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## *Experimental statistical indicators on granular exposures to climate-related physical risks*[1]

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ABSTRACT

*Central banks world-wide are considering climate change more and more as relevant dimension to be taken into account in monetary policy preparation and implementation as well as in macro- and micro-prudential considerations. The European Central Bank has recently announced an action plan to include climate change considerations in its monetary policy strategy. This action plan also foresees the development of statistical indicators for climate change risk analysis covering green financial instruments, the carbon footprint of financial institutions and their exposures to climate-related physical risks. In this paper, we cover the derivation of physical risk indicators, which require the application of new methods for central bank statisticians, borrowed from geographers, meteorologist, climate scientists and disaster management experts.*

*First, we present the necessary data layers, covering: i) location, ii) physical hazards, such as floods, earthquakes, wildfires, landslides, and subsidence, iii) assets exposures to those physical hazards, and iv) final potential impact stemming from the realization of the hazards. Second, we briefly describe available data sources and procedures for linking climate with financial information from heterogenous datasets including public and commercial data providers. Finally, we propose experimental statistical indicators of physical hazard, testing consistency of various specifications across data sources and spatial aggregation.*

# Contents



[1] This paper should not be reported as representing the views of the European Central Bank. The views expressed are those of the authors and do not necessarily reflect those of the European Central Bank.

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# 1. Introduction

Climate change and sustainability used to be a topic for environmentalists and non-governmental organisations (NGOs). Now it mobilises all groups of society, sometimes with strongest voices coming from younger population and it is high on the agenda of governments, businesses, insurers, and private investors. Since a number of years also central banks have significantly upgraded their analysis to cover for the impact of climate change on macroeconomic outcomes, financial markets and institutions, and increased their dedication to contribute within their mandate to integrate the effects of the climate crisis in the exercise of their tasks.[3] Thereby, central banks aspire to be able to achieve their mandates in a world of climate change and provide support to sustainable finance in facilitating the transition to a less carbon intensive economy. However, significant challenges exist with regards to the lack of good quality, comparable and readily accessible data.[4]

In July 2021, as an outcome of its monetary policy strategy review, the European Central Bank announced an action plan to include climate change considerations in its monetary policy strategy. In addition to a comprehensive incorporation of climate factors in its monetary policy assessments, the Governing Council intends to adapt the design of its monetary policy operational framework in relation to disclosures, risk assessment, corporate sector asset purchases and collateral framework (ECB, July 2021). For assessing the economic impact and financial system vulnerabilities stemming from physical and transitional risks, and monitoring the transition to a greener economy via sustainable finance, the ECB action plan also foresees the development of statistical indicators for climate change risk analysis covering green financial instruments, the carbon footprint of financial institutions and their exposures to climate-related physical risks[5].

Significant data-related challenges exist both with respect to the availability of consistent data and the underlying methodology. Reporting standards and disclosure standards of climate information are being developed to improve the availability and quality of climate information. In Europe, there is a mosaic of legislative initiatives addressing various aspects of sustainability: i) the EU taxonomy defining sustainable activities; ii) the EU green bond standard (GBS) which builds on the taxonomy to classify sustainable financial instruments; and iii) the Corporate Sustainability Reporting Directive (CSRD) covering disclosure of environmental and social matters at company level. Until full implementation of the legislation[6], development of interim experimental indicators based on existing data is required, given the urgency of the climate agenda.

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[3] The creation of the Network on the Greening of the Financial Sector in 2017 and its development since then is a visible expression of the importance central banks attach to climate-related questions. The NGFS started with 8 founding members consisting of central banks and supervisors. As of June 2021, it has 95 members and 15 observers.

[4] See the Network for Greening the Financial System progress report on bridging climate-related data gaps (NGFS, May 2021).

[5] These three priorities were identified by an ad-hoc expert group of the European System of Central Banks (ESCB) Statistics Committee (STC) via a consultation of various stakeholders needs, comprising several ESCB committees and the Single Supervisory Mechanism (SSM) fora. In addition, the expert group provided an overview of available data sources to address current data gaps and methodological challenges for each set of indicators. In this paper we draw on the group's findings.

[6] The legislative proposal was published on 6 July 2021, alongside the Commission's new sustainable finance strategy, and it is anticipated that application will commence in 2023. The adaptation and mitigation aspects of the EU taxonomy will come into effect in 2022. The definition of activities related to the four other environmental objectives in the EU taxonomy (sustainable use and protection of water and marine resources, transition to a circular economy, pollution prevention and control, protection and restoration of biodiversity and ecosystems) will be finalised in the course of 2022 and enter into force in January 2023. The Corporate Sustainability Reporting Directive (CSRD) published on 21 April 2021 replaces the Non-Financial Reporting Directive (NFRD) (ECB, September 2021).

One important field where further progress is required relates to indicators on the physical risks related to financial portfolios. Physical risks are related to the exposure of the society and the economic systems to extreme climate events due to gradual global warming and associated physical changes (e.g. rising sea levels, changes in precipitation patterns), as well as to natural disasters (e.g. hurricanes, floods and heatwaves). These events may result in enhanced risks for, among others, non-financial and financial corporations.

Exposure of financial and non-financial corporations to climate related physical risks can be direct if affecting their fixed capital and productivity (e.g. when headquarters or plants of non-financial corporations are in coastal areas under risks of a sea-level rise). And it can also be indirect, when seen from the side of their clients' and investees' exposures to these risks (NGFS, September 2020). For instance, insurance companies may face larger claims due to major physical hazards and be under pressure to liquidate assets at a loss to cover for these (liquidity risk). The risk profile of mortgage portfolios with real estate located in the affected areas may change. Financial institutions' portfolio may be impacted to the extent it includes financial assets issued by firms located in vulnerable regions, or from sectors largely exposed to climate (physical and transition) risks. From a lender's perspective, higher cost, lower revenue and impairment of collaterals could reduce the affected non-financial firms' ability to repay bank loans and increase default rates (credit risk).

This paper elaborates on the elements necessary for the derivation of experimental indicators on the exposure of financial institutions to climate-related physical risks through their asset portfolios. The derivation of such indicators, ideally available at different levels of granularity (e.g. instrument, institution, industry, sector), requires the integration of three types of (not easily available) information. First, detailed information on the investment and loan portfolio of financial institutions is needed. Second, the physical location of the assets in which financial institutions have invested is necessary. While in the case of households (e.g. mortgage portfolios) this would typically be only a single location, for non-financial corporations both the location of the head office and of core production plants are relevant. The last element is given by information on the physical hazard associated with these locations.

Already existing analyses by central banks and supervisors rely in large part on climate-information and physical risk metrics from commercial data providers linked to granular financial information collected for regulatory purposes. These help identifying gaps in data availability, metrics and underlying methodology. [7] Main gaps are generally related to data quality and granularity, commonly agreed physical risk metrics, forward-looking and downstream emissions aspects, heterogeneity of climate-related disclosures among firms and financial institutions (The ECB/ ESRB, July 2021).

Physical hazard information is the starting point for assessing the impact of climate related physical risks on financial institutions and their portfolio. The analytical part of this paper focuses on granular indicators related to physical hazards and its various specifications. We explore public hazard datasets, which allow extracting hazard value at exact location, enabling compilation of physical hazard indicators in a flexible and transparent manner, both at granular and aggregated level, and further linking it to other sources. We compare the physical hazard scores available from commercial datasets with indicators compiled by using publicly available granular hazards data. We also share our experience in using physical hazard data – both from technical and methodological perspectives –

[7] The report of the joint ECB/ESRB Project Team on climate risk monitoring investigates climate risks for the European financial system, with focus on banks, insurers and investment funds (The ECB/ ESRB, July 2021). A recent ECB's economy-wide stress test (ECB, September 2021) assesses the resilience of non-financial corporates (NFCs) and euro area banks to climate risks, under several scenarios for climate policies and macroeconomic conditions.

which might help to establish the technical infrastructure and analytical tools for physical risk analysis at other institutions.

The remainder of this paper is structured as follows. Section 2 provides general considerations on measuring the impact of physical risks, with focus on the portfolios of financial institutions. Section 3 describes different data sources required for the analysis organised by analytical layers. In Section 4 we focus on physical hazard indicators, testing various specifications and comparing them with risk metrics available in commonly used commercial data sets. Finally, we conclude, and outline envisaged future work.

## 2. Measuring the impact of physical risks

Physical risk is defined by the NGFS (NGFS, September 2020) as the economic costs and financial losses resulting from the increasing severity and frequency of: i) *extreme climate change-related weather events* (such as heat waves, landslides, floods, wildfires and storms), ii) *longer term progressive shifts of the climate* (such as changes in precipitation, extreme weather variability, ocean acidification, and rising sea levels and average temperatures), iii) *losses of ecosystem services* (e.g., desertification, water shortage, degradation of soil quality or marine ecology), and iv) *environmental incidents* (e.g., major chemical leakages or oil spills to air, soil and water/ocean).

In the paper we focus on the first category and rely on the hazard classification developed within the Sendai Framework for Disaster Risk Reduction[8] and used by the Joint Research Centre (JRC)[9] of the European Commission, which is our main source of hazard data.

It is important to clarify the distinction between physical hazard and physical risk. Physical risk is the expected impact, in terms of monetary value, stemming from the realisation of a physical hazard. Many factors enter into the calculations of physical risk (IPCC, September 2020): i) *hazard's location, frequency and severity*, ii) *exposure* – total value of assets and socioeconomic elements (such as population, jobs) exposed to a hazard; and finally, iii) *vulnerability* – degree of damage expected at different intensities of a hazard, including mitigation approaches aimed at lessening the adverse impacts of hazards (e.g. flood protection or insurance).

The final aim of central bankers and supervisors is to assess the propagation of the physical risk into the financial system. Figure 1 illustrates the spillovers from *Physical impact* of a hazard into the *Financial risk channel* – first on the financial situation of businesses and households and then on to financial institutions exposed to the affected sectors via their lending and equity portfolios. With regards to the *Financial risks channel*, a wide range of indicators measuring physical risks in the financial sector has been already proposed and applied in analytical studies.[10, 11] These studies rely on indicators of physical hazards available from commercial sources, as thorough *Physical impact* analyses building on information on physical hazards for analytical purpose in central banking are still at an early stage.

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[8] Project facilitated by co-facilitated by the United Nations Office for Disaster Risk Reduction (UNDRR) and the International Science Council (ISC): https://council.science/sendai-hazard-review/.

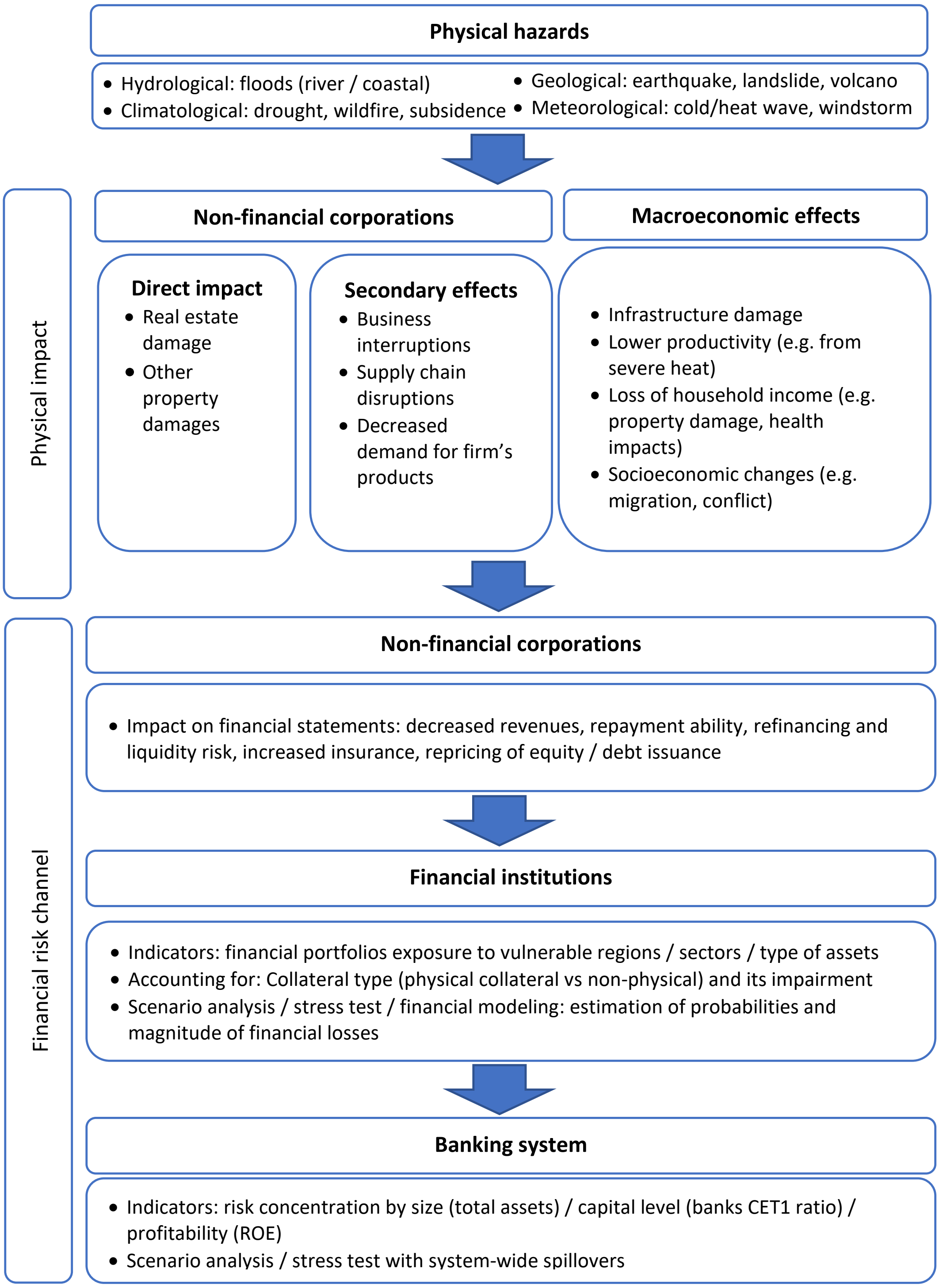
[9] JRC Risk Data Hub: https://drmkc.jrc.ec.europa.eu/risk-data-hub#/.

[10] The FSB's Task Force on Climate-related Financial Disclosures (TCFD, June 2017) recommended several metrics and targets for climate risk management and disclosure, and published detailed guidance for banks, insurance companies, asset owners and asset managers, which were incorporated in the Commission Guidelines on non-financial reporting (Commission, 2019).

[11] The ECB examined a wide range of indicators at financial sector level for micro- and macroprudential analysis [ (ECB, September 2021), (The ECB/ ESRB, July 2021)].

Against this background and after providing a general overview on physical risk analysis, in this paper particular attention is given to the first step of the analysis, as sketched in Figure 1, shedding light on the concepts related to physical hazards and the underlying data.

*Figure 1 Spillovers from physical hazards to banking system*




Sources: Adapted from (NGFS, September 2020) and (The ECB/ ESRB, July 2021).
Notes: CET1 stands for Common Equity Tier 1; ROE stands for return on equity.

# 3. Data layers for physical risk analysis

## 3.1. Overview of Geographic Information System (GIS) data formats

Climate information, such as hazards or carbon footprints, are commonly obtained from commercial data providers, typically available as scores or derived indicators, and later linked to regulatory databases via common identifiers, such as the Legal Entity Identifier (LEI), ISIN or business register identifier. Usually, the data are accessible in a tabular form – a standard for economic analysis – and can be processed using popular statistical and econometric software.

In this paper, we process the hazard data in their original Geographic Information System (GIS) format – a standard for encoding geographical information and representing location data. This has the advantage of extracting information at the exact location, as well as flexibility in building derived indicators depending on analytical needs. Spatial data are structured in vector and raster formats. Assessing physical risks requires location information, terrain characteristics, climate and atmospheric maps, as well as financial, economic and socioeconomic variables and combining these different types of data over spatial dimension.

In stocktaking of existing and potential data sources for the analysis of the physical risk, as well as in setting up the infrastructure for the data processing, we have drawn from GIS science, arranging the information in analytical layers reflecting three dimensions required for the physical risk analysis: hazards, exposure and vulnerability. In addition, we separate the sources for location information which is the basis for combining those dimensions (see Figure 3 Analytical layer required for the physical risk analysisFigure 3).

Figure 2 presents the main features of each format and application.

- Raster data represent the world as a surface divided in a regular grid of cells. Raster files can contain one or more layers (or bands in GIS terminology), each representing a single characteristic. Hazard data are usually available as single band raster, where grid cell indicates a value of hazard intensity, e.g. water depth for flooding.[12] (See right-hand panel of Figure 2).
- Vector files are based on coordinates representing geographic features such as points (e.g. longitude and latitude coordinates of a specific address), lines (e.g. streets) or polygons - set of connected vector lines (e.g. geographical boundaries used to represent regions or other areas). (See left-hand panel of Figure 2).
- An overlay of raster and vector files allows computing so called zonal statistics, e.g. in case of flooding, an average water depth (based on a raster) in each region (as defined by vector file).

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[12] See Section Physical hazards information for hazard measures.

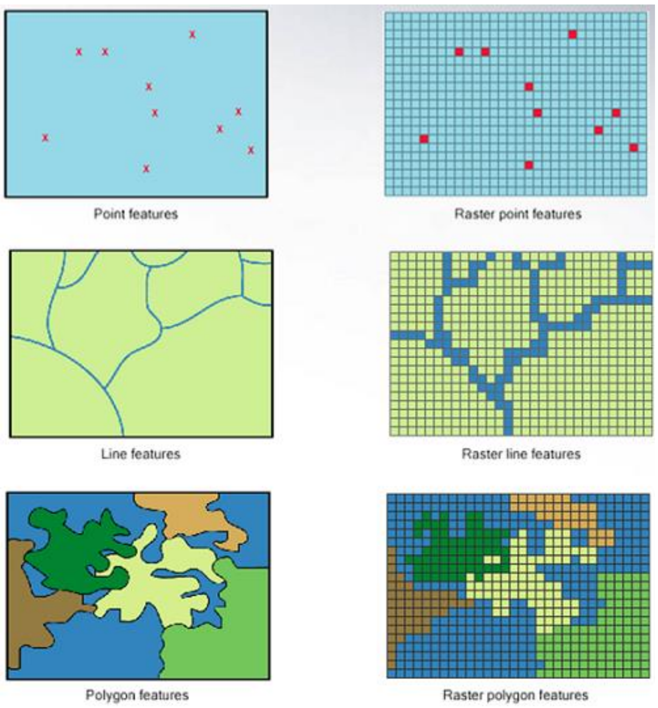
*Figure 2 GIS data formats and its uses – vector and raster files*

***Vector***

comprised of vertices and paths with three basic types: points, lines and polygons, representing map features

Typical uses:

- points of interest (e.g. company location)
- country boundaries, regions (NUTS), cities, streets and buildings
- custom area shapes (polygons)



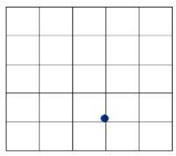
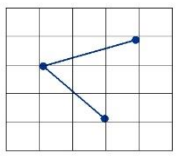
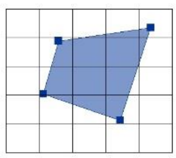

***Raster***

made up of pixels (also referred to as grid cells)

Typical uses:

- remote sensing images (e.g. satellite pictures)
- elevation data
- population statistics
- physical hazard data

***Data structure in vector and raster files***

| **Format** | **Type** | **Examples** | |
|---|---|---|---|
| Vector | Point | POINT (30 10) |  |
| Vector | LineString | LINESTRING (30 10, 10 30, 40 40) |  |
| Vector | Polygon | POLYGON ((35 10, 45 45, 15 40, 10 20, 35 10)) |  |
| Raster | Single band | RASTER @ VALUES (4, 2, 5, 3, 7, 6, 6, 9, 10) |  |

Sources: (ArcMap, 2021), (GISGeography, June 2021), (Gandhi V. (2017) Vector Data. In: Shekhar S., 2017), (ISO 19125 Standards).

For each analytical layer required for physical risk analysis, several data sources were identified (Table 1) – a mixture of public data sources, granular regulatory datasets and private data providers. In the selection of sources, we give priority to datasets with at least EU-wide coverage (or wider), which are harmonised across countries, and with transparent methodology on how data are obtained and compiled. Datasets with granular information are preferable (firm, bank level), also with respect to location information (address level versus regional or country level data). In the following section, we elaborate on each analytical layer and available data sources, which comprise necessary input for the calculation of physical risks.

*Figure 3 Analytical layer required for the physical risk analysis*

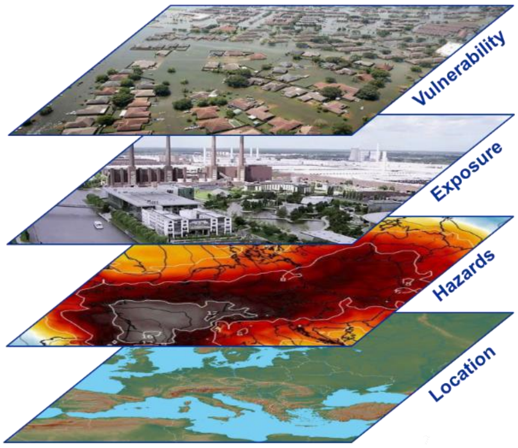



*Table 1. Identified data sources per layer*

| **Layer** | **Variables** | **Sources – examples** |
|---|---|---|
| **Location** | Location of borrower (address) / collateral (NUTS3) | ESCB Register of Institutions and Affiliates Data (RIAD) / ESCB Analytical Credit dataset |
| | Administrative Units / Statistical Units | Eurostat GISCO geodata |
| | Location of companies and their facilities | Orbis, OECD ADIMA, The European Pollutant Release and Transfer Register (E-PRTR) |
| **Hazards** | Hydrological: floods (river / coastal)<br>Climatological: drought, wildfire, subsidence<br>Geological: earthquake, landslide, volcano<br>Meteorological: cold / heat wave, windstorm | JRC: type of hazard and its intensity e.g. exposed area, probability of occurrence, intensity (e.g. depth of flood) for different time horizons<br><br>IPCC: data on observed and projected evolution of atmosphere (e.g. temperature) and other variables for different time horizons and climate change scenarios<br><br>Four Twenty Seven: intensity of physical risks and risk scores for millions of firms across the world at address level |

| | | |
|---|---|---|
| **Exposures** | Use of land: commercial/industrial, residential, agriculture<br>Critical services: roads, railways, energy, health facilities, education, fire departments | JRC / Corine Land Cover |
| | Socio-economic impact: population, labour | JRC (from Eurostat). Orbis: # of employees |
| | Financial variables: loan / collateral value | Analytical Credit dataset (AnaCredit) |
| | Holdings / issuance of assets exposed to physical risk (market risk) | Securities Holdings Statistics (SHS) / Centralised Securities DataBase (CSDB) |
| | Financial variables: fixed assets, revenues, liquidity etc. | Orbis / Credit registers |
| **Vulnerability** | Global damage function | JRC calculations: expected loss (or impact) for each hazard and different time periods (2, 5, 10, 15 and 25 years) |
| | Insurance<br>Impact and adaptation | EIOPA dashboard on insurance gap<br>Peseta IV |

## 3.2. Location information

Historically macroeconomic data were available at a country level. In the area of sustainability, the IMF Climate Change Dashboard[13] is a prominent example of a data hub containing cross-country indicators. It also includes metrics on physical risk, such as frequency of various types of natural disasters, non-life insurance penetration, and a composite risk indicator comprising different components of the physical risks such as hazard and exposure, vulnerability and lack of coping capacity. Global coverage is a huge advantage of the IMF Dashboard; however, more detailed analysis requires data at sub-national level, which, if available, is rarely harmonised.

In Europe, more and more datasets include regional breakdowns. The nomenclature of territorial units for statistics (NUTS)[14] is the statistical classification in Europe, diving the EU into regions at three levels of detail: 92 regions at NUTS 1, 242 regions at NUTS 2 and 1166 regions at NUTS 3 level. The NUTS3 regions are presented also by breakdowns indicating dominant terrain characteristics within the area such as: urban-rural, metropolitan areas, islands, coastal, mountainous and border regions[15]. Eurostat offers several statistical datasets with regional breakdown at NUTS 2 or NUTS 3 level, including among others: GDP, business demography statistics, health, tourism, labour market, energy statistics, crime, poverty and social exclusion indicators[16].

The lower granularity refers to postcodes. In the EU, there is a classification of local administrative units (LAUs)[17] which refers to a range of different administrative units, including municipalities, communes, parishes or wards. Countries might have different approaches to division at post codes and LAUs, they are also frequently updated and are not always consistent across classifications (e.g. a

[13] https://climatedata.imf.org/
[14] https://ec.europa.eu/eurostat/web/nuts/background
[15] Vector files including definitions of NUTS and LAU regions are available at the Eurostat GISCO website. At a global level, World Bank provides vector files for administrative boundaries including national boundaries, disputed areas and coastlines. The Global Administrative Areas (GADM) a project by the The Food and Agriculture Organization of the United Nations (FAO) to map administrative units in the World, including subnational division up to 5 levels.
[16] See Eurostat regional datasets.
[17] https://ec.europa.eu/eurostat/web/nuts/local-administrative-units

single postcode can be spread across different LAU or NUTS3). Correspondence tables[18] help in the mapping between different classifications but they changed across time, which adds to challenges in using them in the analysis, e.g. a specific address can be allocated to different regions under different versions of a classification.

While regional information is sufficient for the analysis of certain type of physical risk, such as heat or cold waves, other types of hazard (e.g. floods and landslides) are required at higher granularity. Physical hazard data are already available in form of high-resolution maps; however, financial aspects are often lacking precise location information necessary for adequate risk assessment, e.g. location of collateral.

Having data at exact location allows for more flexibility in the analysis, which is not restricted to regional boundaries. In economic analysis, geospatial tools enable investigations of interactions of proximity to certain markets, urban areas or infrastructure affects productivity, trade and labour market.

Precise location is also crucial in the physical risk analysis. Several datasets considered in Table 1. Identified data sources per layerTable 1 contain address information (e.g. Orbis, E-PRTR, RIAD / AnaCredit). For integration with the physical hazards layer the address needs to be converted to latitude and longitude - so called geocoding. While there are many tools which are available to facilitate this process, large scale geocoding is computationally intensive. It is also particularly challenging for databases covering more than one country, with outcome depending on the way the addresses are registered (e.g. including alphabet). The geocoded data are the basis for further analysis.

## 3.3. Physical hazards information

High-quality information on physical hazards is a pre-requisite for an accurate evaluation of the economic and financial risks posed by climate change. Over the last few years, a growing number of data sources on physical hazards became available, allowing for increasingly refined analyses.

The main sources of physical hazard data, with (at least) EU-wide coverage are: the Risk Data Hub (RDH), created by the Joint Research Centre (JRC) of the European Commission, the Sixth Annual Report of the Intergovernmental Panel on Climate Change (IPCC) and Four Twenty Seven, a commercial data provider affiliated to Moody's.

### *JRC and IPCC data*

The JRC - Risk Data Hub (RDH) collects data on past natural disasters at different levels of geographical detail (local, subnational and national) and provides projections and estimates of their impact in terms of economic damage and human losses[19].

One of the advantages of RDH is that its indicators are based on documented public sources and complied using a transparent and reproducible methodology. Moreover, the RDH provides a comprehensive and detailed overview of past hazards and susceptibility to future hazards for Europe.

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[18] See e.g. correspondence table between NUTS and LAU (https://ec.europa.eu/eurostat/web/nuts/local-administrative-units) and NUTS and postcodes.
[19] Considered as fatalities, injured and affected people.

Finally, JRC data are expected to become more and more central in the study of climate change at EU level[20], making them a natural starting point of our analysis.

The data in RDH come from different sources, both official and unofficial[21]. The resulting dataset comprise homogenized information on multiple hazards and multiple assets at European level for a total of more than 18,900 records.

RDH distinguishes between "man-made/technological hazards" and "natural hazards". The latter, the relevant ones for this study, are divided in 5 categories, each comprising several subcategories:

1. Geophysical hazards: earthquake, landslide, tsunami, volcano
2. Hydrological: river flood, costal flood, flash flood, avalanches
3. Meteorological: cold wave, heat wave, hail, lightening, windstorm, extreme weather (hot days, cold days, tropical nights, torrential rain)
4. Climatological: drought, wildfire, subsidence
5. Biological: epidemics/pandemics, insects infestation, animal and plant disease.

The hazards currently covered in RDH are coastal flooding, river flooding, landslides, earthquake, subsidence and wildfire[22]. For each hazard RDH provides estimates of the intensity and the frequency based on historical records and models' projection. The intensity measures the severity of the hazard, while the frequency relates to the probability of occurrence and is expressed in terms of return periods, namely the time interval between two realizations of the same hazard[23].

RDH does not include data on temperature changes, however this information is available from the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021)[24].
The IPCC provides data on observed and projected evolution of atmosphere, oceans and other variables such as population density and anthropogenic $CO2$ emissions. The projections are based on a set of simulation models[25] and are available for different time horizons and scenarios on the possible developments of the anthropogenic drivers of climate change[26].

### *Four Twenty Seven data*

Another widely used source of data for physical hazards is Four Twenty Seven, a commercial database that provides information on the probability and intensity of physical risks for millions of firms across the world at address level.

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[20] See European Commission (2021) "Forging a climate-resilient Europe - the new EU strategy on adaptation to climate change", COM(2021) 82 final, 24 February – see reference in the data supplement.
[21] For more information on the underlying data sources visit the JRC website (link).
[22] The database is planned to expand to include also flash floods, droughts, windstorms and tsunami. According to the Fifth Assessment Report of the IPCC (IPCC, 2014), the main physical risks in Europe are floods, water stress and heat stress including wildfires, most of which are already covered by RDH.
[23] If measured in years, the return period indicates the number of years until the next event occurs. For example, a return period of 100 years means that the event will occur on average once every 100 years, therefore the probability that a similar event could occur in one year is 1% (1/100).
[24] See Table 3 in the Annex for the complete list of physical hazards extracted from JRC and IPCC.
[25] The data underpinning the Sixth Assessment Report of IPCC come from the Coupled Model Intercomparison Project Phase 6 (CMIP6) of the World Climate Research Programme. CMIP6 aggregates the results of the models from the various research groups that participate in the simulation exercise. The results of the different models are pooled together to obtain a distribution of projections used to compute the statistics of interest (e.g. mean, median, etc.).
[26] See Figure 5 in the Annex for an overview of the available horizons-scenarios pairs.

Four Twenty Seven classifies physical risks in 7 categories and 23 subcategories[27] and assign a score to each of them. Different scores are computed in different ways, but in general[28] they are all subject to a standardization procedure that converts the raw data into a value comprised between 0 and 100, representing increasing levels of risk.

Four Twenty Seven incorporates climate projections from a number of sources. For what concerns temperature and precipitations, its indicators are based on an ensemble average of the models that took part in the Coupled Model Intercomparison Project Phase 5 (CMIP5)[29], which formed the basis also for the Fifth Assessment Report of the IPCC.

The projection horizon incorporated in Four Twenty Seven data is 2030-2040 and as historical benchmark it is taken the period 1975-2005. Finally, the scores produced by Four Twenty Seven are based on the "no policy change" scenario, that corresponds to the highest emission pathway considered under CMIP5[30].

In section **Error! Reference source not found.** of the paper, selected indicators across sources (JRC-IPCC and Four Twenty Seven) are compared to assess their consistency and to get a better understanding of the level of granularity required to have accurate risk estimates.

## 3.4. Exposure layer and sources

*Financial exposure*

In order to quantify the impact of physical hazards in economic terms, climate information need to be combined with financial data. With respect to financial variables, different sources can be employed: credit, business and securities registers. Within the sources available to the European System of Central Banks (ESCB), AnaCredit contains information on credit exposures, while the Centralised Securities Database (CSDB) and the Securities Holdings Statistics (SHS) cover securities. The advantage of leveraging internal sources is having accessible up-to-date, harmonised and granular information for European companies and financial institutions.

AnaCredit contains detailed, harmonised information on individual euro area bank loans above €25,000, providing an overview of portfolio exposure of financial institutions starting from 2018. It contains also information on the collateral type (physical or other) and NUTS3 (or postal code) of collateral location - which when linked to physical hazards in the region can provide valuable information on risk to collateral impairment.

For non-financial sector, Orbis, a commercial dataset by Bureau van Dijk, contains detailed financial statements, non-financial and contact information (e.g. company identifiers, name, address, number of employees, NACE sector) of around 400 million global listed and private companies. The coverage differs by country and characteristics of companies (larger and older companies are better represented). However, currently it is the largest single source for firm-level information and it contains several variables relevant from the physical risk perspective: fixed assets such buildings and

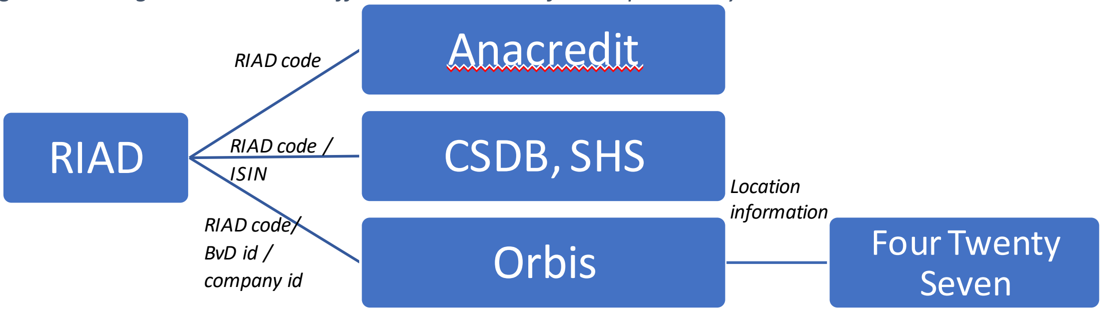
[27] See Table 4 in the Annex for a description of the available indicators.
[28] For wildfires the severity and frequency are built upon the Keetch-Byram Drought Index (KBDI), a measure of drought conditions based on rainfall, air temperature and other meteorological factors (see Keetch, Byram (1968) "A Drought Index for Forest Fire Control").
[29] The projection horizon of each of these models begin in 2020 and extends at least until 2100.
[30] Also known as Representative Concentration Pathway (RCP) 8.5.

machinery, inventories, and financial information, which allow assessing liquidity and financial resilience of balance sheet in case of adverse impact, such as a natural catastrophe.

Market risk stemming from potential repricing of equity and debt can be assessed based on two databases: the Centralised Securities Database (CSDB) and the Securities Holdings Statistics (SHS). The CSDB is the reference database on individual securities information issued by European resident firms (e.g. price, issuer name and outstanding amount), while SHS gathers holding information on mutual funds shares, debt securities and equities with focus on EU-issued instruments, however, it also discloses details of internationally traded securities held by European investors.

The Register of Institutions and Affiliates Data (RIAD) is a counterparty database including contact information of financial entities, as well as their borrowers. It is a central point for linking information between databases. It is also a source for location information of lenders and borrowers. Consequently, the quality of the address information contained herein is crucial for successful geocoding. Through the RIAD code, a unique identifier assigned to each company, it is possible to directly retrieve information from AnaCredit and CSDB and indirectly to Orbis, thanks to the a matching exercise that returns for BVD_ID (i.e. the Bureau van Dijk identifier) the corresponding RIAD code for entities covered by two sources. Further, the other databases can be matched between each other via RIAD mapping tables (e.g. Orbis and AnaCredit).

*Figure 4 Linkages between the different databases of the exposure layer*




### *Socio-economic exposure*

Socio-economic data can further enhance the analysis of physical risk. Information on population demographics of affected areas allow for capturing social impact, e.g. increase in extreme temperature on health and productivity, or job losses due to disruptions in company operations or bankruptcies. Eurostat provides detailed population information based on the census at 1km x 1km grid[31].

Further, geospatial data such as Land Cover[32] maps areas into different types, such as artificial surfaces, agricultural areas, forest and seminatural areas, wetlands and water bodies. It covers 44 classes of the 3-level nomenclature[33], including categories for road and rail network, port and airports – which can enhance further the analysis by taking into account potential damages to company surroundings, such as critical public infrastructure. The snapshots of land cover (available for year 2000, 2006, 2012, and 2018) are complemented by maps highlighting changes between the years,

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[31] See Eurostat GEOSTAT project.
[32] See geospatial data at Corine Land Cover.
[33] CORINE Land Cover nomenclature.

allowing for further analysis related to climate and sustainability indicating depletion of natural resources (e.g. changes from forest to urban or agricultural area).

## 3.5. Vulnerability information

One of the most challenging data gaps in the physical risk assessment is related to vulnerability. Following the definitions[34] in the IPCC AR5 report (IPCC 2014 Summary for policymakers in: Climate Change 2014: Impacts, Adaptation, and Vulnerability, 2014), vulnerability depends on two elements: i) *sensitivity* - "degree to which a system or species is affected (…) by climate variability or change", directly or indirectly, adversely or beneficially, and ii) *adaptive capacity* – "'the ability (…) to adjust to potential damage, to take advantage of opportunities, or to respond to consequences". Vulnerability is the resulting final propensity to be adversely affected, which increases with higher sensitivity and lower adaptive capacity.

Vulnerability is usually hazard-specific – and different type of information are needed for different type of assets. For instance, year of construction can a good indicator of resilience of a building, given that building regulation is usually more stringent for newer buildings. However, to have a better assessment of a building vulnerability different parameters are required, in case of floods this is information on elevation above the ground, and flood barrier protection are required, while whether a building is earthquake-proof depends on its construction, such as flexible foundation and materials used.

Comprehensive study of climate change impact and adaptation in Europe is conducted by the JRC within PESETA project[35], providing comparable projections across sectors and EU regions. In the most recent report (Feyen L., 2020), several impact categories[36] are analysed under three climate scenarios: warming of 3°C and no adaptation, while the mitigation benefits of achieving the Paris warming targets are evaluated by estimating impacts with 1.5°C and 2°C global warming. The study combines biophysical projections of the individual hazards with socioeconomic impact models allowing for estimations of welfare loss in terms of monetary values (EUR 2015 value and share of GDP), including damage to capital stock, sectoral productivity reduction, and changes in consumption. Adaptation measures which would need to be implemented to reduce the risks are also listed individually for each hazard (e.g. cooling techniques, drought-resistant crops, early warning systems). However, authors point to challenges in evaluating returns on such investments and loss reduction attributed to adapting specific measures are estimated only for floods at a country level.

Among adaptation measures, insurance is a measure which can be applied against various risk to alleviate financial losses and helping to rebuild damages. (L. Fache Rousová, July 2021) estimate that catastrophe damages amounting to 1% of GDP translate to 0.25 percentage points decrease in quarterly GDP growth in case of no insurance coverage. On the other hand, high share (75%) of uninsured losses can lead to almost immediate recovery in GDP growth.

[34] Please see (Ravindranath, 2019) for discussion on the definitions and relation between hazards, exposures and vulnerability in the IPCC AR4 and AR5 report.
[35] Please see PESETA – Projection of Economic impacts of climate change in Sectors of the EU based in bottom-up Analysis.
[36] Human mortality from heat and cold waves, windstorms, water resources, droughts, river and coastal flooding, wildfires, habitat loss, forest ecosystems, agriculture and energy supply.

To address limited information on insurance of natural catastrophes, EIOPA launched a dashboard on insurance protection gap[37], covering historical data on insured and uninsured losses, economic value of residential and commercial areas (in square km) exposed to natural hazards, and vulnerability indicators of the building stock inventory to earthquakes and windstorms. Further enhancement to the dashboard is envisaged for 2022.

# 4. Physical hazards indicators: a deeper dive

While physical risk indicators, incorporating financial dimension and potential impact into financial stability, have been analysed in several studies, less attention is dedicated to the measures of the underlying physical hazards. It might be dictated by novelty of this type of data and limited experience with processing and analysing geo-spatial information.

We attempt to fill this gap investigating more closely different data sources from various angles. First, we compare Four Twenty Seven selected scores with granular data from the JRC and IPCC. Second, the hazard values at the specific location level are compared to aggregates in the surrounding area to investigate whether the region averages can be a good proxy for individual hazard. We use Germany for illustration. It is a subset of Four Twenty Seven data, which were used in the ECB reports ( (The ECB/ ESRB, July 2021), (ECB, September 2021)), comprising around 90 thousands German firms selected from Orbis dataset, mainly located in urban areas[38].

## 4.1. Comparison of Four Twenty Seven and public data sources (JRC, IPCC)

Based on the provided methodology[39], a subset of indicators which seems best aligned are selected for comparison across datasets[40]. Atmospheric indicators, in particular related to heat stress, are the most comparable as they are based on the CMIP in Four Twenty Seven and IPCC[41]. From hazards available from JRC, earthquakes, river and coastal flooding are compared to the Four Twenty Seven scores although the underlying models or unit of measure might differ. Table 2 lists the variables that can potentially be compared, highlighting the differences and the steps needed to make them as similar as possible.

*Table 2: Comparable hazard indicators between JRC/IPCC and Four Twenty Seven*

| JRC/IPCC hazard | Four Twenty Seven hazard | JRC/IPCC definition | Four Twenty Seven definition | Methodology |
|---|---|---|---|---|

[37] For details please see: https://www.eiopa.europa.eu/content/pilot-dashboard-insurance-protection-gap-natural-catastrophes_en

[38] According the CORINE Land Cover inventory, 94% of the German companies in Four Twenty Seven are established on artificial surfaces. This is in line with the sector representativeness, which has services, manufacturing, and utilities as the dominant business in the subsample. Agricultural areas cover about 4% of the landscapes, while wetlands, water bodies, and forests together cover less than 1% of the total land.

[39] See Table 3 and Table 4 in the Annex.

[40] As for IPCC data, we consider projections for the near-term horizon (2021-2040) under the worst-case scenario (SSP5-8.5). This allows us to compare our indicators with those of Four Twenty Seven, which share similar assumptions. Moreover, while the differences across alternative emission pathways increase with the projection horizon, in the near-term they are relatively small

[41] Although we use data from the Sixth Assessment Review (AR6), while Four Twenty Seven indicators are based on data from the fifth review (AR5).

| | | | | |
|---|---|---|---|---|
| River flood | 1. Floods - Flood Frequency<br>2. Floods - Flood severity | Water raise due to river flooding. Estimates based on the extreme events intensities (water heights).<br><br>Reference period 1990–2013; return periods 10, 20, 50, 100, 200, 500 years. | 1. A simulated measure of how frequently the site floods<br>2. A simulated measure of the depth of inundation during a 1-100 year flood<br><br>Baseline period: 1975-2005 (Rainfall) and 1985-2011 (Flood Frequency/Severity). Projection Period: 2030-2040 (Rainfall). | Rescale the JRC index with 100 years return period to match the reference period. |
| Cooling degree days | Heat Stress - Energy Demand | Index which uses the mean, maximum and minimum daily temperature to proxy the energy demand for cooling.<br><br>CMIP6 - Near Term (2021-2040) SSP5-8.5 (rel. to 1986-2005) | Differential in the projected average annual number of cooling degree days compared to the baseline period.<br><br>Baseline period: 1975-2005. Projection Period: 2030-2040. | Select the baseline period of IPCC to match the one of Four Twenty Seven. |
| Maximum temperature | Heat Stress - extreme heat days | Mean of daily maximum temperature.<br><br>CMIP6 - Near Term (2021-2040) SSP5-8.5 (rel. to 1986-2005) | Daily temperature > local 90th percentile (change in the number of days in a year compared to baseline period).<br><br>Baseline period: 1975-2005. Projection Period: 2030-2040. | |
| Maximum of maximum temperatures | Heat Stress - Extreme Temperature | Maximum of daily maximum temperature.<br><br>CMIP6 - Near Term (2021-2040) SSP5-8.5 (rel. to 1986-2005) | Percent change in projected annual maximum temperature compared to the baseline period.<br><br>Baseline period: 1975-2005. Projection Period: 2030-2040. | Select the baseline period of IPCC to match the one of Four Twenty Seven. |
| Coastal flood Sea level rise | Sea Level Rise - Absolute Coastal Flood Frequency | Water raise due to coastal flooding. Estimates based on modelled extreme events intensities (water heights). Return periods 10, 20, 50, 100, 200, 500 years. | A projection of how frequently the site may flood in 2040.<br><br>Baseline period: 1986-2005. Projection Period: 2040. | Rescale the JRC index with 100 years return period to match the reference period. |
| Total precipitation | Wet Days (>10 mm) | Near-surface total precipitation (mm/day, percentage change).<br><br>CMIP6 - Near Term (2021-2040) SSP5-8.5 (rel. to 1986-2005) | Daily rainfall volume > 10mm (change in the number of days in a year compared to the baseline period).<br><br>Baseline period: 1975-2005 (Rainfall) and 1985-2011 (Flood Frequency/Severity). Projection Period: 2030-2040 (Rainfall). | |
| Max 1-day precipitation amount | Very Wet Days (>95th p) | Maximum 1-day precipitation amount (mm, percentage change).<br><br>CMIP6 - Near Term (2021-2040) SSP5-8.5 (rel. to 1986-2005) | Daily rainfall volume > local 95th percentile (absolute number of days in a year compared to baseline period).<br><br>Baseline period: 1975-2005 (Rainfall) and 1985-2011 (Flood Frequency/Severity). Projection Period: 2030-2040 (Rainfall). | |
| Max 5-day precipitation | Rainfall Intensity | Maximum 5-day precipitation amount (mm, percentage change).<br><br>CMIP6 - Near Term (2021-2040) SSP5-8.5 (rel. to 1986-2005) | Percentage change in the total maximum volume (mm) of rainfall in a 5-day period.<br><br>Baseline period: 1975-2005 (Rainfall) and 1985-2011 (Flood Frequency/Severity). Projection Period: 2030-2040 (Rainfall). | Transform the JRC data into a categorical index applying the same threshold used by Four Twenty Seven. |
| Peak ground acceleration (PGA) | Earthquakes - shaking intensity | Peak ground acceleration (PGA) for return periods of 250, 475, 975, 1500 years. It measures the maximum ground acceleration occurred during earthquake shaking at a location. | Modified Mercalli index. It measures the effect of earthquake shaking at the site and surrounding area (higher values indicate greater impact).<br><br>Baseline period: 1950-2018. Projection Period: N/A. | Use the correspondence table between PGA and Modified Mercalli Index |

| | | | | |
|---|---|---|---|---|
| | | | | to compare the two indicators[42] |

First, we look at the indicators related to increased global temperatures which will have an impact on increased energy demand for using cooling system, such as air conditioning. Number of days with extreme temperature will have potential impact on health and productivity. Most of the indicators extracted from the IPCC are expressed as changes with respect to a baseline period – given that impact and needed adjustments are often relative to the current situation[43].

Heat stress indicators selected from Four Twenty Seven show relatively high correlation with the IPCC data, even though Four Twenty Seven data are based on the earlier models[44] (CMIP5 versus CMIP6 compared here, panel 2a). This indicates high consistency between two data sources with respect to this subset of indicators.

Comparing indicators related to the precipitation - with implications to flood risk - showed higher discrepancies (2b). It might be partially explained by the fact that for those indicators, Four Twenty Seven uses additional input for modelling, such as the World Resources Institute Aqueduct Global Maps, not incorporated yet among our data sources. It illustrates that use of different models and assumptions may have a large impact on the outcome. A large role for lack of alignment plays also the definition of indicators - Four Twenty Seven indicators are non-linear truncated indicators (days exceeding 95$^{th}$ percentile precipitation volumes locally, days with more than 10mm precipitation), which capture extreme conditions versus overall phenomenon (change in precipitation) for the IPCC indicators.

At this stage, it would be not possible to assess superiority of one or other source and more investigations are necessary to understand the difference in the methodology and impact on the final indicators.

The use of different indicators measuring seemingly the same phenomena matter and need to be selected carefully. In case of increase of precipitation various measures – here, total precipitation (mm/day percentage change), maximum precipitation within different time span (1-day, 5-days) - show lower correlation than for temperature, even stemming from the same data source with consistent underling methodology. This might be explained by higher local variability of the phenomena as rain intensity might be more affected by local terrain and vegetation (mountains, forest, lakes) than temperature – which also translate to larger challenges in precipitation projections. It should be also noted that we compare changes in the precipitation – it might be that absolute values of rain intensity provide more consistent results across indicators.

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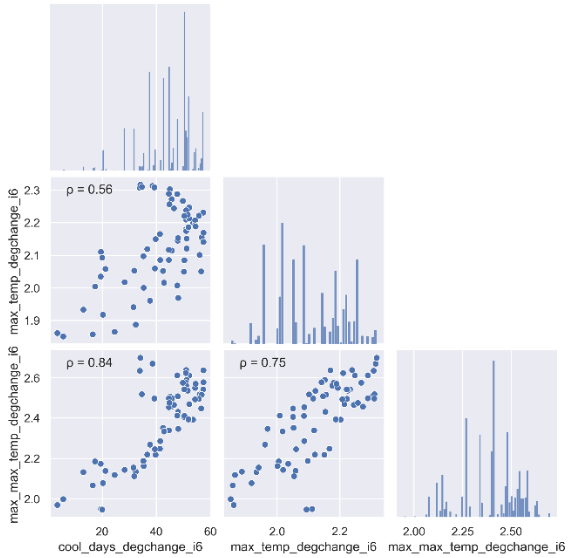
[42] The U.S. Geological Survey developed a concordance table (available in Appendix I) to map peak ground acceleration with the Modified Mercalli index. For more information of the way the concordance table is constructed and its limits see link.

[43] For instance, increase in extreme temperatures might require installation of air-conditioning system in regions where it was not needed before (e.g. Germany), while regions exposed in the past to high temperatures do not require such adaptations (e.g. Spain).

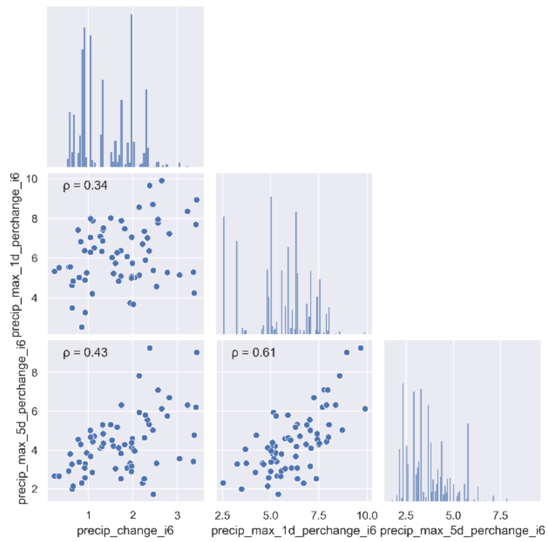
[44] There are few differences between the models e.g. the most recent one are available at higher resolution.

## Correlations between indicators related to the same hazard

### 1a. IPCC – temperature



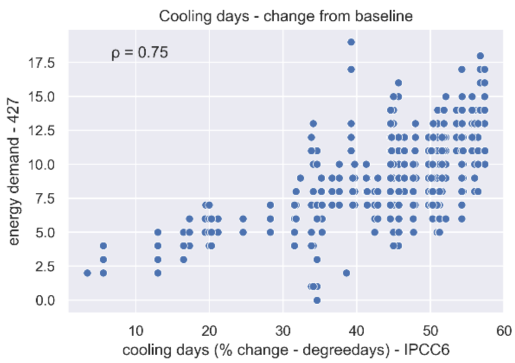

### 1b. IPCC – precipitation

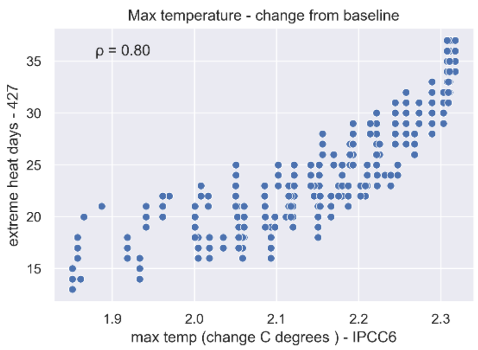



Notes: Correlation matrix across indicators. Diagonal shows histograms for individual variables.

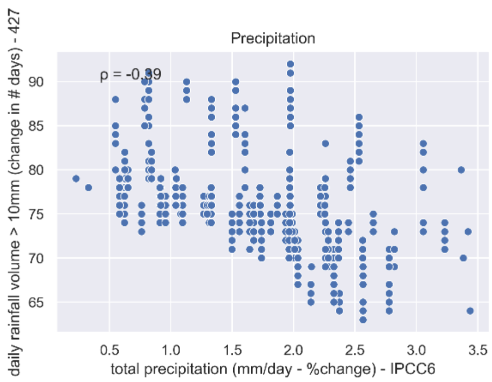
## Four Twenty Seven versus IPCC

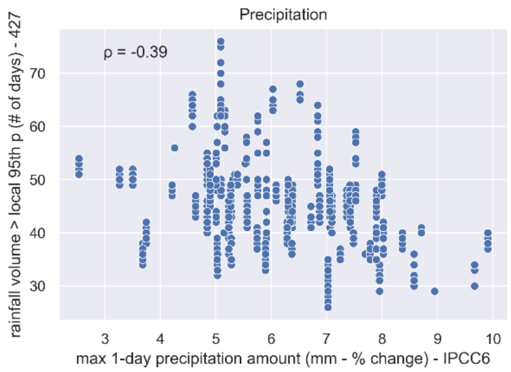
### 2a. Heat stress



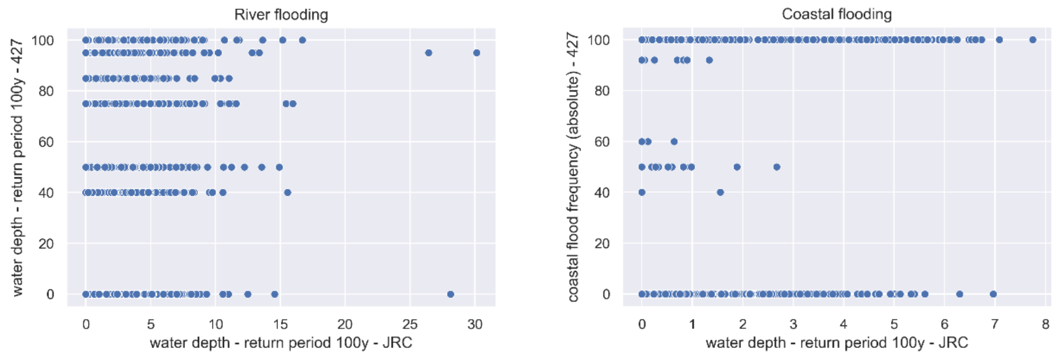

### 2b. Precipitation



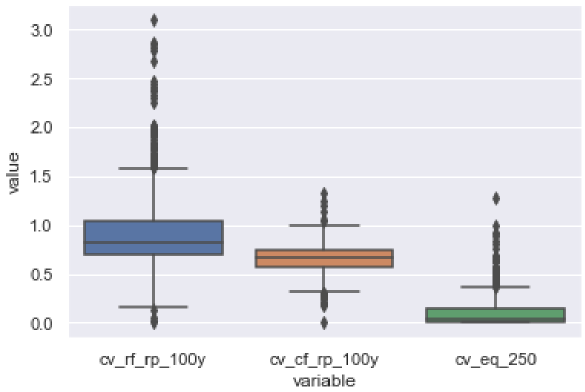
Looking at the floods, it is not possible to compare the JRC data with Four Twenty Seven (Panel 3a), as in the latter only risk scores (from 1-100) are available versus flood intensity measured as water depth (in meters) for the JRC, and there is low correspondence between indicators in two sources.

**Four Twenty Seven versus JRC**
**3a.**




Working directly with GIS files allows us to compute different statistics across areas. First, we compare the variability of the hazard values across NUTS3 regions to assess whether the hazard values at exact location can be approximated by regional averages. As expected, variability for river floods is the highest as it is local phenomenon, followed by coastal floods with lowest variability for earthquakes.

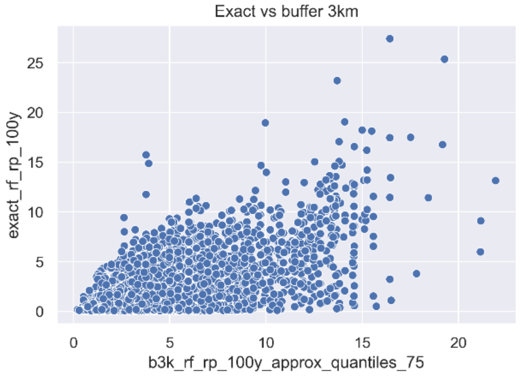
**Coefficient of variation across NUTS3 in Europe**




Notes: Coefficient of variation across NUTS3 in Europe for three hazards: cf- coastal flooding, rf – river flooding, e.q. - earthquakes.

Second, we compare exact values at location versus surrounded area (radius of 3 km) for river floods. Incorporating the impact in neighbouring area would better reflect the risk – even if company is not flooded, as damages into infrastructure in a surrounding affected area might have an impact on a company operation. It is a show case that the GIS statistical tools allow flexible derivation of indicators, tailoring it to the analytical needs.

**Exact values versus aggregate statistics (**75th percentiles**) in the radius of 3 km around company location – river floods (water depth in meters)**




Notes: Exact values of water depth versus $75^{th}$ percentiles for river flooding in Germany.

# 5. Conclusions and future work

Impact analysis of physical hazard on individual businesses and its subsequent conversion it into economic losses is still at early stage. As with other climate-related data (e.g. emissions), quality and availability of required information often lack harmonisation across countries and regions, which translates into limitations for modelling of physical risk and climate projections under different emission pathways. Global models suffer from low resolution, which are downscaled[45] to achieve fine-scale information at regional level. They also rarely account for 'tipping points' and cannot predict rare, extreme events which might have very high social and financial impact. While some variables can be well modelled, such as temperature; other still pose challenges (precipitation), particularly at local level. Consequently, while it is important to study potential risks at the economy-wide scale, some caution should be exercised when drawing conclusion for individual entities (T. Fiedler, 2021).

Companies are incentivised to report risks and opportunities for their business stemming from climate change, including impact on their investment and supply chains (TCFD, June 2017). However, modelling of financial impact of climate change still poses many challenges, even for climate scientists and projections are reported with high uncertainty. In particular, smaller companies might encounter difficulties to disclosure such information. While the ecosystem of climate impact consultancy services is developing rapidly, the reliability of the assessment is difficult to verify and it might take years till analysis reaches more mature stage.

One of the challenges in modelling are posed by availability of the data. While central banks possess comprehensive data sources on financial exposures, there are many gaps in climate information, in particular for vulnerability of entities to damages stemming from various hazards. With this respect information on climate adaptation measures, including insurance, is very limited and usually available only at highly aggregated level (e.g. country), while more detailed data are needed for proper calculations of financial exposure to physical risk.

[45] Two popular methods are applied for downscaling: i) dynamical downscaling – which incorporates additional information such as detailed topography, vegetations and land use to fine-tune global scale models, and ii) statistical downscaling – which uses empirical statistical relationship between global and local variables (African And Latin American Resilience to Climate Change (ARCC), September 2014).

This paper focus on the physical hazards where more and more public data sources becomes available. While the data and methodology originate from the field of disaster management, the underlying frameworks (Sendai Framework[8] and EU initiative[20]) are being further developed and harmonised to benefit also the analysis related to climate change. Those enhancement should translate to better quality hazard indicators.

With respect to future work, development in three areas are envisaged:

First, there are efforts required to improve coverage and reporting of location information in available granular databases which is prerequisite for correct identification of physical risk. It is worth to consider shifting to reporting of addresses (or latitude / longitude information), where currently only regional information (postal code, NUTS3) is available. This would be especially beneficial in case of information on thelocation of collateral to improve measurement of its potential impairment.

Second, we envisage inclusion of further types of hazards and data sources when they become available, concentrating on priorities expressed in the key areas of central banking, such of monetary policy, financial stability, banking supervision and economic analysis. Here, one area not explored yet is accounting for multi-hazard risk and modelling of co-occurring events (e.g. floods and landslides).

Third, enhancements are needed for the firm level analysis. It is important to identify the location, not only of company headquarter but also its facilities. However, data sources with such information are limited and if available only for selected companies and sectors. Assessing the climate impact on the entire value chain of the company would be further step – requiring details on company operations and their network of suppliers and clients. Such information would translate to better assessment of physical risk exposures of financial institutions portfolios.

From a broader perspective, more experience gained with geospatial tools and implementation of regular geocoding applied to different internal databases would allow for incorporation of spatial aspects in economic analysis and research beyond climate.

# 6. Annex I: Data sources

## *JRC and IPCC data*

Table 3 provides an overview of the list of physical hazards extracted from JRC and IPCC, as well as a brief definition for each variable. For a more detailed explanation of how they are calculated please refer to the JRC and IPCC websites.

*Table 3: list of hazard data extracted from JRC and IPCC*

| Hazard | Measure | Definition |
|---|---|---|
| **Joint Research Centre - Risk Data Hub** | | |
| Coastal flood | Water heights (m) | Water raise due to coastal flooding. Estimates based on modelled extreme events intensities (water heights) for return periods of 10, 20, 50, 100, 200, 500 years. |
| River flood | Water heights (m) | Water raise due to river flooding. Estimates based on the extreme events intensities (water heights) simulated in the reference period 1990–2013 for return periods of 10, 20, 50, 100, 200, 500 years. |
| Landslides | Categorical variable, 5 classes:<br>1 - low<br>5 - high | Indicator combining the physical characteristics of the terrain with the daily maximum precipitation in that area. The resulting landslide hazard provides an estimate of the predisposition to landslide of an area for return periods of 2, 5, 10, 20, 50, 100, 200, 500 years. |
| Earthquake | Peak ground acceleration (cm/s2) | Peak ground acceleration (PGA)[46] for return periods of 250, 475, 975, 1500 years. The areas with potential impact from seismic hazards are approximated by using the USGS's Instrumental Intensity scale greater than 0.18 PGA, equivalent to "Moderate" potential damage level. |
| Subsidence | Categorical variable, 5 classes:<br>1 - low<br>5 - high | Indicator for subsidence potential of an area. Such potential is based on the amount of clay content of the soil: soils with fine texture and clay content greater than 35% have high subsidence potential, while soils with less fine texture and clay content have low potential. |
| Wildfire | Dummy variable | Indicator for Wildland–Urban Interface area (WUI)[47]. |
| **IPCC Sixth Assessment Report (AR6). CMIP6 - Near Term (2021-2040) SSP5-8.5 (relative to 1986-2005) - Annual** | | |
| Mean temperature | Degree Celsius (change) | Mean near-surface air temperature. |
| Minimum temperature | Degree Celsius (change) | Mean of daily minimum temperature. |
| Minimum of minimum temperatures | Degree Celsius (change) | Minimum of daily minimum temperature. |
| Frost days | Days (change) | Minimum temperature below 0 degree Celsius. |
| Heating degree days | Degree-days index[48] (change) | Index which uses the mean, maximum and minimum daily temperature to proxy the energy demand for heating. |
| Maximum temperature | Degree Celsius (change) | Mean of daily maximum temperature. |
| Maximum of maximum temperatures | Degree Celsius (change) | Maximum of daily maximum temperature. |
| Days with TX above 35ºC | Days (change) | Number of days with maximum temperature above 35 degree Celsius. |

[46] The Peak Ground Acceleration (PGA) is defined as the maximum ground acceleration that occurred during earthquake in a specific location. PGA is measured as the amplitude of the largest absolute acceleration recorded on an accelerogram at a site during an earthquake.

[47] WUI areas are defined as the space where urbanized areas and wilderness (i.e. unoccupied land) come into contact. Human settlements in WUI are at greater risk of wildfires.

[48] The degree-days index is a measure of how much (in degrees) and for how long (in days) the temperature is below/above a certain level. They are commonly used to calculate the energy consumption required to heat/cool buildings.

| | | |
|---|---|---|
| Bias Adjusted TX35 | Days (change) | Number of days with maximum temperature above 35 degree Celsius (bias adjusted using ISIMIP3 method). |
| Days with TX above 40ºC (TX40) | Days (change) | Number of days with maximum temperature above 40 degree Celsius. |
| Bias Adjusted TX40 | Days (change) | Number of days with maximum temperature above 40 degree Celsius (bias adjusted using ISIMIP3 method). |
| Cooling degree days | Degree-days index (change) | Index which uses the mean, maximum and minimum daily temperature to proxy the energy demand for cooling. |
| Total precipitation | mm/day (percentage change) | Near-surface total precipitation. |
| Maximum 1-day precipitation | mm (percentage change) | Maximum 1-day precipitation amount. |
| Maximum 5-day precipitation | Mm (percentage change) | Maximum 5-day precipitation amount. |
| Consecutive Dry Days | Days (change) | Maximum number of consecutive dry days (pr<1mm). |
| Standardized Precipitation Index | Percentage (change) | Index that compares cumulated precipitation for 6 months with the long-term precipitation distribution for the same location and cumulation period. |
| Snowfall | mm/day (change) | Snowfall. |
| Surface wind | m/s (percentage change) | Wind speed expressed in meters per second. |
| Sea level rise | Meters (change) | Total sea level rise.[49] |
| Population density | Persons/km2 (change) | Population density. |
| CO2 anthropological emissions | kg/m2 (change) | Anthropogenic CO2 emissions. |

Figure 4 provides an overview of the horizons-scenarios pairs available from IPCC report. The time horizons are three: near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2100). The scenarios are five and consider the possible trajectories of the anthropogenic drivers of climate change discussed in the climate literature. The projections start in 2015 and include scenarios that range from low (SSP1-1.9) to very high (SSP5-8.5) emissions. More in detail, scenarios SSP1-1.9 and SSP1-2.6 include very low and low GHG emissions and CO2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO2 emissions; scenario SSP2-4.5 includes intermediate level of GHG emissions and CO2 emissions remaining around current levels until the middle of the century; scenarios SSP3-7.0 and SSP5-8.5 include respectively high and very high GHG emissions and CO2 emissions that roughly double from current levels by 2100 and 2050.

[49] Differently than the other variables, the sea level rise is calculated relative to the period 1995-2014.

*Figure 5: Temperature projection from the IPCC by scenario and projection horizon*

| Scenario | Near term, 2021–2040 | | Mid-term, 2041–2060 | | Long term, 2081–2100 | |
|---|---|---|---|---|---|---|
| | Best estimate (°C) | *Very likely* range (°C) | Best estimate (°C) | *Very likely* range (°C) | Best estimate (°C) | *Very likely* range (°C) |
| **SSP1-1.9** | 1.5 | 1.2 to 1.7 | 1.6 | 1.2 to 2.0 | 1.4 | 1.0 to 1.8 |
| **SSP1-2.6** | 1.5 | 1.2 to 1.8 | 1.7 | 1.3 to 2.2 | 1.8 | 1.3 to 2.4 |
| **SSP2-4.5** | 1.5 | 1.2 to 1.8 | 2.0 | 1.6 to 2.5 | 2.7 | 2.1 to 3.5 |
| **SSP3-7.0** | 1.5 | 1.2 to 1.8 | 2.1 | 1.7 to 2.6 | 3.6 | 2.8 to 4.6 |
| **SSP5-8.5** | 1.6 | 1.3 to 1.9 | 2.4 | 1.9 to 3.0 | 4.4 | 3.3 to 5.7 |

Source: Sixth Assessment Report of the Intergovernmental Panel on Climate Change, p. 19 (IPCC, 2021). 'SSPx' refers to the Shared Socio-economic Pathway or 'SSP' describing the socio-economic trends underlying the scenario. Temperature increases are defined relative to the pre-industrial period (1850-1900).

### *Four Twenty Seven data*

Table 4Table 3 provides an overview of the physical hazards available in Four Twenty Seven, with a brief definition for each variable. For more information please refer to company website.

*Table 4: Available hazards in Four Twenty Seven*

| Hazard | Measure | Unit | Description | Methodology |
|---|---|---|---|---|
| Earthquakes | Shaking intensity | Modified Mercalli index[50] | Measures the effect of earthquake shaking at the site and surrounding area (higher values indicate greater impact) | Baseline period: 1950-2018<br>Projection Period: N/A |
| Floods | Flood Frequency | Return period | A simulated measure of how frequently the site floods | Baseline period: 1975-2005 (Rainfall) and 1985-2011 (Flood Frequency/Severity)<br>Projection Period: 2030-2040 (Rainfall) |
| Floods | Flood Severity | Meters | A simulated measure of the depth of inundation during a 1-100 year flood | Baseline period: 1975-2005 (Rainfall) and 1985-2011 (Flood Frequency/Severity)<br>Projection Period: 2030-2040 (Rainfall) |
| Floods | Rainfall Intensity | Percentage change in mm | Percent change in the total maximum volume (mm) of rainfall in a 5-day period in an average year across the projection period | Baseline period: 1975-2005 (Rainfall) and 1985-2011 (Flood Frequency/Severity)<br>Projection Period: 2030-2040 (Rainfall) |
| Floods | Very Wet Days (>95th p) | Number of days | The absolute number of days in a year when the daily rainfall volume is projected to exceed the historical local 95th percentile | Baseline period: 1975-2005 (Rainfall) and 1985-2011 (Flood Frequency/Severity)<br>Projection Period: 2030-2040 (Rainfall) |
| Floods | Wet Days (>10 mm) | Difference in the number of days | The additional number of days in a year when the daily rainfall volume is projected to exceed 10 mm compared to the historical baseline | Baseline period: 1975-2005 (Rainfall) and 1985-2011 (Flood Frequency/Severity)<br>Projection Period: 2030-2040 (Rainfall) |
| Heat Stress | Energy Demand | Difference in degree days above 65F | Differential in the projected average annual number of cooling degree days compared to the baseline period | Baseline period: 1975-2005<br>Projection Period: 2030-2040 |

[50] The Modified Mercalli index measures the intensity of an earthquake at a given location based on the effects reported by untrained observers (e.g. people awakening, movement of furniture, damage to buildings, etc.). The scale is composed of 12 increasing levels of intensity that range from imperceptible shaking to catastrophic destruction.

| | | | | |
|---|---|---|---|---|
| Heat Stress | Extreme Heat Days | Difference in days from baseline period | Projected numbers of additional days in a year where the daily temperature exceeds the local 90th percentile (during baseline period) | Baseline period: 1975-2005<br>Projection Period: 2030-2040 |
| Heat Stress | Extreme Temperature | Percent change from baseline (C) | Percent change in projected annual maximum temperature compared to the baseline period | Baseline period: 1975-2005<br>Projection Period: 2030-2040 |
| Hurricanes and Typhoons | Cumulative Windspeed | Cumulative knots | Cumulative wind speed of all cyclones and tropical storms during baseline period in that location | Baseline period: 1980-2016<br>Projection Period: N/A |
| Sea Level Rise | Absolute Coastal Flood Frequency | Return period of inundation | A projection of how frequently the site may flood in 2040 | Baseline period: 1986-2005<br>Projection Period: 2040 |
| Sea Level Rise | Relative Coastal Flood Frequency | Factor of change | Change in frequency of coastal storms between baseline and projection periods | Baseline period: 1986-2005<br>Projection Period: 2040 |
| Water Stress | Current Baseline Water Stress | Ratio (unitless) | Ratio of total annual withdrawals divided by available supply | Baseline period: 1950-2008<br>Projection Period: 2040 |
| Water Stress | Current Interannual Variability | Standard deviation | Difference in rainfall year-to-year divided by average total annual supply | Baseline period: 1950-2008<br>Projection Period: 2040 |
| Water Stress | Future Water Demand | Cubic km | Projected total water withdrawn for consumption within proximate watershed(s) | Baseline period: 1950-2008<br>Projection Period: 2040 |
| Water Stress | Future Water Supply | Cubic km | Projected total available water supply within proximate watershed(s) | Baseline period: 1950-2008<br>Projection Period: 2040 |
| Water Stress | Water Demand Change | Percent | Change in projected water demand compared to historical baseline | Baseline period: 1950-2008<br>Projection Period: 2040 |
| Water Stress | Water Supply Change | Percent | Change in the projected availability of water supply compared to historical baseline | Baseline period: 1950-2008<br>Projection Period: 2040 |
| Wildfire | Burnable Fuel Availability | Percent | Extent of surrounding area containing burnable vegetative fuels | Baseline period: 1975-2005<br>Projection Period: 2030-2040 |
| Wildfire | Change in days with high wildfire potential | Difference in high risk days | Change in annual number of "high" KDBI days | Baseline period: 1975-2005<br>Projection Period: 2030-2040 |
| Wildfire | Change in maximum wildfire potential | Difference in KBDI[51] | Change in annual maximum KBDI value | Baseline period: 1975-2005<br>Projection Period: 2030-2040 |
| Wildfire | Days with high wildfire potential | High risk days | Number of days with "high" wildfire potential | Baseline period: 1975-2005<br>Projection Period: 2030-2040 |
| Wildfire | Maximum wildfire potential | KBDI | Maximum annual wildfire potential | Baseline period: 1975-2005<br>Projection Period: 2030-2040 |

[51] The Keetch-Byram Drought Index (KBDI) measures drought conditions based on rainfall, air temperature and other meteorological factors (see Keetch, Byram (1968) "A Drought Index for Forest Fire Control").

### *Correspondence table PGA-Modified Mercalli*

Figure 6 shows the correspondence table between Modified Mercalli Index (MMI) and Peak Ground Acceleration (PGA) developed by the U.S. Geological Survey. In the table the two indices correspond respectively to the first and third row. For more information of the way the concordance table is constructed and its limits see link.

| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <.17 | .17-1.4 | 1.4-3.9 | 3.9-9.2 | 9.2-18 | 18-34 | 34-65 | 65-124 | >124 |
| PEAK VEL.(cm/s) | <0.1 | 0.1-1.1 | 1.1-3.4 | 3.4-8.1 | 8.1-16 | 16-31 | 31-60 | 60-116 | >116 |
| INSTRUMENTAL INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |

*Figure 6: correspondence table MMI-PGA. Source: USGS link.*

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