAPT

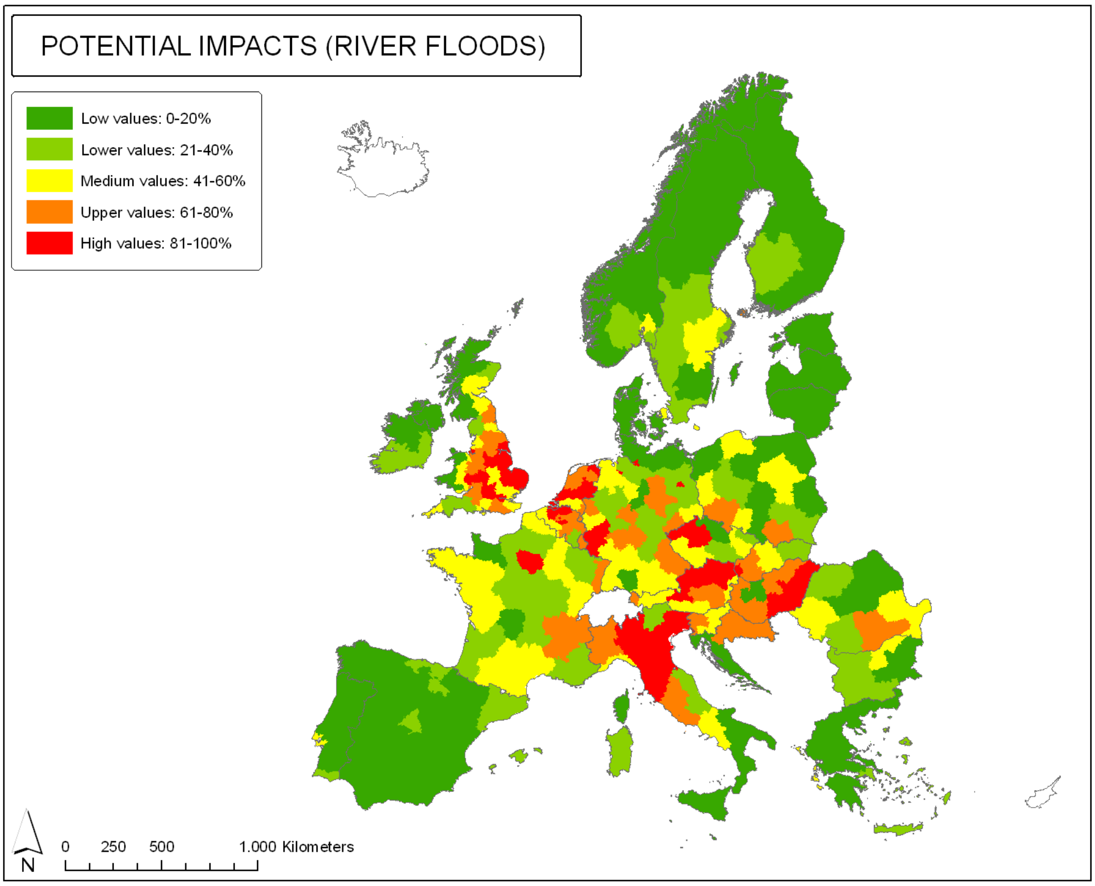
4. OUTCOMES OF THE MARKET SCOPING EXERCISE

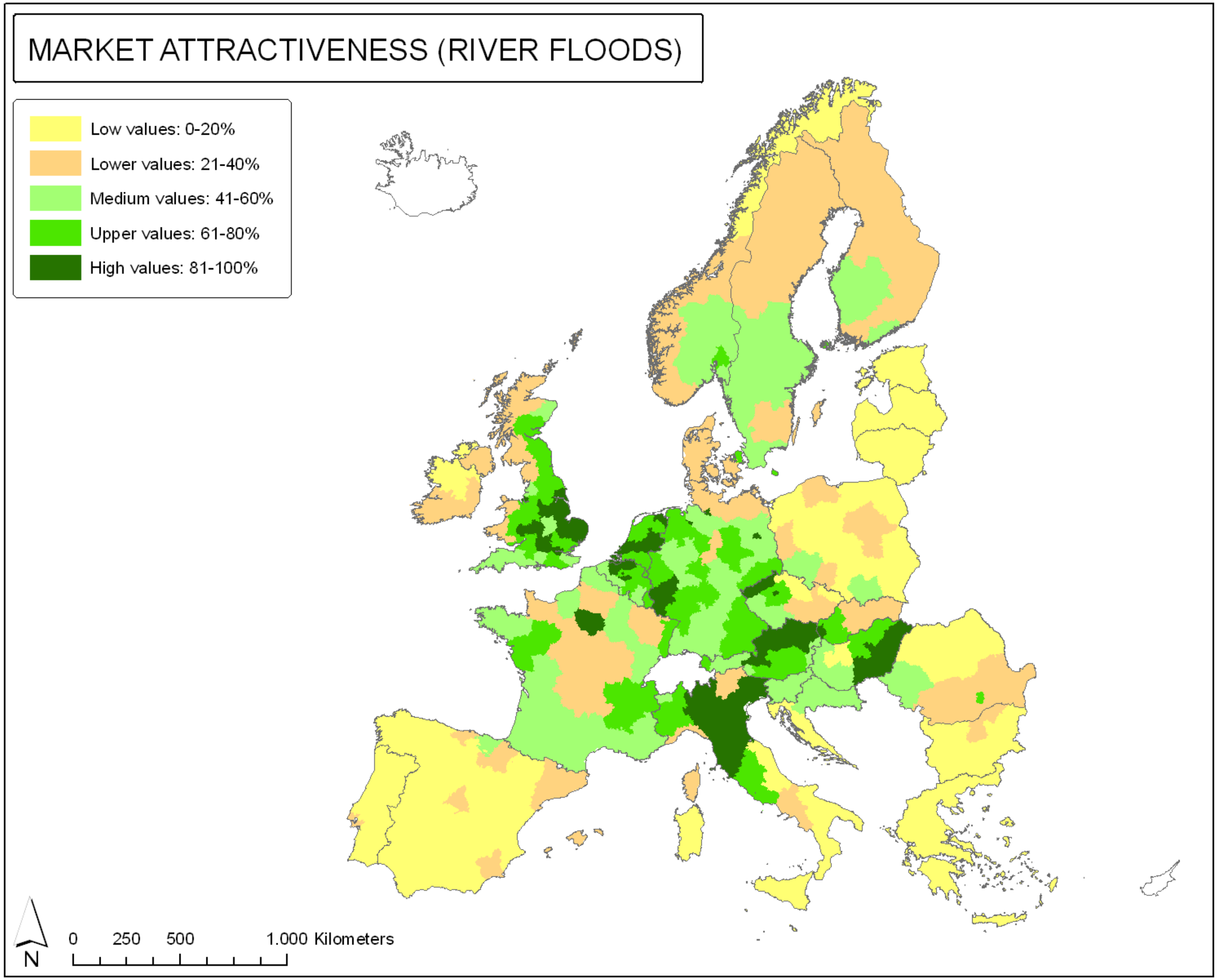
4.1. Presentation of results

The final market attractiveness maps are separately provided for each hazard. This section contains a brief description of these final maps and includes the maps for impact, adaptive capacity and market attractiveness.

4.1.1. River floods

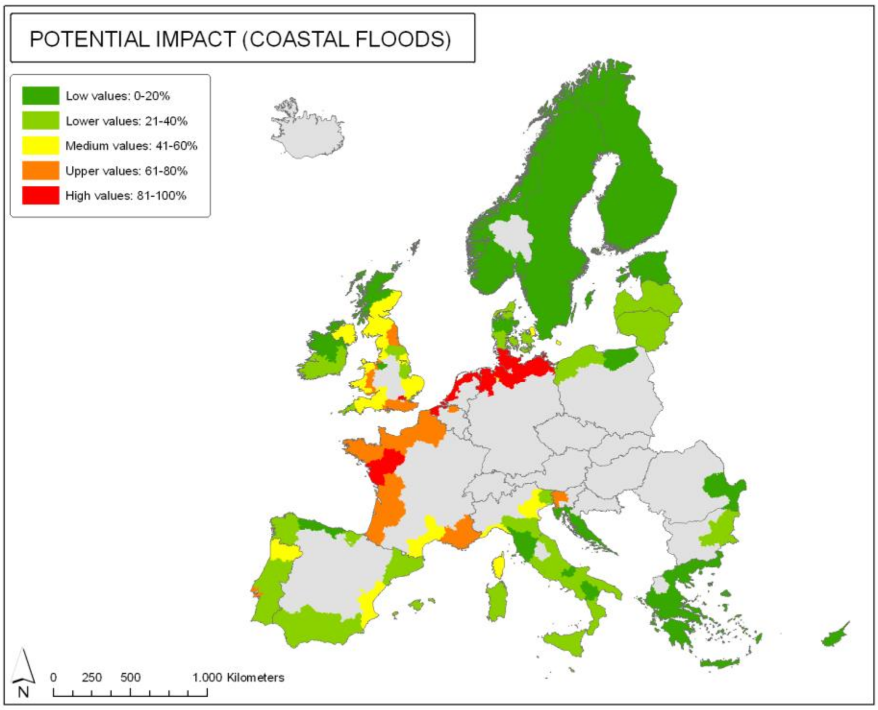
The results do not show a very clear pattern, although Northern Italy and Central Europe are the areas with better potential. Also, the Paris region and South-East England are areas highlighted in terms of market opportunities. The results do not include Switzerland, Iceland and Cyprus.

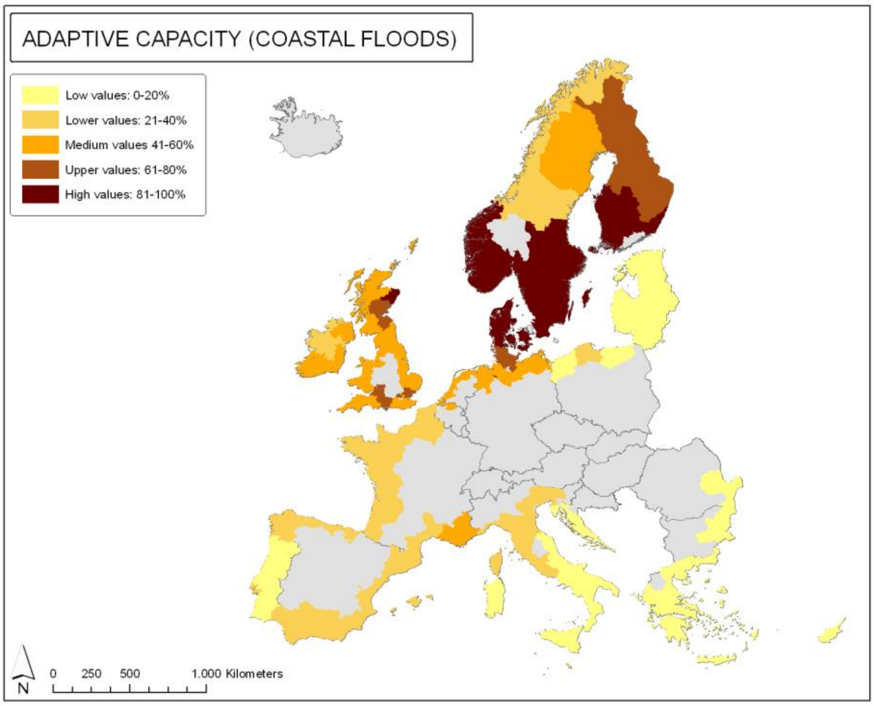


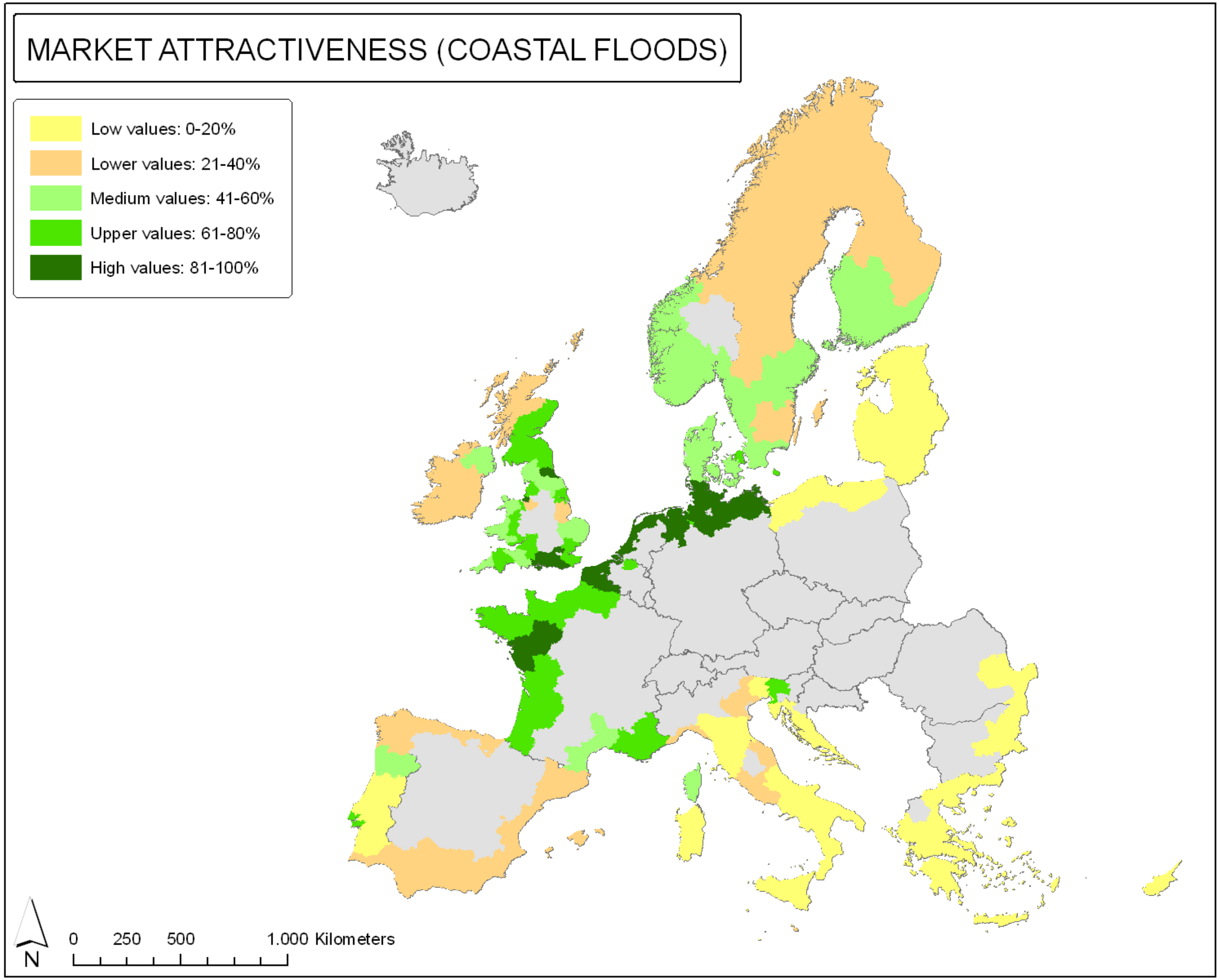

MARKET ATTRACTIVENESS (RIVER FLOODS)
Low values: 0-20%
Lower values: 21-40%
Medium values: 41-60%
Upper values: 61-80%
High values: 81-100%
N
0 250 500 1.000 Kilometers

4.1.2. Coastal floods

The coastal areas of Belgium, the Netherlands and Germany score the highest in terms of market attractiveness, as well as areas in France and England close to La Mancha channel. The Atlantic coast of France also is detected as an interesting area.

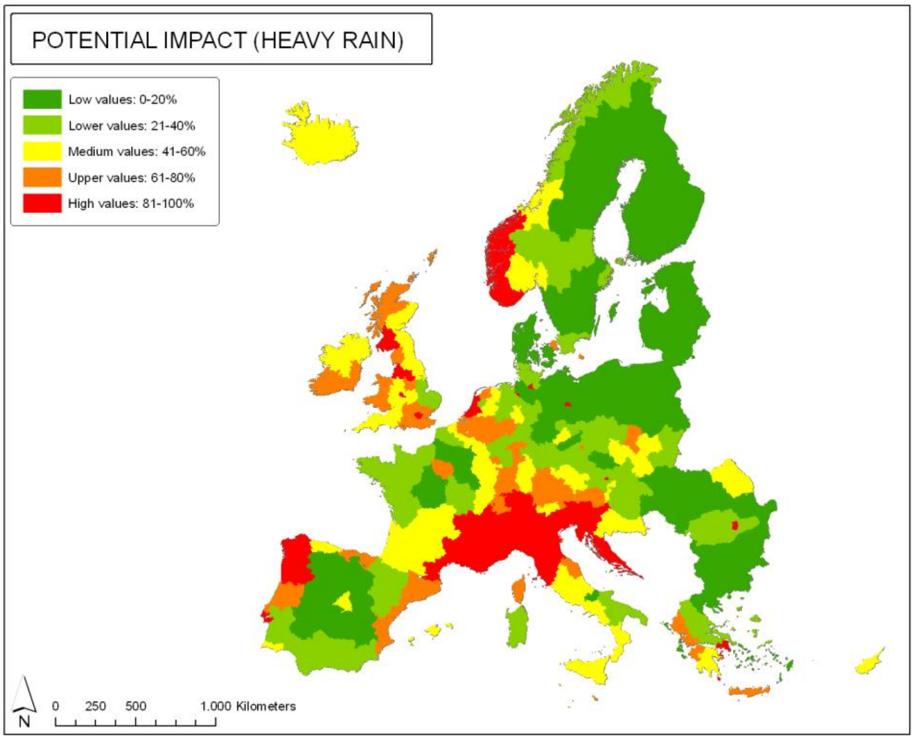


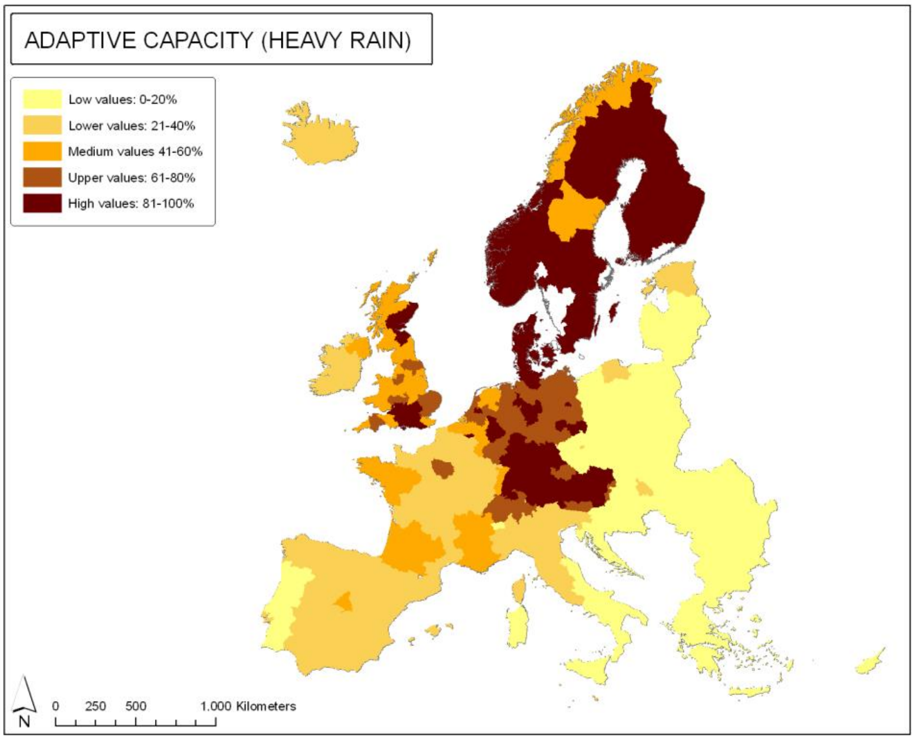


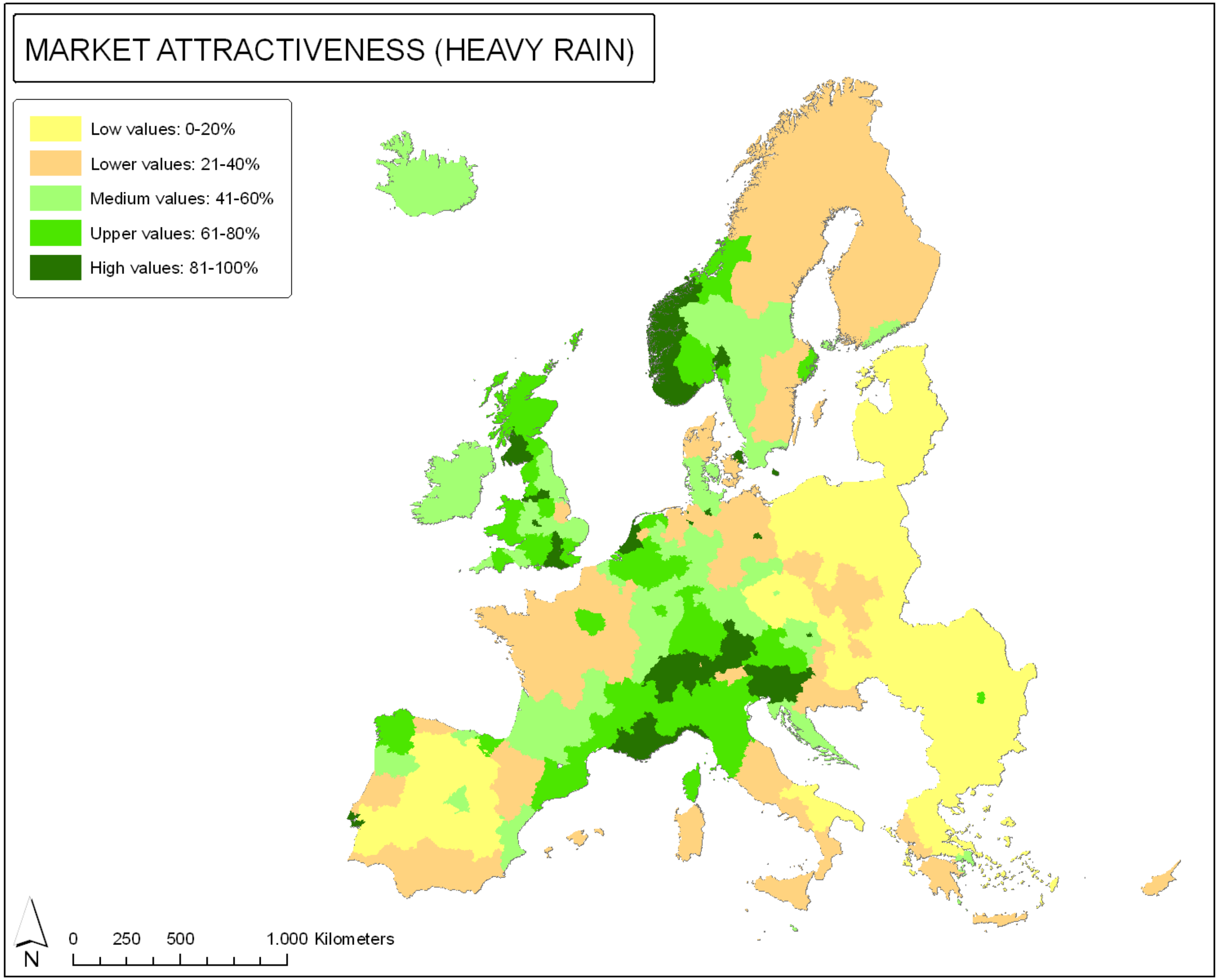

MARKET ATTRACTIVENESS (COASTAL FLOODS)
Low values: 0-20%
Lower values: 21-40%
Medium values: 41-60%
Upper values: 61-80%
High values: 81-100%
N
0
250
500
1.000 Kilometers

4.1.3. Heavy precipitation

The most attractive areas are dispersed across Europe, including Switzerland and Slovenia, as well as regions in England, South of France, Austria, the coast of Norway or the Netherlands. The Lisbon area is also included in this group.

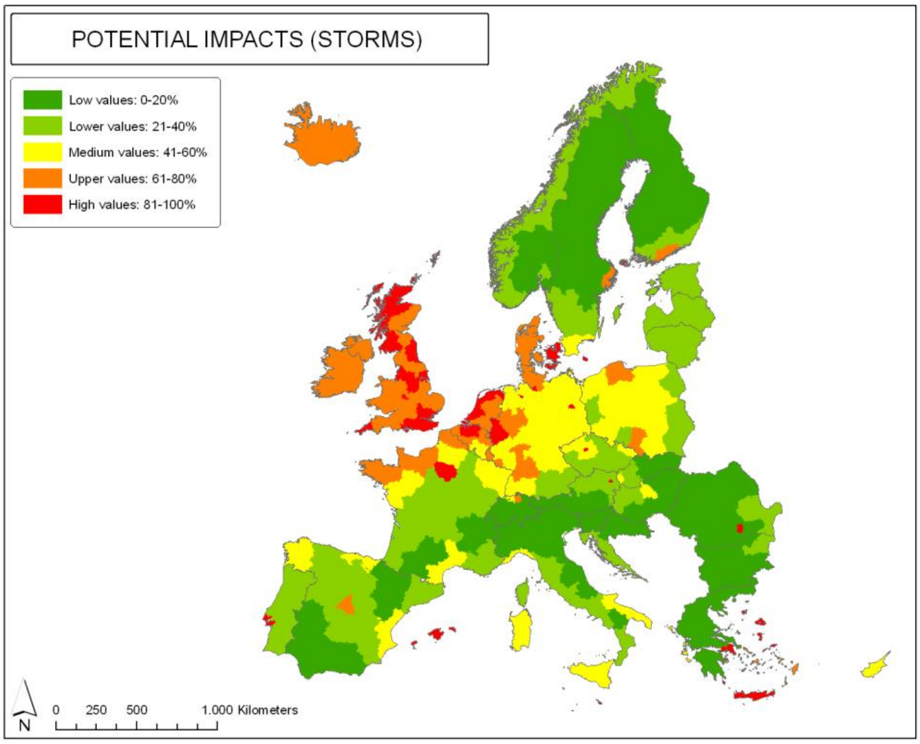


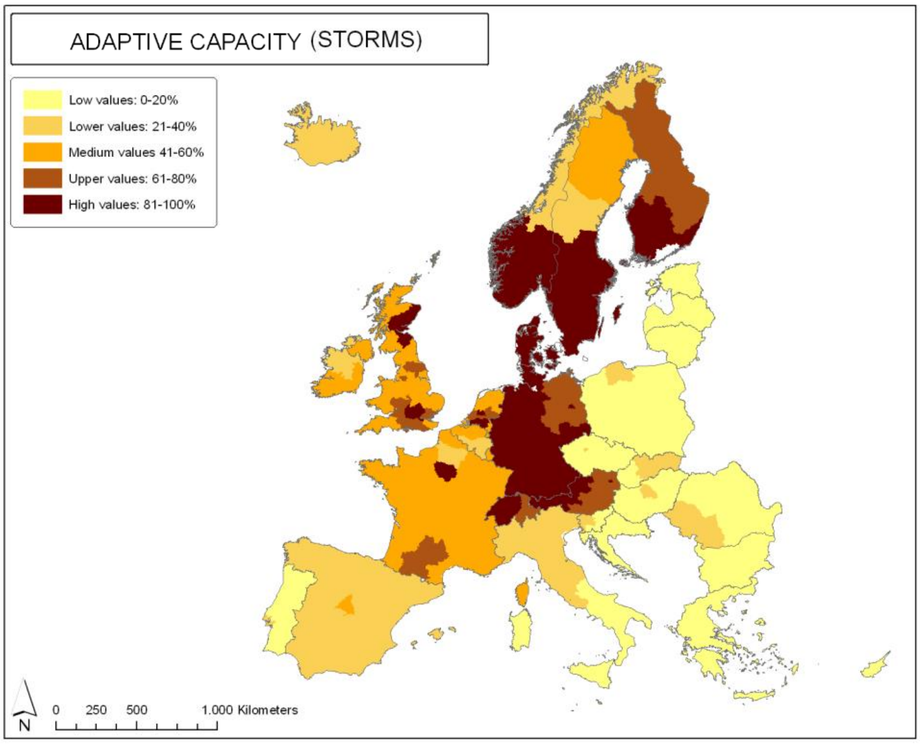


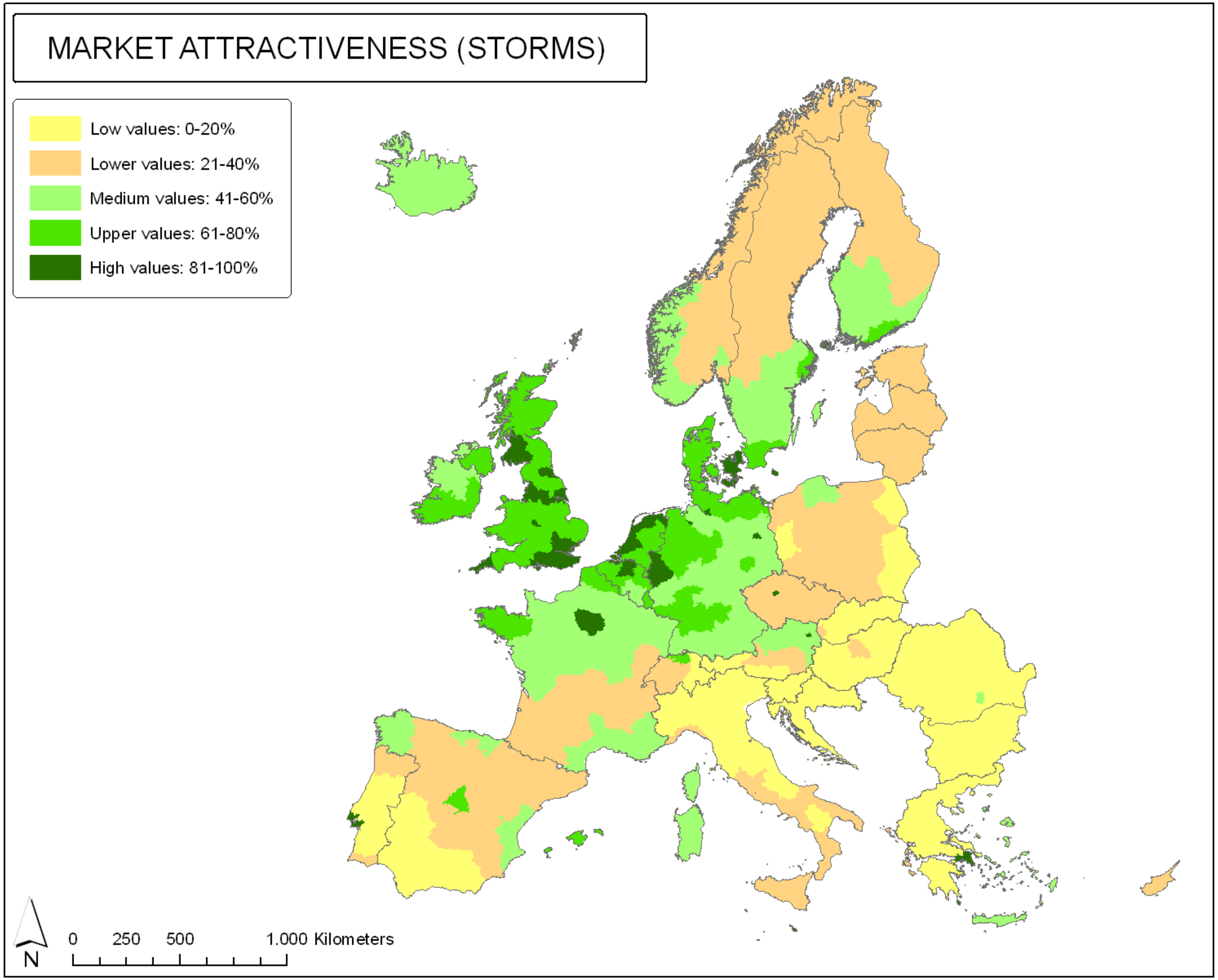

MARKET ATTRACTIVENESS (HEAVY RAIN)
Low values: 0-20%
Lower values: 21-40%
Medium values: 41-60%
Upper values: 61-80%
High values: 81-100%
N
0 250 500 1.000 Kilometers

4.1.4. Wind storms

The analysis identifies some large urban areas as the most attractive for innovations dealing with this hazard: i.e. London, coast of Netherlands, Paris, Lisbon, Athens, Copenhagen, etc.

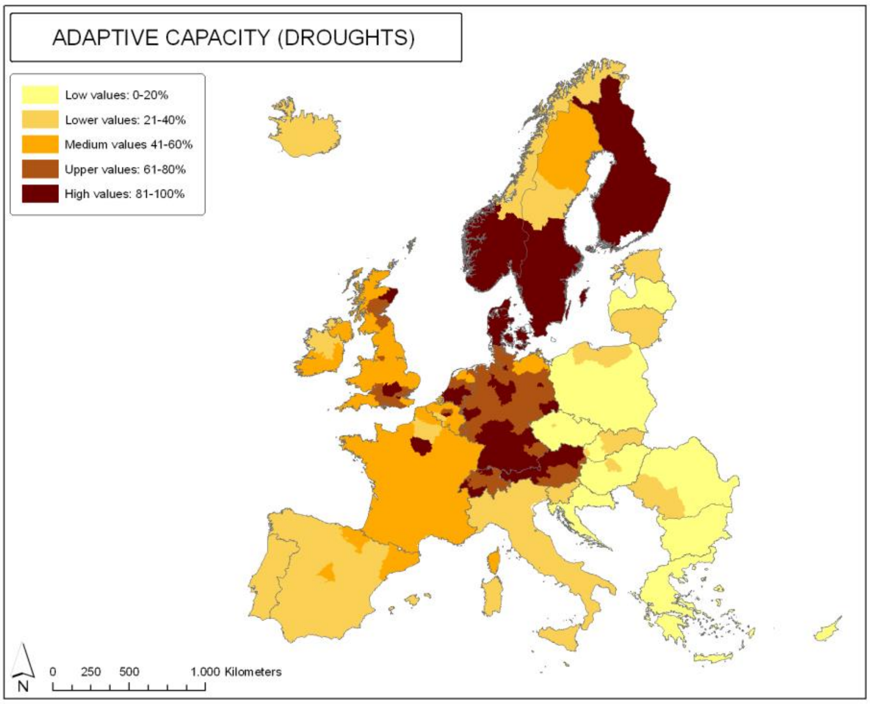


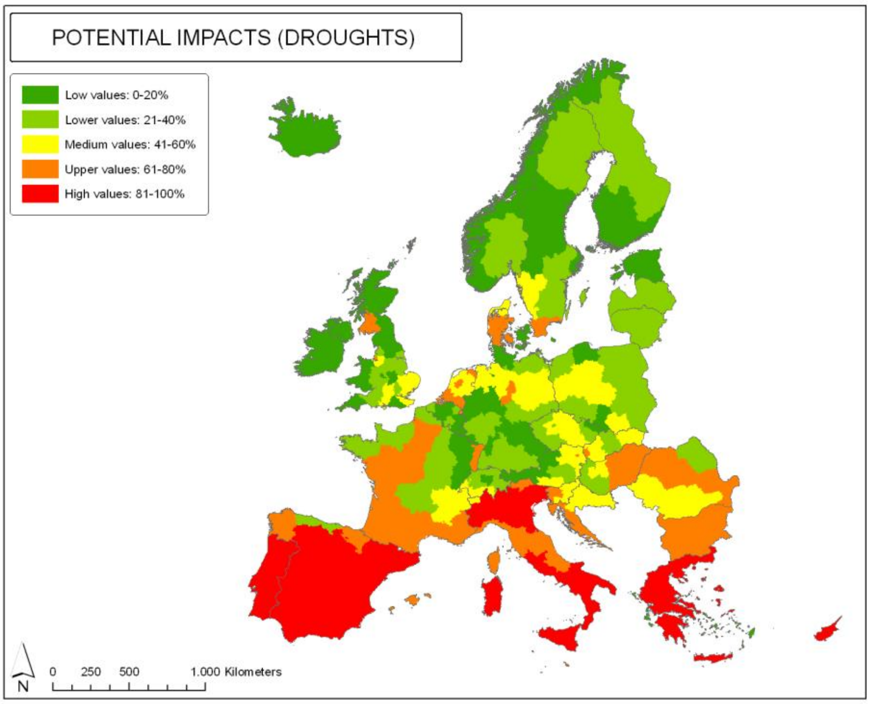



MARKET ATTRACTIVENESS (STORMS)
Low values: 0-20%
Lower values: 21-40%
Medium values: 41-60%
Upper values: 61-80%
High values: 81-100%
N
0 250 500 1.000 Kilometers

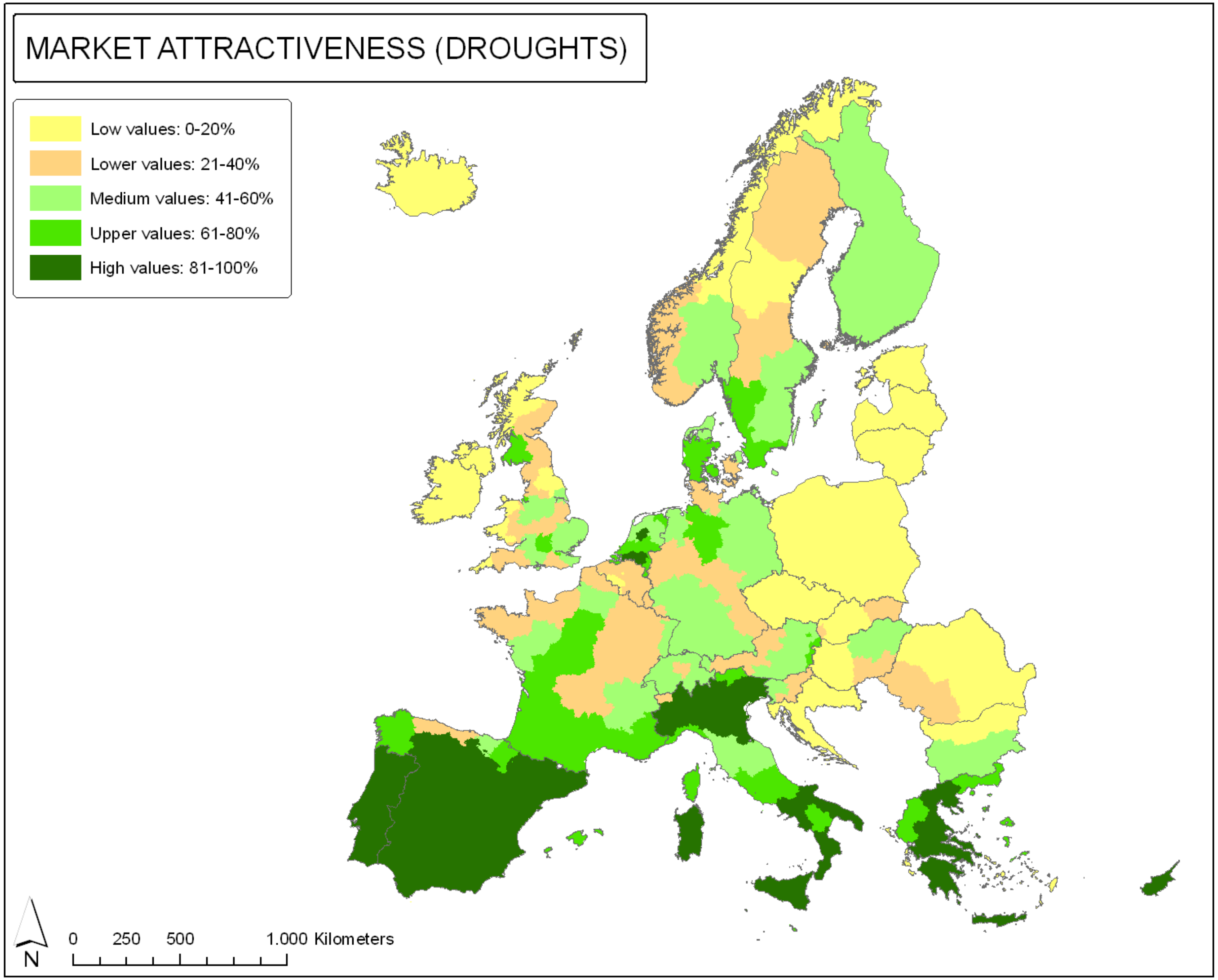
4.1.5. Droughts

The map highlights the Southern Mediterranean area as the main target for innovations dealing with water management in agriculture. Also, the North of Italy, i.e. the Po river basin and some areas in the Netherlands with high added-value production get the top score.





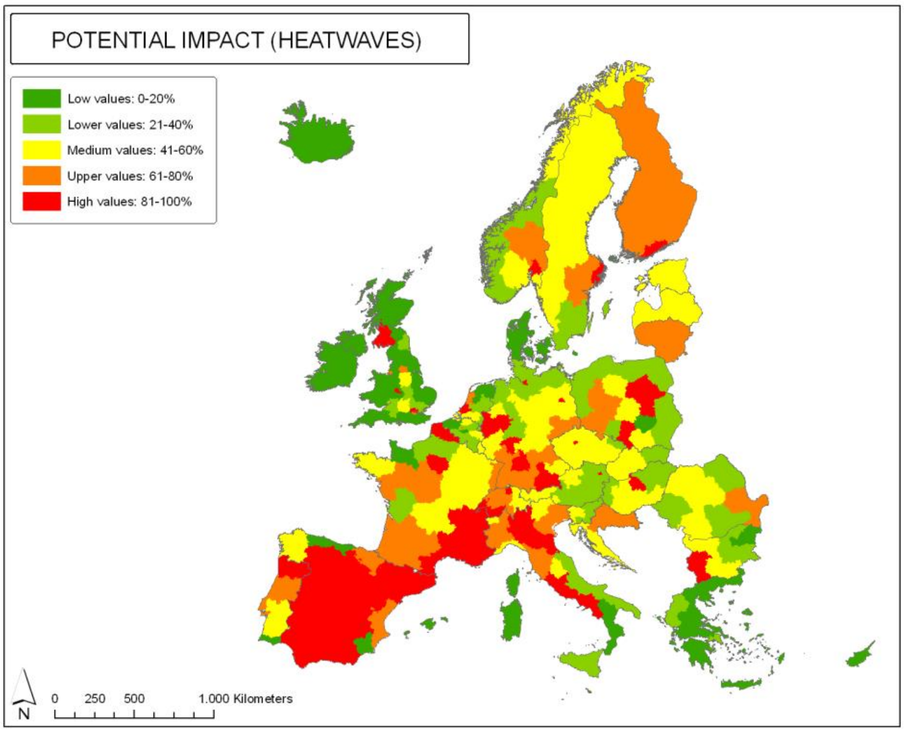
BRIGAID

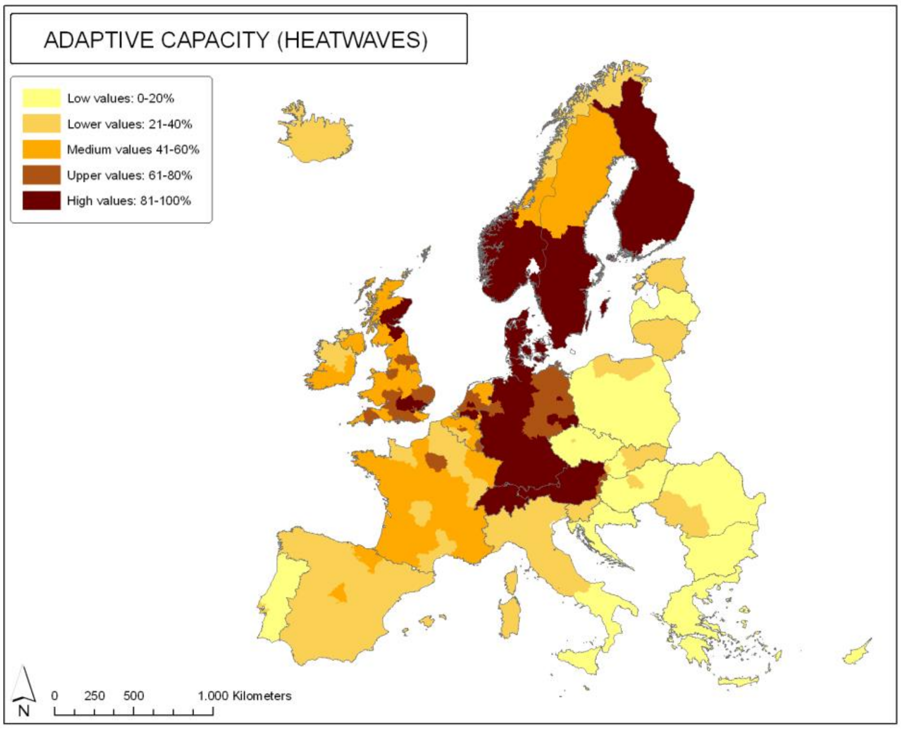


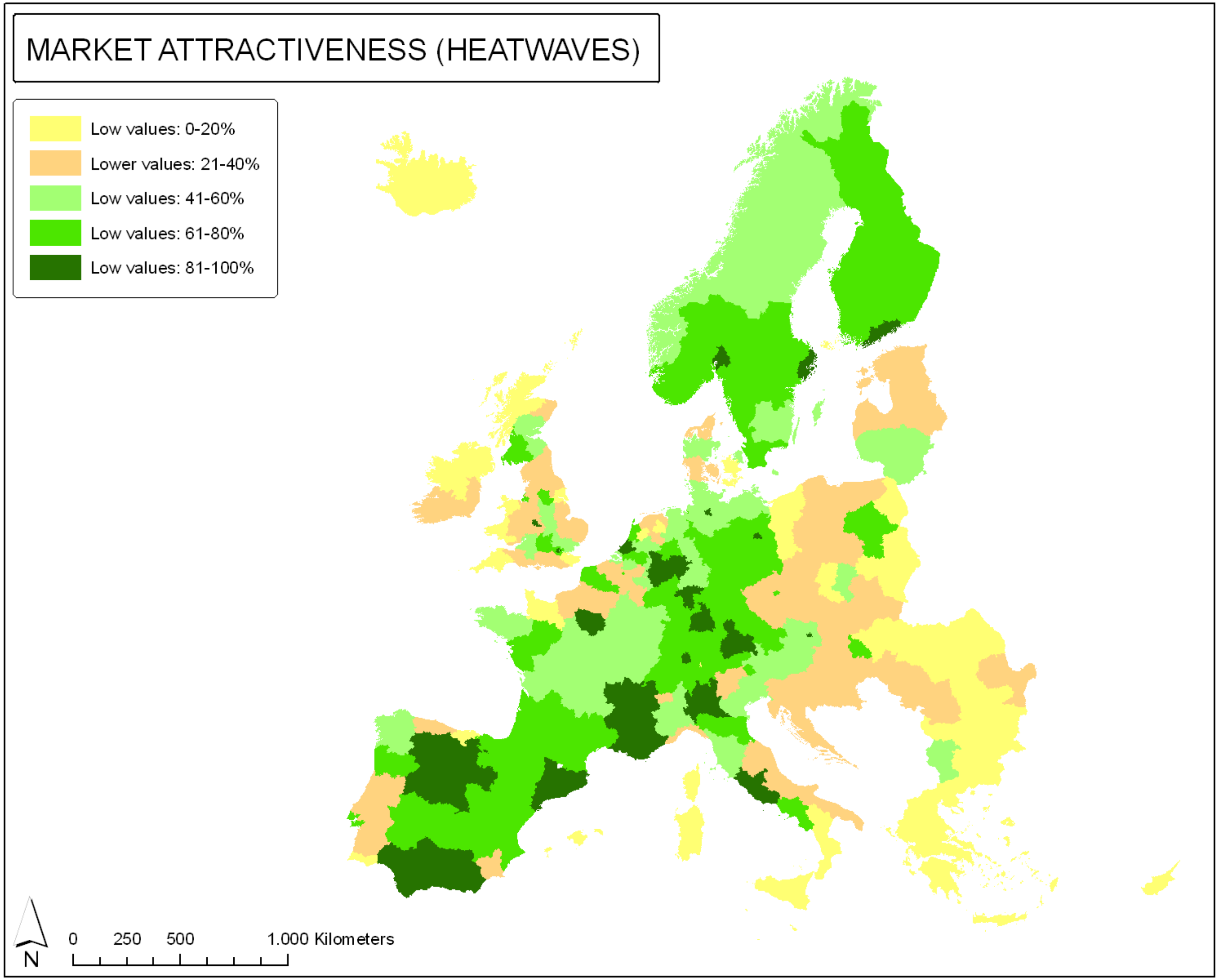
MARKET ATTRACTIVENESS (DROUGHTS)
Low values: 0-20%
Lower values: 21-40%
Medium values: 41-60%
Upper values: 61-80%
High values: 81-100%
N
0
250
500
1.000 Kilometers

4.1.6. Heatwaves

There is not a clear regional pattern for the areas with highest market attractiveness scores. In general, United Kingdom and Eastern Europe are the least affected areas while regions more densely populated in Italy and Spain, and Central and Northern Europe get the top values.

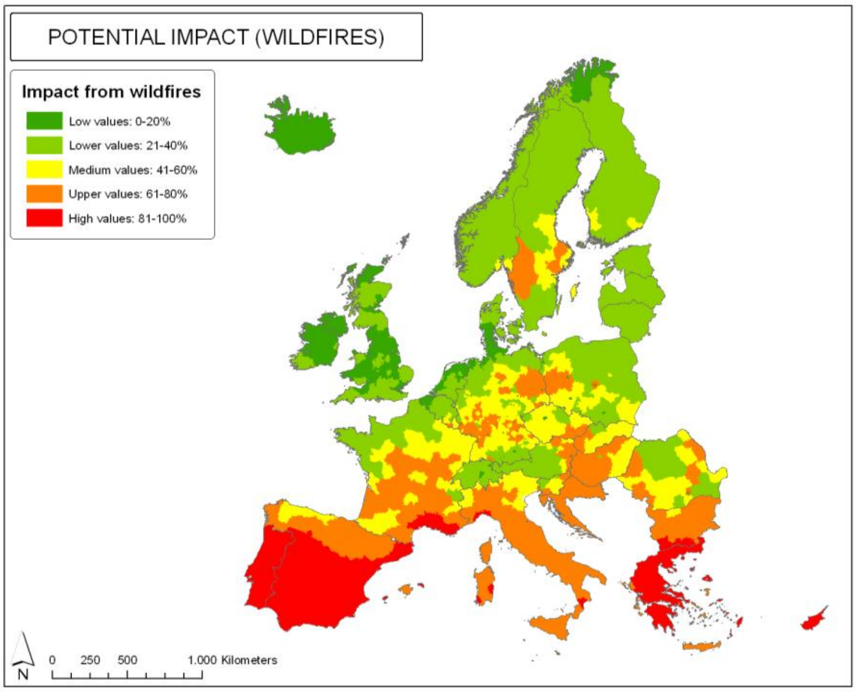


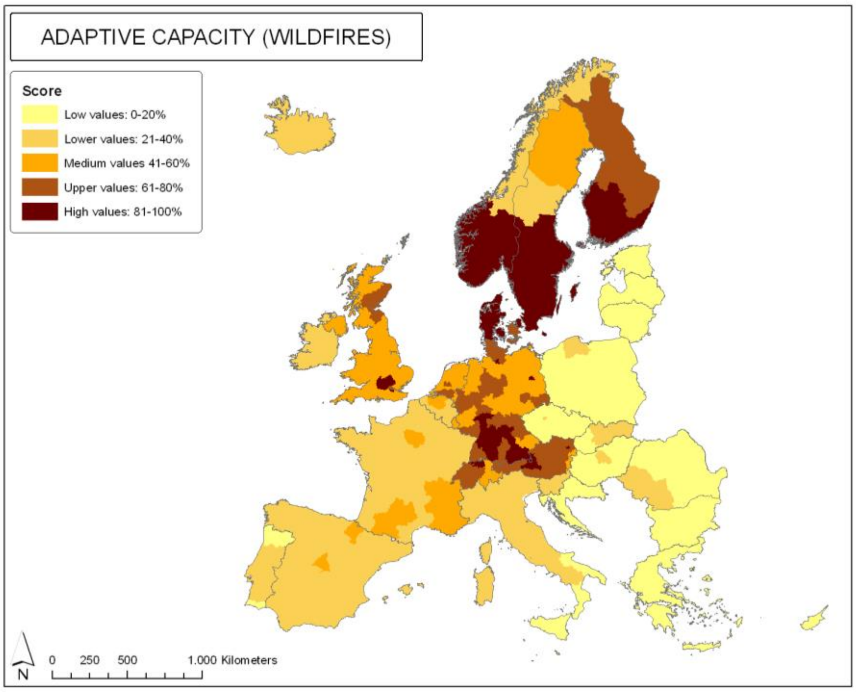


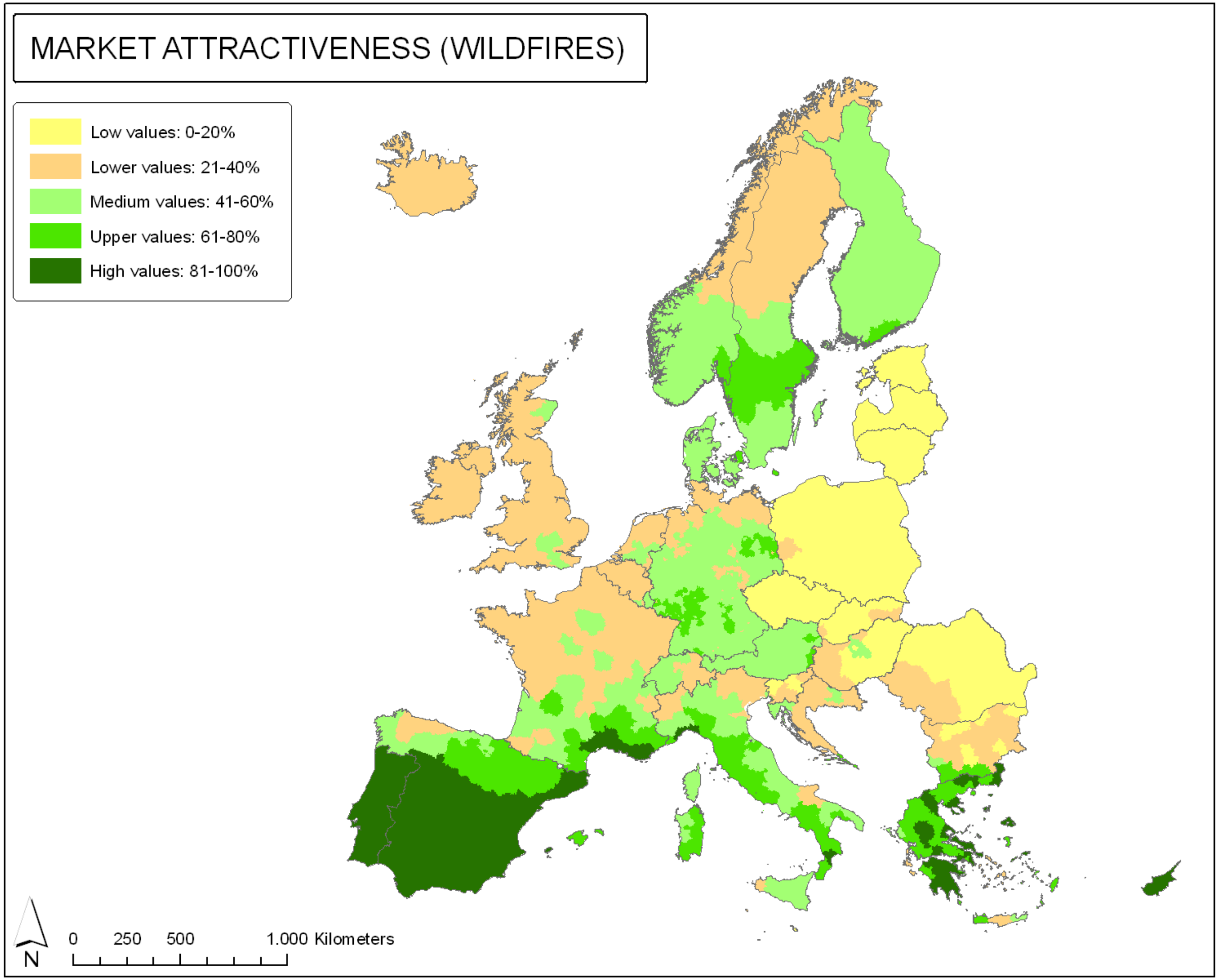

MARKET ATTRACTIVENESS (HEATWAVES)
Low values: 0-20%
Lower values: 21-40%
Low values: 41-60%
Low values: 61-80%
Low values: 81-100%
N
0 250 500 1.000 Kilometers

4.1.7. Wildfires

The results show a higher market attractiveness in Southern countries, in particular Spain and Portugal. Also areas in Greece, Southern France and Southern Italy are within the most interesting areas. These correspond very well with the regions currently most affected by wildfires. Some areas in Germany and Sweden are the best examples of areas with high adaptive capacity where current wildfire hazard is not relevant although it is expected to increase, thus creating new market opportunities.






MARKET ATTRACTIVENESS (WILDFIRES)
Low values: 0-20%
Lower values: 21-40%
Medium values: 41-60%
Upper values: 61-80%
High values: 81-100%
N
0
250
500
1.000 Kilometers

4.2. Exploitation of the final outcomes

In terms of definition of the final outcomes, it has been decided to prepare the information in formats that can be easily managed by the final users, e.g. innovators applying the MAF+ framework, with aim of performing analyses tailored to their specific requirements and the characteristics of their innovations.

Thus, in addition to the set of final maps included in this report which describe variations in market attractiveness for innovations dealing with the different hazards, the outcomes of the work undertaken will be delivered to the innovators under the format of a geodatabase -also transformed into a spreadsheet format. These products contain all the information generated in the market scoping and provides a key advantage: this information can be visualised or consulted at different levels of aggregation, from the integrated market attractiveness score to the disaggregated data for each sub-criterion. This approach aims to drive Open Innovation[15] and allow the users to customise the market scoping results accordingly to their market strategies and needs.

These results will be shared with all the innovators involved in BRIGAID. There are several reasons why we use this open approach for the production and delivery of the final outcomes:

- We were not able to establish a standard and universal weighting of the relative importance of the different criteria for the definition of market attractiveness. In many cases, the aggregation of these criteria into a sole metric measuring the market attractiveness can reduce the quality of the information provided. This may happen when an innovation is addressing one of the specific issues considered within the framework, and thus the innovator may not be interested in aggregating this information with other criteria.
- The innovator has usually a much better knowledge specific criteria that should be considered for the identification of most relevant markets for the innovation.
- This approach facilitates the integration of the results with other relevant data and information, e.g. risk perception studies, legislation, etc… that is probably available at a local level and can act as a driver or barrier for the adoption of the innovation.
- The market scoping exercise has been designed to provide an analysis at a European scale to spot potential market opportunities. However, it does not provide a detailed analysis below the NUTS2 scale. The innovator could choose to deepen the market scoping by performing an additional research and looking into more detail in those areas previously selected because of high potential market opportunities. Some of the criteria of our analysis can be improved by using higher resolution data locally available in some European areas, e.g. estimation of exposed elements, while other criteria should probably not change too much. Thus, the selected approach facilitates integration of more detailed data into the current analysis.
- Some of the criteria considered have a dynamic component. Whenever possible, we have used statistics and indicators that are regularly updated by official institutions. Therefore, the method selected for presenting the results should facilitate their update. This provides another advantage over static maps.

15 Open Innovation is an approach to innovation that is seen by the EU as key for translating the results of its scientific research into competitive edge. This user-centric approach promotes and exploits co-creation, collaboration and an open transfer of knowledge (European Commission 2016).

The outcomes can be easily integrated into user-friendly tools that ease the users to obtain specific answers to tailored questions. The data are structured in a way that basic questions are straightforwardly responded, e.g. which are the regions with higher market attractiveness for innovations dealing with a specific hazard, while more complex questions can also be considered, thus taking advantage of all the different available information.

For each hazard, a final map depicting market attractiveness has been calculated. However, the geodatabase to be provided to innovators enables the creation of more complete maps with more comprehensive or specific information.

As example, the figure 19 shows a map related to river floods that integrates information on the differences in both the expected potential impacts from this hazard and the estimated adaptive capacity. Depending on the characteristics of the innovation (i.e. software/infrastructure; grey/green infrastructure; lifetime; pricing;…), the user may be more interested in one of the two criteria considered, or even in considering only some of the available sub-criteria. In addition, the colour legend, and the percentile thresholds selected for the classification of categories can be easily modified and adapted.

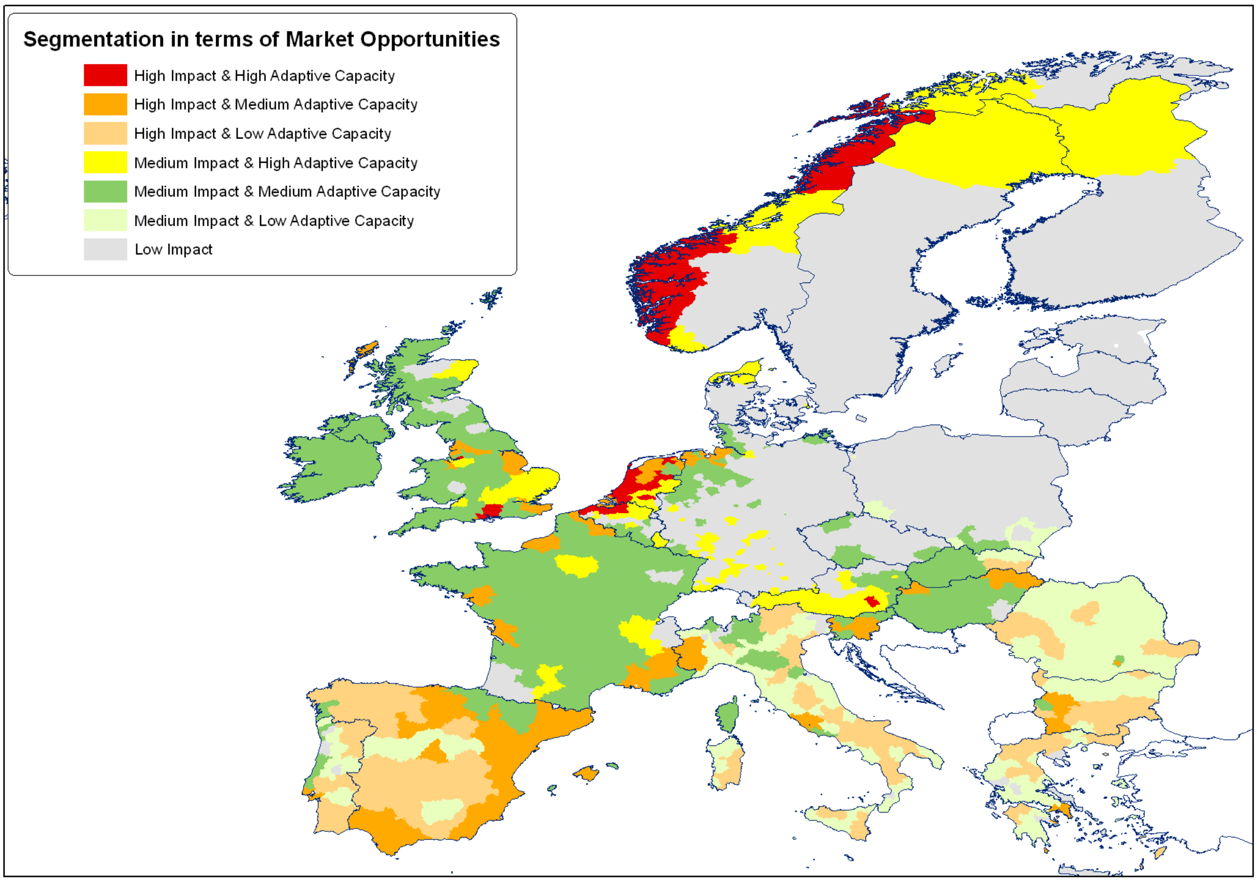


Figure 19. *Example of an alternative to display the results for one hazard*

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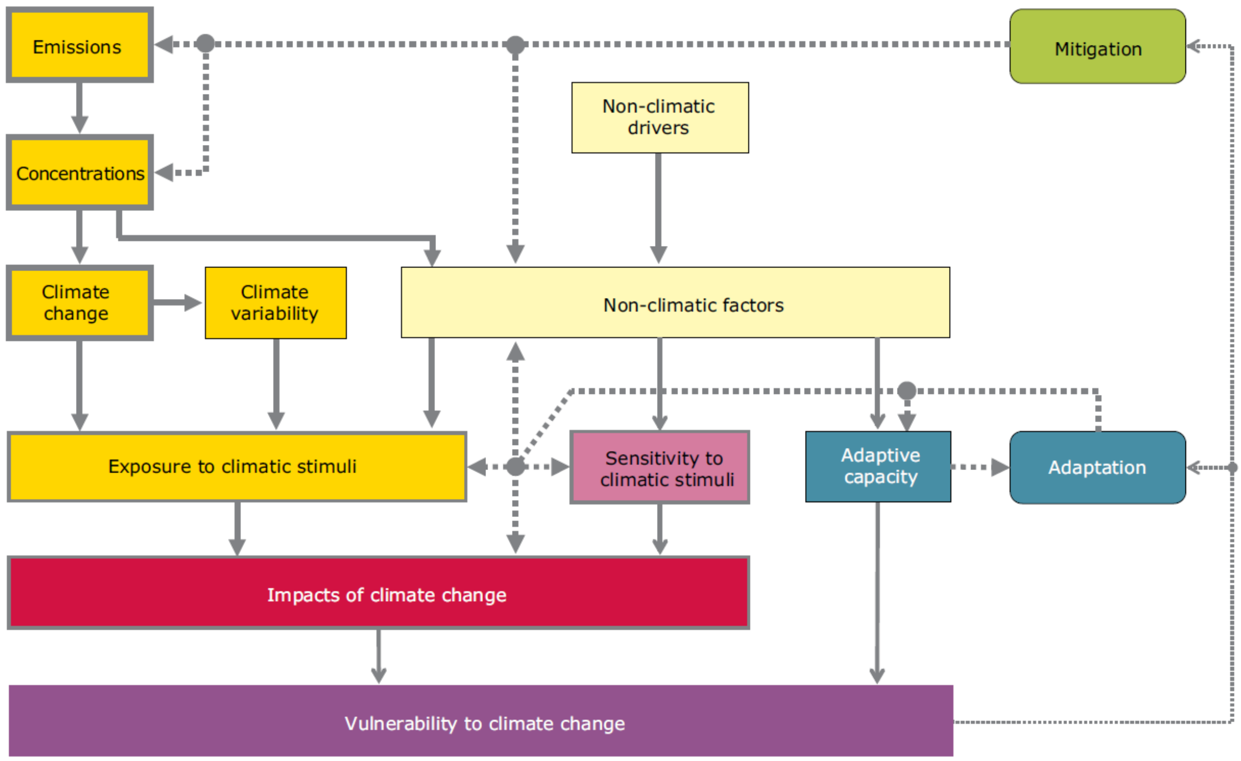
List of abbreviations

CCA	Climate Change Adaptation
CDD	Consecutive Dry Days
DoA	Description of Actions document, part of the BRIGAID Grant Agreement.
DRR	Disaster Risk Reduction
EC	European Commission
EEA	European Environment Agency
EFTA	European Free Trade Agreement
EU	European Union
FAO	Food and Agriculture Organization (United Nations)
FFDI	Forest Fire Danger Index
GDP	Gross Domestic Product
GVA	Gross Value Added
IPCC	Intergovernmental Panel on Climate Change
LAU	Local Administrative Unit
MAF+	Market Analysis Framework. (It is a specific BRIGAID tool).
NUTS	Nomenclature of Territorial units for Statistics
OECD	Organisation for Economic Co-operation and Development
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention Climate Change
WMO	World Meteorological Organization
WP	Work Package

APPENDIX 1. ASSESSMENT FRAMEWORKS

This appendix shows the graphical components of the vulnerability frameworks mentioned within section 2. For each of them, the definitions of the elements of these frameworks are provided:

a) Vulnerability Assessment framework



Source: Adapted from Füssel and Klein, 2006.

Figure 20. *Vulnerability Assessment Framework. Extracted from (EEA, 2012), based on (Füssel and Klein, 2006)*

A definition of the terms used in this framework is provided by (Greiving et al, 2011) who applied this Vulnerability Assessment framework in the ESPON-Climate project.

Exposure: *The nature and degree to which a system is exposed to significant climatic variations.*

Sensitivity: *The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. [. . .] The effect may be direct [. . .] or indirect [. . .]*

Impacts: *Consequences of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential and residual impacts. [. . .]*

Adaptive capacity: *The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.*

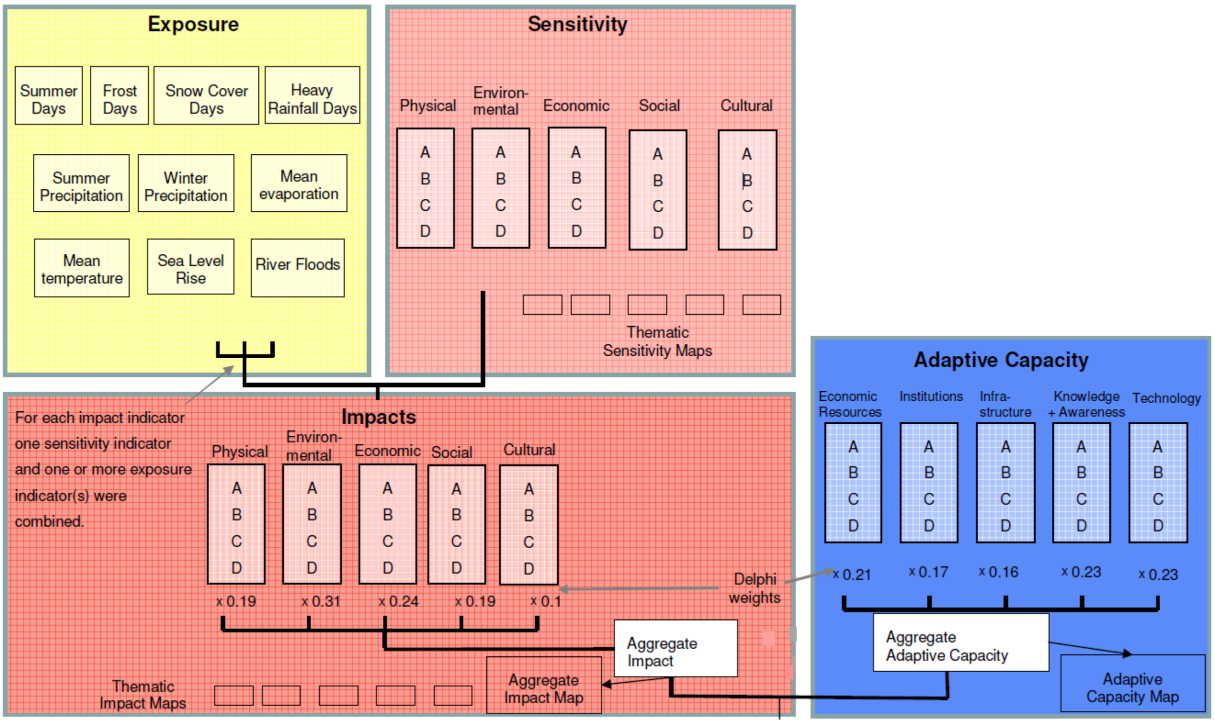
Vulnerability: *The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of* *the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.*

In addition, some descriptive information on the ESPON initiative is provided.

Box 2. ESPON Climate: Climate Change and Territorial Effects on Regions and Local Economies (extracted from ESPON, 2011)

The ESPON Climate project aims to provide a typology of regions based on climate change vulnerability. Based on the findings of the project it is possible to already outline climate change based implications for the regions referenced by these typologies. These implications point towards more in-depth, quantitative research that will systematically compare the average impact, adaptive capacity and vulnerability scores of the various types of regions.
Territorially differentiated adaptation strategies call for an evidence basis. This is what the ESPON Climate project is mainly about; a pan-European vulnerability assessment as a basis for identifying regional typologies of climate change exposure, sensitivity, impact and vulnerability.
The results of ESPON Climate have to be seen as a possible vulnerability scenario which shows what Europe's future in the wake of climate change may look like, and not as a clear-cut forecast. Nonetheless, it gives some evidence-based hints as to what adaptation should be about in view of the identified regional typologies of climate change.
Climate changes differ between regions, i.e. each region has a different *exposure* to climate change. In addition, each region has distinct physical, environmental, social, cultural and economic characteristics that result in different *sensitivities* to climate change. Together exposure and sensitivity determine the possible *impact* that climatic changes may have on a region. However, a region might in the long run be able to adjust, e.g. by increasing its dikes. This *adaptive capacity* enhances or counteracts the climate change impacts and thus leads to a region's overall *vulnerability* to climate change.

GRAPHICAL OVERVIEW OF THE METHODOLOGY



b) Risk-Hazard assessment framework

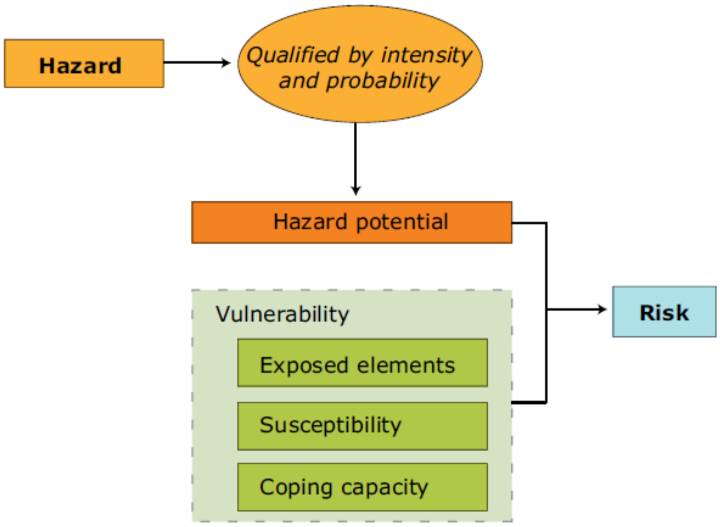


Figure 21. *Risk-Hazard Framework. Extracted from (EEA, 2012), based on (UNDHA, 1993)*

The Risk-Hazard framework is applied based on the definitions of terms provided by (IPCC, 2014).

Hazard*: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts.*

Adaptive (or coping) capacity*: The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.*

Exposed elements*: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.*

Impacts: *Impacts (consequences, outcomes) Effects on natural and human systems. In this report, the term impacts is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. […].*

Risk: *The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability or likelihood of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. In this report, the term risk is often used to refer to the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, ecosystems and species, economic, social and cultural assets, services (including environmental services) and infrastructure.*

Vulnerability: *The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.*

APPENDIX 2. DESCRIPTION OF THE INDICATORS

This appendix provides more detailed information on the indicators used for the assessment of market attractiveness of European regions in the context of BRIGAID project.

A) HAZARD INDICATORS

The description of these indicators has been extracted from the document 'Pan-European climate change indicators and loading conditions' (see Appendix 3 to this deliverable). This document provides further detail on the selection criteria and calculation methods for this set of indicators.

River floods

Proposed indicator:

Extreme river water levels with a 100-year return period, relative to water levels with a 10-year return period under historical climate

Data sources:

The data used to calculate the indicators of river flood hazard were obtained from a publicly available dataset (Paprotny and Morales-Nápoles, 2016) produced in the FP7 project RAIN. The domain of the river flood calculation covers most of Europe.

Modelling of river floods consisted of two steps. Firstly, extreme river discharges with given return periods were calculated using a Bayesian Network-based hydrological model, under present and future climate. Secondly, selected river discharge scenarios were used to obtain water levels through a one-dimensional hydrodynamic model.

Limitations and uncertainty:

The analysis includes several sources of uncertainties. One is related with input data. River discharge scenarios were calculated using a statistical model, which is less accurate then river gauge measurements, and has limited accuracy in very small catchments (in the range of hundreds of km^2). The results do not include changes in land use (build-up areas, lakes, marshes), both in historical or future scenarios. Uncertainty is also related with DEM's vertical accuracy, which also omits most flood defences. Moreover, the elevation model does not include the bed or embankments of rivers.

Another source of uncertainty is the type of events analysed. As noted before, only rivers with catchments that have an area of at least 100 km^2 were included in the calculation, while flash floods and urban floods were also not analysed.

Last but not least, there is uncertainty related with future climate projections. The difference between RCP 4.5 and RCP 8.5 scenarios is sometimes very large. This alone illustrates the significant uncertainty related with climate change and the climate models, as the latter are known to have limited accuracy for precipitation, let alone extreme rainfall.

Results:

Regions with the highest average water levels are concentrated around large rivers, as outlines of Danube, Elbe, Loire, Po, Rhine or Vistula rivers could be clearly seen. Elevated values of the indicator could be found in more mountainous areas (Norway, Portugal, Spain, Switzerland).

It is projected that, in general, extreme river water levels will be higher in the future. An average 100-year surge at local or regional level will be about 10 cm higher in 2071–2100 compared to 1971–2000. In the upper quintile, a future 100-year water level will be about 80–90 cm above 10-year level in the historical scenario. However, the trends will vary enormously from one location to another. In about 30% (RCP 4.5) or 40% (RCP 8.5) of local units the hazard is actually projected to decrease. Negative trends will mostly occur in northern Europe due to substantially reduced snowfall, which in turn would cause less severe snowmelt. In most of other locations, including large parts central and southern Europe, more cases of extreme rainfall are expected, resulting in higher frequency of extreme river flow occurrences.

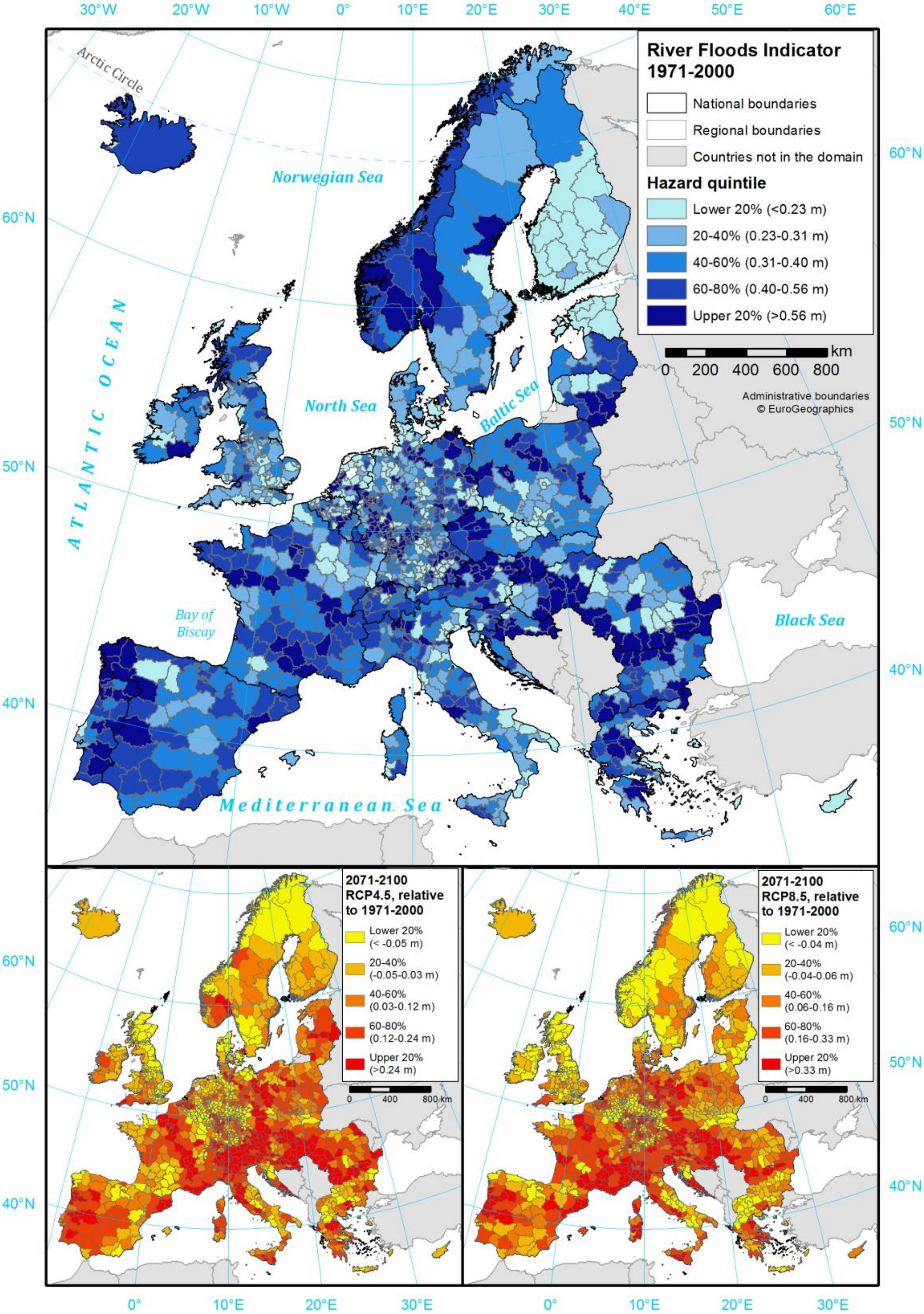


Figure 22. ***Quantiles of normalized river flood hazard indicator (100-year water level in a given scenario minus 10-year water level in the historical scenario) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios***

Coastal floods

Proposed indicator:

Extreme water levels of storm surges with a 100-year return period, relative to water levels with a 10-year return period under historical climate

The indicator has been prepared for 3 scenarios: historical climate (1971–2000) and future climate under two socio-economic development assumptions (2071–2100, RCP 4.5 and 8.5).

However, the baseline water level was not changed. The 10-year return period was chosen as an approximation of the lowest flood protection standards that can be found throughout Europe (see e.g. Scussolini et al. 2016). Meanwhile, the 100-year return period is very widely used in Europe as flood protection standards and scenario for flood hazard/risk mapping. A review of literature identified the use of this return period in e.g. Austria, Croatia, the Czech Republic, Finland, France, Germany, Hungary, Ireland, Italy, Poland, Switzerland and the United Kingdom. It is also the only return period explicitly mentioned in the EU's “Flood Directive” (European Union 2007).

Data sources

The impacts of the sea level rise on coastal floods was studied in few global and pan-european studies. At a European scale, storm surge heights of a 100-year return event were obtained from DIVA projections (Vafeidis et al. 2005; see also ESPON, 2011). These surge heights were, however, not obtained through a hydrodynamic model and their accuracy was never presented. Therefore, it was decide to elaborate the indicator using RAIN project and JRC data.

The data used to calculate the indicator of coastal flood hazard are obtained from a publicly available dataset (Paprotny and Morales Nápoles, 2016c) produced in the project RAIN.

Limitations and uncertainty:

The analysis includes several sources of uncertainties. One is related with input data. Storm surge heights are derived through a hydrodynamic model, which performance for individual stations is very diverse. For example, much lower accuracy was observed over the Mediterranean Sea, compared to North or Baltic seas. Due to the relative coarse resolution of the model (~12 km) the complicated shape of the coast of Norway, Finland or Greece couldn't be properly incorporated. Datasets on GIA and SLR have even coarser resolutions, causing relatively steep changes between many coastal segments.

Methodologically, several components that could locally influence surge heights are omitted, such as tide-surge interaction, the impact of sea level rise on tides or ground motion other than GIA. Those effects could be locally very significant as these are very local factors with a number of causes, and no large-scale datasets are available.

Finally, there is uncertainty related to future projections. Accuracy of storm surge projections is dependent on the accuracy of air pressure and wind speed/direction projections. The difference between RCP 4.5 and RCP 8.5 scenarios is sometimes very large, to the point that opposite trends are indicated. This alone illustrates the significant uncertainty related with climate change. Meanwhile, sea level rise is a combination of several climate-related factors, which are understood and quantified to a varying degree, especially below the scale of the whole globe. Existing estimates have a low spatial resolution and large uncertainty bounds.

Results:

Overall, the values of the indicator in the historical scenario (1971–2000) are rather low, and range from 7 to 94 cm at local level. In approx. 80% of local units the value of the indicator is below 40 cm. In *Figure 20*general, sharp geographic divisions are visible in the distribution of surge heights. In the Mediterranean or Black seas, surges are mostly no larger than half a metre, therefore the flood hazard indicator does not exceed 20 cm in most of southern European countries. Only in the northern part of the Adriatic Sea, surges could be larger, with Venice being one of the endangered locations in that area. Hazard increases moving northwards, with only small surges in the Portuguese or Spanish coasts. In the French coast, the hazard indicator rises from the middle quintile by the Bay of Biscay to the top quintile in the English (La Manche) Channel. Highest surge are observed in the southern coasts of the North Sea, i.e. in Belgium, Denmark, Germany, the Netherlands and the UK. Large surges are also present in the entire Baltic Sea, especially in its southern and eastern coasts, from Germany through Poland, Lithuania, Latvia, Estonia up to Finland. Meanwhile, hazard in the middle quintile or lower can be observed in Norway, Iceland or Ireland. Those patterns are the result of the distribution of paths of extra-tropical cyclones (ETCs). It is projected that, in general, storm surges will become more intense in the future. An average 100-year surge at local or regional level will be 30–50 cm higher in 2071–2100 compared to 1971–2000.

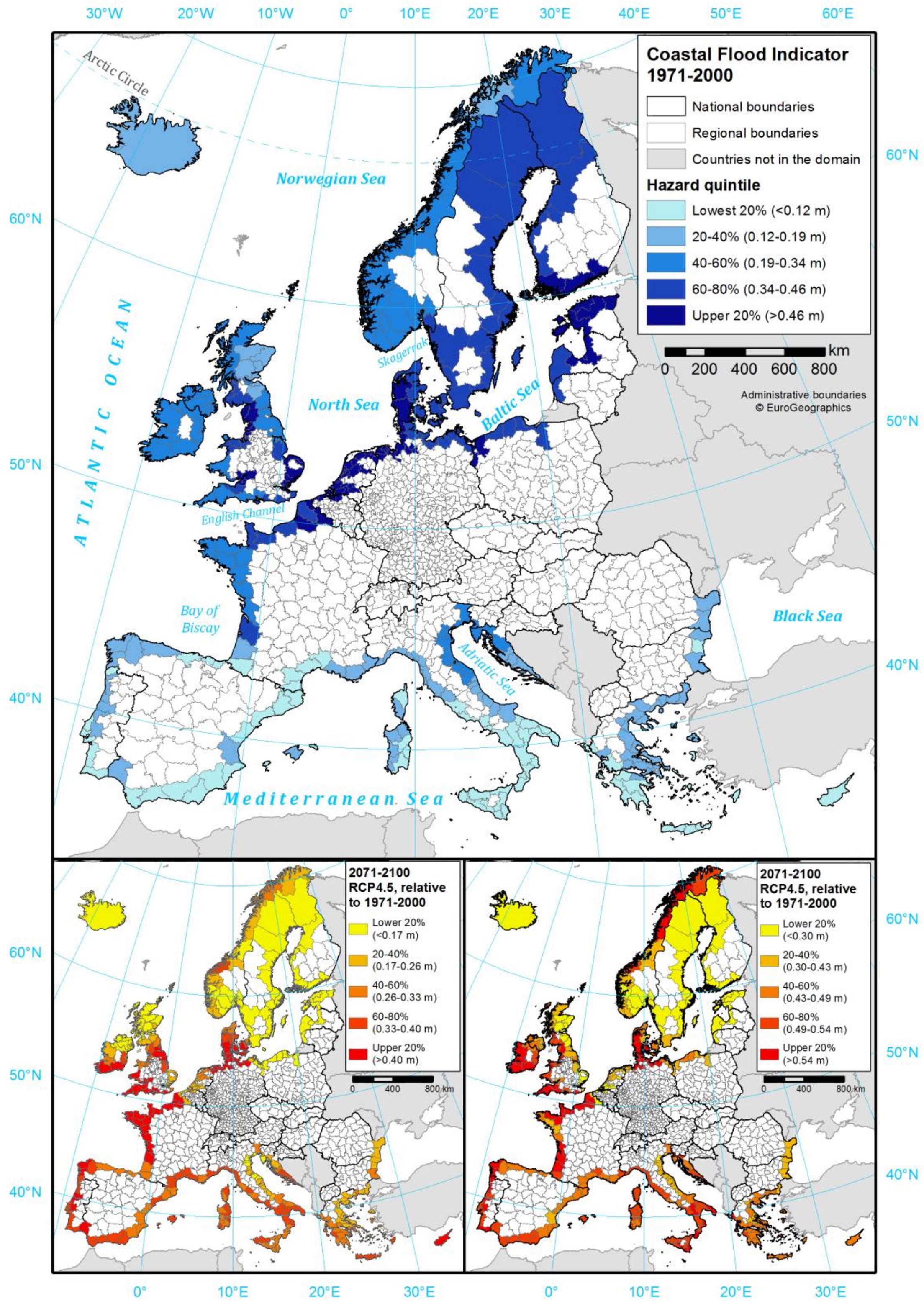


Figure 23. ***Quantiles of normalized coastal flood hazard indicator (100-year storm surge in a given scenario minus 10-year storm surge in the historical scenario) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios***

Pluvial floods (heavy precipitation)

<u>Proposed indicator:</u>

The daily precipitation intensity (RX1day) for a specific return period of 5 years.

This indicator was selected for BRIGAID project because most urban drainage systems are designed for return periods between 2 and 20 years. Although this indicator was also computed separately for the summer and winter seasons, the annual values were finally selected for further use.

<u>Data sources:</u>

For future conditions, IPCC, in addition to other indicators (i.e. Simple daily intensity index -SDII- index and Precipitation from very wet days -R95p- index). also considers the changes in the 2081–2100 return period (RP) for rare daily precipitation values, RX1day, that have a 20-year return period during historical period 1986–2005. Similar indicators are used by the European Environment Agency. The map below show an example for the estimation of changes in heavy precipitation across Europe in summer and winter seasons.

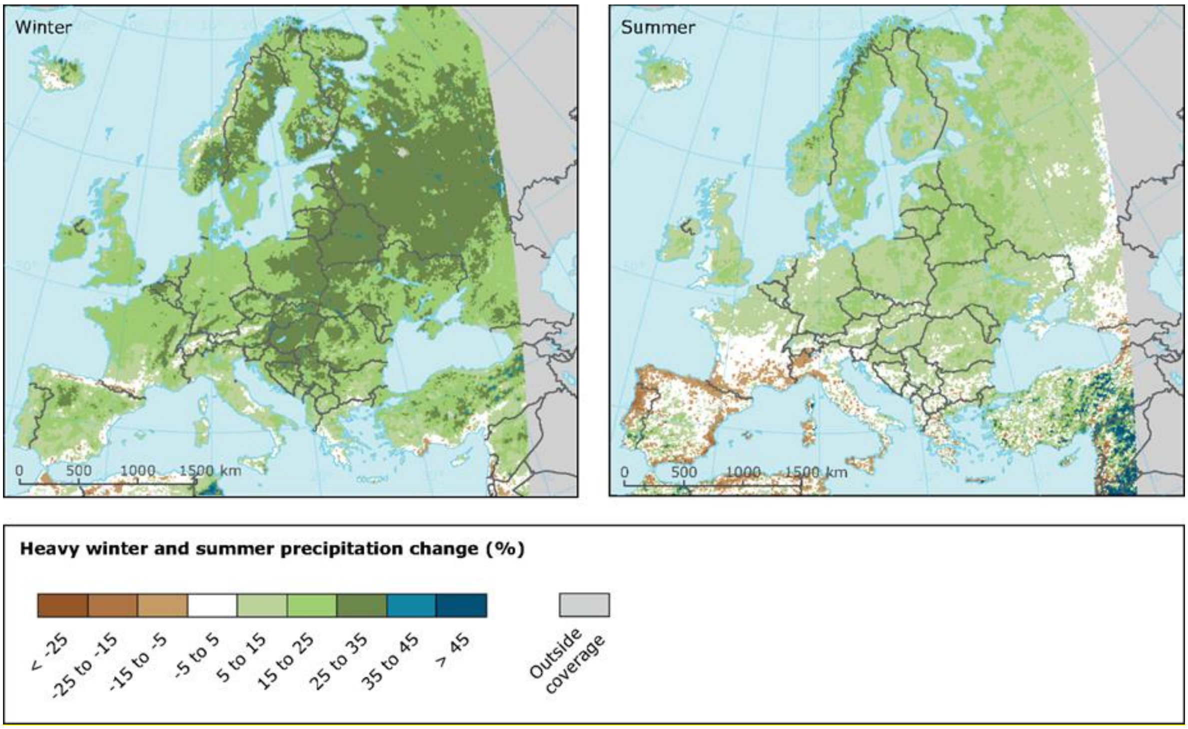


Figure 24. ***Projected changes in heavy precipitation in winter and summer (source: EEA. http://www.eea.europa.eu/data-and-maps/indicators/precipitation-extremes-in-europe-3/assessment)***

In the RAIN project (Groenemeijer et al. 2016), the maps of heavy precipitation were prepared for 5 climate scenarios (1971-2000, 2021-2050 RCP 4.5, 2021-2050 RCP 8.5, 2071-2100 RCP 4.5, 2071-2100 RCP 8.5). For each scenario, 10-year return period of 3-hour, 24-hour, 48-hour and 72-hour precipitation was calculated as the mean of multi-model ensemble of regional climate models. These maps have been used as input for the calculation of the RX1day with return period of 5 years.

Limitations and uncertainty:

The benefit of this indicator is that it is based on direct meteorological outputs of the climate models. The mean of a large ensemble of both global and regional climate model runs were considered. Hence, the climate change signals used on this basis of the extreme precipitation indicator are expected to be rather robust. There are, however, some limitations:

- The mean climate change signal (mean obtained from the full set of climate models) does not provide information on the uncertainty in the climate change signal.
- Daily precipitation may not be fully representative for pluvial flooding such as flooding as a consequence of sewer surcharge. Many urban drainage systems have response times smaller than 1 day, which means that sub-daily precipitation may be more appropriate.
- Just one selected return period was considered whereas urban drainage systems in different parts of Europe are designed for various return period, typically in the range between 2 and 20 years.
- Just one season was considered whereas the extreme precipitation amounts in many places of Europe strongly vary from season to season.
- This first volume of rainfall will be stored in the underground sewer network, hence does not contribute to the urban flooding. A threshold could be applied to the extreme precipitation intensities or the exceedance above this threshold considered but this threshold strongly depends on the specific system properties.
- For the impact analysis on pluvial flooding, an urban drainage and surface inundation model would be required. Such models are very detailed and should be considered for local impact analysis.

Results:

The heavy precipitation hazard indicator based on the daily precipitation intensity for a return period of 5 years, is provided for any location in Europe. This does, however, not mean that pluvial floods and other heavy precipitation induced disasters can happen at any location. The pluvial flood hazard, for instance, depends on the local conditions in terms of topography, land use and drainage system properties.

Figure 24 shows that heavy precipitation is variable across Europe with higher intensities over elevated areas such as the Alps because of the orographic lifting. Also some other areas show higher precipitation extremes such as the western Norwegian Coast, due to the passage of mid-latitude cyclones directed from west to east, and regions bordering the coasts in the Mediterranean region due to coastal cyclones that transport humid air masses. At the national level, Slovenia, Switzerland and Italy show the highest intensities The extreme precipitation intensities are projected to increase over entire Europe, with increases up to more than 5 mm for RCP4.5 and more than 9 mm for RCP8.5.

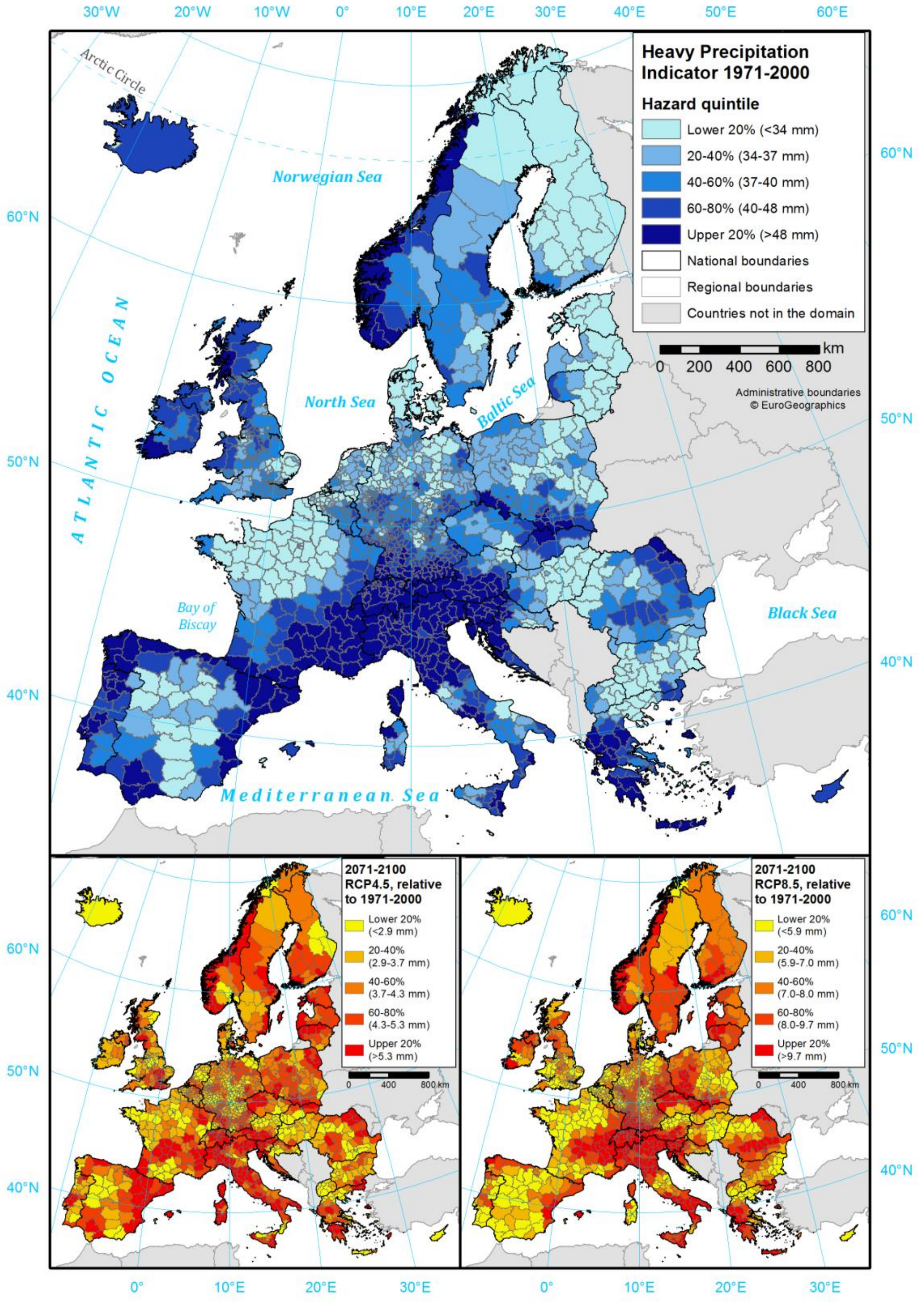


Figure 25. ***Quantiles of normalized heavy precipitation hazard indicator (daily precipitation intensity for a return period of 5 years) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios***

Wind storms

Proposed indicator:

The 99th percentile of daily wind speed corresponding to a stronger storm

The European Environment Agency (EEA) considers changes in the 98th percentile of daily maximum wind speed as an indicator of wind storms. However, in our analysis, the 99th percentile was selected as to consider extreme wind storms.

Data sources:

In the RAIN project (Groenemeijer et al. 2016), the maps of wind storms were prepared for 5 climate scenarios (1971-2000, 2021-2050 RCP 4.5, 2021-2050 RCP 8.5, 2071-2100 RCP 4.5, 2071-2100 RCP 8.5). For each scenario, the 5, 10, 20 and 50-year return period of daily maximum 10 m wind speed was calculated as the mean of multi-model ensemble of regional climate models. Changes in return periods in the future relative to present return periods were also provided. JRC calculated maps with the same parameter.

Limitations and uncertainty:

A benefit of this indicator is that it is based on direct meteorological outputs of the climate models. There are, however, some limitations:

- Just one percentile, 99th, was considered, which corresponds to very extreme storms. Less extreme wind storms may also cause damage.
- The specific impact of extreme wind storms may depend on the types of buildings and other local conditions, which need to be considered in a more specific / detailed impact analysis.

Results:

There are strong regional differences with both negative and positive changes. For the RCP4.5 scenario, the changes are primarily negative, whereas for the RCP8.5 scenario they are both positive and negative. Higher changes are expected for Iceland, the UK and the coastal areas of north-western Europe and Norway. In the historical climate (1971-2000), the 5 and 95 percentiles of the wind storms' indicator values across Europe are 4.6 and 12.3 m/s. For the RCP4.5 scenario, the 99th percentile of daily wind speed decreases to more than 0.12 m/s in comparison with the historical climatic conditions. For the RCP8.5 scenario, this percentile increases up to more than 0.10 m/s. Hence, the range of extreme wind speed values remains almost the same. The same applies to the values at the regional and national levels.

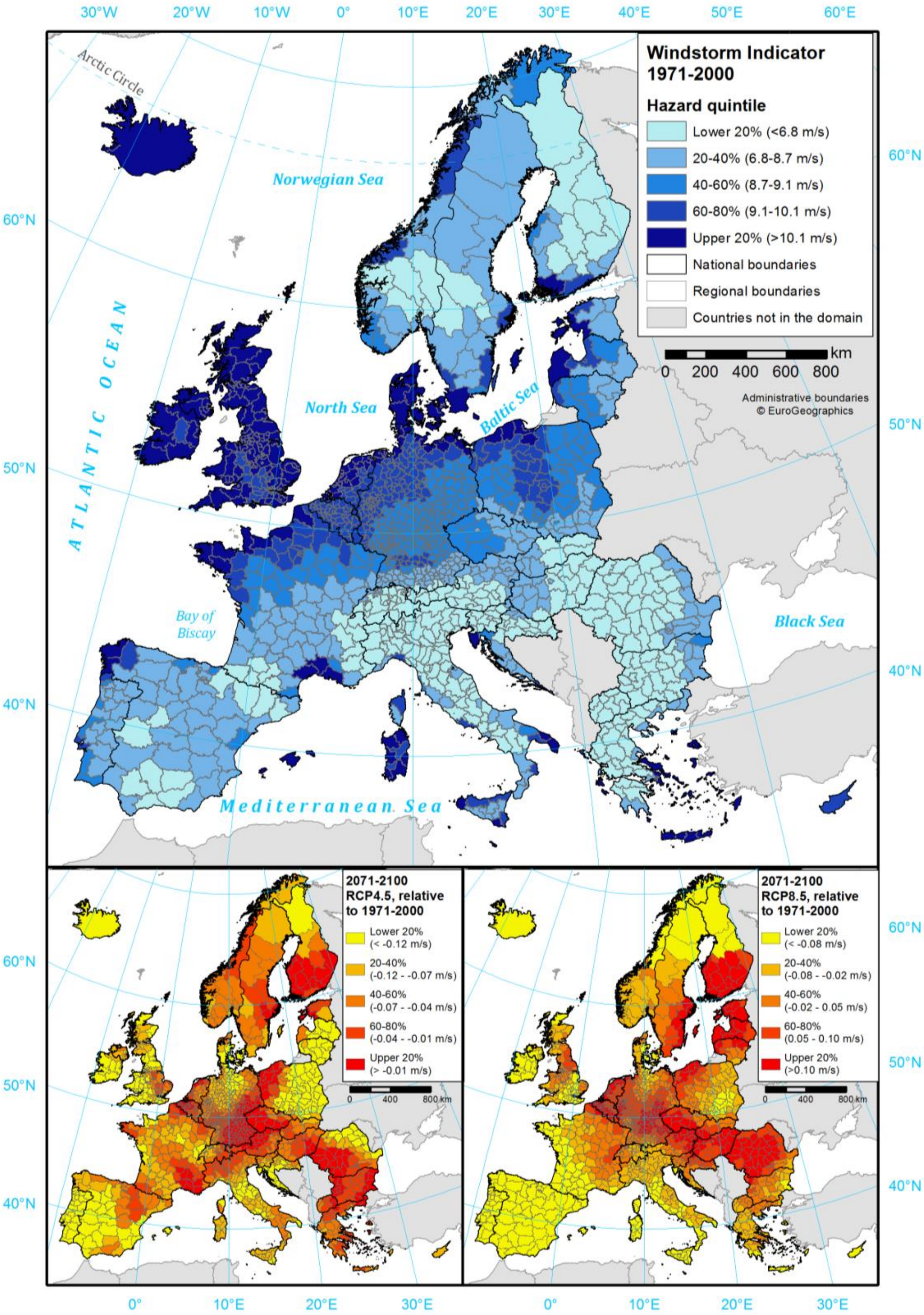


Figure 26. ***Quantiles of normalized wind storms (99th percentile of daily maximum wind speed) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios***

Droughts

Proposed indicator:

A**nnual CDD** expressed as the **maximum number of consecutive dry days when precipitation is less than 1 mm and considering t**he largest CDD in the 30-years period.

Therefore, the CDD value considered on the basis of the indicator has an empirical return period of 30 years. This is consistent with the IPCC

Data sources:

The indicator can be computed directly from meteorological variables available in the climate model outputs.

Limitations and uncertainty:

A benefit of this indicator is that it is based on direct meteorological outputs of the climate models. There are, however, some limitations:

- Next to the number of successive days with no or little rainfall days, there are many more properties of the temporal rainfall variability that are of importance for impact analysis of droughts, such as the cumulative rainfall amounts, the temperature and evaporation amounts, the impacts on soil moisture, low river flows, etc.
- Different types of drought related impacts exist. Quantification of such impacts would require a very specific type of local impact model.

Results:

The droughts' hazard indicator shows strong regional differences. There is a clear north-south variation in the number of CDDs with much higher drought hazard conditions in Southern Europe. At the national level, the Southern European countries Cyprus, Spain, Portugal, Greece and Italy have the highest CDD indicator days. They are projected to increase all over Europe, with increases up to more than 8 CDDs for RCP4.5 and more than 18 CDDs for RCP8.5. The changes are strongest for the more dry countries of Southern Europe.

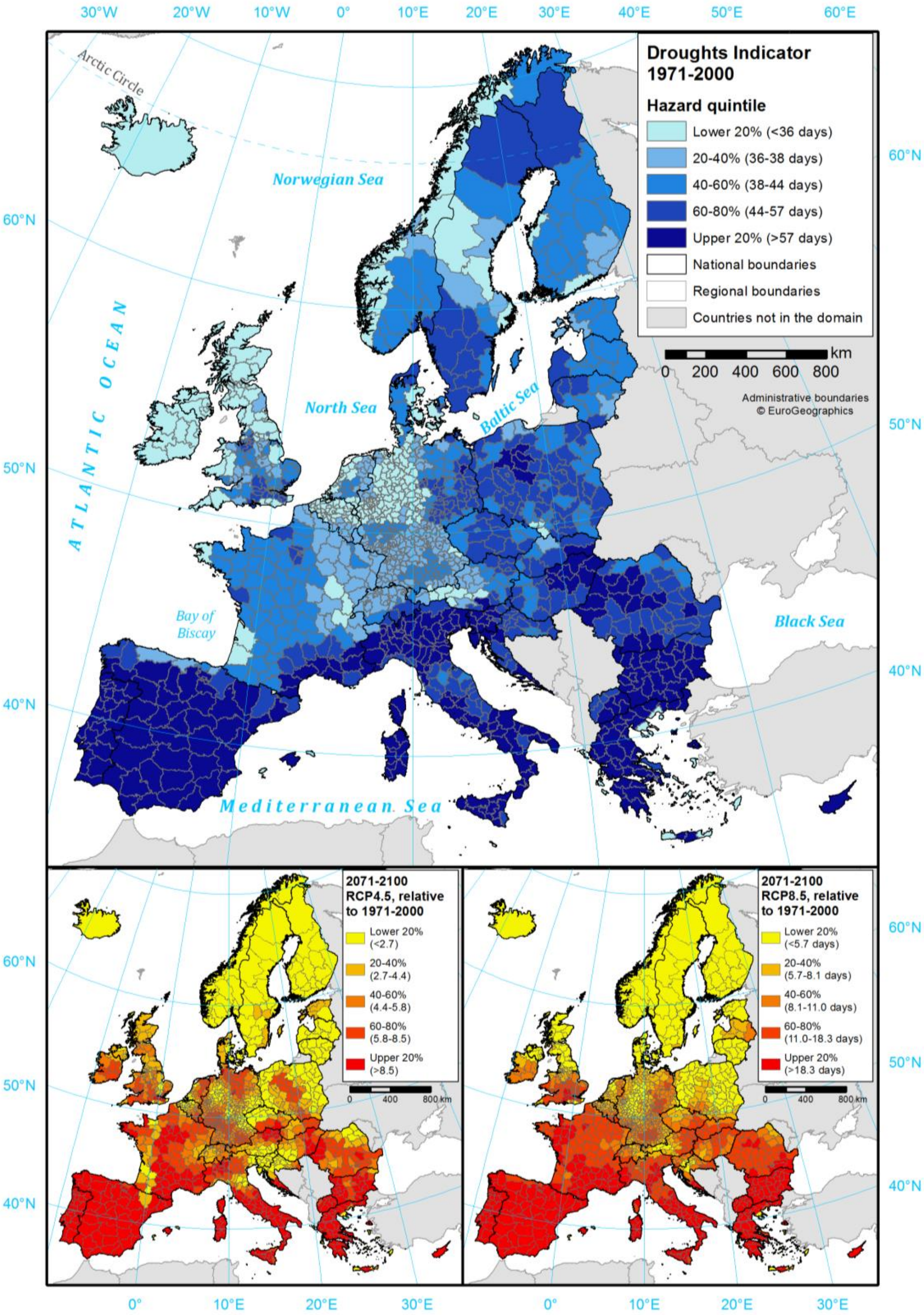


Figure 27. ***Quantiles of normalized drought hazard indicator (maximum number of consecutive dry days when precipitation is less than 1 mm) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios***

Heatwaves

<u>Proposed indicator:</u>

Number of heat waves over a period of 30 years

This indicator follows the WMO definition of heat waves (see section 3.1).

<u>Data sources:</u>

Meteorological outputs of the climate models

<u>Limitations and uncertainty:</u>

The benefit of this indicator is that it is based on direct meteorological outputs of the climate models. There are, however, some limitations:

- Next to the number of heat waves, the intensity and duration of the heat waves may be important as well.
- Just one potential definition of heatwaves was considered whereas many more definitions exist, or information on the full temporal variability of temperature values may be useful for specific types of heat wave related impacts.
- Daily temperature values were considered whereas also the maximum and minimum daily temperature values are of importance as well.
- Different types of heat wave related impacts exist. Quantification of such impacts would require a very specific type of local impact model.

<u>Results:</u>

The heatwaves indicator based on the total number of heat waves in 30 years is provided for any location in Europe. It shows a higher number of heat waves for the inland areas of Southern Europe. At the national level, Spain and Portugal have the highest number of heat waves. In the historical climate (1971-2000), the 5 and 95 percentiles of total number of heat waves in 30 years across Europe are 9 and 57. They are projected to increase quite strongly over entire Europe, with increases up to more than 60 heatwaves in 30 years for RCP4.5 and more than 80 RCP8.5. The maximum number of heat waves at the national level increases from 80 (historical climate) to 150 (RCP4.5) and 181 (RCP8.5) in 30 years.

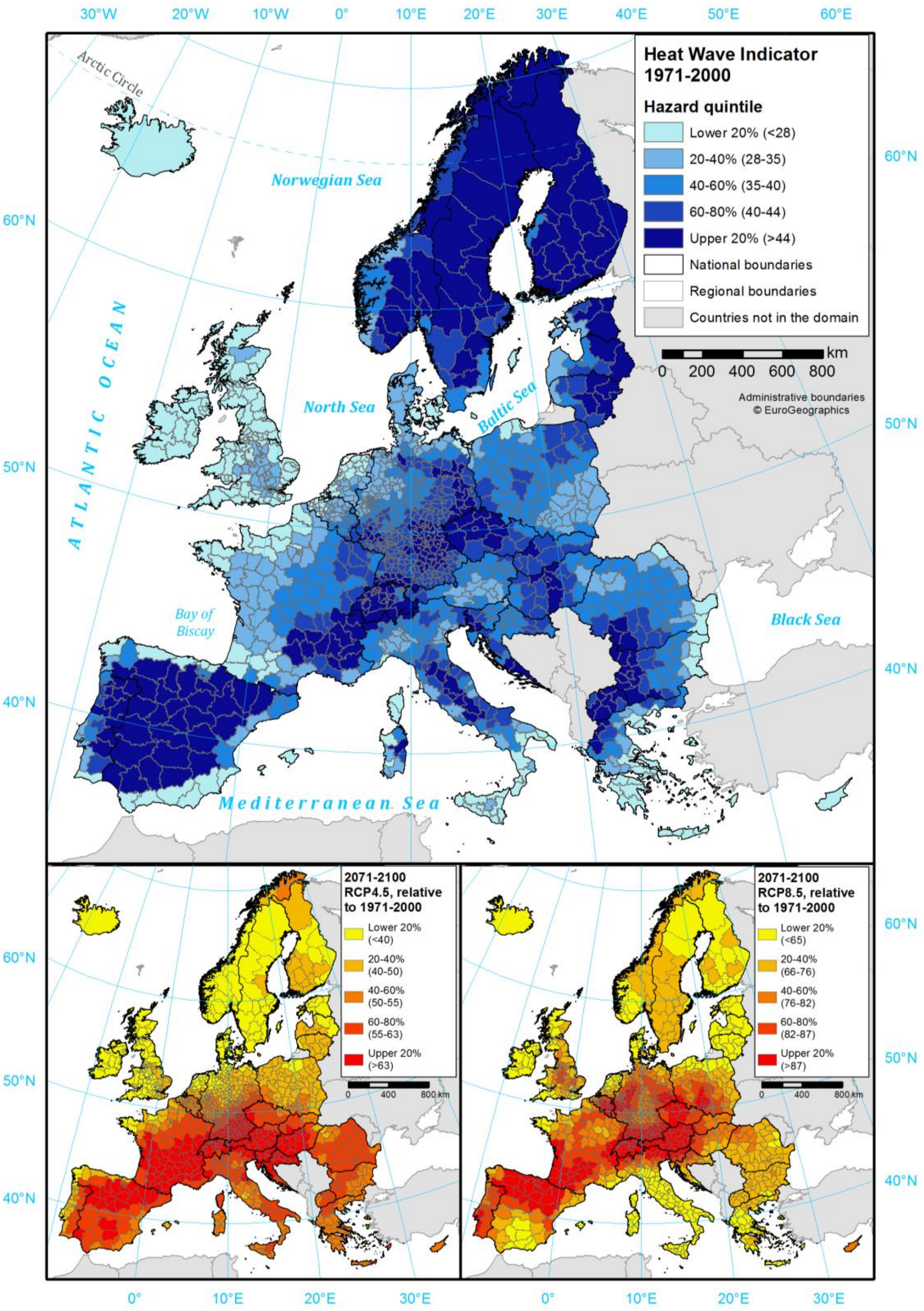


Figure 28. ***Quantiles of normalized heat waves hazard indicator (number of heat waves over a period of 30 years) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios***

Wildfires

<u>Proposed indicator:</u>

The Forest Fire Danger Index (FFDI)

The Forest Fire Danger Index (FFDI; Nobel et al., 1980) is defined as:

$$FFDI = 2exp(0.987logD - 0.45 + 0.0338T + 0.0234V - 0.0345H$$

where H is the relative humidity from 0-100%,

T is the air temperature in degree Celsius,

V is the average wind speed 10 meters above ground, in meter per second and

D is the drought factor in range 0-10 (Sharples et al., 2009).

<u>Data sources:</u>

This indicator has been calculated using the simplified version of the formula proposed by Nobel et al. (1980). This formula is frequently used and can be computed directly from meteorological variables available in the climate model outputs.

The calculation was done for each day of the time series and the final index computed by averaging the FFDI for all days of the 30-year time series.

<u>Limitations and uncertainty:</u>

A benefit of this indicator is that it is based on direct meteorological outputs of the climate models. There are, however, some limitations:

- The average index for all days of the 30-year period was considered, whereas specific drought seasons would be more relevant.
- Other meteorological and hydrological conditions next to relative humidity, air temperature and wind speed may play a role but were not considered such as precipitation.
- Wild fires are in different regions of Europe induced by other meteorological and hydrological conditions. Hence, different indicators may need to be considered.

<u>Results:</u>

The wildfire hazard indicator based on the Forest Fire Danger Index (FFDI) is provided for any location in Europe but with strong regional differences, as was also the case for the drought and heatwave indicators. There is a strong north-south variation in the FFDI with much higher wild fire hazard conditions in the drier countries of Southern Europe. At the national level, the Southern European countries Cyprus, Spain, Portugal and Greece have the highest FFDI values. They are projected to increase all over Europe but the changes are strongest for the more dry countries of Southern Europe.

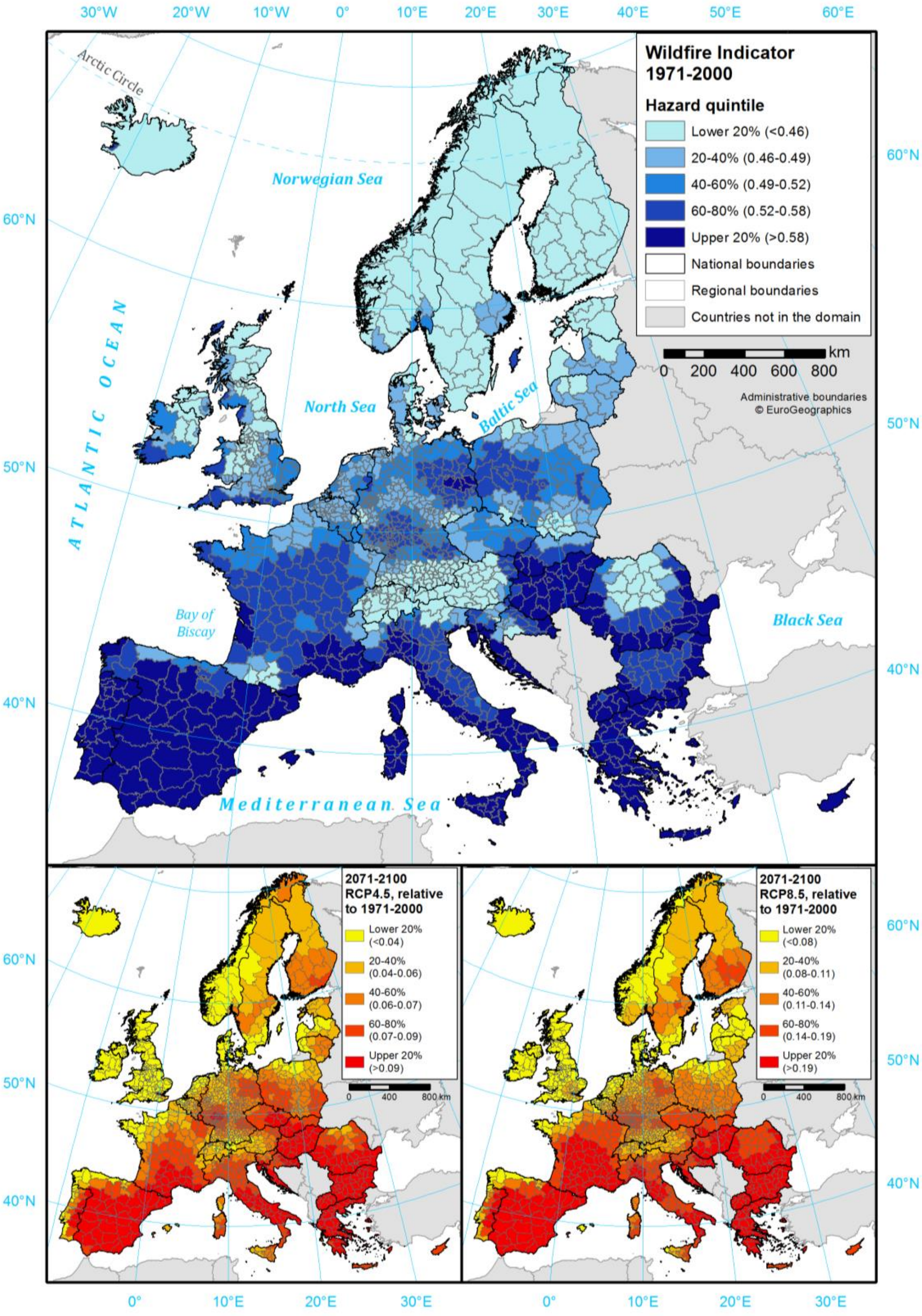


Figure 29. *Quantiles of normalized wild fires hazard indicator (Forest Fire Danger Index) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios*

B) EXPOSED ELEMENTS INDICATORS

The exposed elements indicators are described per hazard using tables and visual information as support for a better understanding of the information produced.

River and coastal floods

Indicator	Justification	Source	Data quality, comments	Code (if applicable)
Land use inside the boundaries of the 100-year return period river flow	The 100 year return-period is a commonly used reference for characterizing flood hazard. It is used by EEA in the production of an indicator on Projected change in river floods (see figure *). Also, the 100 year return period is specifically mentioned in the Floods Directive as a minimum return period to be considered for the development of flood hazard maps by Member States, i.e. "*These maps will identify areas with a medium likely hood of flooding (at least a 1 in 100 year event) and extreme events or low likelihood events, in which expected water depths should be indicated. In the areas identified as being at risk the number of inhabitants potentially at risk, the economic activity and the environmental damage potential shall be indicated.*" The 10-year return period was chosen as an approximation of the lowest flood protection standards that can be found throughout Europe (see e.g. Scussolini et al. 2016). The flood risk scenarios need to consider potential damages, which are directly dependent on land use and flood protection level and affected population as key variables.	River floods and coastal floods hazards indicators (elaborated by BRIGAID) and 2012 CORINE land cover maps (EEA)	Other studies and projects are also providing data on damages produced by river and coastal floods (i.e. Alfieri et al, 2016). These data are being collected when possible and are used for validation of our indicators on exposed elements or even can substitute our own data in case these have a better quality/reliability.	
Population directly affected by a 100-year return period river flow		River floods and coastal floods hazards indicators (elaborated by BRIGAID) and population density grid (EEA)		

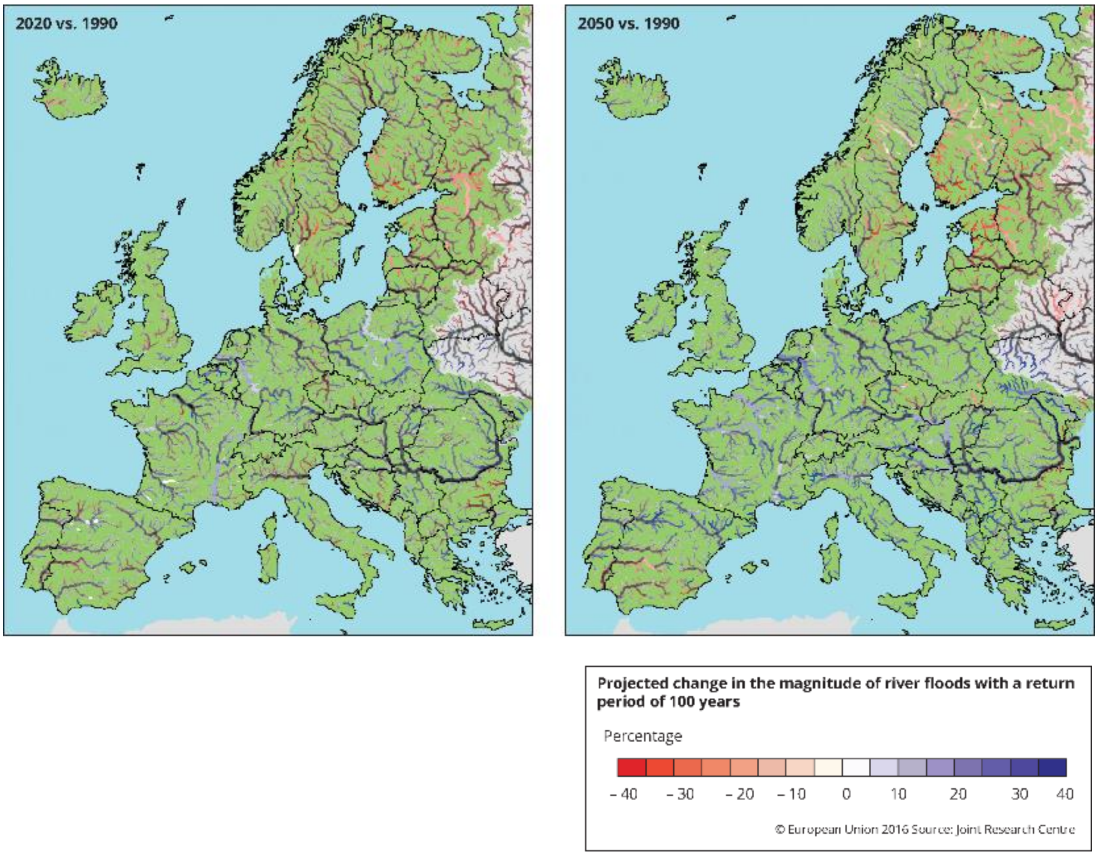


Figure 30. ***Projected change in river floods in Europe (EEA)***

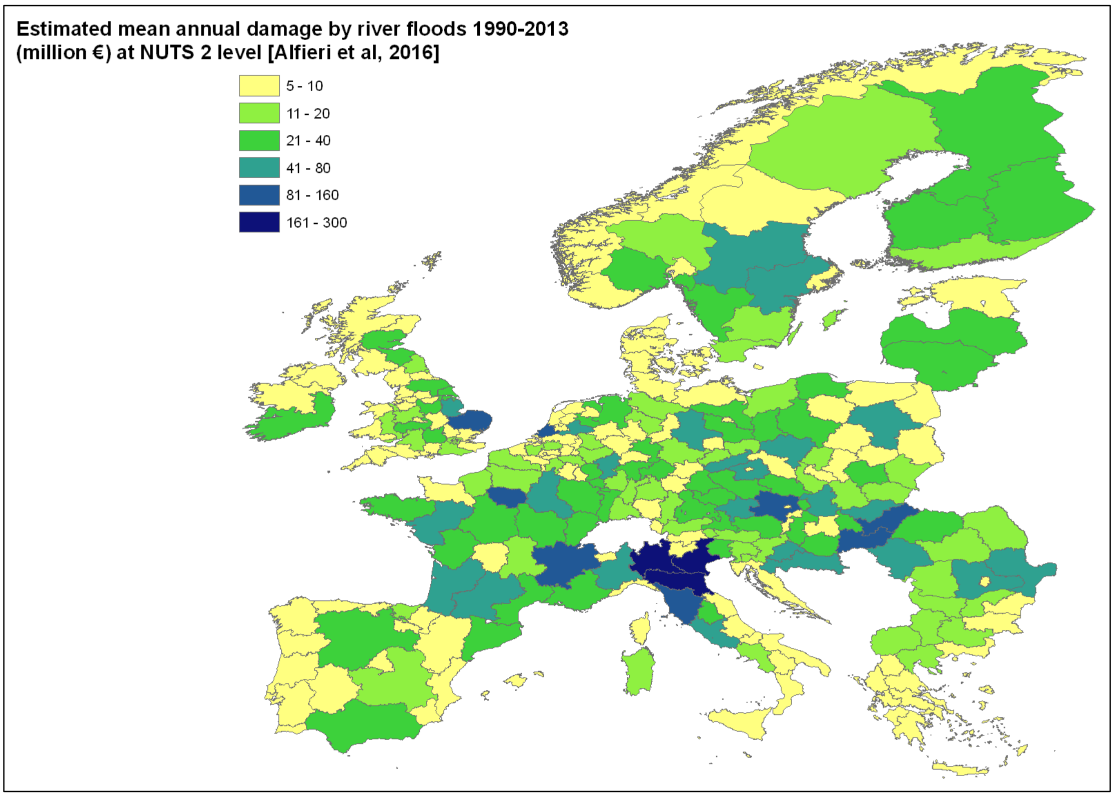


Figure 31. ***Estimated mean annual damage by river floods (1990-2013)***

Pluvial floods (heavy precipitation) and wind storms

Indicator	**Justification**	**Source**	**Data quality, comments**	**Code** (if applicable)
Population density	These indicators relate to affected assets by storms and heavy precipitation as well as to population affected. The population density provides a direct measurement of the people in risk, and the share of urban population takes into account that this phenomena (in particular pluvial flooding) tend to have a bigger effect on cities and highly urbanized areas. Regarding this, houses in residential areas are often more affected than bigger buildings. The number of vehicles also provides additional information on assets likely to be damaged.	Eurostat		t_demo_pop: tgs00096
Density of constructions		CORINE land use map (2012)		
Households living in houses (non-apartments) in urban areas		Eurostat		urb_cpop1
Stock of Vehicles		Eurostat		tran_r_vehst

Droughts

Indicator	**Justification**	**Source**	**Data quality, comments**	**Code** (if applicable)
Total irrigated area	The effects of droughts will be assessed with a clear focus on the agriculture sector due to two main reasons: agricultural sector is the largest water consumer in drought-prone European areas and the sector most vulnerable to droughts and most of drought-related BRIGAID innovations are focusing on agriculture. The extent of irrigated areas provide information on the potential effects of droughts on socio-economic activity. The water stress index quantify the level of exploitation of freshwater resources	Eurostat		ef_lu_ofirrig
Total irrigated area of non-annual crops		Eurostat		ef_lu_ofirrig
Index of water exploitation		EEA		

Heatwaves

Indicator	Justification	Source	Data quality, comments	Code (if applicable)
Urban population	The CLIMATE-ADAPT platform provides a very valuable reference on the factors influencing vulnerability to urban heatwaves by identifying the “multiple factors influence the exposure of heat and the sensitivity to it”. This information together with a review of factors more often considered in literature has been used for the selection of indicators. The inhabitants of cities form the group of population which tend to be most affected by heatwaves. The share of people over 65 years old living in cities is an indicator of the importance of this vulnerable group, which is even more vulnerable for the case of households only inhabited by pensioners. The economic capacity is another indicator of vulnerability, because population with lower incomes has a much reduced capacity to protect from heatwaves effect. *An additional indicator relates to the importance of tourism since this is a key economic activity in many of the European countries most affected by heatwaves that can be quite affected by this phenomena.*	Eurostat		urb_cpop1
Share of elderly living in cities (population over 65)		Eurostat		urb_cpop1
Percentage of households inhabited by a lone pensioner;		Eurostat		urb_cpop1
Purchasing power standards of urban population / share of low-income households		Eurostat		urb_cpop1
Number of touristic beds per 1000 inhabitants		Eurostat		urb_ctour

Factors that tend to increase vulnerability to heat waves …		Response capacity
Exposure	Sensitivity	
High thermal disomfort values	High share of elderly people	Increasing the share of green urban areas
Lack of green urban areas	High share of low-income households – socio-economic status	Decreasing soil sealing
High degree of soil sealing	High population number	Commitment to fight climate change – awareness of and trust in city governance
Increased background heat and heatwaves	High share of very young population	Trust in other people
Population density	High share of lonely pensioner households	Education
Less ventilation	Abundance of many assets	Socio-economic status - financial resources
Little shadowing	Abundance of key services for the city and for other regions	Awareness of business and citizens
Insufficient building insulation	Low cooling water availability	Well-functioning institutional structures and processes
Heat generation by production, transport, heating, etc.	…	Sufficient capacities in administrations to act
Specific geographical location and topography		Sufficient number of hospital beds
…		…

Figure 32. *Factors that tend to increase vulnerability to heat waves (source: Climate-ADAPT)*

Wildfires

Indicator	Justification	Source	Data quality, comments	Code (if applicable)
Total forested area	The basic data source for this analysis is the forest map or Europe produced by the European Forest Institute, which is a comprehensive and complete European map on forest area at 1 x 1 kilometre resolution.	European Forest Institute (1)		
Forested area within natural protected areas	In order to take into account the higher importance of some forest areas in terms of environmental value as well as in terms of population potentially affected by wildfires, two other indicators have been calculated	Maps of natural protected areas (EEA)		
Forested area close to urban areas		Urban Atlas (EEA)		

(1) To be referenced as:

Kempeneers, P., Sedano, F., Seebach, L., Strobl, P., San-Miguel-Ayanz, J. 2011: Data fusion of different spatial resolution remote sensing images applied to forest type mapping, IEEE Transactions on Geoscience and Remote Sensing, in print.

Päivinen, R., Lehikoinen, M., Schuck, A., Häme, T., Väätäinen, S., Kennedy, P., & Folving, S., 2001. Combining Earth Observation Data and Forest Statistics. EFI Research Report 14. European Forest Institute, Joint Research Centre - European Commission. EUR 19911 EN. 101p.

Schuck, A., Van Brusselen, J., Päivinen, R., Häme, T., Kennedy, P. and Folving, S. 2002. Compilation of a calibrated European forest map derived from NOAA-AVHRR data. European Forest Institute. EFI Internal Report 13, 44p. plus Annexes;

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C) ADAPTIVE CAPACITY INDICATORS

The adaptive capacity indicators are described in table format to facilitate comparison.

Category	Sub-category	Indicator	Justification	Source	Data quality, comments	Code (if applicable)
Awareness	Education	Percentage aged 25-64 with tertiary education (%, 2015, NUTS II)	Education has been shown to be a key determinant of climate change awareness. We capture this using Eurostat data on the proportion of the working age population (aged 25-64) with a tertiary education (ISCED levels 5-8).	Eurostat	Data for all countries available except some Greek regions	edat_lfse_04
	Internet	Percentage of 16-74 year-olds who use the internet at least once per week (%, 2016, NUTS II)	Internet access is an indicator of the availability of reliable and complete information on climate change and adaptation, which in turn is an important indicator of awareness and the need for adaptation.	Eurostat	Data for all countries available except Switzerland (average EU data imputed)	isoc_r_iuse_i
	Adaptation platform	Existence of a national online climate change and adaptation web portal (2017, national)	The existence of high quality information on climate change and adaptation is an important component of awareness. We apportion points based on the existence of a national online web portal related to climate change adaptation. Countries are given zero points if no portal is in existence, one point if a portal has only recently been launched (in the last three years), and two points if the portal has been online for more than three years.	Climate-ADAPT	Data for all countries available	
	Public climate change perceptions	Seriousness of climate change as a problem; relative importance of climate change as a problem (2015, national)	The public's perception of the seriousness and relative importance of climate change is indicative or awareness. We use Eurobarometer survey data regarding EU citizen's view on how serious a problem they perceive climate change to be and whether climate change ranks in the top four problems faced by their country.	Eurobarometer	Full data available for all European countries, average data imputed for EFTA members	Eurobarometer Climate Change survey QA2.2 and QA1T.

Category	Sub-category	Indicator	Justification	Source, code	Data quality, comments	Code (if applicable)
	Government awareness	National willingness to develop policies and take adaptation action (2014, national)	National regulator awareness is indicative of both government awareness and the public awareness that underlies this. We draw on a question in a self-assessment survey of national climate adaptation regulators that asked, "in my country, the willingness to develop policies and to take adaptation actions at the national level is...".	EEA self-assessment survey of the climate adaptation policy process	Full data for all countries except Croatia and Iceland	Q.4
Hazard-specific	River floods	Number of European past floods per 10,000 km2 (2006-2015, national)	Past flood events show an interlinkage with increased awareness for flood protection and can be used as an indication of hazard-specific awareness of river floods.	River floods: EEA; Country area: Eurostat, World Bank Country Profiles	Data for all countries available. Data on river floods compiled by ETC-ICM and EEA	
	Coastal Floods/Storm surges	Number of storm surges (1991-2016, national)	An increased awareness for coastal flood protection is linked to the number of storm surge events during the last years.	eSurge-Project Database	Data for events in all countries available, data sorted according to six European regions. For some events additional web search was necessary to indicate relevant countries/regions where the events happened. For France and Spain, Storm surge events are differentiated between Mediterranean and Atlantic coast.	

Category	Sub-category	Indicator	Justification	Source, code	Data quality, comments	Code (if applicable)
	Wildfires	Proportion of country burnt by wildfires (%, 2011-2015, national)	The ha of land burnt per country, adjusted by country size, is an indicator of the relative occurrence of wildfires in a country, which in turn is an indicator of the specific awareness of this hazard.	European Forest Fire Information System (ha burnt); Eurostat (country size)	Relatively poor data coverage. Average EU data is imputed for all missing countries (UK, NL, LU, IE, IS, DK, CZ, BE)	
	Droughts	Past drought events (1991-2010, country groups)	Months of drought experienced in region as indicated by a combined drought indicator capturing hydrological drought, which will be linked with an increase in drought awareness in affected countries.	Spinioni et al. (2013)	Data for all European countries, given in 13 regional groups.	
	Wind storms	Insurance damages from major windstorms (1998-2013, national)	Insurance damages from major European windstorms are indicative of media coverage and awareness.	European Wind Storm Catalogue	Affected countries and total insurance damages for 23 major storms	
	Urban Flash Floods	Number of Flash floods (2006-2016, NUTS II)	Urban flash floods are one main extreme event which causes damages in urban areas. The occurrence of flash floods is an indication on the awareness of urban flood disasters.	EM-DAT International Disaster Database	Data for all countries available	
Ability	Scientists /engineers	Percentage of scientists and engineers in population (%, 2015, NUTS II)	The proportion of a region's population working as a scientist or engineer is indicative of a region's technical capacity; that is, the region's/community's ability to understand issues and develop, process, and have knowledge on assessments, e.g. vulnerability assessments regarding natural, social, and economical factors.	Eurostat	Complete data coverage apart from five French and one Finnish regions.	hrst_st_rcat
	R&D expenditure	Research and development expenditure per capita (€ per cap, 2014, national)	Higher research and development expenditure per capita indicates a greater ability to understand issues, develop knowledge, carry out assessments, and to understand natural, social, and economic processes - all important for the take-up of BRIGAID innovations.	Eurostat	Complete data coverage at national level except for Switzerland.	rd_e_gerdtot

Category	Sub-category	Indicator	Justification	Source, code	Data quality, comments	Code (if applicable)
Action	National Adaptation Policy	Status of National Adaptation Strategy (2017, national)	The implementation of a National Adaptation Strategy indicates that policy process on adaptation has started at the national level.	Climate-ADAPT	Data for all countries available	
		Status of Action Plans (2017, national)	The approving of an Action Plan assumes that the policy process has reached the development of concrete adaptation actions and their prioritisation.	Climate-ADAPT	Data for all countries available	
		Status of Impacts, vulnerability and adaptation assessments (2017, national)	The assessment of impacts and vulnerability is a precondition for a targeted approach to adaptation. It shows the preparedness for action and is a clear indicator of preparedness to act on climate change adaptation.	Climate-ADAPT	Data for all countries available	
		Level at which risk and vulnerability assessments are available (2014, national)	This indicates if risk and vulnerability assessments are available at the national or sub-national level. The availability on more detailed scale assumes a higher preparedness level as assessments will reach regional and local level.	EEA Self-assessment survey of the adaptation policy process	Complete data for all countries except Croatia	
		Assessment of national level vertical integration mechanisms (2014, national)	Integration of different institutions at national level is a cornerstone for mainstreaming of adaptation policy and resulting activities.	EEA Self-assessment survey of the adaptation policy process	Complete data for all countries except Croatia	
		Assessment of national horizontal integration mechanisms (2014, national)	Integration of different institutions between national, regional and local level is an important indication of reaching regional and local authorities and initiating coordinated activities between the different levels.	EEA Self-assessment survey of the adaptation policy process	Complete data for all countries except Croatia	
		Prioritisation of adaptation options implemented (2014, national)	Prioritisation of adaptation actions give an indication of how far and detailed adaptation policy has reached in the different countries and how coordinated current adaptation activities are chosen.	EEA Self-assessment survey of the adaptation policy process	Complete data for all countries except Croatia	

Category	Sub-category	Indicator	Justification	Source, code	Data quality, comments	Code (if applicable)
		Number of stakeholder groups involved in national adaptation strategy (2014, national)	To increase awareness, commitment, etc., stakeholder groups should be included in the different steps of the policy process. This indicates how far the word has spread and how different opinions are included in the process.	EEA Self-assessment survey of the adaptation policy process	Complete data for all countries except Croatia	
	Government effectiveness	World Economic Forum Global Competitiveness (Basic Requirements) (2016, national)	Strong, effective, and responsive institutions are an important determinant of a region's ability to act on climate change innovation. The "basic requirements" index of the World Economic Forum's Global Competitiveness Report summarises indicators of a countries institutional environment, infrastructure, macroeconomic environment, and health and primary education.	World Economic Forum	Complete data for all countries	GCI.A
	Economic resources	GDP per capita (Euro, 2013, NUTS II)	The ability to act on climate change adaptation depends in large part on resources, especially economic resources.	Eurostat	Complete data for all regions except Switzerland	nama_10r_2gdp
	Funding possibilities	Planned ESIF funding related to Climate adaptation and risk prevention (Euro, 2014-2020, national)	As an indicator of action, EU Commission data on ESIF funding related to climate adaptation and risk prevention summarises the amount of money earmarked for joint EU-Member State investment in this topic for the period 2014-2020.	EU Commission	Complete data for all countries, except for Switzerland, Iceland, Luxembourg and Norway.	
	Adaptation measures	Number of Case studies in Climate-ADAPT platform (2016, national)	The database shows adaptation activities studies which are planned and implemented in the different countries. It is an indication of concrete on the ground assessment and implementation. The total data coverage might be limited at the moment, but it will be regularly updated by the EEA. Therefore, we assume the database will get more robust in the next years.	Climate-ADAPT	Data gaps for Iceland. Due to the lower certainty of this indicator, it receives a lower waiting in the composite indicator (10% of action score)	

APPENDIX 3. PAN-EUROPEAN CLIMATE CHANGE INDICATORS AND LOADING CONDITIONS

Pan-european climate change indicators and loading conditions

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Why climate change indicators?

Pan-european climate change indicators are required for two purposes:

- *As loading conditions for WP5 (Task 5.1): future climate conditions, to be applied during the project to test whether the innovations are “climate proof”*
- *As input for innovation opportunity mapping as part of the market scoping exercise at the European scale in WP6 (Task 6.1)*

In Task 5.1, the overall goal is to establish test conditions for the different innovations, including uncertainties (lead by KU Leuven, in collaboration with TU Delft). To establish these test conditions, projections of the effects of climate change are made for floods, droughts, and extreme weather, on a local, regional and national scale. These projections are based on outputs from, amongst others, the EU projects RAIN, DROUGHT-R&SPI and the EU Floods Directive. If necessary, additional predictions are made using high resolution statistical downscaling. The output of this analysis is used to:

- *establish a statistical distribution of hydrological and meteorological conditions that innovations may encounter over their life time on a local, regional, and national geographical scale;*
- *specify the testing conditions of innovations.*

The results of the statistical distribution are used to evaluate the general effectiveness of innovations for their flexibility in adapting to uncertainties in climate projections, and to develop normalization techniques for translating the general effectiveness of innovations back into the national, regional, or local effectiveness (see Task 5.6).

These test conditions related to climate change are also of use for Task 6.1 that aims to identify the markets that have a high potential of adopting innovative climate change adaptation measures. The first step in that identification process is to segment the market for adaptation measures in Europe considering for the different regions the i) exposure to changes in climate and their ii) sensitivity to these changes. This step uses available indicators for climate change vulnerability developed by the European Environment Agency and combine them with selected outcomes from Task 5.1 (specifically the small-scale projections of the effects of climate change for floods, droughts, and extreme weather). In a subsequent step, the resulting market segments are examined on the basis of their adaptive capacity and willingness to implement innovative adaptation measures. This analysis combines preliminary outcomes of Task 5.2 (specifically the analysis to predict acceptance of innovations by end-users) and a review of the EU and National Adaptation Strategies. The output is an assessment of the different geographical regions within Europe on the basis of their vulnerability to climate change and the willingness of their societies to implement (innovative) adaptation measures. This information feeds into the analysis of target markets in Task 6.3.

Whereas WP6 looks into indicators for impacts and adaptive capacity, to identify the "level of opportunity" for innovations, this report focuses on the "hazard potential". It focuses on the development of indicator maps for the hazard potential linked to floods, droughts and extreme weather related natural disasters in view of climate change. It summarizes the selected approach for the selection, derivation and mapping of the pan-european climate change hazard indicators and the results, both for the purpose of providing loading conditions for testing the innovations (WP5) and in support of the innovation opportunity mapping (WP6).

More specifically, pan-European maps are obtained for indicators on the hazard potential for the different types of disasters considered in the BRIGAID project:

- *Floods (innovations by WP2):*
    - *River floods*
    - *Coastal floods*
- *Droughts (innovations by WP3)*
- *Extreme weather (innovations by WP4):*
    - *Heavy precipitation / pluvial floods*
    - *Heatwaves*
    - *Wildfires*
    - *High wind speed (wind storms)*
    - *Hail*

Because the level of opportunity for innovations is strongly related to the severity of the impact of climate change, we have to look for indicators that:

- *We can derive from the available global and regional European climate model runs for the latest generation of models; or already available indicator products from such runs.*
- *Are good indicators for the above listed types of threats or disasters; 1 indicator is selected per type of threat or disaster.*

Because none of the BRIGAID innovations so far is related to hail, and because hail is not available as a direct output from climate models, we omit this type of threat for the hazard potential mapping.

Climate change hazard analysis

Available climate model results

The hazard potential in view of climate change is assessed from climate model simulations. The climate model simulation results that are most up-to-date and available are the ones that form the basis of the 5th Assessment Report of the Intergovernmental Panel for Climate Change (IPCC, 2013, 2014). It are the climate model runs conducted by the Coupled Model Intercomparison Project of the World Climate Research Programme – Phase 5 (CMIP5). At the European scale, corresponding regional climate model simulations have been conducted by the EURO-CORDEX project. CORDEX (COordinated Regional climate Downscaling EXperiment) is an international ongoing downscaling project of the World Climate Research Programme (WCRP). One of its aims is to provide a quality-controlled data set of RCM simulations for the recent past and 21st century projections, covering the majority of populated land regions on the globe. They are based on GCM projections produced within the CMIP5. Their data archive can be found on: http://cordex.dmi.dk/.

The future climate model simulations with these models are available for the latest greenhouse gas scenarios by the IPCC, based on the Representrative Concentration Pathways (RCP scenarios) (van Vuuren et al., 2011).

From these available climate model outputs, climate change impacts on meteorological variables are derived. This is done for specific meteorological conditions, e.g. seasonal rainfall or rainfall extremes, or combined in indicators that are representative for specific types of threats, e.g. floods, droughts, heatwaves, wind storms. The more detailed impacts on floods, hydrological droughts, wildfires, etc. require the meteorological changes to be propagated in an impact model (e.g. coastal wave, catchment hydrological, river hydraulic, wildfire risk).

Need for downscaling

Specific or local impact analysis, however, requires the climate model outputs to be downscaled. The global and regional climate models have resolutions (spatial, temporal) that are too coarse for being representative for many of the above-listed threats. Extreme rainfall induced floods in cities (urban pluvial floods), for example, are the consequence of extreme, local and short-duration convective rain storms. This is because the characteristic spatio-temporal scales of urban drainage are generally small, often characterized by temporal scales of a few minutes and spatial scales of 1–10 km^2. This is much smaller than the spatial resolution of RCMs that is between 12 by 12 km and 50 by 50 km. The atmospheric processes that explain extreme local rainfall, such as cumulus formation and small scale cloud processes, are only represented explicitly by model physics at spatial resolution smaller than about 3 km. In the coarser resolution climate *models, these processes are accounted for but in an indirect way by cumulus parameterization to represent the collective influence of clouds (e.g. rainfall, radiation budget) within a larger area (single grid). As a result, the GCMs and RCMs have poor accuracy in simulating precipitation extremes.*

Local area models vs. statistical methods

Several climate research centres in Europe are currently developing very high resolution climate models that permit convection to be simulated explicitly (this means with grid resolutions of about 3 km), hence to obtain higher accuracy for the local results such as precipitation extremes. These high resolution RCMs are called local area models (LAMs). To date, they are, however, only available for specific regions and for a limited number of climate model runs. For Belgium, for instance, within the scope of the ongoing CORDEX.BE project for the Belgian Science Policy Office (BELSPO), in which KU Leuven is involved, three LAMs are being refined and fine scale climate simulations conducted with these models. It are the LAMs set up by RMI (ALARO model), KU Leuven – Geography dept. (CCLM model), and ULg (MAR model) (Termonia et al., 2016). Because of these limitations, the climate change signals are to be downscaled and/or bias corrected by other means, which is typically done by statistical downscaling methods. Different types of methods exist for such statistical downscaling (Figure 2, Figure 3). KU Leuven has international expertise in these methods (e.g. Willems et al., 2012).

For this project, the quantile perturbation technique is proposed as statistical downscaling method because it accounts for the changes in extremes (Willems & Vrac, 2011; Willems, 2013). The method moreover intrinsically involves bias correction. One method is selected here, but the approach and developed tool will be open such that it can be replaced by other downscaling methods; hence to allow testing the sensitivity of that method.

Uncertainties in climate change exposure

Because of the high uncertainties in the future greenhouse gas concentrations and the climate modelling physics, these uncertainties need to be explicitly quantified and considered. This is typically done by means of an ensemble approach, where an ensemble of greenhouse gas scenarios and climate model runs are considered. As explained above, these runs consist of the coarse-scale GCM runs, the regional scale RCM runs and ev. the LAM runs. Current generation GCMs (CMIP5) are available at spatial scales of 150-100 km; the RCMs (e.g. EURO-CORDEX) at spatial scales between 50 km and 12 km; the LAMs at scales down to 3-4 km. As explained, the number of LAM runs is for most regions of Europe still very limited, as many regions started with LAM modelling only recently. The number of LAM runs is currently too low to be solely used on the basis of the climate change impact analysis. For that reason, they have to be combined with the larger ensemble sets of GCM and RCM simulations. In order to overcome the differences in spatial scales, statistical downscaling is applied. This downscaling can be done in different steps: (1) from the spatial (and temporal) scales of the GCMs to the RCMs; (2) from the *scales of the RCMs to the LAMs; (3) from the scales of the LAMs to the more local scale required by the impact models. The use of RCMs and LAMs in a way complementary to the GCMs is what we call dynamic downscaling, whereas the statistical downscaling involves statistical or stochastic modelling methods discussed before to bridge the gap between the different spatial and temporal scales involved. Because the RCM results largely depend on the GCM in which the RCM was nested, it is important to consider a broad ensemble of GCMs next to the RCMs. Because RCM runs most often are available for a subset of available GCM runs only, it would be useful to combine both GCM and RCM runs, as per the process outlined before. If an ensemble of LAM runs would be available for the impact study area, these can be integrated in that process in a similar way. If only few LAM runs are available, these rather can be considered while evaluating the statistical downscaling approaches. Figure 1 schematically illustrates the proposed concept of integrating the different types of climate model runs in order to study climate change impacts.*

After analysis of the outputs of all available climate models, after statistical downscaling and bias correction, for specific variables (e.g. rainfall, temperature), a probability distribution of climate change conditions and related testing conditions for the innovations are derived.

Climate scenarios

Since it is computationally not practical or feasible to consider the impact for each of the climate model outputs (e.g. more than 200 global model runs are available in the CMIP5 database), the climate change impacts are typically assessed for a limited set of scenarios. Synthesized scenarios may be developed for that purpose. This can be done based on a methodology of constructing tailored scenarios for assessing the conditions under both normal and extreme conditions from an array of future climate change signals. These scenarios are derived from the climate model simulations. They may depend on the specific type of threat or impact considered, hence tailored to this type. Following the procedure by Ntegeka et al. (2014), a tailoring process is proposed to generate scenarios that can optimally represent the spectrum of climate scenarios. These tailored scenarios have the advantage of being few in number as well as having a clear description of the seasonal variation of the climate signals, hence allowing easy interpretation of the implications of future changes. It would be useful to work with few scenarios, e.g. high, mean and low (similar is done by Ntegeka et al., 2014) to emcompass the range of climate model ouputs and consider the uncertainty in the climate change impacts.

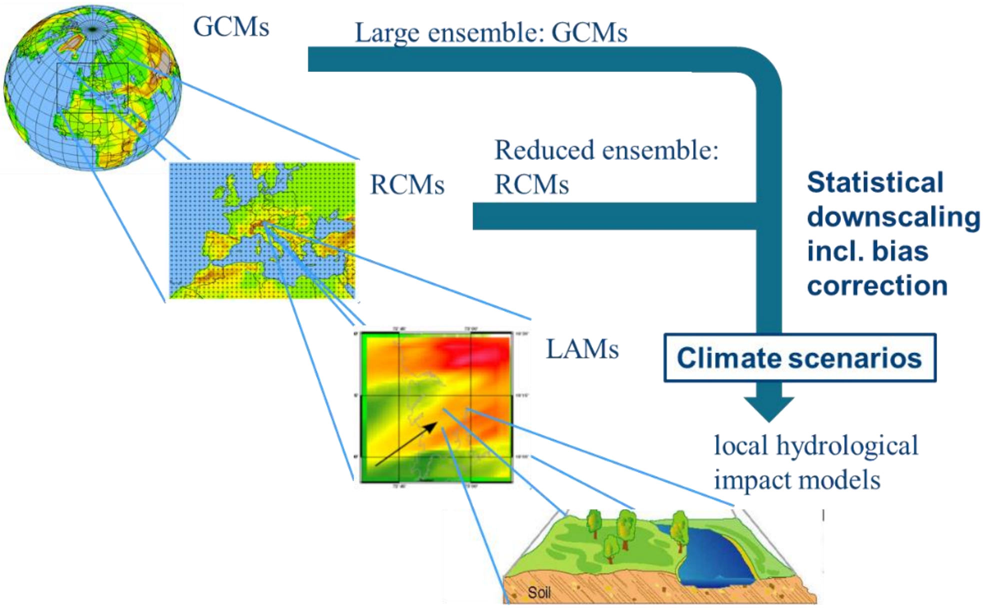


Figure 1. Process where ensembles of GCM and RCM simulations are considered for statistical downscaling and bias correction, and obtain climate scenario's, useful for local hydrological impact analysis

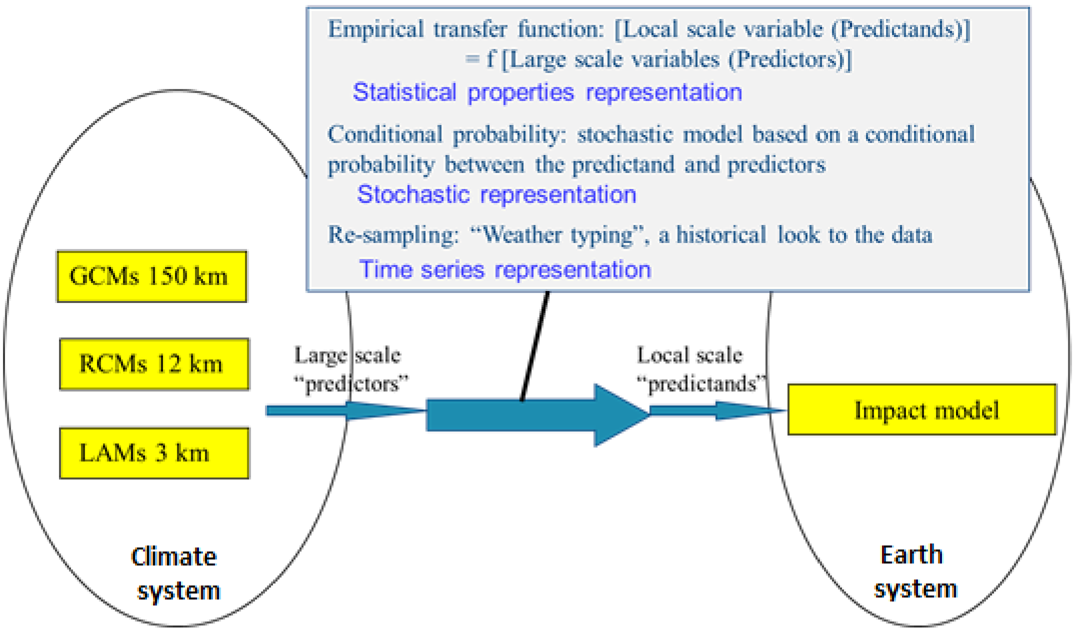


Figure 2. Types of methods for statistical downscaling where the coarse scale climate model outputs (the so-called "predictors") are transferred to local scale impact model inputs (the so-called "predictands")

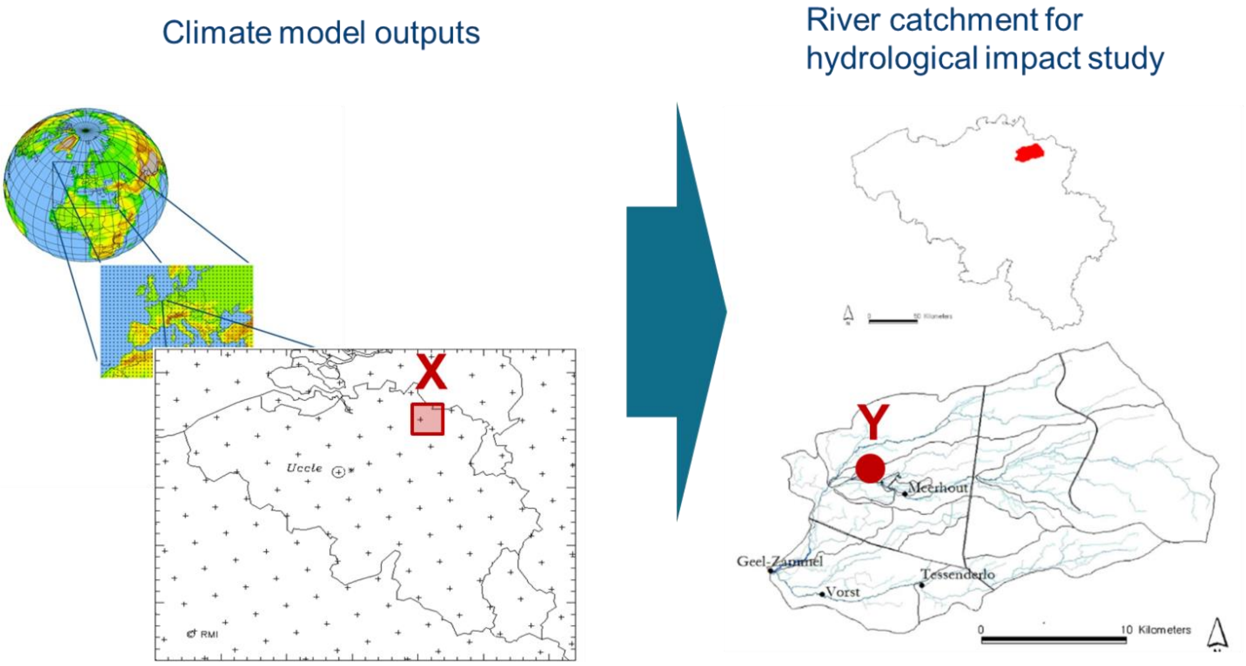


Figure 3. Transfer of the climate model outputs X to the impact model (i.e. hydrological) inputs Y

Testing whether the innovations are climate proof

Question is how it can be tested whether the innovations are climate proof, taking the future impacts of climate change or related testing conditions and their uncertainties into account. The innovation is climate proof when it is effective in any of the climate scenarios. Because of the great uncertainties, this effectiveniss testing cannot be based on precise, deterministic future evolutions. The different climate scenarios need to be considered as testing conditions and the technical effectiveness and social acceptability re-evaluated for each of these scenarios.

Due to the high level of uncertainty in the future climate trends, this effectiveness can strongly vary from scenario to scenario. To keep high effectiveness in all climate scenarios, it may be needed to make the innovation flexible-adaptive and sustainable:

- <u>Flexible-adaptive</u>: It should be possible to make adaptations later, preferably while keeping the cost as low as possible, if the climate is found to evolve towards a highly unfavourable climate scenario. The idea is to prevent that adaptations are made that would make further adjustments in the future impossible or prohibitively expensive. This requires the introduction of a great amount of flexibility, e.g. into control measures or associated technical designs. Preferably, allowance should also be made for the future periods of the various climate scenarios in comparison with the life cycle of the innovation.
- <u>Sustainable</u>: Sustainable decisions are effective in each climate scenario as well as cost-efficient regardless of the exact development of the future climate (within the known bandwidth; high/medium/low climate scenarios). This also means that adaptations are sought that are not only advantageous in the context of climate change, but also offer benefits for other purposes. Climate scenarios often reveal weaknesses in the present solutions or management strategies. By studying the effects of climate scenarios, and therefore representing the meteorological situation more extremely than it actually is, problems in the solution or management - which are already present, but less visible - are more easily identified. Simple and small - but non-sustainable - solutions in the short term are then often not enough. Often, more intelligent, more advanced, more structurally effective solutions that are also sustainable in the long term, are needed.

To make these principles more specific, few examples from the flood management sector are given below. Flexible design means that we no longer work with fixed design rules (which on average produce the best designs in all circumstances), as was traditionally the case in engineering. Instead, more allowance is made for unknown time- and place-specific factors and we accept that our knowledge is imperfect and can/will change significantly in the near future. This process is known as 'active learning', and also implies that designs are no longer driven by engineers, but also supported by and based on the knowledge of all the stakeholders in society. In urban hydrology, which is very much dependent on place-dependent, local knowledge, this means, for example, that (representatives of) local communities become more involved in the decision-making process. Making designs adaptive means, in this context, that for upgrading or renovation, already-changed climatic conditions are taken into account and facilities are provided to allow subsequent measures to be implemented (at a limited cost), such as additional capture of rainwater, storage and pumping capacity.

Examples of sustainable measures are source control measures (e.g. capture and retain rainwater more upstream, infiltration, prevent pollution). This requires structural modifications such as a thorough revision of urban planning legislation, better alignment between urban water management and spatial planning, town planning, land management, agriculture, green areas management, recreation and sports infrastructure management. It also requires a change in mentality among the population possibly induced by financial incentives, such as a rainwater tax, by no longer quickly discharging rainwater via a duct or pipe to the sewer, but having it infiltrate on-site into the ground wherever possible. Conventional, simpler, centralised end-of-pipe solutions (e.g. construction of buffer or retention basins, modification of barrages, by public services) are then no longer enough. Source control measures such as the upstream capture of rainwater discharge from the sewer and having this rainwater infiltrate as much as possible into public and private open spaces, also in the urban environment, are always cost efficient, regardless of climate change. They have a positive effect on water management and also address other problems that are associated with strong urbanisation (e.g. increasing sealing of surfaces). They not only reduce flood risks, but also counteract trends towards lower water availability for drinking water, agriculture and industry (problem of desiccation and decreasing groundwater levels) and provide multiple functions to open spaces (better management of scarce open space). Source control measures and eco-solutions are therefore a good example of measures that are particularly useful in any case, regardless of climate change, as they address the adverse effects not only of climate change, but also of the other trends such as urbanisation.

These principles follow the risk concept. The technical ‘risk’ of certain events - meteorological events or climate evolutions in this case - is quantified as the convolution (multiplication of all possible combinations) of ‘probability of occurrence’ of the events with the ‘potential effects’ of these events. The risk may be high if either the probability or the effects, or both, are high. In the case of climate scenarios, the exact probability of their occurrence is not known. It is also very difficult to estimate. We can, however, calculate the effects of the different climate scenarios, e.g. in impact models. For water management, for example, there are hydrological and hydrodynamic river and sewer models. For agriculture, there are crop growth models and models that quantify agricultural production under certain management and weather conditions. Models available to quantify the health effects of air pollution include air quality models. If the climate scenarios in these impact models (or in other impact assessment tools) are extrapolated, an assessment is obtained of the potential effects of the climate scenarios. If the effects of a given scenario are high, it is important – in addition to pursuing a policy that is aimed at preventing the scenario from occurring – to take the potential scenario into account. This builds on the precautionary principle. In the same way as we, as a “prudent man”, take out insurance to protect ourselves against high-risk events, even if the probability of their occurrence is small (e.g. fire, accidents). Only if the effects of a specific climate scenario are irrelevant; we can ignore that scenario. If the effects of a given climate scenario are relevant, and the precautionary principle therefore has to be applied, the next question is how it should best be taken into account. The probability of occurrence is in fact not known. This can be done by making the climate adaptation strategy or solution or innovation ‘climate proof’ such that the solution becomes ‘no regret’.

The climate scenarios, as described before, and the potential effects cover a range that is expected to encompass the future reality with a high level of probability. There is, however, no absolute certainty. The climate scenarios are based on a number of greenhouse gas scenarios simulated in a series of climate models, but both future estimates of greenhouse gases and physical climate knowledge and therefore also the climate models, are subject to uncertainties. Furthermore, climate transitions with a far-reaching impact are likely to occur in Europe with a definite, but unknown, probability. These far-reaching transitions have not been taken into account in the development of the climate scenarios. Such additional uncertainties cannot yet be explicitly taken into account. It is, however, important that we are aware of their existence. There is, in fact, a definite, but unknown (hopefully small probability) that the future is more extreme than suggested in the current climate scenarios.

Figure 4 indicates that there are different types of uncertainties. Statistical uncertainties are uncertainties that are statistically quantifiable. These allow probabilities to be assigned to estimates, e.g. because

measurements are available to calculate these probabilities. However, because the future climate has not yet occurred, no measurements are available and the uncertainties regarding the future climate cannot be quantified statistically. Instead, and as explained before, we typically work with scenarios, e.g. climate scenarios. They can be used to estimate scenario uncertainties. These are less accurately quantified uncertainties, and are mainly indicative. The (climate) scenarios represent hypothetical future evolutions. The aim is, of course, to use hypotheses that are plausible, so that the whole range of scenarios provides an approximate, but realistic, insight into 'quantifiable'
uncertainty.

In addition to quantifiable uncertainty, there are other uncertainties that are not quantifiable, e.g. physical processes that have not yet occurred in the past, but that may occur in the future in an unpredictable manner (e.g. under changing climate conditions). There are some uncertainties of which we are aware, such as feedback mechanisms. While they cannot be explicitly taken into account, because they are totally unpredictable, it is nevertheless good that we are aware of their existence. There may even be uncertainties of which we are not yet aware (Figure 4). These uncertainties are of course much more dangerous, but because we are not aware of their existence, we cannot formulate them either. We can only hope that they are non-existent or small. In brief, the lack of knowledge about the future climate can be divided up into a quantifiable part and a non-quantifiable part. In the non-quantifiable part, we further distinguish between lack of knowledge of which we realise that it exists or, in other words, of which 'we know that we do not know', and other uncertainties of which 'we do not know that we do not know'.

Based on our climate knowledge and models, our knowledge of the (future) climate may vary from fully known or 'definite' to fully 'indefinite', cfr. Figure 4. Regardless of our level of confidence, we may be right or wrong as the result of 'ignoring' certain processes or feedback mechanisms. Such ignorance may even be more important than the quantifiable uncertainty. We do not have any idea of the latter, and - as already pointed out - it cannot be directly taken into account in the testing of the innovations, but it is important to communicate about it.

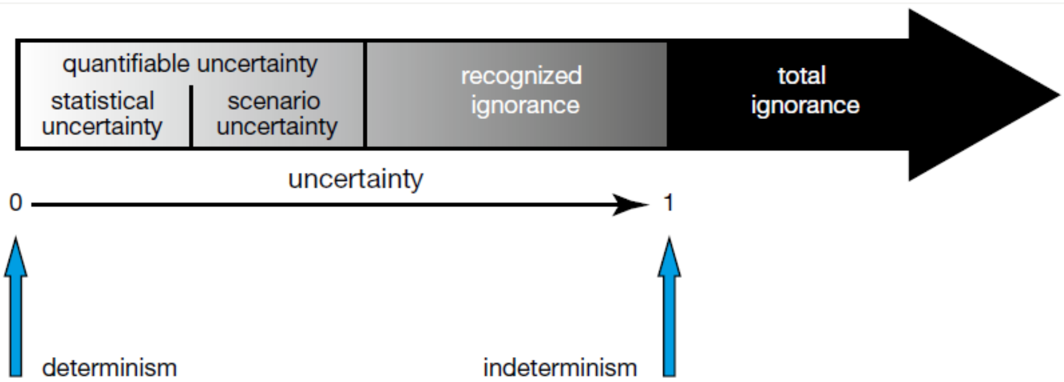


Figure 4. Different levels of uncertainty from the ideal world where everything is known (left) to complete unawareness (right). Source: Willems (2012)

Tiered approach

Because the detailed climate change impact analysis approach by means of statistical downscaling is time-consuming, it is limited in Task 5.1 to the specific test locations considered in the project. Moreover, a step-wise approach is followed in accordance to the WP5 TIF, where a 3-tier structure for testing is proposed:

1) *A simple technical test, involving inputs from available maps, statistics and databases only;*

2) *A detailed technical test, involving model computations and/or field testing;*

3) *Advanced testing, involving probability analysis in addition.*

As innovators cannot be expected to be climate experts, a simple test is most attractive for a first-stage assessment. Depending on the relevance for further application and market development, more detailed testing could be required.

The tiered way of working in establishing load conditions goes as follows:

- *Tier 1: consider pan-european hazard maps and hazard indices that indicate whether there is a hazard, and in some cases the order of magnitude of some essential (but not all relevant) parameters.*
- *Tier 2: include local national hazard maps and studies that provide a better resolution and more detailed insight in loading conditions.*
- *Tier 3: high resolution downscaled local (modelling) studies.*

For Tier 1, pan-european hazard or exposure indicator maps have been set up, which are also useful on the basis of the innovation opportunity mapping of Task 6.1. Some indicator maps are already existing from recent projects such as RAIN and by the EC Joint Research Centre (JRC). For these maps, we aimed to access the digital data. If these digital data were not available and for other/missing indicators, we produced these ourselves from the full set of available CMIP5 and EURO-CORDEX climate model results. The latter obviously could only be done for indicators that could be derived directly from the climate model outputs on meteorological variables. This has put a constraint on the selection of indicators that we could produce ourselves. For the existing indicators, in some projects not only meteorological indicators but also pan-european or regional maps on specific types of impacts were produced. This most often involved a simplified impact model.

In conclusion, in Tier 1 of Task 5.1 (and as direct input for Task 6.1), pan-european climate change hazard potential indicator maps were produced that are based on:

- *Existing climate change exposure indicator maps (RAIN, JRC);*

- *Additional climate change exposure indicator maps obtained from the available CMIP5 and EURO-CORDEX climate model ensemble.*

For Tier 2, the same can be done but based on existing climate change impact maps obtained from national or regional projects.

Tier 3 then involves detailed impact analysis done for the test locations, by the time this is required by the detailed test plan for each innovation. This detailed analysis can be based on a state-of-the-art methods including statistical downscaling and bias correction. It may also involve detailed quantification of the uncertainties through an ensemble approach and climate scenario development where the scenarios are tailored to the type of impact analysis required by the test plan of the innovation.

Tier 1 approach

Climate models, RCP scenarios and historical and future periods

All proposed indicators were derived for the CMIP5 ensemble and the EURO-CORDEX ensemble.

For the river floods hazard, the indicator was based on one RCM run only (COSMO_4.8_clm17 RCM realization r12i1p1, nested in the EC-Earth GCM). For coastal floods, the indicator was based on the RCM RCA4 realization t12i1p1 nested in the EC-EARTH GCM.

For the other indicators (heavy precipitation / pluvial floods, heat waves, droughts, wildfires, wind storms), they were based on the full ensemble of available climate model runs. The CMIP5 ensemble is applied to correct the uncertainty range provided by the EURO-CORDEX ensemble, as per the methodology by Willems (2013), which is summarized next. When the full range of climate change signals derived from the EURO-CORDEX control runs are compared with the full range of climate change signals derived from the CMIP5 ensemble runs, systematic differences are found. It is assumed that these differences have two causes. The first cause is that the higher resolution RCMs provide change signals that systematically differ from the coarser resolution GCMs. Due to the higher resolution of the RCMs, their change signals may be more accurate for local impact impact analysis. The second cause is the difference in the ensemble set of models considered. The EURO-CORDEX RCMs were nested in a more limited set of GCMs than the full CMIP5 ensemble. And it is well-known that RCM results are strongly controlled by the GCM in which they are nested (Rummukainen, 2010). The climate change signals obtained from the RCM ensemble and the GCM ensemble were therefore compared in two ways: comparing the EURO-CORDEX versus CMIP5 climate change signals from the subset of common models, and comparing the CMIP5 climate change signals from this subset and the full ensemble. The subset of common models is for the CMIP5 GCMs the GCMs in which a RCM was nested for at least one of the available EURO-CORDEX runs. The comparison of climate change signals was done based by comparing the frequency distribution of all climate change signals considered, similar to the quantile mapping approach (Willems, 2013; Sunyer et al., 2015; Hundecha et al., 2016). In case a signifcant systematic difference was found between the frequency distributions of the EURO-CORDEX based climate change signals and the CMIP5 based climate change signals (for the subset of common models), correction factors or terms were derived and applied to the climate change signals of the full ensemble set of CMIP5 runs. These correction factors or terms could be derived on a quantile basis; correction terms for temperature, correction factors for the other meteorological variables. For the ensemble mean of climate change signals, for instance, the ratio of the ensemble mean for the EURO-CORDEX based changes over the mean of the CMIP5 changes was derived and considered representative for the systematic difference in climate change impact due to the higher model resolution; this factor was then applied to the ensemble mean obtained from the full CMIP5 ensemble with the aim to potentially improve or bias correct the latter mean. This type of correction was done for each meteorological variable that is considered on the basis of the hazard indicators considered in this report, and for each grid cell.

After this combined use of the CMIP5 and EURO-CORDEX ensembles and correction of the range of indicator values for each grid cell, the ensemble mean values are for each grid cell mapped as indicator values. It is important to note that these mean values should not be interpreted as the most likely future climate conditions. Different climate models may give higher or lower values. This uncertainty is not explicitly addressed in our Tier 1 approach. Taking the ensemble mean is obviously better than selecting just one climate model. In our Tier 2 or 3 approaches, the uncertainty provided by the ensemble set of climate models is explicitly considered.

The historical period considered is 1971–2000 and the future periods 2071-2100 (mean year 2085), 2016-2045 (mean year 2030), and 2036-2065 (mean year 2050). The changes are considered for the “median” and “high” RCP scenarios, which are the RCP4.5 and RCP8.5 scenarios. For the coastal and river floods’ indicators, only results for the future period 2071-2100 were provided.

All proposed indicators or loading conditions are derived from the following GCM/RCM output variables downloaded from the CMIP5 and EURO-CORDEX public databases: precipitation, maximum daily temperature, minimum daily temperature, mean daily temperature, wind speed, radiation, sea level pressure (SLP) and relative humidity.

Table 1 and Table 2 show the list of climate model runs that were available and considered as CMIP5 and EURO-CORDEX ensembles for this study. The indicators were obtained at the resolutions of the regional and global climate models (the EURO-CORDEX runs were available at two spatial resolutions: 12 km and 50 km). At the end, for the Tier 1 approach in this project, in order to obtain smooth spatial maps, the results were averaged at the coarser resolution of the CMIP5 models. This avoids that additional spatial smoothing had to be conducted. The CMIP5 models have a spatial resolution that ranges between 1.12 and 3.75 degrees.

Note from Table 1 and Table 2 that for coastal and river floods only one RCM (RCA4), nested in only one GCM (EC-EARTH) was considered. This means that we have to be very careful that our coastal and river flood loading conditions are not being interpreted as the best estimate of the future climate conditions but as one possible realization of the future climate. For the other indicators, the more robust mean climate change signals are being considered.

To obtain the future downscaled values of the indicators, the climate change signals derived from the climate models – as explained above – were applied to perturb the indicator values for the current climate. The indicator values for the current climate were obtained from observations and reanalysis datasets. For the heavy precipitation, heatwave and drought indicators, the E-OBS dataset of the European Climate Assessment was used, whereas the ERA-Interim reanalysis dataset was considered for the windstorm and wildfire indicators. The E-OBS dataset has the limitation that some raster cells have missing data. This leads to missing data for about 2.5% of the total set of 117,522 local units in the BRIGAID domain. The missing raster cells were not taken into account in the normalization process. For the original maps (before normalization), a version is available where the raster cells with missing data were interpolated or expanded for the cells with missing data at the border of the BRIGAID domain. The latter was done by expanding using the value of the closest raster cells. The disadvantage of the missing raster cells was considered limited in comparison with the advantage of the E-OBS data being based on station data, hence more accurate / less biased than climate model based results. Table 3 presents basic information on the used datasets for the historical climate. One note here is that because the ERA-Interim data start from 1979, the period 1979-2008 was considered as the historical period (to have also a 30-year period) for the wildfire and windstorm indicators. While perturbing the maps for the observations and reanalysis datasets with the climate change signals (which were obtained at the coarser resolutions of the climate models), the climate change signal maps were regridded to the finer resolution of the observations and reanalysis datasets. The latter resolutions are for each type of indicator reported in Table 3: 0.5 degree for the drought and heatwave indicators, 0.25 degree for the extreme precipitation indicator and 0.75 degree for the windstorm and wildfire indicators.

Table 1. CMIP5 GCM runs used in this study for different indicators (control, RCP4.5 and RCP8.5 runs of each GCM were used)

GCM	River / coastal floods	Extreme precipitation / Droughts	Heatwaves	Wildfires	Wind storms
ACCESS1-0_r1i1p1			√		√
bcc-csm1-1_r1i1p1			√		
ACCESS1-3_r1i1p1		√			√
bcc-csm1-1-m_r1i1p1		√	√		
BNU-ESM_r1i1p1		√			√
CanESM2_r1i1p1		√	√		
CMCC-CMS_r1i1p1		√	√		√
CNRM-CM5-r1i1p1		√	√	√	√
CSIRO-Mk3-6-0_r1i1p1		√			
EC-EARTH_r12i1p1	√	√			
GFDL-CM3_r1i1p1					√
GFDL-ESM2G_r1i1p1		√	√	√	√
GFDL-ESM2M_r1i1p1		√	√	√	√
HadGEM2-AO_r1i1p1		√	√		√
HadGEM2-ES_r1i1p1		√	√		√
HadGEM2-CC_r1i1p1			√		√
inmcm4_r1i1p1		√	√	√	√
IPSL-CM5A-LR_r1i1p1		√	√	√	√
IPSL-CM5A-MR_r1i1p1		√	√	√	√
IPSL-CM5B-LR_r1i1p1		√		√	√
MIROC-ESM_r1i1p1		√			
MIROC-ESM-CHEM_r1i1p1		√			
MPI-ESM-LR_r1i1p1		√	√		√
MPI-ESM-MR_r1i1p1		√	√		√
MRI-CGCM3_r1i1p1		√	√	√	√

BRIGAID

NorESM1-M_r1i1p1	✓

Table 2. EURO-CORDEX RCM runs used in this study for different indicators (control, RCP4.5 and RCP8.5 runs of each RCM and indicator were used)

RCM	Driving GCM	Coastal floods	River floods	Other hazard types	
				50 km resolution	12 km resolution
COSMO_4.8_clm17	EC-Earth_ r12i1p1		✓		
SMHI-RCA4_v1	CanESM2_r1i1p1	✓		✓	
CNRM-ALADIN53_v1	CNRM-CM5_r1i1p1			✓	✓
SMHI-RCA4_v1	CNRM-CM5_r1i1p1			✓	✓
CCLM4-8-17_v1	CNRM-CM5_r1i1p1				✓
SMHI-RCA4_v1	CSIRO-Mk3-6-0_r1i1p1			✓	
SMHI-RCA4_v1	EC-EARTH_r12i1p1			✓	✓
IPSL-INERIS-WRF331F_v1	IPSL-CM5A-MR_r1i1p1			✓	✓
SMHI-RCA4_v1	IPSL-CM5A-MR_r1i1p1			✓	✓
SMHI-RCA4_v1	MIROC5_r1i1p1			✓	
SMHI-RCA4_v1	HadGEM2-ES_r1i1p1			✓	✓
CCLM4-8-17_v1	HadGEM2-ES_r1i1p1				✓
KNMI-RACMO22E_v1	HadGEM2-ES_r1i1p1				✓
CLMcom-CCLM4-8-17_v1	MPI-ESM-LR_r1i1p1			✓	✓
MPI-CSC-REMO2009_v1	MPI-ESM-LR_r1i1p1			✓	✓
SMHI-RCA4_v1	MPI-ESM-LR_r1i1p1			✓	✓
SMHI-RCA4_v1	NorESM1-M_r1i1p1			✓	
SMHI-RCA4_v1	GFDL-ESM2M_r1i1p1			✓	

Table 3. Basic information on the historical datasets used for the different indicators

Indicator	Dataset	Variable	Resolution (deg.)
Extreme precipitation	E-OBS	Precipitation	0.25
Droughts	E-OBS	Precipitation	0.50
Heat waves	E-OBS	Maximum temperature	0.50
Wind storms	ERA-Interim	10-m U wind component 10-m V wind component	0.75
Windfires	ERA-Interim	10-m U wind component 10-m V wind component 2-m temperature 2-m dew point temperature	0.75

Spatial domain

The pan-European indicators for the climate change related hazard potential were derived for the territory of Europe. However, comprehensive and spatially-consistent data, both on the loading conditions and the socio-economic environment, do not cover the entire geographical extent of the continent. The modelling domains for the meteorological and hydrological hazards differ, and are presented in the relevant methodologies' sections of the different indicators. Meanwhile, the domain for normalizing the loading conditions, and further analyses are defined as follows:

- All 28 European Union (EU) members, but without their dependencies, both in Europe and overseas[16], and also without outlying regions of Portugal and Spain: Azores, Madeira, Canary Islands, Ceuta and Melilla;
- All 4 European Free Trade Agreement (EFTA) members (Iceland, Liechtenstein, Norway, Switzerland) and
- Macedonia[17].

In case of Cyprus, the normalization was done for the entire island. However, demographic and economic data used to support the normalization excluded areas controlled by the Turkish Republic of Northern Cyprus. The map of the domain is presented in Figure 5.

[16] This exclusion covers all dependent territories of Denmark (Faroe Islands and Greenland), France (overseas departments and other possessions outside Europe), Norway (Svalbard and other polar territories), the Netherlands (territories located in the Caribbean) and the United Kingdom (Guernsey, Isle of Man, Jersey and all British Overseas Territories).

[17] Also referred to as the Former Yugoslav Republic of Macedonia (FYROM).

Figure 5. Spatial domain considered for the pan-European hazard indicator analysis and mapping

Normalization of climate indicators and loading conditions

Innovations dealing with different hazards need to be evaluated in a way that allows a direct comparison of their utility. That required normalized loading conditions. Here, normalization was carried out by establishing the spatial distribution of the intensity of the hazard indicators. This was done at three levels: local, regional and national. At each level, different spatial aggregation methods were used, but all involved political divisions of Europe: countries, regions and local administrative units. Table 4 summarizes the geographical units used in the normalization, while further details are provided in the following subsections.

Table 4. Summary of units at national, regional and local scale. Names of regional and local units in national languages. Source: based on European Union (2014) and Eurostat (2015, 2017)

NATIONAL				REGIONAL		LOCAL	
NUTS0	Country	Area (km²)	Population (1-1-2015)	Names of units*	No. of units	Names of units*	No. of units
AT	Austria	83 879	8 576 261	*Gruppen von Bezirken*	35	Gemeinden	2 354
BE	Belgium	30 530	11 258 434	Arrondissementen / Arrondissements	44	Gemeenten / Communes	589
BG	Bulgaria	110 370	7 202 198	Oblasti	28	Naseleni mesta	4 617
HR	Croatia	56 600	4 225 316	Županije	21	Gradovi, općine	556
CY	Cyprus	9 251	847 008	-	1	Demoi, koinotites	614
CZ	Czech Republic	78 868	10 538 275	Kraje	14	Obce	6 253
DK	Denmark	42 923	5 659 715	*Landsdele*	11	Sogne	2 178
EE	Estonia	45 227	1 313 271	*Maakondade rühmad*	5	Linn, vald	230
FI	Finland	338 440	5 471 753	Maakunnat / Landskap	19	Kunnat / Kommuner	320
FR	France**	543 965	64 277 242	Départements	96	Communes	36 573
DE	Germany	357 367	81 197 537	Kreise, kreisfreie Städte	402	Gemeinden	11 426
EL	Greece	132 049	10 858 018	*Omades perifereiakés enótites*	52	Demoi	326
HU	Hungary	93 011	9 855 571	Megyék + Budapest	20	Települések	3 154
IS	Iceland	103 000	329 100	*Hagskýrslusvæði*	*2*	Sveitarfélög	74
IE	Ireland	69 797	4 628 949	*Regional Authority Regions*	8	Electoral Districts	3 441
IT	Italy	302 073	60 795 612	Provincie	110	Comuni	8 092
LV	Latvia	64 573	1 986 096	*Statistiskie reģioni*	*6*	Republikas pilsētas, novadi	119
LI	Liechtenstein	160	37 366	-	1	Gemeinden	11
LT	Lithuania	65 286	2 921 262	Apskritis	10	Seniūnijos	563
LU	Luxembourg	2 586	562 958	-	1	Communes	106
MK	Macedonia	25 436	2 068 864	*Statistički regioni*	*8*	Naseleni mesta	1 817
MT	Malta	315	429 344	*Gzejjer*	*2*	Kunsilli	68
NL	Netherlands	41 542	16 900 726	*COROP-gebieden*	*40*	Gemeenten	408
NO	Norway	323 772	5 166 493	Fylker	*19*	Kommuner	428
PL	Poland	312 679	38 005 614	*Podregiony*	*72*	Gminy	2 479
PT	Portugal**	89 103	9 869 783	Entidades Intermunicipais (Comunidades Intermunicipais + Áreas Metropolitanas)	23	Freguesias	4 050
RO	Romania	238 391	19 870 647	Județe + Bucuresti	42	Comuni, municipii, orașe, sectoarele Bucureștiului	3 186
SK	Slovakia	49 035	5 421 349	Kraje	8	Obce	2 927
SI	Slovenia	20 273	2 062 874	*Statistične regije*	12	Občine	211
ES	Spain**	498 466	44 154 159	Provincias + consejos insulares	50	Municipios	8 110
SE	Sweden	438 574	9 747 355	Län	21	Kommuner	290
CH	Switzerland	41 291	8 237 666	Kantone / Cantons / Cantoni	26	Gemeinden / Communes / Comuni	2 453
UK	United Kingdom	248 530	64 875 165	*Upper-tier authorities or groups of lower-tier authorities (unitary authorities or districts)*	173	Wards (or parts thereof)	9 499
	Total study area	**4 857 363**	**519 351 981**	**Total no. of regional units**	**1 382**	**Total no. of local units**	**117 522**

Notes: * names of regional and local units are given in the administrative languages of their respective countries (separated by a slash). Regional units that are statistical regions rather than actual administrative divisions are indicated in italics; ** Excludes parts of the countries that are located outside the study's domain.

Local level

At local level, the normalization was carried out firstly by averaging the indicators' values for every local administrative (LAU) unit in the study area. Then, an empirical probability distribution of each aggregated indicator was obtained. Hence, for an innovation applicable to a certain intensity of a natural hazard, the corresponding percentile of the normalized distribution of hazard was calculated.

The aim of using LAUs, which equal municipalities or similar units, was to capture the lowest, local decision level. In many countries, they are the most important layer of administration apart from the central government, and are responsible for a significant part of road infrastructure, waste and water management, spatial planning, housing, volunteer fire service, schools, social care or sometimes even health care.

The local administrative units are defined using Eurostat's two-level LAU classification (Eurostat 2015). The lowest level (LAU 2) is used for all countries, except for Greece, for which LAU 1 units are used due to data availability[18]. The boundaries of LAUs are obtained from a map provided by Eurostat (2017), originally developed by EuroGeographics. The precision of the boundaries' geometrical representation corresponds to a 1:1,000,000 scale map, which is sufficient for the purposes of this analysis. The administrative divisions in the map are nominally accurate as of 2013[19].

There are almost 118,000 LAU 2 units in the study area (see Table 4). They vary greatly in size: the Swedish municipality of Kiruna has around 20,000 km^2, while more than a thousand LAUs have less than 1 km^2. By population, the city of Berlin is the biggest LAU 2 unit with more than 3 million inhabitants, whereas many local units have less than a dozen inhabitants, according to Eurostat (2017).

Regional level

At regional level, the normalization is carried out firstly by averaging the indicators' values for every regional unit in the study area. Then, an empirical probability distribution of each aggregated indicator is obtained. Hence, for an innovation applicable to a certain intensity of a natural hazard, the corresponding percentile of the normalized distribution of hazard is calculated. Additionally, the total population and gross domestic product (GDP) is calculated for regional units within that percentile, and divided by the grand total for the entire study area. This creates an empirical probability distribution corrected by taking into account the different size of regional units.

Regions are important geographical, administrative, economical or cultural divisions of countries. Here, we utilize EU's *Nomenclature of Territorial Units for Statistics* (NUTS), version 2013. The NUTS regions are either administrative divisions of countries, or groupings of smaller administrative units created purely for statistical purposes. The aim of the NUTS classification is to reduce differences in the population of units of the same level. NUTS uses three levels – 1, 2 and 3. Additionally, national level is considered to be level "0". The most detailed level 3 (NUTS 3) is utilized in this study. As presented in Table 4, in 17 countries NUTS 3

[18] However, in some countries (Estonia, France, Germany, Lithuania, Macedonia, Spain, Switzerland) there are areas not belonging to any local administrative unit, typically forest compounds, lakes or military zones. Nonetheless, those areas have their LAU identifiers, and were therefore included in the map of LAUs. Also, in case of Ireland and United Kingdom, electoral divisions are used by Eurostat as LAU 2 units instead of administrative divisions; this is largely due to the heterogenous and complex system of local government in those countries, especially in the UK.

[19] The map was corrected by aggregating LAU units for Latvia and Slovenia, as the map showed the level of localities, which is one level down from LAU 2 classification.

indicates actual administrative units and in 13 – statistical regional units (indicated by italics). Yet, in a given country, some of the statistical units might also be actual administrative units. In the remaining 3 countries no subdivisions are distinguished at this level, as the countries are too small; in other words, the whole country constitutes a single NUTS 3 region. It should be noted that NUTS classification was also implemented in the EU law[20] and is used e.g. for allocating structural funds (Eurostat 2015).

The boundaries of NUTS 3 units (2013 edition) are obtained from a map provided by Eurostat (2017), originally developed by EuroGeographics. The precision of the boundaries' geometrical representation corresponds to a 1:1,000,000 scale map, which is sufficient for the purposes of this analysis[21]. To complete the normalization process, the following statistical data at regional level are collected from Eurostat (2017)[22]:

- Resident population as of 1 January 2015; and
- GDP in current prices in euro generated in 2014.

A statistical summary of the 1382 regions is shown in Table 5. Regions vary greatly in size and wealth, with the largest and wealthiest being metropolises or their parts (Madrid, Paris, London). Meanwhile, many regions in eastern and northern Europe are sparsely populated or relatively poor.

Table 5. Summary statistics for NUTS 3 regions in the study area. Source: based on Eurostat (2017)

Category	Study area total	Study area average	Largest region		Smallest region	
Area (km²), 1-1-2015	4 857 361	3515	SE332 Norrbottens län	105 205	UKI42 Tower Hamlets	22
Population ('000s), 1-1-2015	517 399	375.8	ES300 Madrid	6385.3	CH054 Appenzell Innerrhoden	15.9
Population density per km²	107	X	FR101 Paris	20 976	IS002 Landsbyggd	1
GDP (bln euro), 2014	14 710	10.3	FR101 Paris	207	EL643 Evrytania	0.2
GDP per capita ('000 euro)	28.3	X	UKI31 Camden and City of London	410.3	MK006 Pološki	1.9

[20] For the official listing of all NUTS 2013 units within the EU, see European Union (2014). For a list of NUTS units of non-EU states, see Eurostat (2017).
[21] The map was modified by adding the autonomous Mount Athos to region EL527 Chalkidiki, the only LAU unit in the EU not included in the NUTS classification.
[22] Except for GDP data for Liechtenstein, which are from Amt für Statistik (2017), and for Switzerland, which are from Bundesamt für Statistik (2017). Regional GDP is not available for Iceland; GDP per capita was assumed the same in both NUTS3 regions of Iceland.

National level

At national level, the normalization is carried out by calculating the 95th percentile of the indicators' values for every country in the study area. Then, an empirical probability distribution of each aggregated indicator is obtained. Hence, for an innovation applicable to a certain intensity of a natural hazard, the corresponding percentile of the normalized distribution of hazard can be calculated.

The study area is composed of countries with very different sizes and territorial structures (Table 4). At this level, mitigation of natural hazards is done by the central governments and their agencies. This layer of administration usually has most financial means and authority to employ innovations in dealing with natural hazards, through research & development, water management, infrastructure or environmental administrations and their budgets. However, the country-wide scale of operations of those institutions also implies they will be interested mainly in innovations applicable for the majority, if not all, of their territories. Hence, the 95th percentile of hazard intensity is considered here, as it is a benchmark of (nearly) universal applicability of the innovation in a given country.

Overview of climate change hazard indicators

This section presents the different indicators for the hazard potential related to climate change as considered in Tier 1. They are classified according to the different types of threats or disasters considered in BRIGAID.

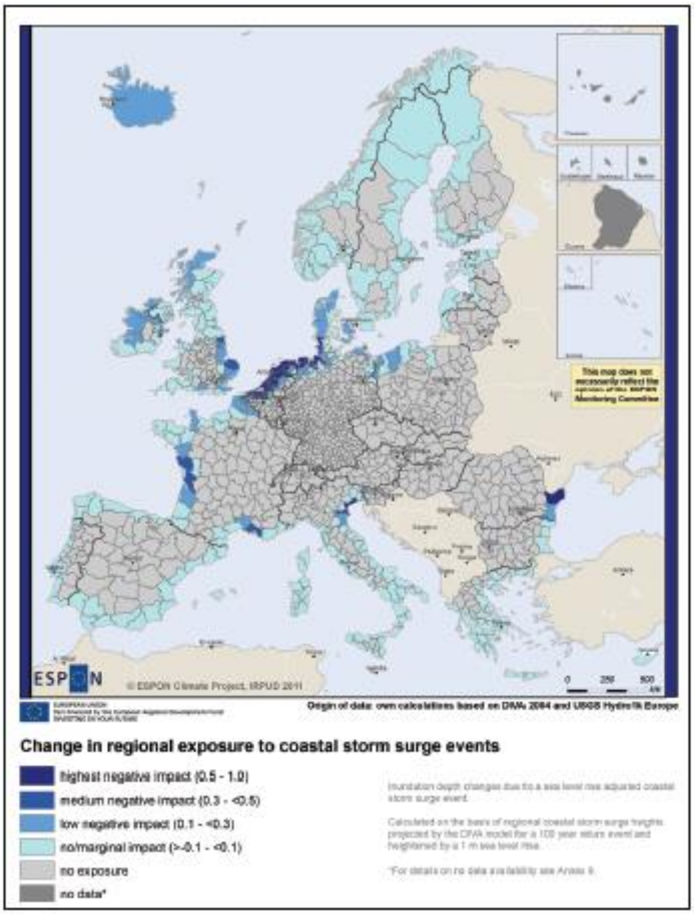
Coastal floods

A coastal flood is the temporary covering by water of land not normally covered by water, caused by high water levels in the sea. High water level may occur due to strong winds blowing sufficiently long over an adequately large area, especially toward the coast, causing a large water run-up at the coast. Unfavourable bathymetric conditions and high astronomical tide further increase the run-up. Coastal floods include floods in estuaries and coastal lakes, caused by influx of seawater into those systems. However, compound events, i.e. the co-occurrence of high sea water levels and high river discharges in those areas, are not considered here. In deriving the future projections of hazard, changes in storminess, sea level rise and glacial isostatic adjustment are considered, but not local effects such as ground subsidence, coastal erosion and accumulation or changes in tide-surge interactions (Paprotny et al., 2016). It should be also noted that high water levels caused by seiches or geophysical events are not considered here.

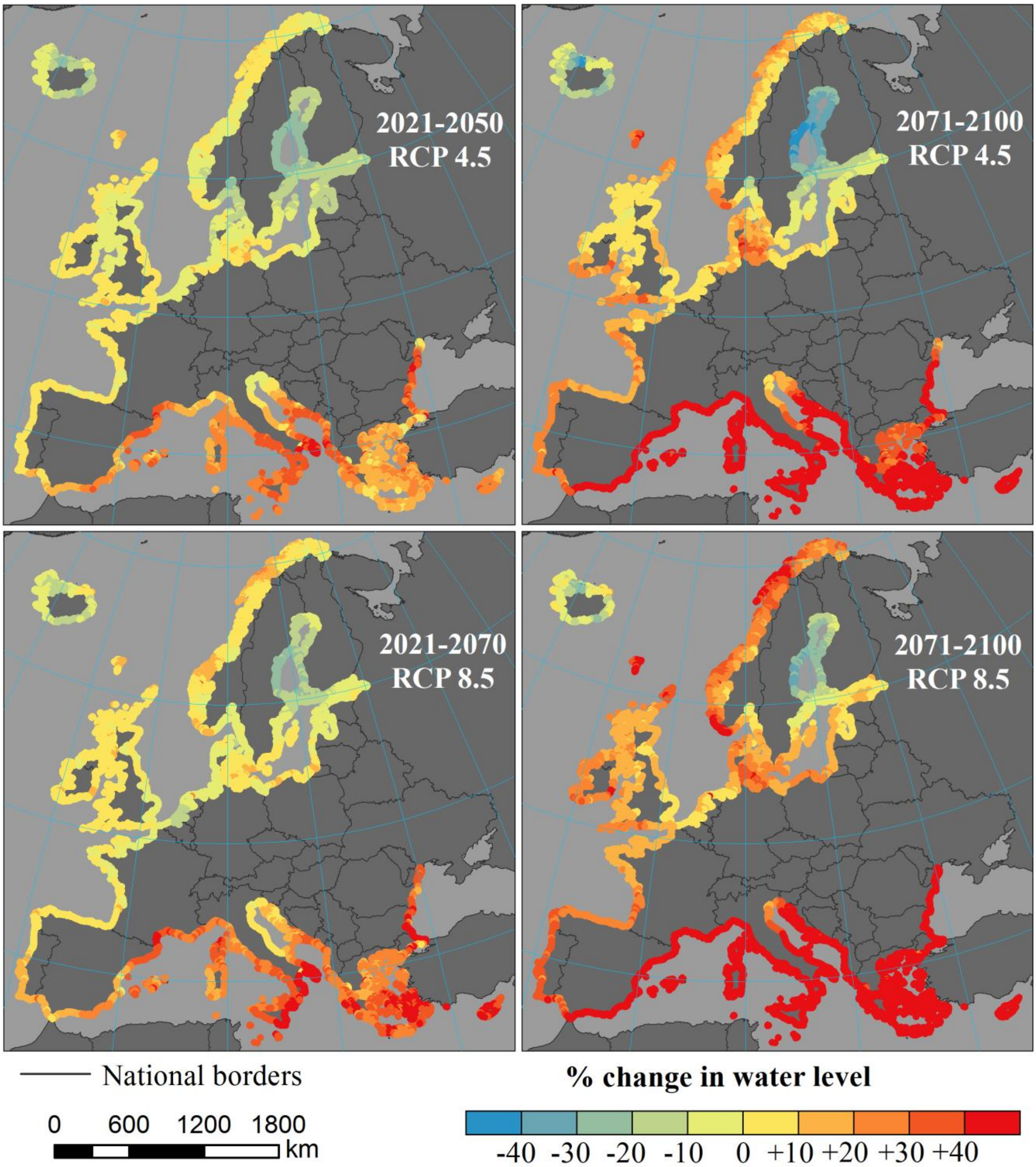
Existing indicators

The impacts of the sea level rise on coastal floods was studied in few global and pan-european studies. See the note by Dominik Paprotny (TU Delft) on “Flood mapping and analysis for BRIGAID project” (version November 2016).

Storm surge heights of a 100-year return event were obtained from DIVA projections (Vafeidis et al. 2005; see also EPSON, 2011). These surge heights were, however, not obtained through a hydrodynamic model and their accuracy was never presented. Therefore, RAIN or JRC data were used.



Hazard indicator to coastal flooding (EPSON, 2011)



Change in 100-year water level relative to 1971-2000

Proposed indicator

Extreme storm surges with a 100-year return period, relative to water levels with a 10-year return period under historical climate

As per the Tier 1 approach, those loading conditions were prepared for 3 scenarios: historical climate (1971–2000) and future climate under two socio-economic development assumptions (2071–2100, RCP 4.5 and 8.5).

However, the baseline water level was not changed. The 10-year return period was chosen as an approximation of the lowest flood protection standards that can be found throughout Europe (see e.g. Scussolini et al. 2016). Meanwhile, the 100-year return period is very widely used in Europe as flood protection standards and scenario for flood hazard/risk mapping. A review of literature identified the use of this return period in e.g. Austria, Croatia, the Czech Republic, Finland, France, Germany, Hungary, Ireland, Italy, Poland, Switzerland and the United Kingdom. It is also the only return period explicitly mentioned in the EU's "Flood Directive" (European Union 2007).

Yet, due to the use of Gumbel distribution the indicator is scalable: the difference in water level between 100-year and 10-year return periods is representative also for other return periods with a difference of one order of magnitude, e.g. 500-year versus 50-year. Therefore, the indicator is informative of how much the flood protection needs to be increased to reduce the probability of flood by one order of magnitude.

Methodology

The data used to calculate the indicator of coastal flood hazard are obtained from a publicly available dataset (Paprotny and Morales Nápoles, 2016c) produced in the project RAIN. The summarized methodology and detailed results were presented in a report by Groenemeijer et al. (2016), with more details on the methodology and elaboration on the accuracy of the storm surge modelling was presented by Paprotny et al. (2016). Below, the main aspects of the methodology are summarized.

The domain of the coastal flood calculation covers most of Europe's coast (Figure 6). The storm surges were calculated within the EURO-CORDEX domain, spanning over the maritime waters around the continent. The coastline, along which coastal flood extents were obtained, is consistent with the river flood modelling domain (see next) and has a total length of 225,800 km. The coastline geometry was obtained from the pan-European CCM2 dataset (de Jager and Vogt, 2010).

Modelling of coastal floods consisted of two steps. Firstly, a time series of 6-hourly sea levels was generated using a two-dimensional hydrodynamic model driven by meteorological data. Secondly, extreme value analysis was carried out on this time series and the resulting return periods were combined with information on sea level rise and glacial isostatic adjustment obtained from external datasets.

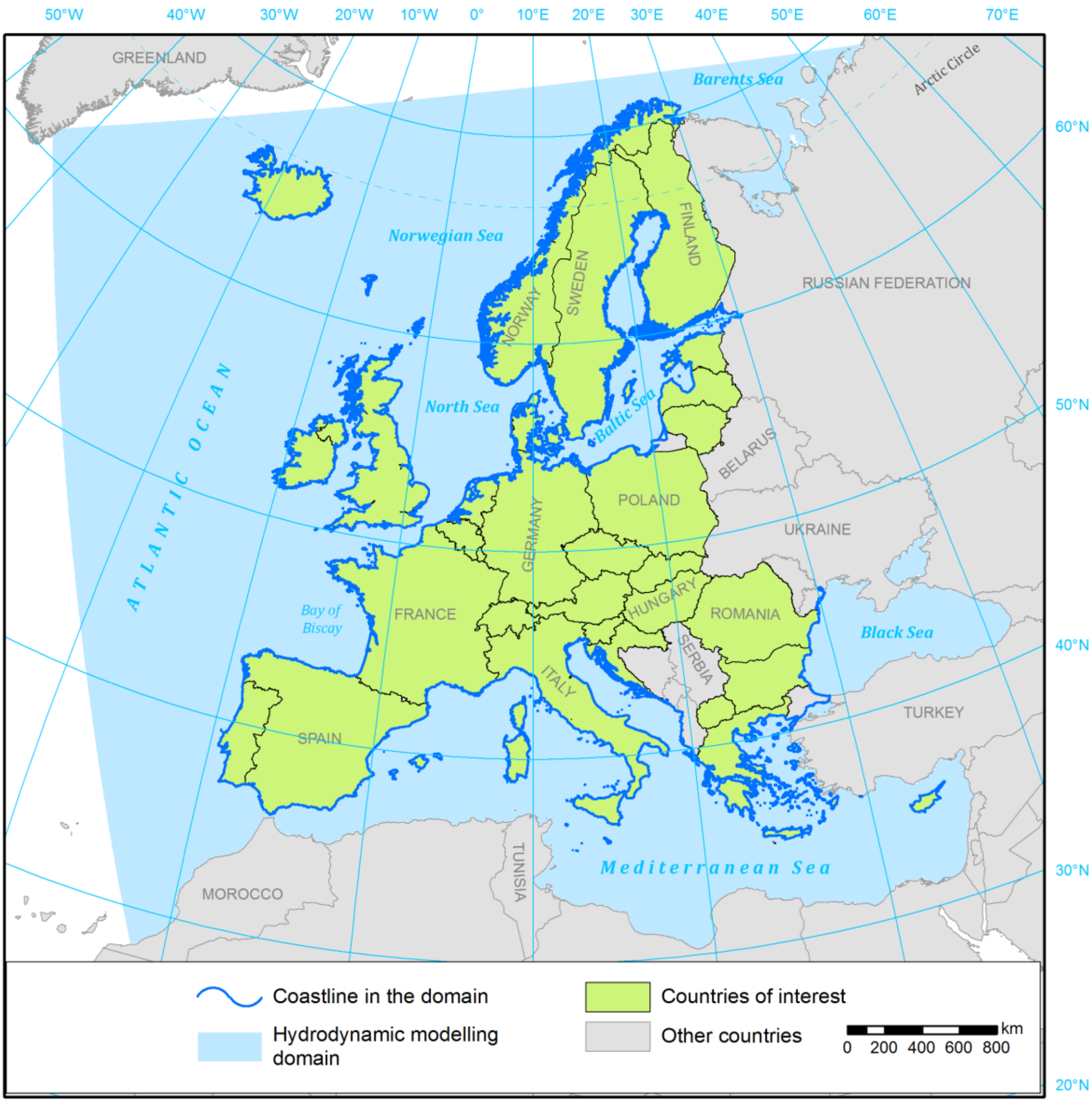


Figure 6. Domain used in the RAIN project to obtain coastal flood hazard maps. The coastline geometry was obtained from the CCM2 dataset (de Jager and Vogt 2010)

Simulations of storm surges were carried out using Delft3D software by Deltares (2013). The mathematical core of the model is comprised of a 2D derivate of de Saint-Venant equations, known as shallow water equations, which provide depth-averaged flows of water. The model was forced by data provided by the Rossby Centre of the Swedish Meteorological and Hydrological Institute. Those climate simulations utilized EURO-CORDEX framework, with RCA4 regional circulation model (Strandberg et al. 2014) forced by the EC-EARTH general circulation model, realization t12i1p1. The meterological input consisted of 6-hour series of air pressure and wind speed (northward and eastward components). The resolution of the climate data is 0.11° and the same grid was used to set-up the model in Delft3D, though the domain's size was slightly reduced for *computational efficiency. Additionally, ERA-Interim climate reanalysis (Dee et al. 2011) was used to perform a calibration of the model. The validation has shown that a good accuracy of modelled storm surges when compared with observations from 161 tide gauges from around Europe. For details we refer to Paprotny et al. (2016).*

From the 6-hourly series of storm surges annual maxima were calculated, and by applying extreme value analysis return periods were obtained. Generalized Extreme Value (GEV) distribution was used for the purposes of the analysis. The surge heights calculated this way are relative to local mean sea level. This indicator was used directly for the historical indicator of extreme water level, as we assumed that high tidal level is part of the "normal" conditions in a given location. For the future climate, apart from the changes in storminess two additional factors were used: sea level rise and glacial isostatic adjustment. Therefore, the indicator of storm surge (SI) with can be written as:

$$SI_{hist} = SURGE_{100,hist} - SURGE_{10,hist}$$

$$SI_{rcp4.5} = SURGE_{100,rcp4.5} - SURGE_{10,hist} + SLR_{rcp4.5} + GIA$$

$$SI_{rcp8.5} = SURGE_{100,rcp8.5} - SURGE_{10,hist} + SLR_{rcp8.5} + GIA$$

where:

hist, rcp4.5 and rcp8.5 are the historical scenario (1971–2000) and two future scenarios, RCP 4.5 and RCP 8.5 (2071–2100), respectively;

$SURGE_X$ is the surge height with a X-year return period;

SLR is the increase in mean sea level (2071–2100 mean level relative to 1971–2000), based on regional projections compiled from external datasets: dynamic and steric component from CNRM-CM5 general circulation model (Voldoire et al. 2013) and contributions of groundwater depletion, glacier and ice sheet mass balance, and ice sheet dynamics from estimates by Slangen et al. (2014) and Carson et al. (2016)[23].

GIA is the glacial isostatic adjustment, which is climate-scenario independent. It represents the vertical movement of the Earth's crust (2071–2100 mean level relative to 1971–2000). The data were obtained from ICE-6G_C (VM5a) model output with a 1° resolution (Peltier et al. 2015).

Limitations and uncertainty

The analysis includes several sources of uncertainties. One is related with input data. Storm surge heights are derived through a hydrodynamic model, which performance for individual stations was very diverse. For example, much lower accuracy was observed

[23] The "dynamic" component is the change in ocean circulation patterns, while the "steric" component is the evolution in ocean volume due to changes in temperature and salinity. Ice sheet dynamics and groundwater depletion projections are the same for RCP 4.5 and RCP 8.5.

over the Mediterranean Sea, compared to North or Baltic seas. Due to the relative coarse resolution of the model (~12 km) the complicated shape of the coast of Norway, Finland or Greece couldn't be properly incorporated.. Datasets on GIA and SLR have even coarser resolutions, causing relatively steep changes between many coastal segments.

Methodologically, several components that could locally influence surge heights were omitted, such as tide-surge interaction, the impact of sea level rise on tides or ground motion other than GIA. Those effects could be locally very significant. as these are very local factors with a number of causes, and no large-scale datasets are available.

The indicator assumes that the existing flood protection corresponds to a 10-year water level, and the desired flood protection to a 100-year water level. In practice, the nominal and actual protection levels vary enourmously between locations. In the Netherlands, for instance, there are dike section that would protect against a 1 in 10,000 years event, while in Poland dikes with a protection standard lower than 10-year return period were allowed to be built between 1997 and 2007. However, as noted above, due to the use of Gumbel distribution the indicator is representative for other return periods with a difference of one order of magnitude.

Finally, there is uncertainty related to future projections. Accuracy of storm surge projections is dependent on the accuracy of air pressure and wind speed/direction projections. The difference between RCP 4.5 and RCP 8.5 scenarios is sometimes very large, to the point that opposite trends are indicated. This alone illustrates the significant uncertainty related with climate change. Meanwhile, sea level rise is a combination of several climate-related factors, which are understood and quantified to a varying degree, especially below the scale of the whole globe. Existing estimates have a low spatial resolution and large uncertainty bounds. Storm surge projections are based only one climate change model, similarly the dynamic and steric components of SLR from another model, which provide less confidence than an ensemble of climate models.

River floods

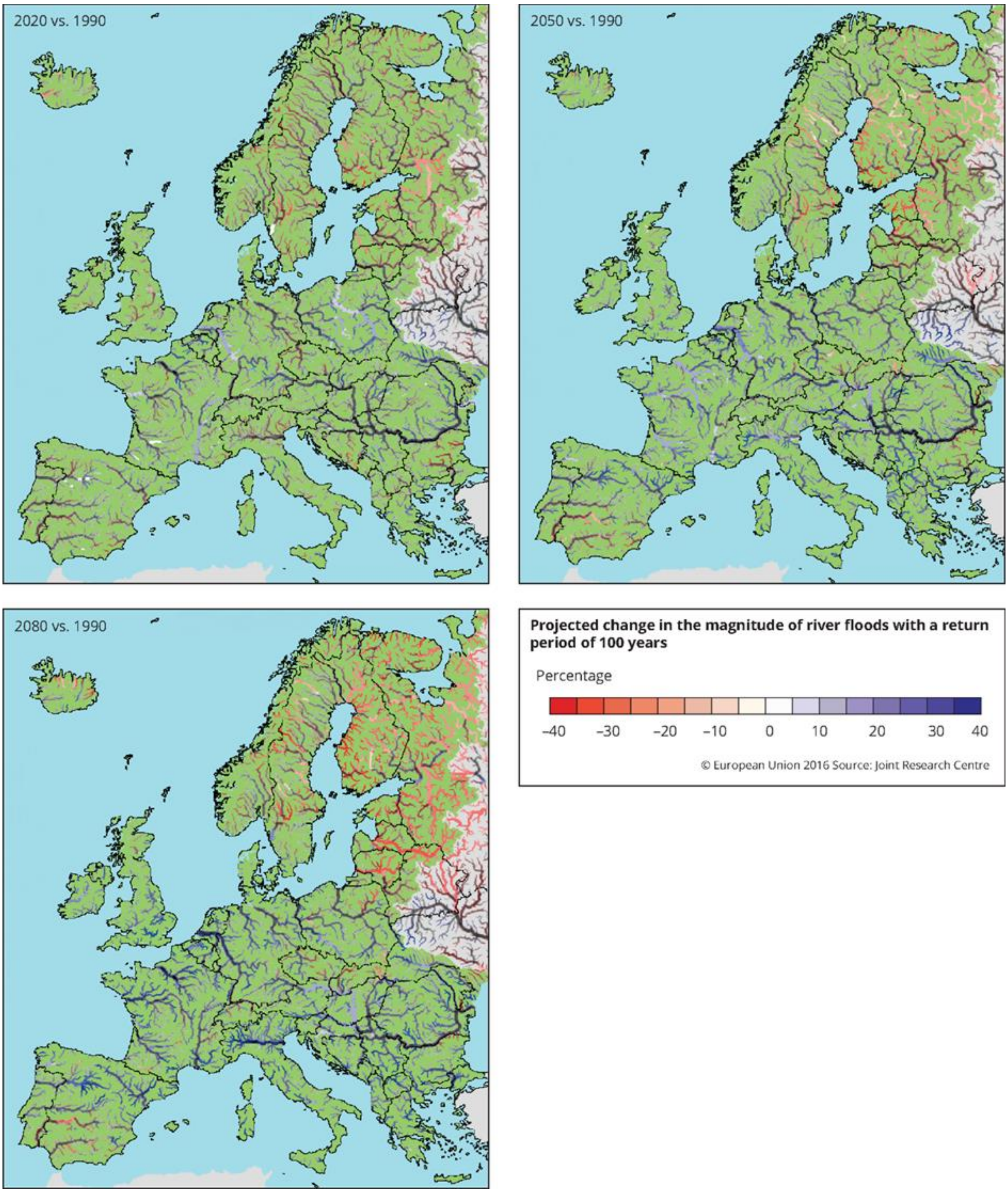
A river flood is the temporary covering by water of land not normally covered by water, caused by high discharge in a river. High discharge may occur due to extreme precipitation and/or snow melt in areas located upstream, that have sufficient intensity and duration, in combination with soil saturation. Rivers include also mountain torrents and Mediterranean ephemeral water courses (European Union, 2007), however only river sections with catchments bigger than 100 km^2 are included in this study. Cases of flooding caused by ice jams are also not included in the modelling framework (Groenemeijer et al., 2016). Urban floods, caused by insufficient sewage system capacity, and flash floods, caused by very short yet intense rainfall over a small area, are considered under “heavy precipitation”. In deriving the future projections of hazard, changes in precipitation, snowmelt and general runoff generation conditions are considered, but not effects of new hydraulic structures (Paprotny and Morales Nápoles, 2016a).

Existing indicators

IPCC considers the changes in annual mean runoff.

The European Environment Agency uses changes in the frequency of very severe flood events and in river floods with a return period of 100 years. The frequency of very severe flood events is derived from a combination of information available in global databases such as the Dartmouth Flood Observatory and the Emergency Events Database (EM-DAT) of the Centre for Research on the Epidemiology of Disasters (CRED), data reported by EU Member States under the EU Floods Directive and an additional country consultation in all EEA member and cooperating countries. Future change in the risk of river floods is simulated using a hydrological model driven by an ensemble of climate simulations.

The below map is an example of the change in river floods with a return period of 100 years for Europe.



The catchment runoff is only an indirect estimator of the river flood hazard. There are several recent projects that produced global and pan-european maps with the flood hazard, expressed by the return period of river flooding. Examples are the European Flood Alert System (EFAS) by the EC Joint Research Center (JRC) and its global extension GloFAS, and projects such as RAIN and CFFlood. See the note by Dominik Paprotny (TU Delft) on “Flood mapping and analysis for BRIGAID project” (version November 2016).

Other types of impacts that may be considered are water depth, velocity, flow rise rate, debris impact, etc.

Proposed indicator

Extreme river water levels with a 100-year return period, relative to water levels with a 10-year return period under historical climate

The rationale for the indicator is the same as for coastal floods.

Methodology

The data used to calculate the indicators of river flood hazard were obtained from a publicly available dataset (Paprotny and Morales Nápoles, 2016a) produced in a FP7 project RAIN[24]. The summarized methodology and detailed results were presented in a report by Groenemeijer et al. (2016), with more details on the methodology and elaboration on the accuracy of the results presented by Paprotny and Morales Nápoles (2016b) and Paprotny et al. (2017). Below, the main aspects of the methodology are summarized.

The domain of the river flood calculation covers most of Europe (Figure 7). Because the RAIN project, like BRIGAID, focused on EU countries, all river basins at least partially located in this group of states were included (including Cyprus, geographically part of Asia). Some additional neighbouring basins were added for complete coverage of Europe, except for basins located completely within the territory of the former Soviet Union. Also, the outermost regions of Madeira, the Azores and the Canary Islands were omitted because they were outside the EURO-CORDEX domain, which was used in the climate model that served as input for the hydrological model. The total domain's area is 5.67 mln km^2, and includes 498,420 km of rivers with catchments bigger than 100 km^2.

[24] European Union's Seventh Framework Programme, project "Risk Analysis of Infrastructure Networks in response to extreme weather" (2014–2017).

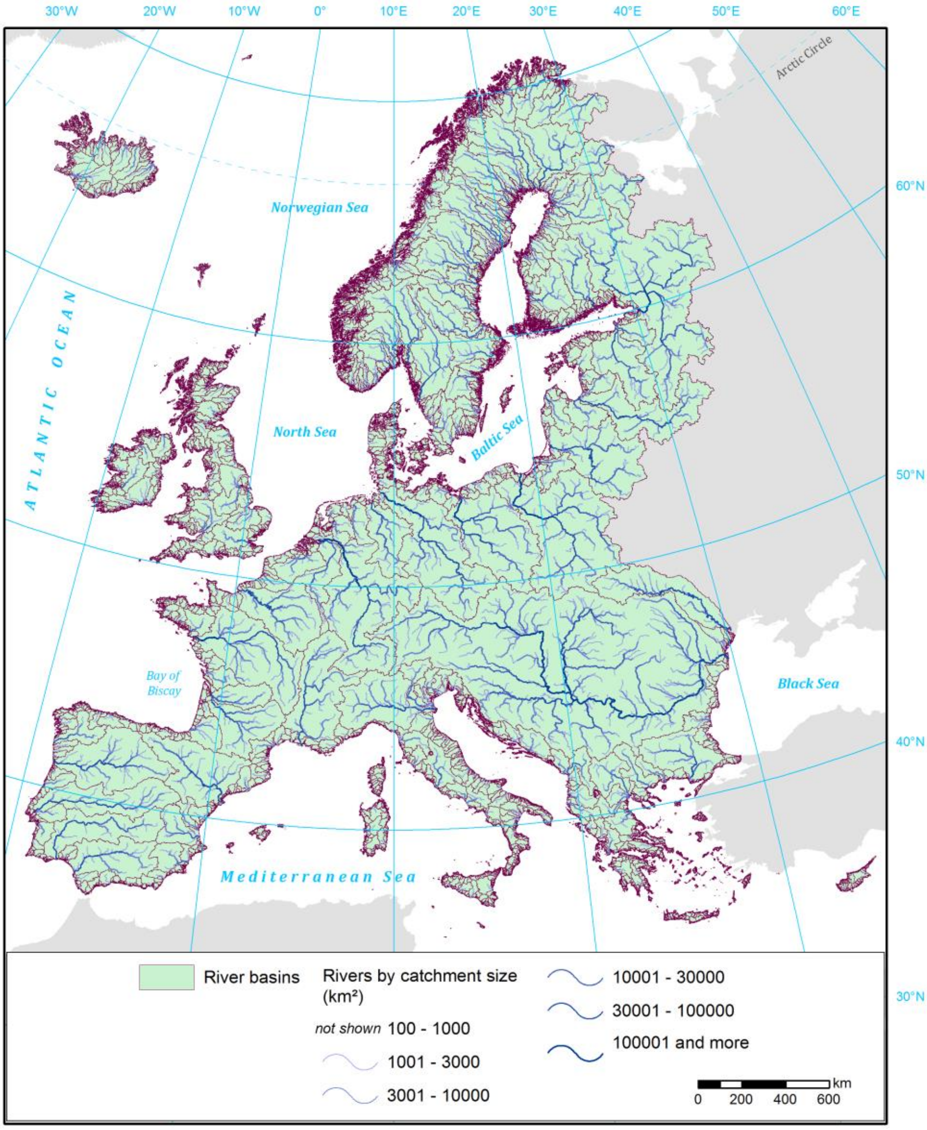


Figure 7. Domain used in RAIN project to obtain river flood hazard maps; for the sake of clarity, only rivers with a catchment area larger than 1000 km^2 are presented on the map. Delimitation of rivers and basins from CCM2 dataset (de Jager and Vogt, 2010)

Modelling of river floods consisted of two steps. Firstly, extreme river discharges with given return periods were calculated using a Bayesian Network-based hydrological model, under present and future climate. Secondly, selected river discharge scenarios were used to obtain water levels through a one-dimensional hydrodynamic model.

Several statistical models of estimating river discharge were developed, to be used on various spatial scales, from local to global. However, using a non-parametric Bayesian Network (NPBN) for that purpose was first investigated by Paprotny and Morales Nápoles (2015, 2016b). The model utilizes the fact that many characteristics of catchments influence the intensity of river discharges. In the NPBN model, the probability distributions of 7 variables are used to describe the conditional probability distribution of annual maxima of daily river discharge. The model was quantified with 1841 European river gauge stations with almost 75,000 years of observations. For each gauge station, the following characteristics of their upstream catchments were calculated: area, steepness, annual maximum of daily precipitation and snowmelt, extreme runoff coefficient, fraction covered by lakes, fraction covered by marshes and fraction covered by build-up areas. Data were obtained from several pan-European and global datasets. Using the series of annual maxima of daily river discharge estimated by the NPBN, an extreme value analysis was carried out. The validation has shown that good accuracy was achieved, compared to other hydrological models, for estimating river discharges with given return periods over Europe. The method was then used to model annual maxima of river discharges in all European rivers within the domain. The hydrologic network was derived for that purpose from the pan-European river and catchment database CCM2 (de Jager and Vogt 2010), and was comprised of almost 2 mln km of rivers. Simulations were done for both present and future climate (spanning from 1951 to 2100) using climate model output from EURO-CORDEX, that employed a combination of the EC-Earth GCM (run by ICHEC) with the COSMO_4.8_clm17 RCM, realization r12i1p1. The climate model resolution was 0.11° on a rotated grid, or approx. 12 km. For more details about the model we refer to Rockel et al. (2008) and Kotlarski et al. (2014).

Annual maxima of discharge were used to undertake an extreme value analysis. Return periods of discharges were calculated under the assumption that the distribution of annual maxima follows Gumbel distribution. Once those river discharge scenarios have been obtained they were used as input for SOBEK v2.13 hydrodynamic model (Deltares 2015). In order to minimize computational time, the modelling option chosen was a one-dimensional (1D), steady-state, lumped representation of the river network. The model required the following inputs:

- River network, which was derived from the CCM2 dataset. Only rivers with catchment larger than 100 km^2 were included.
- Calculation points, where hydraulic calculations of water flow are performed. Those were defined, on average, every 2 km of rivers.
- Upstream boundaries, where water enters the model. Those was defined using discharge scenarios calculated using NPBN model.
- Downstream boundaries, where water is withdrawn from the model. As those are located at the edge of the sea to which the river drains[25], the boundaries were defined as to represent mean sea level.
- Lateral discharge: an option to enter or withdraw water from the model at locations different than the boundaries. Extreme discharges were inserted at upstream boundaries to the model at the same time, while they in fact do not occur simultaneously. Hence, discharge in the river below the intersections of two rivers will be typically lower than the sum of the two contributing rivers. Using the lateral discharge option, the surplus water was withdrawn from the model, preserving a proper representation of flood scenarios.
- Cross-sections of the river, which were obtained from the EU-DEM digital elevation model (DHI GRAS, 2014) and vary in length depending on the topography. They were defined approximately every 2 km of the river network. Due to the resolution of the EU-DEM (100 m), flood defences are mostly not included in the profiles. Because the river beds are not included in the elevation model, it was assumed that the topography in the EU-DEM represents the mean water levels in the rivers, as has been done in other pan-European studies (e.g. Alfieri et al., 2014). Consequently, mean discharges were subtracted from extreme discharges in the entire model. Mean discharge values were obtained from the same Bayesian Network as for extreme discharges, simply by replacing extreme rainfall/snowmelt and runoff coefficients by annual means.

[25] The only exception were 2 rivers draining to lake Prespa in the Balkans.

The absolute water levels (i.e. relative to mean sea level) from the SOBEK model, available at the calculation points, were linearly interpolated along the rivers to increase the density of estimates. After the data for the 10- and 100-year return periods were extracted, the indicators of extreme water levels (EWI) were calculated as follows:

$$EWI_{hist} = WL_{100,hist} - WL_{10,hist}$$

$$EWI_{rcp4.5} = WL_{100,rcp4.5} - WL_{10,hist}$$

$$EWI_{rcp8.5} = WL_{100,rcp8.5} - WL_{10,hist}$$

where:

- *hist*, *rcp4.5* and *rcp8.5* are the historical scenario (1971–2000) and two future scenarios, RCP 4.5 and RCP 8.5 (2071–2100), respectively;
- WL_X is the extreme river water level with a *X*-year return period.

Limitations and uncertainty

The analysis includes several sources of uncertainties. One is related with input data. River discharge scenarios were calculated using a statistical model, which is less accurate then river gauge measurements, and has limited accuracy in very small catchments (in the range of hundreds of km^2). The results do not include changes in land use (build-up areas, lakes, marshes), both in historical or future scenarios. Uncertainty is also related with DEM's vertical accuracy, which also omits most flood defences. Moreover, the elevation model does not include the bed or embankments of rivers. It is assumed that the surface of DEM represents roughly the mean water level in the river, though some other studies used 'bankfull' discharge (approximated by 2-year return period of water levels). Furthermore, imperfections of the DEM and mismatch with the river layer also occasionally cause very large errors in some model runs. Those locations, where one of the simulations indicated water levels was vastly different from the remaining scenarios, were not included in the normalization. Also, estimates for river sections located on lakes, as defined by the CCM2 dataset, were excluded from the analysis.

Another source of uncertainty is the type of events analysed. As noted before, only rivers with catchments that have an area of at least 100 km^2 were included in the calculation, while flash floods and urban floods were also not analysed. Furthermore, we estimate the extreme river discharge based on two main factors causing flood – rainfall and snowmelt, while floods in northern Europe are also caused by ice and frazil blocking the river flow. We also do not include the reduction of the flood wave through reservoirs or bypass channels but rather consider the flow under 'natural' conditions.

Methodological limitations also apply, especially to the water level and flood extent modelling, which were obtained from the hydrodynamic model utilizing one-dimensional "steady state" simulation and GIS mapping, which is not as accurate as a full two-dimensional simulation. Validated showed a sometimes significant tendency to overestimate hazard.

The indicator assumes that the existing flood protection corresponds to a 10-year water level, and the desired flood protection to a 100-year water level. In practice, the nominal and actual protection levels vary enourmously between locations. In the Netherlands, for instance, there are dike section that would protect against a 1 in 10,000 years event, while in Poland dikes with a protection standard lower than 10-year return period were allowed to be built between 1997 and 2007. However, as for coastal floods, due to the use of Gumbel distribution the indicator is representative for other return periods with a difference of one order of magnitude.

Last but not least, there is uncertainty related with future climate projections. The difference between RCP 4.5 and RCP 8.5 scenarios is sometimes very large. This alone illustrates the significant uncertainty related with climate change and the climate models, as the latter are known to have limited accuracy for precipitation, let alone extreme rainfall. Also, the results of only one climate model were analyse, which provides less confidence than an ensemble of climate models.

Heavy precipitation / pluvial floods

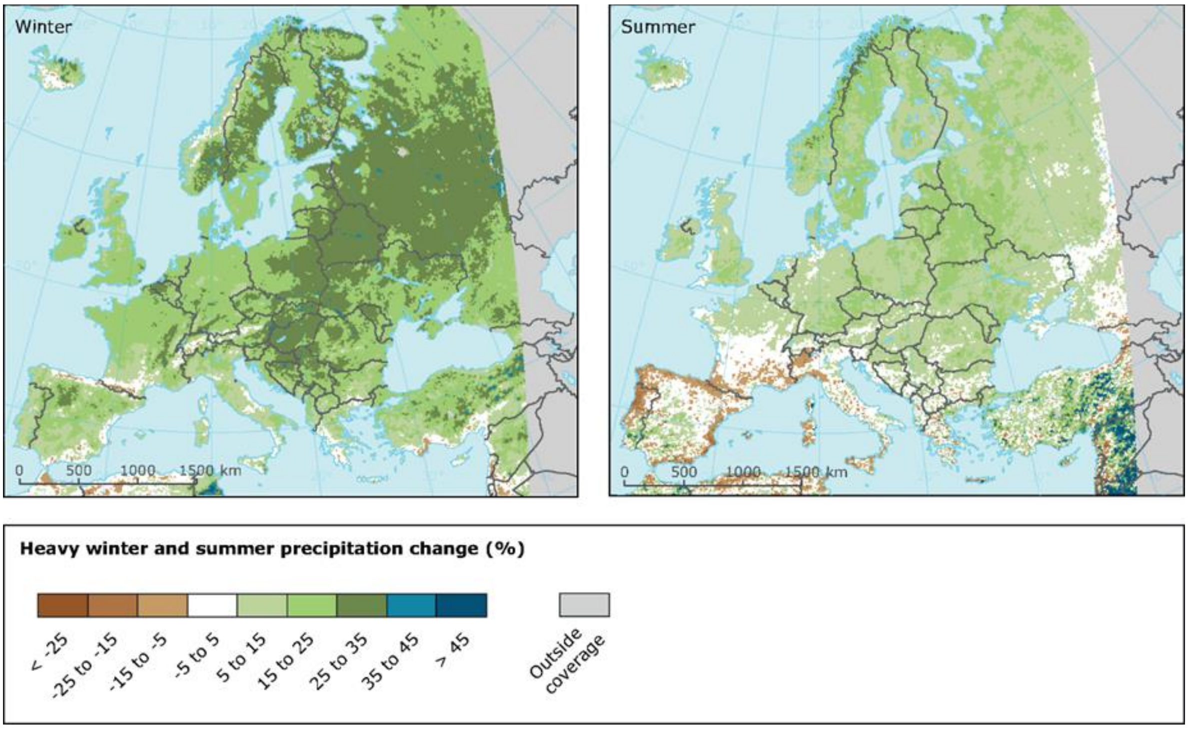
Extreme precipitation induced hazards such as pluvial floods, flash floods, landslides, mudflows, etc. are the result of short-duration rainfall intensities when they exceed a given threshold, e.g. the threshold above which a flood initiates. This threshold corresponds to the criteria used for infrastructure design in different European countries and regions. Infrastructure such as land-based transportation and emergency services are especially vulnerable to extreme precipitation events, as they can lead to the flooding of tunnels and can damage streets, railway lines and bridges. Also electricity and telecommunication networks can be affected by heavy precipitation.

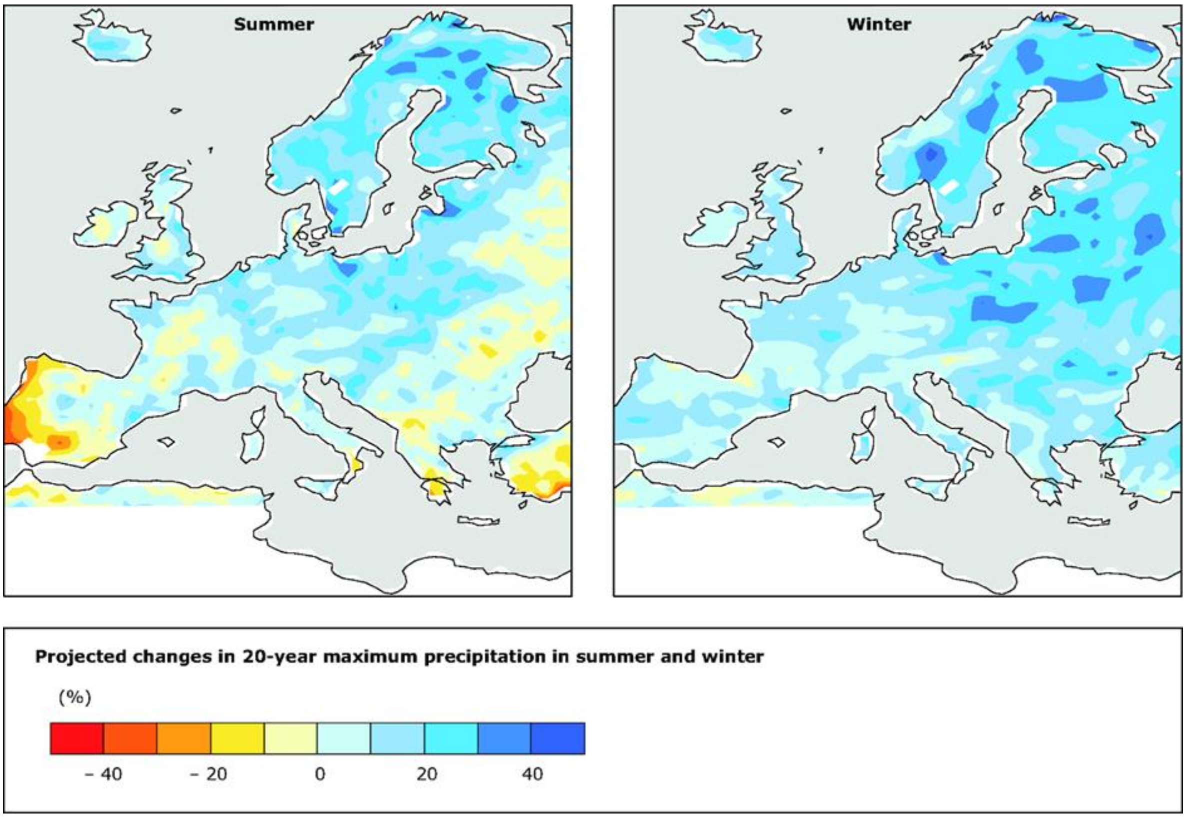
Existing indicators

The IPCC AR5 report makes use of the following indices for heavy precipitation amounts and precipitation intensity:

- Simple daily intensity index (SDII) index: Ratio of annual total precipitation to the number of wet days (≥1 mm)
- Precipitation from very wet days (R95p) index: Amount of precipitation from days >95th percentile

For future conditions, next to the changes in SDII and R95p IPCC also considers the changes in the 2081–2100 return period (RP) for rare daily precipitation values, RX1day, that have a 20-year return period during historical period 1986–2005. Similar indicators are used by the European Environment Agency. The maps below are the example results for the summer and winter seasons for Europe.


Winter
Summer
0 500 1000 1500 km
Heavy winter and summer precipitation change (%)
< -25
-25 to -15
-15 to -5
-5 to 5
5 to 15
15 to 25
25 to 35
35 to 45
> 45
Outside coverage


Summer
Winter
Projected changes in 20-year maximum precipitation in summer and winter
(%)
– 40
– 20
0
20
40

In the RAIN project (Groenemeijer et al. 2016), the maps of heavy precipitation were prepared for 5 climate scenarios (1971-2000, 2021-2050 RCP 4.5, 2021-2050 RCP 8.5, 2071-2100 RCP 4.5, 2071-2100 RCP 8.5). For each scenario, 10-year return period of 3-hour, 24-hour, 48-hour and 72-hour precipitation was calculated as the mean of multi-model ensemble of regional climate models.

Other types of impacts include the occurrence of urban floods and flash floods.

Proposed indicator

*Because most urban drainage systems are designed for return periods between 2 and 20 years, the **daily precipitation intensity (RX1day) for a specific return period of 5 years** was selected for this project. Although this indicator was also computed separately for the summer and winter seasons, the annual values were finally selected for further use in the BRIGAID project tier 1 approach.*

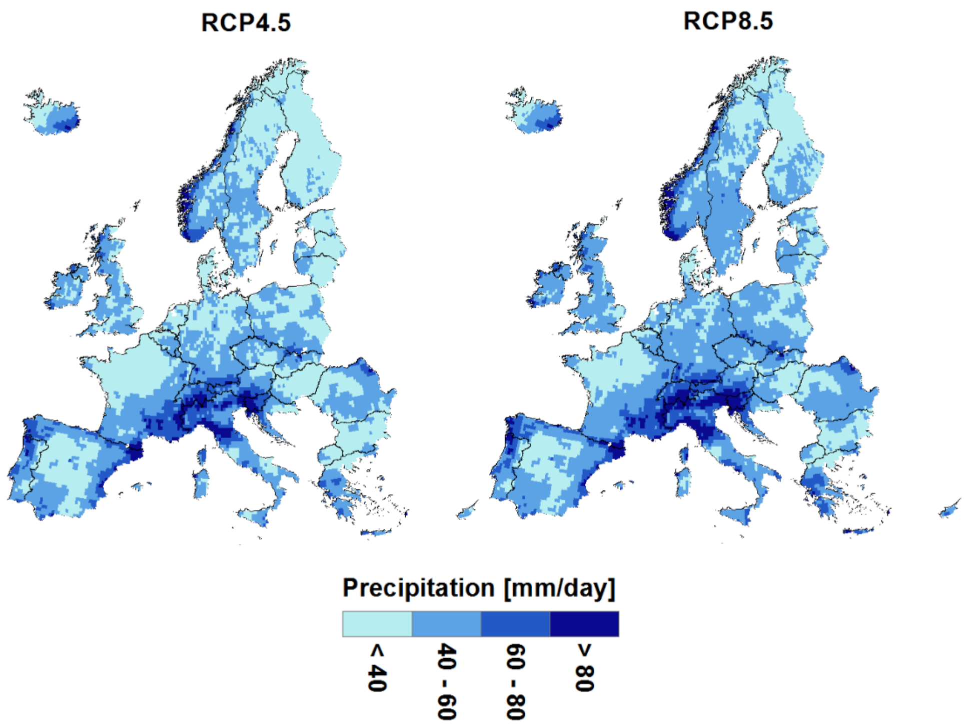


Figure 8 shows the extreme precipitation indicator maps for the historical climate and the RCP4.5 and RCP8.5 climate scenarios. Figure 9 and Figure 10 show the change factors upon which these maps were based on.

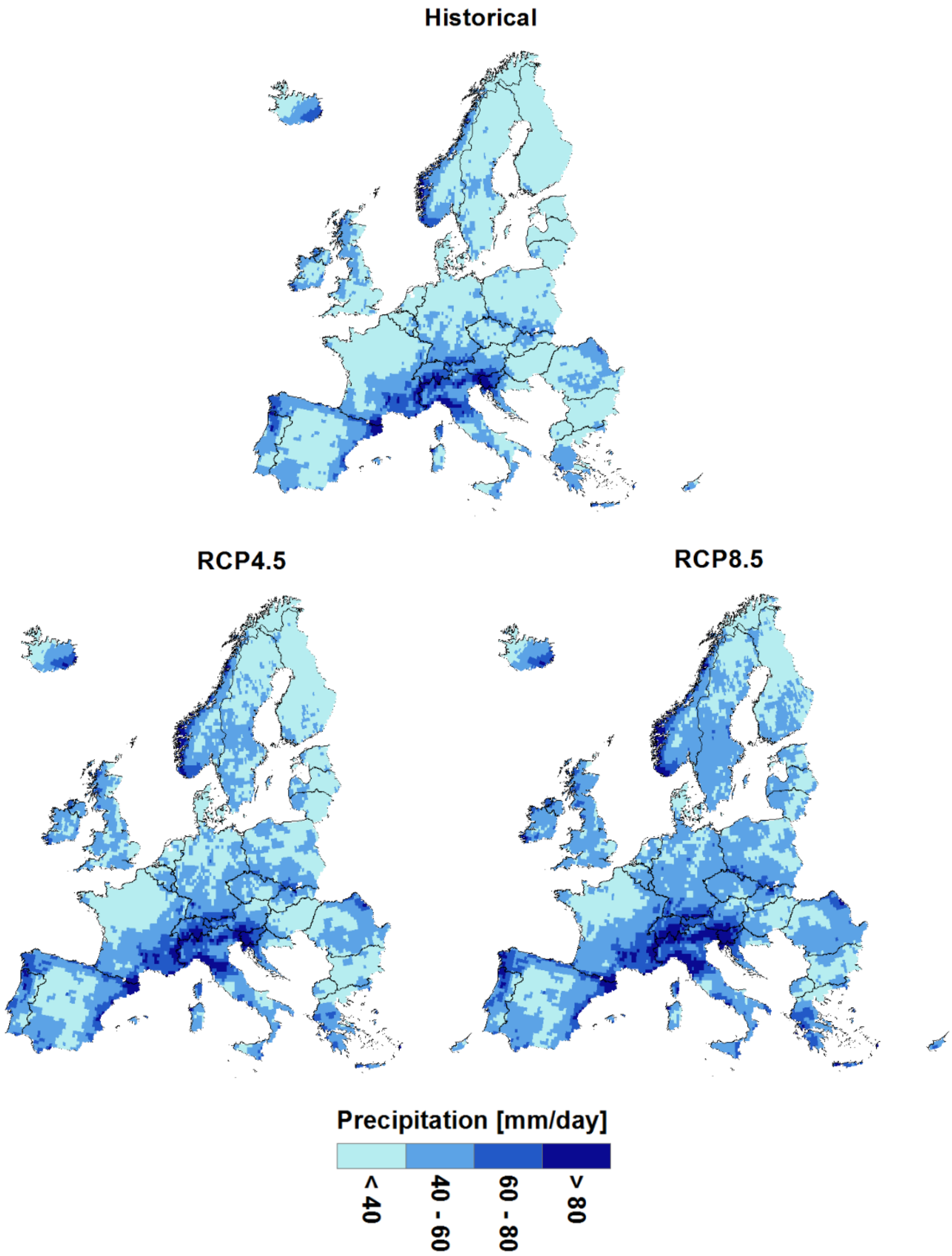


Figure 8. Historical and future extreme daily precipitation (RCP4.5 and RCP8.5) for 5-year return period over Europe.

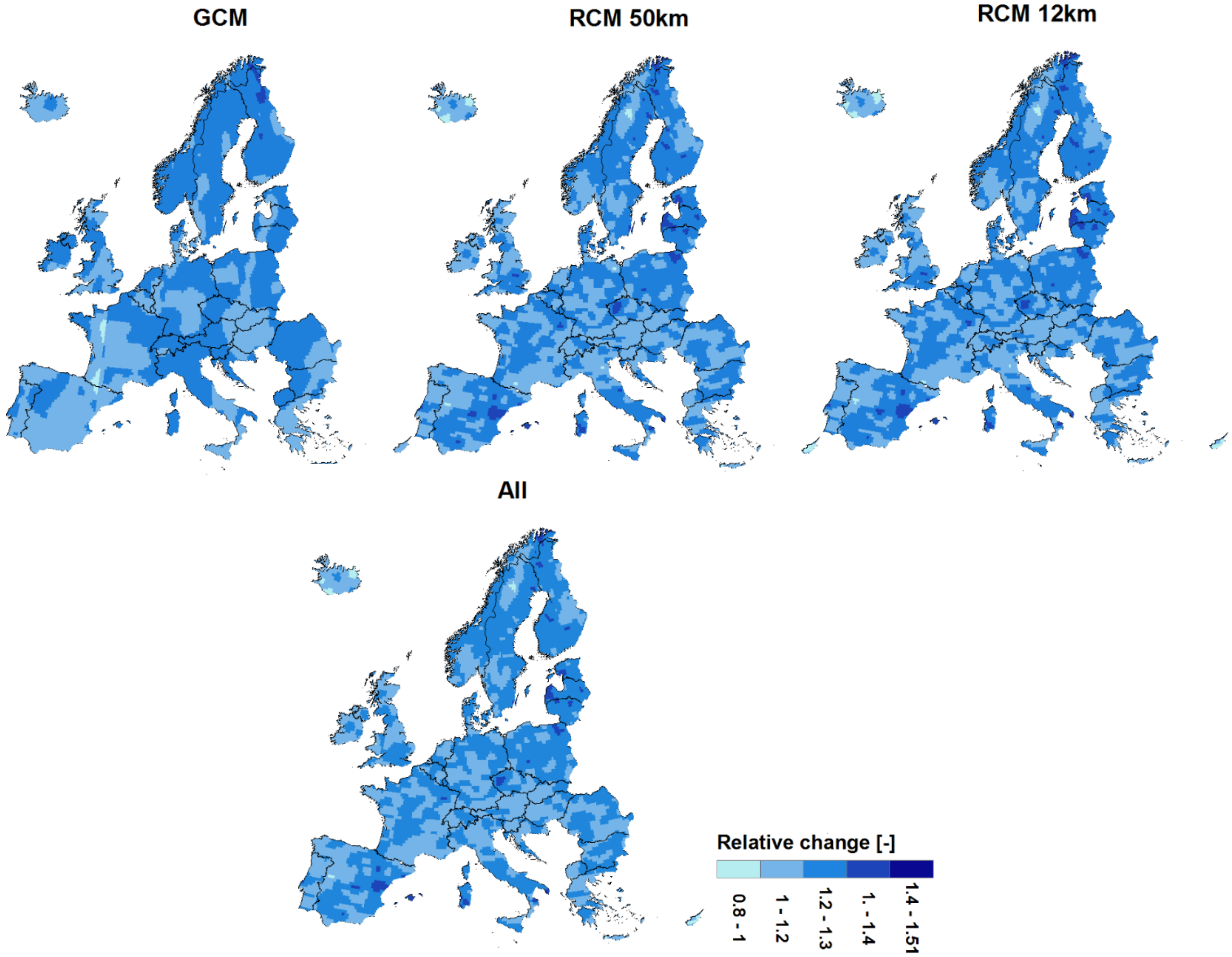


Figure 9. Climate change signals for extreme daily precipitation (RCP4.5) for 5-year return period over Europe.

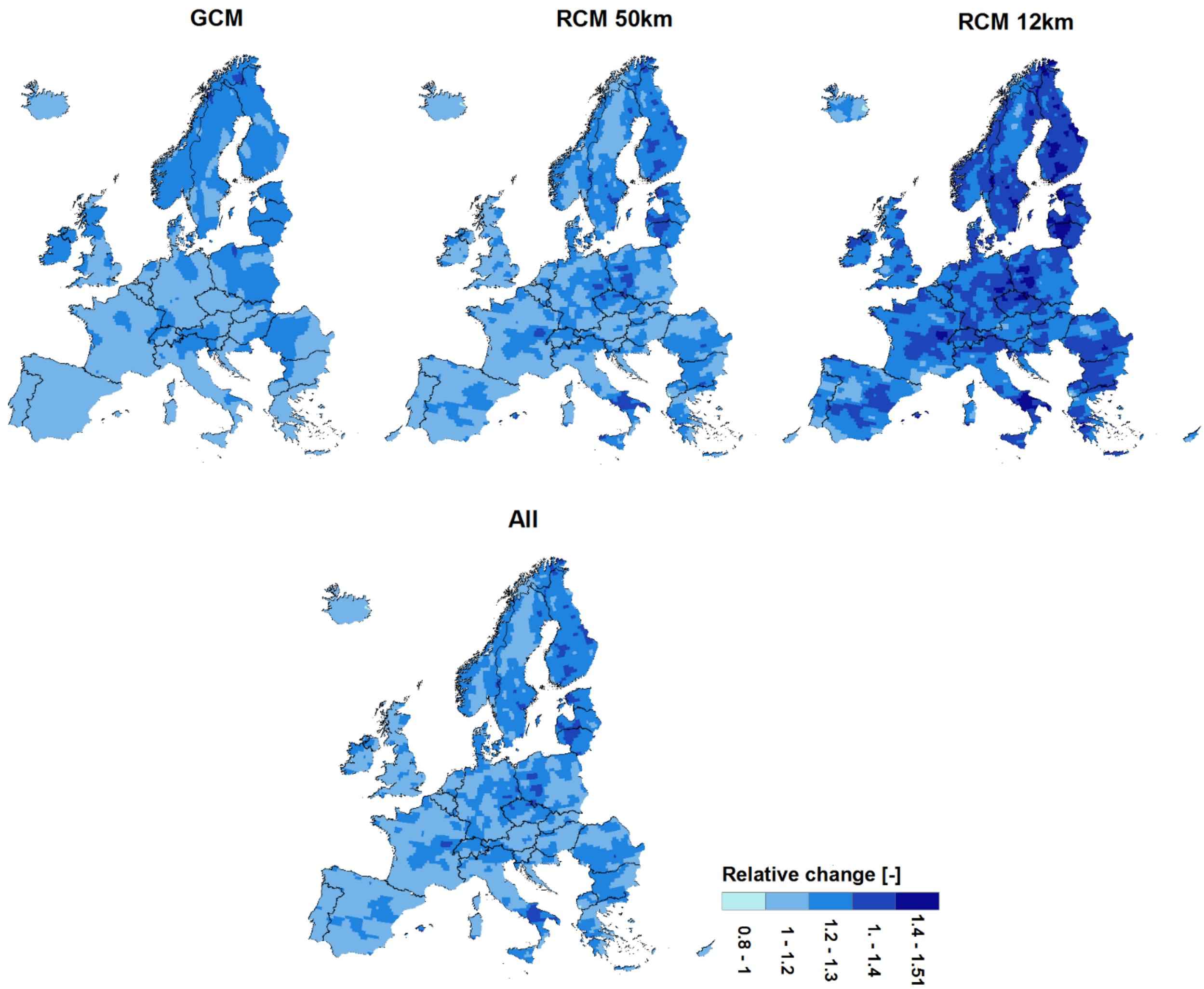


Figure 10. Climate change signals for extreme daily precipitation (RCP8.5) for 5-year return period over Europe.

Limitations and uncertainty

The benefit of this indicator is that it is based on direct meteorological outputs of the climate models. The mean of a large ensemble of both global and regional climate model runs were considered. Hence, the climate change signals used on this basis of the extreme precipitation indicator are expected to be rather robust. There are, however, some limitations:

- The mean climate change signal (mean obtained from the full set of climate models) does not provide information on the uncertainty in the climate change signal. This can be easily obtained from the ensemble results and will be considered in the tier 2 and/or 3 approaches.
- Daily precipitation may not be fully representative for pluvial flooding such as flooding as a consequence of sewer surcharge. Many urban drainage systems have response times smaller than 1 day, which means that sub-daily precipitation may be more appropriate. The

most relevant time scale does, however, vary from system to system. Moreover, sub-daily precipitation data are only available for a limited number of climate model runs.

- Just one selected return period was considered whereas urban drainage systems in different parts of Europe are designed for various return period, typically in the range between 2 and 20 years.
- Just one season was considered whereas the extreme precipitation amounts in many places of Europe strongly vary from season to season.
- This first … mm of rainfall will be stored in the underground sewer network, hence does not contribute to the urban flooding. A threshold could be applied to the extreme precipitation intensities or the exceedance above this threshold considered but this threshold strongly depends on the specific system properties.
- For the impact analysis on pluvial flooding, an urban drainage and surface inundation model would be required. Such models are very detailed and should be considered for local impact analysis.

Heat waves

Heat waves are several consecutive days with very warm days. Based on the WMO definition, heatwaves are defined as periods of more than 5 consecutive days with daily maximum temperature exceeding the mean maximum temperature of the May to September season for the control period (1971–2000) by at least 5°C (Jacob et al., 2014).

Alexander and Herold (2016) defined heatwaves (HWs) using different approaches:

i. HW amplitude (HWA) represents the hottest day of the hottest yearly event;
ii. HW magnitude (HWM) is the average daily magnitude across all HW events within a year over the period considered (May-Sept);
iii. HW number (HWN) is the yearly number of HW events;
iv. HW duration (HWD) is the maximum length of a HW event in a year;
v. HW frequency (HWF) is the sum of participating HW days according to the definition criteria.

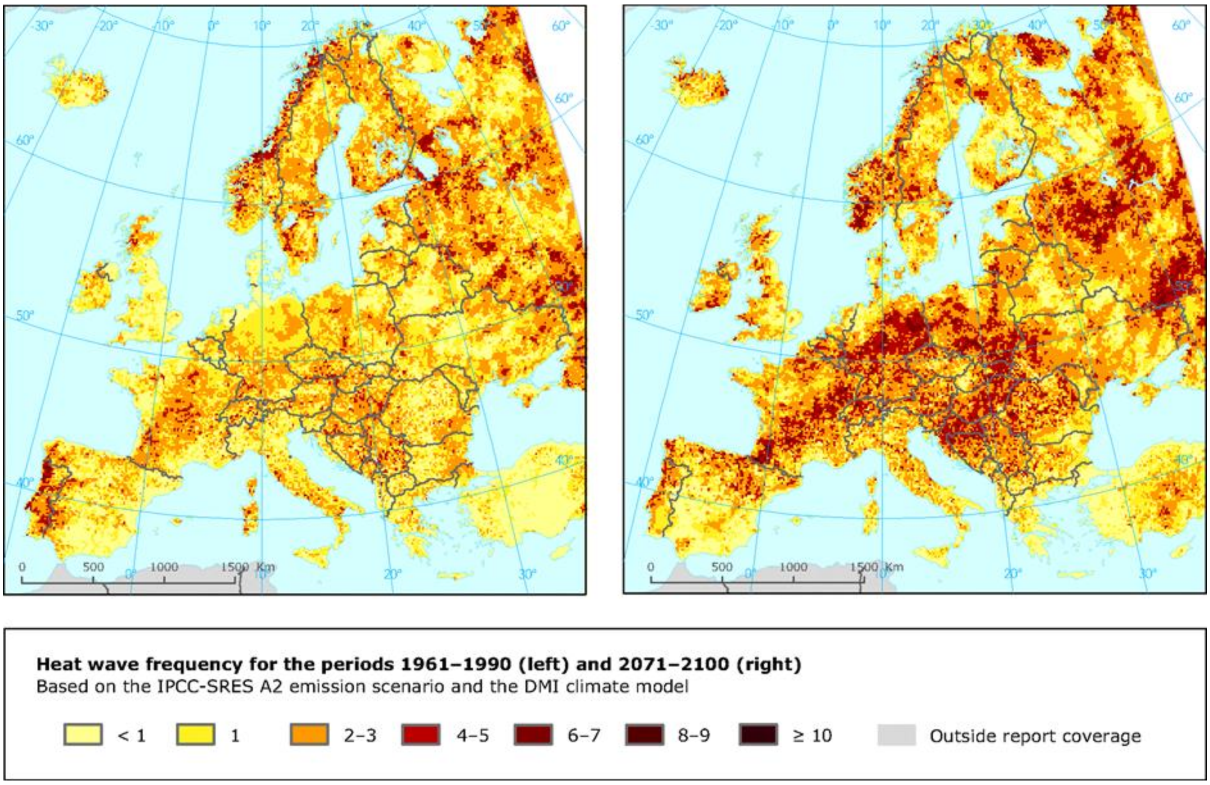
Existing indicators

Some indicators are related to the heat wave duration, other to the heat wave magnitude.

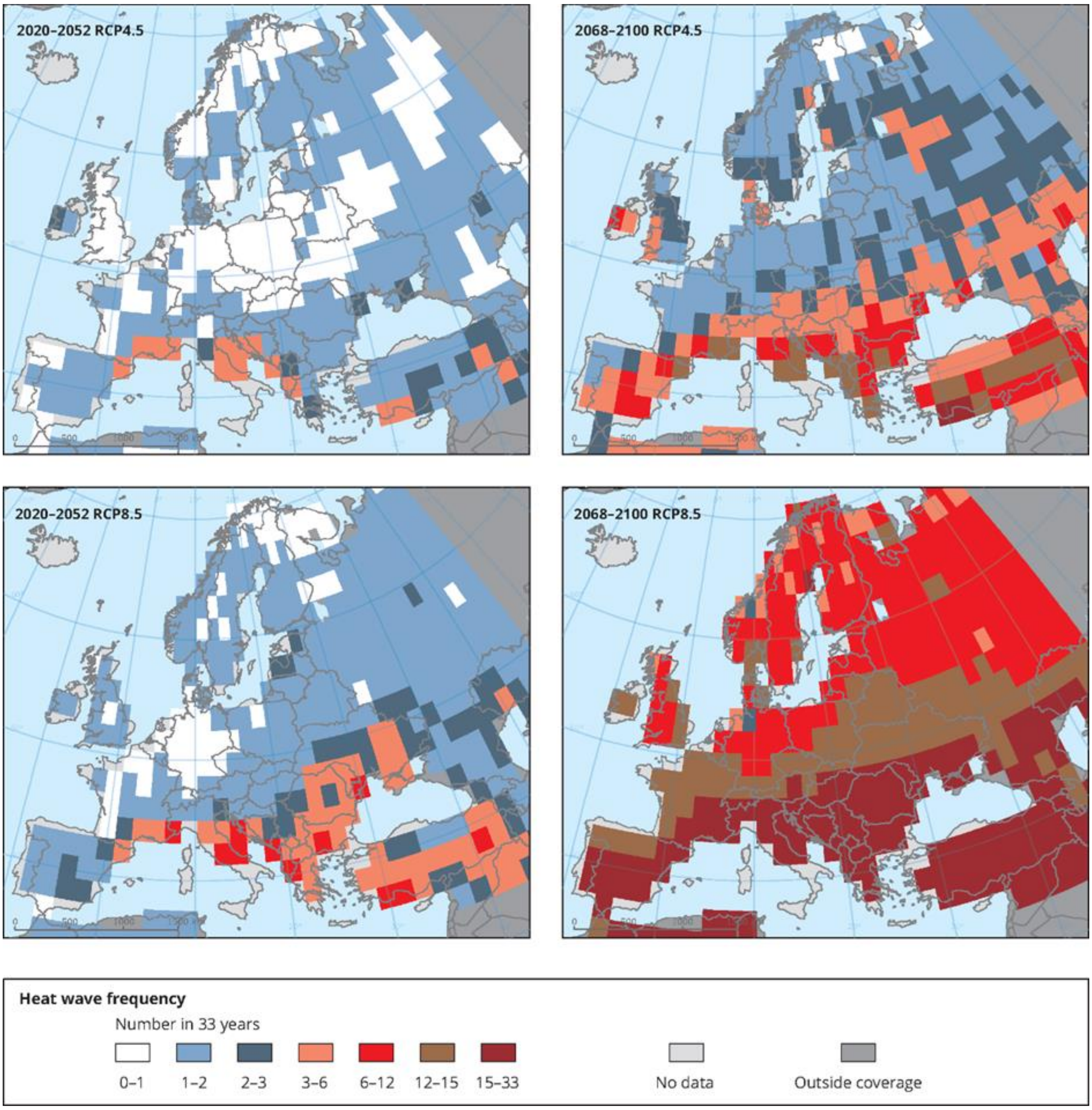
The IPCC AR5 report makes use of the following indices for impact on several warm days:

- Warm days (TX90p) index: Days (or fraction of time) when daily maximum temperature >90th percentile
- Warm nights (TN90p) index: Days (or fraction of time) when daily minimum temperature >90th percentile

The maps below are the examples of change in the number of heat waves provided by the European Environment Agency.



Occurrence of heat wave events with a duration of 7 days based on IPCC-SRES A2 (left: 1961-1990 average; right: 2071-2100 average) (source: http://www.eea.europa.eu/data-and-maps/figures/occurrence-of-heat-wave-events-with-a-duration-of-7-days-left-1961-1990-average-right-2071-2100-average)



The top maps show the median of the number of heat waves in a multi-model ensemble of the near future (2020–2052) and the latter half of the century (2068–2100) under the RCP4.5 scenario, and the lower maps are for the same time periods but under RCP8.5 (source: http://www.eea.europa.eu/data-and-maps/figures/number-of-extreme-heat-waves)

The JRC prepared maps using the Heat Wave Magnitude Index (Forzieri et al. 2016).

Proposed indicator

*Following the WMO definition of heat waves (see above), the **number of heat waves** over a period of 30 years was selected as indicator for this project.*

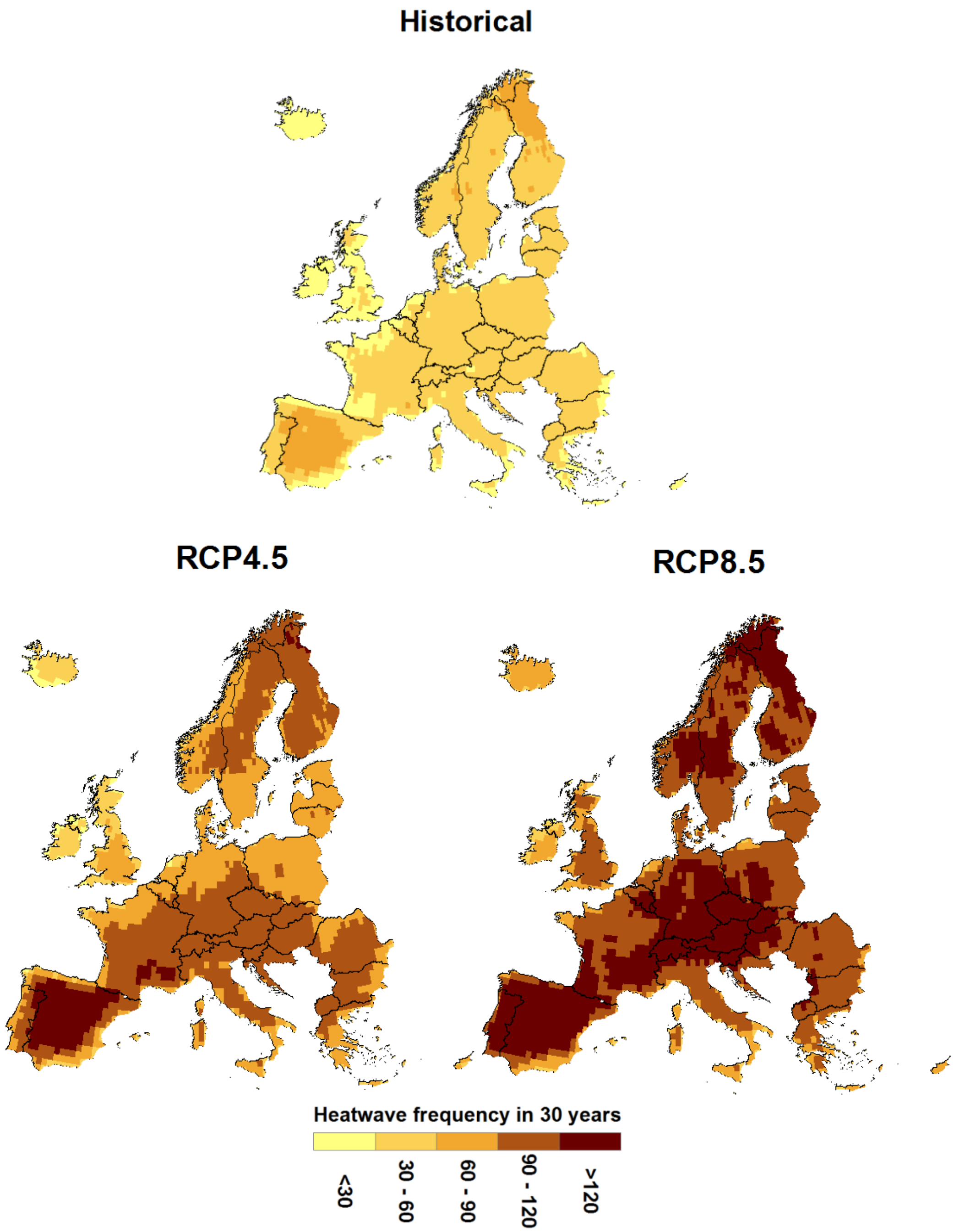


Figure 11. Historical and future heatwave frequency (RCP4.5 and RCP8.5) over Europe based on the WMO heatwave indicator.

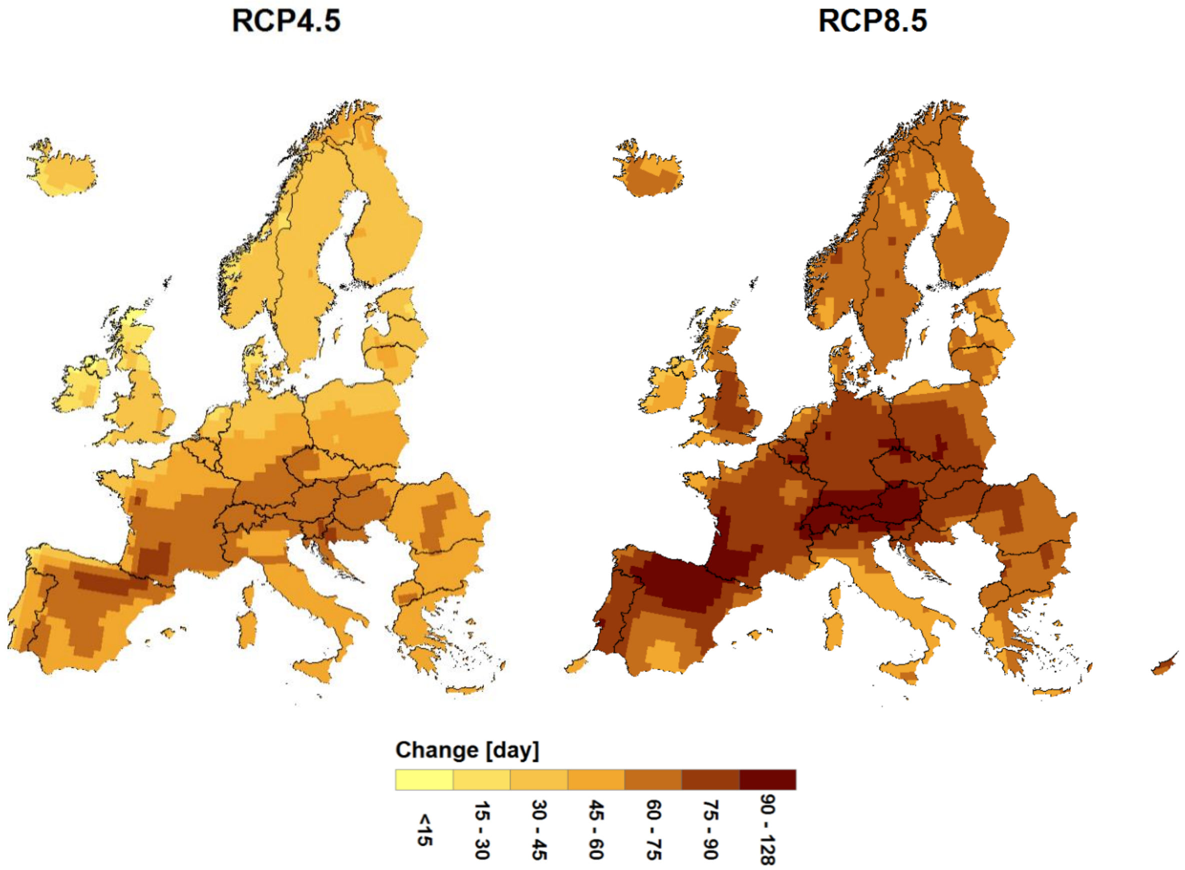


Figure 12. Climate change signals for heatwave frequency (RCP4.5 and RCP8.5) over Europe based on the WMO heatwave indicator.

Limitations and uncertainty

The benefit of this indicator is that it is based on direct meteorological outputs of the climate models. The mean of a large ensemble of both global and regional climate model runs were considered. Hence, the climate change signals used on this basis of the heat waves' indicator are expected to be rather robust. There are, however, some limitations:

- The mean climate change signal (mean obtained from the full set of climate models) does not provide information on the uncertainty in the climate change signal. This can be easily obtained from the ensemble results and will be considered in the tier 2 and/or 3 approaches.
- Next to the number of heat waves, the intensity and duration of the heat waves may be important as well.
- Just one potential definition of heat waves, the WHO one, was considered whereas many more definitions exist, or information on the full temporal variability of temperature values may be useful for specific types of heat wave related impacts.
- Daily temperature values were considered whereas also the maximum and minimum daily temperature values are of importance as well.

- Different types of heat wave related impacts exist. Quantification of such impacts would require a very specific type of local impact model.

Droughts

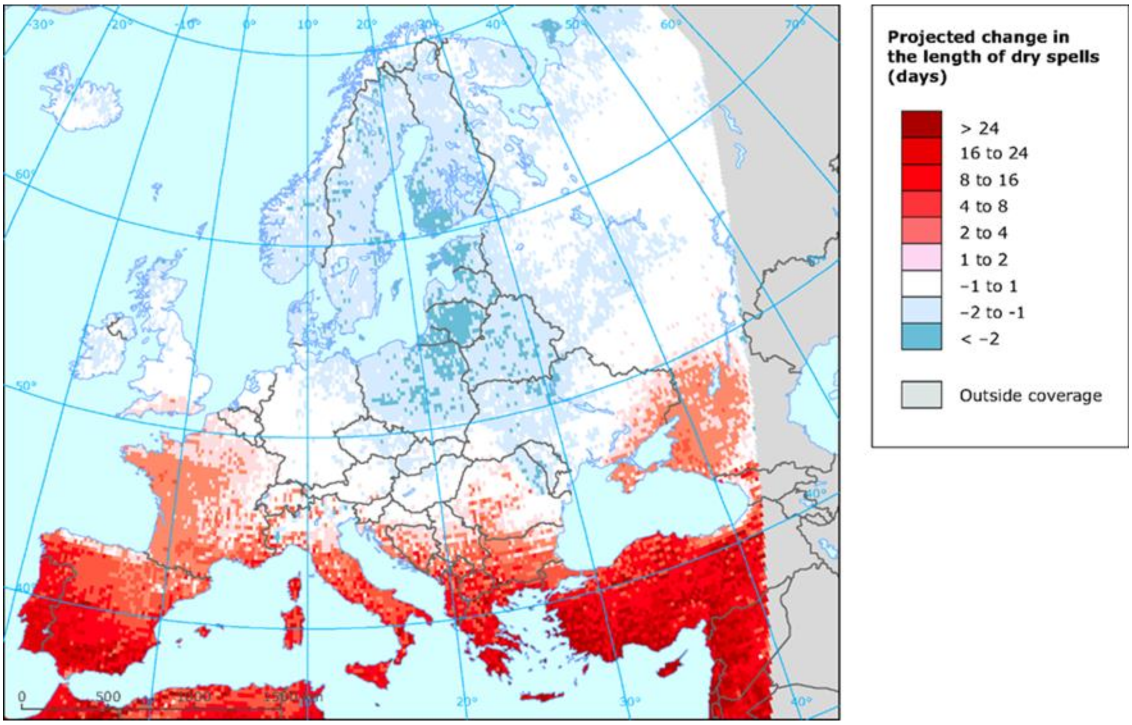
Droughts are the result of a period of consecutive dry days or days with very low rainfall. Such meteorological droughts can lead to hydrological, agricultural, socioeconomic droughts, depending on the types of impacts.

Existing indicators

The IPCC uses the consecutive dry days (CDD) index as indicator for droughts:

- Consecutive dry days (CDD) index: Maximum number of consecutive days when precipitation <1 mm

The European Environment Agency uses the length of dry spells as an indicator for droughts. The map below is the example result for changes in the length of dry spell (in days) for Europe from 1971-2000 to 2071–2100 for the RCP8.5 scenario based on the ensemble mean of different regional climate models (RCMs) nested in different general circulation models (GCMs).



More specific impacts, such as the pan-european impacts on river low flows can be obtained for the larger rivers in Europe from EC Joint Research Center (JRC). JRC produced maps of 7-day minimum river discharge with return periods from 2 to 100 years (Forzieri et al. 2016).

Other types of impacts incl. the impacts on soil moisture, river discharge, groundwater level, vegetation productivity, etc.

Proposed indicator

For the climate indicators and loading conditions in this project, only the meterological drought is considered, as BRIGAID considers innovations that address many different types of meteorological drought impacts. The meteorological drought is the primany one, of relevance for any type of impact on nature and society.

To be consistent with the IPCC definition, the **annual *CDD*** was selected for this project, expressed as the ***maximum number of consecutive dry days when precipitation is less than 1 mm***. The largest CDD in the 30-years period was considered. So, the CDD value considered on the basis of the indicator has an empirical return period of 30 years. It can be computed directly from meteorological variables available in the climate model outputs.

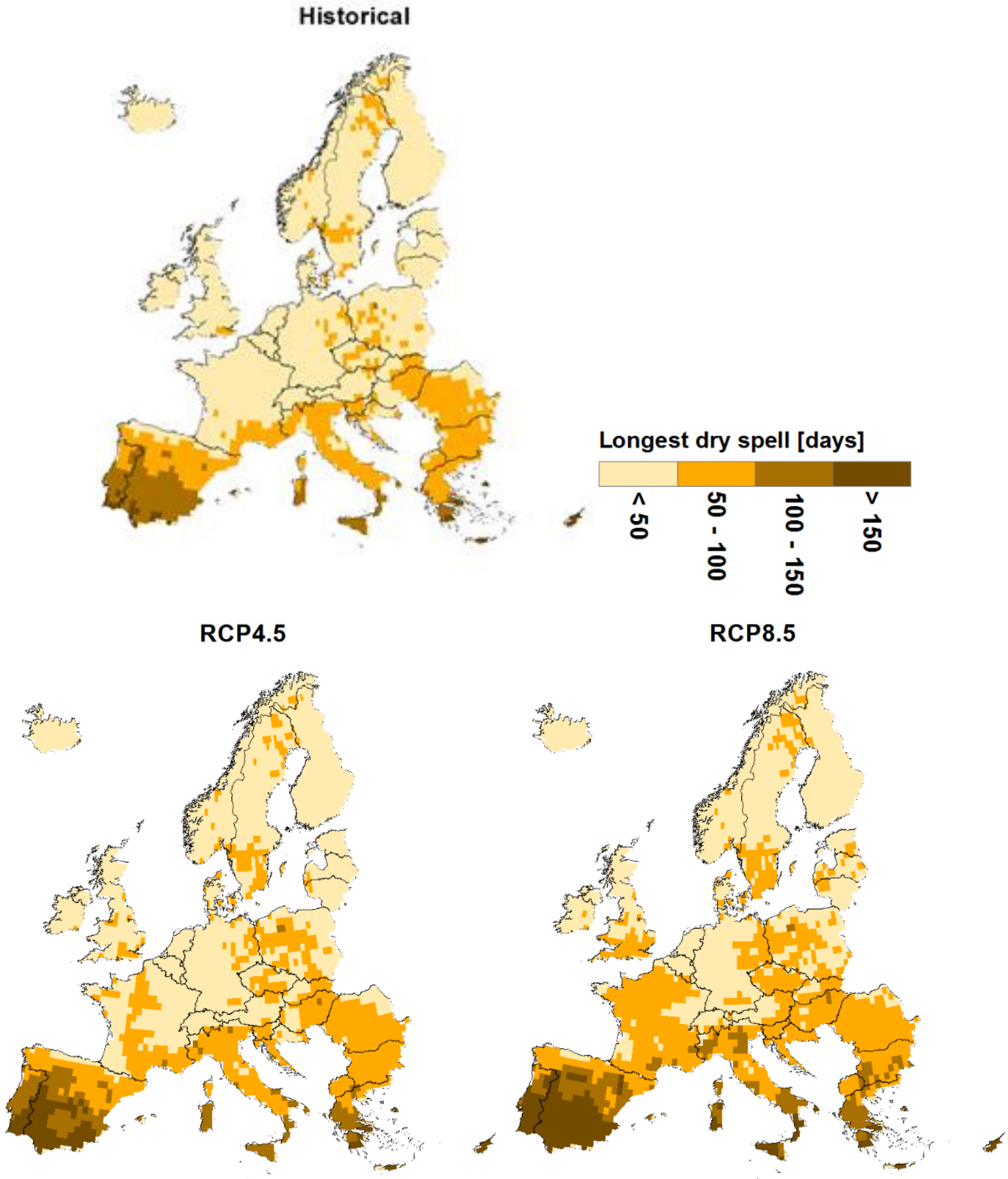


Figure 13. Historical and future drought (RCP4.5 and RCP8.5) over Europe based on longest dry spell indicator.

BRIGAID

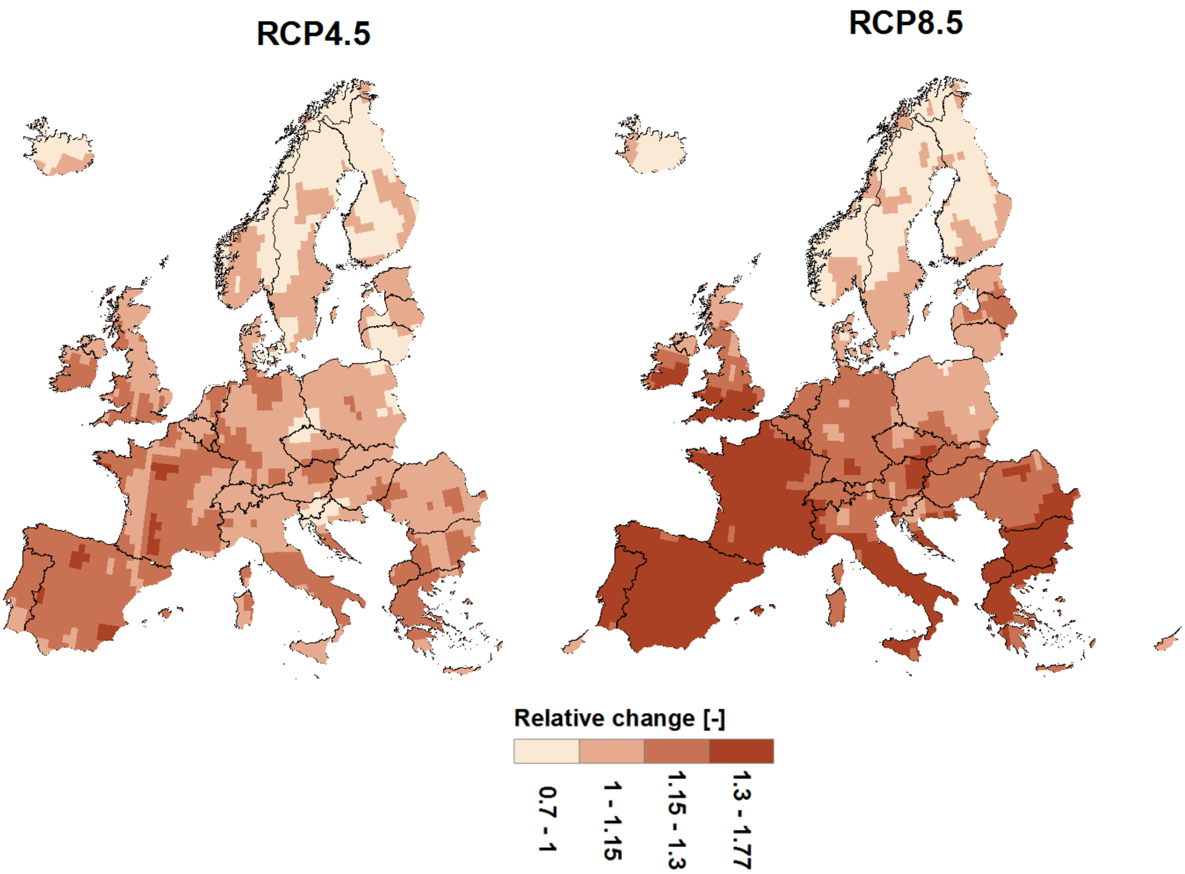


Figure 14. Climate change signals for drought (RCP4.5 and RCP8.5) over Europe based on longest dry spell indicator.

Limitations and uncertainty

As for the extreme precipitation and heat waves indicators, the benefit of this indicator is that it is based on direct meteorological outputs of the climate models. The mean of a large ensemble of both global and regional climate model runs were considered. Hence, the climate change signals used on this basis of the droughts' indicator are expected to be rather robust. There are, however, some limitations:

- The mean climate change signal (mean obtained from the full set of climate models) does not provide information on the uncertainty in the climate change signal. This can be easily obtained from the ensemble results and will be considered in the tier 2 and/or 3 approaches.
- Next to the number of successive days with no or little rainfall days, there are many more properties of the temporal rainfall variability that are of importance for impact analysis of droughts, such as the cumulative rainfall amounts, the temperature and evaporation amounts, the impacts on soil moisture, low river flows, etc.
- Different types of drought related impacts exist. Quantification of such impacts would require a very specific type of local impact model.

Wildfires

Global warming affects the sparking of wildfires. In fact, warmer temperatures enable fuels to ignite and burn faster, resulting in faster wildfire expansion. Wind can help the wildfire expansion, while precipitation can decrease the chances of a wildfire igniting.

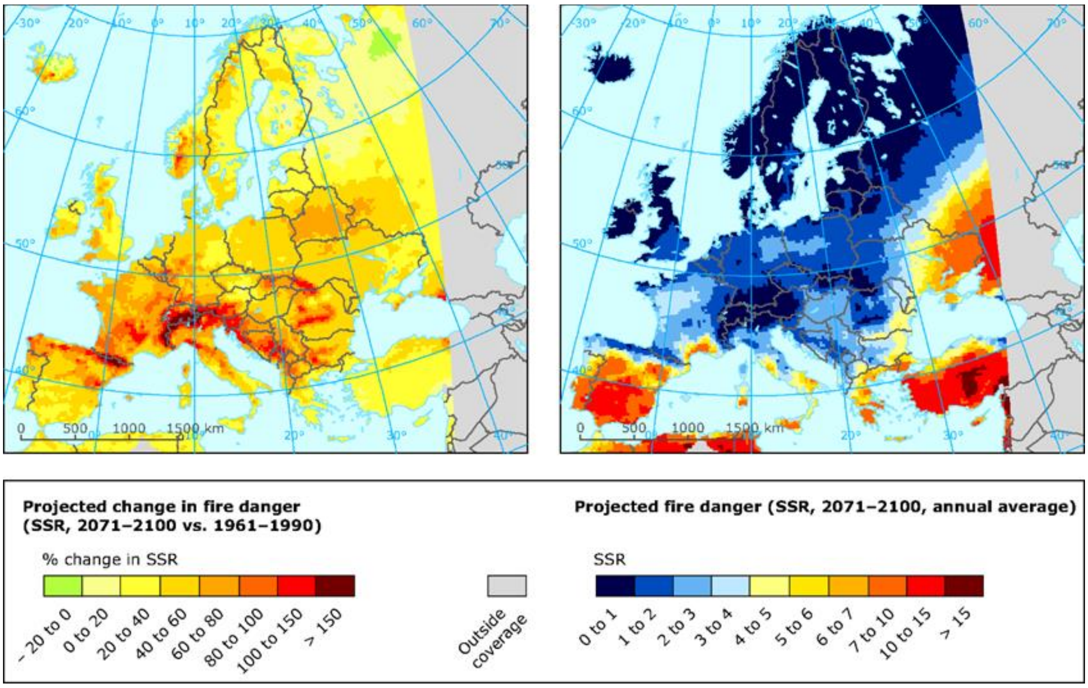
Existing indicators

There are different types of wildfire indicators:

- *Fire Weather Index (FWI)*
- *Daily Severity Rating (DSR)*
- *Monthly Severity Rating (MSR)*
- *Seasonal Severity Rating (SSR)*
- *Forest Fire Danger Index (FFDI)*

The FWI is commonly used in Europe to rate the daily fire danger conditions, with large FWI values most commonly associated with high wind speeds, followed secondly by low relative humidity and then thirdly by high temperatures. FWI can be transformed with a simple equation into a daily severity rating (DSR) index, which is deemed to be linearly related with fire suppression difficulties. Daily severity values can be averaged over different months of the year or over the fire season obtaining a Monthly or Seasonal Severity Rating (MSR, SSR) index, which allows objective comparison of fire danger from year to year and from region to region.

The map below shows the fire danger expressed by the SSR using RACMO2 RCM derived from ECHAM5 GCM for the SRES A1B emission scenario for Europe (left: projected change in SSR by 2071–2100 as compared to 1961–1990 baseline period; right: projected annual average SSR in 2071–2100).



The Forest Fire Danger Index (FFDI; Nobel et al., 1980) is defined as:

$$FFDI = 2exp(0.987logD - 0.45 + 0.0338T + 0.0234V - 0.0345H$$

where H is the relative humidity from 0-100%, T is the air temperature in degree Celsius, V is the average wind speed 10 meters above ground, in meter per second and D is the drought factor in range 0-10 (Sharples et al., 2009). The drought factor has its maximum value of 10.

In the RAIN project (Groenemeijer et al. 2016), the maps of wildfires were prepared for 5 climate scenarios (1971-2000, 2021-2050 RCP 4.5, 2021-2050 RCP 8.5, 2071-2100 RCP 4.5, 2071-2100 RCP 8.5). For each scenario, the daily probability of Fire Weather Index exceeding value of 20 and 45 was calculated as the mean of multi-model ensemble of regional climate models.
JRC has produced maps of return periods of percentage of area burned (Forzieri et al. 2016).

Other types of impacts include the probability of fire, probability of ignition, burned area, etc.

Proposed indicator

In this project, wildfire danger is considered, being assessed by meteorological conditions only (air temperature, wind speed, meterological drought conditions). Other local conditions that affect the wildfire danger and risk are not readily available at pan-european level. Given that the meteorological conditions are the primany factors controlling the wildfires, these were considered here for the pan-European analysis.

The ***FFDI*** *was considered as indicator for this project, using the* ***simplified version of the formula proposed by Nobel et al. (1980)****. This formula is frequently used and can be computed directly from meteorological variables available in the climate model outputs. A* *detailed description of the simplified version of the fomula by Nobel et al. (1980) follows next:*

As indicator before, for the wildfires' indicator, the ERA-Interim reanalysis dataset was considered for the historical period. Because relative humidity is not available in ERA-Interim dataset, the following procedure was used to calculate relative humidity from air temperature and dew point temperature:

$$RH = \frac{e_a}{e_s} \times 100$$

in which,

$$e_a = 0.6108 \exp\left(\frac{17.27T_{dew}}{237.3+T_{dew}}\right)$$

$$e_s = 0.6108 \exp\left(\frac{17.27T_{mean}}{237.3+T_{mean}}\right)$$

where e_a is the actual vapor pressure, e_s is the saturation vapor pressure, T_{mean} is the air temperature and T_{dew} is the dew point temperature.

Wind speed, which is another variable required for windfire computation, was calculated using the U (eastward wind) and V (northward wind) wind components based on the Pythagorean Theorem.

Finally, the Forest Fire Danger Index (FFDI) as a wildfire indicator was computed following the equation given before. This was done for each day of the time series and the final index computed by averaging the FFDI for all days of the 30-year time series.

Limitations and uncertainty

As for the extreme precipitation, heat waves and droughts indicators, the benefit of this indicator is that it is based on direct meteorological outputs of the climate models. The mean of a large ensemble of both global and regional climate model runs were considered. Hence, the climate change signals used on this basis of the wildfires' indicator are expected to be rather robust. There are, however, some limitations:

- The mean climate change signal (mean obtained from the full set of climate models) does not provide information on the uncertainty in the climate change signal. This can be easily obtained from the ensemble results and will be considered in the tier 2 and/or 3 approaches.
- The average index for all days of the 30-year period was considered, whereas specific drought seasons would be more relevant.
- Other meteorological and hydrological conditions next to relative humidty, air temperature and wind speed may play a role but were not considered such as precipitation.
- Wild fires are in different regions of Europe induced by other meteorological and hydrological conditions. Hence, different indicators may need to be considered. This will be done in the tier 2 and/or 3 approaches.

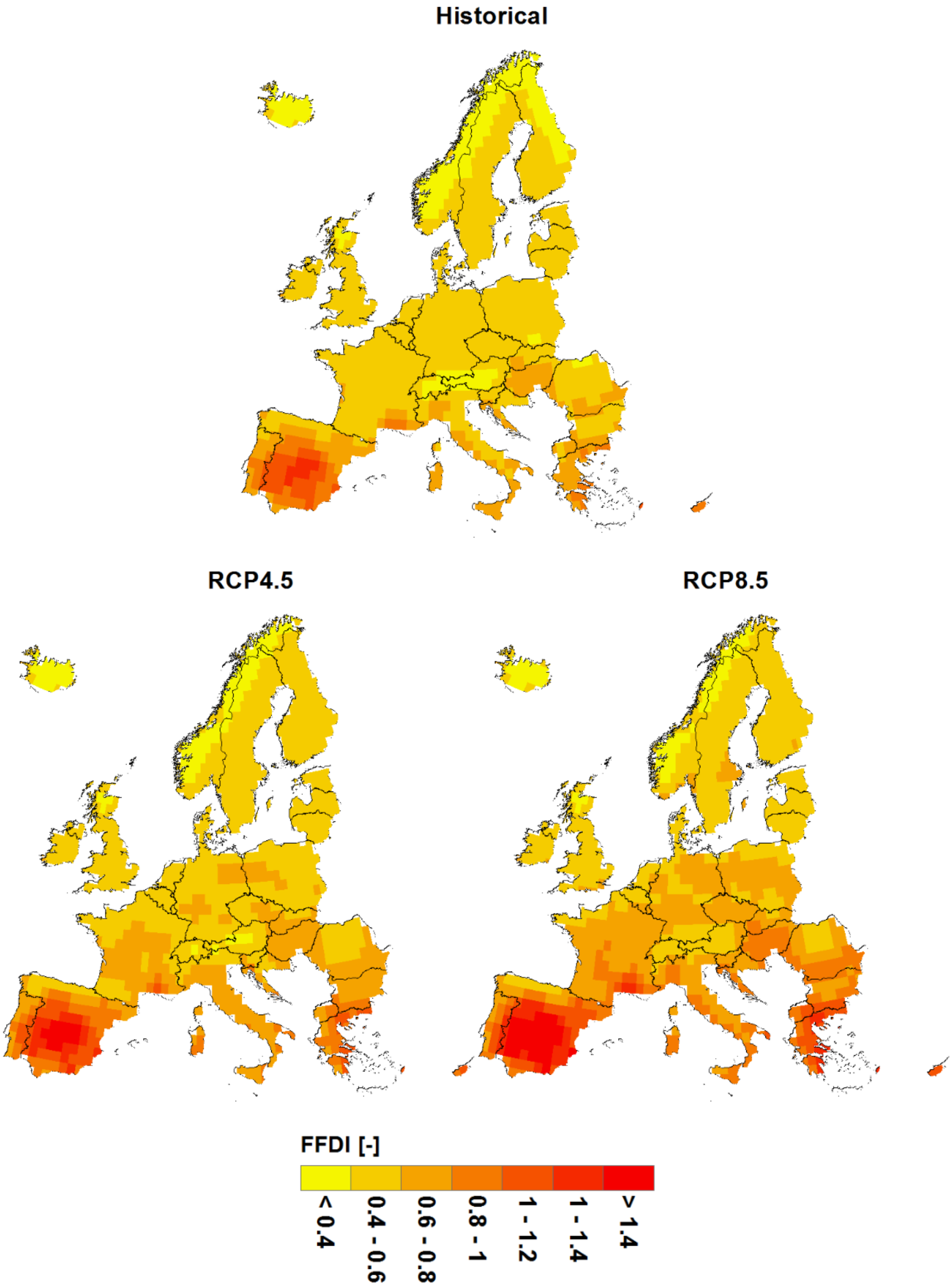


Figure 15. *Historical and future wildfire hazard (RCP4.5 and RCP8.5) over Europe based on the FFDI index.*

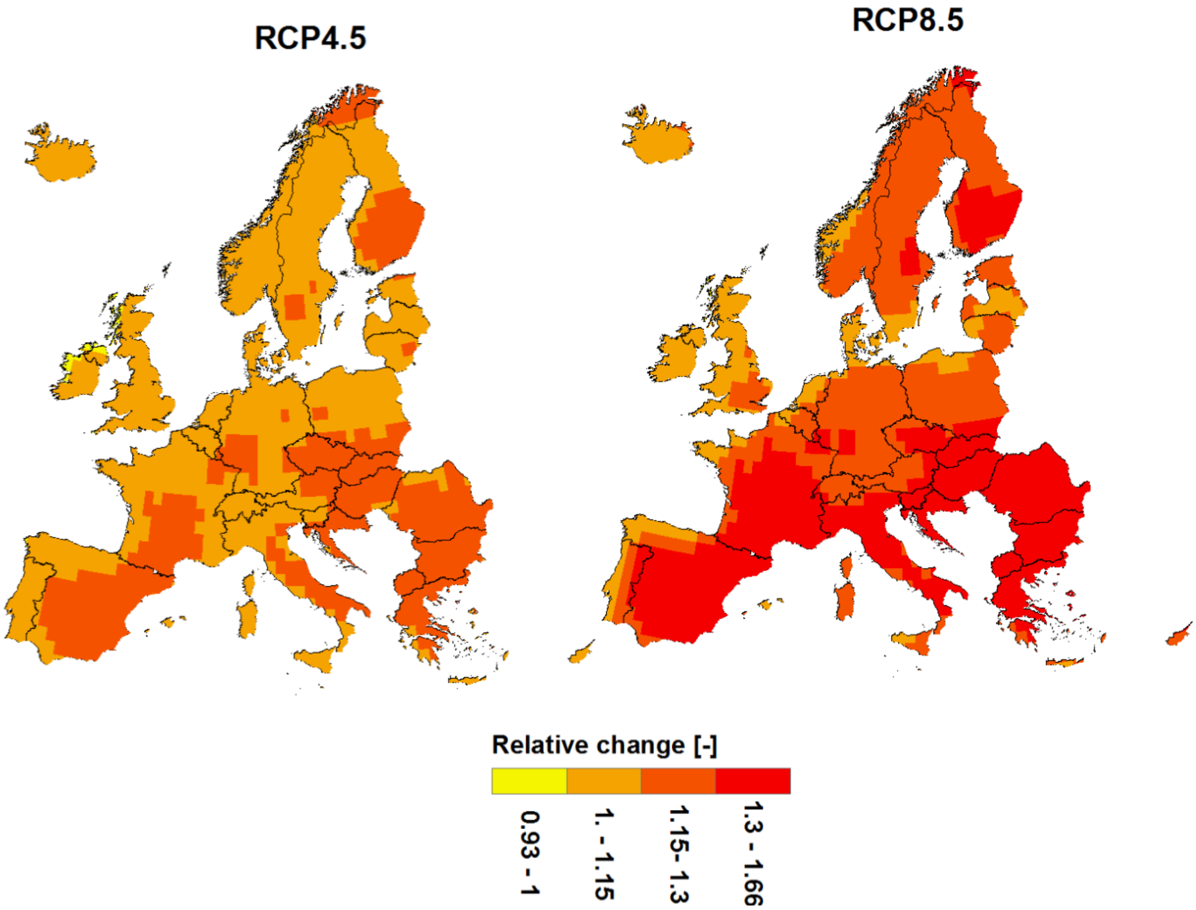


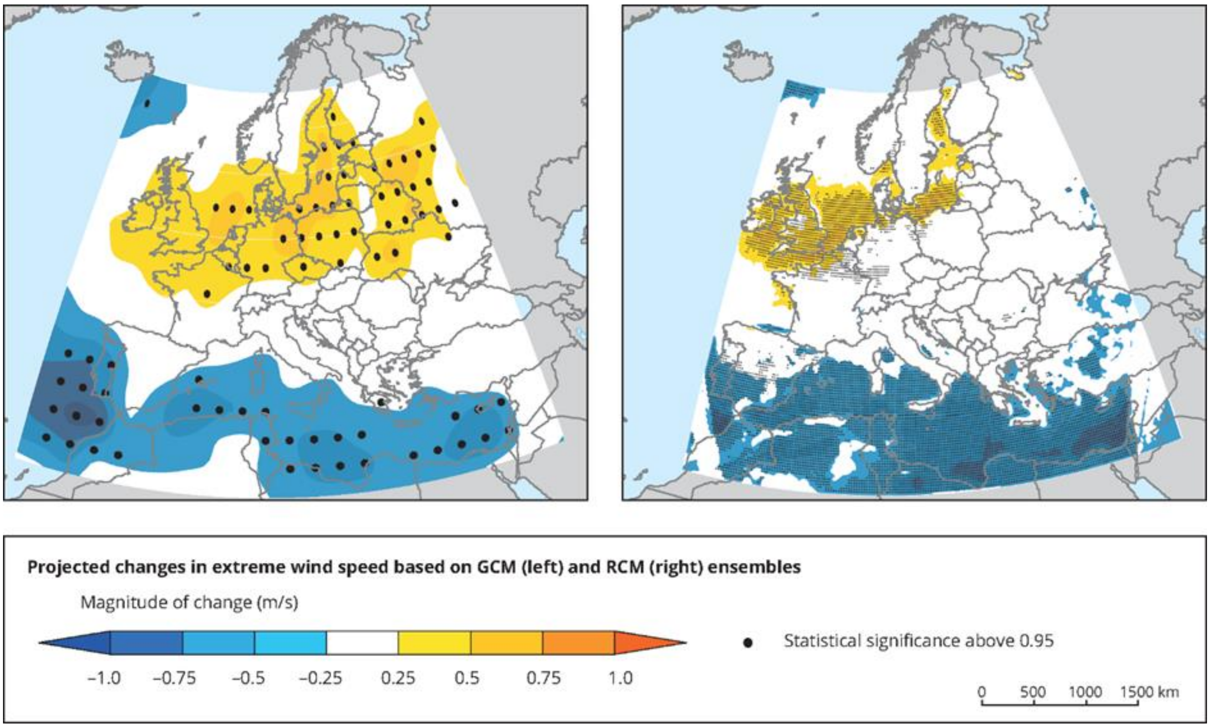
Figure 16. *Climate change signals for the wildfire hazard (RCP4.5 and RCP8.5) over Europe based on the FFDI index.*

Wind storms

Storms (atmospheric disturbances) are defined by strong sustained winds, which are mostly accompanied by heavy precipitation and lightning and in some case also by hail. European storms range from localized to continental events.

Existing indicators

The European Environment Agency (EEA) considers changes in the 98th percentile of daily maximum wind speed as an indicator of wind storms. The map below shows changes in extreme wind speed for A1B (2071–2100) relative to 1961–2000 using 9 GCMs and 11 RCMs.



Other types of impacts include impacts on wind gusts.

In the RAIN project (Groenemeijer et al. 2016), the maps of wildfires were prepared for 5 climate scenarios (1971-2000, 2021-2050 RCP 4.5, 2021-2050 RCP 8.5, 2071-2100 RCP 4.5, 2071-2100 RCP 8.5). For each scenario, the 5, 10, 20 and 50-year return period of daily maximum 10 m wind speed was calculated as the mean of multi-model ensemble of regional climate models. Changes in return periods in the future relative to present return periods were also provided. JRC calculated maps with the same parameter.

Proposed indicator

In this project, sustained winds were considered, as this is the primany one for pan-European analysis, without consideration of gusts, lightning, hail or combination with precipitation. The ***99th percentile of daily wind speed*** corresponding to a stronger storm was considered as indicator for this project. The 99th percentile was selected as to consider extreme wind storms.

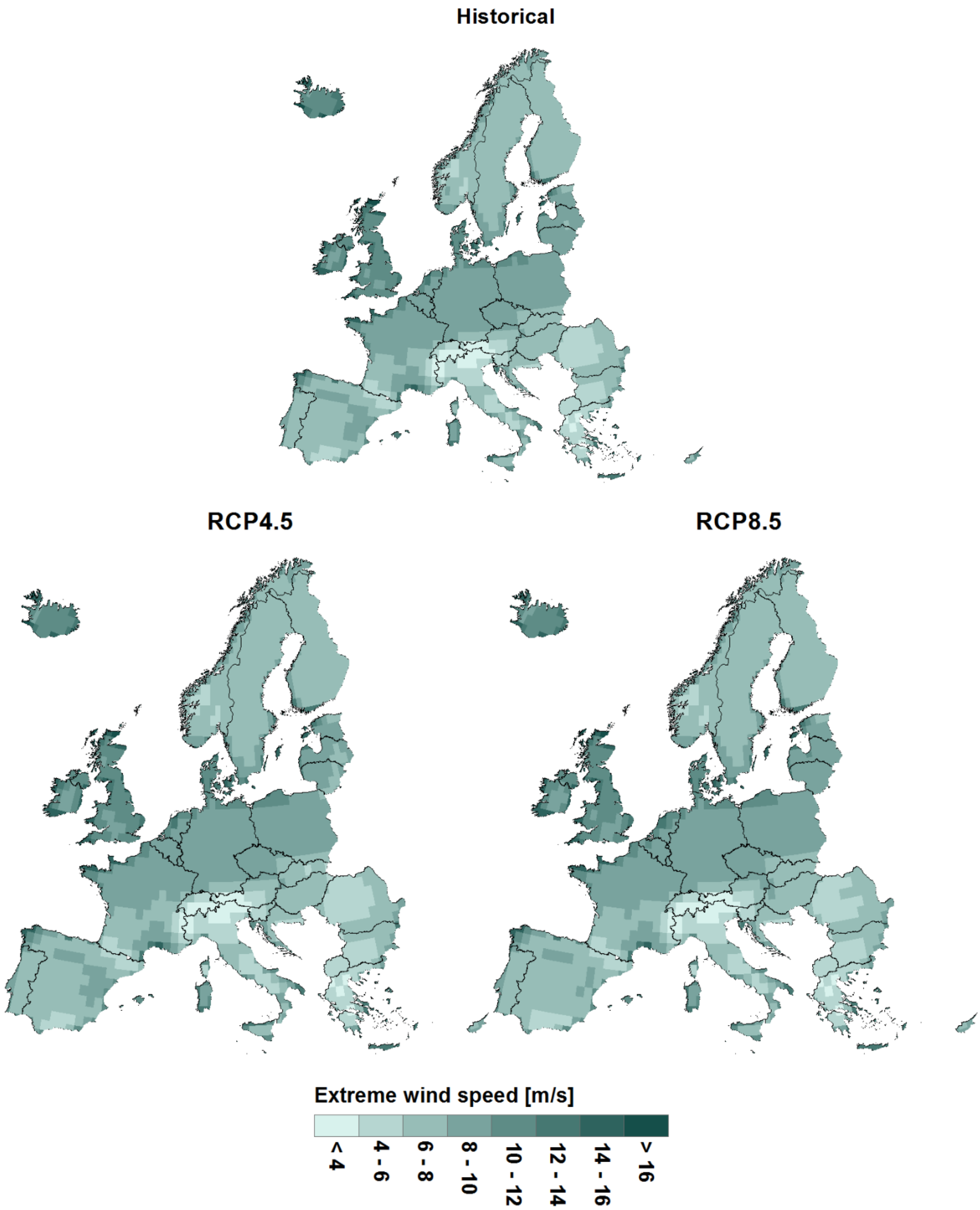


Figure 17. Historical and future extreme daily wind speed (RCP4.5 and RCP8.5) over Europe based on 99th percentile indicator.

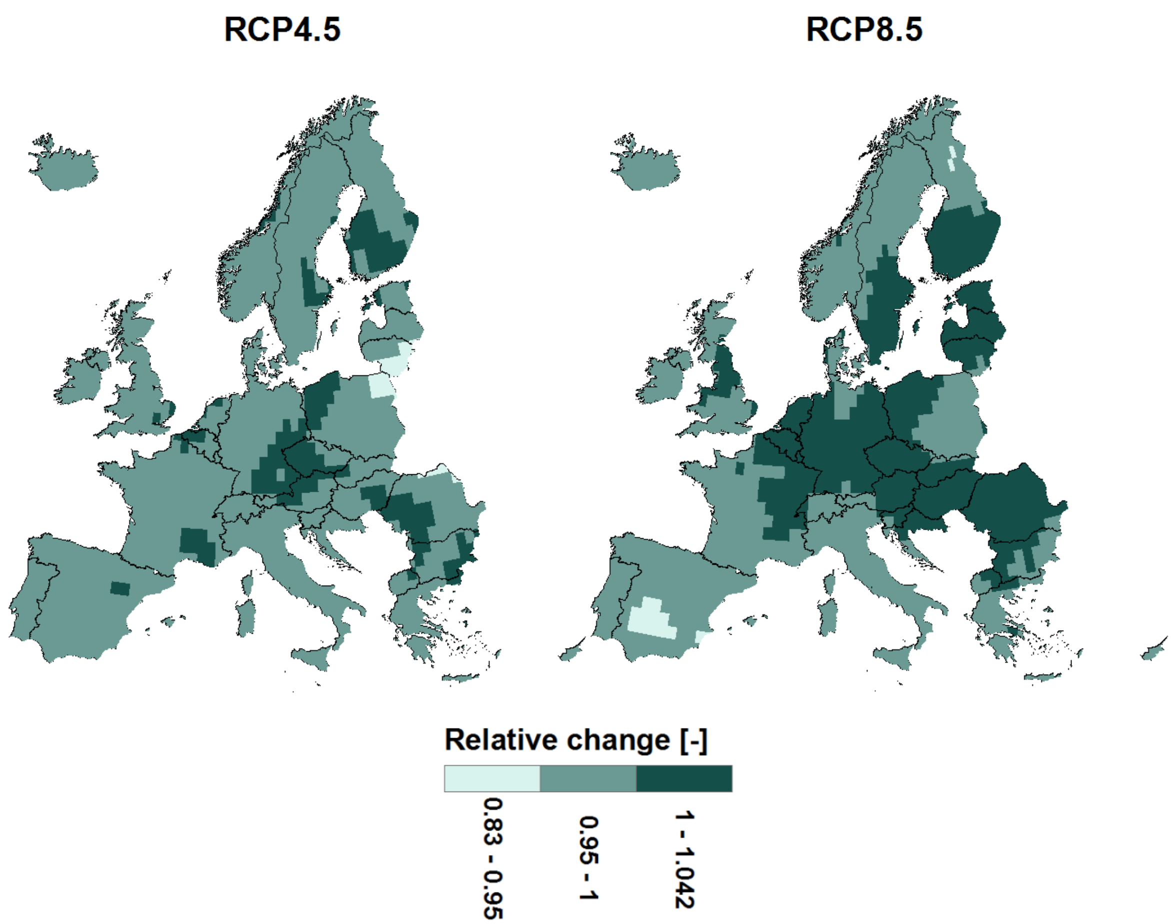


Figure 18. Climate change signals for extreme daily wind speed (RCP4.5 and RCP8.5) over Europe based on 99th percentile indicator.

Limitations and uncertainty

As for the other indicators, except for the coastal and rivers floods' indicators, the benefit of this indicator is that it is based on direct meteorological outputs of the climate models. The mean of a large ensemble of both global and regional climate model runs were considered. Hence, the climate change signals used on this basis of the wind storms indicator are expected to be rather robust. There are, however, some limitations:

- The mean climate change signal (mean obtained from the full set of climate models) does not provide information on the uncertainty in the climate change signal. This can be easily obtained from the ensemble results and will be considered in the tier 2 and/or 3 approaches.
- Just one percentile, 99th, was considered, which corresponds to very extreme storms. Less extreme wind storms may also cause damage.
- The specific impact of extreme wind storms may depend on the types of buildings and other local conditions, which need to be considered in a more specific / detailed impact analysis, which may be applied in the tier 2 and/or 3 approaches.

Results

Summary

The different indicator maps, after normalization, are hereafter shown per hazard type. Table 6 gives a summary of the normalized loading conditions by level, indicator and scenario. It provides the 5, 50 and 95 percentile values of the normalized hazard indicator at local and regional level, and minimum, mean and maximum values at the national level.

Table 6. Summary results of normalized loading conditions by level, indicator and scenario. For coastal and river floods, the statistics are only for units connected to the coastline or rivers

Hazard	Indicator	Scenario	Local normalization (by percentile)			Regional normalization (by percentile)*			National normalization		
			5%	50%	95%	5%	50%	95%	Min	Mean	Max
Coastal floods	Storm surge height, 100-year return period, in meters**	*hist*	0.09	0.25	0.56	0.09	0.25	0.70	0.08	0.41	0.87
		rcp4.5	0.30	0.55	1.08	0.12	0.47	1.11	0.21	0.65	1.37
		rcp8.5	0.50	0.72	1.08	0.36	0.66	1.06	0.45	0.82	1.57
River floods	River water level, 100-year return period, in meters**	*hist*	0.09	0.26	1.24	0.15	0.35	1.11	0.39	1.43	2.88
		rcp4.5	0.07	0.32	1.74	0.10	0.40	1.55	0.37	1.89	4.13
		rcp8.5	0.07	0.34	1.93	0.08	0.43	1.67	0.41	1.97	4.79
Heavy precipitation	Daily precipitation with a 5-year return period [mm]	*hist*	32	42	102	30	40	97	30	71	188
		rcp4.5	35	48	126	33	45	122	29	79	205
		rcp8.5	38	56	150	34	50	139	32	88	213
Heat waves	Total number of heat waves in 30 year	*hist*	16	38	58	19	38	51	15	47	80
		rcp4.5	50	97	124	54	90	114	46	101	150
		rcp8.5	70	119	146	77	117	139	68	125	181
Droughts	Maximum number of consecutive days when precipitation is less than 1 mm	*hist*	0.43	0.52	0.81	0.40	0.50	0.77	0.37	0.63	1.26
		rcp4.5	0.47	0.59	0.95	0.44	0.56	0.90	0.41	0.72	1.54
		rcp8.5	0.49	0.66	1.13	0.47	0.62	1.09	0.46	0.82	1.93
Wildfires	Average daily Forest Fire Danger Index [-]	*hist*	4.6	8.5	12.3	4.7	8.8	12.1	4.1	10.7	16.4
		rcp4.5	4.5	8.4	12.2	4.6	8.8	12.0	4.1	10.6	16.2
		rcp8.5	4.5	8.5	12.3	4.6	8.9	12.1	4.1	10.6	15.9
Windstorms	99^{th} percentile of daily wind speed [m/s]	*hist*	28.5	38.0	69.6	30.4	38.5	69.1	33.8	57.5	117.5
		rcp4.5	31.4	41.8	75.5	33.5	42.5	74.6	37.8	62.9	131.0

	rcp8.5	33.5	45.3	79.8	36.0	46.0	80.9	41.3	68.5	143.5

Notes: * percentile of regional units, not regional population or GDP; ** above 10-year surge height (coastal) or water level (river) in the historical scenario; *** periods of more than 5 consecutive days with daily maximum temperature exceeding the mean maximum temperature of the May to September season for the control period (1971–2000) by at least 5°C.

Coastal floods

Out of seven hazards considered in this report, coastal floods have the smallest spatial extent. Only 30,000–50,000 km^2, or less than 1%, of the study area is at risk of a 1 in 100 years flood (depending on the methodology of calculating flood extents; Vousdoukas et al. 2016). Only 5.3% (6,275) of local administrative units, 29% (394) of regions and 76% (25) of countries have access to the coastline. The indicator of coastal flood hazard, therefore, was only calculated for those units and the percentiles pertain only to them. The indicator shows the difference between 100-year and 10-year storm surges.

Overall, the values of the indicator in the historical scenario (1971–2000) are rather low, and range from 7 to 94 cm at local level. In approx. 80% of local units the value of the indicator is below 40 cm. At regional level, units with larger GDP indicate slightly higher hazard than those with large populations (Figure 19). In Figure 20 sharp geographic divisions are visible in the distribution of surge heights. In the Mediterrenean or Black seas, surges are mostly no larger than half a metre, therefore the flood hazard indicator does not exceed 20 cm in most of southern European countries. Only in the northern part of the Adriatic Sea, surges could be larger, with Venice being one of the endangered locations in that area. Hazard increases moving northwards, with only small surges in the Portuguese or Spanish coasts. In the French coast, the hazard indicator rises from the middle quintile by the Bay of Biscay to the top quintile in the English (La Manche) Channel. Highest surge are observed in the southern coasts of the North Sea, i.e. in Belgium, Denmark, Germany, the Netherlands and the UK. Large surges are also present in the entire Baltic Sea, especially in its southern and eastern coasts, from Germany through Poland, Lithuania, Latvia, Estonia up to Finland. Meanwhile, hazard in the middle quintile or lower can be observed in Norway, Iceland or Ireland. Those patterns are the result of the distribution of paths of extra-tropical cyclones (ETCs). They typically sweep Europe eastwards, starting with southern England or northern France and continuing through the southern North Sea into Scandinavia. Additionally, storms cause seawater to move through the Danish Straits into the Baltic Sea, filling the basin and resulting in potentially very large surges in the German and Polish coasts. Meanwhile, the Mediterrean region and far north of Europe are outside the main paths of ETCs. In southern Europe, occurrence of tropical cyclones is possible, though they only exceptionally form in the Atlantic Ocean near Europe.

It is projected that, in general, storm surges will become more intense in the future. An average 100-year surge at local or regional level will be 30–50 cm higher in 2071–2100 compared to 1971–2000. In the upper quintile, a future 100-year surge will be about 90–100 cm above 10-year surge in the historical scenario. However, there are many differences between various parts of Europe, as three distinct factors have to be considered: changes in storm patterns, sea level rise and glacial isostatic adjustment. In 5% (311, RCP 4.5) or 3% (172, RCP 8.5) local units the hazard will decrease. Those are mostly located in the Baltic Sea, where storms will become weaker as their main paths will move further north, and sea level rise will be largely offset by the upwards movement of the Earth's crust (up to 1 cm per year). In the south of Europe, sea level rise will multiply the values of the indicator even 6-fold (RCP 4.5) and 10-fold (RCP 8.5). In the western coasts of Europe (Iberian peninsula, France, the British Isles) both sea level rise and increased storm activity will contribute to higher surges.

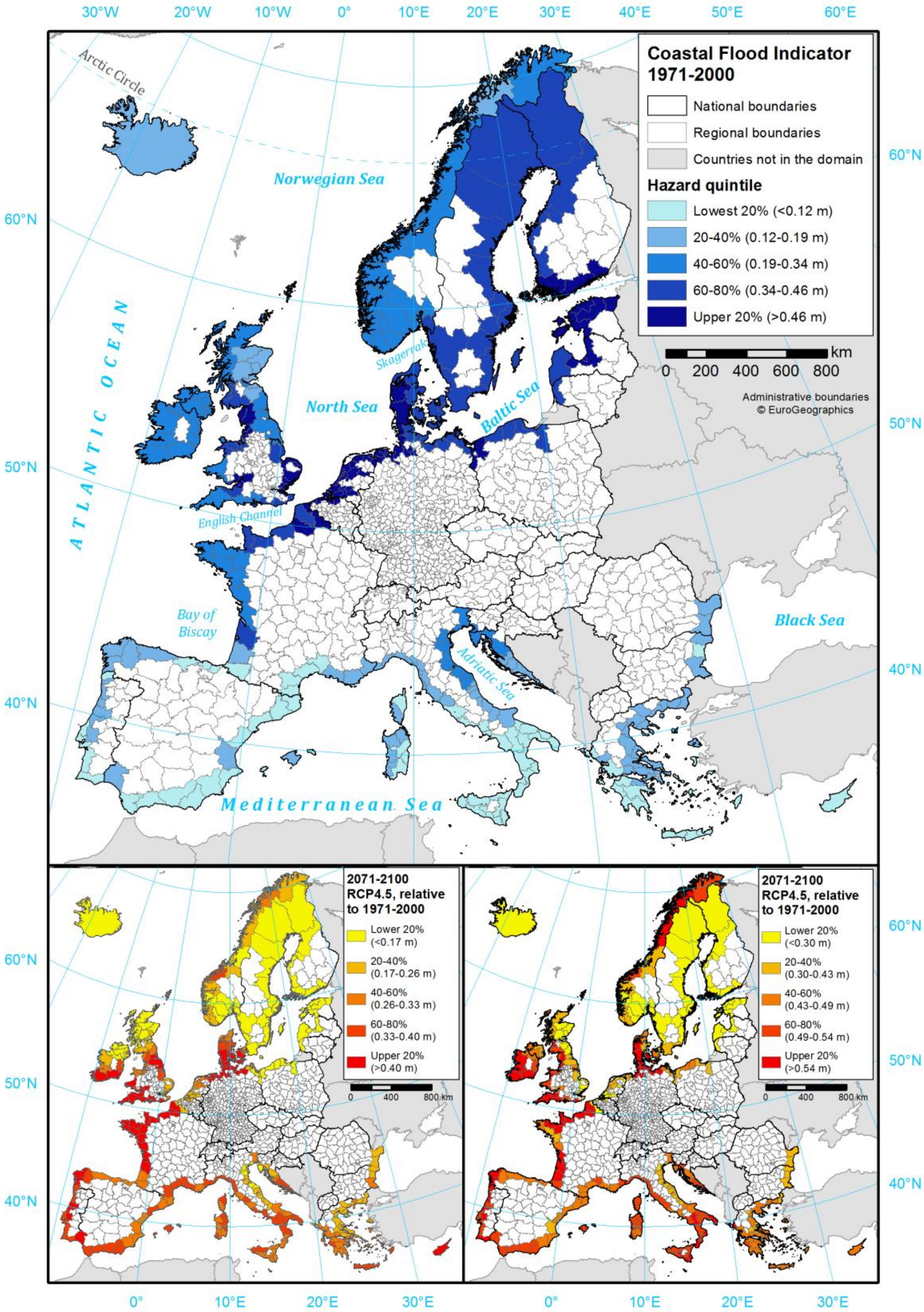


Figure 19. Quantiles of normalized coastal flood hazard indicator (100-year storm surge in a given scenario minus 10-year storm surge in the historical scenario) at regional level for historical

scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios

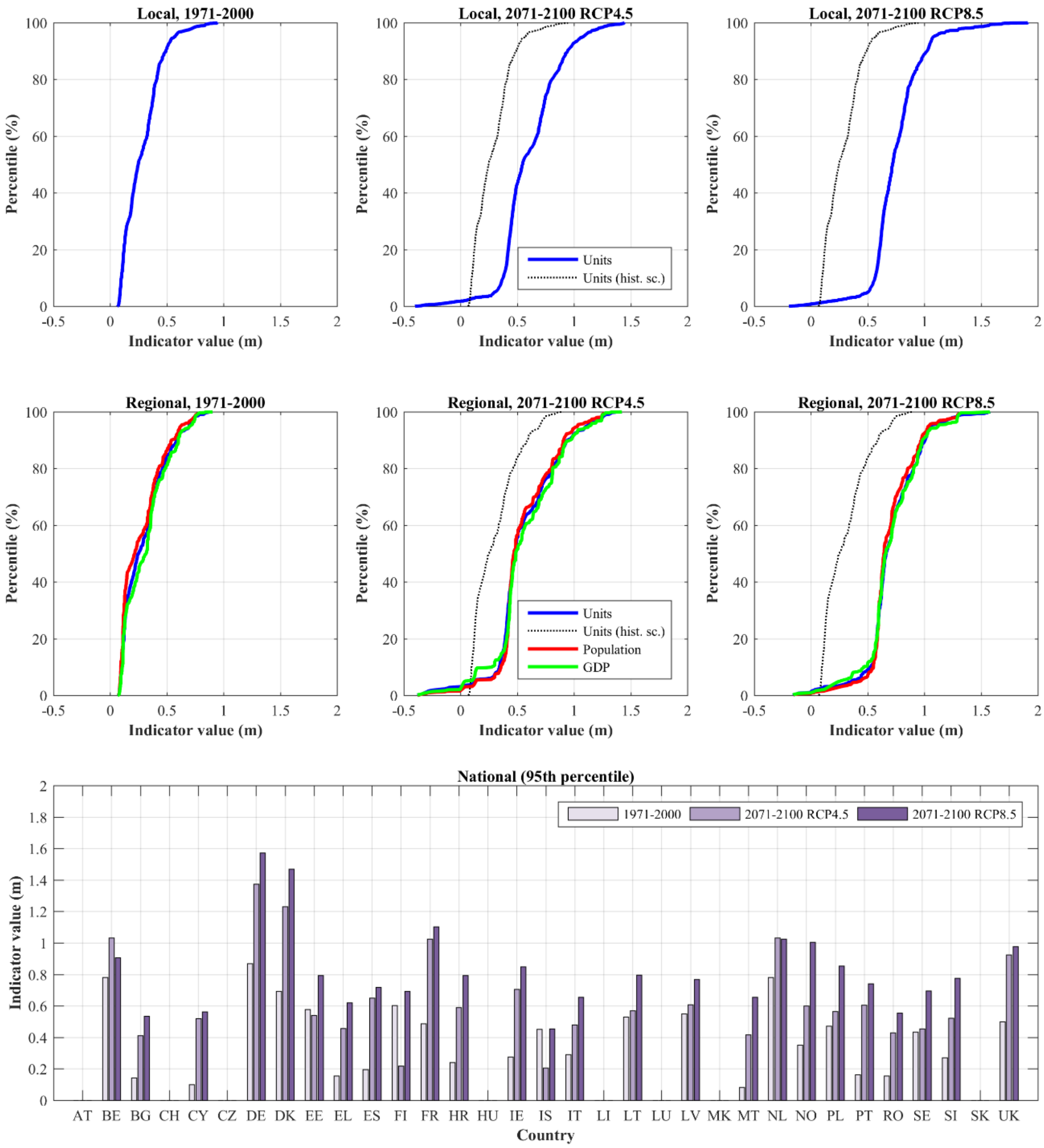


Figure 20. Normalized coastal flood hazard indicator at local, regional and national level, by climate change scenario. Histograms only for units connected to the coastline (6275 local, 394 regional). For country codes, see Table 4

River floods

River floods have a larger spatial extent than coastal floods, however it also pertains only to parts of Europe. According to 100-year flood zone delimitation by Paprotny et al. (2017), the hazard extends over 293,000 km^2, or 6% of the study area. A total of 42% (49,369) of local administrative units, 97% (1,338) of regions and all countries except Malta have access to rivers with catchment area larger than 100 km^2. The indicator of river flood hazard, therefore, was only calculated for those units and the percentiles pertain only to them. The indicator shows the difference between 100-year and 10-year river water level.

Overall, the values of the indicator in the historical scenario (1971–2000) are diversified, which is largely caused by different size of catchments. In approx. 80% of local units the value of the indicator is below 50 cm. At regional level, units with larger GDP indicate slightly higher hazard than those with large populations (Figure 22). In Figure 21 the are no distinct geographic divisions in the distribution of water levels. Regions with the highest average water levels are concentrated around large rivers, as outlines of Danube, Elbe, Loire, Po, Rhine or Vistula rivers could be clearly seen. Elevated values of the indicator could be be found in more mountainous areas (Norway, Portugal, Spain, Switzerland).

It is projected that, in general, extreme river water levels will be higher in the future. An average 100-year surge at local or regional level will be about 10 cm higher in 2071–2100 compared to 1971–2000. In the upper quintile, a future 100-year water level will be about 80–90 cm above 10-year level in the historical scenario. However, the trends will vary enormously from one location to another. In about 30% (RCP 4.5) or 40% (RCP 8.5) of local units the hazard is actually projected to decrease. Negative trends will mostly occur in northern Europe due to substantially reduced snowfall, which in turn would cause less severe snowmelt. In most of other locations, including large parts central and southern Europe, more cases fo extreme rainfall are expected, resulting in higher frequency of extreme river flow occurrences. From the histograms in Figure 22, it can be noticed that regions with larger population and GDP are slightly lower at risk of adverse changes in water levels in the future.

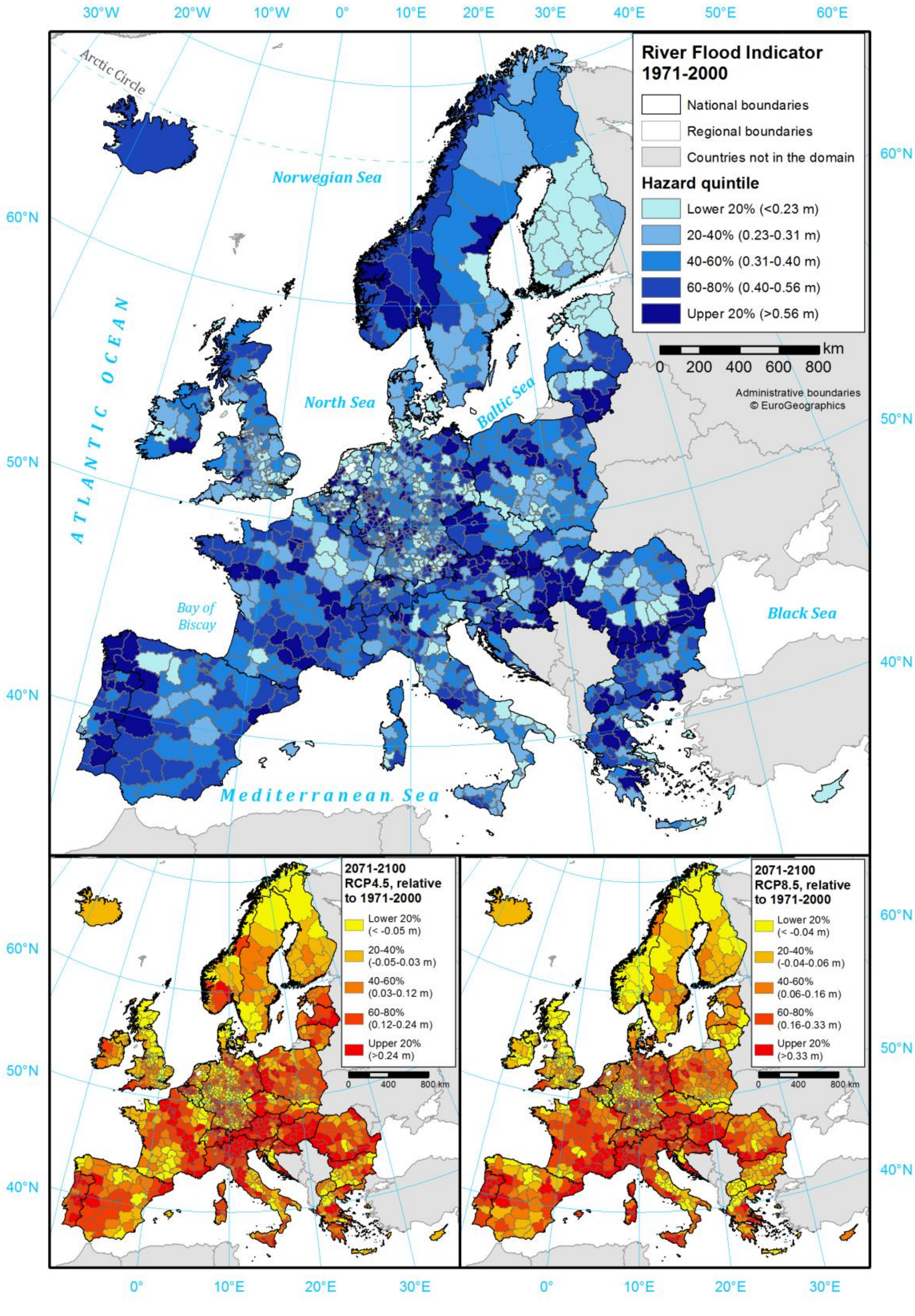


Figure 21. Quantiles of normalized river flood hazard indicator (100-year water level in a given scenario minus 10-year water level in the historical scenario) at regional level for historical scenario

(main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios

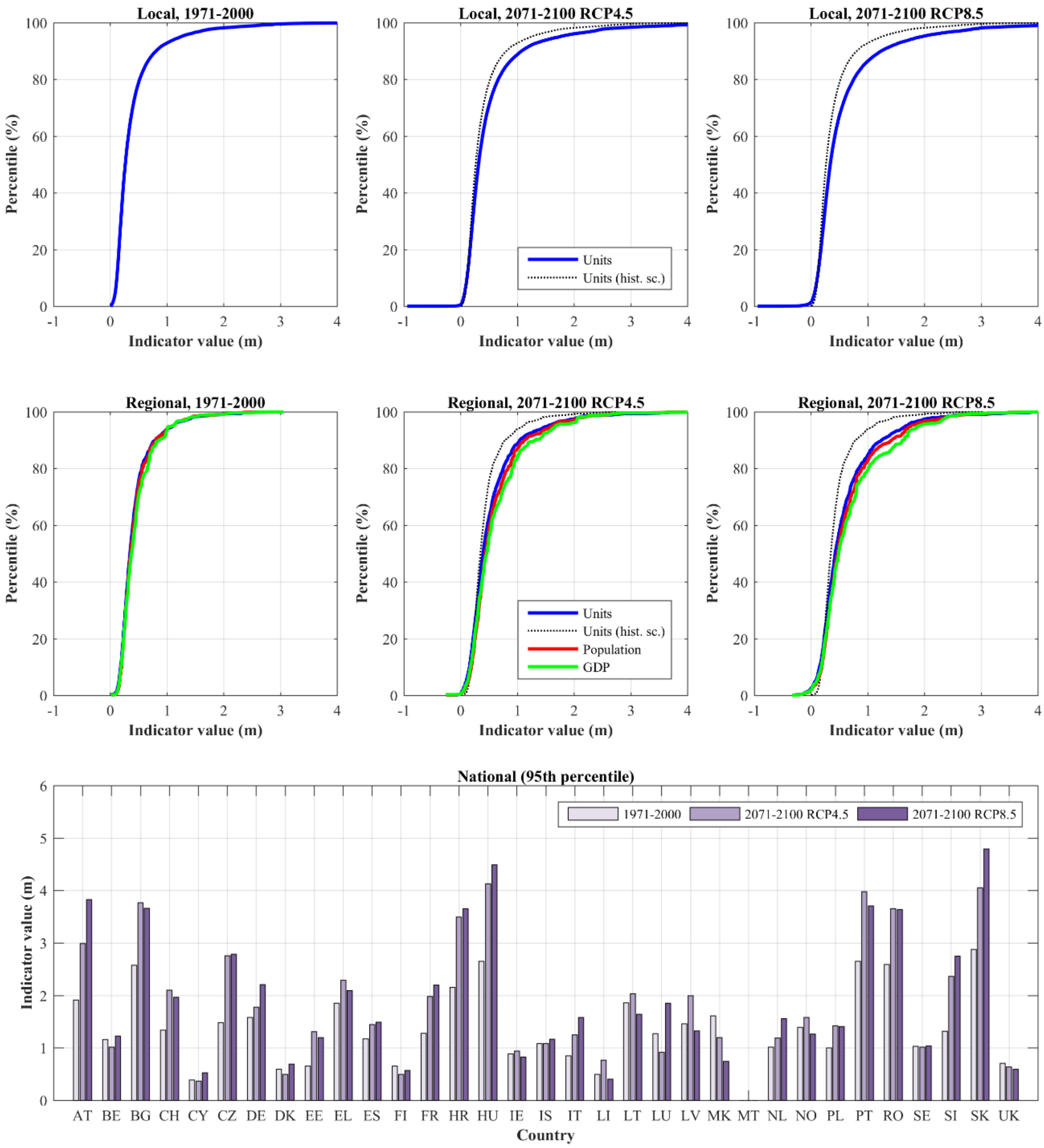
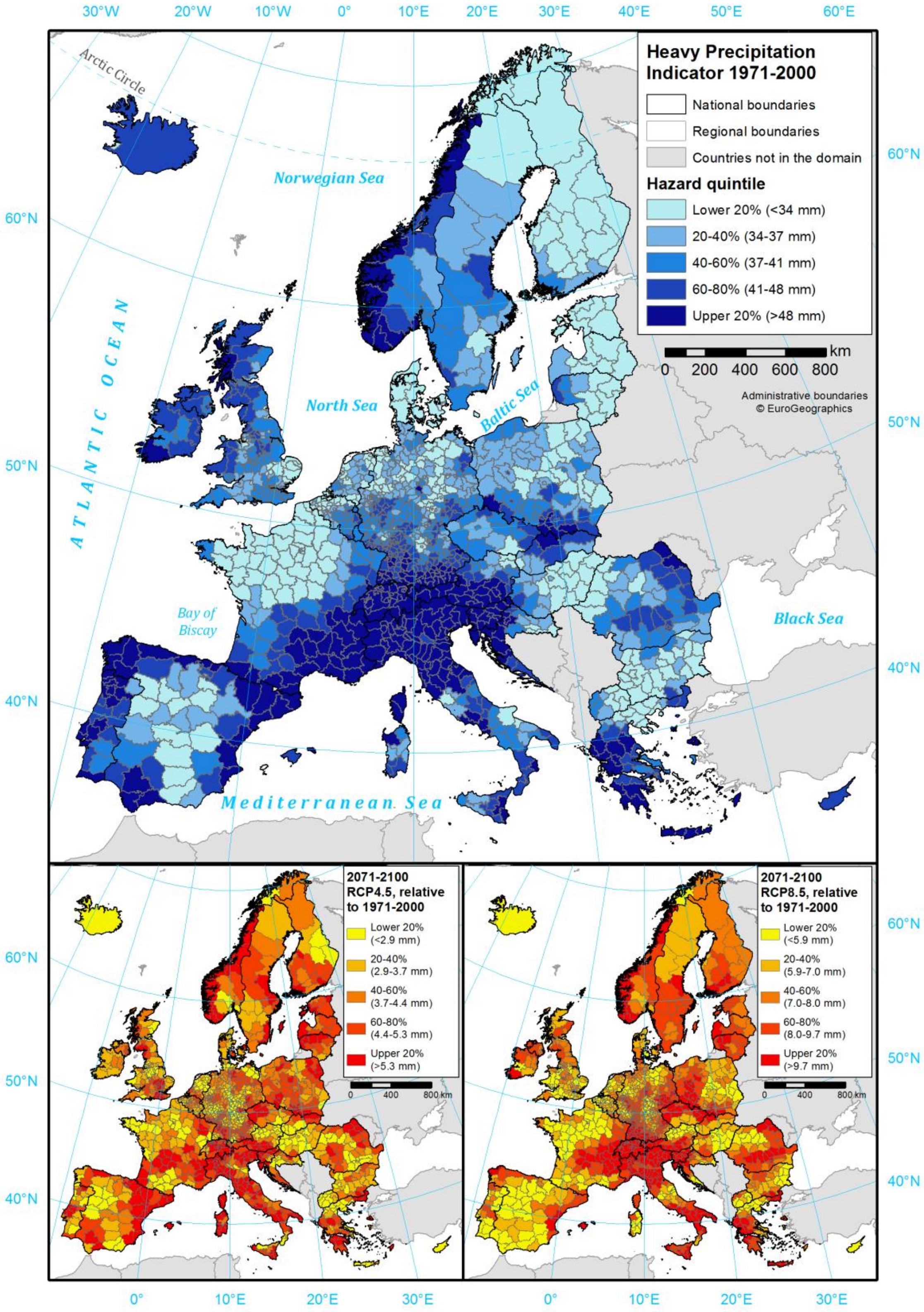


Figure 22. Normalized river flood hazard indicator at local, regional and national level, by climate change scenario. Histograms only for units for which river water level estimates were available (49,369 local, 1338 regional). For country codes, see Table 4

Heavy precipitation

The heavy precipitation hazard indicator based on the daily precipitation intensity for a return period of 5 years, is provided for any location in Europe. This does, however, not mean that pluvial floods and other heavy precipitation induced disasters can happen at any location. The pluvial flood hazard, for instance, depends on the local conditions in terms of topography, land use and drainage system properties.

Figure 23 shows that heavy precipitation is variable across Europe with higher intensities over elevated areas such as the alps because of the orographic lifting. Also some other areas show higher precipitation extremes such as the western Norwegian Coast, due to the passage of mid-latitude cyclones directed from west to east, and regions bordering the coasts in the Mediterranean region due to coastal cyclones that transport humid air masses. At the national level, Slovenia, Switzerland and Italy show the highest intensities (Figure 24). In the historical climate (1971-2000), the 5 and 95 percentiles of local extreme precipitation intensities vary from 27.2 mm to 69.2 mm across Europe. The extreme precipitation intensities are projected to increase over entire Europe, with increases up to more than 5 mm for RCP4.5 and more than 9 mm for RCP8.5 (Table 6). This causes an increase of the 5 and 95 percentiles of local extreme precipitation intensities across Europe from 27.2 - 69.2 mm (historical climate) to 29.9 – 75.2 (RCP4.5) and 31.7 – 79.3 (RCP8.5). The maximum intensities at the regional level increase from 69.1 (historical climate) to 74.3 (RCP4.5) and 80.9 (RCP8.5). At the national level, they increase from 117.5 (historical climate) to 131.0 (RCP4.5) and 143.5 (RCP8.5).



Heavy Precipitation Indicator 1971-2000
National boundaries
Regional boundaries
Countries not in the domain
Hazard quintile
Lower 20% (<34 mm)
20-40% (34-37 mm)
40-60% (37-41 mm)
60-80% (41-48 mm)
Upper 20% (>48 mm)
km
0 200 400 600 800
Administrative boundaries © EuroGeographics
Arctic Circle
Norwegian Sea
ATLANTIC OCEAN
North Sea
Baltic Sea
Bay of Biscay
Black Sea
Mediterranean Sea
30°W 20°W 10°W 0° 10°E 20°E 30°E 40°E 50°E 60°E
60°N 50°N 40°N
2071-2100 RCP4.5, relative to 1971-2000
Lower 20% (<2.9 mm)
20-40% (2.9-3.7 mm)
40-60% (3.7-4.4 mm)
60-80% (4.4-5.3 mm)
Upper 20% (>5.3 mm)
0 400 800 km
2071-2100 RCP8.5, relative to 1971-2000
Lower 20% (<5.9 mm)
20-40% (5.9-7.0 mm)
40-60% (7.0-8.0 mm)
60-80% (8.0-9.7 mm)
Upper 20% (>9.7 mm)
0 400 800 km
0° 10°E 20°E 30°E

Figure 23. Quantiles of normalized heavy precipitation hazard indicator (daily precipitation intensity for a return period of 5 years) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios

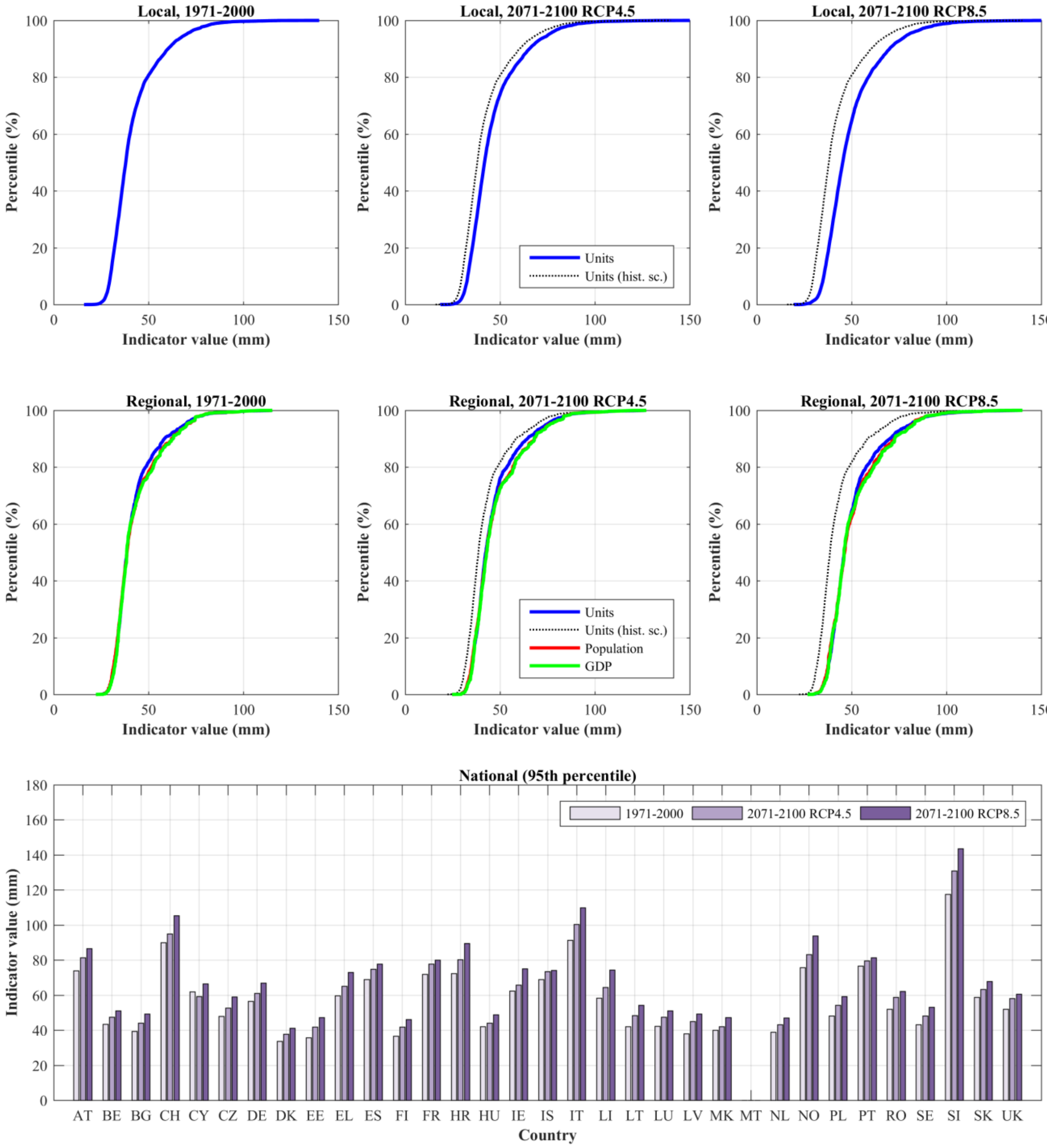
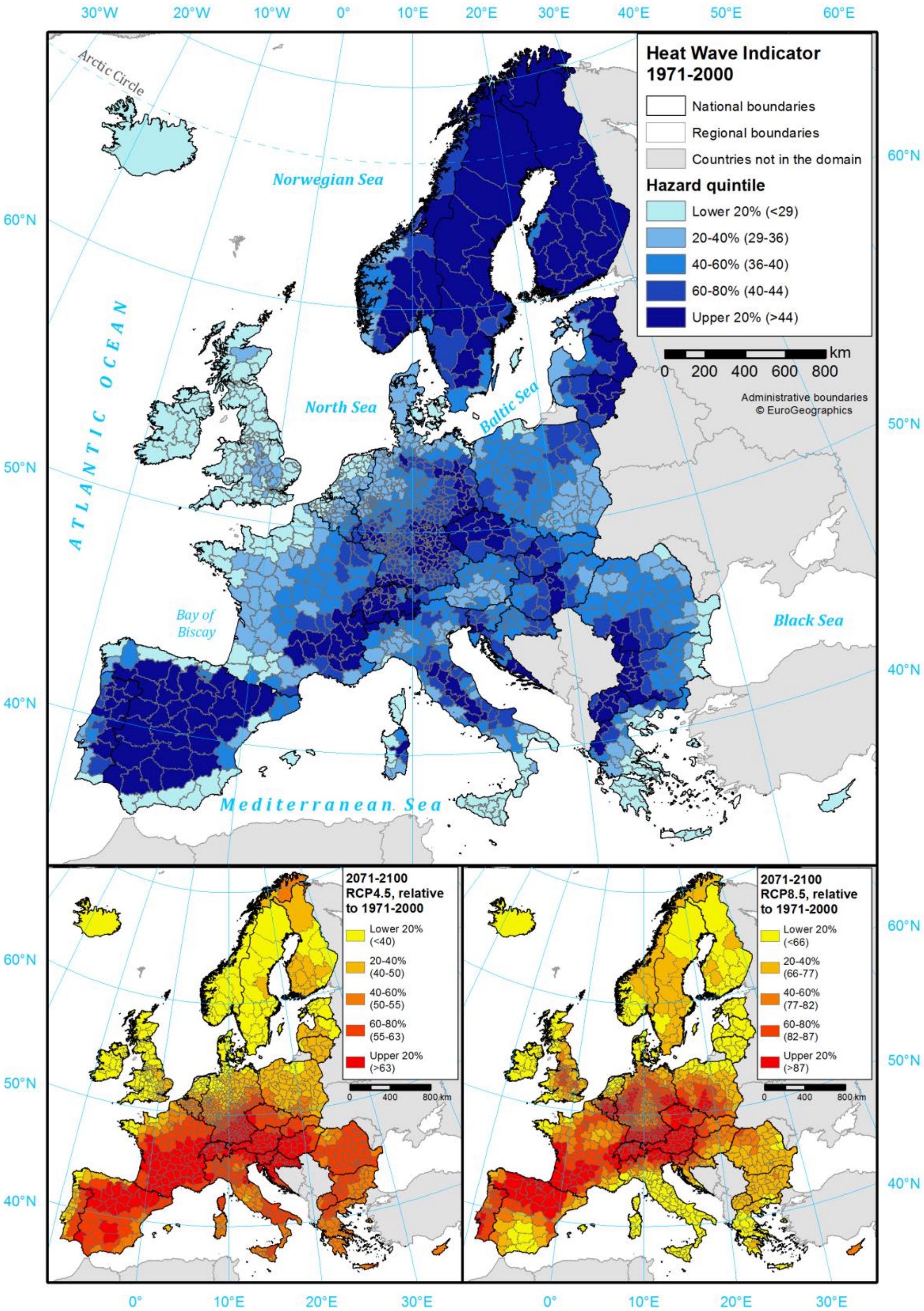


Figure 24. Normalized heavy precipitation hazard indicator at local, regional and national level, by climate change scenario.

Heat waves

The heat waves' hazard indicator based on the total number of heat waves in 30 years, is provided for any location in Europe. Figure 25 shows higher number of heat waves for the inland areas of Southern Europe. At the national level, Spain and Portugal have the highest number of heat waves (Figure 26). In the historical climate (1971-2000), the 5 and 95 percentiles of total number of heat waves in 30 years across Europe are 9 and 57. They are projected to increase quite strongly over entire Europe, with increases up to more than 60 heatwaves in 30 years for RCP4.5 and more than 80 RCP8.5 (Table 6). This causes an increase of the 5 and 95 percentiles of the total number of local heat waves in 30 years across Europe from 9 - 57 (historical climate) to 37 – 124 (RCP4.5) and 61 – 146 (RCP8.5). The maximum number of heat waves at the regional level increases from 51 (historical climate) to 114 (RCP4.5) and 139 (RCP8.5) in 30 years. The mean number of heat waves at the regional level increases from 38 (historical climate) to 90 (RCP4.5) and 117 (RCP8.5) in 30 years. At the national level, the maximum number of heat waves increases from 80 (historical climate) to 150 (RCP4.5) and 181 (RCP8.5) in 30 years.



Heat Wave Indicator
1971-2000
National boundaries
Regional boundaries
Countries not in the domain
Hazard quintile
Lower 20% (<29)
20-40% (29-36)
40-60% (36-40)
60-80% (40-44)
Upper 20% (>44)
km
0 200 400 600 800
Administrative boundaries
© EuroGeographics
Norwegian Sea
North Sea
Baltic Sea
Black Sea
Bay of Biscay
Mediterranean Sea
ATLANTIC OCEAN
Arctic Circle
30°W 20°W 10°W 0° 10°E 20°E 30°E 40°E 50°E 60°E
60°N 50°N 40°N
2071-2100
RCP4.5, relative to 1971-2000
Lower 20% (<40)
20-40% (40-50)
40-60% (50-55)
60-80% (55-63)
Upper 20% (>63)
0 400 800 km
2071-2100
RCP8.5, relative to 1971-2000
Lower 20% (<66)
20-40% (66-77)
40-60% (77-82)
60-80% (82-87)
Upper 20% (>87)
0 400 800 km
0° 10°E 20°E 30°E

Figure 25. Quantiles of normalized heat waves hazard indicator (number of heat waves over a period of 30 years) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios

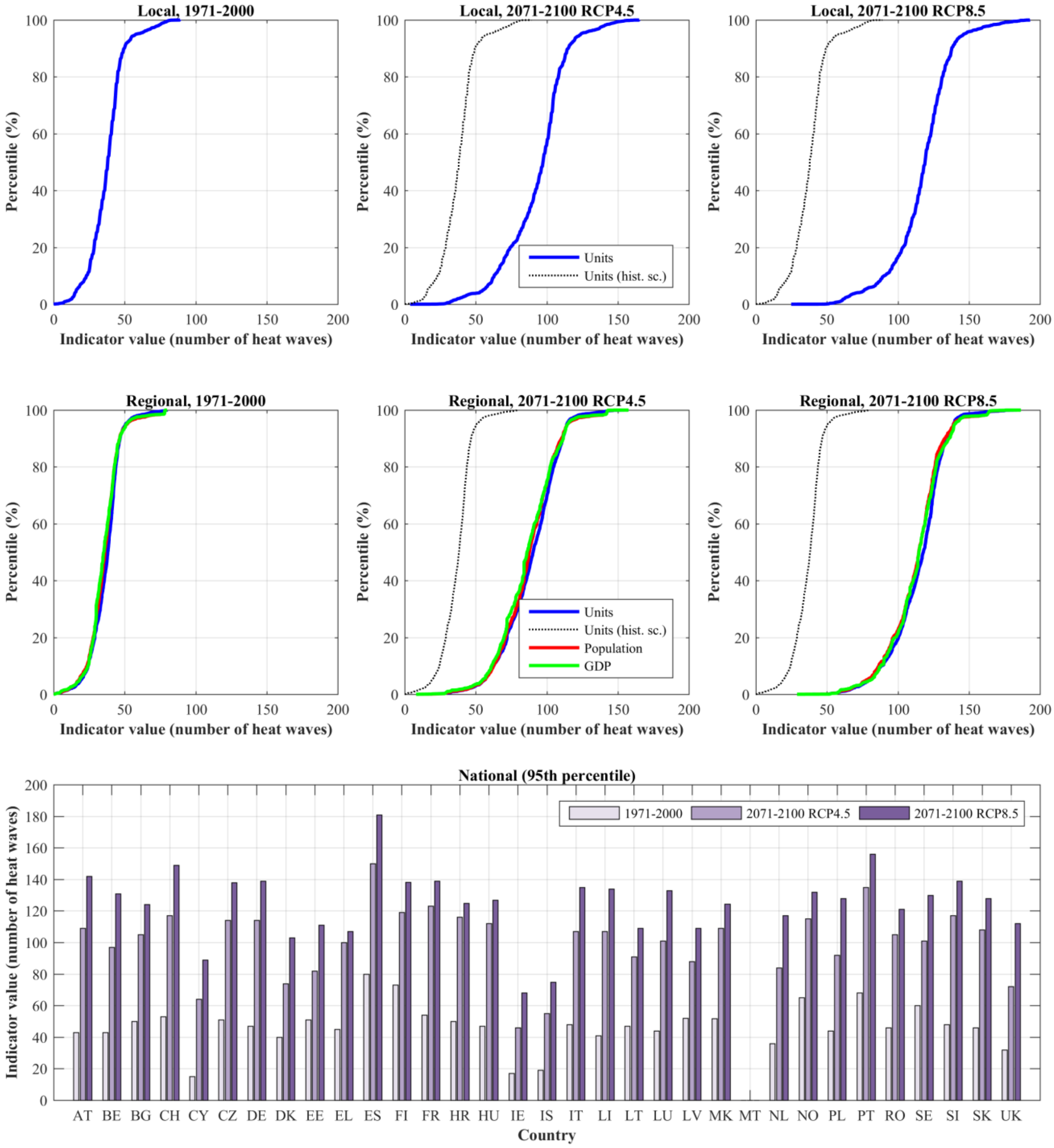


Figure 26. Normalized heat waves hazard indicator at local, regional and national level, by climate change scenario.

Droughts

The droughts' hazard indicator based on the CDD indicator, which represents the maximum number of consecutive dry days when precipitation is less than 1 mm, is provided for any location in Europe but with strong regional differences. Figure 27 shows a strong north-south variation in the number of CDDs with much higher drought hazard conditions in Southern Europe. At the national level, the Southern European countries Cyprus, Spain, Portugal, Greece and Italy have the highest CDD indicator days (Figure 28). In the historical climate (1971-2000), the 5 and 95 percentiles of CDDs across Europe are 28 and 99. They are projected to increase all over Europe, with increases up to more than 8 CDDs for RCP4.5 and more than 18 CDDs for RCP8.5 (Table 6). This causes an increase of the 5 and 95 percentiles of the total number of CDDs across Europe from 28 - 99 (historical climate) to 31 – 125 (RCP4.5) and 32 – 149 (RCP8.5). The changes are strongest for the more dry countries of Southern Europe. The maximum number of CDDs at the regional level increases from 97 (historical climate) to 121 (RCP4.5) and 139 (RCP8.5). The mean number of CDDs at the regional level increases from 40 (historical climate) to 45 (RCP4.5) and 50 (RCP8.5). At the national level, the maximum number of CDDs increases from 188 (historical climate) to 205 (RCP4.5) and 213 (RCP8.5).

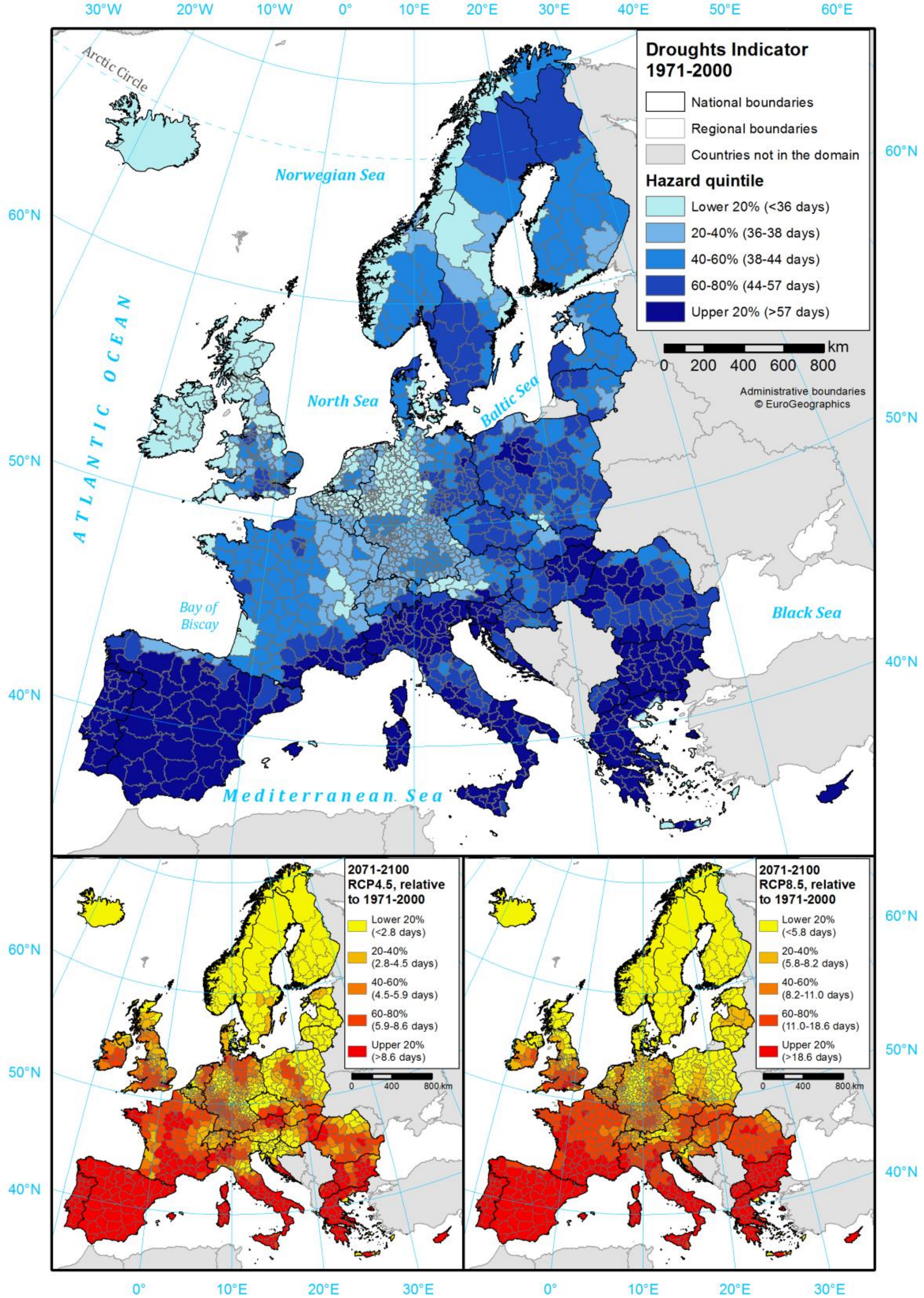

Droughts Indicator 1971-2000
National boundaries
Regional boundaries
Countries not in the domain
Hazard quintile
Lower 20% (<36 days)
20-40% (36-38 days)
40-60% (38-44 days)
60-80% (44-57 days)
Upper 20% (>57 days)
km
0 200 400 600 800
Administrative boundaries © EuroGeographics
Arctic Circle
Norwegian Sea
North Sea
Baltic Sea
ATLANTIC OCEAN
Bay of Biscay
Black Sea
Mediterranean Sea
2071-2100 RCP4.5, relative to 1971-2000
Lower 20% (<2.8 days)
20-40% (2.8-4.5 days)
40-60% (4.5-5.9 days)
60-80% (5.9-8.6 days)
Upper 20% (>8.6 days)
2071-2100 RCP8.5, relative to 1971-2000
Lower 20% (<5.8 days)
20-40% (5.8-8.2 days)
40-60% (8.2-11.0 days)
60-80% (11.0-18.6 days)
Upper 20% (>18.6 days)

Figure 27. Quantiles of normalized drought hazard indicator (maximum number of consecutive dry days when precipitation is less than 1 mm) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios

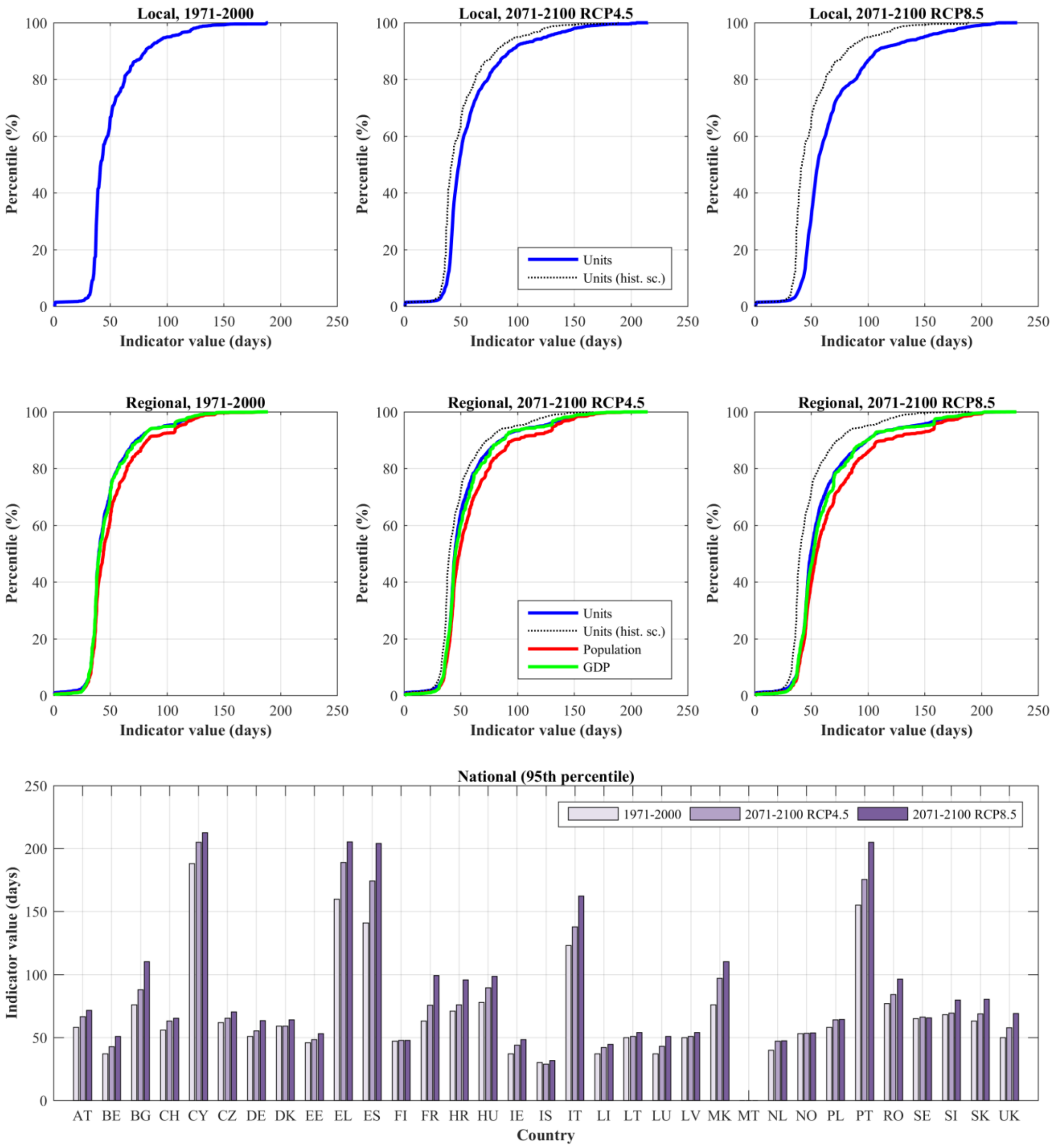


Figure 28. Normalized droughts hazard indicator at local, regional and national level, by climate change scenario.

Wild fires

The wild fire hazard indicator based on the Forest Fire Danger Index (FFDI) is provided for any location in Europe but with strong regional differences, as was also the case for the drought and heatwave indicators. Figure 29 shows a strong north-south variation in the FFDI with much higher wild fire hazard conditions in the drier countries of Southern Europe. At the national level, the Southern European countries Cyprus, Spain, Portugal and Greece have the highest FFDI values (Figure 30). In the historical climate (1971-2000), the 5 and 95 percentiles of the FFDI values across Europe are 0.43 and 0.81. They are projected to increase all over Europe, with increases up to more than 0.09 for RCP4.5 and more than 0.19 for RCP8.5 (Table 6). This causes an increase of the 5 and 95 percentiles of the FFDI values across Europe from 0.43 – 0.81 (historical climate) to 0.47 – 0.95 (RCP4.5) and 0.49 – 1.13 (RCP8.5). The changes are strongest for the more dry countries of Southern Europe. The maximum FFDI value at the regional level increases from 0.77 (historical climate) to 0.90 (RCP4.5) and 1.09 (RCP8.5). The mean FFDI value at the regional level increases from 0.50 (historical climate) to 0.56 (RCP4.5) and 0.62 (RCP8.5). At the national level, the maximum FFDI value increases from 1.26 (historical climate) to 1.54 (RCP4.5) and 1.93 (RCP8.5), while the mean FFDI value increases from 0.64 (historical climate) to 0.74 (RCP4.5) and 0.84 (RCP8.5).

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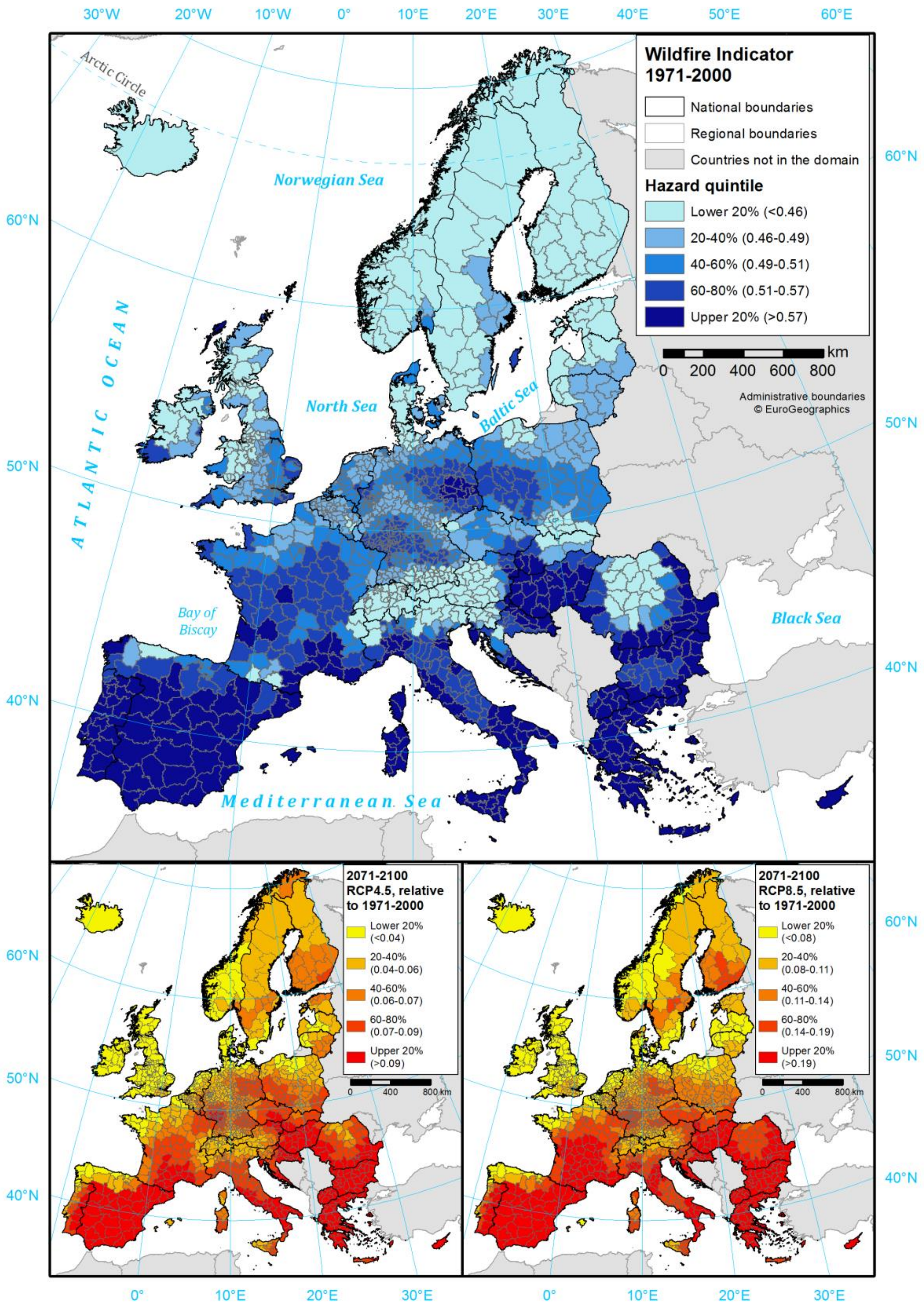

Wildfire Indicator 1971-2000
National boundaries
Regional boundaries
Countries not in the domain
Hazard quintile
Lower 20% (<0.46)
20-40% (0.46-0.49)
40-60% (0.49-0.51)
60-80% (0.51-0.57)
Upper 20% (>0.57)
km
0 200 400 600 800
Administrative boundaries © EuroGeographics
Arctic Circle
Norwegian Sea
North Sea
Baltic Sea
ATLANTIC OCEAN
Bay of Biscay
Black Sea
Mediterranean Sea
30°W 20°W 10°W 0° 10°E 20°E 30°E 40°E 50°E 60°E
60°N 50°N 40°N
2071-2100 RCP4.5, relative to 1971-2000
Lower 20% (<0.04)
20-40% (0.04-0.06)
40-60% (0.06-0.07)
60-80% (0.07-0.09)
Upper 20% (>0.09)
0 400 800 km
2071-2100 RCP8.5, relative to 1971-2000
Lower 20% (<0.08)
20-40% (0.08-0.11)
40-60% (0.11-0.14)
60-80% (0.14-0.19)
Upper 20% (>0.19)
0 400 800 km
0° 10°E 20°E 30°E

Figure 29. Quantiles of normalized wild fires hazard indicator (Forest Fire Danger Index) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios

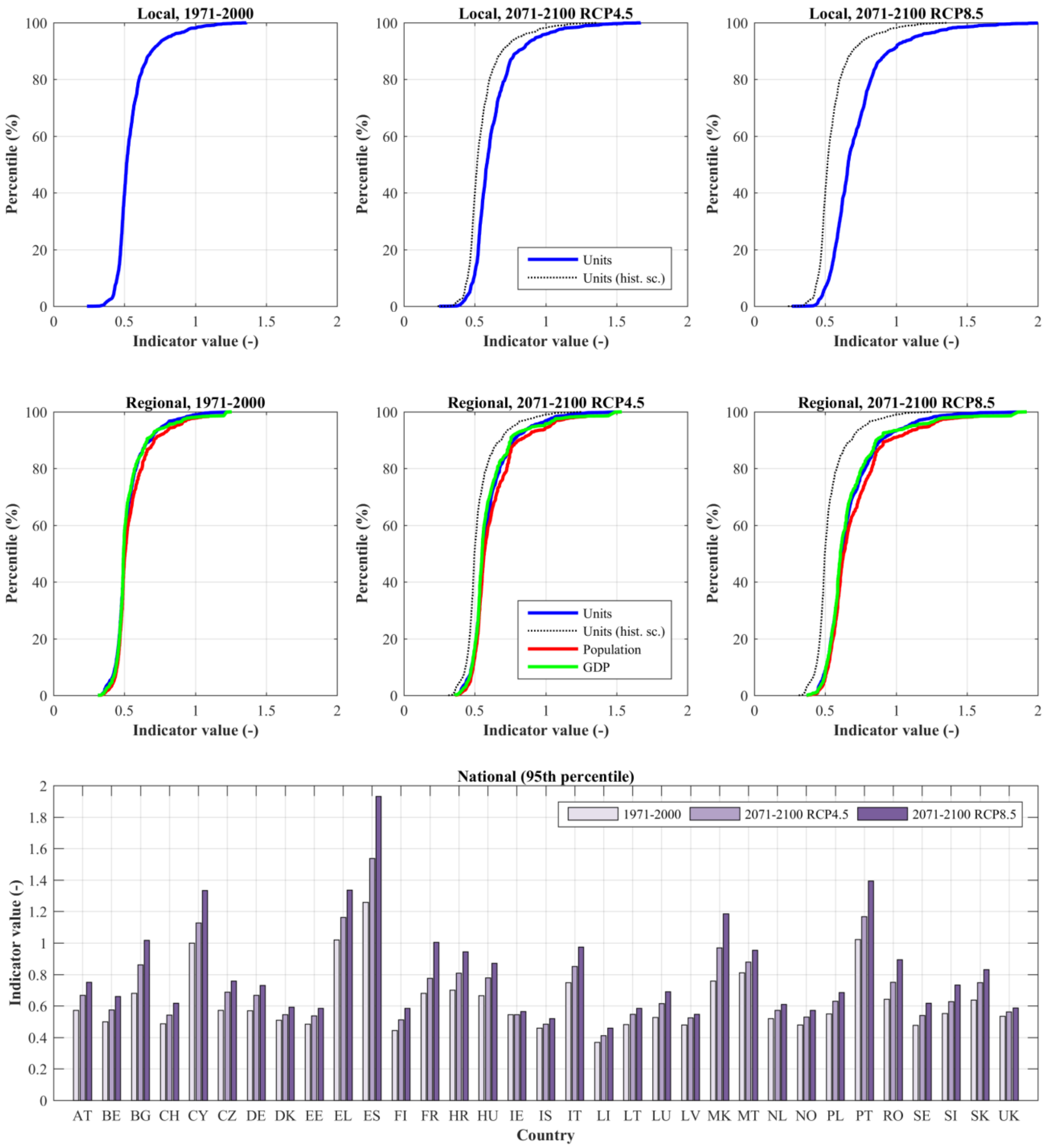

Figure 30. Normalized wild fires hazard indicator at local, regional and national level, by climate change scenario.

Wind storms

The wind storms' hazard indicator based on the 99th percentile of daily wind speed (in m/s) is provided for any location in Europe but with strong regional differences. There are both negative and positive changes. For the RCP4.5 scenario, the changes are primarily negative, whereas for the RCP8.5 scenario they are both positive and negative. Figure 31 shows higher changes (lower decreases for the RCP4.5 scenario and higher increases for the RCP8.5 scenario) for Iceland, the UK and the coastal areas of north-western Europe and Norway. In the historical climate (1971-2000), the 5 and 95 percentiles of the wind storms' indicator values across Europe are 4.6 and 12.3 m/s. For the RCP4.5 scenario, the 99th percentile of daily wind speed decreases to more than 0.12 m/s in comparison with the historical climatic conditions. For the RCP8.5 scenario, this percentile increases up to more than 0.10 m/s (Table 6). The 5 and 95 percentiles of the 99th percentile of daily wind speed values across Europe change from 4.6 – 12.3 m/s (historical climate) to 4.5 – 12.3 m/s (RCP4.5) and 4.5 – 12.3 (RCP8.5). Hence, the range of extreme wind speed values remains almost the same. The same applies to the values at the regional and national levels.

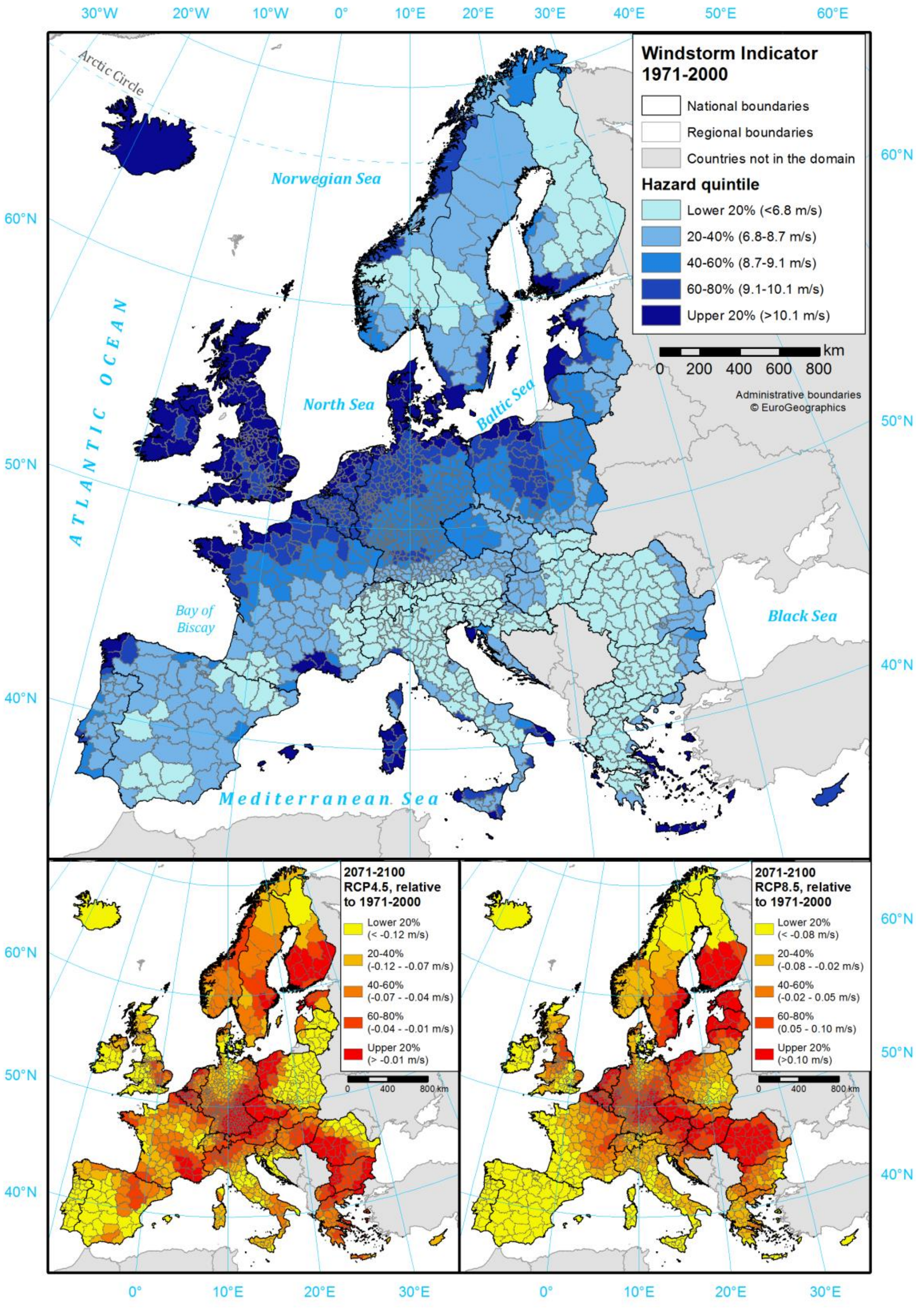
Windstorm Indicator
1971-2000
National boundaries
Regional boundaries
Countries not in the domain
Hazard quintile
Lower 20% (<6.8 m/s)
20-40% (6.8-8.7 m/s)
40-60% (8.7-9.1 m/s)
60-80% (9.1-10.1 m/s)
Upper 20% (>10.1 m/s)
km
0 200 400 600 800
Administrative boundaries
© EuroGeographics
Arctic Circle
Norwegian Sea
North Sea
Baltic Sea
ATLANTIC OCEAN
Bay of Biscay
Black Sea
Mediterranean Sea
30°W
20°W
10°W
0°
10°E
20°E
30°E
40°E
50°E
60°E
60°N
50°N
40°N
2071-2100
RCP4.5, relative to 1971-2000
Lower 20%
(< -0.12 m/s)
20-40%
(-0.12 - -0.07 m/s)
40-60%
(-0.07 - -0.04 m/s)
60-80%
(-0.04 - -0.01 m/s)
Upper 20%
(> -0.01 m/s)
2071-2100
RCP8.5, relative to 1971-2000
Lower 20%
(< -0.08 m/s)
20-40%
(-0.08 - -0.02 m/s)
40-60%
(-0.02 - 0.05 m/s)
60-80%
(0.05 - 0.10 m/s)
Upper 20%
(>0.10 m/s)
0 400 800 km

Figure 31. Quantiles of normalized wind storms (99th percentile of daily maximum wind speed) at regional level for historical scenario (main map) and relative change (subtraction) between 2071–2100 and 1971–2000, in two scenarios

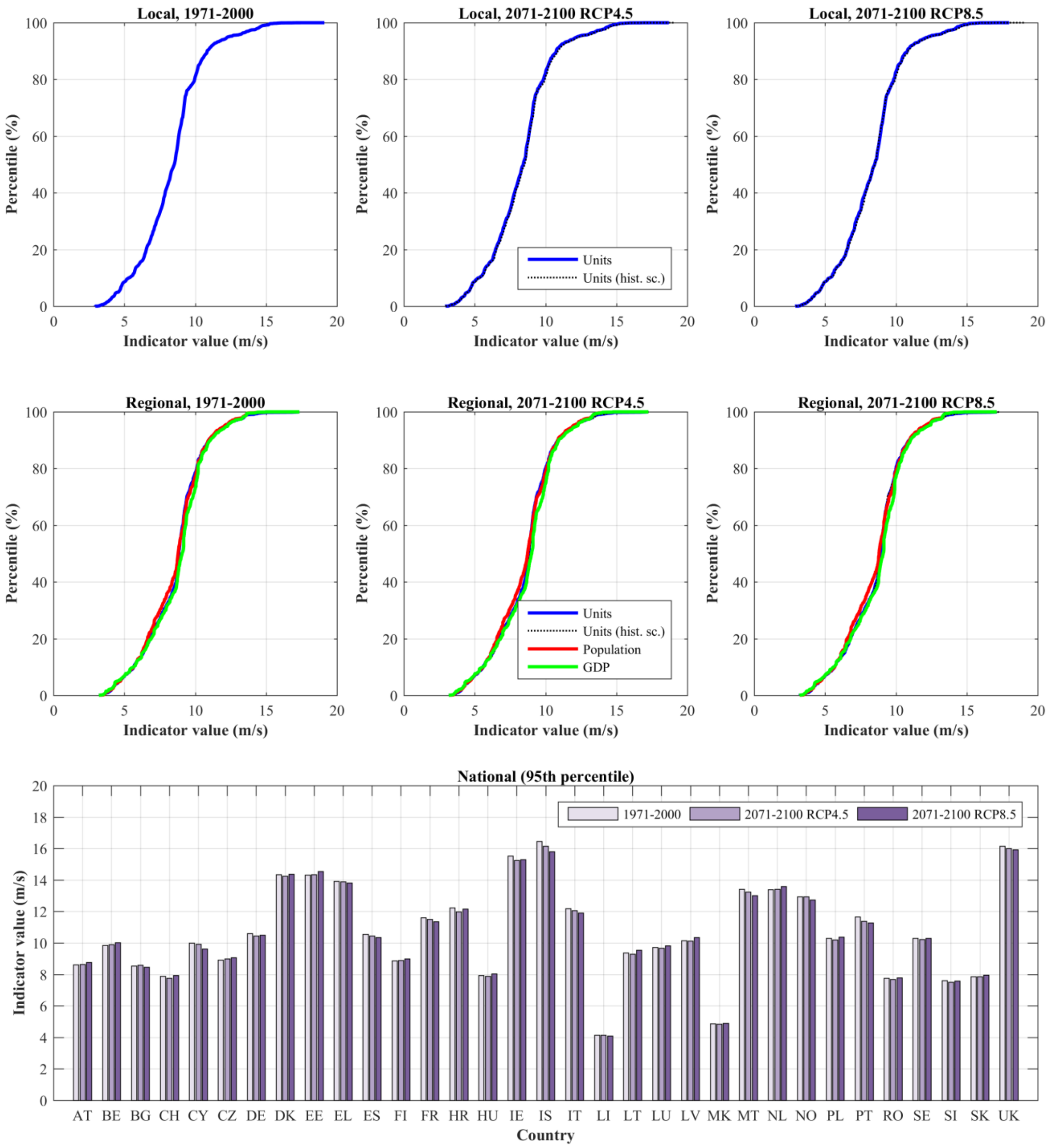

Figure 32. Normalized wind storms hazard indicator at local, regional and national level, by climate change scenario.

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BRIGAID

GIS files readme

General information

The GIS dataset of climate change indicators and loading conditions (WP5 & 6) contains a set of normalized indicators for 7 hazards and 3 scales (local, regional and national).

Further information

For information on the underlying hydrological and meteorological data, normalization process and analysis of the results, see this report.

Contact

For inquiries regarding flood indicators and technical issues with this dataset, please contant Dominik Paprotny (TU Delft), d.paprotny@tudelft.nl

For inquiries regarding remaining indicators, please contact Patrick Willems (KU Leuven), patrick.willems@kuleuven.be

Disclaimer and copyright

The data provided herein were made using large-scale datasets and are intended for providing an European-wide overview of present and future probability of occurrence of extreme weather hazards. Extreme caution should be made when drawing local-scale conclusions from the data.

The data are provided to BRIGAID partners solely for the needs of BRIGAID project, and they are not to be distributed outside the project.

When using the data to prepare maps, the information on the copyright of the administrative boundaries data needs to be provided: " © EuroGeographics for the administrative boundaries".

Contents and data format

The GIS files are ESRI Shapefiles and are formatted in ETRS89 / ETRS-LAEA projection (EPSG:3035). There are 3 shapefiles, each with different scale of analysis (local, regional and national):

- *'AllIndicators_local'*
- *'AllIndicators_regional'*
- *'AllIndicators_national'*

Each shapefile contains basic information about the geographical units and values for all hazard indicators corresponding to a given unit. The data structure is the same for all 3 shapefiles, as shown in the below table.

Table. Data structure of GIS files.

Field name	Field type	Field length	Description
ID	Text	2 (national), 5 (regional), 15 (local)	Local: modified LAU 2 code; regional: NUTS 3 code; national: NUTS 0 code
Name	Text	200	Name of local/regional/national unit
Area	Long integer	6	Surface area, sq. km
Population	Long integer	9	Resident population, persons, 1.1.2015 (only regional & national level)
GDP	Long integer	7	Gross domestic product (GDP), million euro, 2014 (only regional & national level)
CstFl_hist	Double	Precision: 8, scale: 3	Coastal flood indicator, historical scenario (1971-2000), in meters
CstFl_rcp4	Double	Precision: 8, scale: 3	Coastal flood indicator, RCP 4.5 scenario (2071-2100), in meters
CstFl_rcp8	Double	Precision: 8, scale: 3	Coastal flood indicator, RCP 8.5 scenario (2071-2100), in meters
RvrFl_hist	Double	Precision: 8, scale: 3	River flood indicator, historical scenario (1971-2000), in meters
RvrFl_rcp4	Double	Precision: 8, scale: 3	River flood indicator, RCP 4.5 scenario (2071-2100), in meters
RvrFl_rcp8	Double	Precision: 8, scale: 3	River flood indicator, RCP 8.5 scenario (2071-2100), in meters
Drght_hist	Double	Precision: 8, scale: 3	Drought indicator, historical scenario (1971-2000), in days
Drght_rcp4	Double	Precision: 8, scale: 3	Drought indicator, RCP 4.5 scenario (2071-2100), in days
Drght_rcp8	Double	Precision: 8, scale: 3	Drought indicator, RCP 8.5 scenario (2071-2100), in days
HtWvs_hist	Double	Precision: 8, scale: 3	Heat wavesindicator, historical scenario (1971-2000), number of heat waves
HtWvs_rcp4	Double	Precision: 8, scale: 3	Heat wave indicator, RCP 4.5 scenario (2071-2100), number of heat waves
HtWvs_rcp8	Double	Precision: 8, scale: 3	Heat wave indicator, RCP 8.5 scenario (2071-2100), number of heat waves
Wldfr_hist	Double	Precision: 8,	Wildfire indicator, historical scenario (1971-2000),

		scale: 3	dimensionless index
Wldfr_rcp4	Double	Precision: 8, scale: 3	Wildfire indicator, RCP 4.5 scenario (2071-2100), dimensionless index
Wldfr_rcp8	Double	Precision: 8, scale: 3	Wildfire indicator, RCP 8.5 scenario (2071-2100), dimensionless index
Wndst_hist	Double	Precision: 8, scale: 3	Windstorm indicator, historical scenario (1971-2000), in m/s
Wndst_rcp4	Double	Precision: 8, scale: 3	Windstorm indicator, RCP 4.5 scenario (2071-2100), in m/s
Wndst_rcp8	Double	Precision: 8, scale: 3	Windstorm indicator, RCP 8.5 scenario (2071-2100), in m/s
HPrcp_hist	Double	Precision: 8, scale: 3	Heavy precipitation indicator, historical scenario (1971-2000), in mm
HPrcp_rcp4	Double	Precision: 8, scale: 3	Heavy precipitation indicator, RCP 4.5 scenario (2071-2100), in mm
HPrcp_rcp8	Double	Precision: 8, scale: 3	Heavy precipitation indicator, RCP 8.5 scenario (2071-2100), in mm

The same files are also provides for the intermediate periods 2016-2045 (mean year 2030), and 2036-2065 (mean year 2050).