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MACRO-ECONOMIC / TOP-DOWN ASSESSMENT OF CLIMATE IMPACTS ON THE EU ECONOMY

Final report

March – 2025

EUROPEAN COMMISSION

Directorate-General for Climate Action
Directorate A - Strategy, Analysis & Planning
Unit A2 - Foresight, economic analysis and modelling

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DIRECTORATE GENERAL FOR CLIMATE ACTION
FINAL REPORT

April 2024
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FINAL REPORT

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AFOFI	Agriculture, Forestry and Fishery
AFOLU	Agriculture, Forestry and Other Land Use
AMOC	Atlantic Meridional Overturning Circulation
AR-IPCC	Assessment Report – Intergovernmental Panel on Climate Change
BECCS	Bioenergy with carbon capture and storage
BCR	Benefit-Cost Ratio
CO_2	Carbon Dioxide
CH_4	Methane
CRED	Centre for Research on the Epidemiology of Disasters
DACCS	Direct Air Carbon Capture and Storage
EAD	Expected Annual Damage
EADRR	Expected Annual Damages Reduction Rate
EEA	European Environment Agency
EM-DAT	Emergency Events Database
ENSO	El Niño–Southern Oscillation
ESR	Effort Sharing Regulation
EU	European Union
EU-ETS	European Union Emissions Trading System
F-gases	Fluorinated Greenhouse Gases
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GRP	Gross Regional Product
LULUCF	Land Use, Land-Use Change and Forestry
NATDIS	Natural Disasters Database
NDCs	Nationally Determined Contributions
NOAA	National Oceanic and Atmospheric Administration
NZE	Net Zero Emissions
OECD	Organisation for Economic Co-operation and Development
RCP	Representative Concentration Pathway
RES	Renewable Energy source
SSPs	Shared Socioeconomic Pathways
WAIS	West Antarctic Ice Sheet
WBGT	West Bulb Globe Temperature

WTP	Willingness-To-Pay

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Executive summary

This is the final report of the study "Macro-economic / Top-down assessment of climate impacts on the EU economy". The study aims to support the European Commission, DG CLIMA, in analysing the socio-economic implications of hazards triggered by climate change. Specifically, the scope of the study is to provide qualitative and quantitative insights on the impacts of major potential hazards on key macro-economic variables beyond GDP or consumption, and to identify the dissemination channels across the economy of climate-related shocks at sectoral level. In doing so, the study gathers and provides evidence to help the European Commission consider the extent to which the impacts of climate-related shocks may affect the ability of the European Union (EU) to achieve its climate mitigation targets.

To achieve these objectives, the study relied on a step-by-step approach. First, a comprehensive literature review of the scientific and institutional literature and publications on the socio-economic costs of inaction and climate-related hazards, economic implications of climate tipping points, and climate damage functions at macro-economic and sectoral levels was carried out to increase the knowledge around the topic and facilitate the activities in the subsequent steps. The review also included an overview of climate-related events that happened over the past two decades in the EU and nearby regions, and overall informed and shaped the following modelling process. This ensured that the model-based economic analysis reflects the existing scientific understanding and empirical evidence. These insights guided the selection of variables, parameters, and scenarios in the modelling, enhancing the accuracy and relevance of the results.

Second, a detailed modelling exercise with the NEMESIS model was performed to assess the macro-economic impacts on the European economy of future damages caused by climate change and of adaptation measures. Two reference scenarios were defined at global and European level to frame the context and represent two potential futures with high and low GHG emissions: these are, respectively, the "No further action" and "Paris Agreement Compliant" scenarios. The reference scenarios were compared with a series of scenarios including the climate impacts and their socio-economic impacts based on the quantitative information retrieved from the literature review, in order to assess the resulting macro-economic effects. Additional scenarios were also developed to consider the role of adaptation policies in mitigating the economic impacts of the damages and the resulting macro-economic effects, including the related investment costs of adaptation measures. Sensitivity analyses were also carried out to test key assumptions, parameters, or relationships implemented or pre-existing in the model. Overall, this modelling framework allowed for the analysis of the economic costs (or benefits) for the EU of mitigation policy, climate hazards caused by climate change, adaptation policies, and of their combination.

The macro-economic assessment with the NEMESIS model emphasised the **important role of investments that positively contribute to GDP growth in the "Paris Agreement Compliant" scenario, but that also increase capital costs, generate inflationary pressures in the EU, and a decline in the EU competitiveness** compared to the rest of the world. This leads to a GDP loss by -0.7% compared to the "No Further Action" scenario, but **limitations of the NEMESIS model** with respect to available mitigation options in the model and limited availability of credit to finance the additional investments needs should be taken into account when interpreting these results.

From the literature review, **ten different impact areas of climate change were identified with quantitative figures usable for the macro-economic modelling**. These impact areas are **coastal-flooding, labour productivity, agriculture, energy demand and supply, droughts, forestry, fisheries, and river floodings**. Instead, the studies that assess the economic impacts of future climate change on the EU tourism and ecosystem services were excluded from the scope because these are too segmented in their scope for tourism, and too aggregated and very scarce for ecosystem services.

When including the climate change damages in the modelling, more significant GDP losses were estimated. In 2050, the EU GDP loss is of -1.5%, and -1.9% in 2060 in the "No Further Action" scenario, and of -0.9% and -1.5% respectively in the "Paris Agreement Compliant" scenario. The expected effects of climate change damages on employment follow similarly those on the EU GDP. In 2050, in the "No Further Action" scenario, the total potential job loss is of 1.4 million in comparison with the same scenario without climate damages. These losses are about 675 000 jobs in the "Paris Agreement Compliant" scenario.

The implementation of adaptation measures on top of climate change damages mitigates the expected GDP losses. In the "No Further Action" scenario, in 2050, without adaptation the EU GDP declines by -1.5%, whereas it is -0.9% with adaptation. Thus**, in 2050 EU GDP losses are reduced by about 40% thanks to the implementation of adaptation measures**. Similarly, in the "Paris Agreement Compliant" scenario, the EU GDP loss corresponds to -0.9% without adaptation and to -0.5% with adaptation in 2050. **The employment gains coming from the implementation of the adaptation measures are also important**, of 115 000 jobs in the "No further Action" scenario and of 73 000 jobs in the "Paris Agreement Compliant" scenario.

At Member States level, there are no major differences, in relative terms, across Member States in the benefit of adaptation measures, but the countries that are most impacted in absolute terms are also the ones benefiting the most from adaptation, and inversely. The extent of these investments to mitigate the climate change damages on the EU economy, corresponding to €69 billion (constant 2020) in 2050 in the average case (0.33% of EU GDP), is important, but represents a moderate share of the total investment in 2050, of 1.5% in the "No Further Action" scenario. Nevertheless, these investments will be added to other important investment needs for the EU economy in the coming decades, such as for the digital economy and the achievement of carbon neutrality, and will continue to grow after 2060, particularly in a "No Further Action" scenario.

A series of **sensitivity analyses were carried out**, notably on variables such as the share of insured damages and the value of the benefit-cost ratio of adaptation measures for damages impacting labour productivity. **While results did not change significantly in these two cases, more marked impacts of climate damages were observed when introducing a climate-related risk premium at country and sectoral level**. In 2050, when this additional layer on firms' financing is considered, EU GDP declines by -1.8% and -1.3% in the "No Further Action" and "Paris Agreement Compliant" scenarios without adaptation, and by -1.3% and -0.9% with adaptation. The economic losses induced by climate change damages reduce firms' profitability, pushing up the risk perceived by investors, while the implementation of adaptation measures mitigates this reduction of firms' profitability, but the financing of the related adaptation investments increases their debt, therefore partially counterbalancing the positive effects on their profitability.

To summarise, **the impacts of climate change on the EU economy in the middle of the century are expected to be significant** (-1.5% of EU GDP and up to -2.3%), **even if deep decarbonisation, compliant with the Paris Agreement, is achieved** (-0.9% and up to -1.5%). In case of no additional GHG mitigation effort worldwide, the upward trend on the economic impacts of climate change damages would continue, while it would stabilise in a Paris Agreement compliant scenario. **Adding potential additional climate-related risks on firms' financing reinforce the negative impacts on the EU economy** (-1.8% instead of -1.5% EU GDP in the "Paris Agreement Compliant" scenario and up to -2.8% instead of -2.3% EU GDP in the "No Further Action" scenario). **These economic losses can be mitigated with appropriate adaptation measures in both scenarios**.

All **these results must be considered with caution**, in particular the sensitivity of firms' financing which is **based on an exploratory approach**, but also for climate change damages and adaptation measures. Our modelling exercise is limited to 2060, and the extent to which climate damages would continue to grow up with temperature raise thereafter. We do not include tipping points that may exacerbate economic losses, and some potential snowball effects cannot be considered in macro-economic modelling. Finally, we must also mention that the benefits from implementing adaptation measures are important because our methodology selected the efficient ones, but there might exist important maladaptation lowering their expected benefits, or even increasing the economic losses.

1. Introduction

1.1 Overview of this study

This document is the Final report for the project "Macro-economic / top-down assessment of climate impacts on the EU economy". The project, running from November 2022 until March 2024, was awarded by the European Commission (DG for Climate Action) and was being carried out by a Consortium including Ramboll, SEURECO, and Ecologic Institute.

The aim of this Final report is to describe the final results produced under the contract, and it includes a detailed overview of the findings emerging from the literature review performed as part of Task 1 as well as a description of the methodology adopted, and final results developed from the modelling work (Task 2).

The literature review took stock of the scientific and institutional literature on the socio-economic costs of inaction and climate-related hazards, economic implications of climate tipping points, and climate damage functions at macro-economic and sectoral levels. The review also provides an overview on actual climate-related events that happened over the past two decades in the EU and nearby regions.

The section on the modelling work includes a detailed presentation of the methodological steps performed and provides a detailed summary of the modelling results. The aim of the model-based economic analysis was to assess the macro-economic implications of selected climate-related shocks, or a joint occurrence of such shocks.

The findings from the literature review were used to inform and shape the modelling process, ensuring that the model-based economic analysis reflects the existing scientific understanding and empirical evidence. These insights guided the selection of variables, parameters, and scenarios in the modelling, enhancing the accuracy and relevance of the results.

1.1.1 Background to the study

This study falls within the context of the EU Climate Law regulation framework aimed at reaching climate neutrality in the EU economy by 2050. As an intermediate step of the final climate neutrality goal, the EU will set climate targets to be achieved by 2040. In order to establish these targets, the European Commission needs to agree on a projection of greenhouse gas (GHG) emissions at the EU level for the period 2030-2050. The EU Climate Law requires the costs of inaction to be considered as part of this projection. The present study seeks to address this point by analysing the socio-economic consequences of climate hazards triggered by climate change.

More specifically, this project qualitatively and quantitively assessed the impacts of extreme climate events induced by climate change on relevant macro-economic variables beyond GDP or consumption. It also identified the dissemination channels of these impacts throughout the EU economy and evaluated the extent to which climate-related impacts compromise the achievement of the EU mitigation targets.

The project was structured into two main tasks:

- **Task 1: Literature Review**. The objectives of Task 1 were, on one hand, to provide qualitative insights on the impacts of major potential climate-related hazards on key macro-economic variables and sectors and, on the other hand, to identify the data to be used as input for the macro-economic modelling exercise.
- **Task 2: Model-based economic analysis**. The objective of Task 2 was, based on the input data provided in Task 1, to assess quantitatively, with the use of an economic model,

the macro-economic implications of selected climate-related shocks, or a joint occurrence of these shocks, on key macro-economic variables depicting the EU economy.

This final is organised into the following chapters:

- **Executive summary**
- **Chapter 1**: Introduction
- **Chapter 2**: Review on the socio-economic costs of inaction and climate-related hazards
- **Chapter 3**: Macro-economic modelling of climate related shocks
- **Chapter 4**: Summary and concluding remarks
- **Bibliography**.

2. Review on the socio-economic costs of inaction and climate-related hazards

This chapter is a comprehensive review of the scientific and institutional literature focusing on the socio-economic costs of inaction and climate-related hazards, on the economic implications of climate tipping points and climate damage functions at macro-economic and sectoral levels. The chapter also includes an overview of past climate-related events over the past couple of decades and their associated costs.

2.1 Classification of hazards triggered by climate change

A standard classification of climate hazards is essential to extract the relevant information from the different sources considered. The documents/databases that have been used to select the climate hazards are listed below, along with the extreme events that they cover:

- The **COACCH** (Co-designing the Assessment of Climate Change Costs) study addresses: sea-level rise, heatwaves, river floodings, coastal floodings and droughts.
- The **PESETA IV** (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) report covers the following hazards: heat waves, cold waves, windstorms, drought, river floodings, coastal floodings and wildfires.
- The **Study on Adaptation Modelling** developed by DG CLIMA covers heatwaves, droughts, forest fires, land desertification, heavy precipitation, windstorms, hailstorms, flow and river flow, landslides and avalanches and coastal and sea level rise.
- One of the two databases used in this project, **EM-DAT** (Emergency Events Database) launched by the Centre for Research on the Epidemiology of Disasters (CRED), contains information on past climatological, meteorological, and hydrological disasters. More concretely, it covers droughts, extreme temperatures, floods, landslides, storms, and wildfires.
- **NATDIS** (Natural Disasters Database) is the other database used and it includes: floods, landslides, earthquakes, snow avalanches, volcanic eruptions, wildfires, tropical storms and cyclones, windstorms, thunderstorms, hail, tornadoes and waterspouts, cold, snow and freezing rains, heatwaves, droughts, severe weather and tsunamis.

Table 1 Summary of hazards addressed

	Flooding		Storm		Extreme temperature		Droughts/Land desertification	Wildfire	Landslide	Earthquakes	Avalanches	Other
	River flooding	Sea level rise/Coastal flooding	Windstorms	Hailstorms	Heatwaves	Cold waves						
COACCH	**X**	**X**			**X**		**X**					
PESETA V	**X**	**X**	**X**		**X**	**X**		**X**				
Study on adaptation modelling (DG CLIMA)	**X**	**X**	**X**	**X**	**X**		**X**	**X**	**X**		**X**	
EM-DAT	**X**		**X**	**X**	**X**	**X**	**X**	**X**	**X**			
NATDIS	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**

The various hazards identified in the literature can be defined as follows:

- **Sea level rise**. This is the gradual increase in the level of oceans, and it is primarily caused by the melting of glaciers and ice caps as a result of global warming.
- **Coastal flooding**. This phenomenon occurs when water from the ocean or other bodies of water inundates coastal areas. It can be caused by a combination of factors, including sea level rise, storm surges, and high tides.
- **River flooding**. This happens when rivers overflow their banks due to heavy rainfall, snowmelt, or other factors.
- **Storm**. A storm is a violent disturbance of the atmosphere characterised by strong winds, heavy precipitation, lightning and thunder.
- **Extreme temperatures**. This refers to prolonged periods of abnormally high or low temperatures.
- **Drought**. A drought is a sustained period of unusually low precipitations.
- **Wildfire**. An uncontrolled fire that occurs in natural areas such as forests or grasslands.
- **Landslide**. A landslide is the movement of a rock or earth down a slope. Landslides can be triggered by heavy rainfall, earthquakes, or other factors.
- **Earthquake**. An earthquake is a sudden and violent shaking of the ground caused by the movement of tectonic plates.
- **Avalanche**. This is a mass of snow, ice, and rock that moves rapidly down a mountainside. Avalanches can be triggered by heavy snowfall, warming temperatures, or human activity.

2.1.1 Classification used in this study

The selection of the climate impacts considered in this study is based on various reasons, going from the availability and measurability of data to the magnitude of the impacts on economic or human capital. Following this reasoning, the hazards considered in this study are:

- Sea level rise
- Heatwaves
- Higher average temperature
- River flooding
- Coastal flooding
- Windstorms
- Wildfires
- Water scarcity & droughts.

The climate impacts in this study were selected upon data availability and their link with climate change. For instance, river flooding and coastal flooding are intensified by climate change, leading to increased risks of inundation and damage to ecosystems and built environments. It was therefore judged relevant to include these types of events in the analysis.

2.1.2 Structuring the socio-economic impacts

We listed below how similar studies have structured their list of “socio-economic” impacts. As Table 2 shows, the list of impacts differs for each study, even if several cross or/and overlap and are not exactly framed as socio-economic impacts. Indeed, the impacts covered concern directly some economic activities (e.g. agriculture, energy, etc.) or sectors in a broader sense (buildings, water systems, coastal zones, etc.), but some others also directly refer to climate hazards (windstorms, drought, etc.) or impacts (health, labour productivity, etc).

Table 2 List of impacts in similar studies

EC adaptation study (2020)	PESETA II (2014)	PESETA IV (2020)	IPCC AR6 WGII (2022)	COACCH (2021)	OECD (2015)
Sector Impacts	***Biophysical Impacts***	***Impact Category***	***Impacts and risks***	***Sectors***	***Sectors***
Water supply	Agriculture	Heat and cold waves	Ecosystems and biodiversity	Agriculture	Agriculture
Agriculture/Crops	Energy	Windstorms	Food systems and food security	Energy supply	Coastal zones
Forestry	River floods	Water resources	Water systems and water security	Energy demand	Extreme events
Fish dynamics	Droughts	Drought	Risks from sea level rise	Forestry	Health
Ecosystems and biodiversity	Forest fires	River flooding	Health and well-being	Fisheries	Energy demand
Energy	Transport infrastructure	Coastal flooding	Migration and displacement	Riverine floods	Tourism demand
Tourism	Coasts	Wildfires	Human vulnerability	Transport	Ecosystems
Cities and urban areas	Tourism	Habitat loss	Cities, settlements and infrastructure	Labour productivity	Water stress
Critical infrastructures	Habitat suitability	Forest ecosystems	Economic sectors	Sea level rise	Human security
Buildings	Human health	Agriculture	Compound, cascading and transboundary risks		Tipping points
Transports	Dynamic linkages land-water-energy	Energy supply			
Health and heat		Economic integration			
Health and other					

2.1.3 Structure used in this study

Based on the summary provided in Table 2, we selected the following sectors/impacts. This list is relatively exhaustive and will allow us to cover a large range of sectors/impacts covered in the literature.

- Agriculture
- Forestry
- Fisheries

- Energy supply and demand
- Labour productivity
- Coastal flooding
- River flooding
- Droughts
- Ecosystem services
- Tourism.

The selection of these sectors/impacts is justified as they cover a wide range of areas extensively studied in the literature, allowing for a comprehensive analysis of climate change consequences. These sectors/impacts, including agriculture, forestry, fisheries, energy, labour productivity, flooding, droughts, ecosystem services, and tourism, represent significant areas vulnerable to climate change with implications for society, economy, and the environment.

2.2 Past hazard events and impacts within the EU

This section presents an overview of the past climate events in Europe that took place in the last 20 years (2003/2002 to 2022). The analysis draws upon two databases: the Emergency Database (EMDAT)[1] developed by the Centre for Research on the Epidemiology of Disasters (CRED), which served as a preliminary screening tool for this analysis; and the Natural Disasters (NATDIS)[2] database developed by the Observatoire Permanent des Catastrophes Naturelles which provided more detailed and accurate information.

The EMDAT encompasses around 900 cases of climatological, meteorological, and hydrological extreme events in Europe in the last two decades, which however do not represent all the extreme events that took place in Europe in the same period. In a later stage, a comparison with the NATDIS database, was included to provide a more comprehensive analysis of available data on past climate-related hazardous events. The NATDIS database counts more than 4,600 events in Europe since year 2001, making it a more comprehensive source of information compared to the EMDAT database[3]. The latest version of the database includes all events happening up to 2022 and their related costs.

Additionally, the CATDAT[4] database from the RiskLayer that provides information on the total economic loss cause by weather and climate was used as a complementary source of information for this analysis. The EEA analysed the database and provided pertinent information, and as a result, the related charts were directly extracted from the EEA website and used in the present analysis.

It is important noting that for ease of comprehension, if there were discrepancies in how certain countries were classified between the EMDAT and NATDIS databases, a decision was made to unify the categorization. For example, if France was categorized as "Western Europe" in EMDAT and "Southern Europe" in NATDIS, it was renamed as "Western Europe" in both databases to maintain

[1] https://www.emdat.be/

[2] https://www.catnat.net/component/edocman/4-espace-telechargements/5-bases-de-donnees/8-bases-de-donnees-statistiques/26-natdis-database

[3] It also contains information on other types of events which are not considered in EMDAT, so NATDIS does not necessarily register more observations for the same type of events, although this is likely to be the case.

[4] CATDAT (Dataset URL is not available) https://www.eea.europa.eu/data-and-maps/data/external/catdat-dataset-url-is-not-available.

consistency. This adjustment was solely implemented to facilitate a more seamless and meaningful comparison of the data, while keeping the original information intact.

2.2.1 EMDAT

2.2.1.1 Frequency and occurrence of hazardous events

The EMDAT database provides information on 920 hazards events and the classification of each event used in this analysis are displayed in Table 3. In comparison with the classification used for this study, outlined in section 2.1.1, it does not include data on sea level rise, higher average temperature and coastal flooding. It does however include landslides, which are not part of the classification of hazards used in this study.

Table 3 Detail of climate events included in each category analysed in the EMDAT database

Meteorologic:	Climatic:	Hydrologic:
Storm Extreme temperature	Glacial lake outburst Wildfire Drought	Flood Landside

The figures below showcase the distribution of climate hazards in Europe from 2003 to 2022. It reveals that meteorological hazards constituted the majority of hazardous events. Together, meteorological and hydrological hazards make up 90% of the total climate events observed in Europe during the period. This highlights the paramount importance of weather and water-related phenomena in shaping the climate landscape of the continent. On the other hand, climatological events represent only 8% of events.

Upon closer examination of the climate hazard, it becomes apparent that there exists a significant disparity between the various types of climate hazards. Figure 1 shows that meteorological events represent more than half of the events that happened in the past twenty years while Figure 2 illustrates that the three most common phenomena, representing more than 90% of registered events are, from least to most frequent: extreme temperatures (including both heat and cold waves), storms and floods.

Figure 1 Distribution of climate hazards by type in Europe from 2003 to 2022 in Europe

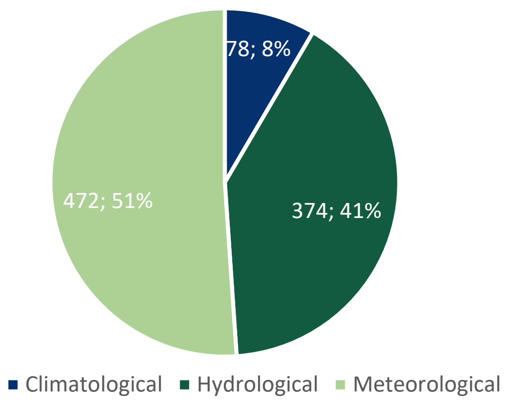
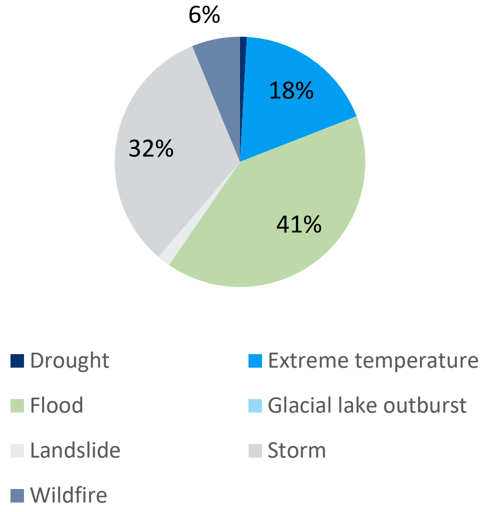


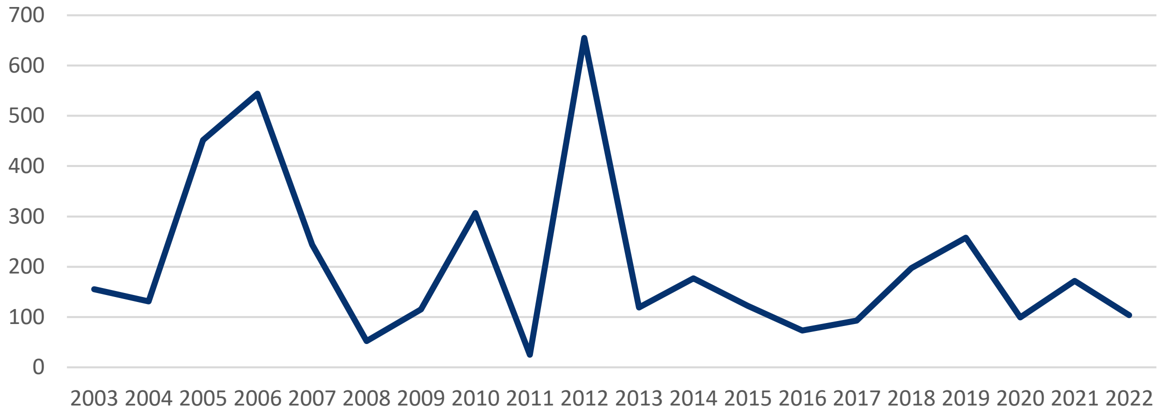
Figure 2 Distribution of climate hazards in Europe from 2003 to 2022 in Europe



Source: EMDAT.

Moreover, it was judged relevant to examine whether there have been any changes in the intensity of events over time. The EMDAT database offers valuable information in this regard, providing the start date and end date for each event. Figure 3 provides an assessment of the overall intensity of climate events over the past 20 years by measuring the cumulative number of days during which all types of hazardous events persisted annually. This quantification offers valuable insights into the frequency and duration of these events. For example, in 2012, the total sum of days with extreme climate events reached a theoretical value of 700, while in 2016, it was significantly lower at just lasted 73 days. However, a clear trend cannot be discerned. Instead, there are instances where events have been exceptionally prolonged, such as the prolonged droughts across Europe in 2012. These moments in time highlight the significance of specific events rather than indicating a consistent increase or decrease in event intensity over the examined period.

Figure 3 Intensity (in number of days an event lasted) of extreme climate events from 2003 to 2022 in Europe



Source EMDAT.

Furthermore, analysing the average duration of each type of event provides valuable insights. On average, climatological events have lasted 10.9 days, hydrological events have lasted 5 days, and meteorological events have had the shortest duration of 2.8 days. Among meteorological events, droughts have been the longest-lasting, with an average duration of 24.7 days. These figures highlight the varying temporal characteristics of different types of events and underscore the extended nature of droughts as a significant climate hazard.

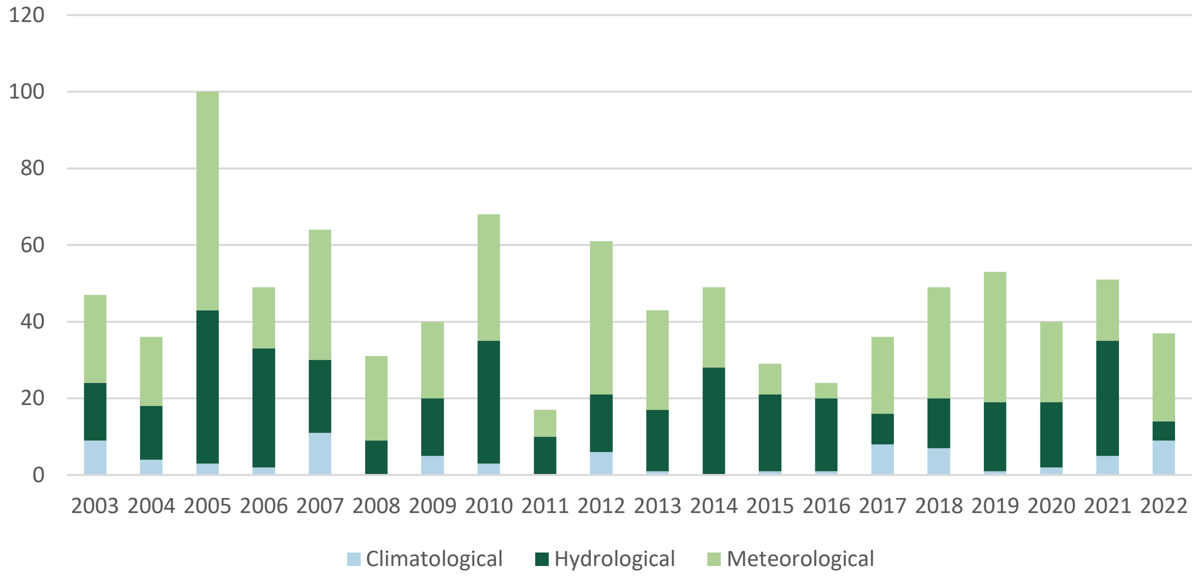
Table 4 Average length of a hazardous event from 2003 to 2022 in Europe

Climatological	Hydrological	Meteorological
10.9	**5.1**	**2.8**

Source EMDAT.

Looking at the temporal evolution of climate hazards, Figure 4 shows that no clear trend can be identified with respect to growth or reduction of a specific hazard over time. The figure however allows to see that the number of events registered in the database varies largely depending on the year, going from 100 listed in 2005 to 17 events registered in 2011. The peak in 2005 is explained by a combination of different hydrological and meteorological events, notably floods and heatwaves.

Figure 4 Temporal evolution of number of climate hazards from 2003 to 2022 in Europe



Source: EMDAT.

2.2.1.2 Geographical distribution of climate hazard events in Europe

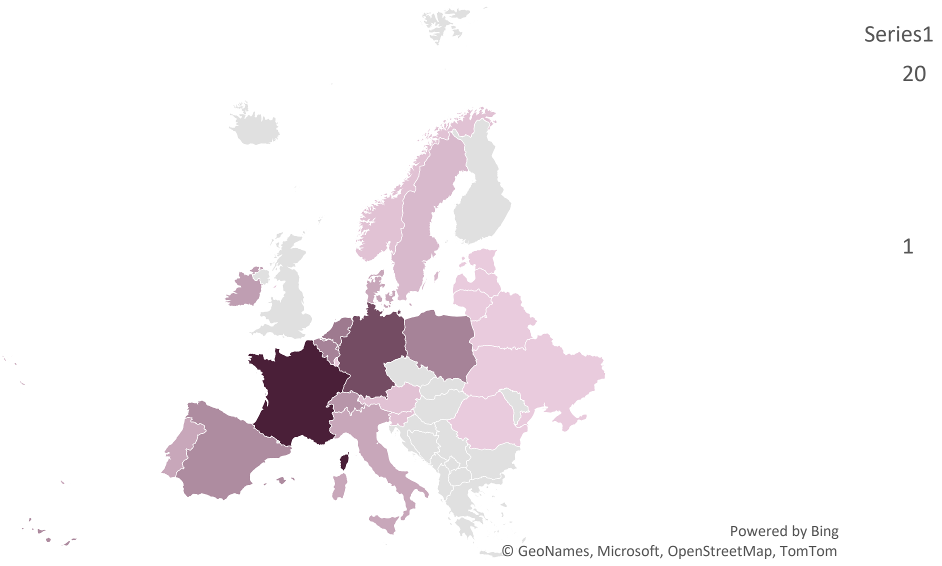
In order to illustrate the geographical distribution of the events, four different regions were defined in accordance with the EMDAT differentiation. Table 5 portrays which countries are included in each region. This structure seems logical given that countries within the same region are more likely to experience similar meteorological conditions.

Table 5 Detail of which countries are included in each region in the EMDAT database

Eastern Europe:	Northern Europe:	Southern Europe:	Western Europe:
• Poland • Russia • Czech Republic • Romania • Hungary • Slovakia • Bulgaria • Belarus • Moldova • Ukraine	• United Kingdom • Sweden • Norway • Ireland • Finland • Lithuania	• Albania • Italy • Greece • Spain • Portugal • Croatia • Cyprus • Slovenia • Bosnia • Macedonia • Montenegro • Serbia • Slovenia	• France • Switzerland • Austria • France • Germany • Netherlands • Luxembourg

Figure 5 a heat map, offers a clear depiction of the countries most affected by climate hazardous events in Europe. It provides a quick and easy way to identify the regions most prone to such hazards. Notably, the map reveals that Western Europe, with France prominently featured, has experienced the most significant effects of climate change over the last 20 years.

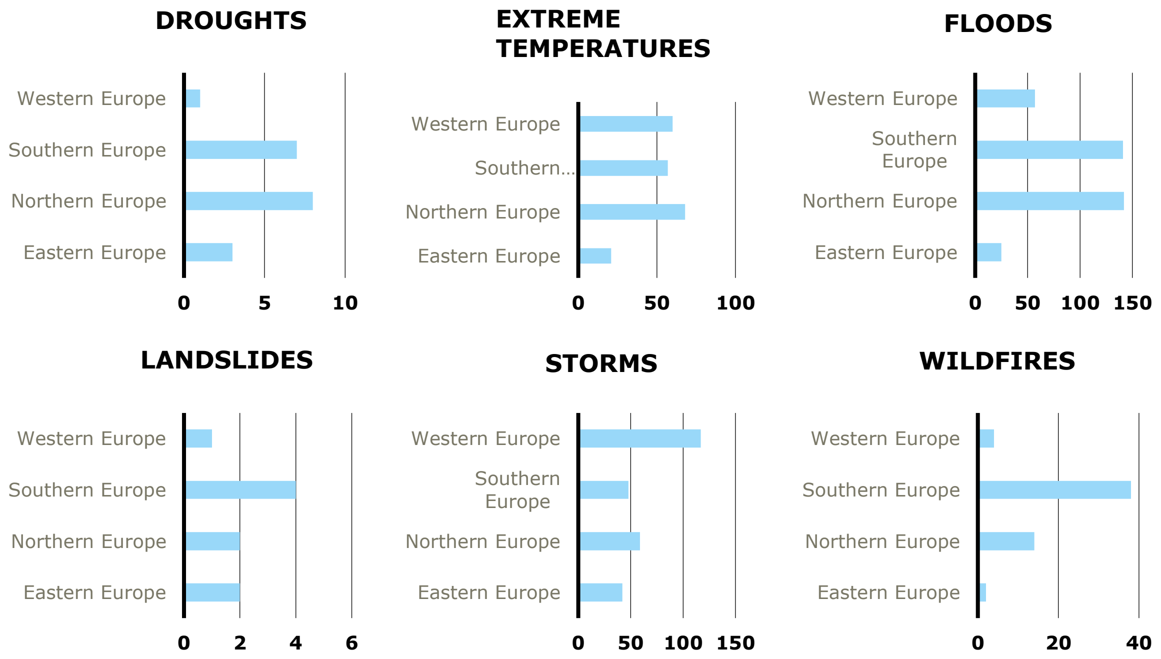
Figure 5 Heat map showcasing the European countries with the highest number of hazardous events from 2003 to 2022



Source: EMDAT.

Additionally, the figure below provides a representation of the frequency with which different hazards impact each of the four regions considered. Droughts and floods are relatively more common in Northern and Southern Europe, whereas storms are more present in the Western region of the continent. Extreme temperatures are frequent in all of Europe, but to a relatively lower extent in Eastern Europe. Finally, wildfires are especially present in the Southern region.

Figure 6 Frequency of climate-related hazards by region from 2003 to 2022 in Europe (in number of events)

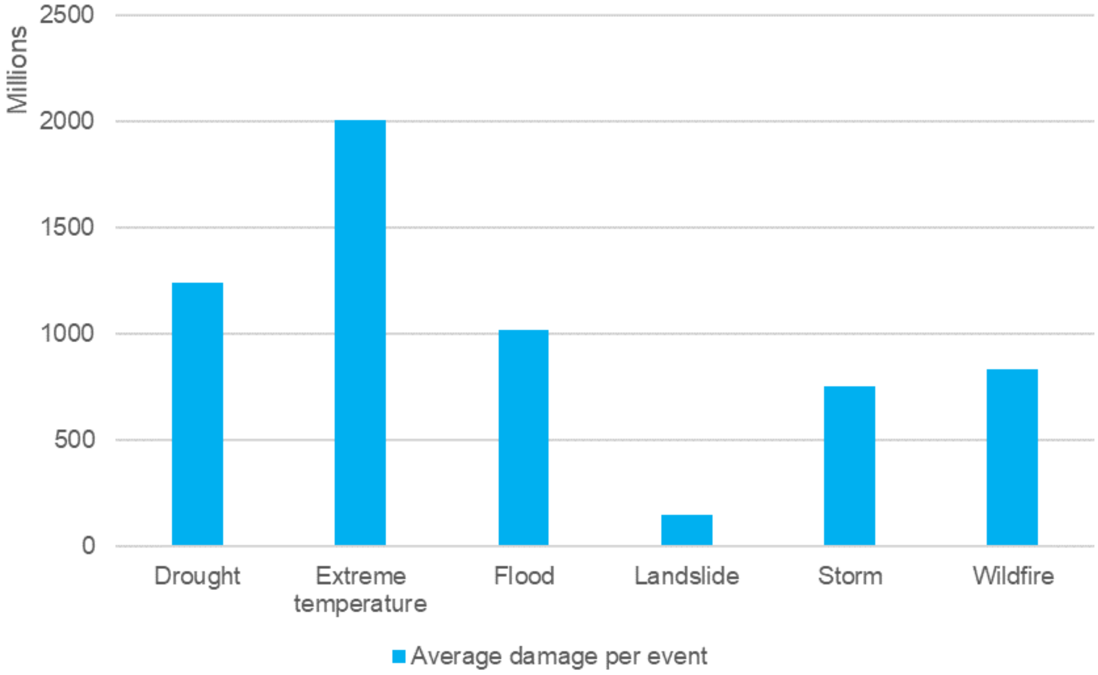


Source: EMDAT.

2.2.1.3 Social and economic cost of hazardous events

With respect to the monetised damages (which do not include deaths or injuries), extreme temperatures appear to be the costliest with an average cost per event of approximately 2,000 Million USD, followed by droughts and floods (see the figure below).

Figure 7 Average cost by climate hazards (in Millions USD) in Europe from 2003 to 2022



Source: EMDAT.

Significant disparities exist in the reporting of economic costs associated with various hazards, as demonstrated by the substantial variation depicted in Table 6. It is crucial to note that the availability of reliable cost data for events such as extreme temperatures or landslides is limited. The reliability of cost data for these hazards is compromised due to the scarcity of cases where costs were registered. Additionally, the presence of outliers can greatly impact the average cost reported for a specific hazard, further undermining the accuracy of the data.

Table 6 Share of events with damages reported out of all events reported by hazard in Europe from 2003 to 2022

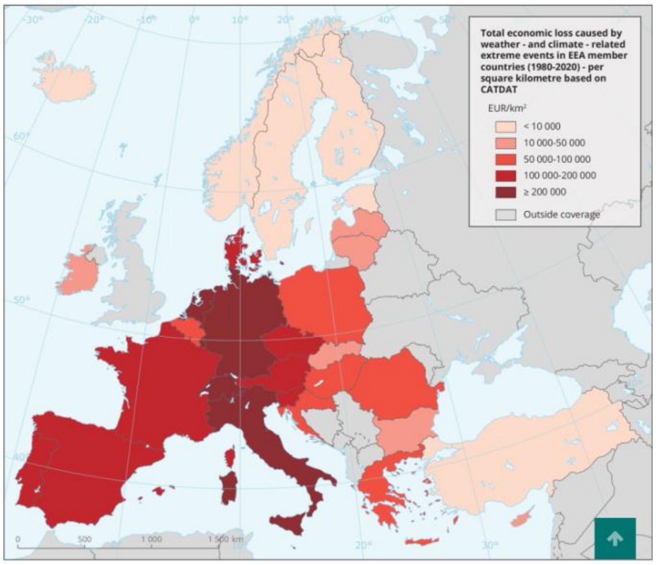
	Share of events with damages reported
Drought	57.89%
Extreme temperature	6.80%
Flood	36.44%
Landslide	11.11%
Storm	35.34%
Wildfire	34.48%

Source: EMDAT.

To gain a more comprehensive understanding of the economic impact of hazardous events, it is important to consider the analysis conducted by the EEA using the CAT DAT database. This analysis covers a broader time frame, from 1980 to 2020. Figure 8 highlights that Southern Europe and

Central Europe have experienced the highest economic losses resulting from weather and climate-related events. By incorporating the EEA's analysis, we can obtain a more detailed and extensive view of the economic consequences associated with these events, particularly in these regions.

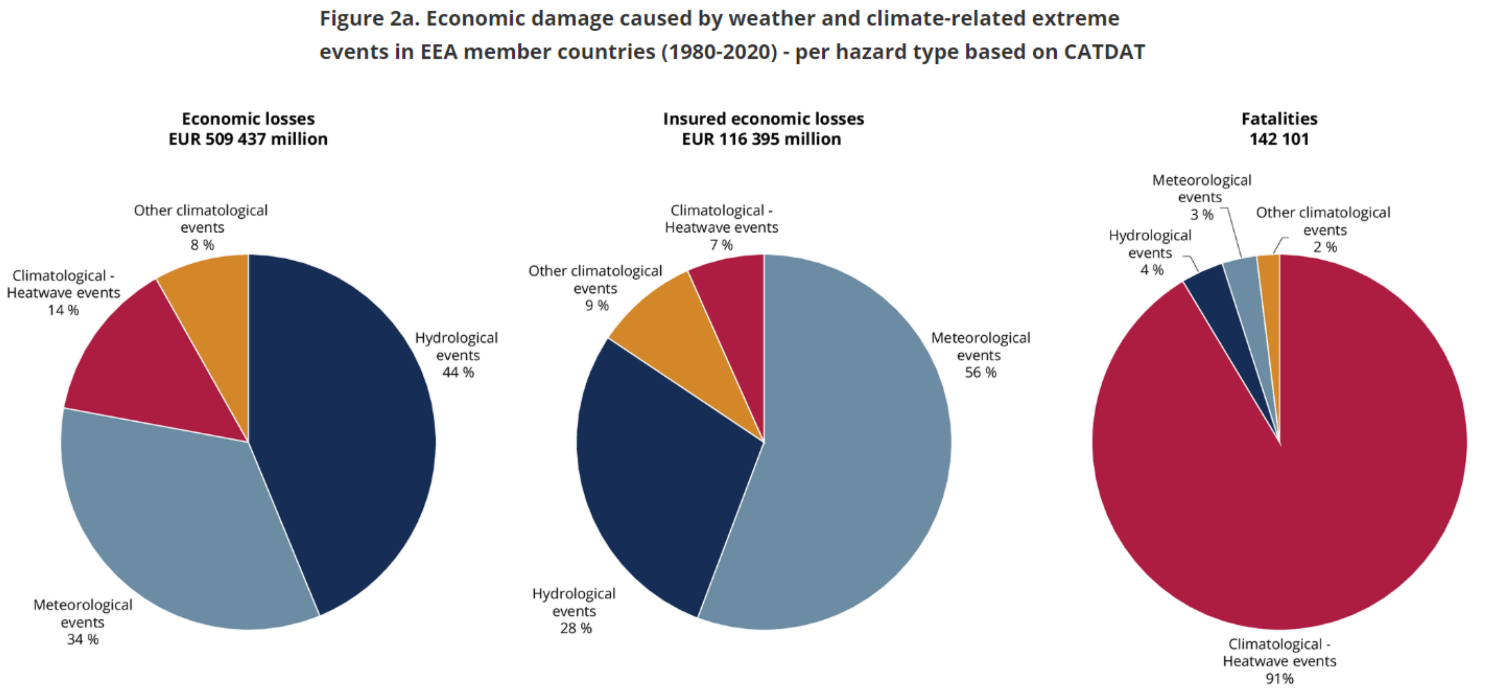
Figure 8 Total economic loss caused by weather- and climate-related extreme events in EEA member countries (1980-2020) - per sq. kilometre based on CATDAT



Source: CATDAT EEA.

Furthermore, the analysis conducted by the EEA interestingly sheds light on the extent to which these economic losses have been covered by insurance. Figure 9 reveals that 56% of meteorological events have been insured, indicating a relatively higher level of coverage for these types of events than the others. In contrast, only 7% of climatological events have been insured, indicating a lower level of insurance coverage for these types of events. This information highlights the discrepancy in insurance coverage between different categories of hazardous events and emphasizes the need to enhance insurance mechanisms for climatological events to mitigate the financial impact on affected regions.

Figure 9 Annual economic damage caused by different types of events from 1980 to 2021 in Europe



Source: CATDAT EEA.

2.2.1.4 NATDIS database

2.2.1.4.1 Occurrence of hazardous events

The NATDIS's database counts a total of 5,145 climate events from five different origins, yet only meteorologic, climatic, and hydraulic events were considered in this analysis. Table 7 describes what each type of event refers to.

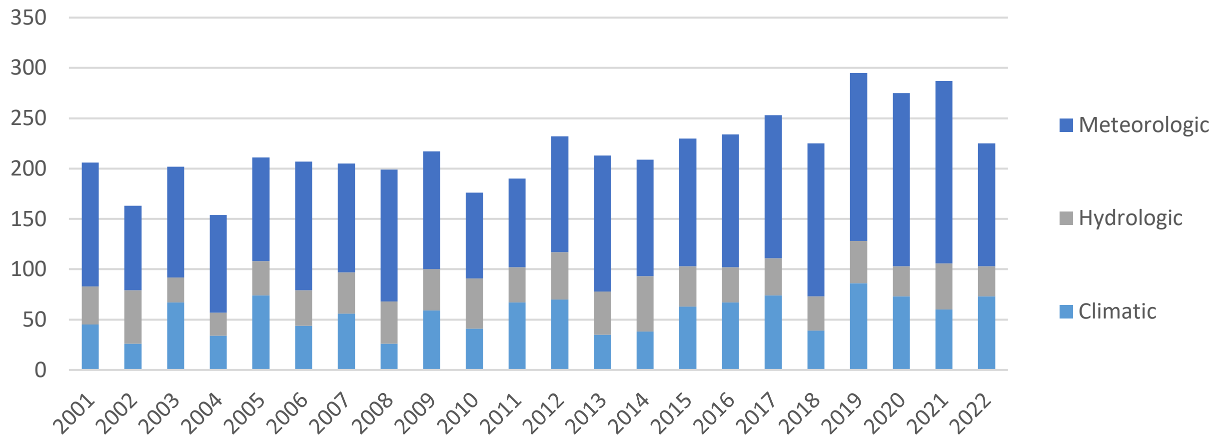
Table 7 Detail of the climate events included in each category analysed in the NATDIS database

Meteorologic:	Climatic:	Hydrologic:
Floods Snow avalanches Tropical storms and cyclones Windstorms Thunderstorms Hail Tornadoes and waterspouts Cold and snow and freezing rains Severe weather.	Wildfires Cold, snow and freezing rains Heatwaves Droughts.	Floods

The NATDIS database suggests there have been an overall increase of extreme climate events throughout the years, with an average below 200 events a year before 2011, to above 200 after this period. The figure below particularly suggests that meteorologic events hold a relatively significant responsibility in this increase.

Overall, meteorological events have been the most frequent natural disasters in Europe over the last 20 years, accounting for 57% of all extreme climate events. Hydrological events, on the other hand, only account for 18% of events, while climatic events account for 25%. Within the category of meteorological events, thunderstorms and snow avalanches have contributed significantly to the total numbers. Indeed, there have been as many thunderstorms as hydrological events in total in the past 20 years.

Figure 10 Evolution of climate hazards overtime and distribution between different origins from 2001 to 2022 in Europe



Source: NATDIS.

It is important to note that when examining the distribution of specific events within a certain category, only a few events make up a large share of the numbers for both meteorological and climatic events. According to Figure 11, wildfires represent 83% of all climatic events, which is more than hydrological events and constitutes 20% of the total events in the NATDIS database. This suggests that wildfires, along with thunderstorms and floods, pose some of the most significant threats.

Figure 11 Share of climatic events from 2001 to 2022 in Europe

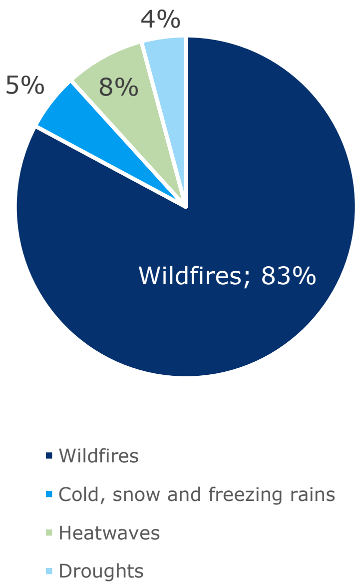
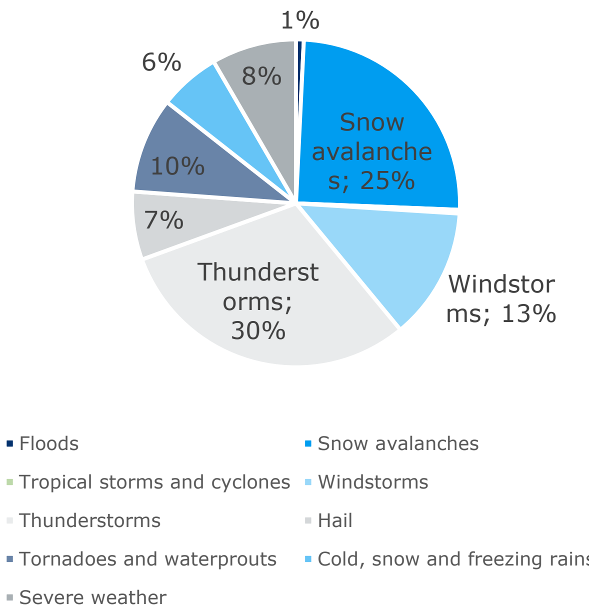


Figure 12 Share of meteorologic events from 2001 to 2022 in Europe



Source: NATDIS.

2.2.1.5 *Geographical Distribution of Climate Hazard Events in Europe*

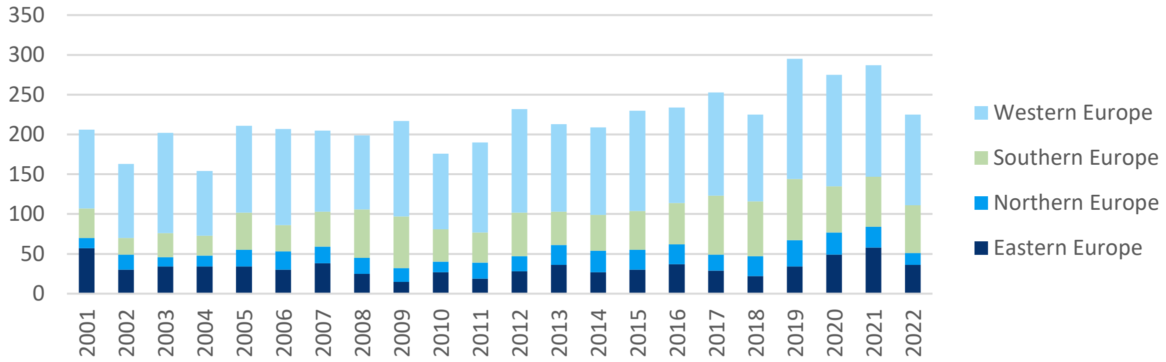
Table 8 represents the countries included in each region analysed in the NATDIS database.

Table 8 Detail of countries included in each region analysed in the NATDIS database

Eastern Europe:	Northern Europe:	Southern Europe:	Western Europe:
• Poland • Russia • Czech Republic • Romania • Hungary • Slovakia • Bulgaria	• United Kingdom • Sweden • Denmark • Norway • Ireland	• Italy • Greece • Spain • Portugal • Croatia • Cyprus • Slovenia	• France • Switzerland • Austria • France • Germany Netherlands

Upon examining the regions most affected by extreme climate events, the NATDIS database analysis indicates that Western Europe has been facing a greater impact in recent years compared to other regions. As depicted in Figure 13, while all regions have seen a relative increase in the occurrence of climate events, Western Europe has been the most affected in the past year. Specifically, 53% of the events have occurred in Western Europe, with Southern Europe experiencing 22% of the events. The remaining events were fairly evenly distributed between Northern Europe (10%) and Eastern Europe (15%).

Figure 13 Most affected areas by extreme climate events in Europe from 2001 to 2022



Source: NATDIS

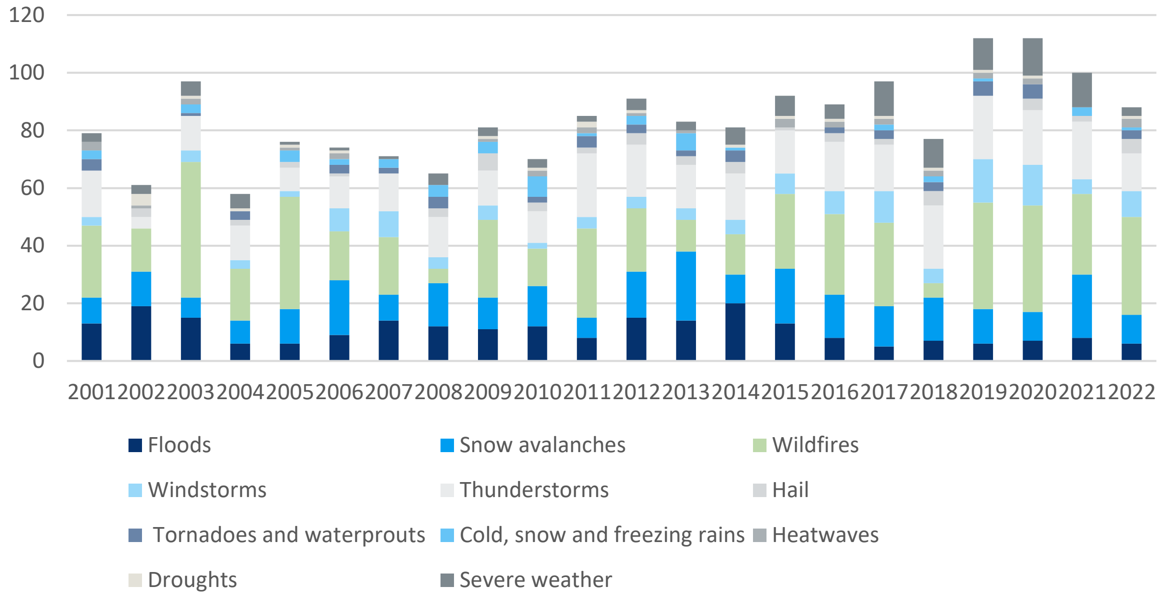
As displayed in Figure 14, France has been one of the most affected countries in the past twenty years with a total of 1839 climate events, this represents 38% of the total climate events analysed in this report. This is explained by the significant occurrence of events like floods (234), snow avalanches (290) and thunderstorms (328) and wildfires (528).

Figure 14 Map showcasing the most impacted European countries by extreme climate events from 2001 to 2022

Source: NATDIS.

Upon closer examination of the data pertaining to France, it is clear that wildfires have been a significant factor contributing to the high numbers of extreme climate events in the country as shown by Figure 15.

Figure 15 Distribution of extreme climate events in France from 2001 to 2022

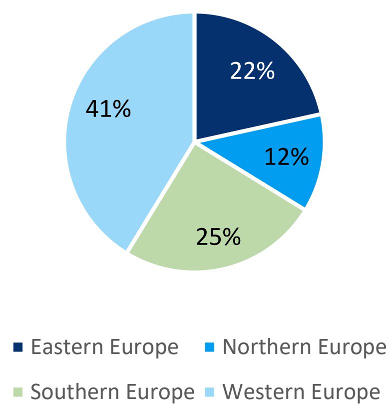


Source: NATDIS.

2.2.1.6 Social and economic cost of extreme hazardous events

According to the NATDIS database, the total cost of climate events in Europe from 2001 to 2022 amounted to 440 billion USD. This number represents the sum of the original cost of all the climate events that occurred during this period, including damages to property and infrastructure, economic losses, and other related expenses.

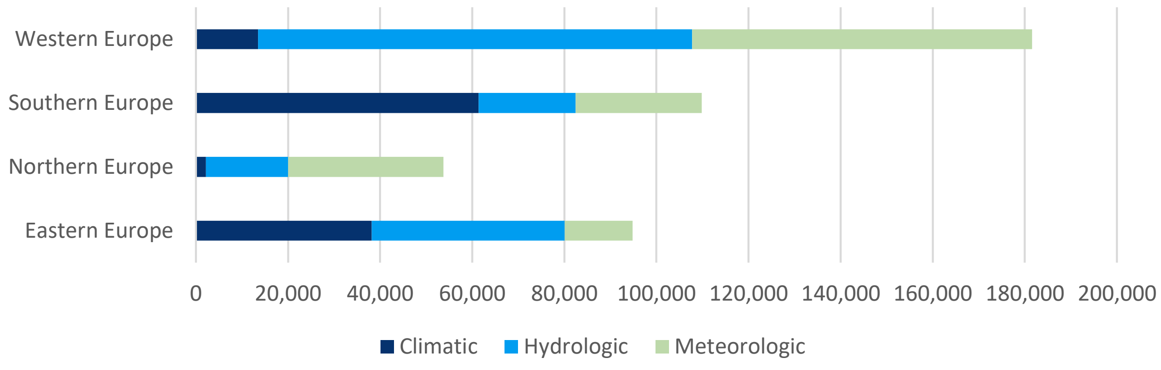
Figure 16 Economic losses of extreme climate events in European regions – Relative share (%) Source: NATDIS.



Looking at the economic impact of extreme climate events in Western Europe in recent years, it is predictable that the region has incurred the greatest economic burden from these events, accounting for 41% of total economic losses. Within Western Europe, the majority of the economic losses can be attributed to Germany and France, which bear 85% of the total economic losses in the region.

In contrast, the remaining regions share the cost of climate change more evenly, with Northern Europe accounting for 12% of the total economic cost, Southern Europe for 25%, and Eastern Europe for 22%. It is worth noting that within Northern Europe, the United Kingdom shoulders a significant 77% of the total economic costs in the region.

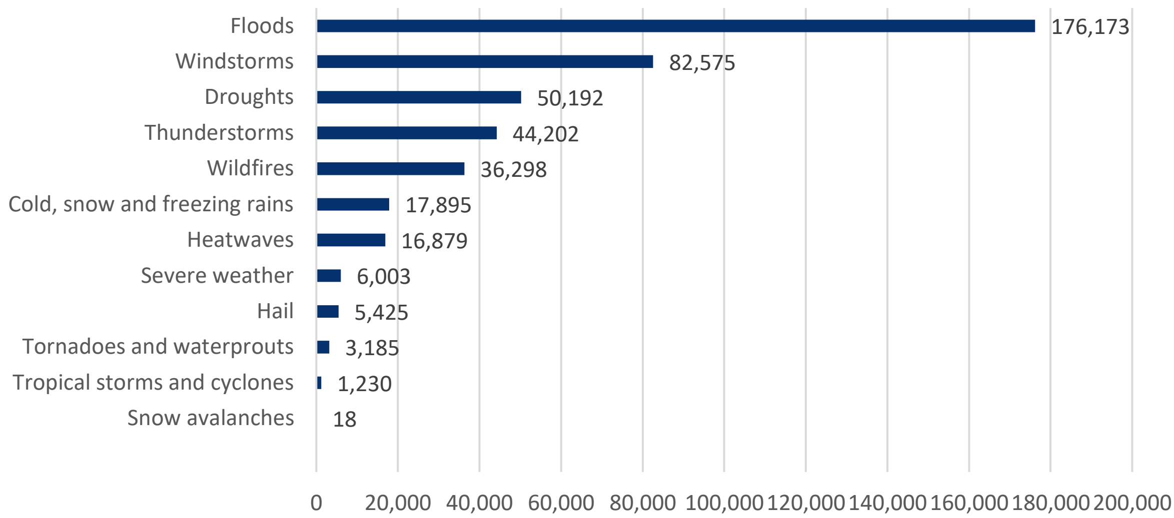
Figure 17 Economic losses (original cost in Million dollars) of extreme climate events by category for each region 2001-2022



Source: NATDIS.

Interrogating which extreme climate events are responsible for such high cost, the figure below shows that floods are, by far, the costliest climate events, due to the extensive damage they can cause to property and infrastructure. Floods can damage homes, businesses, and other structures, including their foundations, walls, electrical systems, and furniture. Repairing or replacing this property can be very costly. Floods can also damage roads, bridges, and other critical infrastructure, such as water treatment plants and power stations. Repairing or replacing this infrastructure can be very expensive and time-consuming. Floods can cause businesses to shut down for extended periods, resulting in lost revenue, reduced productivity, and potential job losses, which can have significant economic impacts on both the affected businesses and the wider community. On the contrary, some climate events such as hail, snow avalanches and tornadoes have a lower cost. This can be partly explained by the fact that the areas impacted by these events are generally more limited.

Figure 18 Sum or original losses (in million USD) from 2001 to 2022 in Europe

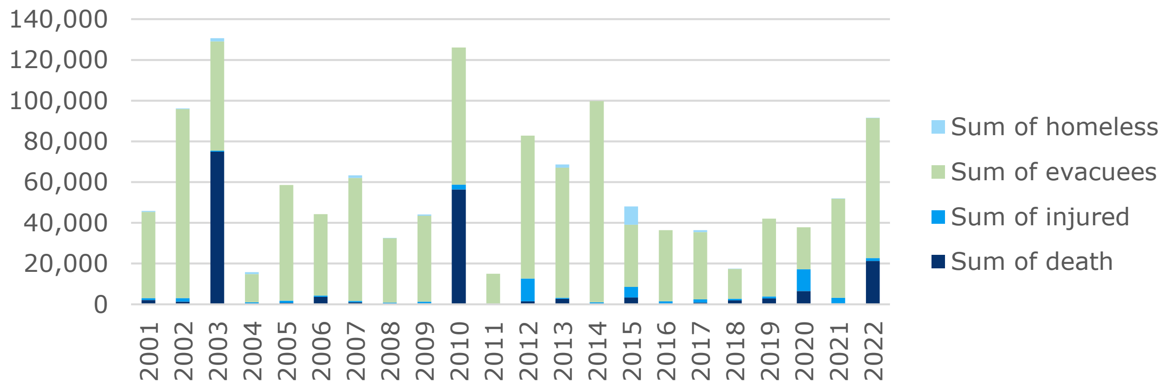


Source: NATDIS.

Human cost of extreme climate events from 2001 to 2022 in Europe

Additionally, it is important to consider the overall impact of extreme climate events on human lives. Although the impact is typically measured by the number of fatalities, it is also essential to factor in the number of evacuees, injured individuals, and displaced persons. In the figure below, there is an uneven distribution of such impact, with no significant trend of increase or decrease over time. However, there are notable peaks in 2003 (heatwaves, floods, thunderstorms, wildfires), 2010 (floods, heatwaves, wildfires), and 2022 (wildfires), with particularly high numbers of fatalities.

Figure 19 Total social cost of extreme climate events from 2001 to 2022 in Europe

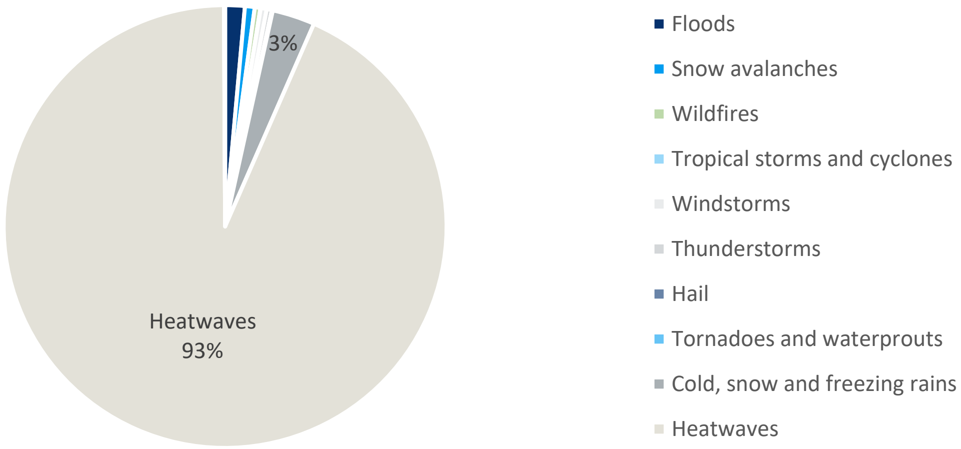


Source: NATDIS.

Additionally, according to the NATDIS database, it seems that heatwaves are the most significant threat to public health, contributing to 93% of total death related to hazardous climate events in the EU in the past 20 years. This is explained by the fact that heatwaves can lead to dehydration, heat exhaustion, and heatstroke, which can be fatal without prompt medical attention. Additionally, high temperatures can exacerbate existing health conditions such as cardiovascular disease, respiratory illness, and kidney disease[5].

In contrast, other events (windstorms, wildfires, thunderstorms, severe weather, tornadoes and waterspouts, tropical storms and cyclones, hail, droughts) only have more limited impact in terms of human deaths, even when combined together.

Figure 20 Total sum of death for each climate event from 2001 and 2022 in Europe



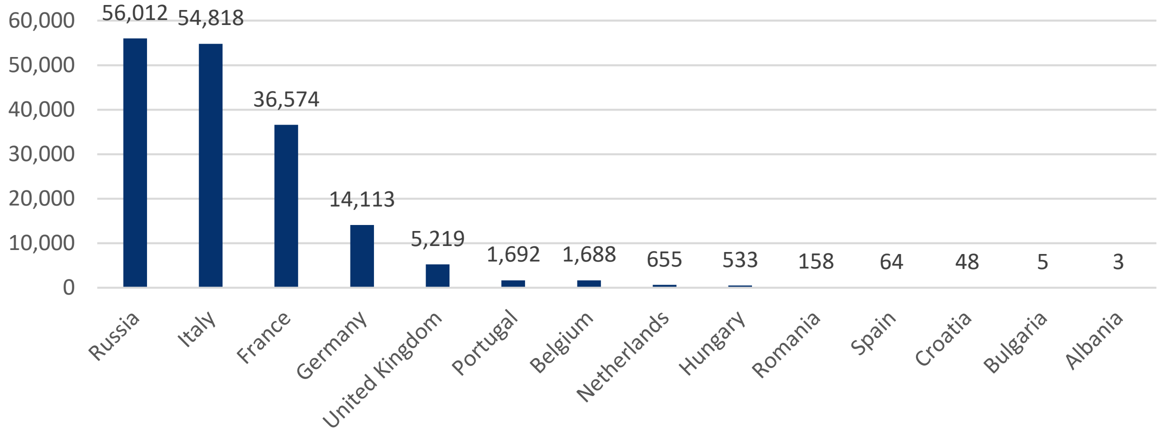
Source: NATDIS.

Upon closer examination of the human cost of heatwaves, it is evident from Figure 21 that Russia, Italy, France, and Germany have experienced the highest number of losses due to this phenomenon. This is not surprising for countries like France, Germany, and Italy, which have already been identified as countries particularly affected by heatwaves. In the case of Russia, it is important to

[5] EEA (2023). Cooling buildings sustainably in Europe: exploring the links between climate change mitigation and adaptation, and their social impacts https://www.eea.europa.eu/publications/cooling-buildings-sustainably-in-europe

notice that the 56,012 deaths can be attributed to a single heatwave that occurred in 2010, which also impacted Sweden and Finland.

Figure 21 Total deaths due to heatwaves from 2001 to 2022 in Europe



Source: NATDIS.

2.2.2 Conclusion

In conclusion, the EMDAT database includes approximately 900 cases of climatological, meteorological, and hydrological extreme events in Europe over the past two decades.

- The database categorizes events based on climate hazards, including droughts, extreme temperatures (heat and cold waves), floods, landslides, storms, and wildfires.
- Analysis of the EMDAT data shows that the frequency of different hazards varied over the years, with no clear trend of growth or reduction for a specific hazard.
- Extreme temperatures were found to be the costliest hazard, followed by droughts and floods, although data limitations make it challenging to draw definitive conclusions on the economic costs.
- The duration of events varied, with specific instances of prolonged events, such as the extended droughts across Europe in 2012, highlighting the significance of certain events rather than indicating a consistent increase or decrease in event intensity over time.
- Geographically, the EMDAT database divides Europe into four regions: Eastern Europe, Northern Europe, Western Europe, and Southern Europe. Each region experiences different frequencies of hazards, with droughts and floods being more common in Northern and Southern Europe, storms in Western Europe, and extreme temperatures across all regions.
- The observed patterns in the EMDAT data align with the projected climate change impacts outlined by the European Environment Agency (EEA) for different biogeographical regions in Europe.
- Western Europe, particularly the Atlantic region, is characterized by heavy precipitation and storms, which can increase the likelihood of flash floods. The EEA predicts increased flood risk and damages from winter storms in Northern Europe, while Eastern Europe is expected to face hotter temperatures, decreased summer precipitation, and an elevated risk of wildfires and river floods. The Mediterranean region, Southern Europe, is projected to be

highly affected by extreme heat, leading to increased droughts and forest fires, with interactions between different hazards more likely to occur in this region.

Findings from the NATDIS database analysis include:

- The NATDIS database covers a wide range of natural disasters worldwide, including earthquakes, floods, hurricanes, and droughts, between 2001 and 2022.
- France has been the most impacted country in the past 20 years, with a total of 1,839 climate events, mainly attributed to storms, floods, snow avalanches, and wildfires.
- Meteorological events have been the most frequent natural disasters in Europe, accounting for 57% of all extreme climate events, followed by climatic events at 25% and hydrological events at 18%.
- Western Europe has faced the greatest impact in recent years, with 53% of the events occurring in this region, followed by Southern Europe at 22%. Northern and Eastern Europe experienced 10% and 15% of the events, respectively.
- Floods have been the costliest climate events, resulting in significant economic losses due to property damage and infrastructure destruction. Germany and France have borne 85% of the total economic losses in Western Europe.
- Heatwaves have posed the most significant threat to public health, contributing to 93% of total climate-related deaths in the European Union over the past 20 years.
- Russia, Italy, France, and Germany have experienced the highest number of fatalities due to heatwaves, with Russia accounting for a significant portion of deaths resulting from a single heatwave in 2010.

2.3 Future hazards and impacts within the EU

This chapter discusses the economic assessments for different policy fields and identify major climate impacts for Europe.

For **sea-level rise on coastal areas** the global integrated assessment model DIVA is used. Lincke et al. (2018) calculated annual sea flood costs and protection costs for 2015 to 2100 for EU 28 countries. They use the following scenarios: RCP2.6 (linked to SSP1, SSP2, SSP3), RCP4.5 (linked to SSP1, SSP2, SSP3, SSP5), a medium RCP6.0-SSP2 and RCP8.5-SSP5. The scenarios represent the global coastal mean-sea-level rises between 32 cm and 75 cm until 2100. The DIVA model estimates annually that the number of people flooded in the EU could range from 1.8 million (RCP2.6) to 2.9 million (RCP8.5) by the 2050s and, potentially, 4.7 million (RCP2.6) to 9.6 million (RCP8.5) by the 2080s, if there is no investment in adaptation. This flooding, along with other impacts of sea- level rise such as erosion, leads to high economic costs in the case of no adaptation. The expected damage costs in Europe (EU28) from the combination of climate and socio-economic change are estimated at €135 billion/year to €145 billion/year for the 2050s (mid estimates for RCP2.6 and RCP4.5 respectively), rising to €450 billion/year to €650 billion/year by the 2080s for the same scenarios. These costs include direct impacts. (Lincke et al. 2018)[11]

Vousdoukas et al. (2020) estimated damages from coastal flooding within the JRC PESETA IV project. For current level of coastal protection annual damages will grow to 239 bn Euro per year (0.52% of the GDP) for EU+UK in 2100 under a high emissions scenario (RCP 8.5) and 111 bn € per year (0.24% GDP) in 2100 under a moderate mitigation scenario (RCP 4.5). For mid-century (2050) 10.9 €billion and 14.1 €billion were estimated for RCP4.5 and RCP8.5.

Figure 22 Annual damages and population exposed to coastal flooding for EU and UK at present and in 2100 under two emissions scenarios, with and without adaptation

	Today	High emissions		Moderate mitigation	
		No adapt	Adapt	No adapt	Adapt
Damages (€ billion/year)	1.4	239	23	111	12
People exposed (million/year)	0.1	2.2	0.8	1.4	0.6

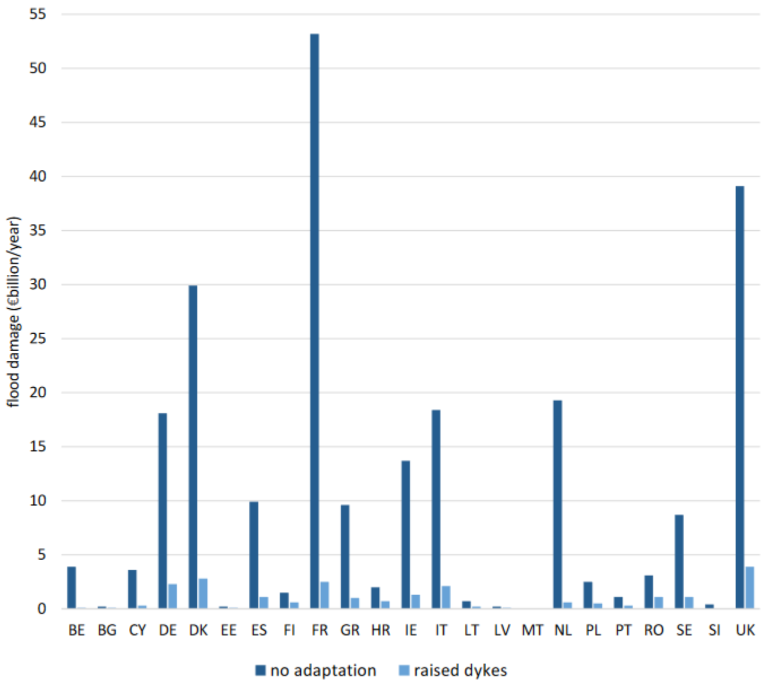
Source: Vousdoukas et al. (2020)

In all EU countries with a coastline, coastal flood risk will increase. The highest absolute increase in coastal flood impacts without adaptation in 2100 are estimated for France, the UK, Italy and Denmark. For some countries, coastal flood losses could amount to a considerable proportion of their GDP, especially under the RCP 8.5 for 2100, e.g. in Cyprus (4.9%), Greece (3.2%), Denmark (2.5%), Ireland (1.8%) and Croatia (1.8%).

With adaptation activities the annual damages are reduced to 23 bn € for high emissions and 12 bn € for moderate mitigation in 2100. For adaptation, dykes are raised to a level of protection that maximises their economic benefit (avoided flooding) relative to their cost. The estimated average annual cost of adaptation for the EU and UK over the period 2020-2100 is 1.9 bn €/year in the high emissions scenario and 1.3 bn €/year in the mitigation scenario.

With adaptation (raised dykes), flood damages are reduced substantially in the different countries, see the estimated flood damages per country without and with adaptation in the following figure. Costs for adaptation activities are linked to the value of assets and the coastline length which needs additional protection. The highest adaptation costs are estimated for France (217-314 €million/year), Germany (145-243 €million/year), Italy (137-189 €million/year), and Denmark (145-243 €million/year).

Figure 23 National annual damages without and with adaptation (for high emissions scenario RCP 8.5 in 2100)



Source: Vousdoukas et al. (2020)

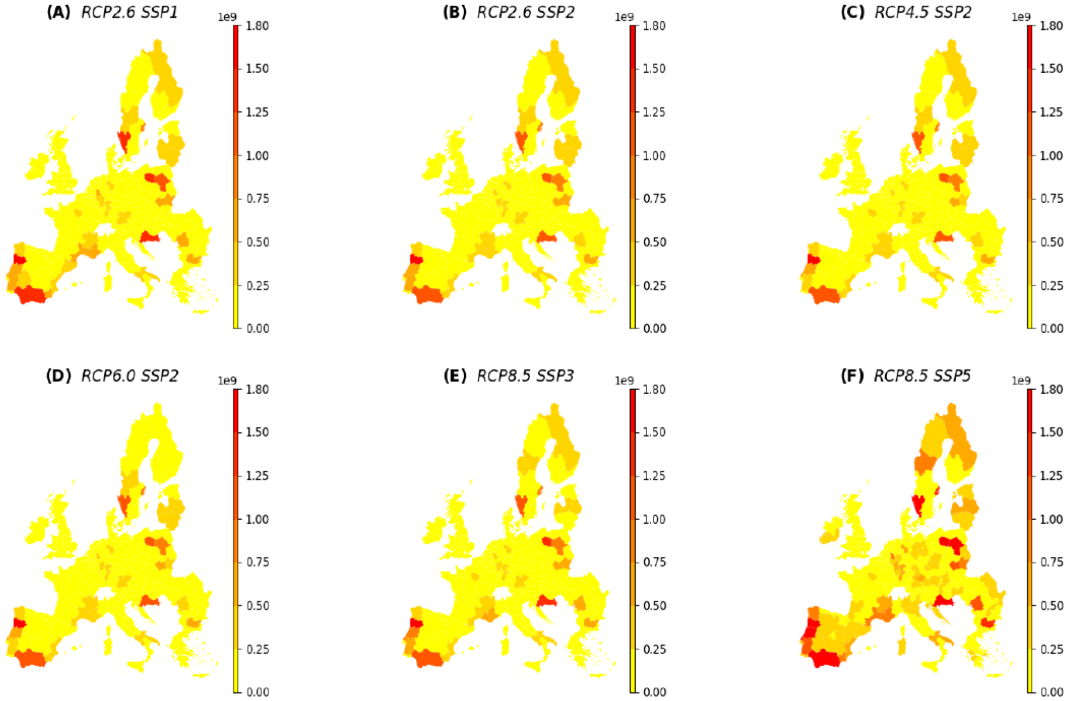
Schinko et al. (2020) estimated annual expected sea-flood cost (in billion USD 2014) in 2050 and 2100 without additional adaptation under the two selected scenarios RCP 2.6 and RCP 4.5 for G20 countries. Sea flood costs for Germany are calculated between 3.6 (RCP2.6) and 5.3 (RCP 4.5) bn USD annually in 2050, for France between 3.2 and 5 bn USD and for Italy between 1.4 and 2.4 bn USD. In a scenario with adaptation the estimates are lower: Germany 1.1 (RCP 2.6) to 1.4 (RCO 4.5) bn USD per year in 2050, France 1.2 to 1.6 and Italy 1 to 1.6 bn USD per year. The protection costs in the adaptation scenario are calculated 0.28 to 0.37 bn USD annually for Germany, 0.32 to 30.36 for France and 0.1 to 0.13 bn USD per year for Italy. Ridder et al. (2020) estimated sea-flood costs for Belgium based on Schinko et al. (2020) with 0.5 to 0.65 bn Euro per year for 2050, in a scenario without adaptation.

Peric & Grdic (2015) analysed impacts of sea-level rise on national level for Croatia. The developed model calculates the cost of land loss, the cost of relocating people and the cost of protection as a result of future sea level rise by 50 and 88 cm. In case of a 50 cm sea level rise, the total projected costs amount to €7.6 bn and in the 88 cm sea level rise scenario, the total projected costs will amount to €9.6 bn, both are linked to annual protection costs of €1.3 Mio.

COACCH project has used the GLOFRIS model to assess the potential direct impacts of climate change **on river floods in Europe**. The annual expected damage costs (EAD) in Europe with climate change are projected to increase to approximately €12 billion by the 2050s (for the mid estimates for both RCP2.6 and RCP4.5), rising to approximately €20 billion by the 2080s. These estimates include the combined effects of climate and socio-economic change, and are based on current prices, with no discounting. It should be noted that the damages reported here only include direct physical losses and can be discussed as rather conservative. (Lincke et al. 2018)

For 2050, the projected average EAD across regions under RCP4.5-SSP2 is €123 million per year, which remains relatively constant for RCP 2.6 and RCP 4.5 scenarios (panels A to E). The difference becomes larger for high-end carbon emission scenario RCP8.5 in combination with a socio-economic scenario characterized by high economic growth (SSP5) (panel F). Under this scenario, the average EAD across NUTS2 regions is €252 million. The lowest observed EAD per region is €43,000 and the highest is €3.6 billion, therefore the differences between high- and low-risk regions becomes larger. Reason is the high growth of economic assets under this scenario, which is assumed to occur evenly across regions.

Figure 24 Expected annual damage estimates for 2050 for several RCP-SSP combinations



Source: Lincke et al. (2018)

Alfieri et al. (2018) compare estimates of river flood risk in Europe from three recent case studies, assuming global warming scenarios of 1.5, 2, and 3°C from pre-industrial levels. The study Alfieri et al. (2015) is a continental study mentioned as JRC-EU in the report, Alfieri et al. (2017) as JRC-GL (Global assessment) and Dottori et al. (2018) as ISIMIP (Global assessment). The average of the three case studies are described in the table below as "Super-ensemble". The reference period 1976-2005 is used as baseline and is for all three assessments based on model simulations.

Figure 25 Expected annual damage from the three case studies at specific warming level

Expected Damage	Baseline (B€/year)	1.5 °C Total (B€/year)	1.5 °C Relative Change (%)	2 °C Total (B€/year)	2 °C Relative Change (%)	3 °C Total (B€/year)	3 °C Relative Change (%)
JRC-EU	5	11	116	13	137	14	173
JRC-GL	3	8	188	9	243	11	331
ISIMIP	13	26	97	23	72	26	97
Super-ensemble	7	15	113	15	110	17	145

Source: Alfieri et al. (2018).

The results by Alfieri et al. (2018) show average relative changes in flood impacts of the three ensembles (super-ensemble) rise from 113% at 1.5°C, up to 145% at 3°C. These results show an initial growth of impacts at 1.5°C and then a further stabilization for higher specific warming levels, e.g. linked to a substantial reduction in mean precipitation in Southern Europe.

The country-specific analysis expected flood damages across all three case studies and the three specific warming levels (1.5, 2, 3°C). The results show that all models predict consistently a relevant increase in future flood impacts for Western and Central Europe. JRC-GL predicts large impacts for Slovak Republic, Hungary, and Poland, for which ISIMI predicts smaller amounts. High impacts can be seen for Ireland, Slovenia, Germany, Austria, Croatia, Belgium and France.

PESETA IV projected **drought losses** covering the sectors: agriculture, energy, water supply, shipping transport and building & infrastructure (based on soil subsidence). Drought damages for 2050 for a 1.5 and 2°C warming scenario (under future socioeconomic conditions) are estimated with 12.4 and 15.5 bn € per year. Compared to the baseline (1981-2010) this results in an increase of drought damages of 37 and 70% for 1.5 and 2°C warming scenario. The strongest increase in absolute drought losses is projected for southern and western parts of Europe (see Figure 26). (Cammalleri et al. 2020)

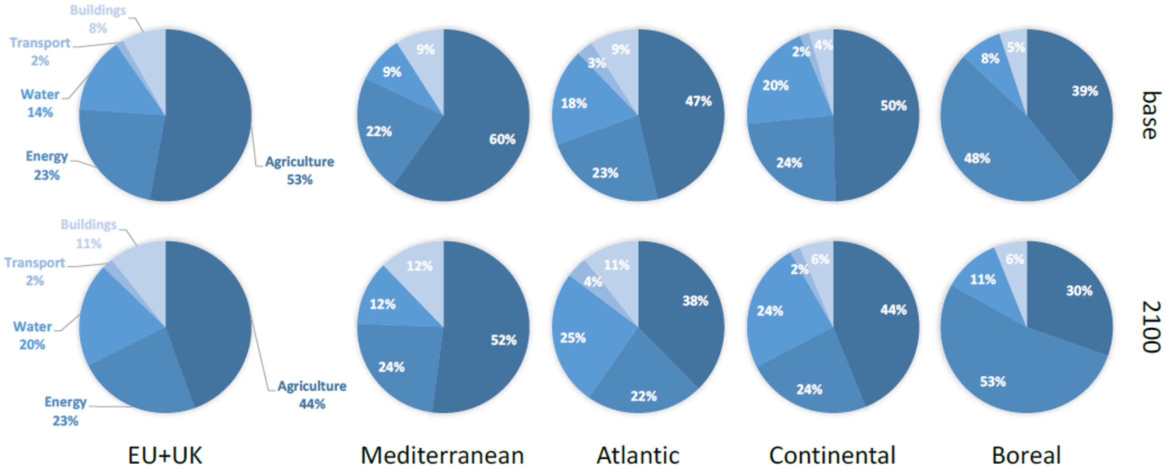
Figure 26 Projected expected annual damage (in mio. €) for the baseline and the global warming levels for EU and UK aggregated for European sub-regions12. (for static economy and socioeconomic conditions in 2050 and 2100)

	Base economy				Economy 2050		Economy 2100		
Region	**base**	**1.5°C**	**2.0°C**	**3.0°C**	**1.5°C**	**2.0°C**	**1.5°C**	**2.0°C**	**3.0°C**
Mediterranean	3,627	5,029	5,888	7,866	6,072	7,087	11,603	13,523	18,096
Atlantic	2,546	2,480	4,188	6,947	3,348	5,561	7,750	12,811	21,351
Continental	2,590	2,079	2,066	2,383	2,803	2,776	5,076	5,013	5,758
Boreal	285	97	38	57	131	51	294	110	174
EU+UK	9,048	9,685	12,181	17,254	12,354	15,475	24,723	31,457	45,380

Source: Cammalleri et al. (2020).

Drought losses are estimated highest for the agriculture, public water supply and energy sector. The impacts in the shipping transport sector are limited compared to the other sectors but could have relevant regional effects. Infrastructures could increasingly be impacted by damages from drought-induced soil subsidence (see Figure 27). (Cammalleri et al. 2020)

Figure 27 Share of drought losses by economic sector (agriculture, energy, water supply, infrastructure & building, transport) for EU+UK and for European sub-regions (Baseline = 1981-2010)



Source: Cammalleri et al. (2020).

Also the effects of **windstorms** are estimated by PESETA IV. During the last decades, Europe was impacted by a number of severe windstorms resulting in human fatalities and injuries, damage to roads, power plants, the agriculture sector, forests, infrastructure, and private properties. Currently highest absolute losses are seen in Germany with 850 million € per year, France with 680 million € per year and Italy with 540 million. € annually, and with relative high losses compared to their size of economy high in Bulgaria, Estonia Latvia, Lithuania and Slovenia (0.08-0.07% of GDP). Climate model projections suggest small changes in wind hazard with global warming, with non-significant trend – An increase of maximum wind speeds is more likely to be reduced over 16% of land area in EU and increase over 10% of land areas (incl. Alpine area) and remain relatively stable over the rest of Europe. Southern-Europe shows the largest share of the area with an increase in wind extremes. Therefore, economic impacts due to windstorms are quite stable for different warming levels (Figure 28, left panel). The expected absolute losses are higher if future socioeconomic change is taken into account, because of the growth of the size of the economy and higher values of the exposed assets (Figure 28, right panel). An increase for windstorm annual losses is projected with almost 7 bn. € per year for 1.5 and 2°C global warming by 2050. (Spinoni et al. 2020)

Figure 28 Wind losses for the EU and UK assuming that current socioeconomic conditions continue into the future (left panel) and according to changing socioeconomic conditions (right panel)

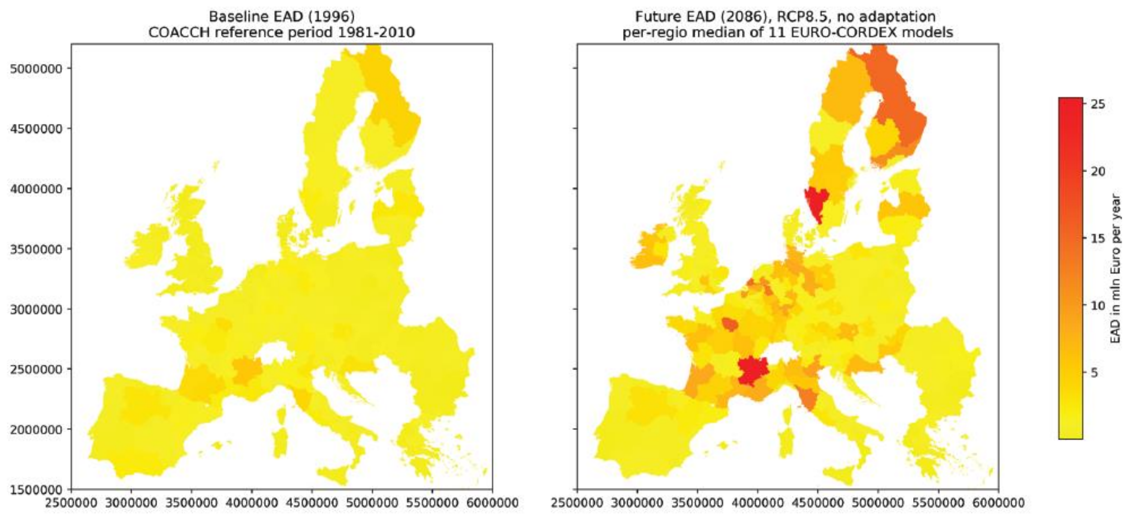
Changing socioeconomic conditions				Current conditions			
base	1.5˚C	2.0˚C	3.0˚C	base	1.5˚C	2.0˚C	3.0˚C
Wind losses (€ billion)				Wind losses (€ billion)			
4.6	11.3	11.4	11.4	4.6	4.5	4.6	4.6
Wind losses (% of GDP)				Wind losses (% of GDP)			
0.04	0.03	0.03	0.03	0.04	0.04	0.04	0.04

Source: Spinoni et al. (2020)

Expected annual damage was calculated for direct damage to **road infrastructure from river flooding**. 954 mio to 1147 mio € annually by 2050 are estimated for RCP 4.5 and RCP 8.5 for direct climate impacts on transport, without adaptation. For 2080 1,5 – 2.3 bn per year are estimated for these scenarios. With adaptation, a part of increase in damage can be avoided, but requires large investment costs mainly to wide-scale improvement of the river flood protection infrastructure. With adaptation, the expected annual flood damages are estimated with 392 mio € for RCP 4.5 and 502 € for RCP 8.5. The research team summarizes that road damage only contributes a small percentage (2.3 %) to the total river flood damage observed in the European Union (€0.205 billion of €8.8 billion annually). (Lincke et al. 2018)

The figure below shows the distribution across EU regions. It shows high risks for Germany, France and Italy.

Figure 29 Expected annual damage (EAD) to road infrastructure in 1996 and 2086



Source: Lincke et al. (2018)

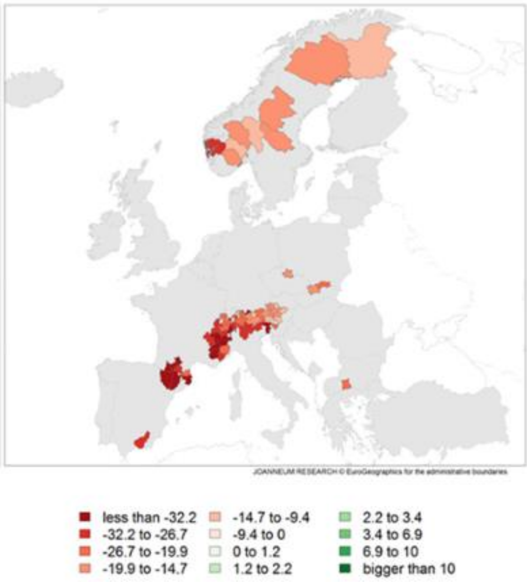
TopDAD project estimated cost of traffic disruptions as a result of extreme precipitation. ToPDAD assessed the economic impact of urban downpour for Switzerland using the MatSim traffic model. They analysed one-day disturbances affecting passenger transport. The Swiss estimates are upscaled for the EU, resulting in additional costs between 0.3 billion to 1.5 billion € compared to traffic flows without disruption. (TopDAD 2015, Perrels et al. 2015)

Another TopDAD case study analysed an extreme rain event and the resulting damage in the greater London-area. It focused on a one-hundred year pluvial flooding and evaluates the effects of different adaptation strategies. It considers longer disruptions. The projected costs to such flood events for London areas would be up to almost 40 bn. € for RCP 8.5 during the period 2015-2050 and more than 50 bn € for RCP 8.5 for the period 2050-2100. Physical measures could reduce risk of flooding by about 40%. Combining physical measures with a less costly priority recovery fund showed only small additional benefits, compared to the physical measures only. (TopDAD 2015, Perrels et al. 2015)

The WEATHER project assessed total costs from extreme weather events on transport infrastructure. It includes Heatwaves, Snow/frost days, Floods, storms and alpine hazards/landslides. Based on the EMDAT database the authors summarized the historical frequencies of the extreme events. Different scenarios have been used to analyse the losses: (1) Increase in frequencies: 1%, 5%, 10%, 100%, (2) Increase in intensity:10%, (3) Extreme scenario: combination of 10% increase in frequency and intensity, combination of 100% increase in frequency and 10% increase in intensity. Przyluski et al. (2011) includes more information on how the information was operationalized for the economic-wide assessment, e.g. assumptions on capital loss. The estimation was done for eight different climate zones: Scandinavia (SC), the British Islands (BE), France (FR), Mid Europe (ME), Eastern Europe (EA), the Alps (AL), the Iberian Peninsula (IP), and the Mediterranean Area (ME). Przyluski et al. (2011) calculated 2.5 billion/year € for 1998-2010, and by 2040-2050 an increase of 20% is expected. Road transport comprises the highest share, estimated at 1.8 million/year € today, with an increase of 7% estimated for 2040-2050. 306 million/year € is assessed for the rail sector (for 2010), a significant increase of 72% is expected for the years 2040-2050. (Przyluski et al. 2011)

Climate change will affect **ski tourism as well as beach tourism**. Studies summarize that tourism expenditures are reallocated spatially and sectoral, reductions are compensated with increased expenditures in other regions or to free time activities in the home region. The following figure includes a spatial representation of number of overnight stays for different ski tourism regions in Europe. The figures shows that regions in the south of the Alps are more affected by climate change than regions in the middle or north of the Alps. Losses seem the highest for France and may exceed 40% of the overnight stays. (Perrels et al. 2015)

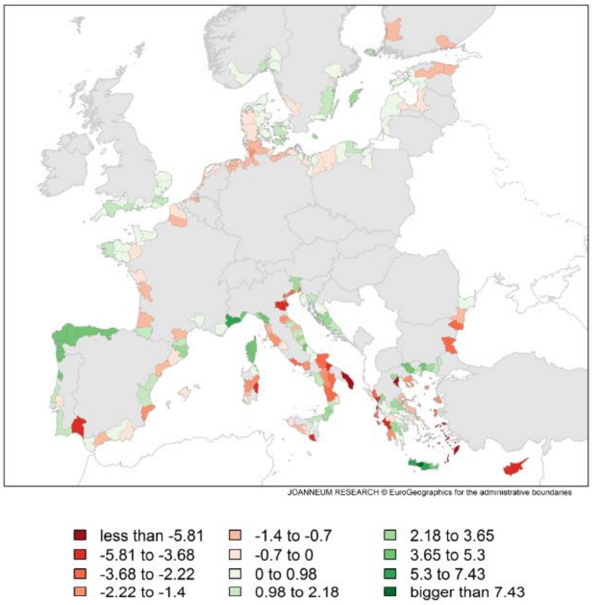
Figure 30 Change in winter overnight stays in [%] (2035-2065 vs. baseline) in skiing dominated regions for RCP4.5/SSP4: tourists adapt in time, place and/or activity



Source: Perrels et al. (2015)

For beach tourism regions, TopDAD also estimated climate effects on overnight stays. The map below shows the impacts without adaptation. Adaptation activities such as providing support to cope with heat e.g. indoor air conditioning can reduce the effects slightly. While the Mediterranean and northern Europe loose overnight stays, northern Spain, France and the UK gain overnight stays. Also compared to the impacts on ski-tourism regions, estimates decrease much less, e.g. because beach tourism activities are moved in time to the shoulder season, but the same destinations are frequented. Estimated regional revenues show these differences as well: ski tourism with up to 50% decrease of regional revenues and beach tourism with estimated change between a decrease of 4% and an increase of 7 % for revenues per regions (Perrels et al. 2015).

Figure 31 Changes in summer overnight stays in [%] (2035-2065 vs. baseline) in beach dominated areas for RCP8.5/SSP5



Source: Perrels et al. (2015)

The regional PESETA II study (Barrios & Ibañez Rivas, 2013) reviewed the economic impacts of climate change to the EU's tourism sector to 2100 focusing on summer tourism and using a travel cost approach and hedonic valuation of recreational demand and related amenities. The study found that climate change would decrease tourism revenues by 0.31% to 0.45% of GDP per year in southern Europe. Other EU countries, in particular the British Isles and northern European regions, are expected to see positive tourism impacts under climate change. Barrios & Ibañez Rivas (2013) estimated an annual increase of 0.29% of GDP for northern European regions and a gain of 0.32% for the British Isles in 2100. Summer tourism in central European regions shows more moderate changes, varying from losses of 0.16% of GDP to gains of 0.13% of GDP in 2100 (Barrios & Ibañez Rivas, 2013).

Further national studies on winter tourism look into alpine skiing in Sweden, Moen & Fredman (2007) estimated economic losses in the range of 946.5 to 1755.3 million SEK per year (91-169 million €/year) based on a static and linear relationship between projected future days with snowfall, ski-season lengths, and visitor expenditures. Bigano & Bosello (2007) applied different climate change scenarios and related decreases in snow cover, finding the expected average reduction in income from winter tourism to be 10.2% in 2030 and 10.8% in 2090 for Italy.

SOCLIMPACT project analysed climate impacts on tourism for European islands due to sea level rise and heatwaves. The work shows that touristic expenditures can drop quite substantially by large amounts, with an average of -13.4% (with ranges across islands from -7.2% to -25.1%) in the RCP2.6 climatic scenario and an average of -22.3% (with ranges across islands from -12.3% to -41.1%) in the RCP8.5 scenario compared to a baseline scenario (no climate change). This has damaging effects on the islandic economies, especially for the tourism-dependent islands. The team estimated with the GEM-E3 model cumulative GDP losses over the 2040-2100 period could be on average 1.2% in the RCP2.6 scenario and 3.2% in the RCP8.5 scenario due to less tourism arrivals. For islands with high GDP-share of tourism, GDP losses of up to 6.9% are estimated, e.g. for Balearic islands, Crete. (Vrontisi et al. 2021)

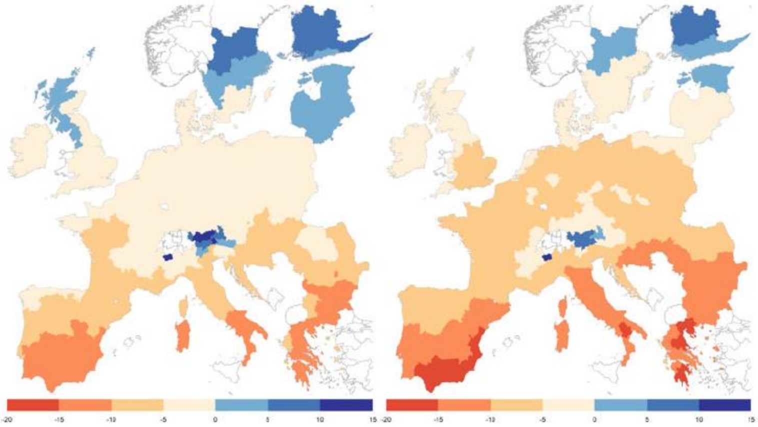
The TopDAD project reviewed studies on impacts of climate change on health and **labour productivity**. The available studies are rich for impacts of heat and heat waves in Europe. Less studies are discussing cold and the impacts of changes in humidity are unclear. A meta-analysis of studies of labor productivity in office environments concluded that increasing temperatures from 23 to 30 °C reduces productivity by about 9%, i.e. 1.3% per 1°C. (Seppanen et al. 2006, van Oort et al. 2015). A reduction of the work performance resulting in an estimated output loss of between 0.12 % and 0.48 % of GDP is estimated for Germany (Hübler et al. 2008).

Future changes in labour productivity under climate change were analyzed in different projects. They find non-linear impacts of temperature and total precipitation on productivity for all the industry and services sectors considered, except for manufacturing. The optimal temperature for the industry and construction sectors are comparatively lower than services, as the workers in this sector are more exposed to outside temperatures. Therefore, the service sector experiences lower impacts. Furthermore, the authors conclude that based on the estimations there is significant negative direct impact of temperature shock and indirect impact of heatwaves (based on Warm Spell Duration Index) on both industrial and construction labour productivity. (Schleypen et al. 2021)

The Lancet Countdown on Health and climate change (van Daalen et al. 2022) estimated optimal annual mean temperature beyond which labour productivity in Europe declines has been estimated to be 9.3°C (95% CI: 7.9°C to 10.6°C) for high-exposure work conditions (in agriculture, forestry, mining and quarrying, and construction) (van Daalen et al. 2022). In these four high-exposure sectors, the increased temperature caused a 0.98% decline in the number of working hours in the period 2016-2019, compared with the reference period of 1965-1994. The largest declines in working hours are estimated to be in Cyprus, the South Aegean in Greece and the Balearic Islands in Spain. Northern European countries show slight increase in labour productivity (van Daalen et al. 2022).

The COACCH project estimated that climate change could reduce industrial labour productivity by 4.3% and construction sector labour productivity by 6.6% by the late century (RCP 8.5, by 2070, in EU). For both industrial and construction productivity, the highest declines will occur in Greece (Peloponnese, Thessaly, and Attica), Italy (Puglia), Spain (Region of Murcia and Andalusia), and Portugal (Algarve) while some regions in Austria, Estonia, Finland, Sweden, and the north-eastern and north-western Italian regions will gain. Under a more moderate warming scenario of RCP4.5, industrial and construction sector productivity will decline by 2.7% and 3.1% (2070). (Schleypen et al. 2019)[13]

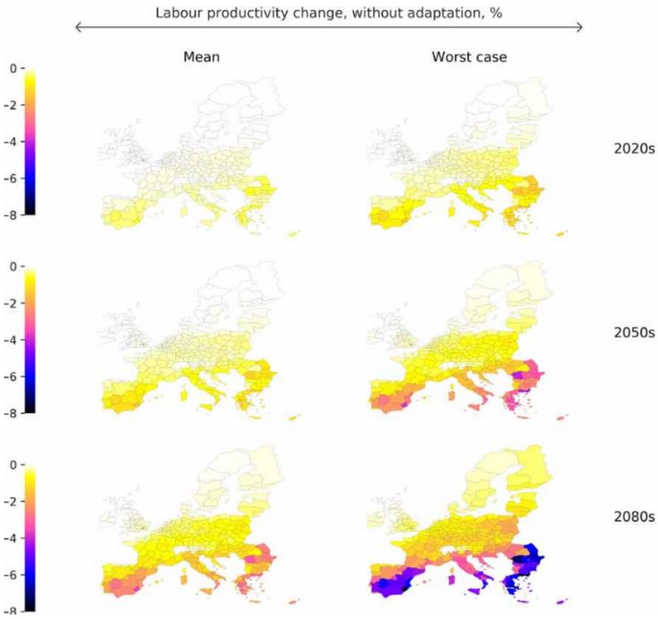
Figure 32 Future impact under RCP8.5 on industrial (left-panel) and construction productivity (right-panel) by 2070.



Source: Schleypen et al. (2019)

The International Labour Organization (ILO 2019) estimated that 0.03% of total working hours could be lost in the year 2030 due to heat stress in Europe and Central Asia, 0.03%. In the worst-case scenario, European labour productivity could be decreased by around 0.3%, 0.8% and 1.6% for 2020s, 2050s and 2080. For Southern Europe the highest losses were indicated (Szewczyk et al. 2021). Dasgupta et al. (2021) estimate consequences on effective labour understood as working hours and output during these working hours. In southern Europe it is expected to decrease by up to 13.6% under 1.5°C temperature increase (2030-2050), 18.2%s under 2.0°C of temperature increase (2050-2070) and 28.5% under 3.0°C temperature increase (2070-2090) (Dasgupta et al. 2021).

Figure 33 Labour productivity for warming levels, without adaptation



Source: Szewczyk et al. 2021

TopDAD reviewed studies looking at mortality and economic cost of extreme events. Most studies of **health impacts** in the wake of extreme events relate to flooding and storms, with increase in deaths, trauma and infectious diseases. Landslides have similar impacts. For example, Hurricane Katrina in the US caused around 1800 deaths in 2005. (van Oort et al. 2015) In a scoping assessment of the health costs of climate change from coastal flooding in the EU, focusing on mental health problems such as depression, costs are estimated at up to 1.5 bn € per year by the period 2071-2100 (Watkiss and Hunt 2012) However, the highest number of deaths are estimated for extreme temperature e.g. with 72,210 lives lost during the European heatwave in 2003. (van Oort et al. 2015)

Current trends on mortality due to heatwaves are estimated for 2000-2020 by van Daalen et al. (2022). They estimate an overall average increase of 15.1 annual deaths per million inhabitants per decade for the general population. Especially Portugal and Spain show the highest increase with average increase of 30.6 annual deaths per million per decade in Spain.

Naumann et al. (2020) discuss an increased mortality from extreme heat without adaptation for the EU and UK. They estimate 90,000 deaths per year for 2100 and a 3°C global warming scenario and 30,000 deaths annually for 1.5°C global warming scenario.

COACCH has assessed the impact of climate change on heat-related mortality in monetary terms. This has included an analysis of the urban heat island effect. When this is included, the spatial distribution of temperature projections in Europe changes, with rising risks for highly populated cities, even for low warming scenarios. For EU28, the estimated total number of annual excess deaths from heat is estimated at 85,000 (RCP2.6), 145,000 (RCP4.5) and 300,000 (RCP8.5) per year by the end of the century. Economic costs of European heat-wave-related health impacts for various RCP scenarios (no adaptation or acclimatization) are estimated with 102 bn/year for RCP2.6 up to 176 bn/year for RCP8.5 by 2050 and up to 313 bn/year for RCP8.5 by end of century (2080). Is has to be mentioned that the monetary values derived are based on the full Value of Statistical Life estimates. The use of a Value of a Life Year Lost, combined with estimates of average life expectancy losses leads to significantly lower total economic costs from heat events, lowering the values by over an order of magnitude (Ščasný et al. 2020).

Climate impacts on **energy supply and production** are estimated by PESETA IV. For a static power system for the year 2020, hydropower production is expected to increase in the total EU (0.9% with 1.5°C global warming (median value); 2.3% and 3.2% with 2 and 3°C warming). The total increase in hydropower is due to development in the Northern EU countries, which show an increase of water availability. It replaces other energy sources this leads to annual economic benefits in northern Europe of around 1.3 €billion (2015 values) with 3°C warming. Due to a reduction in water availability hydro and nuclear production are reduced in southern Europe, especially in summer. Thermal plants substitute other energy sources there, production costs in southern Europe increase by around 0.9 €billion per year (2015 values) with 3°C warming (static power system of 2020). Nuclear production would decrease for total EU by 0.5% with 1.5°C warming and by 1.8% in a 3°C warming static scenario. Wind and solar plants are barely impacted. (Despres & Adamovic 2020)[15]

TopDAD looked further into nuclear power production, especially for France. The 2003 and 2006 heatwaves in France led to a reduction of supply by 10-15%. Under this scenario losses are estimated between 200 and 300 mio € annually (Perrels et al. 2015). COACCH has modelled the projected changes in hydropower production in Europe due to drought events. The highest declines under a RCP4.5 scenario are seen in Finland (6.3%), Estonia (6.2%) and Serbia (5.9%) by 2050s. For 2070 reductions of 10% are calculated for Slovenia, Croatia and Austria. For a RCP8.5 scenario in 2070 hydropower generation could be reduced by 13% in Serbia, Romania, Hungary and Sweden. (Schleypen et al. 2019).

Schleypen et al. (2019) also discuss changes in energy demand for different energy carriers and sectors. The projection of hot days and cold days is included. The highest increase up to additional

30 hot days by 2070 are expected for Greece and Cyprus (average increase for RCP4.5 and 8.5). The number of cold days are reduced in some regions also by 30 cold days per year in 2070, e.g. in Italy, Portugal and Spain.

The most significant increases in energy demand are expected in the industrial sector (11.4%) from natural gas and the service sector from electricity (40.1%) under RCP8.5 by 2070. Under a RCP4.5 scenario, these increases are projected to be 4.9% and 20.6%. Energy demand in the residential sector is projected to decline significantly from natural gas (-27.5%) and petroleum (-41.5%) with only demand from electricity increasing (3.8%) under RCP8.5 by 2070. In the case of the agricultural sector, energy demand from electricity is projected to increase by 2% 2070. A spatial analysis for NUTS2 regions was implemented showing the highest increase in energy demand due to cooling needs in the NUTS-2 regions of Thessaly (Greece), Central Macedonia (Greece), Andalusia (Spain), and Yugoiztochen (Southeastern Belgium). A decline in heating demand leads to highest estimated in the residential sectors are South Aegean (Greece), Algarve (Portugal), and Ceuta (Spain). (Schleypen et al. 2019).

Figure 34 Percentage change in climate-related final energy demand by 2050 and 2070 under RCP4.5 and RCP8.5

		RCP 4.5		RCP 8.5	
	Sector	**2030 - 2050**	**2050 - 2070**	**2030 - 2050**	**2050 - 2070**
Agriculture	Electricity	0.6	1.0	0.8	2.0
	Natural gas	-	-	-	-
	Petroleum	-	-	-	-
Industry	Electricity	0.6	1.0	0.8	2.1
	Natural gas	2.7	4.9	3.8	11.4
	Petroleum	-	-	-	-
Residential	Electricity	1.1	1.8	1.4	3.8
	Natural gas	-25.9	-33.5	-27.5	-41.5
	Petroleum	-23.7	-30.8	-25.1	-38.3
Commercial	Electricity	13.1	20.6	15.9	40.1
	Natural gas	-	-	-	-
	Petroleum	-14.4	-19.1	-15.4	-24.4

Source: Schleypen et al. (2019)

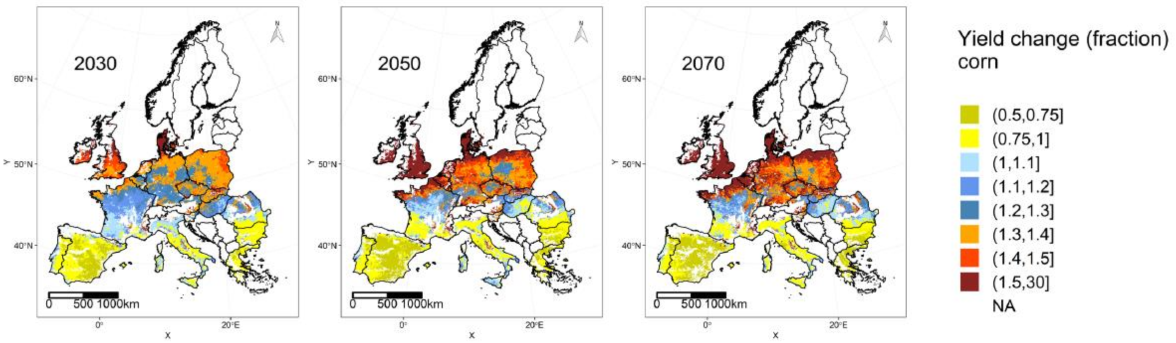
Fernando et al. (2021) estimated economic shocks due to climate events as deviation of sector outputs for four climate scenarios. They analysed different world regions including Europe, but did not differentiate further. The highest impacts are estimated for electricity delivery (-5.13% reduction in sector output in RCP8.5, 2021-2050, compared to current events) and agriculture & forestry (-6.13%).

SOCLIMPACT estimated change of energy demand for European islands especially due to increased cooling demand and desalination (linked to heatwaves and low precipitation). Desalination could result in an average increase of electricity demand by 10% (with ranges across islands from 1% to 40%). While investments increase in order to meet higher electricity demand, higher prices bring GDP losses. GEM-E3 model results indicate that the impact of climate change on electricity demand can bring average cumulative GDP losses over the 2040-2100 period equal to 0.6% of the baseline in the RCP2.6 scenario and 1.2% in the RCP8.5 scenario. (Vrontisi et al. 2021)

Results of the COACCH project show highest negative impacts on both **crop yields and the agricultural sector** in general, are found under a high emission RCP 8.5 scenario when CO2 fertilisation is not considered. GLOBIOM model estimates that under this scenario, the economic costs of agriculture show losses for the producers in SSP2 scenario in the order of 906 mio € for arable production and 831 mio € for the agricultural sector in 2050 (compared to no climate change). These estimates consider the fact that the negative impacts of climate change are more profound in the rest of the world compared to Europe, leading to a relative improvement in Europe's export position, but also increasing pressure on European resources such as land and water. (Boere et al. 2019).

Change in crop productivity estimated for winter wheat and corn shows similar spatial pattern: more negative yield changes in the South of Europe, and more positive yield changes in the North of Europe. Especially Southern Spain show negative impacts across crops, an effect that is especially in the case of winter wheat further amplified with time. Winter wheat indeed shows slightly positive changes of around 10% yield increases in the majority of the European continent throughout the 2030, 2050 and 2070 time-period. Corn on the other hand, shows a largely diverging pattern between the North and the South of Europe, with up to 50% yield losses in the South (see Figure 35). (Boere et al. 2019).

Figure 35 Yield change due to climate for corn productivity under RCP4.5 (HadGEM-ES)



Source: Boere et al. (2019).

Fernando et al. (2021) estimated agricultural productivity's sensitivity to future extreme climate shocks for Europe. The authors estimated a reduction of agricultural productivity due to extreme climate shocks by: droughts -1.96%, extreme temperature -1.89, floods -0.36%, storms 0.22%, wildfires -2.70%.

Gouel (2022) estimated welfare changes for agricultural production due to climate change. For Europe in general estimate show up to a -0.18% welfare loss (change of GDP) for a production function approach for RCP8.5 in 2080s (compared to current climate conditions). The author estimates for some European countries welfare losses, e.g. for The Netherlands up to -0.738% of GDP, other countries show small gains such as France with 0.05% of GDP.

Agriculture yield changes are also analysed for a number of crops in the PESETA IV project. The results show that grain maize is projected to be the most affected crop by climate change in Europe. Under fully irrigated conditions, substantial yield reductions are estimated for most producing countries, being more severe in southern Europe in all scenarios. For the 2 °C warming conditions, northern Europe is projected to experience mean yield decreases ranging from -1% to -14%; while larger decreases of -4% to -22% are projected for southern Europe. Positive changes are projected in a few regions of Northern Europe, e.g. 5% yield gains around discussed for the Netherlands and Lithuania in 2050s. Climate change could further restrict the water available for irrigation. Under an extreme assumption of no irrigation in the future, severe declines in grain maize yield are projected. Under rain-fed conditions, yield decreases of larger than 23% could be experienced in all the EU countries, with up to 80% decrease in countries such as Portugal, Bulgaria, Greece and Spain. For wheat yield changes the uncertainties are larger, but the most models show yield increases for northern Europe around 2050 from 5% to 16% (RCP 8.5 scenario). For southern Europe yield reductions of up to -49% by 2050 are projected. Crop production impacts with market adjustment effects are calculated as well. Increasing crop prices due to climate change outside of Europe will lead to changes in EU farmers' management practices (e.g. input use per unit of land) which in the end causes European yields to readjust. With market adjustments, in southern Europe there is a 3% increase in grain maize and a 2% increase in wheat production. (Hristov et al. 2020) In PESETA IV, drought damages on agriculture are estimated by Cammalleri et al. (2020) (see figures above).

The COACCH project used GLOBIOM model estimates that the costs of climate change for **forest production**, related to the loss of biomass, amount to 62 million Euros in 2050 and 11.2 billion Euros in 2070 (under RCP8.5 and without CO2 fertilization) due to increase temperature and less precipitation. RCP2.6 is providing mostly positive impacts on Europe and RCP8.5 providing mostly negative impacts on Europe towards the medium- to long term. Especially in the short-term, the Northern part of Europe benefits by experiencing an increase in the annual forest increment. This effect remains positive but fades out over the time-horizon. With time, and with an increase in the RCP, the Southern part of Europe is experiencing a decrease of the mean annual growth. Models estimate that swanwood and woodpulp production will decrease by -8.55 and -12.99 for RCP8.5 scenario in 2070 (Boere et al. 2019)17. Damages by forest fires are currently affecting more than half a million hectares each year in Europe, with estimated annual economic damages of €1.5 billion (San-Miguel-Ayanz et al. 2010). Boere et al. (2019) estimate an average of burned forest area in Europe. Average percentage increase amount to between 11% for a RCP2.6 scenario in 2040-2059 up to 140% by 2080-2099 in a RCP8.5 scenario compared to 2009-2018. The areas are estimated to be Portugal, Spain, South of France and Greece.

PESETA IV analysed forest vulnerability over the period 2000-2017. The results show large differences across Europe and for different types of events. Vulnerability is highest for windstorms with a biomass loss of 38% (in case of an event biomass is reduced in average by 38% in the exposed area), followed by forest fires (24%) and insect outbreaks (21%). But large regional differences are described: higher vulnerability values in northern and Mediterranean countries in general and especially for windstorms in north-western Scandinavian Peninsula, northern British Islands and Iberian Peninsula. (Forzieri et al. 2020)

Boere et al. (2019) also estimate **fish productivity** for large marine ecosystems. Greenland Sea, Barents Sea, Norwegian Sea and Baltic Sea experience higher productivity under warming, but show declining rates under high warming conditions. Mediterranean, Iberian Coastal, North Sea, and Canary Current see a rather immediate decline in productivity under global warming. According to the two models used, the range of losses in marine catches by mid-century could be for mid-latitude regions around 30% under RCP 8.5 compared to 2000. According to the projections, the combined capture and aquaculture sector in the EU plus UK stands to incur production losses of 1-2 billion EUR. The losses in the aquaculture sector are projected to be much smaller, but still significant, due to the much higher average value of the typical EU aquaculture product. (lowest lost value in RCP 2.6 scenario: 929 mio. € for capture fisheries and 72 mio € for aquaculture for the year 2050, highest lost value in RCP8.5 scenario: 1,296 mio. € for capture fisheries and 124 mio € for aquaculture for the year 2050). The most serious impacts are expected for Denmark, Spain, France, and the UK.

Climate impacts on **natural systems** are projected to have important economic effects. The IPCC's latest report on climate impacts, adaptation and vulnerability specifically highlights: biodiversity loss, ecosystem structure change, increased tree mortality, increased wildfire, and ecosystem carbon losses as being of important concern. (Parmesan et al. 2022). Barrado et al. (2020)

estimated the loss of tundra habitat for the Alps, Pyrenees and Scandes regions. The loss of tundra habitat, e.g. treeline shifts, can have an important impact on ecosystem functions and its services. The probable shrinkage of habitat for a 2°C warming level is estimated with 50% for the Alps, 91% for the Pyrenees and 61% for the Scandes compared to today.

A World Bank study assessed the economic effect of changes in ecosystem services. Within the EU, the output of sectors that rely directly on ecosystem services (agriculture, livestock, forestry production, and fisheries sectors) could decrease by 5% ($28 billion) by 2030. (World Bank 2021). OECD (2015) used a Willingness-to-pay (WTP) approach to estimate the damages of the loss of ecosystem services to the economy. For all the three groups of OECD countries in Europe (EU large 4, Other OECD EU, Other OECD) analysed, 0.5% of GDP in 2060 is estimated as WTP for RCP6.0, and 1.1% of GDP for RCP8.5.

2.4 Impacts from hazards outside the EU

In a strongly globalised world, Europe is vulnerable to spill-over effects from climate change impacts occurring outside its geographical boundaries. The 2016 report on *Climate change, impacts and vulnerability in Europe*[6], elaborated by the EEA, summarizes the literature available addressing these spill-over effects. It provides a comprehensive overview of the major pathways through which climate impacts in other parts of the world have affected and will affect the EU, including: trade of agricultural commodities, trade of non-agricultural commodities, infrastructure and transport, geopolitical risks, human migrations and finance.

The first channel of impacts on the EU is through trade of agricultural commodities. Impacts of climate events have an effect on the prices of food and feed, which are of great importance to Europe, since it relies to a large extent on imports to meet the domestic demand for food and feed. An example of this was the severe heat wave that occurred in Russia in 2010, which led to the destruction of about 30% of Russia's grain harvest, leading to a global increase in wheat prices of 60 to 80%. A similar situation happened following 6 consecutive years with droughts in Australia which significantly affected the rice production capacity of this country, and led to a 100% increase of the global market price of rice. Given the relatively larger importance of the food sector and the high dependence on food imports from regions outside Europe, the Southern European region is the most susceptible to climate shocks on the market price of agricultural commodities.

The dependency on foreign commodities is not limited to agricultural goods. Europe is also reliant on the imports of other key resources such as metal ores, whose production could be significantly affected by climate change impacts. The floods that hit Thailand in 2011, generating a shortage in the supply of hard drives and an increase in its price, are an example of the potential indirect impacts in Europe. The countries most susceptible to these spill-over effects are small, open and highly developed economies such as the Netherlands. Another factor that could severely affect global trade is related to the shrinkage of the Arctic sea ice. Studies on the accessibility of the Arctic region suggest that this will severely improve throughout the 21st century, which would entail a reduction of 5,500 kilometres and 10 days for shipping routes going from East Asia to Europe. Moreover, new opportunities would arise in the shape of access to new materials and fossil fuels.

Regarding infrastructure and transport, extreme events damaging communication infrastructure like airports, ports, tunnels, roads or pipes can potentially disrupt global trade through shortages in supply. The case of Hurricane Katrina, which partially destructed the New Orleans port and generated a subsequent shortage in the supply of oil and a rise in the global price of oil, illustrates this problematic.

[6] https://climate-adapt.eea.europa.eu/en/metadata/publications/climate-change-impacts-and-vulnerability-in-europe-2016/climate-change-impacts-and-vulnerabilities-2016-thal17001enn.pdf

There is understandable concern that climate change, and especially extreme climate events, could lead to increased geopolitical tensions when occurring in combination with factors such as poverty or economic shocks[7]. The European Commission has acknowledged this risk by including extreme climate events as part of its communication on the EU's approach to external conflicts and crises.

The Mediterranean countries of North Africa and the Middle East are particularly sensitive in this regard. Research suggests that droughts have been one of many drivers of local conflicts that triggered the civil war in Syria[8] [9], which led to the increase of refugee flows towards Europe.

Another channel of the impacts in Europe of extreme climate events happening outside of Europe is through human migration flows. In most cases, climate-related migrations occur within-countries and is temporal. However, past events show that this sort of migration can also be international and permanent, hence transmitting the impacts of climate to those countries that receive the immigrant flow. The situation in North Africa, where precipitation levels are expected to decrease, increasing the risks of drought, and where sea-level rise threatens largely populated areas such as the Nile Delta, is particularly sensitive for Europe. These trends may result in increased migrations towards Europe. A similar situation could happen with climate change impacting the Middle East region.

Finally, climate impacts may generate disruptions in global financial markets, which will have repercussions for the financial flows of various countries. For instance, when the Hurricane Katrina occurred, a substantial amount of the insurance costs fell on the London stock markets[10].

2.5 The economic implications of climate tipping points

A range of studies consider both climate and socio-economic tipping points that may arise as a result of climate change. Climate tipping points are "*conditions beyond which changes in a part of the climate system become self-perpetuating*" which can cause important impacts such as "*substantial sea level rise from collapsing ice sheets, dieback of biodiverse biomes such as the Amazon rainforest or warm-water corals, and carbon release from thawing permafrost*" (Armstrong McKay et al., 2022). Some of the key climatic tipping points established in the literature are summarised in the figure below, as well as the warming threshold at which these tipping points are likely to be crossed.

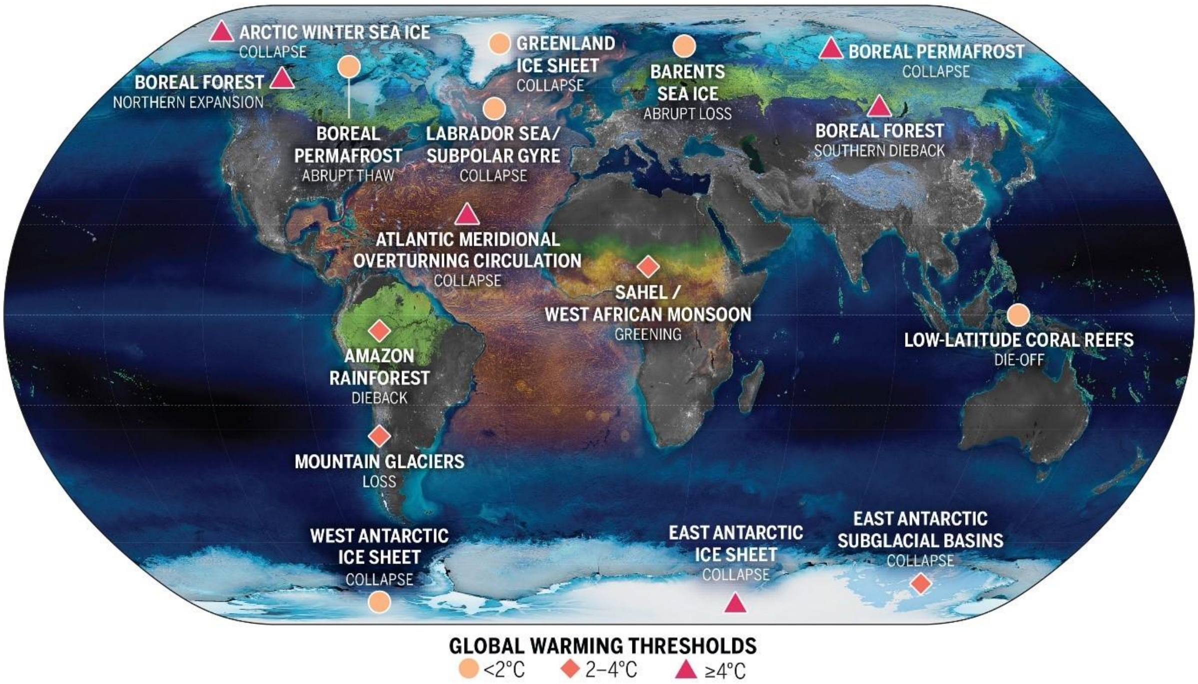
[7] Hsiang, S. M., Burke, M. and Miguel, E., 2013, 'Quantifying the influence of climate on human conflict', Science 341(6151), 1235367 (doi: 10.1126/science.1235367).

[8] Gleick, P. H., 2014, 'Water, drought, climate change, and conflict in Syria', Weather, Climate, and Society 6(3), 331–340 (doi: 10.1175/WCAS-D-13-00059.1).

[9] Kelley, C. P., Mohtadi, S., Cane, M. A., Seager, R. and Kushnir, Y., 2015, 'Climate change in the Fertile Crescent and implications of the recent Syrian drought', Proceedings of the National Academy of Sciences 112(11), 3 241–3 246 (doi: 10.1073/pnas.1421533112).

[10] Nicholls, R. J. and Kebede, A. S., 2012, 'Indirect impacts of coastal climate change and sea-level rise: The UK example', Climate Policy 12(Suppl. 1), S28–S52 (doi: 10.1080/14693062.2012.728792).

Figure 36 The location of climate tipping elements in the cryosphere (blue), biosphere (green), and ocean/atmosphere (orange), and global warming levels at which their tipping points will likely be triggered



Source: Armstrong McKay et al., 2022

While there is a range of studies addressing the climatic and ecological aspect of tipping points, and especially the thresholds at which these will be crossed, there is limited literature on the economic impacts that will emerge. Ecological tipping points, in particular, are especially hard to incorporate into economic risk assessments due to the difficulties associated with ecosystem services valuation (Kopp et al., 2016; Cai et al., 2016). Generally, assessing the climate and economic shocks associated with tipping points is achieved by either: "(1) linking simple climate model scenarios for elements that affect greenhouse gas concentrations or albedo to impact models and (2) applying regional spatial-temporal patterns of climatic changes associated with tipping elements to impact models" (Kopp et al., 2016). This is, however, further complicated by the interactions and feedbacks between various tipping elements, as well as how impacts across different sectors may relate to each other.

Using the PAGE09 integrated assessment model, Hope and Schaefer (2016) calculate the release of carbon dioxide and methane from thawing permafrost to potentially increase the net present value of climate impacts by about $43 trillion (+13%) under an A1B scenario. In another study on thawing permafrost, González-Eguino and Neumann (2016) explore the change in the social cost of carbon, and estimate that the presence of permafrost carbon feedback in the earth's climatic system would reduce the net present value of total welfare by $4.2 trillion between 2010 and 2100.

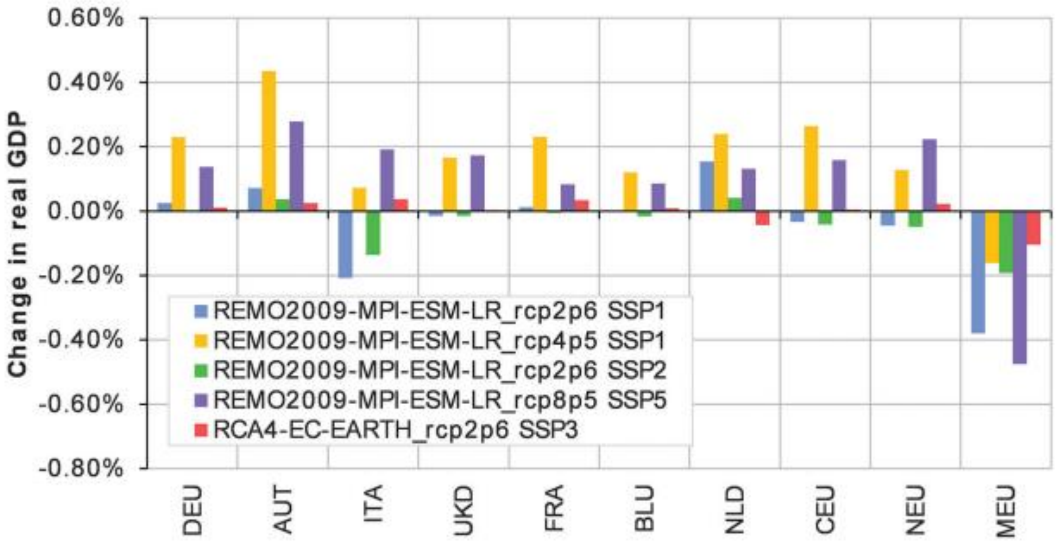
Lemoine and Traeger (2016) explored the "domino effect" associated with tipping points, whereby the occurrence of different tipping points affects the likelihood of other tipping points being crossed. Specifically, they assess the cost of delaying optimal mitigation policy (via a carbon tax) in response to tipping points, noting that a delayed policy response past 2050 until the occurrence of the first tipping point would cost $3.3 trillion. In another study looking at the risk of multiple interacting tipping points, Cai et al. (2016) focused on: the Atlantic Meridional Overturning Circulation (AMOC), disintegration of the Greenland Ice Sheet (GIS), collapse of the West Antarctic Ice Sheet (WAIS), dieback of the Amazon rainforest (AMAZ), and shift to a more persistent El-Niño regime (ENSO).

They assigned these with damages between 5-15% of global GDP, with a combined GDP reduction if all five occur of 38%. However, given the low probability and long-time scales associated with these tipping points, this produces a GDP reduction of only 0.53% by 2100 in the default scenario. Finally, their study also shows an increase in the present social cost of carbon from \$15/tCO_2 to \$116/tCO_2.

The COACCH project assessed a number of climatic and socio-economic tipping points (COACCH, 2021). While climate and ecological tipping points are now well documented and studied, exploring tipping points in the socio-economic domain remains somewhat underexplored. Some of the outcomes of the COACCH study into tipping points are summarized below.

In assessing climate-induced agricultural yield shocks, cropland losses from farmland abandonment could be as high as 7% at the European level. However, there are important regional variations: while there may be positive impacts in many parts of Europe, Southern Europe, especially Spain, Italy, and Greece, show the highest likelihood of passing the tipping point for rural abandonment. In the Mediterranean and South-Eastern European region, changes in cropland availability and yield changes could produce GDP losses of over 0.4% in 2050 (RCP8.5-SSP5).

Figure 37 Changes in real GDP in 2050 due to the combined effect of changed cropland availability and yield changes, relative to a Baseline scenario without climate change (Legend: DEU: Germany; AUT: Austria; ITA: Italy; UKD: United Kingdom; FRA: France; BLU: Belgium and Luxemburg; NLD: Netherlands; CEU: Central Europe; NEU: Northern Europe; MEU: Mediterranean and South-Eastern Europe. Scenarios: Blue: RCP2.6-SSP1; Yellow: RCP4.5-SSP1; Green: RCP2.6-SSP2; Purple: RCP8.5-SSP5; Red: RCP2.6-SSP3)



Source: COACCH, 2021.

COACCH also explored climate change-induced migration, which can be considered a socio-economic tipping point, because at a certain threshold (e.g. temperature increase, sea-level rise), people decide or are forced to move elsewhere. This migration has socio-economic impacts both on the place of origin (e.g., loss of labour force) and the destination (e.g., housing shortages). Overall, migration is expected to increase significantly as a result of emerging climate extremes in certain regions. Under the SSP2 scenario, the number of migrants expected from Africa to Europe is between 0.4-0.9 million from 2050, depending on the degree of temperature increase. Under an SSP3 scenario with 3C of warming, this number increases to 1.2 million migrants annually by 2050, approaching 2 million by 2100.

At the macro-economic level, the COACCH project used the ICES model to assess climate-related shocks, combining the project's sectoral results into a broader macro-economic framework. To establish a socio-economic tipping point, a threshold for large economic shocks was set at a loss of 5% of Gross Regional Product (GRP). The results show that until 2050, no European regions would cross this threshold. Moving into the 2050s, however, high warming scenarios (RCP6.0 and RCP8.5) would lead to this tipping point being crossed in some regions, while in the 2070s, a high warming scenario could cause this tipping point to be crossed in about 20% of European regions.

Figure 38 Number of EU regions with a Gross Regional Product loss larger or equal to 5%

	2050						2070					
	Low Impact		Medium Impact		High Impact		low Impact		Medium Impact		High Impact	
Inter-regional invest. Mobility	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
Scenario												
SSP1-RCP2.6	-	-	-	2	2	26	1	3	1	7	4	105
SSP1-RCP4.5	-	-	-	4	1	23	1	8	2	13	4	105
SSP2-RCP2.6	-	-	-	1	2	16	1	4	1	7	4	98
SSP2-RCP4.5	-	-	-	2	1	16	1	9	3	20	5	114
SSP2-RCP6.0	-	3	-	6	2	15	3	34	5	71	8	120
SSP3-RCP2.6	-	-	-	-	2	12	1	5	2	13	5	104
SSP3-RCP4.5	-	-	-	-	1	13	2	12	3	36	14	130
SSP5-RCP4.5	-	1	-	5	1	33	1	8	1	24	5	111
SSP5-RCP8.5	-	5	-	9	3	55	3	20	4	36	14	125

Source: COACCH, 2021

2.6 Climate damage functions at macro-economic and sectoral levels

2.6.1 Defining climate damage functions

This section presents climate damage functions, providing insights into the impact of climate change on various sectors and infrastructure.

Climate change is universally acknowledged for its far-reaching impacts on the economy and the natural environment. One particularly consequential aspect of these impacts is the increasing occurrence of economic damages, which amplify in severity alongside rising temperatures. To understand and quantify the economic implications of climate change, the utilization of climate damage functions becomes essential. These functions serve as tools that enable us to assess and model the economic costs and damages associated with climate change scenarios[11] [12] [13].

According to The World Bank, climate damage functions 'relate variations in temperature (or other climate variables) to economic impacts in various dimensions and are at the basis of quantitative

[11] Nordhaus, W. 2010. Economic aspects of global warming in a post-Copenhagen environment. Proceedings of the National Academy of Sciences of the United States of America 107: 11721–26.

[12] Anthoff, D., and R. S. J. Tol. 2013. The uncertainty about the social cost of carbon: a decomposition analysis using FUND. Climatic Change 117: 515–30.

[13] https://link.springer.com/article/10.1007/s10640-018-0219-y

modelling exercises for the assessment of climate change policies.'[14] In other words, they unravel the intricate relationship between temperature variations and economic consequences. They serve as the foundation for modelling efforts that support estimates of the social cost of carbon and provide estimates of the costs or damages associated with different climate change scenarios[15].

At the macro-economic level, climate damage functions provide a comprehensive framework for assessing the potential consequences of climate change on economic systems. They consider critical factors such as changes in temperature, sea-level rise, extreme weather events, and other climate-related impacts, incorporating variables and parameters like climate-related infrastructure vulnerabilities, ecosystem services, and socioeconomic factors. By integrating these parameters into economic models, damage functions enable a quantitative estimation of the relationship between climate shocks and their economic repercussions, including the potential reduction in economic output measured by GDP[16].

The estimation of economic costs using climate damage functions encompasses both direct and indirect effects. Direct effects involve immediate consequences such as property damage, infrastructure losses, and crop yield reductions resulting from climate-related events. Indirect effects encompass the cascading impacts through interconnected sectors and supply chains, as well as the long-term effects on productivity, human health, and quality of life[17][18]. This multidimensional approach allows for a comprehensive evaluation of the economic costs associated with climate change, supporting informed decision-making and the development of effective policies to address its impacts.

Hence, summarising**,** a climate damage function serves as a simplified expression of the economic damages associated with climate change. It captures the interplay between climate inputs, such as temperature changes, and the resulting effects on the economy[19]. It should be noted that the economic damages encompass both positive and negative impacts.

2.6.2 Importance of climate damage function research

When it comes to comprehensively evaluating the consequences of climate change and formulating effective climate policies, the utilization of an appropriate damage function is of utmost importance. In fact, such a function is at the very core of economic analysis related to climate change. By employing a suitable damage function, policymakers and analysts can gain critical insights into the economic implications of climate change, enabling them to make informed decisions and devise strategies that effectively address the challenges posed by a changing climate[20]. Indeed, they

[14] https://documents.worldbank.org/en/publication/documents-reports/documentdetail/175901467994702565/estimation-of-climate-change-damage-functions-for-140-regions-in-the-gtap9-database#:~:text=Climate%20change%20damage%20(or%2C%20more,assessment%20of%20climate%20change%20policies.

[15] Hope, C. 2013. Critical issues for the calculation of the social cost of CO2: why the estimates from PAGE09 are higher than those from PAGE2002. Climatic Change 117: 531–43.

[16] Nordhaus, W. 2010. Economic aspects of global warming in a post-Copenhagen environment. Proceedings of the National Academy of Sciences of the United States of America 107: 11721–26.

[17] Carrera, L., Standardi, G., Bosello, F., & Mysiak, J. (2015). Assessing direct and indirect economic impacts of a flood event through the integration of spatial and computable general equilibrium modelling. Environmental Modelling & Software, 63, 109-122.

[18] Jenkins, K. "Indirect economic losses of drought under future projections of climate change: a case study for Spain." Natural Hazards 69.3 (2013): 1967-1986.

[19] https://www.journals.uchicago.edu/doi/full/10.1093/reep/rez021#:~:text=A%20climate%20damage%20function%20is,such%20as%20changes%20in%20temperature.

[20] Farmer JD, Hepburn C, Mealy P, Teytelboym A (2015) A third wave in the economics of climate change. Environ Resour Econ 62:329–357

provide valuable insights into the costs associated with different climate scenarios, enabling informed decision-making, policy formulation, and prioritization of resources for adaptation and mitigation efforts.

2.6.3 Limitations of damage functions

Climate damage functions, while valuable tools for assessing the economic implications of climate change, have inherent limitations that need to be considered. Uncertainty is a primary challenge, as predicting future climate impacts and quantifying associated damages is complex and uncertain[21]. Additionally, these functions may not fully capture the complexity of climate change relationships, potentially leading to gaps or biases in estimating damages. Limited data availability and the difficulty of incorporating non-market impacts further constrain the accuracy and robustness of these functions[22]. The dynamic nature of climate change also poses a challenge, as static relationships may not adequately capture evolving impacts over time. Despite these limitations, climate damage functions provide valuable insights for policymakers, assisting in decision-making processes, prioritizing resources, and evaluating the effectiveness of climate change mitigation and adaptation strategies. Continuous improvements in data, modelling techniques, and interdisciplinary collaborations can help address these limitations and enhance the reliability of climate damage functions. Hence, although they are not a perfect substitute for detailed process-based models, climate damage functions offer a practical method to estimate damages across various scenarios when it is not feasible to directly simulate impacts using complex physical and economic models[23] [24] [25].

2.6.4 Geographic focus of the literature

In the realm of climate damage functions, there is noticeable variation in the geographical focus of research. While certain regions and countries have received extensive attention in studying the economic impacts of climate-related events, other areas have received comparatively less scrutiny. Geographical areas like the United States, Europe, and some developed nations have been extensively studied, with numerous contributions exploring the economic consequences of various climate hazards. However, regions such as Africa, Asia, South America, and the polar regions have generally received less attention in the academic community, leaving gaps in our understanding of the economic damages caused by climate change in these areas.

The United States (US)

The United States has been a significant focus for research on climate damage functions, considering various hazards such as hurricanes, floods, wildfires, and heatwaves. Studies have explored the

[21] Prahl, B. F., Rybski, D., Boettle, M., and Kropp, J. P.: Damage functions for climate-related hazards: unification and uncertainty analysis, Nat. Hazards Earth Syst. Sci., 16, 1189–1203, https://doi.org/10.5194/nhess-16-1189-2016, 2016 https://nhess.copernicus.org/articles/16/1189/2016/

[22] Diaz, D., Moore, F. Quantifying the economic risks of climate change. Nature Clim Change 7, 774–782 (2017). https://doi.org/10.1038/nclimate3411

[23] Nordhaus, W., and J. Boyer. 2000. Warming the world: economic models of global warming. Cambridge, MA: MIT Press.

[24] Fussel, H. M., F. L. Toth, J. G. van Minnen, and F. Kaspar. 2003. Climate impact response functions as impact tools in the tolerable windows approach. Climatic Change 56: 91–117.

[25] Arnell, N. W., S. Brown, S. N. Gosling, J. Hinkel, C. Huntingford, B. Lloyd-Hughes, J. A. Lowe, T. Osborn, R. J. Nicholls, and P. Zelazowski. 2016. Global-scale climate impact functions: the relationship between climate forcing and impact. Climatic Change 134: 475–87.

economic costs and impacts of climate change on different sectors and regions within the US, studying the overall economic impact of natural disasters[26][27], or focusing on hurricanes [28] [29] [30].

A significant study in the field is the one of Hsiang et al. (2017)[31] "Estimating Economic Damage from Climate Change in the United States." This study provides comprehensive estimates of economic damages caused by climate change across different sectors in the US. It quantifies the potential costs under various climate scenarios and emphasizes the importance of reducing greenhouse gas emissions to minimize future damages. Their analysis revealed that unmitigated climate change could lead to substantial economic damages across multiple sectors, including agriculture, labor productivity, energy, and coastal property. They estimated that by the end of the century, the projected increase in temperatures could reduce U.S. GDP by approximately 5%, with high-emission scenarios potentially causing even greater economic losses.

Europe

Europe has emerged as a prominent region in the study of climate damage functions, with extensive research conducted on various hazards such as storms, floods, heatwaves, and sea-level rise. Different European countries have been the focus of investigation, examining economic impacts, adaptation strategies, and costs associated with climate change across sectors and regions.

Some notable contributions include Bosello et al. (2018)[32] work titled " Economy-Wide Impacts of Climate Mitigation and Adaptation Strategies Across European Regions." This research assesses the economic impacts of climate change in Europe, considering multiple sectors and countries. It also evaluates the vulnerability of European regions to climate change and provides valuable insights into adaptation options and associated costs.

Additionally, several studies have explored the impact of climate change on wine grape production across Europe[33] [34] [35].

Specific countries within Europe, including the United Kingdom, Netherlands, Germany, and France, have garnered attention in the literature. For instance, the Netherlands has been the subject of research exploring the economic impacts of flooding on residential property markets[36]. Germany has also been a focus of attention, examining the potential economic impacts of climate change on

[26] https://www.frbsf.org/economic-research/wp-content/uploads/sites/4/wp2020-34.pdf

[27] Armal, S., Porter, J. R., Lingle, B., Chu, Z., Marston, M. L., & Wing, O. E. (2020). Assessing property level economic impacts of climate in the US, new insights and evidence from a comprehensive flood risk assessment tool. Climate, 8(10), 116.

[28] Frame, D. J., Wehner, M. F., Noy, I., & Rosier, S. M. (2020). The economic costs of Hurricane Harvey attributable to climate change. Climatic Change, 160, 271-281.

[29] Peri, G., Rury, D., & Wiltshire, J. C. (2020). The economic impact of migrants from Hurricane Maria (No. w27718). National Bureau of Economic Research.

[30] Strauss, B. H., Orton, P. M., Bittermann, K., Buchanan, M. K., Gilford, D. M., Kopp, R. E., ... & Vinogradov, S. (2021). Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. Nature communications, 12(1), 2720.

[31] Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., ... & Houser, T. (2017). Estimating economic damage from climate change in the United States. Science, 356(6345), 1362-1369.

[32] https://www.sciencedirect.com/science/article/abs/pii/B9780128498873000058

[33] Cardell, M. F., Amengual, A., & Romero, R. (2019). Future effects of climate change on the suitability of wine grape production across Europe. Regional Environmental Change, 19, 2299-2310.

[34] Van Leeuwen, C., Destrac-Irvine, A., Dubernet, M., Duchêne, E., Gowdy, M., Marguerit, E., ... & Ollat, N. (2019). An update on the impact of climate change in viticulture and potential adaptations. Agronomy, 9(9), 514.

[35] Santos, J. A., Fraga, H., Malheiro, A. C., Moutinho-Pereira, J., Dinis, L. T., Correia, C., ... & Schultz, H. R. (2020). A review of the potential climate change impacts and adaptation options for European viticulture. Applied Sciences, 10(9), 3092.

[36] Caloia, F., & Jansen, D. J. (2021). Flood risk and financial stability: Evidence from a stress test for the Netherlands.

European agriculture, including the German context. In France, many studies have focused on heatwaves, assessing for instance the economic impact associated with mortality, morbidity, and loss of well-being during heat waves in France between 2015 and 2019 [37].

These examples highlight the diverse range of research conducted within specific European countries, providing insights into the economic implications of climate change and informing strategies for adaptation and mitigation.

Other regions

Asia, Africa, South America, and the polar regions have received relatively less attention in the field of climate damage functions. Research in these regions has mainly focused on understanding the impacts of climate change on vulnerable sectors and ecosystems, such as agriculture and water resources in Asia, ecosystem services and natural hazards in Africa, Amazon rainforest and deforestation in South America, and polar ice melt and sea-level rise in the polar regions. However, further research is needed to comprehensively assess the economic costs, vulnerabilities, and adaptation strategies specific to these regions, considering their unique geographical, socioeconomic, and environmental characteristics.

2.6.5 Climate event focus of the literature

In terms of the types of climate events, it can be observed that they have received relatively similar degrees of attention in the climate damage function literature. Events such as hurricanes, droughts, wildfires, heatwaves, floodings, and storms have all been subjects of investigation, with researchers exploring their economic impacts and developing methodologies to assess the damages they cause. While there may be variations in the specific focus or emphasis on certain events, overall, these types of climate events have received comparable levels of attention within the climate damage function literature.

Hurricanes

Hurricanes have been extensively studied, with notable contributions in recent literature. The prominence of hurricanes in the literature can be attributed to their destructive nature, wide-ranging impacts, and high economic costs[38] [39]. Similarly, Kopp et al. (2019) analysed hurricane risks in coastal communities and assessed the costs and benefits of different adaptation strategies. These studies have significantly enhanced our understanding of the economic consequences of hurricanes and informed policy decisions for resilience planning. Additionally, a recent study by Strauss et al. (2021) focused on quantifying the economic damages caused by Hurricane Sandy and attributing them to sea-level rise resulting from anthropogenic climate change[40].

[37] Adélaïde, L., Chanel, O., & Pascal, M. (2021). Health effects from heat waves in France: an economic evaluation. The European Journal of Health Economics, 1-13.

[38] Bakkensen, L. A. (2017). Mediterranean hurricanes and associated damage estimates. Journal of Extreme Events, 4(02), 1750008.

[39] Moore, W., Elliott, W., & Lorde, T. (2017). Climate change, Atlantic storm activity and the regional socio-economic impacts on the Caribbean. Environment, development and sustainability, 19, 707-726.

[40] Strauss, B. H., Orton, P. M., Bittermann, K., Buchanan, M. K., Gilford, D. M., Kopp, R. E., ... & Vinogradov, S. (2021). Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. Nature communications, 12(1), 2720.

Droughts

Droughts are another important climate event that has received significant attention in the field of climate damage functions. Recent literature has contributed to understanding the economic impacts of droughts and developing strategies for adaptation and mitigation[41]. For example, Naumann et al. (2021)[42] investigate the impacts of anthropogenic warming on economic drought in Europe. Their study reveals that increased temperatures have amplified the economic consequences of drought events, leading to substantial losses in agricultural and hydroelectric sectors. Frame et al. (2020)[43] examine the economic costs of extreme rainfall and drought events and attribute them to climate change.

Heatwaves

Heatwaves have received significant attention in recent years, given their increasing frequency and intensity. Researchers have explored the economic consequences of heatwaves on various sectors, including agriculture, human health, and energy demand. However, the specific application of climate damage functions to heatwaves is an evolving area of research. For instance, Kolstad and Moore (2020) examine the estimation of economic impacts of climate change using weather observations. Their study focuses on the use of weather data to assess the economic consequences of climate change, providing insights into the methodology and challenges involved in quantifying these impacts[44].

Wildfires

Wildfires and droughts have gained increased attention in recent years due to their devastating impacts on ecosystems, communities, and economies. While research on climate damage functions related to wildfires is relatively limited compared to other hazards, there is growing recognition of the need to understand the economic costs and impacts of wildfires, on water quality[45] agriculture[46] or municipalities[47]. For instance, Wang et al. (2021) investigate the economic footprint of the 2018 California wildfires. Their study quantifies the direct and indirect economic impacts of the wildfires, highlighting the substantial economic losses incurred because of these extreme events[48].

Floodings

Floodings have garnered substantial attention in the climate damage function literature due to their significant economic impacts. Extensive research has focused on various aspects, including vulnerability assessments, mitigation strategies, adaptation costs, and the influence of climate

[41] Fei, C., Jägermeyr, J., McCarl, B., Contreras, E. M., Mutter, C., Phillips, M., ... & Vargo, A. (2023). Future Climate Change Impacts on US Agricultural Yields, Production, and Market. Anthropocene, 100386.

[42] Naumann, G., Cammalleri, C., Mentaschi, L., & Feyen, L. (2021). Increased economic drought impacts in Europe with anthropogenic warming. Nature Climate Change, 11(6), 485-491.

[43] Frame, D. J., Rosier, S. M., Noy, I., Harrington, L. J., Carey-Smith, T., Sparrow, S. N., ... & Dean, S. M. (2020). Climate change attribution and the economic costs of extreme weather events: a study on damages from extreme rainfall and drought. Climatic Change, 162, 781-797.

[44] Kolstad, C. D., & Moore, F. C. (2020). Estimating the economic impacts of climate change using weather observations. Review of Environmental Economics and Policy.

[45] Wibbenmeyer, M., Sloggy, M. R., & Sánchez, J. J. (2023). Economic Analysis of Wildfire Impacts to Water Quality: a Review. Journal of Forestry, fvad012.

[46] Stougiannidou, D., Zafeiriou, E., & Raftoyannis, Y. (2020). Forest fires in Greece and their economic impacts on agriculture. KnE Social Sciences, 54-70.

[47] Liao, Y., & Kousky, C. (2022). The fiscal impacts of wildfires on California municipalities. Journal of the Association of Environmental and Resource Economists, 9(3), 455-493.

[48] Wang, D., Guan, D., Zhu, S., Kinnon, M. M., Geng, G., Zhang, Q., ... & Davis, S. J. (2021). Economic footprint of California wildfires in 2018. Nature Sustainability, 4(3), 252-260.

change on flood risks. The comprehensive understanding of floods is crucial given their widespread occurrence, devastating consequences, and the need for effective management [49] [50].

2.7 Impacts of climate related shocks on achieving mitigation targets

According to existing literature, climate-related shocks and hazards can have significant impacts on countries' abilities to reach their climate mitigation targets, slowing down the progress towards meeting the emission reduction targets by affecting various aspects of countries' mitigation efforts. First of all, extreme events such as floods, landslides, wildfires, etc. can result in significant physical damages to infrastructure and assets that are essential for implementing climate mitigation measures, for example renewable energy systems.

The different components of the energy system are affected by changes in average climatic conditions, variability of conditions, and by the frequency and intensity of extreme weather events (Cronin at al. 2018, Field et al. 2014). On the demand side, rising temperatures and more frequent and intense heatwaves have already been impacting the balance of heating and cooling demand patterns in Europe as well other regions of the world. On the supply side, the technologies currently used for electricity generation are all subject to climate change impacts (Ebinger and Vergara, 2011). While renewable technologies like solar and wind are clearly being affected by changes to the averages and variability of wind, solar and hydropower resources, traditional thermos-electric power plants are also being increasingly affected by rising temperatures.

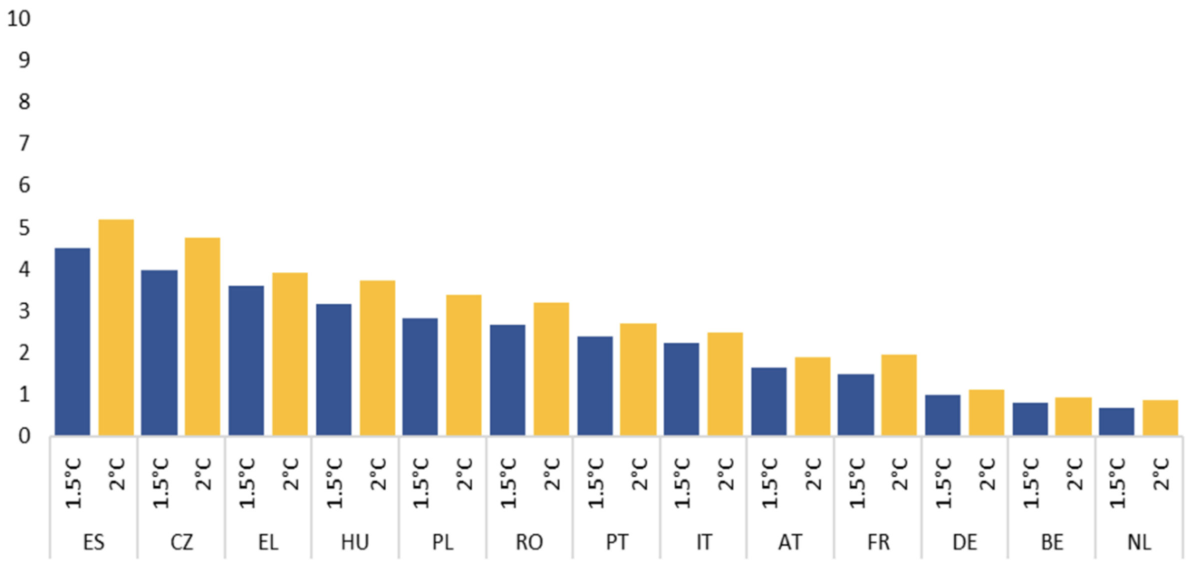
These lead to reductions in the efficiency of power stations, reductions in renewable energy resources, and increased risks of damages to key electricity transmission and distribution infrastructure. Some impacts of climate-related shocks may also result in an increased use of fossil fuels to satisfy existing electricity demand, thereby leading to an increase in greenhouse gas emissions (Cronin at al. 2018). For example, climate-driven changes in hydropower generation are expected to alter power sector CO_2 emissions in several countries, although the net global impact is likely to be modest (Turner et al. 2017). So far, existing literature has focused largely on the climate change impacts of technologies currently in use, while the discussion on future technologies has been more limited.

Secondly, as also highlighted in previous sections, climate-related hazards can cause significant economic losses, both in terms of damage to infrastructures and lost economic activity, and have fiscal consequences for countries. Extreme events can put direct pressures on public spending to replace damaged assets, to provide social transfers and subsidies, or via reduced tax revenue due to reduced output losses in climate-sensitive sectors. In this sense, a recent study by Gagliardi et al. (2022) attempted to quantify the potential fiscal impacts of extreme climate events, and showed that climate-related disasters can lead to debt-increasing effects for EU countries, therefore putting at risk their debt sustainability. This can make it more difficult for countries to invest in mitigation measures, as they may need to divert resources to recovery efforts.

[49] Johnson, K. A., Wing, O. E., Bates, P. D., Fargione, J., Kroeger, T., Larson, W. D., ... & Smith, A. M. (2020). A benefit–cost analysis of floodplain land acquisition for US flood damage reduction. Nature Sustainability, 3(1), 56-62.

[50] Wing, O. E., Pinter, N., Bates, P. D., & Kousky, C. (2020). New insights into US flood vulnerability revealed from flood insurance big data. Nature communications, 11(1), 1444.

Figure 39 Debt-to-GDP difference, 1.5°C and 2°C scenarios compared to the baseline, in 2032 (%)



Source: Gagliardi et al. (2022).

Thirdly, climate-related hazards can result in social and political instability, which can undermine efforts to implement climate mitigation measures. For instance, extreme weather events could have cumulative effects and affect the economic prosperity and well-being of local communities, especially of their most vulnerable members (European Committee of the Regions, 2020). These can consequently lead to displacement of populations, social unrest, and political instability, making it difficult for governments to implement and enforce policies related to emission reductions.

In the specific context of the European Union, climate-related hazards and shocks have been identified as a key challenge for achieving EU's emission reduction targets. The EEA notes that climate change impacts, including extreme weather events, pose a significant threat to the EU's infrastructure, economy, and social well-being, which in turn can hinder the achievement of its climate goals (EEA, 2017). The European Commission's 2021 report on the state of the energy union also highlights the need for a more comprehensive approach to climate adaptation and mitigation, as the two are closely linked and cannot be pursued in isolation (European Commission, 2021).

2.8 Cost and effectiveness of adaptation

The ECONADAPT project produced a comprehensive literature review of the costs and benefits of adaptation (2015). The review assembled an overview of the sectoral coverage of adaptation cost estimates, with only coastal adaptation being comprehensively covered. Agriculture, forestry, and water management/flood infrastructure all had medium coverage, while limited data is available for energy, transport infrastructure, tourism, health, biodiversity, and industry.

The EU research project BASE (Jeuken et al., 2016) explored the costs and benefits of adaptation across a range of sectors in Europe through the AD-WITCH model. For riverine floods, adaptation costs for dike protection across the entirety of Europe are between EUR 669 billion and EUR 1,119 billion depending on the timescale and choice of climate scenario. For adapted buildings, the cost is estimated at EUR 1,623 billion, which is uniform across all RCP scenarios.

Figure 40 Adaptation costs (dike protection) in absolute costs (billion Euros total), undiscounted

Region:	RCP4.5(2030)	RCP4.5(2080)	RCP8.5 (2030)	RCP8.5 (2080)
Nordic:	106	164	129	231
West:	215	260	192	398
South:	117	121	100	99
Central/east:	232	337	310	391
Total:	669	882	731	1,119

Source: BASE, 2016.

In the agriculture sector, the maximum damage projected from riverine floods is 0.87 EUR/m2.The adaptation options explored were improved management and irrigation. For improved management, the expected costs ranged from 0.015-0.066% of GDP for all of Europe, depending on SSP-RCP combinations and timescale. The expected damage reduction obtained through improved management is between 0.045-0.155% of GDP. For irrigation, costs were estimated between 0.003-0.01% of GDP, with an expected damage reduction of 0.009-0.028% of GDP.

With regards to adaptation for human health, implementation of heat health watch warning systems is expected to cost EUR 163.9-323.7 million (RCP8.5-SSP5, until 2099), with projected benefits of EUR 162-646.8 billion.

Finally, the BASE project also explored the economy-wide effects of adaptation in the flood risk, agriculture, and health domains. The table below summarizes damages, adaptation costs, and adaptation effectiveness in 2050 (and 2100 for damage) across the three scenarios, for Europe.

Figure 41 Damages, adaptation costs, and adaptation effectiveness in 2050 (and 2100 for damage) across the three scenarios, for Europe

Region	Scenario	2050 Impacts w/o adaptation (% regional GDP)*	2100 Impacts w/o adaptation(% regional GDP)	2050 Proactive adaptation (2005 USD bn)	2050 Reactive (2005 USD bn)	Total adaptation (% regional GDP)	2050 Adaptation effectiveness (% reduced damage)
Western EU	SSP5 RCP85 (Reference)	0.1576	-0.1199	50.36	0.59	0.14%	50%
Eastern EU	SSP5 RCP85 (Reference)	0.0259	-0.5484	3.34	0.13	0.11%	43%
Western EU	SSP2	0.1509	0.0721	28.94	0.35	0.12%	43%
Eastern EU	SSP2	0.0386	-0.2887	1.84	0.08	0.09%	40%
Western EU	SSP2 RCP45	0.1384	0.1596	21.19	0.28	0.08%	37%
Eastern EU	SSP2 RCP45	0.0513	-0.0139	1.33	0.06	0.10%	35%

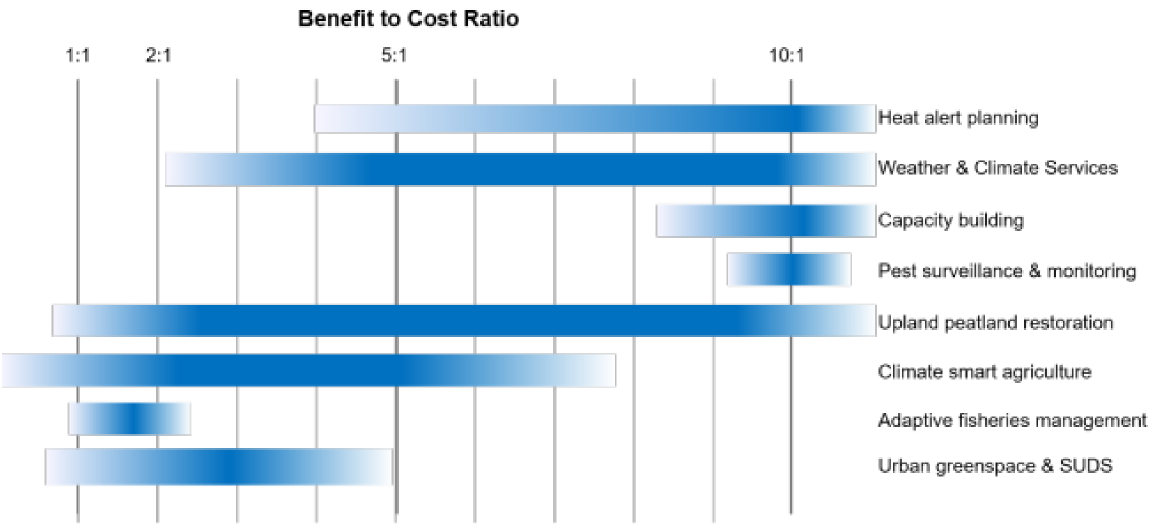
*Negative numbers represent negative impacts (losses), positive numbers represent positive impacts (gains)

Source: BASE, 2016.

The COACCH project (2021) also explored the benefits of adaptation compared to costs, looking especially at important impact categories like coastal and river flooding, as well as health. The studies found that in general, adaptation has significant economic benefits via a reduction of future impacts, reducing damage costs by a factor of 2 to 5, depending on the adaptation targets. Despite the high benefits of adaptation, there remains a high need for additional investment in Europe, with costs rising through 2100.

The figure below summarises the COACCH work into the costs and benefits of early adaptation, examining the benefit-to-cost ratio of a number of no- and low-regret adaptation options across a range of sectors.

Figure 42 Benefit to cost ratio of no and low-regret adaptation measures



Source: COACCH, 2021

At the sectoral level, the COACCH project (2021) explored the damages of coastal flooding with and without adaptation across a range of scenarios, as well as the associated adaptation costs. The results show significant economic benefits of adaptation, estimated at EUR 87-181 billion per year (RCP2.6) to EUR 102-205 billion per year (RCP4.5) in the 2050s, with associated adaptation costs of EUR 14-17 billion per year.

Figure 43 European coastal damage costs and coastal adaptation costs

European Coastal Damage Costs for Various RCP scenarios (no adaptation).

Coastal damage	RCP2.6-SSP2	RCP4.5-SSP2	RCP8.5-SSP5
2050s / mid century	€115-210 Bill/yr	€130-235 Bill/yr	€310 Bill/yr
2080s /end century	€365-795 Bill/yr	€510-1,200 Bill/yr	€2,400 Bill/yr

European Coastal Damage Costs for Various RCP scenarios WITH ADAPTATION

With Adaptation	RCP2.6-SSP2	RCP4.5-SSP2	RCP8.5-SSP5
2050s / mid century	€ 28-29 Bill /yr	€ 28-30 Bill/yr	44 Bill/yr
2080s /end century	€ 46-50 Bill /yr	€ 46-53 Bill/yr	110 Bill /yr

Coastal adaptation costs €/yr

Coastal Adap. Cost	RCP2.6-SSP2	RCP4.5-SSP2	RCP8.5-SSP5
2050s / mid century	€14-16 Bill/yr	€15-17 Bill/yr	€17 Bill/yr
2080s / end century	€15-17 Bill/yr	€16-19 Bill/yr	€33 Bill/yr

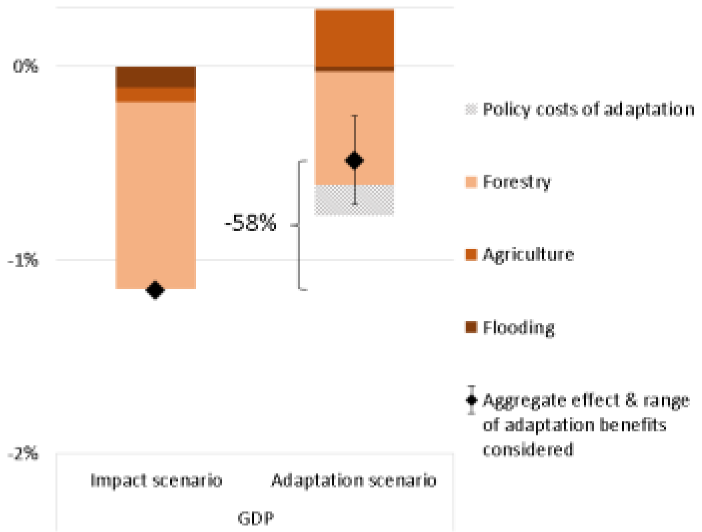
Values are presented as additional impacts or costs relative to the baseline period for the EU 28, from the combination of climate and socio-economic change, and are presented as undiscounted values in future years in current prices.

Source: COACCH, 2021

A similar assessment was carried out for river flooding, which estimated the economic benefits of adaptation between EUR 6.4 billion per year (RCP2.6) to EUR 6.9 billion per year (RCP4.5) in the 2050s. Adaptation costs for river flooding were not estimated. Economic benefits in the transportation sector are also important, between EUR 562 million per year (RCP2.6) and EUR 645 million per year (RCP8.5) in the 2050s.

Finally, the COACCH project also used the COIN-INT model to analyse the macro-economic effects of climate change and adaptation in three national case studies (Austria, Spain, and the Netherlands), with a deeper focus on flood risk management and adaptation in agriculture and forestry. The analysis explored the effectiveness of adaptation in reducing baseline impacts and it's relationship to public sector expenditure and budgets. Results showed that national adaptation is effective in reducing both the sectoral and economy-wide impacts of climate change, with a reduction of impacts of over 50%. Furthermore, the study showed that the benefits of adaptation on government revenues (via taxes, output, trade) more than offset the direct costs of adaptation. As a result, this allows more government consumption and transfer to households. Leading to a net positive outcome for public budgets.

Figure 44 Macro-economic effect in terms of GDP of mean changes from riverine flooding (expected annual damage, EAD), impacts in agriculture & forestry in SSP5 RCP8.5 in Austria in 2050. Note: Bars indicate the percentage change in the impact and adaptation scenario relative to the baseline. Results are based on GCM HadGem2-ESM



Source: COACCH, 2021.

At the national level, Knittel et al. (2017) carried out a study on the costs of adaptation for the Austrian federal budget. To estimate adaptation costs, they tested both a top-down approach based on the government's budget plan, as well as a bottom-up approach based on the Austrian national adaptation strategy and the planned measures. The results showed expenditures of EUR 488 million per year for the top-down approach and EUR 385 million per year for the bottom-up approach, with the variance due to the coverage of adaptation measures in each approach.

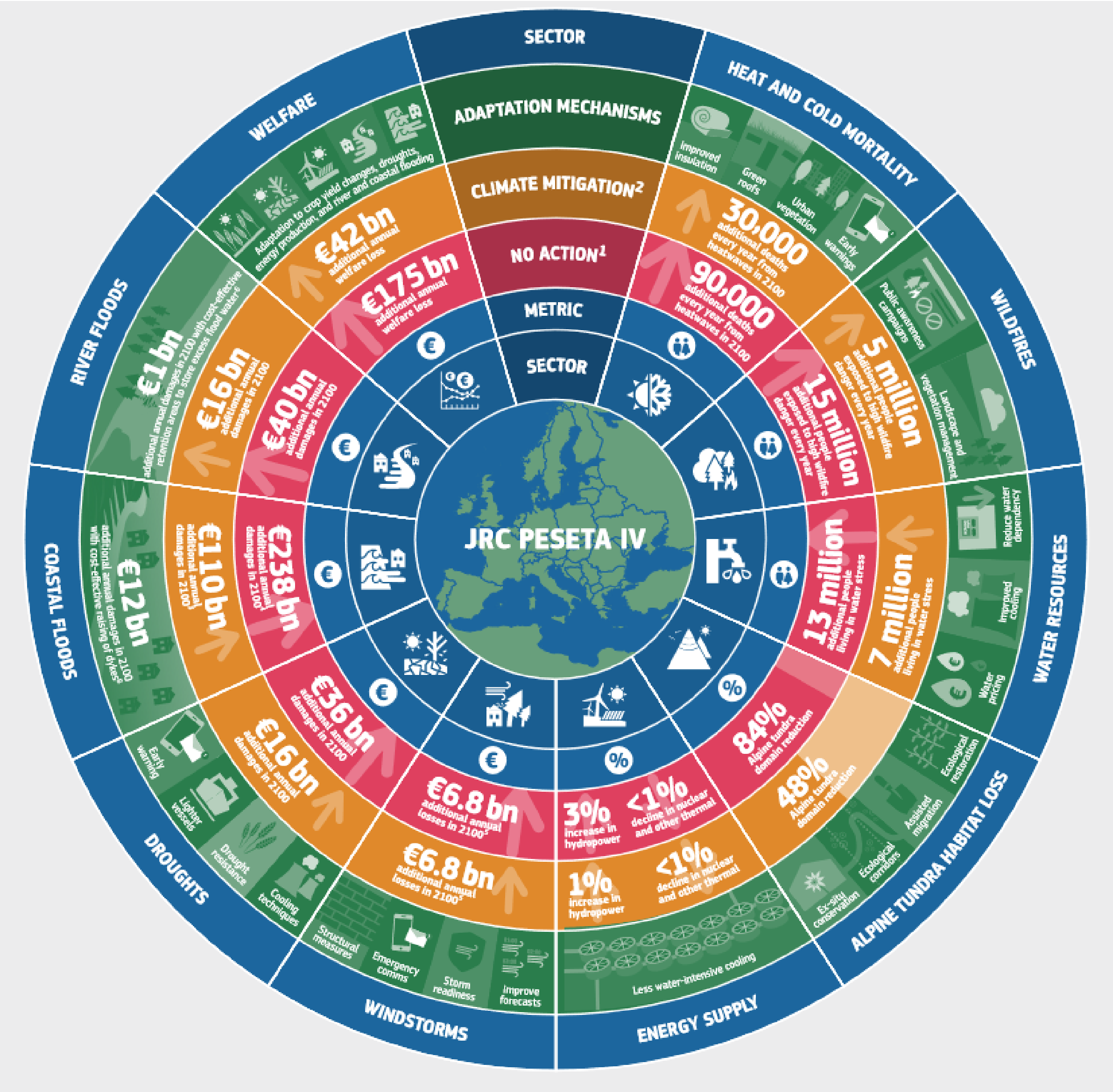
2.9 Conclusions

The screened literature shows a variety of studies estimating sectoral impacts, macro-economic effects, tipping points and impacts on the EU from hazards outside the EU. We screened the EMDAT and NATDIS database according to number and damages of past events. A notable observation is that the data on past events appears to be quite irregular. This finding is particularly intriguing as it highlights the limited availability of comprehensive information on the actual costs and details of previous events. While many studies focus on projecting future climate impacts, the scarcity of robust data on past events underscores the need for further research and enhanced data collection efforts.

A first summary of different future sectoral impacts can be discussed based on PESETA IV and COACCH results.

The PESETA team prepared a summary of climate impacts based on the PESETA IV results (see the figure below) (PESETA IV 2020[23], Feyen et al. 2020[24]). The PESETA IV results show high costs of climate impacts for coastal floods and river floods. Substantial impacts are seen for mortality due to heatwaves (with 90.000 annual deaths). Drought losses are expected to increase to 45 bn €/year with 3°warming in 2100. Labour productivity was included in PESETA III and highlighted as one of the most relevant impacts (Ciscar et al. 2018)[25]; it shows a substantial decline in labour productivity - in average across EU 3.4% and up to 17% reduction in Southern Europe under a high emissions scenario.

Figure 45 Overview of cost of inaction estimated by PESETA IV



Source: PESETA IV (2020).

The COACCH results are in general in line with the PESETA estimations. Highest estimated climate impacts are shown for coastal flooding and health effects due to heatwaves. An overview of the COACCH results is shown in the table below.

Table 9 Summary of COACCH results for different sectors (for no adaptation)

Sectors	Estimated climate impacts 2050s, RCP2.6-SSP2 (€ per year)	Estimated climate impact 2050s, RCP8.5-SSP5 (€ per year)
Coastal flooding	€115-210 Bn	€310 Bn
River flooding	€11 Bn	€18 Bn
Transport (flood impacts)	€954 Mio (RCP4.5-SSP2)	€1147 Mio.
Health (heatwaves)	€102 Bn	€176 Bn
Labour productivity	industrial productivity: - 2.7% construction labour productivity: -3.1% (year 2070, RCP4.5)	industrial productivity: - 4.3% construction labour productivity: -6.6% (year 2070)
Agriculture		906 Mio. (arable production) 831 Mio. (agricultural sector)

3. Macro-economic modelling of climate related shocks

The following section presents in detail the different steps followed to carry out the modelling exercise with the NEMESIS model, used to assess the macro-economic impacts on the European economy of future climate change damages and of adaptation measures.

We start with the presentation of the general methodology implemented (section 3.1), followed by the definition of the two reference scenarios used to evaluate the climate change damages and that define the two global climate contexts in which the EU might evolve in the future (section 3.2). We then continue with a synthesis of the literature on climate change damages on the EU economy based on the findings described in the previous sections but framed to inform the modelling exercise on the extent of the macro- and sector-economic impacts of future climate change in EU (section 3.3). Thereafter, we explain how we implemented these impacts into NEMESIS, and we present the results of the integration of climate damages in the model (section 3.4). The section 3.5 deals with the adaptation to climate change, with a synthesis of the literature quantifying their benefits and costs, 3.5 followed by the analysis of the modelling results when adaptation is included in the model (section 3.6). Finally the last section (3.7) considers an alternative modelling of the interest rates to include a potential specific climate-related risk premium induced by climate damages and/or by adaptation measures3.7.

3.1 General methodology

Our methodology can be summarised into the following four steps:

1. In the first step, the reference scenarios (used as counterfactual scenarios) were defined at global and EU level to frame the global context. These reference scenarios differ by their level of GHG emissions over the century and their related global warming —but, at this step, do not consider climate hazards and adaptation policies.
2. The second step consisted in the introduction of the climate impacts and their socio-economic impacts based on the quantitative information retrieved from the literature review (Task 1), in order to assess their macro-economic effects.
3. The introduction of adaptation policies, in a third step, allowed us to improve the evaluation of the potential macro-economic impacts of climate change in the EU by considering the potential mitigation on the economic impacts of the damages of adaptation measures and by quantifying the related investments needs.
4. Finally, the last point questioned the uncertainty arising (i) from the findings coming from the literature review on the potential impacts of climate change damages and (ii) from key assumptions, parameters or relationships implemented or pre-existing in the model, such as the share of insured damages, or the reaction of the financial sector to substantial investment needs for adaptation to climate change.

Thus, this scenarios' framework allowed for the analysis of the economic costs/benefits for the EU of (i) mitigation policy, (ii) climate hazards caused by global warming, (iii) adaptation policy, and (iv) of their combination.

3.2 The baseline scenarios

3.2.1 Global contexts

With the objective of assessing the "cost of inaction" for the European Union in terms of mitigation policies and adaptation measures, we define two general contexts, regarding the global GHG emissions, the radiative forcing and/or the temperature raise. The IPCC AR6 – Working Group I (2021)[51] worked with five synthetic climate scenarios up to 2100, called SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (see Figure 46). These scenarios associate socio-economic drivers (SSP-Socio-economic Shared Pathways; van Vuuren et al., 2014[52]; Riahi et al., 2015[53]) and an approximate level of radiative forcing (in W/m^2) in the continuation of the AR5 Representative Concentration Pathways scenarios (O'Neill et al. 2016). These scenarios can be summarised[54] as such:

- SSP1-1.9 represents "*emissions pathways leading to warming below 1.5°C in 2100 and limited temperature overshoot of 1.5°C over the course of the 21st century*"
- SSP1-2.6 is "*designed to limit warming to below 2°C*"
- SSP2-4.5 is the scenario "*approximatively in line with the upper end of aggregate NDC emissions levels by 2030*"
- SSP3-7.0 draws "*an intermediate-to-high reference scenario resulting from no additional climate policy* "
- SSP5-8.5 is the "*very high warming end of future emissions pathways from the literature*".

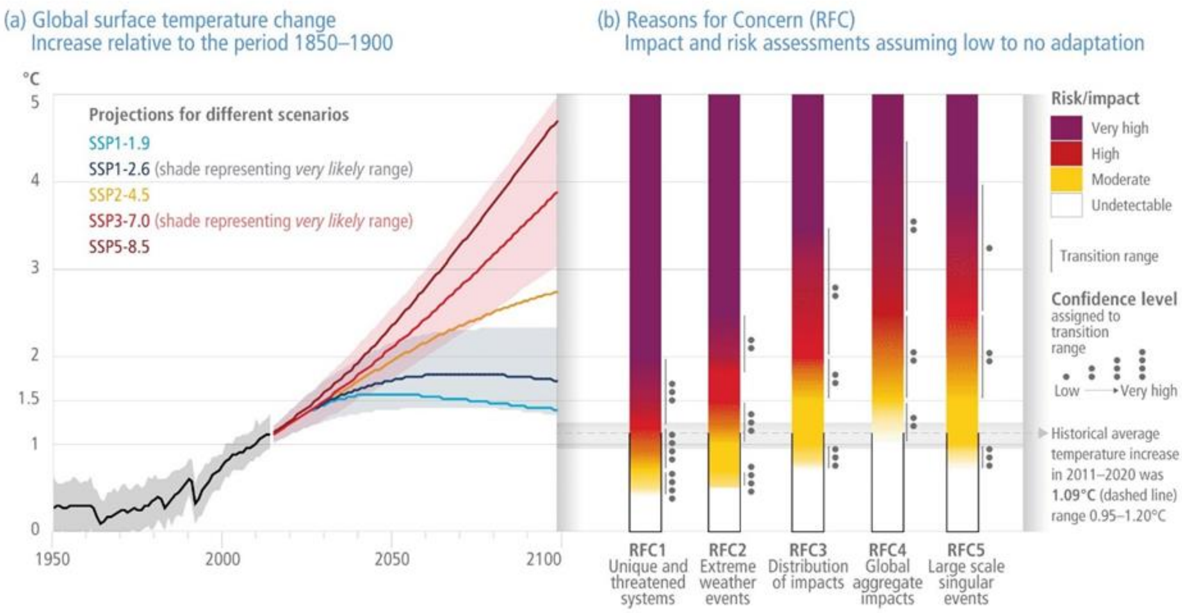
[51] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. Doi:10.1017/9781009157896.

[52] van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R. and H. Winkler, 2014, A new scenario framework for Climate Change Research: scenario matrix architecture, Climatic Change, vol. 122(373-386). Do: 10.1007/s10584-013-0906-1

[53] K. Riahi, D. P. van Vuuren, E. Kriegler, J. Edmonds, B. C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. Crespo Cuaresma, S. KC, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, .L. Aleluia Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J. C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau and M. Tavoni, 2017, « The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview », Global Environmental Change, vol. 42, pp. 153-168. Doi : 10.1016/j.gloenvcha.2016.05.009.

[54] The presentation of the scenarios come from the IPCC AR6 – Working Group I (2021)

Figure 46: Global risks for increasing levels of global warming



Source: IPCC-AR6-WGII, 2022 – Fig. SPM.3.a and SPM.3.b.

Ideally, we should use both extreme cases for the general context, SSP1-1.9 and SSP5-8.5 scenarios, in order to contrast the results. Nevertheless, the scientific community recently discussed the realism of using such "extreme" scenarios (Pielke and Ritchie, 2021[55]), which the IPCC does not or at a very limited extent. The debate is on the usefulness of a scenario with a high level of global warming (mainly SSP5-8.5 and at a lesser extent SSP3-7.0) when working on climate impacts. Comparing historical global emissions with the scenarios used for IPCC AR5 and AR6, Strandsbjerg et al. (2021)[56] show that CO_2 emissions are generally underestimated for non-OECD and overestimated for OECD countries, leading to historical emissions in the medium-high ranges of the scenarios. Schwalm et al. (2020a[57]; 2020b[58]) show that RCP8.5 cumulative emissions projections are consistent with historical emissions, and they also argue that mid-term RCP8.5 emissions match with "business as usual" scenarios. This has been discussed by Hausfather and Peters (2020) showing that uncertainty about land use emissions projections may significantly affect these conclusions. Recent projections confirm that last update of Nationally Determined Contributions (NDCs) moves potential 2100 global warming away from high-temperature (>4°C) scenarios, with temperature raise projections well-below 3°C in 2100 (Sognnaes et al., 2021; van de Ven et al., 2023[59]).

[55] Pielke, Jr., R., nad J., Ritchie, 2021, Distorting the view of our climate future: The misuse and abuse of climate patways and scenarios, Energy Research and Social Science, vol. 72(101890). Doi: 10.1016/j.erss.2020.101890

[56] Strandsbjerg, J., Pedersen, T., Duarte Santos, F., van Vuuren, D., Gupta, J., Encarnação Coelho, R., Aparício, B. A. and R., Swart, 2021, An assessment of the performance of scenarios against historical global emissions for IPCC reports, Global Environmental Change, vol. 66(102199). Doi: 10.1016/j.gloenvcha.2020.102199

[57] Schwalm, C. R., Glendon, S., Duffy, P. B., 2020, RCP8.5 tracks cumulative CO2 emissions, PNAS, vol. 117(33), 19656-19657. Doi: 10.1073/pnas.2007117117s

[58] Schwalm, C. R., Glendon, S., Duffy, P. B., 2020, Reply to Hausfather and Peters: RCP8.5 is neither problematic nor misleading, PNAS, vol. 117(45), 27793-27794. Doi: 10.1073/pnas.2018008117

[59] van de Ven, D.-J., Mittal, S., Gambhir, A., Lamboll, R., Doukas, H., Giarola, S., Hawkes, A., Koasidis, K., Koberle, A.,., McJeon, H., Perdana, S., Peters, G., Rogejl, J., Sognnaes, I., Vielle, M. and A. Nikas, 2023, A multi-model analysis of post-Glasgow climate action and feasibility challenges. Nature Climate Change, vol. 13(570-578). Doi: s41558-023-01661-0

Furthermore, as shown in Table 10, the different climate scenarios lead to a large range of global temperature change in the long-term (2081-2100), from 1.4°C (1.0 to 1.8) in SSP1-1.9 to 4.4°C (3.3-5.7) in SSP5-8.5, but this range is narrowed for mid-term (2041-2060), the time horizon of our study, between 1.6°C (1.2-2.0) and 2.4°C (1.9-3.0) respectively.

Table 10: Changes in global surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered (differences relative to the average of the period 1850–1900).

	Near Term, 2021-2040		Mid-term, 2041-2060		Long-term, 2081-2100	
Scenario	**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: IPCC-AR6-WGI, 2022 – Table SPM.1.

Accordingly, we assume two reference scenarios operating in the two following context:

- **A high GHG emissions pathways, called "No further action"** in which current trends on emissions remain and no additional climate mitigation actions are engaged in the rest of the World (outside EU). We base this scenario on the SSP3-7.0 illustrative scenario of the IPCC AR6 WGI (2021), **that leads to a temperature rise of about 3.6°C [2.8-4.6°C] in the long term, and 2.1°C [1.7-2.6°C] in the mid-term.**
- **A low climate change scenario, called "Paris Agreement Compliant",** in which a rapid and large action to mitigate GHG emissions is realised worldwide and that complies with the Paris Agreement. We tie this global context to the SSP1-1.9 illustrative scenario from IPCC AR6 WGI (2021), **in which global mean temperature raises about 1.4°C [1.0-1.8°C] in the long-term, and 1.6°C [1.2-2.0°C] in the mid-term**.

Finally, we must mention that regional climate modelling generally projects a higher average temperature change than the global mean for a large part of Europe, particularly for North-Eastern Europe, Northern Scandinavia and Inland areas of Mediterranean countries (Dosio and Fischer, 2017, European Environmental Agency, 2022a), but we will not address directly this question in this study —most of the studies considered in the literature review, detailed hereafter, refer to the global context even when using regional climate modelling.

3.2.2 European contexts

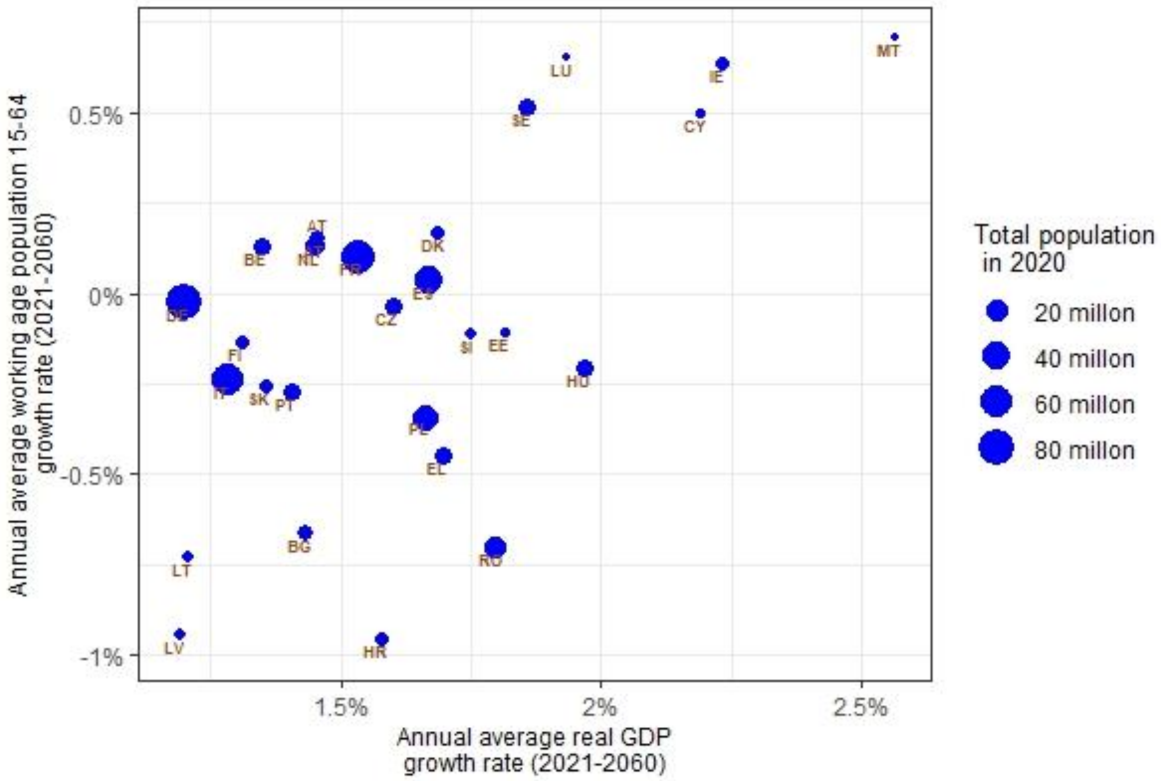
In the European Union, the socio-economic and climate action contexts differ from the two global contexts in both counterfactual scenarios, with no major inconsistency. We assume EU-specific assumptions regarding the population and GDP projections as well as for the GHG emissions mitigation effort up to 2060. As EU represented 6% of total global emissions in 2019[60], we assume that specific assumptions for EU cannot impact significantly the global context.

[60] www.climatewatchdata.org

3.2.2.1 *Socio-economic drivers*

We use population projections by Member State from EUROPOP 2019 (Eurostat, 2019), with a short-term update up to 2032 and medium- and long-term GDP growth projections from the 2021 Ageing Report (European Commission, 2021a) completed with short-term forecasts, up to 2024, from the European Commission (2022). These assumptions are used for both reference scenarios. Figure 47 summarises these assumptions by Member State and Table 11 for the EU-27.

Figure 47: Summary of population and real GDP growth assumptions in the EU



Source: Authors elaboration based on Eurostat (2019); European Commission (2021a), (2022).

Table 11: Summary of EU-27 socio-economic assumptions

Population (million)				
2020	**2030**	**2040**	**2050**	**2060**
447.3	449.5	447.1	441.6	432.9
Working Age Population (million)				
2020	**2030**	**2040**	**2050**	**2060**
287.7	277.8	263.3	250.8	242.7

Real GDP average annual growth rate (%)			
2021-2030	**2031-2040**	**2041-2050**	**2051-2060**
1.8%	1.3%	1.4%	1.4%

Source: Authors elaboration based on Eurostat (2019); European Commission (2021a), (2022).

3.2.2.2 GHG mitigation policies

In the EU, we assume two different climate change mitigation policies in accordance with the two global contexts introduced above:

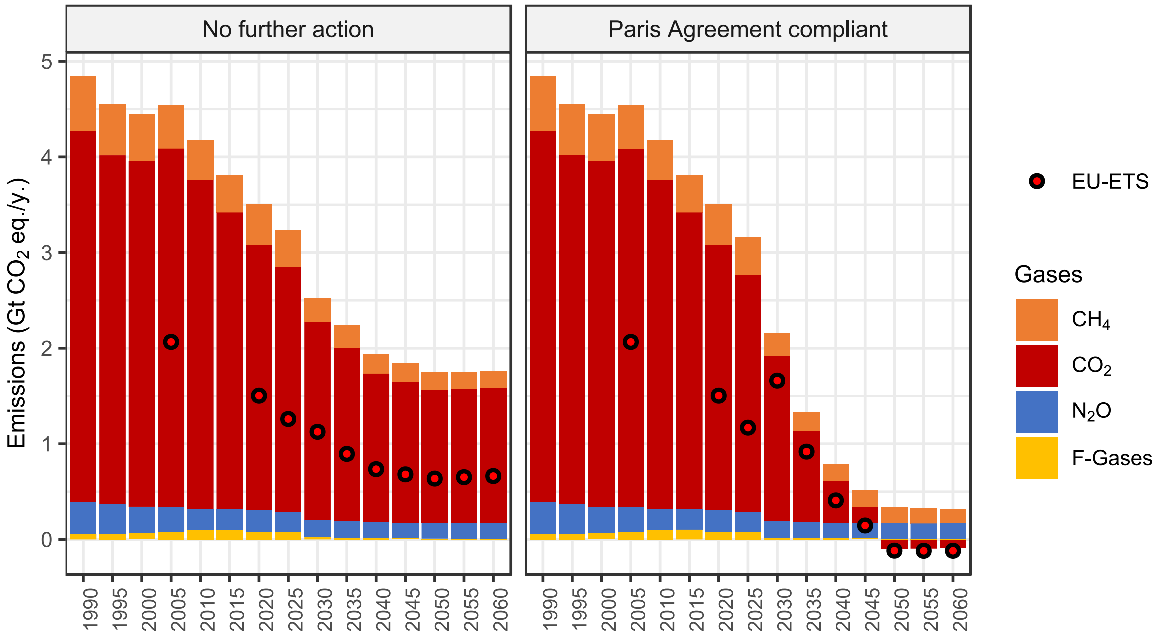
- **In the "No further action" context**, we assume that **EU remains with the 2030 climate and energy framework** (European Council, 2014) and does not achieve the European Green Deal climate target (European Commission, 2019). This scenario follows the 2020 EU reference scenario (European Commission, 2021b) in terms of GHG emissions in both the EU Emissions Trading System (EU-ETS) and Effort Sharing Regulation (ESR) sectors.
- **In the "Paris Agreement Compliant" context**, the **EU commits to a deep decarbonisation**, following the European Green Deal GHG reduction target of at least -55% in 2030 with respect to 1990 and applying the "Fit for 55" policy package for the EU-ETS and ESR sectors (European Commission, 2021c), with notably the inclusion of the road transport and buildings in the EU-ETS from 2025. After 2030, GHG emissions decline regularly to reach Net Zero Emissions (NZE) in 2050, as stated in the European Long-term Strategy (European Union, 2020) and remain at NZE thereafter.

3.2.3 Reference scenarios: An overview

In the "No further action" scenario, EU total GHG emissions (excl. LULUCF and international bunkers) decline to reach 2.5 $GtCO_2$eq. in 2030, i.e. -48% compared to 1990 (Figure 48), with -46% for CO_2 and N_2O, -56% for CH_4, and -58% for F-gases. GHG emissions reach 1.92 $GtCO_2$eq. in 2040 (-60% w.r.t. 1990) and 1.73 $GtCO_2$eq. in 2050 (-64%) and stabilize afterward. The emissions covered by the EU-ETS sectors (same perimeter than in 2022) decline also progressively, with 1.1 $GtCO_2$eq. in 2030, 0.74 in 2040 and 0.64 in 2050, i.e. a reduction of 69% compared to 2005 emissions. In 2050, CO_2 emissions account for 1.39 $GtCO_2$eq, a decline of 64% compared to 1990.

In the "Paris Agreement compliant" scenario, the EU reaches the GHG emissions targets for 2030 and 2050 with -58.5% in 2030 (w.r.t 1990) and -95.5% in 2050, remaining emissions in 2050 are of 0.21 $GtCO_2$eq., assumed as a NZE achievement considering LULUCF emissions. To achieve full decarbonation of the EU economy, the model mobilises negative emissions technologies in the power generation sector with bio-energy combined with carbon capture and sequestration (BECCS) leading to negative emissions in the EU-ETS sector from 2050, with -0.12 $GtCO_2$.

Figure 48: EU GHG emissions (excl. LULUCF) by GHG gas in both reference scenarios

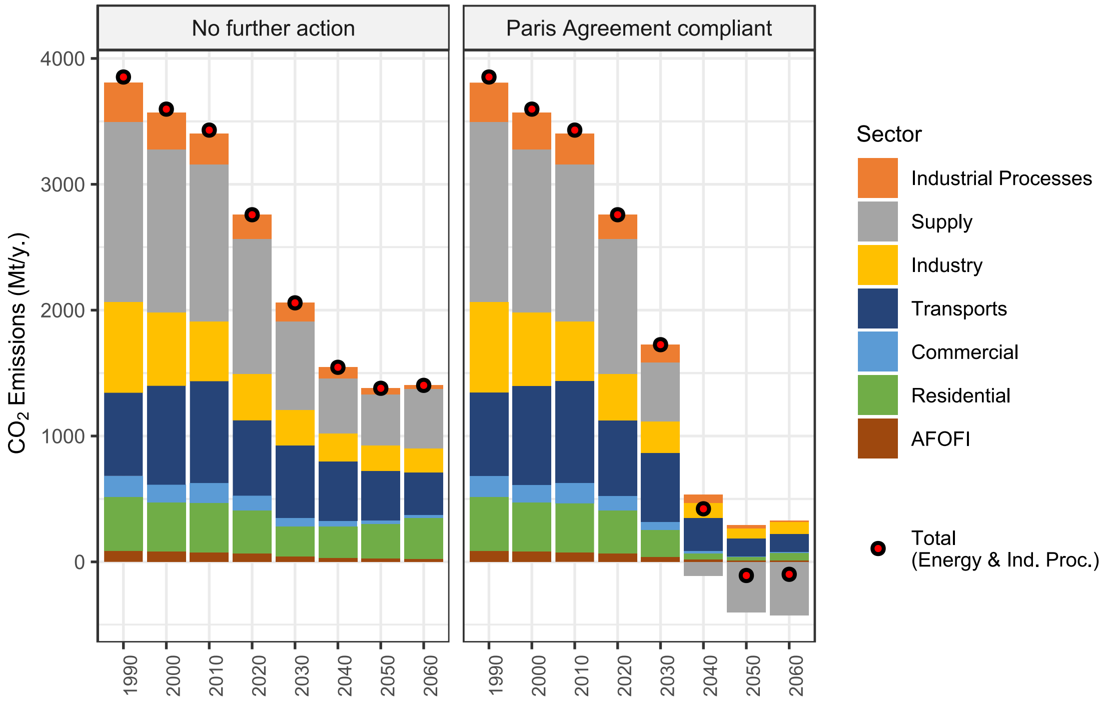


Source: Historical data up to 2015 from EEA (2022) and NEMESIS model thereafter. Emissions exclude LULUCF and international bunkers.

By sector, the CO_2 emissions from energy and industrial processes decline in both reference scenarios for all sectors (Figure 49) but the contribution of each sector to the achievement of the emissions reduction differ significantly. In the "No further action" scenario, the CO_2 emissions reach 1 380 Mt in 2050 (-64% w.r.t. 1990), of which 403 in the supply sector (-72%), 390 in transports (-41%), 306 in buildings (-49%) and 52 for European industry (-72%). In the "Paris Agreement Compliant" scenario, the energy supply, with -400 Mt in 2050, allows residual emissions in the other sectors: 143 Mt in transport, 92 Mt for industry, 68 Mt in buildings, 12 Mt for the AFOFI sector, and also 12 Mt for industrial processes.

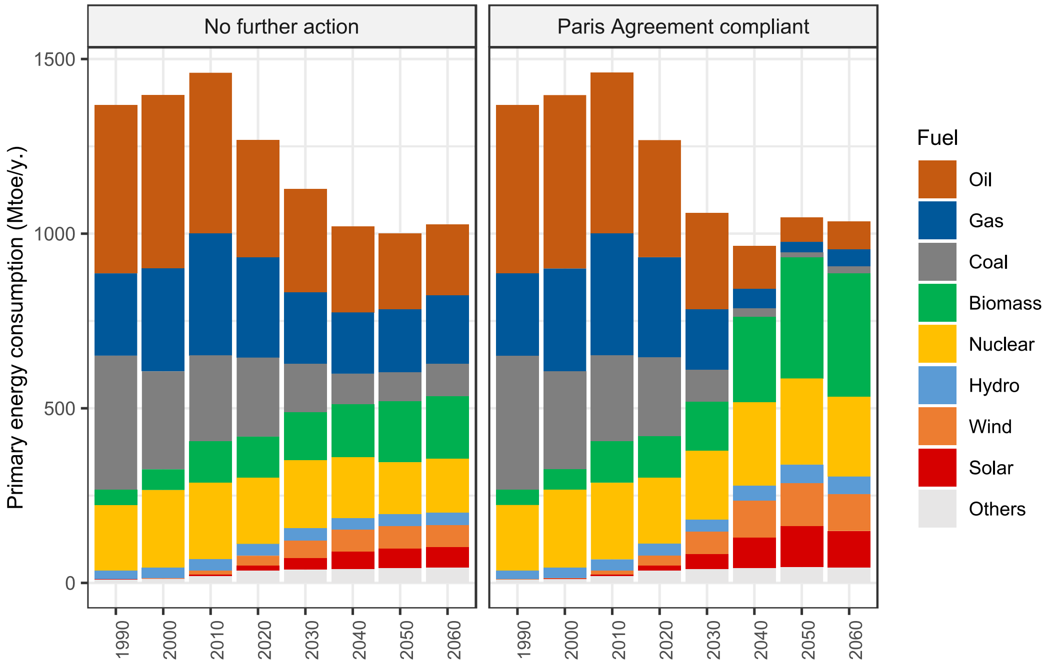
Figure 50 shows the transition of the EU energy system in both reference scenarios towards lower energy consumption, more renewable and a significant reduction of fossil energy consumption. In the "No further action" scenario, the total primary energy consumption in EU is declining rapidly to 1 130 Mtoe in 2030 (overreaching the 32.5% energy efficiency target of the EU 2030 climate and energy framework) and more slowly thereafter reaching 1 000 Mtoe in 2050. Compared to 2020, fossil fuel consumption is reduced: coal is declining significantly (by almost two third) in 2050, followed by oil and gas (one third). Nuclear primary energy is also lower in 2050 (-21% compared to 2020) while renewable sources grow: +50% for biomass, doubling for wind and tripling for solar-hydro being stable. In the "Paris Agreement compliant" scenario, the transition towards renewable energy sources is reinforced with an almost complete phase-out of coal in 2050 (-94% compared to 2020) and to a lesser extent for gas (-80%) and oil (-80%). Bio-energy primary consumption reaches 346 Mtoe in 2050 (+195%), wind 123 Mtoe (+331%) and solar 117 Mtoe (+700%). Nuclear and hydro also contribute to the decarbonisation of the EU energy mix, with respectively +30% and +58% in 2050 compared to 2020.

Figure 49: EU CO_2 emissions from energy and industrial processes by sector in both reference scenarios



Source: Historical data up to 2015 from EEA (2022) and NEMESIS model thereafter. AFOFI: Agriculture, Forestry and Fishery.

Figure 50: EU primary energy consumption by fuel in both reference scenarios



Source: Historical data up to 2010 from Eurostat (2023a) and NEMESIS model thereafter.

Box 1: Comparing NEMESIS and PRIMES results

Here, we compare NEMESIS with PRIMES results for the "Paris Agreement compliant" scenario, considering EU CO_2 emissions by sector and gross inland energy consumption (see figure below).

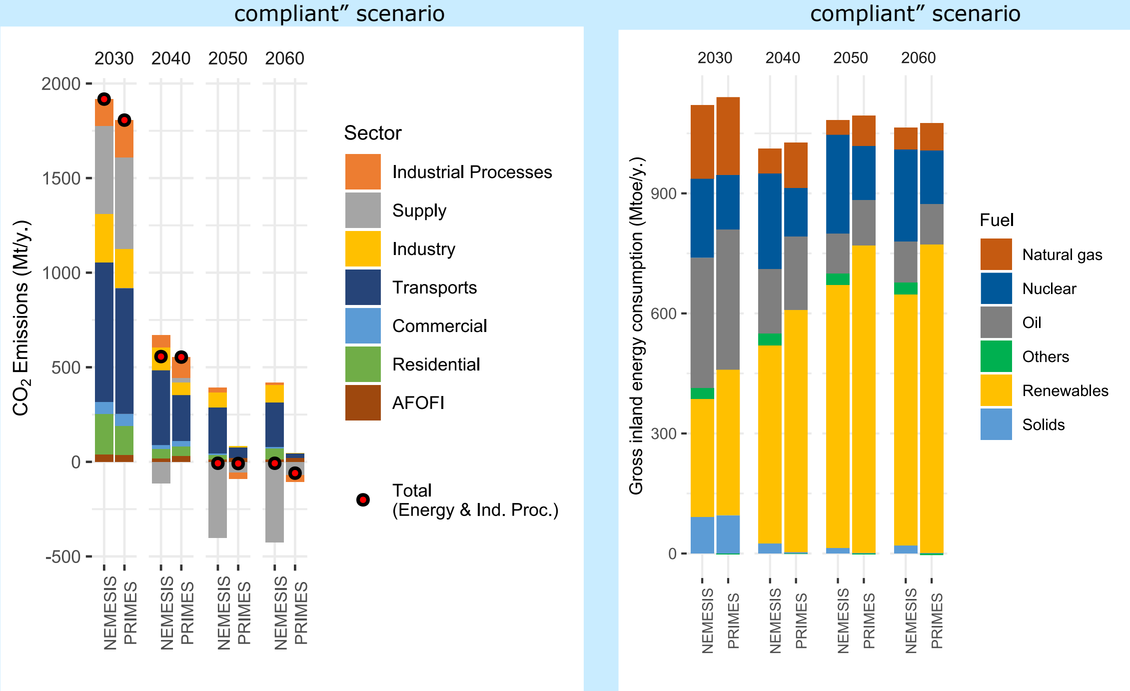
Both models deliver relatively similar results in terms of CO_2 emissions reduction towards NZE for EU. The main difference is the extent of negative emissions in the energy supply sector that is much more prevalent in NEMESIS than in PRIMES, allowing lower emissions mitigation effort on demand-side sector. In 2050, the CO_2 emissions of the energy supply sector equal to -57 Mt in PRIMES and -400 Mt in NEMESIS. The NEMESIS model is a macro-economic model with less technological details and mitigation options (e.g. no hydrogen, no CCS in industry or no e-fuels) than the PRIMES model, and consequently NEMESIS relies more on BECCS to achieve NZE in 2050. Even if this 400 Mt captured and sequestered per year in the middle of the century may be challenging in practice (Rosa et al., 2021), it remains feasible technically when considering the carbon storage potential in EU, estimated to be between 20 and 60 Gt (Fuss et al., 2018) and even up to 300 Gt (International Association of Oil & Gas Producers, 2019).

NEMESIS also shows similarities with PRIMES on how the EU energy system is decarbonised, with a significant decline of fossil fuel energy consumption largely substituted by a large deployment of renewable energy sources, reaching 767 Mtoe in 2050 in PRIMES (70% total EU gross inland energy consumption) and 656 Mtoe in NEMESIS (60%). Nevertheless, the renewable energy sources mobilised differ, with NEMESIS relying strongly on bio-energy, up to 346 Mtoe in 2050, compared with 227 Mtoe for PRIMES, that is nonetheless in line with the aggregated bio-energy potential calculated by Ruiz et al. (2019) for the EU (180-485 Mtoe), even if on the upper bound of the range.

Figure 51: Comparison of NEMESIS and PRIMES results

a) EU CO_2 emissions from energy and industrial processes by sector in "Paris Agreement compliant" scenario

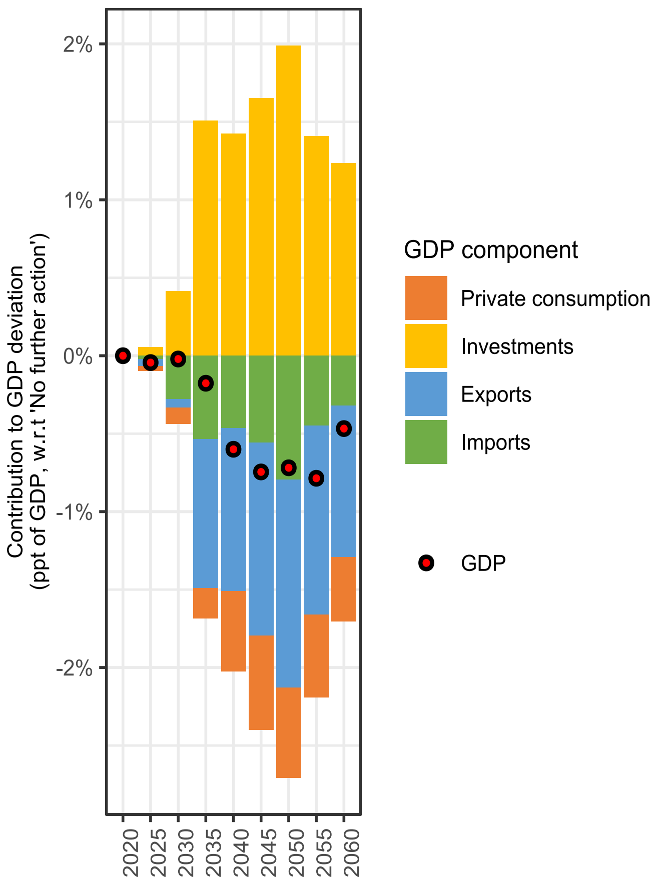
b) EU gross inland energy consumption by fuel in "Paris Agreement compliant" scenario



Source: NEMESIS and PRIMES models (CO_2 emissions for transport include emissions from international bunkers). Scenario "Fit for 55: High Energy prices - OptF" has been used for PRIMES.

Finally, NEMESIS, being a macro-economic model, allows for the assessment of the cost of emissions mitigation in the EU, by calculating the corresponding GDP impacts. The figure below shows the GDP deviation in the "Paris Agreement compliant" scenario in comparison to the "No further action" scenario, as well as the contribution of the GDP component to this deviation. The transition of the European economy towards a carbon neutral economy implies large investments that contribute to push up EU GDP, with a contribution of these investments of +0.4% of GDP in 2030, +1.4% in 2040, +2% in 2050 and +1.2% in 2060. However, these additional investments mobilise additional scarce capital and labour resources and then determine inflationary pressure in EU, that directly affect EU competitiveness, reducing export (-0.1% of GDP in 2030, -1% in 2040, -1.3% in 2050 and -1% in 2060) and increasing imports already mobilised to support the investment needs (-0.3%, -0.5%, -0.8% and −0.3% respectively). Similarly, EU private consumption is also reduced in the "Paris Agreement compliant" scenario by -0.1% of GDP in 2030, -0.5% in 2040, -0.6% in 2050 and -0.4% in 2060, due to the income losses. As a consequence, in 2030, the EU GDP is relatively similar in both reference scenarios, but it declines from 2040 (-0.6%), up to -0.7% in 2050 in "Paris Agreement compliant" compared to "No further action". In 2060, EU GDP loses are reduced by 0.5%. Thus, from 2020 to 2060, the EU GDP loss is about 0.4%.

Figure 52: EU GDP and contribution to deviation in the "Paris Agreement compliant" scenario



Source: NEMESIS model.

This GDP loss is on the lower bound of European Commission's macro-economic impact assessment (European Commission, 2018), where GDP impacts range between -1.3% to +2.2% in comparable scenarios. Nevertheless, we must mention limitations and specific assumptions in the NEMESIS model that influence downward the impacts on GDP:

- NEMESIS has limited mitigation options, especially in hard-to-abate sectors, such as no hydrogen, no CCS in the industry sector, and no e-fuels.
- We do not assume any impact on the rest of the world, doing so would probably limit the negative competitiveness impact, even if lower demand in the rest of the world could also penalise EU exports.
- We assume limited availability of credit implying increasing capital cost to respond to investment needs to realise the climate transition. Relaxing this assumption by assuming

no capital scarcity would significantly modify the impact on EU GDP —see Pollitt and Mercure (2019) for a discussion on that point and Boitier et al. (2022) for a sensitivity analysis.

3.3 Synthesis of the literature review on climate damages and input data collection

For the next step of our methodology, we aim to introduce climate damages in the NEMESIS model in accordance with both global climate contexts. Starting from the literature review, we identified relevant studies that deliver quantitative figures and that could be used in the macro-economic model. We did this in-depth analysis for each hazard or impact discussed previously and listed in Table 12, except for tourism and ecosystem services.

Indeed, the studies that assess the economic impacts of future climate change on EU tourism are particularly segmented in their scope, focusing on winter or summer tourism and looking at some specific countries or regions, such as Spain (Hein et al., 2009), Sweden (Moen and Fredman, 2007) or Northwestern Europe (Nicholls and Amelung, 2008). In addition, most of them have been published more than 10 years ago and do not use recent IPCC climate projections (Nicholls, 2006; Barrios and Ibañez Rivas, 2013). These specifics of the literature on the climate change impacts on EU tourism do not allow for an appropriate inclusion into the macro-economic assessment. As the literature review concluded that "studies summarize that tourism expenditures are reallocated spatially and sectoral, reductions are compensated with increased expenditures in other regions or to free time activities in the home region", the expected macro-economic impacts would have been really limited.

In addition, as the literature review has revealed, economic quantification of the climate change impact on EU ecosystem services is very limited, with two main studies delivering aggregated figures. OECD (2015) assumes a willingness-to-pay for ecosystem services conservation between 0.5 to 1.1 of EU GDP in 2060 according to climate scenarios, a usual complementary approach to monetize ecosystem services for macro-economic modelling (Longo et al., 2012). World Bank (2021) indicates a potential loss of agricultural production of 5% in 2030 in EU.

Table 12:List of impacts included in the macro-economic modelling

Impacts	Included in the macro-economic modelling	Number of studies included
Coastal flooding	Yes	5 (Table 13)
River flooding	Yes	1 (Table 18)
Droughts	Yes	2 (Table 18)
Labour productivity	Yes	7 (Table 14)
Agriculture	Yes	4 (Table 15)
Forestry	Yes	1 (Table 18)
Fisheries	Yes	1 (Table 18)
Energy demand	Yes	5 (Table 16)
Energy supply	Yes	5 (Table 17)
Ecosystem services	No	--
Tourisms	No	--

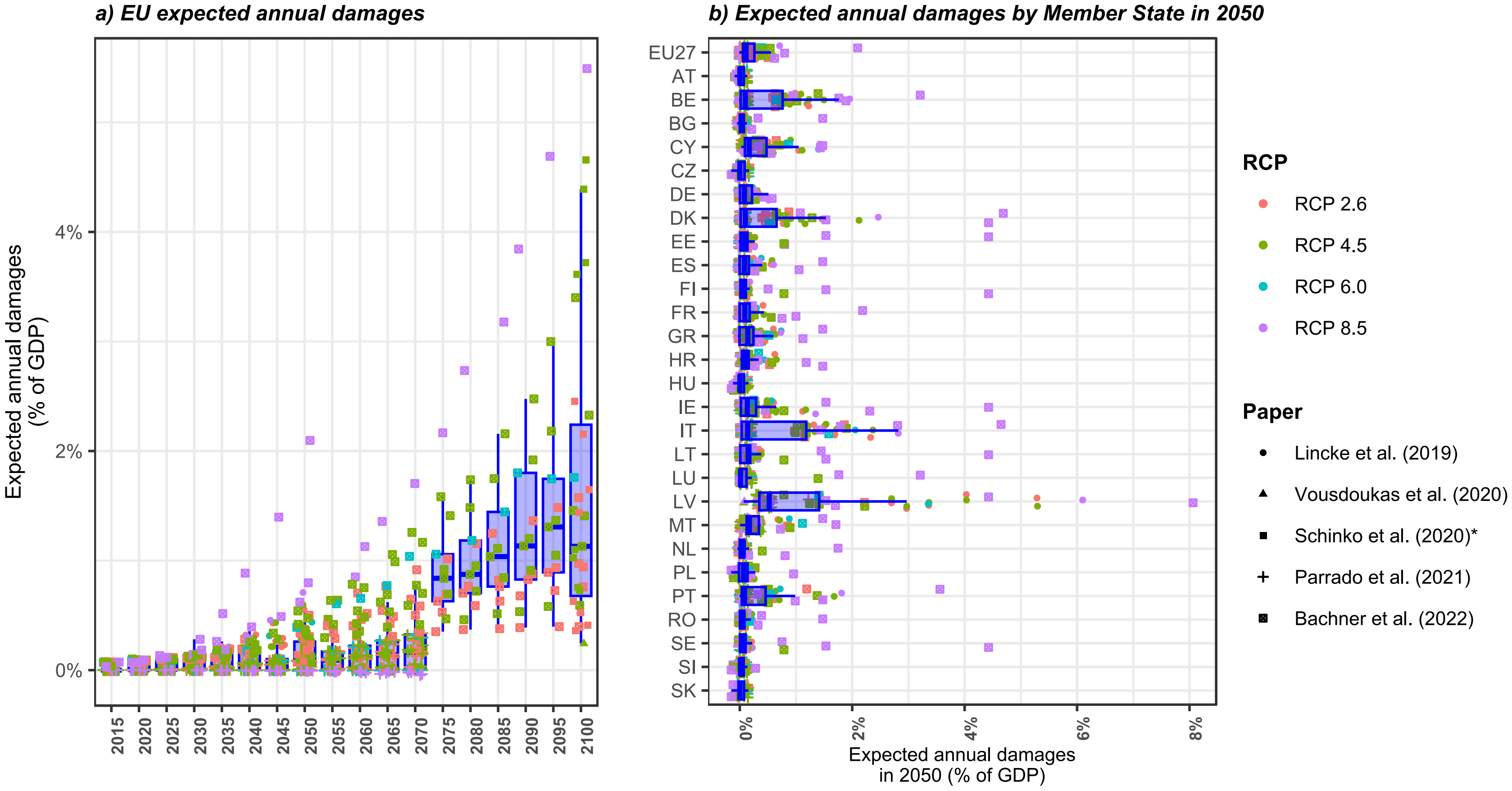
3.3.1 Coastal Flooding

From the literature review, we identified five studies relevant for the macro-economic analysis of coastal flooding economic damages, insomuch as they deliver quantitative results for the EU at an enough detailed level for their implementation in the NEMESIS model, but also to allow their comparison.

Table 13: List of studies used for macro-economic modelling on coastal flooding economic impacts

Study	EU coverage	Direct impacts	Macro-economic impacts	Source of direct impacts	Scenarios covered	Adaptation	Sensitivity	Time	Remark
Lincke et al. (2019)	NUTS-2 level	Yes	No	DIVA model	Combinations of SSP-RCP	With and without adaptation (incl. cost of adaptation)	Ice melting	From 2020 to 2100 by 5-years step	26 different scenarios in total
Vousdoukas et al. (2020)	MS level	Yes	No	Vousdoukas et al. (2016)	RCP4.5 and RCP8.5 summarised in "Moderated mitigation" and "High emissions" respectively; Specific EU-based socio-economic assumptions	With and without adaptation (incl. cost of adaptation - partially)	No	Base year, 2050 and 2100	
Schinko et al. (2020)	Direct impacts: DE, FR & IT Macro impacts: EU-28	Partially available	Yes	DIVA model	SSP2-RCP2.6 SSP2-RCP4.5	With and without adaptation (incl. cost of adaptation)	Ice melting Global climate models	From 2015 to 2100 by 5-years step	Three macro-economic models used (FAIR, GEM-E3; WITCH)
Parrado et al. (2021)	NUTS-2	From Lincke et al. (2019)	Yes	DIVA model	Combinations of SSP-RCP	With and without adaptation for some scenarios (incl. cost of adaptation)	Ice melting Capital mobility	From 2015 to 2070 by 5-years step	64 different scenarios in total Give results for GDP, capital stock and labour productivity
Bachner et al. (2022)	9 EU regions	Yes	Yes (Partial data in Supp. Mat.)	DIVA model	Combinations of SSP-RCP + no climate impact	With and without adaptation (incl. cost of adaptation)	Ice melting	From 2015 to 2100 by 5-years step	72 different scenarios in total Deliver also impacts on migration

Figure 53: Synthetic figures on expected damages from costal floodings



Source: Authors' elaboration based on Lincke et al. (2019), Vousdoukas et al. (2020), Schinko et al. (2020), Parrado et al. (2021) and Bachner et al. (2022). *: cover EU28. The scenarios considered in this figure exclude adaptation measures.

The quantification of the expected annual damages in the EU from coastal flooding is well documented at the EU (Schinko et al., 2021), EU aggregated regions (Bachner et al., 2022), national (Vousdoukas et al., 2020) and even NUTS-2 levels (Lincke et al., 2019 and Parrado et al., 2021). These studies cover almost all AR5 SSP-RCP scenarios and most of them implement a direct impact calculated by the DIVA model (Hincke et al., 2014) into a general equilibrium model.

Sea level rise due to climate change has relatively slow and progressive impacts compared with other climate change induced hazards. In 2030, the expected damages for EU are relatively low, ranging from a minimum of 0% to a maximum of 0.28% of GDP, with median value at 0.02% (Figure 53). The increase of coastal floodings in 2050 in all scenarios leads to higher GDP losses in EU, 0.11% [-0.01— 2.1%][61]. Damages continue to grow in RCP8.5, RCP6.0 and RCP4.5 and even RCP2.6 scenarios, reaching 1.1% [0.3 — 5.5%] of EU GDP in 2100, and remaining relatively stable in RCP2.6 related scenarios.

The range of the expected impacts by Member State is larger than aggregated figures for the EU, with some countries like Latvia (0.5% [0.07-8.1%] of GDP), Italy (0.14% [0.02-4.7%]) or Belgium (0.1% [0.-0.01-3.2%]), being exposed to large economic damages in 2050 (Figure 53) whereas others with no seashore, are not impacted or only indirectly, as in the case of Austria (0% [-0.09-0.13%]) or Hungary (0% [-0.15-0.15%]).

3.3.2 Labour productivity

We identified seven different studies that deliver usable quantitative figures for EU on the expect impacts of climate change on the labour productivity (Table 14). All these studies considered that the impact on labour productivity will come from higher exposure to heat waves and/or more frequent extreme daily temperatures. They also used relatively similar methodologies to calculate the expected impacts. These studies start with global and regional climate model projections that allow the calculation of the Wet Bulb Globe Temperature (WBGT), used as a standardised metric for the assessment of workers exposure to weather conditions: International Standard Organization used this metric as occupational heat stress index (ILO, 2017). Thereafter, they use exposure response functions to calculate the losses of working hours due to higher WBGT. Finally, they introduce the productivity shocks into a general equilibrium model to assess the macro-economic impacts (except in Kjellstrom et al., 2019).

Two studies (Szewczych et al., 2021; Kjellstrom et al., 2019) used historical values as reference to compare their projections, and not a counterfactual scenario without damages, to convert their results. We then used average temperature change over the period they considered (from 1980 to 2010 in both studies) to correct their results based on historical data from NOAA (2023). Furthermore, some studies only deliver the impact on GDP and not on labour productivity. Iin this case, we proxied the impact on labour productivity using the labour cost share in GDP of each region in 2019, as calculated in the EU KLEMS database (Stehrer and Sabouniha, 2023).

Figure 54 shows that in 2030, the expected labour productivity changes due to climate change in EU from the literature is of -0.21% [-0.94 — 0%] in 2030, -0.39% [-1.92 — 0.03%] in 2050 and -0.63% [-2.25 — 0%] in 2090. At Member State level (Figure 54), the potential impact on labour productivity in 2050 may be larger mainly in Mediterranean and South-European countries such as Greece, with -1.18% [-5.9 — -0.31%], Cyprus -0.04% [-5.1 — -0.03%] or Romania -0.24% [-4.8 — -0.11%].

[61] Here and thereafter, these numbers indicate: median [minimum – maximum].

Table 14: List of studies used for macro-economic modelling of the climate change impacts on EU labour productivity

Study	EU coverage	Direct impacts	Macro-economic impacts	Source of direct impacts	Scenarios covered	Adaptation	Sensitivity	Time	Remark
Parrado et al. (2021)	NUTS-2	No	Yes (ICES-XPS model)	Schleypen et al. (2019)	Combinations of SSP-RCP	Without adaptation	Capital mobility	From 2015 to 2070 by 5-years step	18 different scenarios in total (compared to no climate change scenario)
Kjellstrom et al. (2019)	Europe with details for some MS (uncompleted)	Yes	No	Wet Bulb Globe Temperature (WBGT) & exposure response functions (ERP)	1 scenario (+1,5°C in 2030, average 2010-2040, all RCP)	Qualitative	--	2030 (average 2010-2040)	Limited to 2030 No dataset available Results are compared to 1981-2010 average
Szewczych et al. (2021)	EU MS + UK (excl. MT)	Yes	Yes (Economic growth model à la Solow)	WBGT & ERP	2 scenarios (RCP 8.5)	Without and with adaptation		2020, 2050, 2080	Results are compared to 1981-2010 average
Orlov et al. (2020)	Europe (EU27+UK+ EFTA+Balkans)	Yes	Yes (GRACE model)	WBGT & ERP	Combinations of SSP-RCP (SSP1, SSP4, SSP5 and RCP2.6 and RCP8.5)	Without and with adaptation	Climate models & Exposure response functions	2050, 2100	Results are compared to no climate change scenario.
García-Léon et al. (2021)	EU MS + UK	Yes	Yes (CGE model)	WBGT & ERP	RCP 8.5	Without adaptation	SSP5 socio-economic drivers	1981-2000 2001-2020 2021-2034 2035-2044 2045-2054 2055-2064	Results are compared to no climate change scenario.
Knittel et al. (2020)	Some MS and aggregated EU regions (Central, Northern, Mediterranean, Southern)	Yes	Yes (CGE model)	WBGT & ERP	Combination of SSP1, SSP2 and SSP3 with RCP4.5 & RCP8.5	Without adaptation	CGE parameters (capital-labour elasticity, subregional substitutability)	2050	Results are compared to no climate change scenario.
Matsumoto et al. (2021)	EU+8	Yes (not presented)	Yes (CGE model)	WBGT & ERP	Two mitigation scenarios (RCP4.5 & 2°C)	Without adaptation		From 2005 to 2010 by 5-years step	None impact on labour productivity in Europe expected in all scenarios

Figure 54: Synthetic figures on expected labour productivity losses induced by climate change

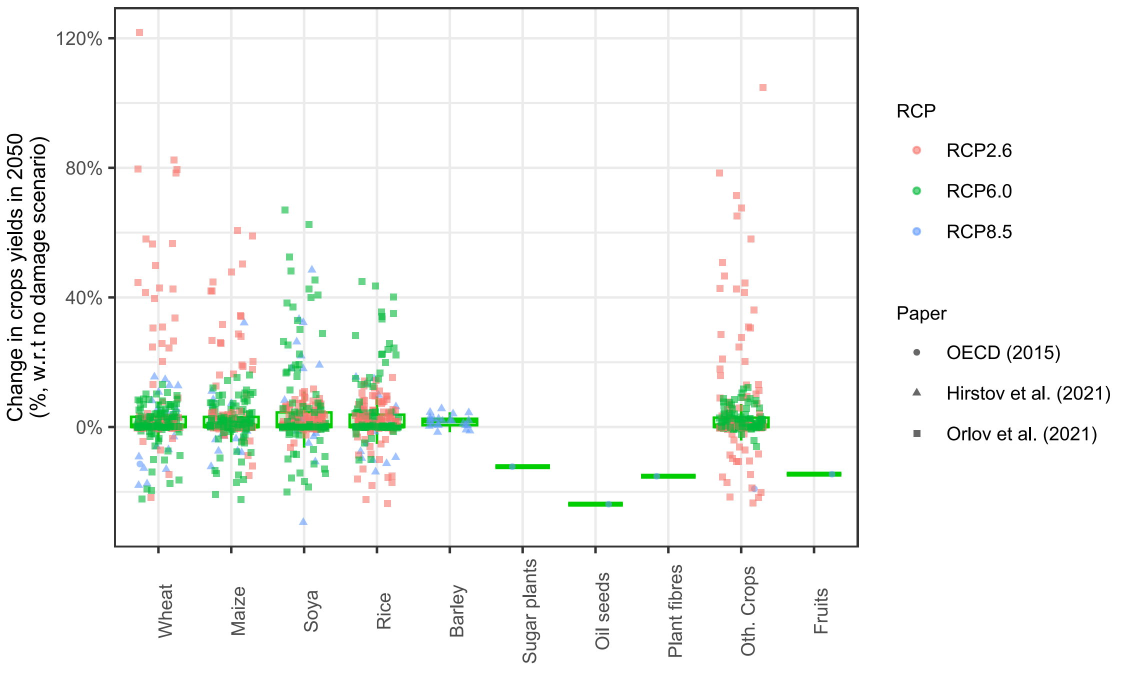
Source: Authors' elaboration based on Kjellstrom et al. (2019), Knittel et al. (2020), Orlov et al. (2020), Garcia-Leon et al. (2021), Matsumoto et al. (2021), Szewczych et al. (2021) and Parrado et al. (2021).

3.3.3 Agriculture

The analysis of the climate change impacts on agriculture in the EU is largely based on similar methodologies. Climate models are used first for climate projections and input biophysical crop yields models. The results of the latter are then introduced in other agriculture specific models for EU (Hristov et al., 2020) or in general equilibrium models detailing the agriculture sector (OECD, 2015; Orlov et al., 2021 and Parrado et al., 2021). The studies include sensitivity analysis mainly based on the bio-physical models' uncertainty, but also on some key parameters of the modelling work, such as capital mobility in Parrado et al. (2021). The inclusion of the "CO_2 fertilization effect", i.e. an increase of photosynthesis due to higher CO_2 concertation in the atmosphere, affects also significantly the results.

Orlov et al. (2021) used the period 1981-2010 as reference to compare their results and not a counterfactual scenario without damages. We have then converted their results by considering the average temperature change over this period with historical data from NOAA (2023). Furthermore, to aggregate the results delivered by crop to total crops production, we used 2019 crops share from Eurostat (2023b, 2023c) for each Member State. Finally, we also proxied change in production into change in crop yield that suppose no change in crop demand. This approximation has nevertheless no impact when implementing the results in the NEMESIS model, because we do not include ex-ante assumption on the demand-side.

Figure 55: EU crops yield change in 2050 due to climate change



Source: Authors' elaboration based on OECD (2015), Hristov et al. (2021) and Orlov et al. (2021). Parrado et al. (2021) is not included because it only delivers results for total crops.

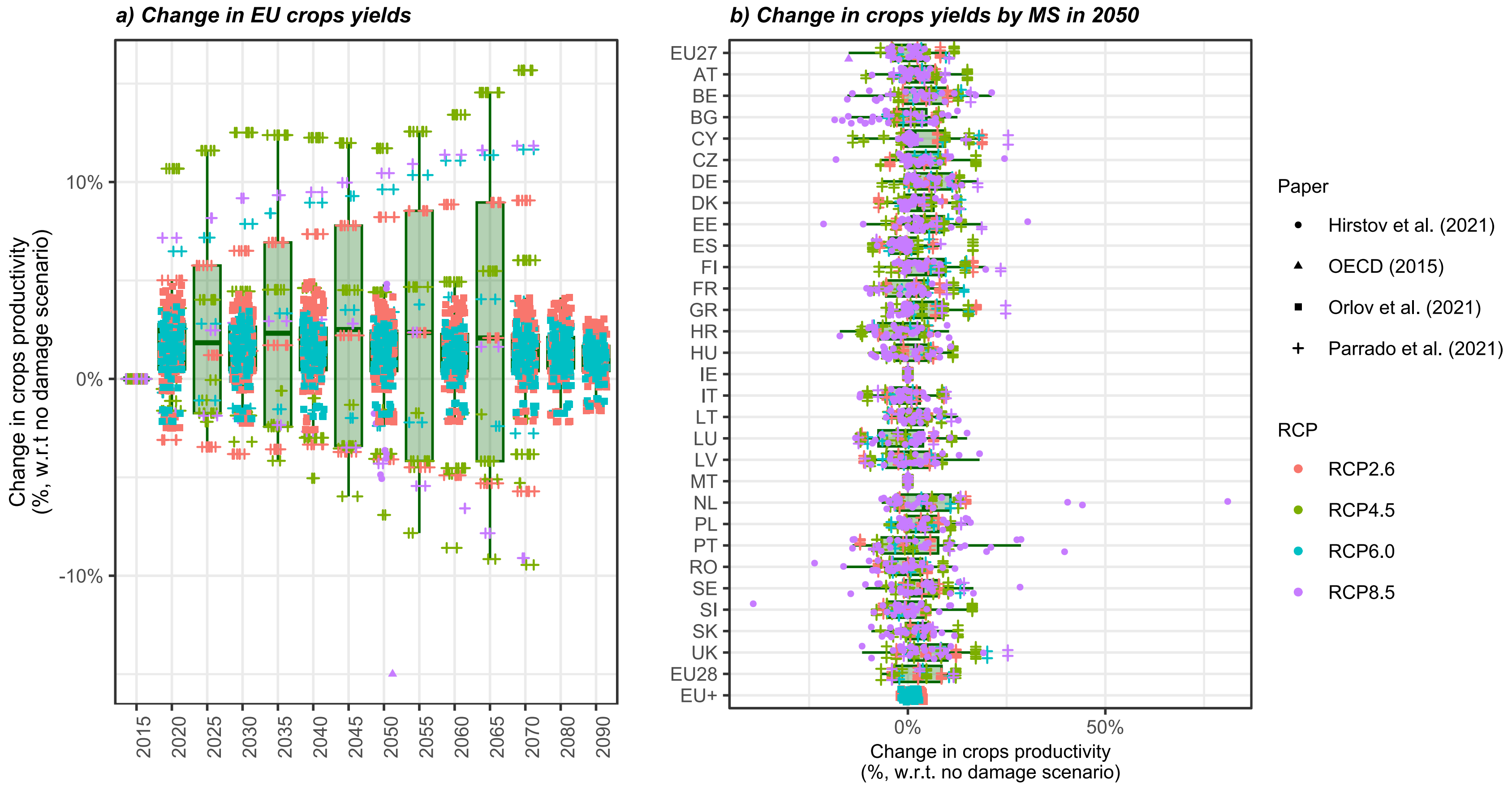
The projected impacts of future climate change on EU crops yield are relatively uncertain. Figure 55 shows positive as well as negative impacts on crops yields. The median impact on EU wheat yields in 2050 is null, but the range of the literature is very large from -22% to +120%. Similarly, the change in soya and maize yield ranges between -29 to 67% and -20% to 61% respectively with also median values at zero. The projected barley yield changes in EU in 2050 are smaller, with +2% [-1.6 — 6%].

Table 15: List of studies on climate change impacts on agriculture identified for the macro-economic modelling exercise

Study	EU coverage	Direct impacts	Macro-economic impacts	Source of direct impacts	Scenarios covered	Adaptation	Sensitivity	CO_2 fertilisation effect	Time	Remark
Hristov et al. (2020)	NUTS-2	Yes	No	Biophysical models (ISI-MIP GGCMs, WOFOST) combined with an agro-economic model (CAPRI)	RCP8.5	Tested (irrigation infrastructures; changing sowing dates and crop varieties; farmers practices;		Yes (in biophysical models)	2025/2045/2050	Data only from the CAPRI model (with endogenous market-based adaptation)
OECD (2015)	Global – 3 regions in EU	Yes	Yes (but not specific to impact to agriculture)	IMPACT Model (Vom Lampe et al., 2014)	+1.5°C in 2030 and +2.2°C in 2050 (≈RCP8.5)	No	--	No	2050	
Orlov et al. (2021)	Europe (EU27 + UK+ EFTA + Balkans)	Yes	Yes (GRACE model)	Heat waves measured with Wet Bulb Globe Temperature & exposure response functions Crops yields, from ISIMIP2b crops models (Frieler et al., 2017)	Combinations of SSP-RCP (SSP1, SSP4 and RCP2.6 and RCP6.0)	Yes, (rainfed vs. fully irrigated, market-based)	Analysis of the contribution to results variance of global climate models, crop modelling, heat metric and SSPs.	No	2041-2070 2071-2100	Results consider impact of heat waves on labour productivity for crops production. Results are compared 2018-2010 period.
Parrado et al. (2021)	NUTS-2	No	Yes (ICES-XPS model)	From Boere et al. (2019)	Combinations of SSP-RCP	Without adaptation	Capital mobility		From 2015 to 2070 by 5-years step	18 different scenarios in total (compared to no climate change scenario)

										Only total crop yields

Figure 56: Climate change impacts on EU crops yields



Source: Authors' elaboration based on OECD (2015), Hristov et al. (2021), Orlov et al. (2021) and Parrado et al. (2021).

The aggregated figures show the same uncertainties on the future impact of climate change on EU total crops yields (Figure 56). The median values are slightly positive, but the uncertainty is important, with 1.5% [-3.8 — 12.5%] in 2030, 1.4% [-15 — 12%] in 2050 and 1% [-1.6 — 3%] in 2080. The variability is also very large at Member State level with for instance, 0% [-23 —12%] in 2050 in Romania, 2% [-10% — 14%] in France or 4% [-7 — 81%] in the Netherlands.

3.3.4 Energy demand and supply

There are several studies on the potential impact of climate change on the EU energy system. We identified five studies considering the impacts on the demand side and five other studies looking at the supply side. These studies are not easily comparable because they cover different sectors and/or fuels.

On the demand side, three studies assessed the impact on electricity demand (Damm et al., 2017; Wenz et al., 2017 and Bloomfield et al., 2021) whereas Kitous and Duprès (2018) covered all fuels and looked at heating and cooling energy demand. Finally, Parrado et al. (2021) covered all fuels and all sectors. Once again, Bloomfield et al. (2021) and Wentz et al. (2017) compared their results to a specific reference period. We have then converted their results by considering the average temperature change over the period they considered with historical data from NOAA (2023).

As Figure 57 summarises, the expected change in energy demand due to climate change in EU will take place in the buildings sector (residential and services) due to a reduction in the demand for heating during winter and increase of the demand for cooling in summer. In the residential sector, the total energy demand is expected to decline of about -6% [-7.6 — -2.8%] in 2030 and 13.8% [-17.7 — -8.6%] in 2050 in comparison to a scenario without damage.

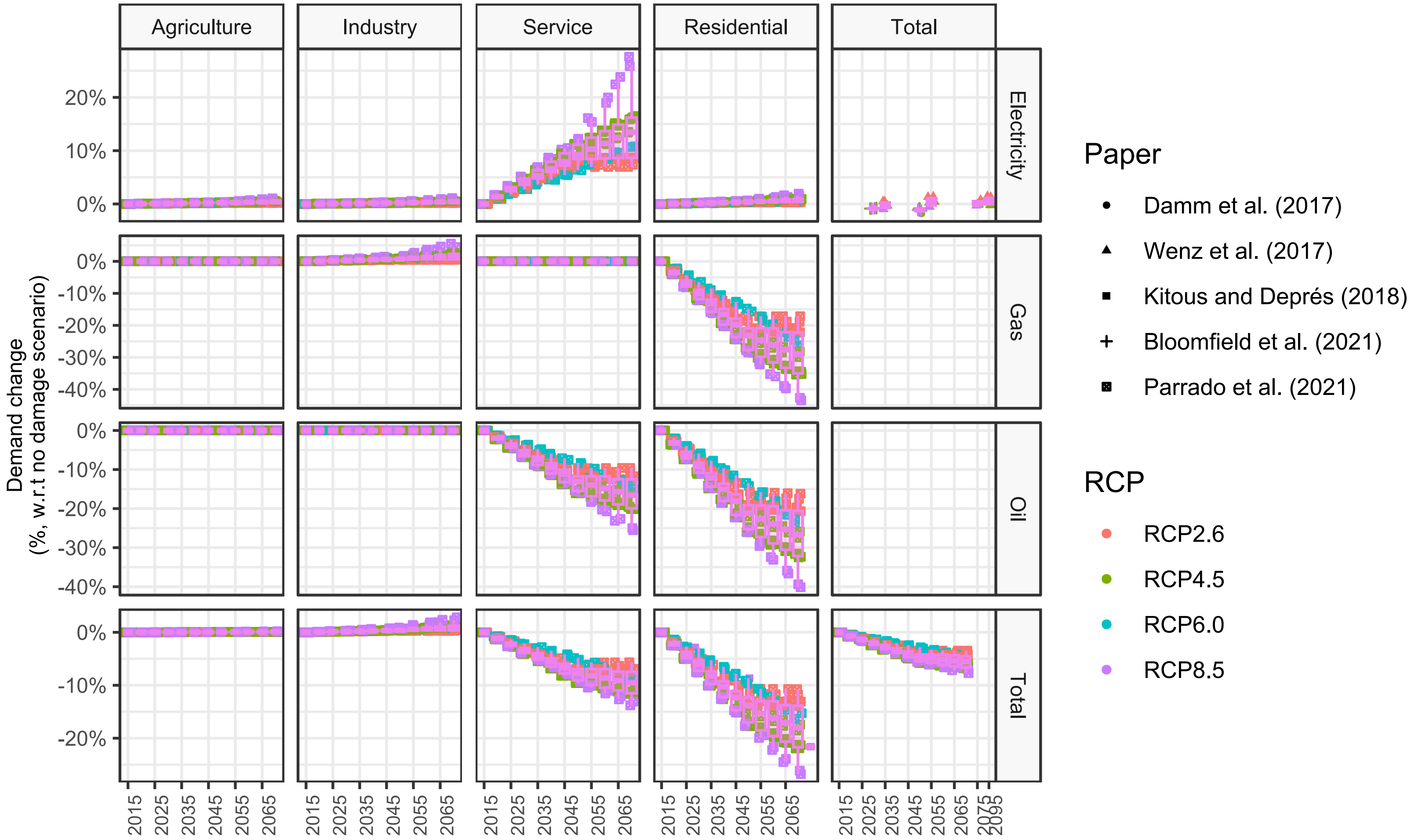
On the supply side, the studies consider mainly the impact on the potential of renewable energy sources in power generation: Gøtske and Victoria (2021) focused on hydro, Parrado et al. (2021) on hydro and wind, Bloomfield et al. (2021) on hydro, PV and wind and Desprès and Adamovic (2020) on all sources (nuclear, thermal, hydro, wind and solar). Furthermore, the comparability of results between studies has been difficult because they do not deliver homogeneous results, Gøtske and Victoria (2021) calculate change on hydro inflow, Bloomfield et al. (2021) capacity factors, whereas Parrado et al. (2021) and Desprès and Adamovic (2020) deliver the change in electricity generation. The link between capacity factor and production is complex. We then realised some testing simulations with NEMESIS, by modifying the capacity factors, in order to proxy the impact on the production.

Figure 58 shows the change in production of electricity by source. The climate change impact on power generation is relatively important but with high uncertainty, in particular for hydro, with ranges from -18% to +25% of production according to scenarios and countries with a median value across Member States indicating no impact. Similarly, the median value of electricity production from solar and wind is also nil, with a variation from -7.5% to 5% and -22% to 10% respectively. For nuclear, the production is expected to be slightly reduced with -1% [-21 — 5%] across Member States in 2050 with, for instance, -1% [-5 — 0%] in France or –4.5% [-21 — -0.5%] in Spain. Finally, the power generation production from thermal sources is expected to decrease slightly -1% [-12 — 9%].

Table 16: List of studies on climate change impacts on energy demand identified for the macro-economic modelling exercise

Study	EU coverage	Direct impacts	Macro-economic impacts	Source of direct impacts	Scenarios covered	Adaptation	Sensitivity	Time	Remark
Damm et al. (2017)	EU MS + UK	Yes	No	Energy system modelling	+2°C (assumed as RCP4.5 in 2050)	--	Yes (RCPs, no considered here)	2050 (proxied)	Data retrieved from the paper. Only electricity
Wenz et al. (2017)	EU+	Yes	No	Relationship between daily electricity consumption and daily average temperature	RCP2.6 RCP4.5 RCP8.5	--	--	2035-2039 2055-2059 2075-2079 2095-2099	Year proxied with the first year of the range Only electricity Results in difference to 2015-2019
Kitous and Després (2018)	EU28 (5 aggregated regions)	Yes	No	Energy system modelling (POLES model)	RCP8.5	Yes (no monetary quantification)	Yes (climate models)	2010-2100 (averaged 2030; 2050 and 2080)	Data retrieved from the paper.
Parrado et al. (2021)	NUTS-2	No	Yes (ICES-XPS model)	Schleypen et al. (2019)	Combinations of SSP-RCP	No	No	2015-2070 (5-year step)	
Bloomfield et al. (2021)	EU27 (with case-study countries: Sweden, Romania, Germany, Italy),	Yes	No	Based on C3S ECEM project (Troccoli, et al. 2018)	RCP4.5 RCP8.5	--	Yes (global/regional climate models + energy demand scenarios)		Data retrieved from http://ecem.wemcouncil.org/ Results in difference to 1980-2000 Only electricity

Figure 57: Impact of climate change on EU energy demand by sector and fuel

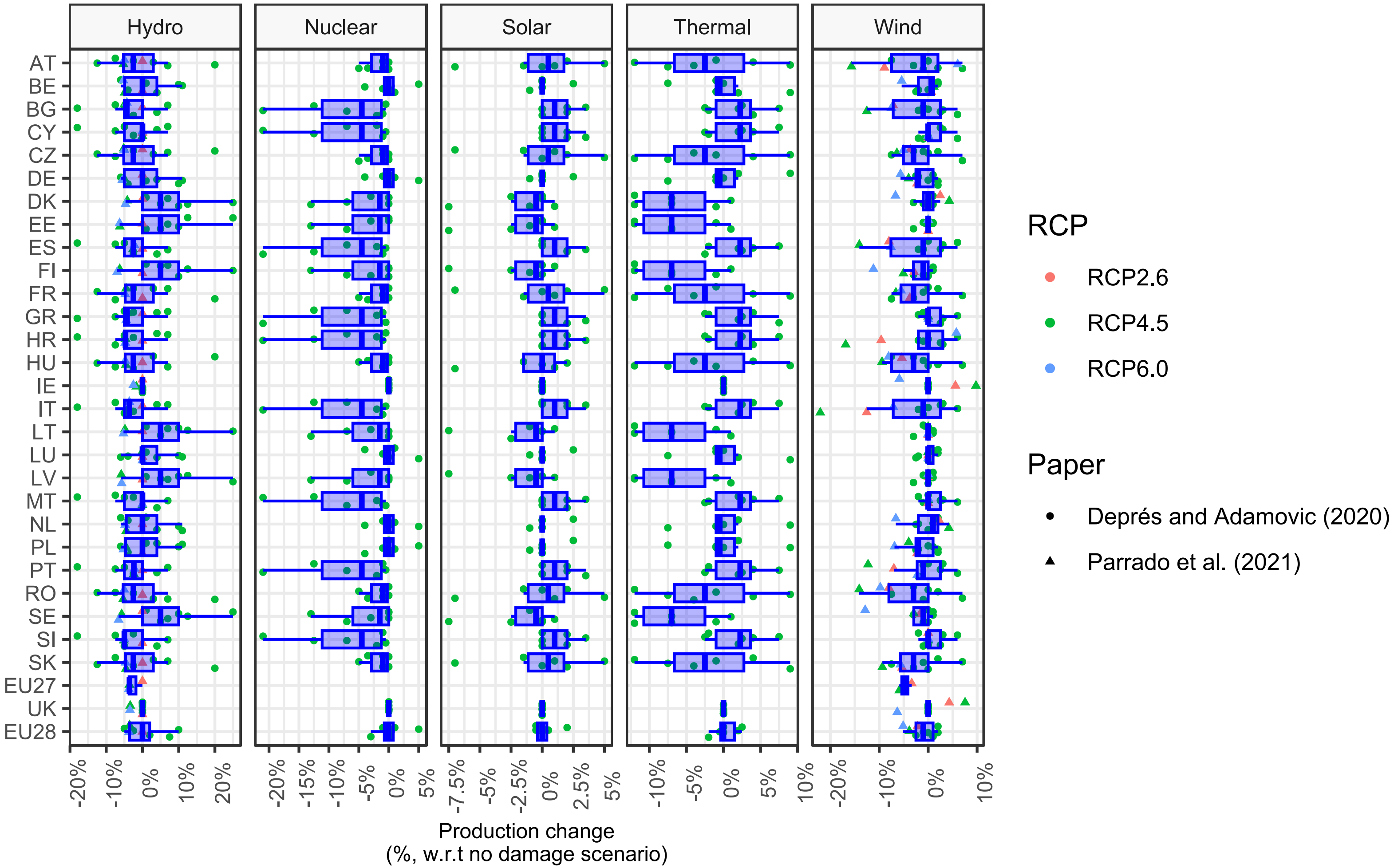


Source: Authors' elaboration based on Damm et al. (2017), Wenz et al. (2017), Kitous and Deprès (2017), Bloomfield et al. (2021) and Parrado et al. (2021).

Table 17: List of studies on climate change impacts on energy supply identified for the macro-economic modelling exercise

Study	EU coverage	Direct impacts	Macro-economic impacts	Source of direct impacts	Scenarios covered	Adaptation	Sensitivity	Time	Remark
Gøtske and Victoria (2021)	EU	Yes	No	Use of runoff data	RCP2.6 RCP4.5 RCP8.5	--	Yes (global/regional climate models)	2071-2100	Comparison with 1991-2020 Cover only hydropower potential
Bloomfield et al. (2021)	EU27 (with case-study countries: Sweden, Romania, Germany, Italy),	Yes	No	Based on C3S ECEM project (Troccoli, et al. 2018)	RCP4.5 RCP8.5	--	Yes (global/regional climate models + energy demand scenarios)		Data retrieved from http://ecem.wemcouncil.org/ Only capacity factor
Parrado et al. (2021)	NUTS-2	No	Yes (ICES-XPS model)	Schleypen et al. (2019)	Combinations of SSP-RCP	No	No	2015-2070 (5-year step)	
Schlott et al. (2018)	EU+	Yes	No	Power generation modelling	RCP8.5	--	Yes (global/regional climate)	2070-2100	Comparison with 1970-2005 RES Power generation Retrieved from Peter (2019)
Després and Adamovic (2020)	EU28 (5 aggregated regions)	Yes	No	Energy system modelling (POLES model)	+1.5°C, +2°C, +3°C	Yes	Yes (global/regional climate)	2025 2030 2050 2060 (Deduced)	

Figure 58: Impact of climate change on EU electricity production by technology in 2050



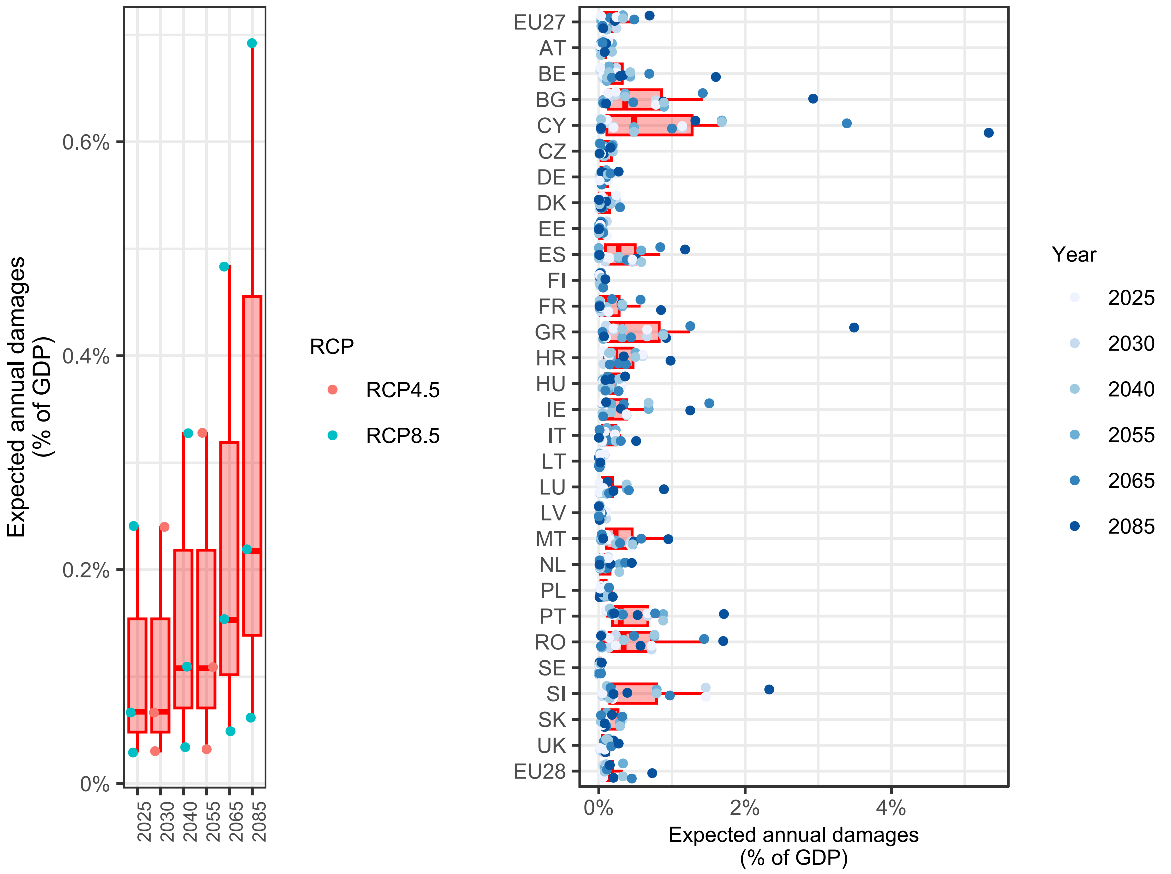
Source: Authors' elaboration based on Deprès and Adamovic (2020) and Parrado et al. (2021).

3.3.5 Other impacts

We summarize the last results of the literature for droughts, river flooding, forestry and fisheries in this section (Table 18), as we identified less relevant studies than for other types of impacts.

Naumann et al. (2021) assessed the socio-economic impacts of future droughts in EU that are supposed to grow in intensity as well as in frequency in the next decade in relation with climate change. Figure 59 presents the results in terms of expected annual damages (in GDP percentage). At EU level, the expected damages represent between 0.03% to 0.22% of EU GDP in 2030, 0.03% to 0.33% in 2055 and 0.06% to 0.7% in 2085. At Member States level, the potential annual GDP losses are larger. In 2055, the strongest impacts are projected for Cyprus (up to -1.7% of GDP), Bulgaria (-0.9%), Greece (-0.9%) or Ireland (-0.7%).

Figure 59: Expected damages from droughts due to climate change in EU



Source: Authors' elaboration based on Naumann et al. (2021).

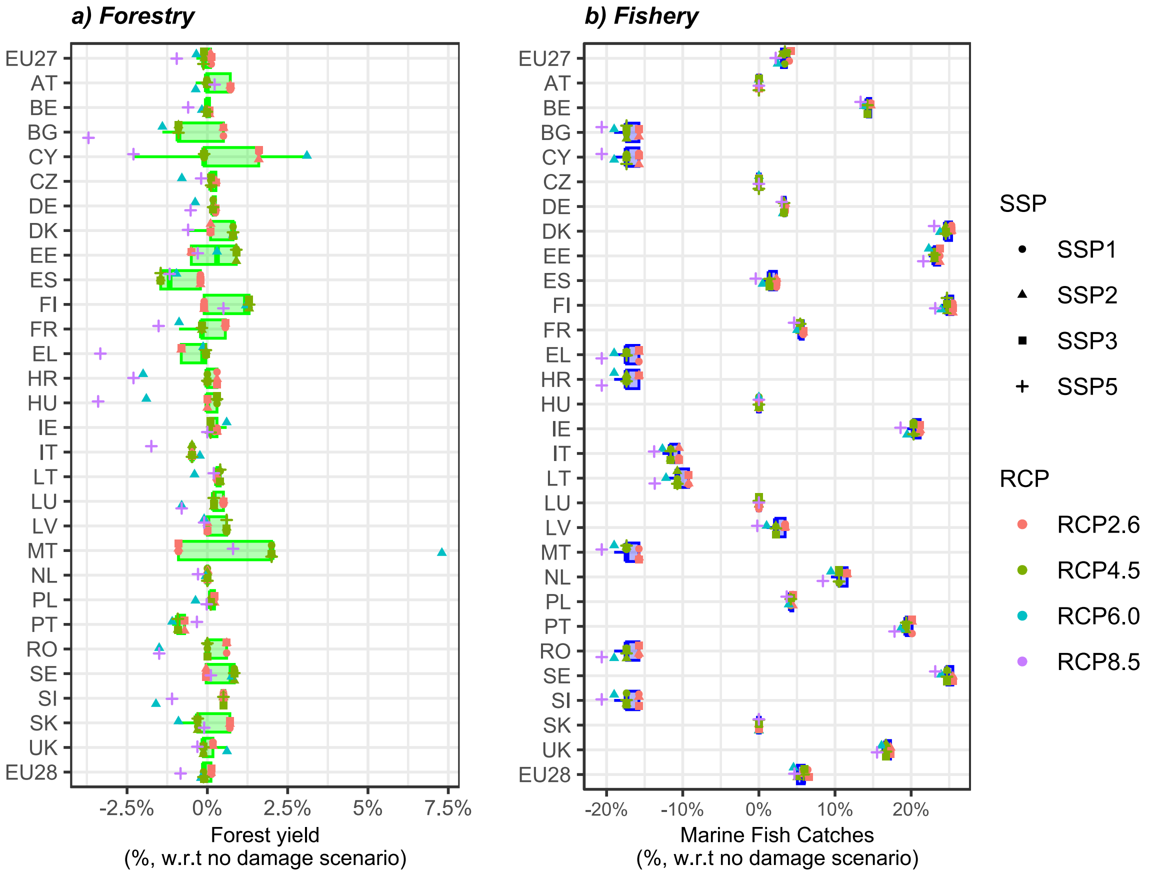
Table 18: List of studies on climate change impacts from droughts, river flooding, and on forest and fishery identified for the macro-economic modelling exercise

Impacts	Study	EU coverage	Direct impacts	Macro-economic impacts	Source of direct impacts	Scenarios covered	Adaptation	Sensitivity	Time	Remark
Droughts	Naumann et al. (2021)	EU MS + UK	Yes	Yes (CGE model)	Drought hazard modelling (LISFLOOD model) + Damages functions	+1.5°C +2°C +3°C +4°C	Yes (proxied - dynamic vulnerability)	Yes (global/regional climate models + global and regional hydrological models)		Reference years 1981-2010 Impact by sector
Forest	Parrado et al. (2021)	NUTS-2	--	Yes (ICES-XPS model)	Based on the biophysical G4M model (Kindermann et al. 2008)	Combinations of SSP-RCP	No	No	2015-2070 (5-year step)	
Fishery	Parrado et al. (2021)	NUTS-2	--	Yes (ICES-XPS model)	bio-physical models: the Dynamic Bioclimate Envelope Model (DBEM) (Cheung et al., 2016) and the Dynamic Size-based Food web model (DSFM) (Blanchard et al., 2012)	Combinations of SSP-RCP	No	No	2015-2070 (5-year step)	
River Flooding	Alfieri et al. (2018)	EU+	Yes	No	Combination of climate, hydrological and inundation modelling	+1.5°C +2°C +3°C	No	Yes (models' combination)	2030 2040 2065 (Deduced)	Comparison with 1976-2005
	Parrado et al. (2021)	NUTS-2	--	Yes (ICES-XPS model)	--	Combinations of SSP-RCP	No	No	2015-2070 (5-year step)	

Parrado et al. (2021) delivered expected impacts on forest yield and marine fisheries catches (see Figure 60). In 2050, the forest yield is expected to decline slightly at EU level, up to 0.9% in the worst case. The largest impacts are expected in Bulgaria (-0.9% [-3.7 — 0.5%]), Cyprus (-0.1% [-2.3 — 3%]), Hungary (0% [-3.4% — 0.3%]) or Finland (-0.1% [-0.1 — 3.1%]).

The impact of climate change on the marine fish catches is diverse between Member States and also relatively important. On the one hand, excluding countries without seashore, those on the North and Baltic Seas' coasts would increase the number of fish catches, e.g. +25% in Denmark or +14% in Belgium. On the other hand, Parrado et al. (2021) project an important reduction of marine fish catches in the Mediterranean and Black Seas, with, for instance, -17% in Romania and in Greece. The projections for countries around the Atlantic Ocean show more moderated changes compared to a no damage scenario, with for instance +5.5% in France.

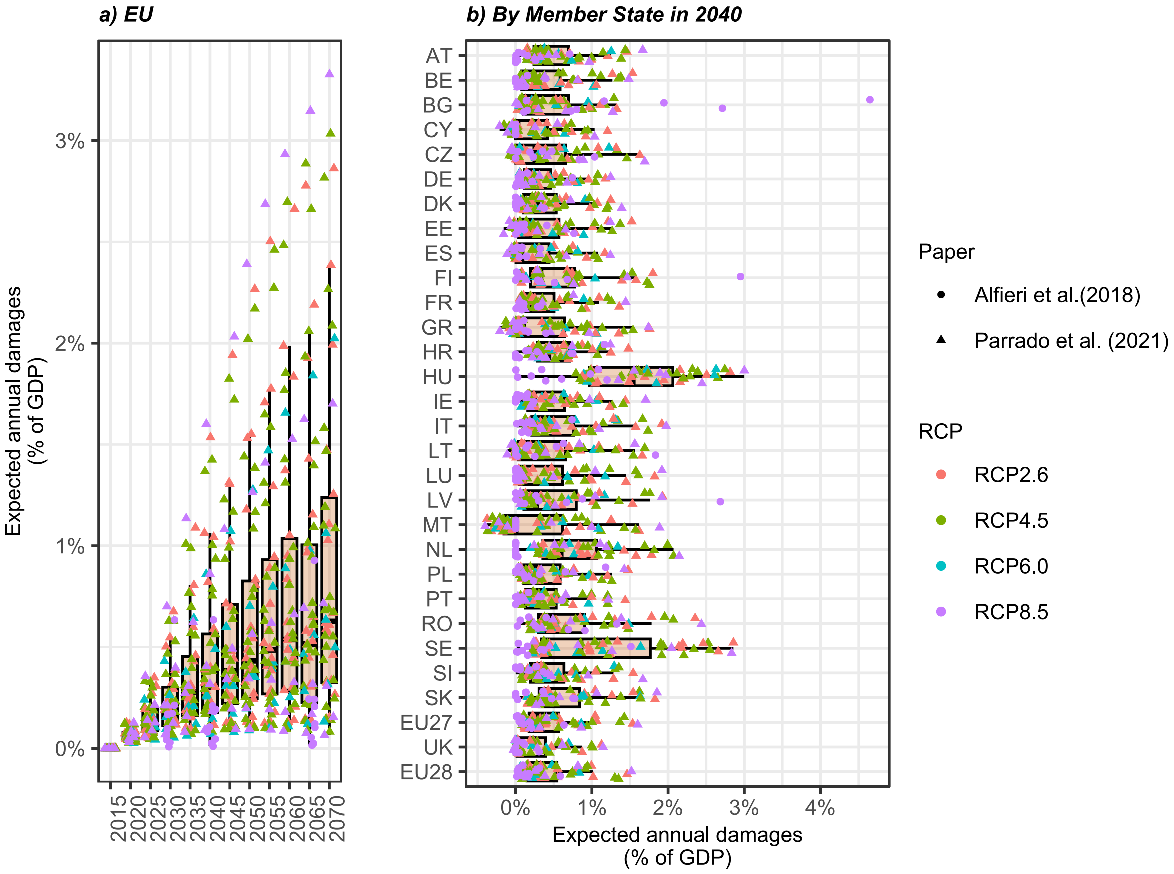
Figure 60: Change in forest yields and marine fish catches due to climate change in EU



Source: Authors' elaboration based on Parrado et al. (2021).

Finally, the expected damages from river flooding are among the most important with, in 2030, a median value of 0.18% [0 — 0.7%] of EU GDP in 2030, 0.43% [0.09 — 2.4%] in 2050 and 0.63% [0.07 — 3.3%] in 2070 (Figure 61). In Hungary, the potential economic losses reach the largest values across all EU countries, with 2.1% [0.9 — 3.8%] of GDP in 2050, followed by Sweden with 1.5% [0.3 — 4.4%].

Figure 61: Expected annual damage in EU of river flooding due to climate change



Source: Authors' elaboration based on Alfieri et al. (2018) and Parrado et al. (2021).

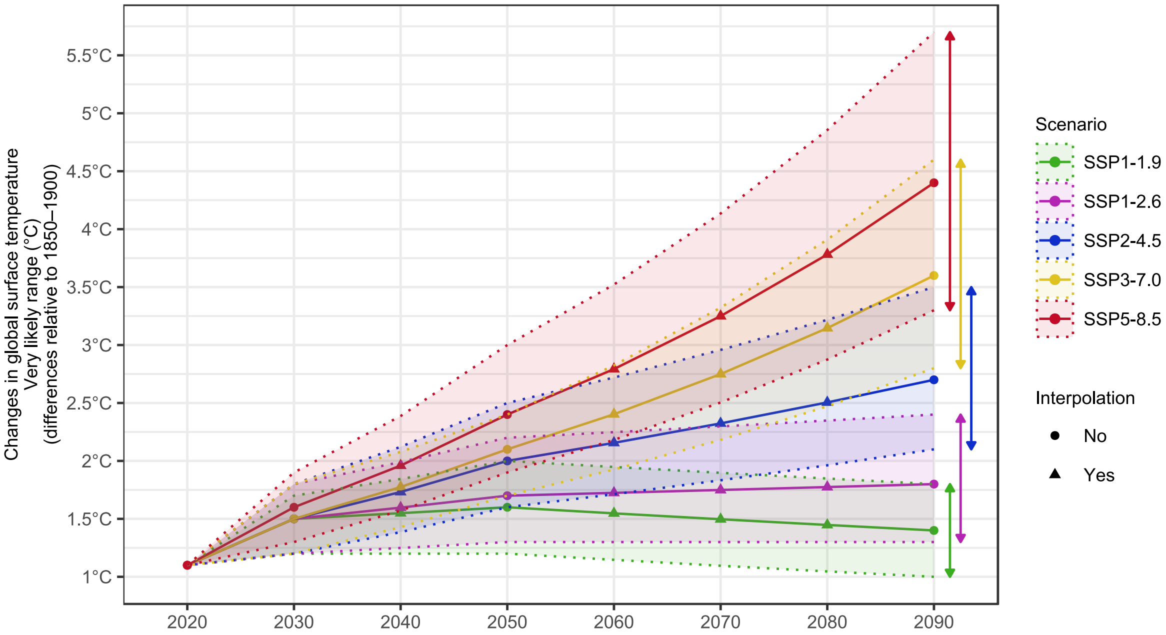
3.3.6 Data processing

Data processing was necessary to deliver the general results of the literature review on the expected economic impacts of climate change in EU, such as correcting results to use a comparable "no damage" scenario as well as for aggregation purposes. Nevertheless, to establish two different global contexts, as described in the section dedicated to the description of the baselines, we must discriminate the results of the literature by RCP. Then, we divided the results from the literature to draw these two global contexts: for the "No further action" scenario, we selected RCP 8.5 and RCP 6.0 scenarios, and RCP2.6 and RCP4.5 scenarios for the "Paris Agreement compliant" scenario.

As our global contexts refer to SSP1-1.9 ("Paris Agreement compliant") and SSP3-7.0 ("No further action" AR6-IPCC illustration scenarios, we applied a correction factor that corresponds to the relative temperature raise in each scenario (Table 10 and Figure 62), to convert the results of each RCP to the appropriate reference. For illustration, in the selected scenarios for "No further action" covering RCP8.5, we applied a correction of 0.9375 (1.5/1.6) in 2030, 0.875 (2.1/2.4) in 2050 and 0.82 (3.6/4.4) in 2090. In the "Paris Agreement compliant" scenario covering RCP4.5, we applied the following correction factors: 1 (1.5/1.5) in 2030, 0.8 (1.6/2.0) in 2050 and 0.52 (1.4/2.7) in 2090.

In addition, as the granularity of the NEMESIS model is not sufficient to isolate crops production, forestry and fishery sectors individually, we used Eurostat (2023d; 2023e) 2019 shares to weight the expected impacts into the aggregated agriculture sector of the model.

Figure 62: Temperature change in IPCC illustrative scenarios



Source: Authors' elaboration based on IPCC-AR6-WGI, 2022 – Table SPM.1. Dots indicate the "best estimates" for 20-year time periods and triangles are interpolations of these points by 10-year step for 2040, 2060, 2070 and 2080. Intervals represent the "very likely" range for each scenario, intermediary points have also been interpolated.

3.3.7 Implementation into the NEMESIS model

3.3.7.1 Implementation

The implementation of each impact in the NEMESIS model went through four different channels:

- The capital destruction that concerns "coastal flooding", "river flooding" and "droughts".
- The change in the availability of production factors for "droughts", "labour productivity" and "energy supply".
- The change in productivity related to "labour productivity", "agriculture", "forestry" and "fishery" impacts.
- The changes in consumption due to change in "energy demand".

The capital destruction was modelled through an increase of production cost of the real estate sector for firms and a loss of income for households. We also assumed that a share of the economic losses is supported by the insurance sector (30% in the standard case, based on EU average value from the NatCatServices database —EEA, 2021) whereas uninsured damages could be covered by public support (0% in the standard case). Changes in the availability of production factors and in productivity were modelled by a change in production cost, assimilated to a change in productivity. Finally, the changes in consumption were introduced with long-term trends modifying consumption choices.

3.3.7.2 Scenarios

The introduction of the climate change economic impacts for the EU into the NEMESIS model was based on the quantitative figures from the literature review presented in the previous sections. The two general contexts defining two scenarios: "No further action" and "Paris Agreement compliant", as presented in section 3.2, were implemented in the model.

Furthermore, to support the analysis of the results, we ran a batch of scenarios that:

- Individualise the economic consequences of each impact; we ran a scenario for each impact and each global context (leading to 20 scenarios).
- Allow us to consider the uncertainty found in the literature regarding the expected economic consequences of each impact, by running three different cases: moderated, medium and strong for each impact and each global context (60 scenarios simulated). The moderate case corresponds to the low bound of the expected impact, the 1st quartile (i.e. the weakest 25%), the medium case reproduces the average values of the impacts' range, and the strong case covers the 3rd quartile, i.e. 25% of the highest expected impacts.

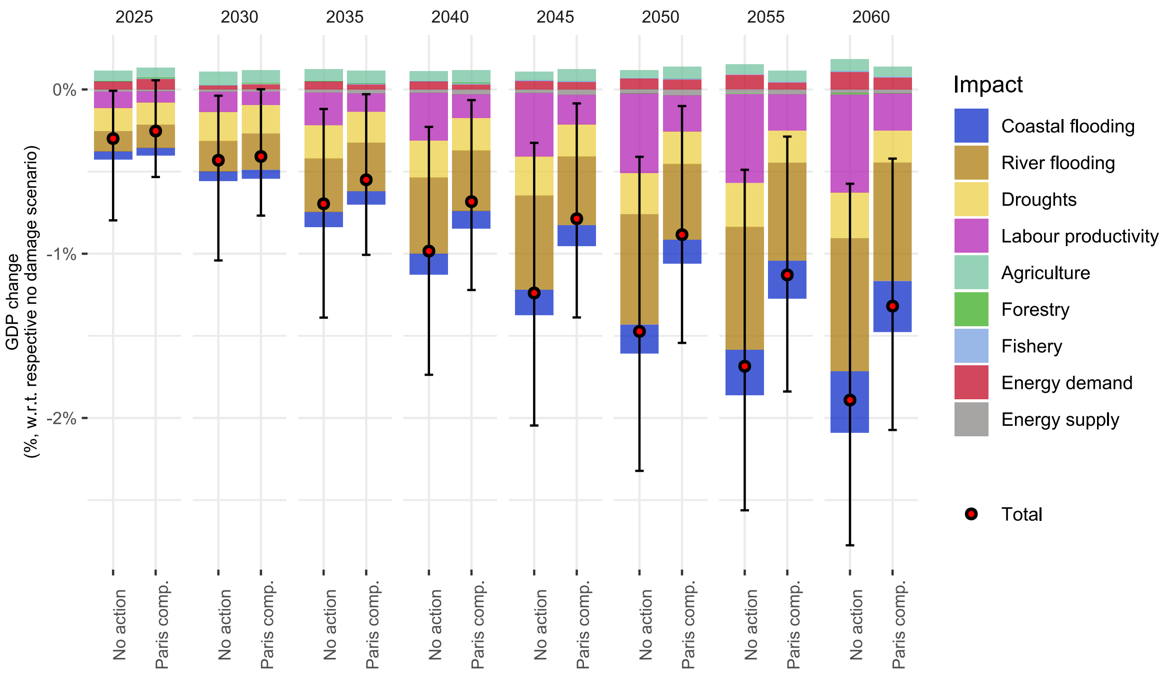
3.4 Including climate damages in the NEMESIS model

3.4.1 Main scenarios

We synthesise in this section the results of the introduction of climate change impacts into the NEMESIS model. Figure 63 combines twenty-six runs of the model to summarise the expected impact of climate change on the European economy.

In the "No further action" scenario, the climate damages could reduce the EU GDP by about 0.43% on average in 2030 (compared the same scenario excluding damages) and up to 1% in the strong case and 0.04% in the moderated case. The economic losses grow overtime, reaching 1% of EU GDP in 2040, 1.5% in 2050 and 1.9% in 2060. In case of more severe impacts, the EU GDP could be reduced by 1.7% in 2040, 2.3% in 2050 and 2.8% in 2060. In the moderate case, these GDP losses are of 0.2%, 0.4% and 0.6% respectively. In the "no further action" scenario, on the 1.5% of GDP loss expected in 2050 due to climate change damages, 0.67% of GDP is due to river flooding, 0.48% to lower labour productivity, 0.25% to droughts, and 0.18% from coastal flooding. The economic consequences of the other impacts are lower: -0.02% of GDP due to impacts on the energy supply, no impact for lower forest yield and change in fish catches, and even slightly positive impacts from agriculture, 0.05%, and from lower energy demand, 0.07%.

Figure 63: EU GDP deviation induced by the introduction of climate change impacts

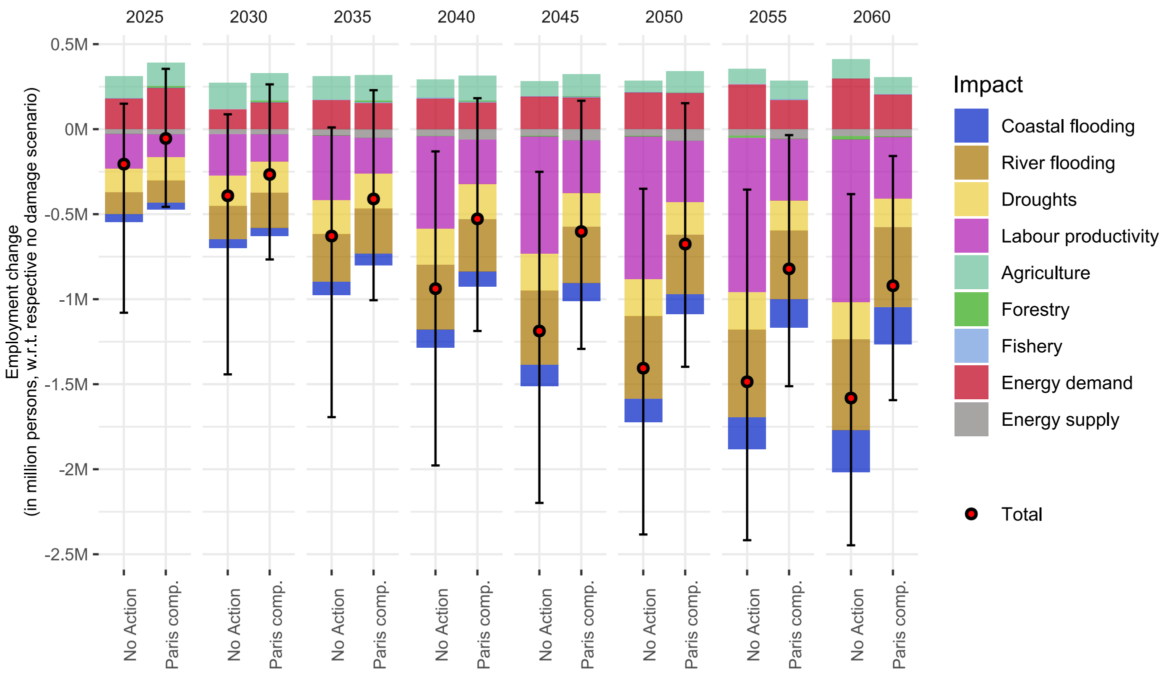


Source: NEMESIS model. The error bars indicate the lower (25%) and upper (75%) bounds when all impacts are included. "No action" means "No further action" scenario and "Paris comp.", the "Paris Agreement compliant" scenario.

In the "Paris Agreement compliant" scenario, the expected impacts on the EU GDP are lowered compared with the "No further action" scenario. In 2030, the EU GDP losses are similar, with -0.4% compared to the same scenario excluding damages. In 2040, the EU GDP is expected to decline about 0.7%, up to 1.2% in the strong case and 0.07% in the moderated case. Thereafter, the EU GDP continues to decline in 2050 by 0.9% in the average case, 1.5% in the strong case and 0.1% in the moderate one. In 2060, these losses reach 1.3%, 2.1% and 0.4% respectively. In the "Paris Agreement compliant" scenario, the contribution of damages from river flooding (0.46% of EU GDP in 2050), droughts (0.2%), coastal flooding (0.15%) and labour productivity (0.22%) are the largest among all impacts, despite significant reduction compared to the "No further action" scenario, notably on labour productivity. Post 2060 projections, based on expected temperature raise in the case of the "Paris Agreement compliant" scenario, should deliver relatively stable economic impacts in 2090 as the temperature will stabilise and even slightly reduce in comparison to 2050.

Thus, comparing both scenarios, the difference of expected damages from climate change will grow overtime, from 0.02% in 2030 and 0.3% in 2040.This difference reaches 0.6% of additional EU GDP losses in the "No further action" scenario in 2050, with 0.8% for the strong case and 0.3% for the moderate one.

Figure 64: EU total employment deviation induced by the introduction of climate change impacts

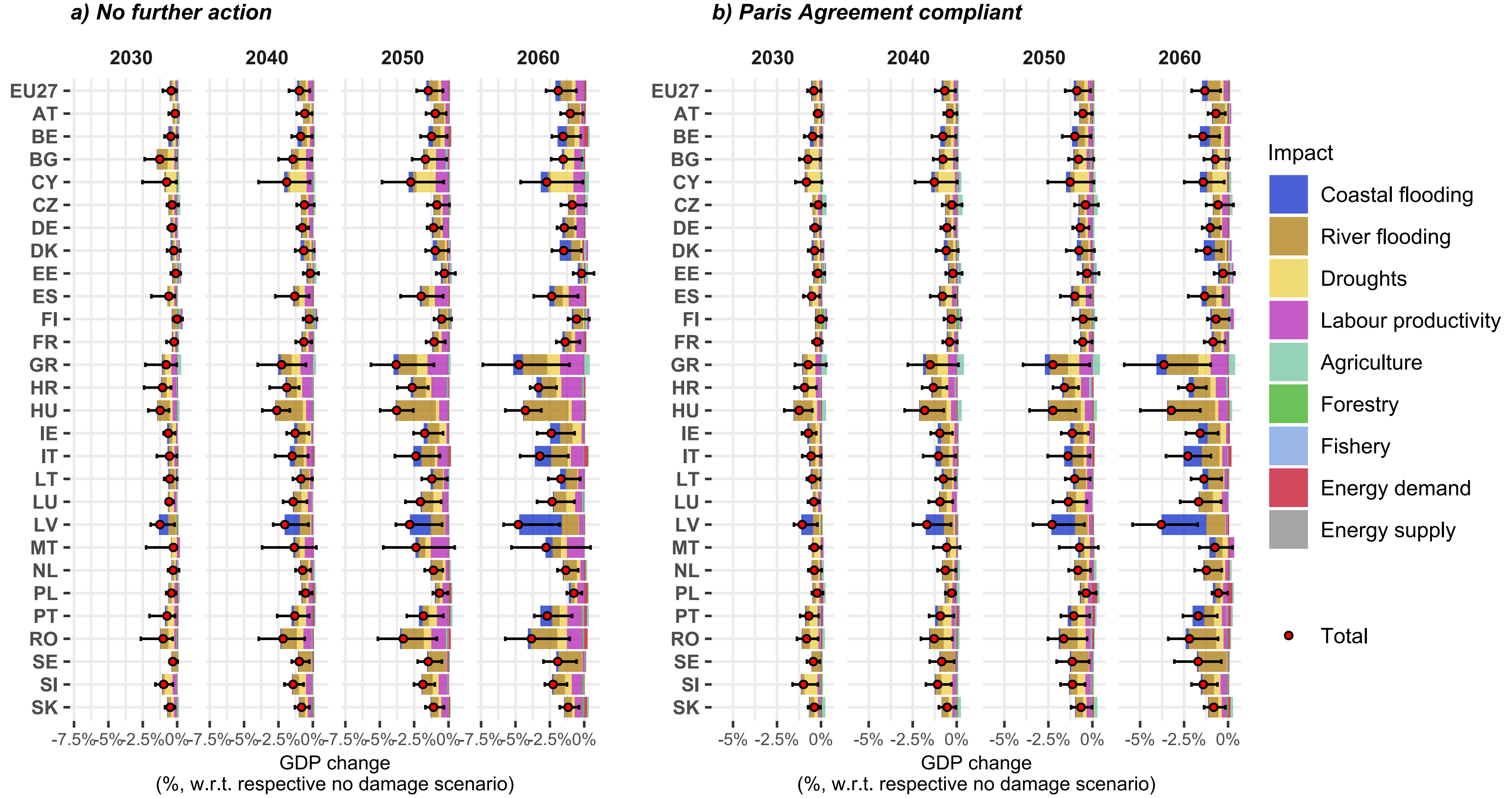


Source: NEMESIS model. The error bars indicate the lower (25%) and upper (75%) bounds when all impacts are included. "No action" means "No further action" scenario and "Paris comp.", the "Paris Agreement compliant" scenario.

The results for employment draw similar insights. In 2050, in the "No further action" scenario, the total potential employment loss is of 1.4 million persons in comparison with the same scenario without climate damages. Among the impacts, 840 000 jobs losses are expected as the consequence of the negative shock on labour productivity, 490 000 from river floodings, 215 000 of droughts and 140 000 of coastal flooding, whereas 210 000 additional persons will be employed thank to the reduction in energy demand and 70 000 more in agriculture, following the positive impact on these sectors. In the strong case, the impact on the European employment in 2050 reaches a loss of 2.4 million of jobs, and of 350 000 in the moderate case.

In the "Paris Agreement compliant" scenario, the employment losses at EU level are lowered, with in 2050, 675 000 jobs destroyed in comparison to the same scenario without damages. It goes up to 1.4 million in the strong case and reduces to 150 000 in the moderate one.

Figure 65: GDP deviation by Member State induced by the introduction of climate change impacts in the "No further action" scenario



Source: NEMESIS model. The error bars indicate the lower (25%) and upper (75%) bounds when all impacts are included. "No action" means "No further action" scenario and "Paris comp.", the "Paris Agreement compliant" scenario. Scales are different between figures a) and b).

At Member States level, the projected economic impacts of climate change are relatively heterogeneous (Figure 65). Some countries, like Estonia, Finland, and France will be moderately impacted compared to other Member States, with in 2050, in the average case and the "No further action" scenario, a GDP loss of 0.3%, 0.5% and 1.1% respectively. On the other hand, countries like Greece, Cyprus, Hungary and Romania will face larger GDP losses: 3.8%, 2.75%, 3.7% and 3.3% respectively. Similarly, in the "Paris Agreement compliant" scenario, these countries show the largest GDP losses, but weaker than in the "No further action" scenario, with respectively -2.2%, - 1.3%, -2.2% and -1.6% of GDP in 2050, with respect to the no damage scenario. Globally, European Mediterranean countries (Portugal, Spain, Italy, Malta, Slovenia, Croatia, Greece and Cyprus) face a two-fold GDP loss compared to other EU countries, with in the "No further action" scenario and in 2050, -2.3% of GDP to compare to -1.2% in the rest of EU. In the "Paris Agreement compliant" scenario, the economic losses are of 1.3% of GDP in European Mediterranean countries, higher than in other EU countries (0.75% of GDP).

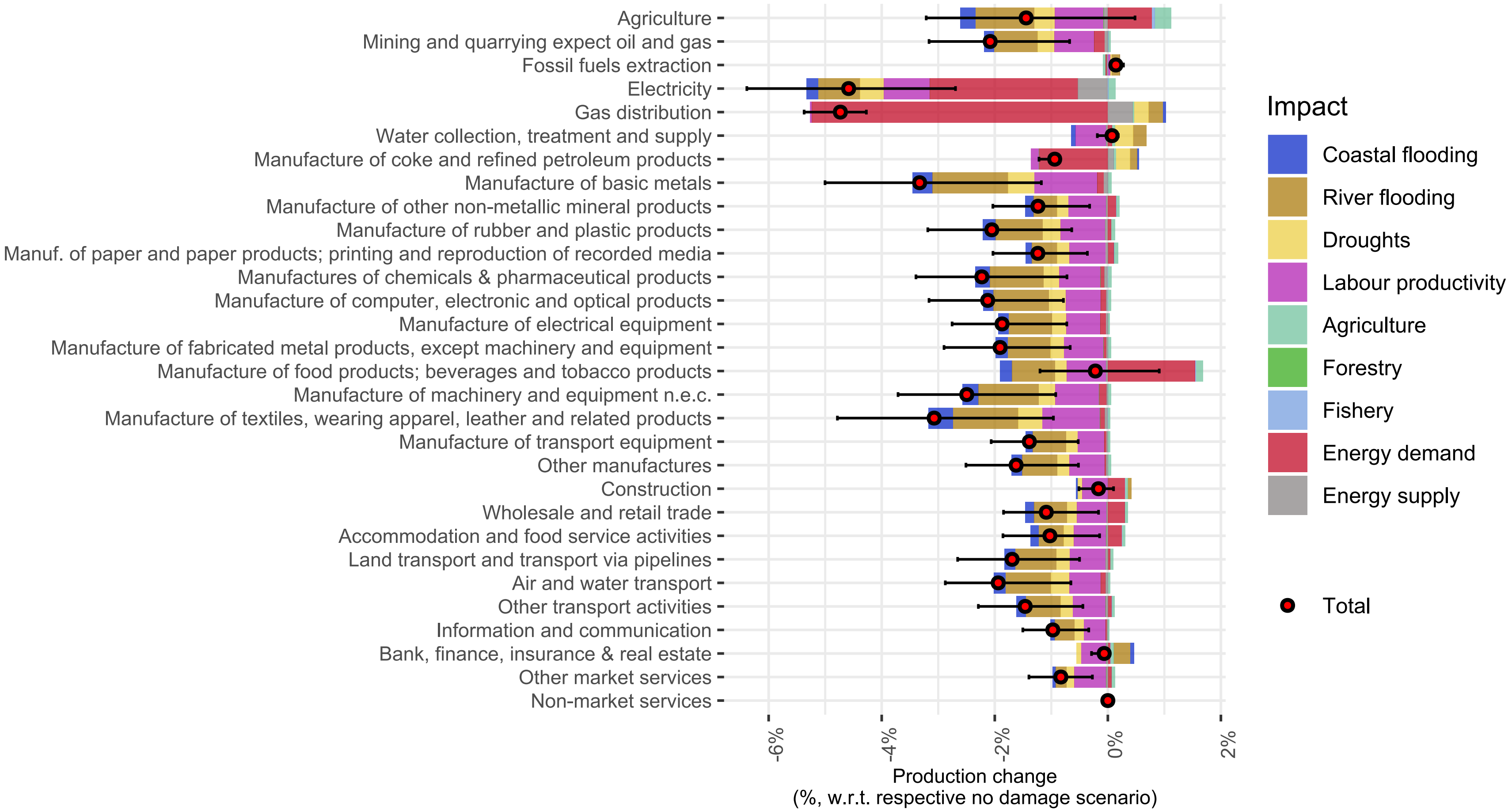
In the strong case, these impacts on GDP are larger, with, in the "No further action" scenario, GDP losses reaching up to 5.6% in Greece, 5.1% in Romania, 5% in Hungary and 4.8% in Cyprus in 2050. Less affected countries also face larger impacts in the strong case: -0.9% of GDP in Estonia, - 1.1% in Finland and -1.6% in France. In the moderate case, Greece loses 1.1%, Romania 0.9%, Hungary 2.6% and 0.3% in Cyprus.

The contribution of the different climate change related impacts varies also importantly across Member States[62]. In Hungary, the GDP loss due to river flooding represents 2.9% of GDP, i.e. more than three quarter of the total expected impact in 2050 in the "No Further action" scenario. In Latvia, out of the 2.8% of GDP loss in 2050, 1.5% come from coastal flooding whereas in Greece, with a GDP loss of 3.8%, 1.5% is attributed to labour productivity losses and 1.3% to river floodings.

Looking at the sectoral level, the modelled climate damages are expected to affect all sectors to a different extent. Production of electricity and gas distribution are the most penalised due to lower energy consumption in the buildings sectors, with more than 4% loss of production in 2050 in the "No further action" scenario. Generally, the industrial sectors are slightly more penalised than office services sectors, due to higher capital intensity. It is also the case in more capitalistic service sectors such as transports services. Despite potential sector's specific impacts of climate change, we do not consider differentiated productivity losses by sector because of limited and non-homogeneous information in the literature. As a consequence, sectors are relatively homogeneously impacted by the losses of labour productivity in our modelling. Next, the manufacture of food products and agriculture are positively impacted by the reduction of energy demand because, for numerous households, lower energy bills allow them to increase demand for other non-durable goods, and particularly for food items and related services.

[62] The sum of the individual impacts on GDP may be different from the scenarios including all impacts simultaneously. In fact, the response of the model to cumulative shocks is not fully linear and some stabilisation mechanisms, here mainly the adjustment of the labour market in the long run, may reduce the economic effects when all impacts are included.

Figure 66: EU sector production deviation due to climate change impacts in the "No further action" scenario



Source: NEMESIS model. The error bars indicate the lower (25%) and upper (75%) bounds when all impacts are included.

3.4.2 Additional sensitivity analysis

One of the assumptions we implemented in the model when including the climate change damages is on the share of insured damages impacting capital, i.e. coastal and river flooding and partially droughts. In the scenarios presented above, we assume a share of 30%, corresponding to the EU average from the NatCatSERVICE database (EEA, 2021). Nevertheless, in this database, the rate of insured damages varies strongly between Members States, from 0.3% in Hungary to 56% in Denmark. Furthermore, EEA (2021) delivers a second estimate of the insured rate based on a second database, CATD, with values that are also very heterogeneous between Member States and different from the NatCatSERVICE database, with 22% of the climate damages insured in EU.

Table 19: Assumptions on the share of insured damages on capital destruction

Share of insured damages on capital destruction				
	Standard case	No insurance	CATD database (EEA, 2021)	NatCatSERVICEdatabase (EEA, 2021)
AT	30%	0%	19.5%	31.7%
BE			45.9%	59.4%
BG			1.8%	5.3%
HR			2.9%	2.4%
CY			1.8%	2.1%
CZ			10.0%	32.5%
DK			55.6%	58.9%
EE			14.6%	25.7%
FI			3.1%	20.9%
FR			40.6%	48.7%
DE			37.0%	47.8%
GR			15.4%	1.9%
HU			0.3%	2.4%
IE			16.3%	52.1%
IT			5.7%	5.7%
LV			5.4%	7.3%
LT			0.5%	0.5%
LU			36.6%	59.0%
MT			0.0%	17.2%
NL			54.8%	48.6%
PL			6.8%	6.6%
PT			3.6%	8.2%
RO			1.1%	0.5%
SK			4.4%	6.4%
SI			42.8%	12.2%
ES			4.1%	25.6%
SE			30.6%	29.3%
EU27			22.4%	31.1%

Source: Authors assumptions and EEA (2021) based on CATD and NatCatSERVICE databases.

Thus, we realised a sensitivity analysis on the insured rate., with three alternative scenarios to the 30% standard case. The first assumes no payment for climate damages from the financial sectors —it is a benchmark scenario, and the two others use EEA (2021) estimated rates by Member State, from CTAD and NatCatSERIVICES databases respectively. These alternative scenarios were ran on the average case for the expected climate change impacts, with all impacts together and for both contexts.

Table 20: EU GDP deviation sensitivity to the share of insured climate damages on capital destruction in 2050

	"No further action"				"Paris Agreement compliant"			
	Standard case (30%)	No insurance (0%)	CATD database	NatCatSERVICE database	Standard case (30%)	No insurance (0%)	CATD database	NatCatSERVICE database
AT	-1.0%	-0.8%	-0.9%	-1.0%	-0.5%	-0.5%	-0.5%	-0.6%
BE	-1.2%	-1.0%	-1.5%	-1.6%	-1.0%	-0.8%	-1.2%	-1.3%
BG	-1.7%	-1.5%	-1.6%	-1.6%	-0.8%	-0.7%	-0.7%	-0.7%
HR	-2.6%	-2.4%	-2.4%	-2.4%	-1.6%	-1.4%	-1.4%	-1.4%
CY	-2.7%	-2.8%	-2.7%	-2.7%	-1.3%	-1.3%	-1.2%	-1.2%
CZ	-0.8%	-0.8%	-0.8%	-0.9%	-0.4%	-0.3%	-0.3%	-0.4%
DK	-1.0%	-0.8%	-1.2%	-1.2%	-0.8%	-0.6%	-0.9%	-0.9%
EE	-0.3%	-0.2%	-0.3%	-0.3%	-0.3%	-0.2%	-0.3%	-0.3%
FI	-0.5%	-0.4%	-0.4%	-0.5%	-0.5%	-0.4%	-0.4%	-0.5%
FR	-1.1%	-1.0%	-1.1%	-1.2%	-0.6%	-0.5%	-0.6%	-0.6%
DE	-1.1%	-0.9%	-1.2%	-1.2%	-0.7%	-0.6%	-0.8%	-0.8%
GR	-3.8%	-2.9%	-3.5%	-3.0%	-2.2%	-1.5%	-2.0%	-1.6%
HU	-3.8%	-2.7%	-2.7%	-2.7%	-2.2%	-1.5%	-1.5%	-1.6%
IE	-1.7%	-1.5%	-1.7%	-2.1%	-1.1%	-1.0%	-1.1%	-1.4%
IT	-2.4%	-2.0%	-2.1%	-2.1%	-1.4%	-1.1%	-1.2%	-1.2%
LV	-2.8%	-2.2%	-2.3%	-2.4%	-2.3%	-1.8%	-1.9%	-1.9%
LT	-1.2%	-0.8%	-0.9%	-0.9%	-1.0%	-0.7%	-0.7%	-0.7%
LU	-2.0%	-2.0%	-2.4%	-2.6%	-1.4%	-1.3%	-1.6%	-1.7%
MT	-2.4%	-2.3%	-2.2%	-2.3%	-0.7%	-0.7%	-0.6%	-0.7%
NL	-1.1%	-0.9%	-1.4%	-1.3%	-0.8%	-0.7%	-1.1%	-1.0%
PL	-0.7%	-0.7%	-0.7%	-0.7%	-0.4%	-0.4%	-0.4%	-0.4%
PT	-1.8%	-1.8%	-1.8%	-1.8%	-1.1%	-1.0%	-1.0%	-1.1%
RO	-3.3%	-2.4%	-2.5%	-2.4%	-1.6%	-1.0%	-1.1%	-1.0%
SK	-1.1%	-1.0%	-1.0%	-1.0%	-0.6%	-0.6%	-0.5%	-0.6%
SI	-1.9%	-1.6%	-2.1%	-1.7%	-1.1%	-1.0%	-1.4%	-1.1%
ES	-2.0%	-1.9%	-1.9%	-2.1%	-1.0%	-0.9%	-0.9%	-1.1%
SE	-1.5%	-1.3%	-1.5%	-1.5%	-1.1%	-1.0%	-1.2%	-1.2%
EU27	-1.5%	-1.3%	-1.5%	-1.5%	-0.9%	-0.7%	-0.9%	-0.9%

Source: NEMESIS model.

We observe that the use of the two alternative national estimates of the share of insured climate damages, does not change the EU GDP losses in 2050 for both contexts. In the "No further action" scenario, the EU GDP loss is of 1.5% in 2050 compared to the same scenario without climate damages when implementing the CATD or NatCatSERV estimates, as in the standard case, and of - 0.9% in the "Paris Agreement compliant" scenario. At Member State level, the projected GDP variations differ according to assumptions on the insurance rate. By considering these differences by Members State and the benchmark scenario with no insured damages, we see that reducing the insurance rate tends to reduce the impact on GDP. For instance, in the "No further action" scenarios, the EU GDP loss in 2050 is slightly lower when we assume no insurance, with -0.18% compared to the standard case. The lower GDP loss comes from a reduction in the trade balance, with higher exports (+0.2% of GDP) and lower imports (+0.12%) whereas the private consumption contributes inversely (-0.15%), and there is almost no change in the investment component (+0.01%). In fact, when the insurance rate is lower, the direct financial burden of climate damages increases for firms and households, whereas it reduces for the insurance sectors, allowing lower insurance premium. As a consequence, the private consumption is lowered, but the positive impact of lower insurance risk premium counterbalances this effect leading to a slight positive impact on GDP, with the insurance and financial sectors (these two are aggregated in NEMESIS[63]) being large contributors to the external trade balance of the EU.

3.5 Synthesis of the literature review on adaptation to climate change and input data collection

After the implementation and the quantification of the macro-economic impacts on the EU economy of climate damages in accordance with both global climate contexts, we now introduce adaptation measures that were not considered previously and may significantly influence the economic impacts. As for climate damages, we started from the literature review (see section 2.8) and identified relevant studies delivering quantitative figures usable by the macro-economic model. Compared to climate damages and mitigation measures, the literature on quantitative macro-economic impact assessment of climate change adaptation measures is much more limited. The literature is developing, but remains scarce because the assessment of macro-economic impacts of adaptation measures necessarily comes after the quantification of the expected climate damages, and because the required large scale vision (global, regional and even national) for this kind of assessment is not always adequate with adaptation measures (European Commission 2020; Singh et al. 2020).

As a consequence, we limited the literature review to the climate damages with the larger economic impacts, namely: coastal and river floods, labour productivity, and droughts. The literature for adaptation measures in the agriculture sector is relatively important (e.g. Gomez-Zavaglia et al., 2020; Malhi et al., 2021) but as we projected moderated expected macro-economic impacts for agriculture (see section 3.4) and as the modelling of the agriculture sector is aggregated in NEMESIS, we did not consider the adaptation measures for the agriculture sector.

Below, we synthetise the literature review done in Task 1 by focusing on studies that deliver quantitative figures usable for an implementation of the adaptation measures into the NEMESIS model. Practically, starting from the studies identified above (see section 2.8), **we collected, when available, or calculated, when feasible, two main indicators: the benefit-cost ratio (BCR) and the expected annual damages reduction rate (EADRR)**. The BCR is the avoided damages resulting from the adaptation measures divided by their cost, while the EADRR is the percentage of total damages avoided by the implementation of the adaptation measure. Both indicators are important: while the former indicates the required investment to achieve the reduction in climate economic damages, the latter indicates the extent of the gross climate damage cost mitigation.

We present below the synthesis of the literature review used to implement the adaptation measures into the NEMESIS model[64] for each of the four types of impacts selected, starting with coastal floods, followed by river floods, continued with labour productivity, and concluded with droughts.

3.5.1 Coastal floods

We identified three studies for climate damages from coastal floods that deliver quantitative figures on the impacts of adaptation measures. These studies: Lincke et al. (2019), Vousdoukas et al. (2020b) and Bachner et al. (2022), implement dykes protection as adaptation measure to reduce damages from costal floodings, to which Bachner et al. (2022) add an autonomous adaptation strategy, coming from migration. We did not include this later in our analysis insomuch as the

[63] There is a version of the NEMESIS model splitting the financial and insurance sector into two different sectors. This version could be used thereafter in the study to improve the modelling of these sectors.

[64] In fact, we do not directly implemented individual and clearly identified adaptation measures in the model but a reduced form that influences: (1) the extent of the damages and (2) the investment needs to achieved this damages mitigation.

inclusion of the planned adaptation (i.e. dykes) almost annihilates totally the autonomous adaptation strategy as a large part of the expected damages are avoided.

Lincke et al. (2019) and Bachner et al. (2022) studies allow the calculation of the BCR and EADRR variables for each Member State (Figure 67). At EU-27 level, the median value of the benefit-cost ratio of adaptation measures to reduce climate damages from costal floods is 0.9 [0.3 – 1.9] in 2030, i.e. below the rentability threshold, but reaches 4.9 [1.8 – 14] in 2050, with significant higher values in Lincke et al. (2019) than in Bachner et al. (2022). At Member States level, the range of BCR values is larger with very high values for Belgium and Italy, more than 20 (Figure 1). Vousdoukas et al. (2020b) also estimate BCR at Member States level, but they only deliver the 2020-2100 average that is 5.7 (RCP 4.5) and 7.1 (RCP 8.5) in EU-27 average and up to 13.9 (RCP 4.5) and 17.7 (RCP 8.5) for the Netherlands.

The adaptation measures reduce significantly the expected damages. The median EADRR from Lincke et al. (2019) and Bachner et al. (2022) for EU-27 in 2050 is of 79% [74 – 87%]. The lowest values are projected for Finland, with 22% [2 - 76%] and, for eight countries, Bulgaria, Cyprus, Spain, Greece, Croatia, Italy, Malta and Portugal, the median value of the EADRR is of 90% or more – all these countries are Southern European countries. In Vousdoukas et al. (2020b), the EADRR for EU-27 is of 89% (RCP 4.5) and 91% (RCP 8.5) in 2100.

Figure 67: Cost-benefit ratio of adaptation measures to costal floods

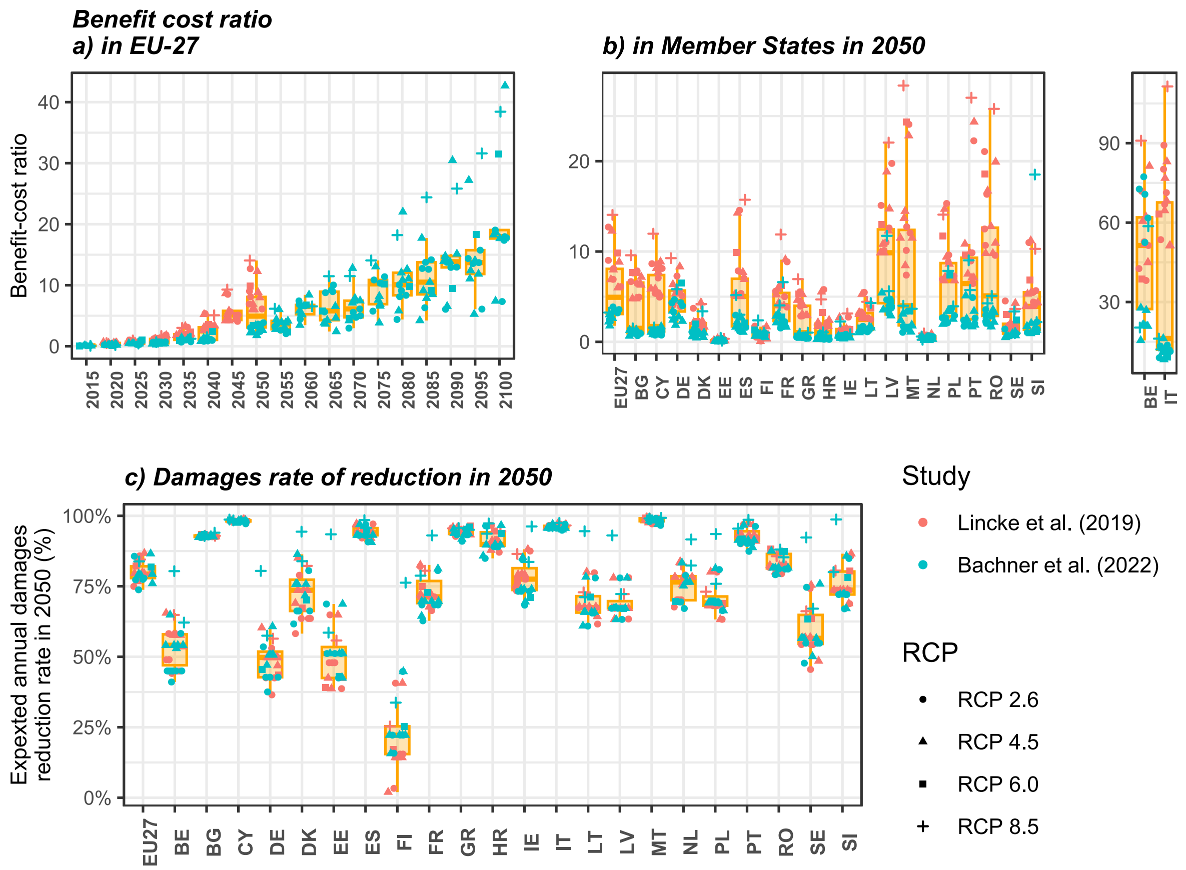
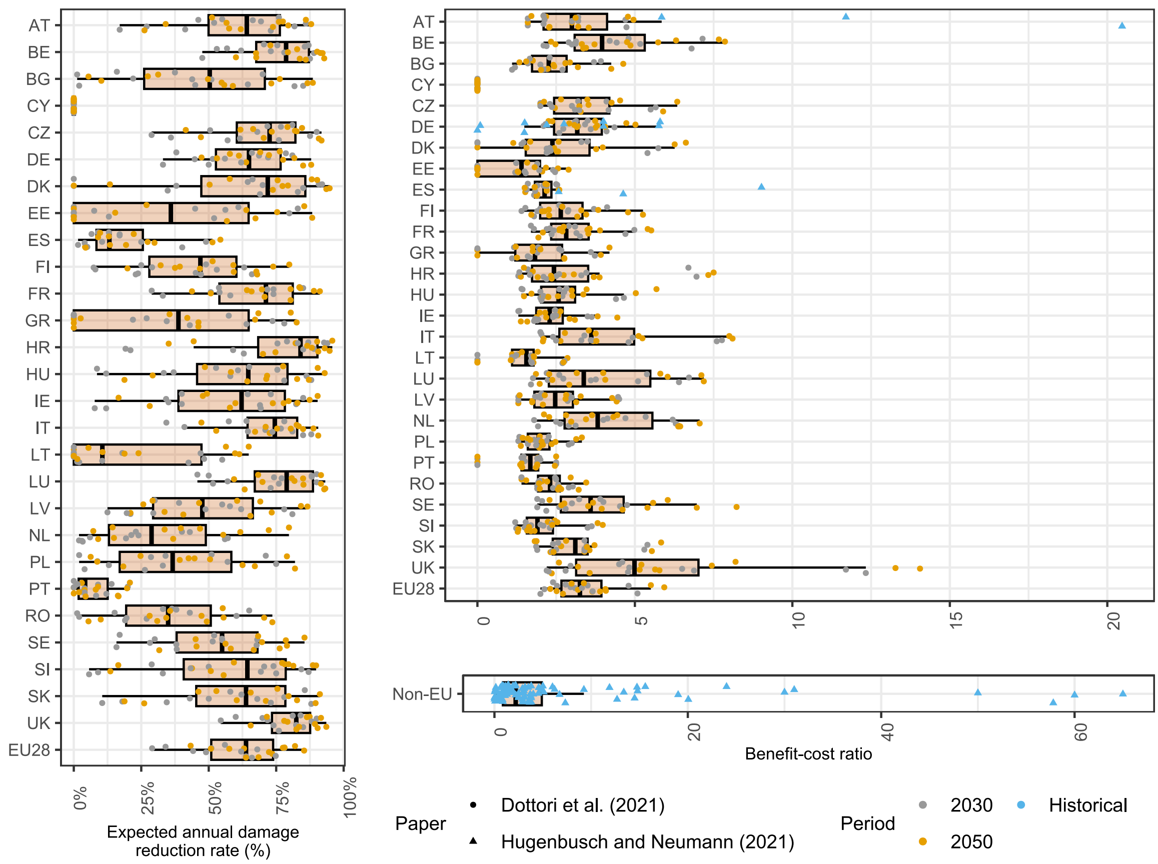


Figure a) BCR for EU-27 on an annual basis; Figure b) BCR in 2050 for all member states, the figure b is split into sub-figures to improve readability, scales differ between sub-figures; Figure c) Rate of reduction of the expected annual damages in 2050 for all member states.
Source: Authors elaboration based on Lincke et al. (2019) and Bachner et al. (2022).

3.5.2 River floods

For river floods, we identified Dottori et al. (2021) as the only one paper delivering projected estimates of impacts of adaptation measures to reduce the climate damages from river floods at a EU-national level. We then compared these projections with historical estimates of BCR, compiled by Hugenbusch and Neumann (2021) based on realised projects all over the world. Dottori et al. (2021) allow us to calculate both indicators: the BCR and EADRR, whereas Hugenbusch and Neumann (2021) only collect BCR. Dottori et al. (2021) considered four different adaptation strategies: river dykes, detention areas, flood proofing of buildings and relocation. We kept the two formers as Dottori et al. (2021) find very low rates of damages reduction for the latter, below 2.5% for 26 over the 28 countries[65] for flood proofing and largely below 1% for relocation for all countries.

Figure 68: Expected annual damage reduction rate and cost-benefit ratio of adaptation measures to river floods



Source: Authors elaboration based on Hugenbusch and Neumann (2021) for historical values and Dottori et al. (2021) for projections. Non-EU covers: Angola, Bangladesh, Fiji, India, Indonesia, Iran, Laos, Nepal, Pakistan, Philippines, Samoa, Seychelles, Tanzania, USA, Zambia and Zanzibar. Values for 2030 and 2050 correspond to 2020-2040 and 2040-2060 average respectively calculated with average corresponding year of exceeding 1.5, 2 and 3°C warming in global climate models projections (see table S1 in Dottori et al. (2021) Supplementary Materials)

At EU level, Dottori et al. (2021) project a reduction rate of the climate damages from river floods resulting from the implementation of adaptation measures of 64% [29 - 85%] (Figure 68). The

[65] The exceptions are Sweden and the United-Kingdom, but the damages reduction rates for flood proofing remains below the rates for dykes or detention areas

lowest potential of damages reduction is in Portugal, 0% [4 - 21%] and the highest in Croatia, 84% [19 - 96%] —for the specific case of Cyprus, for which expected annual damages from river floods induced by climate change are projected in decline, almost no adaptation measure is foreseen. The range of EADRR is very large in many EU countries, as for Hungary, with 65% [9 - 93%].

The BCR are 3.3 [2 – 5.9] on average for the EU. Belgium is the country benefiting the most (4 [2.1 – 7.9]) of the adaptation measures (after the United-Kingdom), followed by the Netherlands (3.8 [1.8 - 7.1]) and Sweden (3.6 [1.9 - 8.2]) whereas the lowest BCR are projected for Estonia (1.4 [0 – 2.9]), Lithuania (1.6 [0 – 2.9]) or Portugal (1.7 [0 – 2.5]) — but still well below one, the cost-effectiveness threshold. The range of BCR calculated by Dottori et al. (2021) is in the range of historical values for Germany and are lower for Austria and Spain, the three EU countries reported by Hugenbusch and Neumann (2021). The BCR historical values for river floods adaptation projects show a larger range, than the projected ones, from a minimum of 0 to a maximum of 65 and with a BCR above 10 for 18 cases on the 109 reported by Hugenbusch and Neumann (2021). Nevertheless, the median value of BCR, 2.5, is closed and even lower of the projected one, 3.3, by Dottori et al. (2021).

3.5.3 Labour productivity

The studies on quantified climate change damages to labour productivity in EU were relatively numerous, seven have been identified in section 3.3.2, but only two have looked at the impact of adaptation measures: Orlov et al. (2020) and Szewczyk et al. (2021). Orlov et al. (2020) used two adaptation measures, air conditioning for indoor workers and mechanisation for outdoor workers (agriculture and construction). The air conditioning is endogenous in each scenario, depending on regional GDP per capita, but there is no scenario without additional air conditioning. For mechanisation, there are scenarios with and without further mechanisation allowing the calculation of the EADRR, but as there is no information on its cost, we cannot calculate BCR. In Szewczyk et al. (2021), two adaptation measures are considered: space cooling and increase in the use of robotic exoskeletons, but as they clearly explain: "*This study does not consider an explicit cost of adaptation. The adaptation measures considered are of autonomous type (Chambwera et al 2014) and, in contrast to planned or public adaptation, it is not driven by specific policy and quantification of the cost is very challenging to envisage*". As a consequence, we cannot calculate the BCR with these studies, we can only retrieve EADRR from them (Figure 69). Thus, we will have to use *ad-hoc* assumption on BCR to assess the cost of the mitigation measures for labour productivity (see Box 2 below).

On average in EU, the reduction of the loss of labour productivity due to heat waves is of 5.5% [4 - 34%] of the expected impact without adaptation in 2050. The estimates from both studies differ significantly, Orlov et al. (2020), 5.1% [4% - 6.8%], show lower reduction rates than Szewczyk et al. (2021), 18% [15 - 34%]. This difference can be explained by the limited coverage of the adaptation measures considered here for the Orlov et al. (2020) study. Despite the inclusion of air conditioning in Orlov et al. (2020) for indoor workers, none of their results allows us to quantify the impact of this measure, contrary to the mechanisation of outdoors works. At Member State level, the largest reduction rates are for the Netherlands (30% [23 - 180%]), Luxembourg (37% [28 – 113%]), Ireland (23% [18 – 34%]) or France (23% [17% - 49%]) and the lowest for Romania (6% [5 – 12%]), Bulgaria (8% [7 – 16%]), Latvia (9% [6 -15%]) and Poland (11% [9 – 24%]).

Figure 69: Labour productivity loss reduction due to adaptation measures (%)

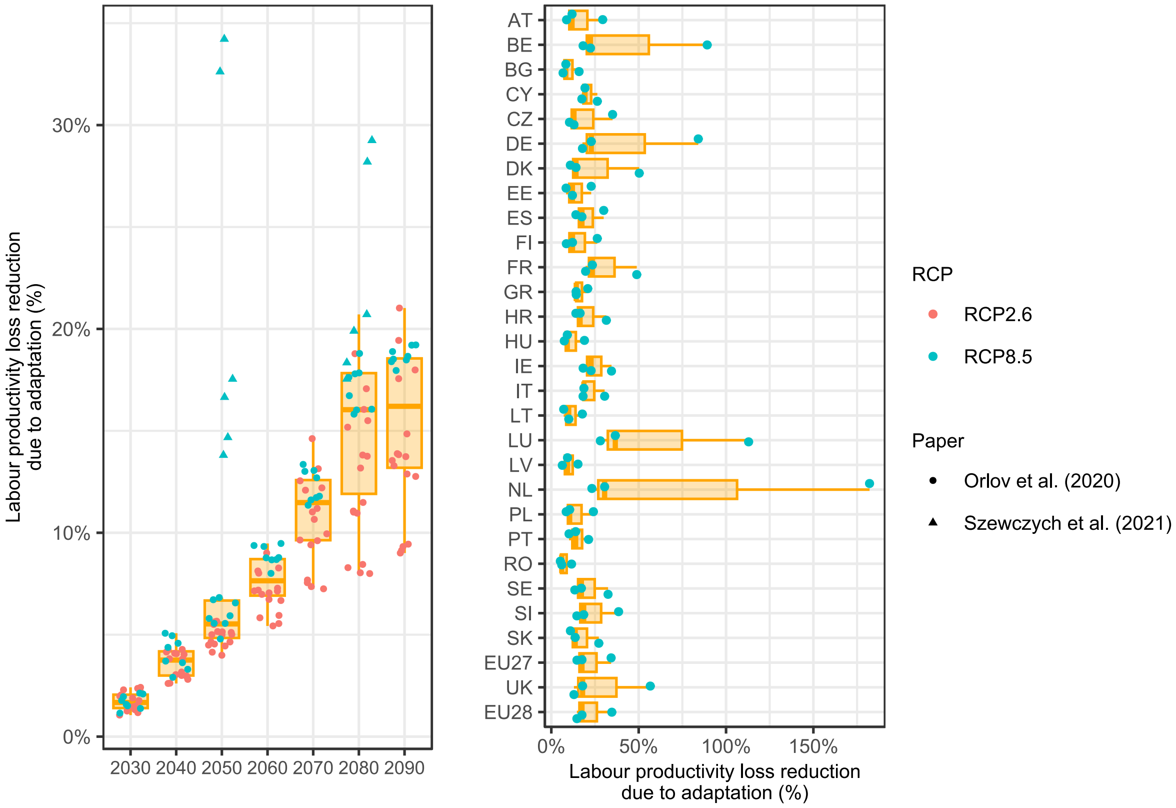


Figure a): EU-27 on an annual basis and b) 2050 for all member states.
Source: Authors' elaboration based on Orlov et al. (2019) and Szwewczyk et al. (2022).

3.5.4 Droughts

We identified only one study that delivered usable detailed information on the implication of adaptation measures to reduce the cost of climate damages from droughts. Naumann et al. (2021) assess the expected annual damages from droughts for two vulnerability cases: one static and another dynamic. In the latter, they assume "*socioeconomic dynamics, including adaptation policy implementation and the development of drought management plan*". The adaptation measures are here related to the economic development following Formetta and Feyden (2019) that have established autonomous relationship between historical drought damages of exposed GDP and GDP per capita. Thus, Naumann et al. (2021) results make it possible to calculate the EADRR, by comparing damages in GDP percentage in both cases, but not the BCR, because the adaptation cost is not calculated with this relationship. The literature review did not allow us to find relevant studies delivering BCR of adaptation measures to climate change economic damages from droughts. Therefore, we used the historical values reported by Hugenbusch and Neumann (2021) in their global survey as proxy for BCR in EU, of 2.7 [1 – 1 800]. The EADRR is of 52% [43% - 61%] in EU-27 in Naumann et al. (2021), with few variations in the different regions for the median values (Atlantic: 50% [33 - 100%], Boreal: 67% [0 - 100%], Continental 56% [33 - 100%], and Mediterranean 52% [44 - 57%]), but larger ranges in particular for the Boreal region.

Figure 70: Damages reduction and benefit-cost ratio of drought adaptation measures

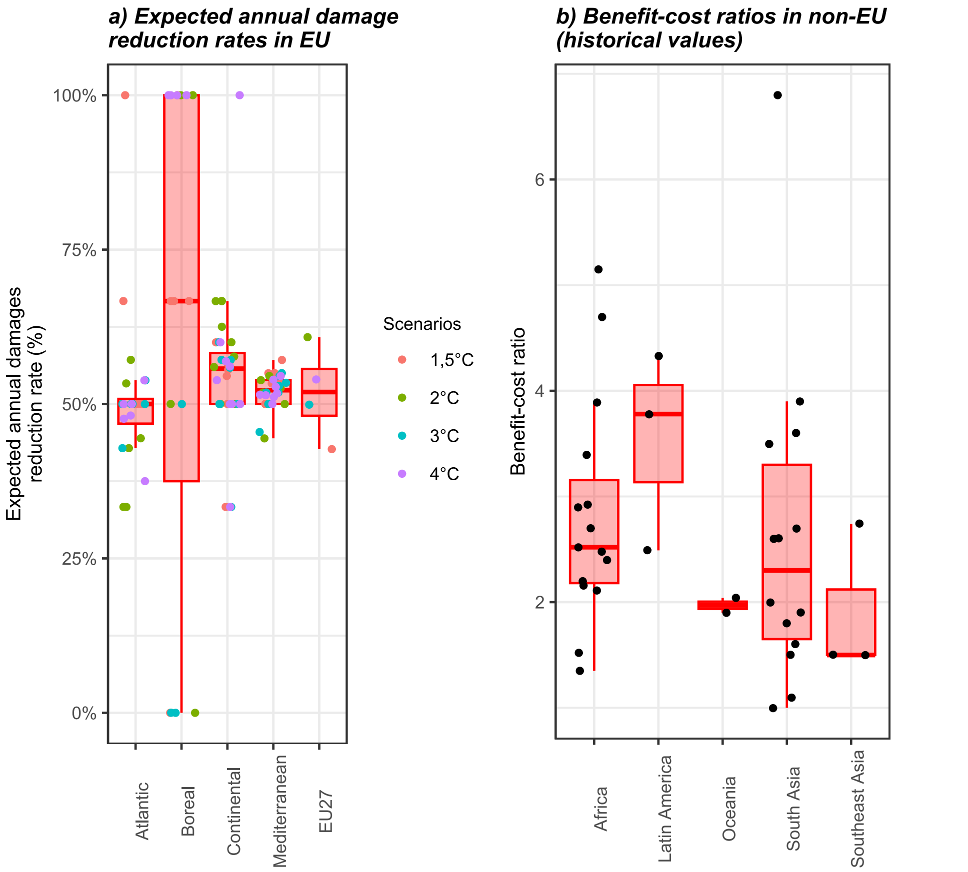


Figure a): Expected annual damage reduction rate in EU from Naumann et al. (2021) and b) Historical benefit-cost ratios for non-EU countries from Hugenbusch and Neumann (2021), BCR above 20 have been removed from the figures, it concerns 9 observation on the 48 in total.
Source: Authors' elaboration based on Naumann et al. (2021) and Hugenbusch and Neumann (2021).

3.5.5 Data processing and implementation into the NEMESIS model

As for climate damages, we adapted the results from the literature review to the two different global contexts: "No further action" and "Paris Agreement compliant" (see section 3.2 for details). The methodology used for the adaptation measures is similar as for climate damages. We divided the results from the literature to draw these global contexts: for the "No further action" scenario, we selected RCP 8.5 and RCP 6.0 scenarios and RCP2.6 and RCP4.5 scenarios for the "Paris Agreement compliant" scenario (for a more detailed explanation please refer to section 3.3.6).

As explained above, we introduced the adaptation measures in the model with the average annual reduction rate of climate damages and the benefit-cost ratio. The former allows for the calculation of the avoided damages by multiplying the climate damages by the expected annual damages reduction rate. Therefore, with the benefit-cost ratio, we can calculate the corresponding cost, here assumed as investment, by multiplying the avoided climate damages by the benefit-cost ratio.

Furthermore, similarly to the implementation of climate damages, we ran a batch of scenarios that:

- Identify the economic consequences of each impact for which the adaptation measures have been quantified as well as for all impacts together –even if adaptation measures were limited to four of them, we then run a scenario for each of these impacts and each global context (leading to 10 scenarios).

- Allow us to consider the uncertainty found in the literature regarding the BCR and EADRR indicators, by running three different cases: moderate, medium and strong (leading to 30 scenarios simulated). The moderate case corresponds to the low bound of the expected climate impact as well as of the BCR and EARDD indicators, the 1st quartile (i.e. the weakest 25%), the medium case reproduces the average values of ranges of each variables and the strong case covers the 3rd quartile, i.e. 25% of the highest.

Finally, due to lack of quantitative usable information on the cost-benefit ratio for adaptation measures that may reduce the economic cost of labour productivity losses induced by climate change, we use a conservative value of 1. We realised a sensitivity on this *ad-hoc* value (see Box 2).

3.6 Including adaptation measures to mitigate climate damages in the NEMESIS model

We synthesise in this section the macro-economic impacts of introducing the adaptation measures for four climate change impacts into the NEMESIS model. Figure 71 combines sixty runs of the model to summarise the expected impacts of climate change on the European economy and namely on EU GDP.

The implementation of the adaptation measures in each global climate context reduces the EU GDP losses induced by climate change damages. In the "No further action" scenario, the EU GDP is lower by -0.4% of GDP, -1%, -1.5% and -1.9% of GDP in 2030, 2040, 2050 and 2060 respectively when considering all climate damages without adaptation in comparison to a scenario without damages. The introduction of the adaptation measures for coastal and river floodings, labour productivity and droughts leads to a reduction in EU GDP losses, with a decline of EU GDP by -0.2%, -0.5%, -0.9% and -1.1% for the same years compared to the no damage scenario. Thus, in 2050, the EU GDP losses are reduced by about 40% thanks to the adaptation measures.

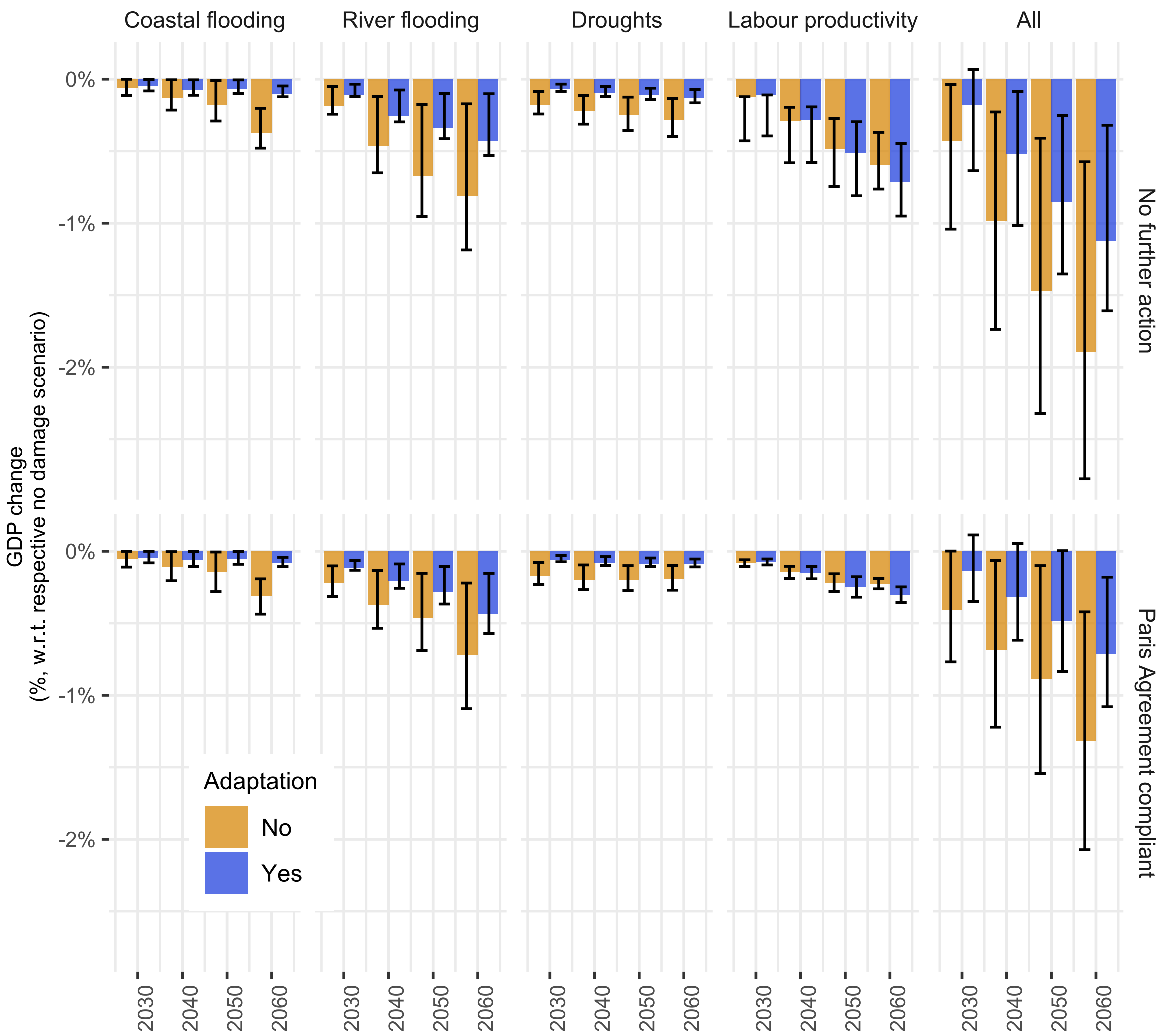
In the "Paris Agreement compliant" scenario, the reduction in EU GDP losses is slightly higher in relative terms, around 45%, following the implementation of adaptation measures. Obviously, the differences are lower, with in 2050, -0.5% with adaptation in comparison to -0.9% without.

Regarding individual climate impacts, the EU GDP losses are also reduced by the implementation of the adaptation measures for each of them except for labour productivity. In the "No further action" scenario, in 2050, the EU GDP losses due to coastal floods, by -0.18% without adaptation, correspond to -0.07% with adaptation, mitigating about 60% of the EU GDP losses. Similarly, when considering river floods, the change in EU GDP is of -0.67% in 2050 when not including adaptation measures and of -0.34% with the measures i.e. around half of the losses are avoided. For droughts, the reduction in EU GDP losses is also important in 2050, a deviation of the EU GDP of -0.25% without adaptation and of -0.11% with, a reduction by 55%. Finally, in the case of climate change impacts on the labour productivity, the adaptation measures do not reduce the EU GDP losses, in 2050, conversely the decline of EU GDP is even slightly stronger, with -0.51% with adaptation and -0.49% without. This result comes from the conservative assumption used for the benefit-cost ratio for this impact, assumed to be equal to one (as we did not find value in the literature), but also because of the weak mitigation of the adaptation measures on the loss of labour productivity. Thus, the benefit and cost of the adaptation measures are similar ex-ante and do not significantly reduce the damages, but the additional investment required to overcome the climate change impacts on labour productivity implies an additional demand, even if weak, impacting upward the prices on the capital markets (real interest rate). This leads to a slight negative impact on the EU GDP, in comparison to no adaptation. We realised a sensitivity analysis on the benefit-cost ratio for the adaptation measures on the impacts of climate change on labour productivity, with BCR of 1.5 and 2 instead of 1 (see Box 2).

Besides the medium case, the benefits on EU GDP of implementing the adaptation measures could reach up to 1% of GDP in 2050, with a EU GDP loss reducing from -2.3% to -1.4% in the upper bound case of the "No further action" scenario with all climate damages. For the low bound case, this is obviously weaker, with a EU GDP loss of -0.4% in 2050 without adaptation and of -0.25% with adaptation.

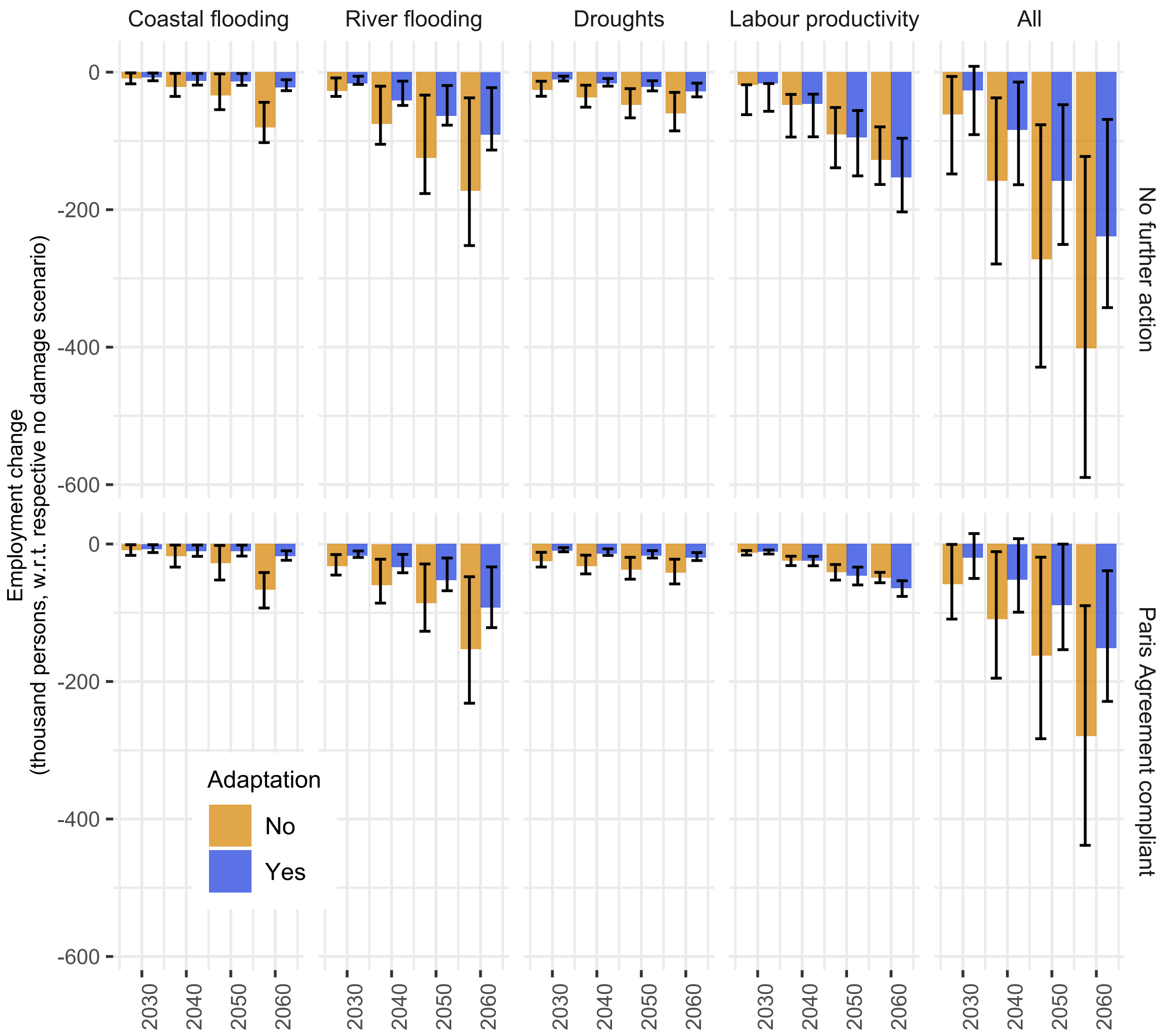
The largest benefit in term of EU GDP of implementing climate change adaptation measures are for river floodings with, in the upper bound case, up to 0.54% of avoided EU GDP losses in 2050, followed by drought with 0.21% and 0.19% of GDP for coastal floodings.

Figure 71: EU GDP deviation without or with adaptation measures for different climate impacts and for all



Source: NEMESIS model.
The error bars indicate the lower (25%) and upper (75%) bounds. The "All" case indicates scenarios in which all climate damages quantified in section 3.3 are included and, when the adaptation measures are implemented, in which adaptation measures are applied on the four following impacts: coastal and river floodings, labour productivity and droughts.

Figure 72: EU employment deviation without or with adaptation measures for different climate impacts and for all



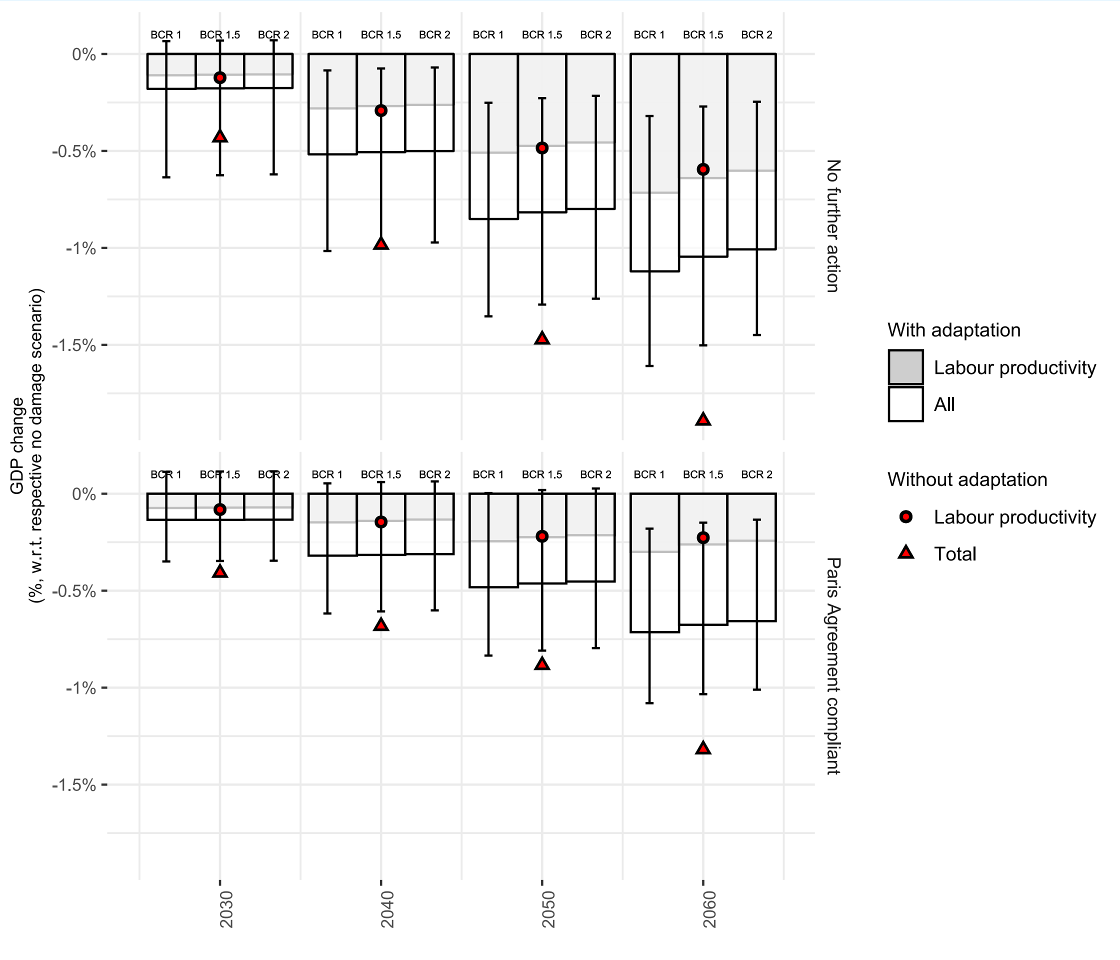
Source: NEMESIS model.
The error bars indicate the lower (25%) and upper (75%) bounds. The "All" case indicates scenarios in which all climate damages quantified in section 3.3 are included and, when the adaptation measures are implemented, in which adaptation measures are applied on the four following impacts: coastal and river floodings, labour productivity and droughts.

As for EU GDP, the total EU employment is also positively impacted (Figure 72) by the implementation of the adaptation measures, with 114 000 jobs saved over the expected 272 000 losses when including climate change damages without adaptation, in 2050, in the "No further action" scenario with all damages. This number goes up to 178 000 when considering the upper bound, with the EU total employment losses passing from 429 000 without adaptation to 251 000 with adaptation. In the lower bound case, the number of jobs saved is more limited, with 29 000 on the loss of 77 000 employment expected in 2050 without adaptation. The adaptation measures to mitigate climate change damages from river floods allow the saving of 61 000 jobs, almost half of the expected loss without adaptation in 2050, in the "No further action" scenario with all damages. The benefit of the adaptation for river floods even reaches 100 000 jobs saved for the upper bund case and limited to 14 000 for the lower case. Adaptation actions for drought and coastal floods reduce the EU employment losses by 26 000 and 20 000 respectively in 2050 for the medium case.

Box 2: Sensitivity analysis on benefit-cost ratio values for the adaptation measure mitigating the climate impact on labour productivity

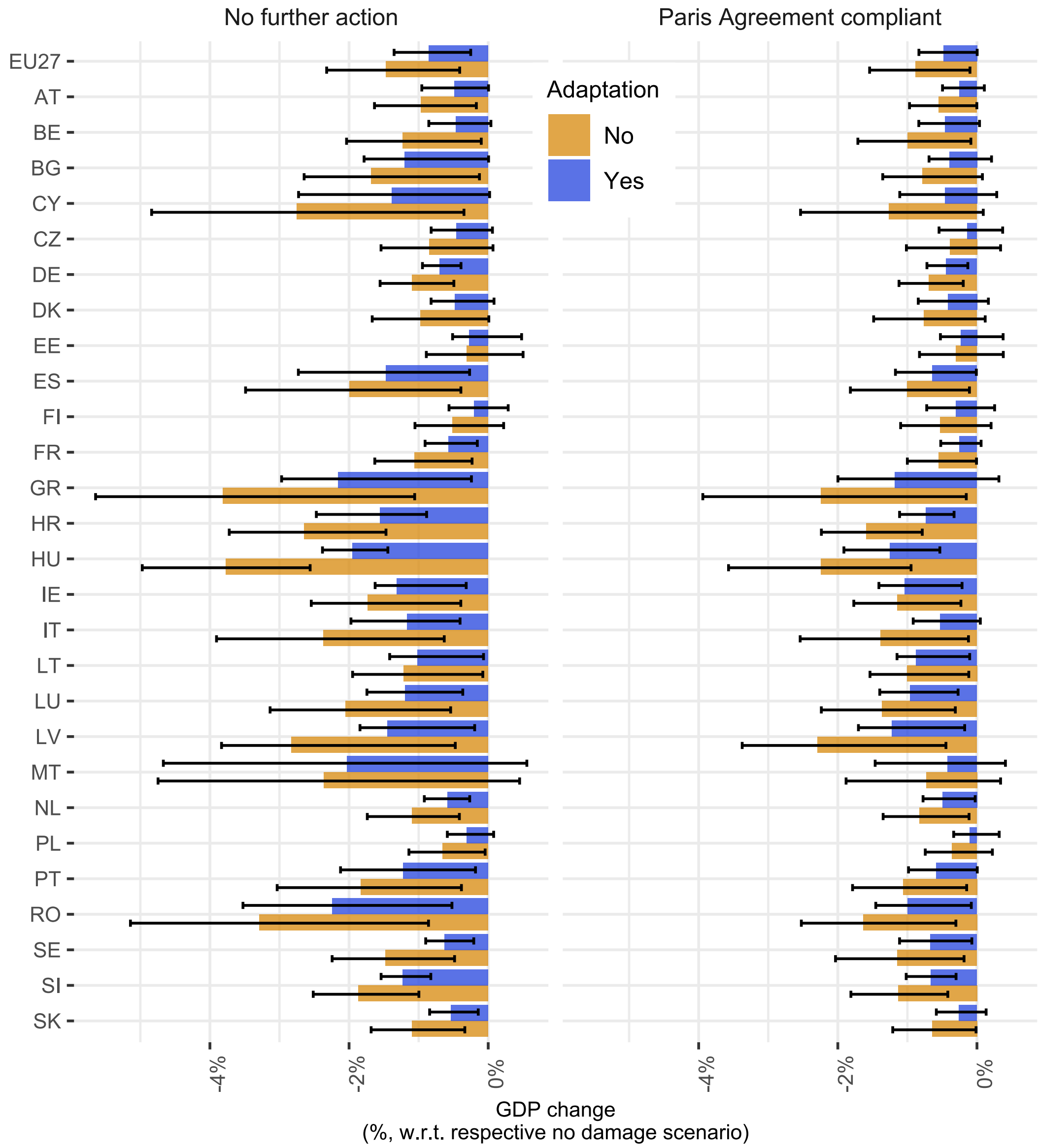
As we did not find in the literature usable benefit-cost ratios of adaptation measures to mitigate climate change impacts on the European labour productivity, we used an ad-hoc and conservative value of one. Figure 73 shows the consequences of using alternative values, namely 1.5 and 2, on the deviation of EU GDP. Higher BCR values improve the macro-economic performance of the adaptation measures for labour productivity that was even slightly negative when using 1 as default value, that is explained by the higher cost of capital induced by the required investment for adaptation. Furthermore, the mitigation of these adaptation measures on EU GDP losses due to lower labour productivity remains very weak and still slightly negative despite higher BCR values. It is explained by the weak reduction rate of the annual expected damages retrieved from the literature review, of 5.5% of the total productivity losses in the central case, significantly limiting the potential benefit despite higher benefit-cost ratios.

Figure 73: EU GDP deviation due to climate change damages without and with adaptation for different values of the benefit-cost ratio



Source: NEMESIS model
The "All" case indicates scenarios in which all climate damages quantified in section 3.3 are included and, when the adaptation measures are implemented, in which adaptation measures are applied to the following impacts: coastal and river floodings, labour productivity and droughts. The red points and triangles are respectively the impact on the EU GDP without adaptation measure, not sensitive to BCR values. The error bars indicate the lower (25%) and upper (75%) bounds when all adaptation measures are included.

Figure 74: GDP deviation by Member States in 2050 without and with adaptation measures for all climate impacts



Source: NEMESIS model.

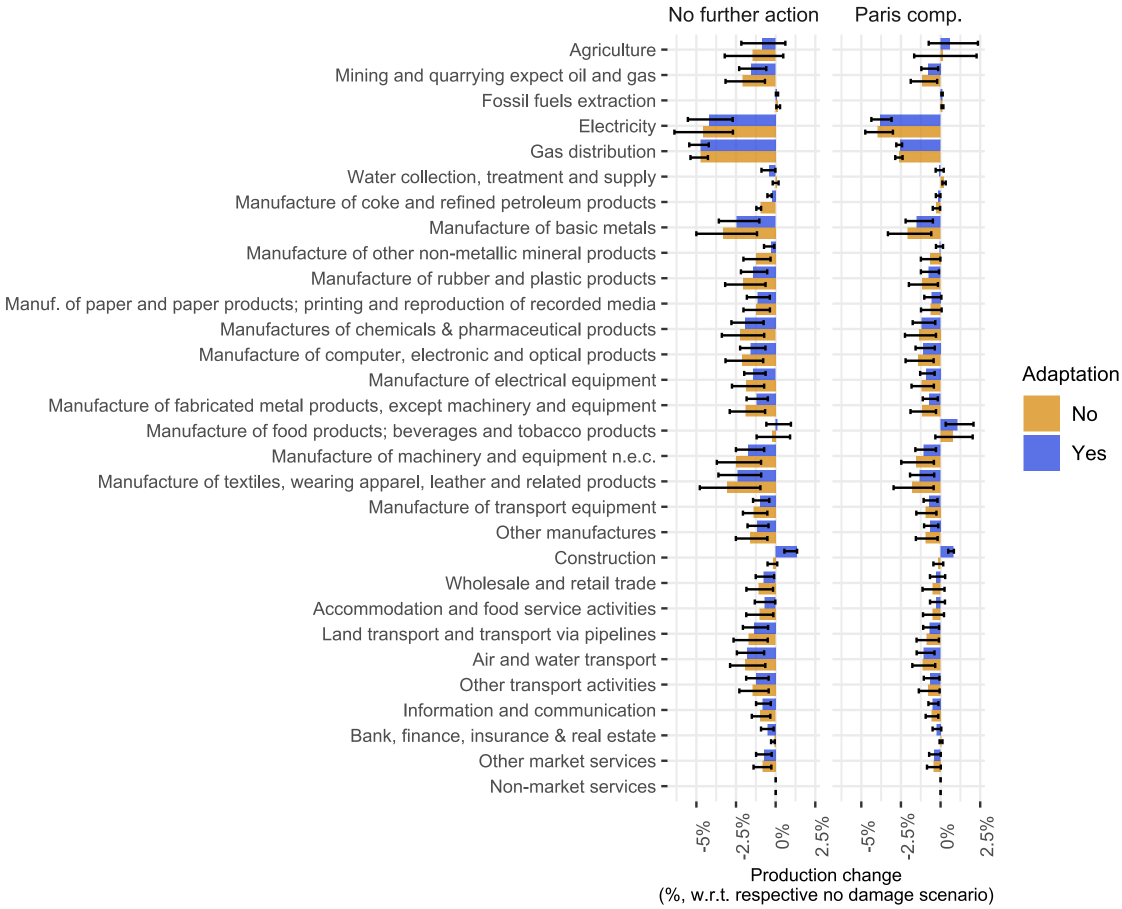
The error bars indicate the lower (25%) and upper (75%) bounds. The results presented concern the case in which all climate damages quantified in section 3.3 are included and, when the adaptation measures are implemented, in which adaptation measures are applied to the following impacts: coastal and river floodings, labour productivity and droughts.

At Member States level, the losses of GDP are also significantly reduced by the adaptation measures for coastal and river floods, drought and labour productivity, all Member states benefit of their implementation (Figure 74). In the "No further action" scenario, and the medium case, the largest GDP losses in 2050 without adaptation are expected in Greece and Hungary, with -3.8% of GDP compared to not considering climate change damages. These GDP losses are reduced to -2.2% and

-1.9% respectively when considering adaptation. In relative terms, there is no major difference between Member States in the benefit of adaptation measures on the reduction of the GDP loss induced by climate change damages, but, obviously, the countries most impacted in absolute terms, are also the ones benefiting the most of the adaptation measures, and inversely.

As a consequence of our methodology, constrained by the results of the literature review, the differentiation at sectoral level of the economic impacts of climate change and adaptation measures is moderated, the EU production by sector does not show large differences especially when comparing the case with and without adaptation. Nevertheless, the reduction of the economic impacts thanks to the implementation of adaptation measures spreads in all sectors in the EU (Figure 75). We also observe slightly higher mitigation of production losses for sectors producing investment goods. It is particularly the case for the "Construction" sector, even positively impacted when adaptation measures are included. In the "No further action" scenario, the production of the "Construction" sector in 2050 is 0.2% lower when including the climate change damages than without and is 1.3% higher when combining climate damages and adaptation measures. This result is explained by the needs of adaptation investments that push up the demand for investments goods.

Figure 75: EU production change by sector in 2050 without and with adaptation measures for all climate impacts



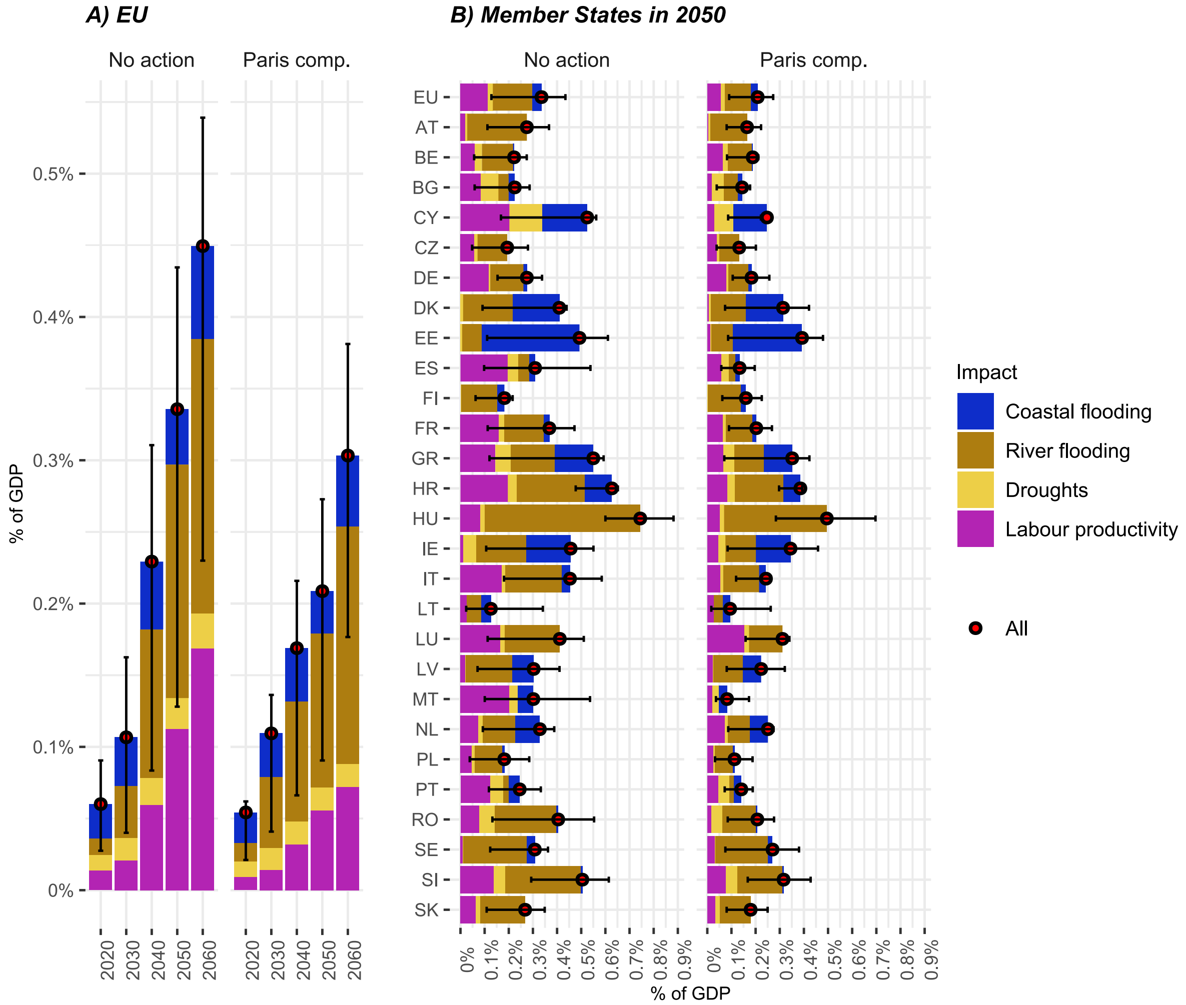
Source: NEMESIS model.

The error bars indicate the lower (25%) and upper (75%) bounds. The results presented are related to the case in which all climate damages quantified in section 3.3 are included and, when the

adaptation measures are implemented, in which adaptation measures are applied to the following impacts: coastal and river floodings, labour productivity and droughts.

Indeed, the adaptation measures must be financed, and this implies important investments, despite the positive impacts expected. In our modelling exercise, the needs of investment for adaptation are calculated from the literature review presented in section 3.5. In fact, the expected annual damages reduction rate applied for each impact and each case, allows the calculation of the avoided costs —the benefits of the adaptation measures in terms of climate change damages mitigation— and with the benefit-cost ratio of these measures, we then calculate the associated cost of the measures for each impact. This implies that the investments for adaptation are added up to other kinds of investment calculated by the model and are exogenous —not depending on the model but on the scenarios and on the cases: moderate, medium and strong. Nevertheless, the additional capital demand required to finance the adaptation measures acts on the capital markets through capital cost, retroacting onto the investment calculated by the model. Figure 76-B presents the extent of the adaptation investments for the EU and the Member States in GDP percentage. In both scenarios, the investments for the adaptation are relatively important, between 0.21% of the EU GDP in 2050 in "Paris Agreement compliant" and 0.33% in "No further action". In 2060, the investment needs reach respectively 0.3% and 0.45% of the EU GDP. In absolute value, in the "No further action", it represents €17 billion (constant 2020) in 2030, €41 billion in 2040, €69 billion in 2050 and €107 billion in 2060, i.e. €42 billion each year on average between 2020 and 2050. In the upper case, it even goes up to €89 billion in 2050 and €127 billion in 2060. In the "Paris Agreement compliant" scenario, those investment needs are lowered with €17 billion (constant 2020) in 2030, €30 billion in 2040, €43 billion in 2050 and €72 billion in 2060, i.e. €29 billion each year on average between 2020 and 2050 –two third of the average investment in the "No further action" scenario.

Figure 76: Investment for adaptation measures in GDP point by impact



Source: NEMESIS model.

A): Total adaptation investments in the EU: B) Total adaptation investments by Member State in 2050. The results presented relate to the case in which all climate damages quantified in section 3.3 are included and in which adaptation measures concern the four following impacts: coastal and river floodings, labour productivity and droughts. "No action" means "No further action" scenario and "Paris comp.", the "Paris Agreement compliant" scenario. Red points and the error bars indicate the medium (50%), lower (25%) and upper (75%) bounds when all adaptation measures are included.

The investment needs to support the adaptation measures vary between Member States (Figure 76-A), with the highest requirements in Hungary, 0.74% of its GDP in the "No further action" scenario in 2050 of which 0.64% to support adaptation measures to river floodings and the lowest needs in Lithuania, with 0.13% of GDP: 0.06% to support adaptation to river floodings, 0.04% to coastal floodings, 0.03% to labour productivity and none for droughts.

The extent of these investments to mitigate the climate change damages on the EU economy, of €69 billion (constant 2020) in 2050 in the central case (0.33% of EU GDP), is important but represent a moderate share of the total investment in 2050, of 1.5% in the "No further action" scenario. Nevertheless, these investments will be added to other important investment needs for the EU economy in the coming decade, as for the digital economy (€125 billion annually in the current decade –European Commission, 2021c) and the achievement of carbon neutrality in the EU

(1.5% of EU GDP over 2031-2050 –European Commission, 2024). Furthermore, if investments required to mitigate GHG emissions in EU will stabilise or decline after 2050, when carbon neutrality is achieved, those for adaptation will continue to grow, and particularly in a "No further action" scenario.

We explore more in details the potential consequences of these additional investment needs for adaptation measures in the following section, through some sensitivity analysis on the financial sector.

3.7 Sensitivity of the results on firms' financing

Previous sections have shown that climate change will impact the EU economy with a continuous upward trend over time, particularly in the case of the "No further action" global context. In this context, these economic losses could be mitigated by implementing some adaptation measures. The modelling exercise with the NEMESIS model has allowed their quantification in terms of GDP, employment and sectoral production, and has considered also some sensitivity of the results on the extent of the expected impacts of the adaptation measures, following findings in the literature. Nevertheless, an additional important uncertainty is how the financial sector may react to these shocks, especially how firms' financing may be affected while they face the additional costs and losses induced by the climate change impacts, and while they need to finance the additional adaptation investments mitigating these costs (Battiston et al., 2021).

Here, we tried, with an exploratory methodology, to add a layer on the top of existing mechanisms in the NEMESIS model to quantify these potential effects of the climate damages and the adaptation measures on the firms financing, particularly the related macro-economic impacts for the EU economy. Our methodology is based on the recent work done by the European Central Bank on the climate stress-tests (Emambakhsh et al., 2023).

In the NEMESIS model, the capital market is modelled assuming that in the long-term the national interest rate (r) equates the long-term equilibrium rate (r^*, exogeneous) and a proportion of the variation from the equilibrium of investment needs, measuring change in capital demand ($\Delta\ln(Inv)$: log-difference of total investment rate, with respect to the reference scenario, the equilibrium situation). To enhance this modelling and consider the impact of climate damages and adaptation measures on the financial sector, we add up a "climate-related risk premium" on the interest rates at national and sectoral level ($ClRP_{c,s}$) as such: $r_{c,s} = r_c^* + \propto . \Delta\ln(Inv) + ClRP_{c,s}$.

Following Emambakhsh et al. (2023) who model this climate-related risk premium as a linear function of the variation of the probability of default (ΔPD), we apply their formulation at sectoral level, as such that: $ClRP_{c,s} = \partial_1 . \Delta PD_{c,s}$, with the probability of default as a logistic function of the leverage and the profitability. In NEMESIS, the leverage is proxied with the gross operating surplus, re-calibrated in 2020, using Eurostat (2023f) minus the financial costs (proxied by the sector user cost of capital). The leverage is proxied with the ratio between liabilities (deduced from Eurostat, 2023f) increased of the investments for adaptation, and the value of the capital stock. All parameters for the probability of default and for the climate-related risk premium come from Emambakhsh et al. (2023). Furthermore, this modelling has been implemented insomuch as the probability of default only changes when considering climate change damages and/or adaptation measures, not in the reference scenarios.

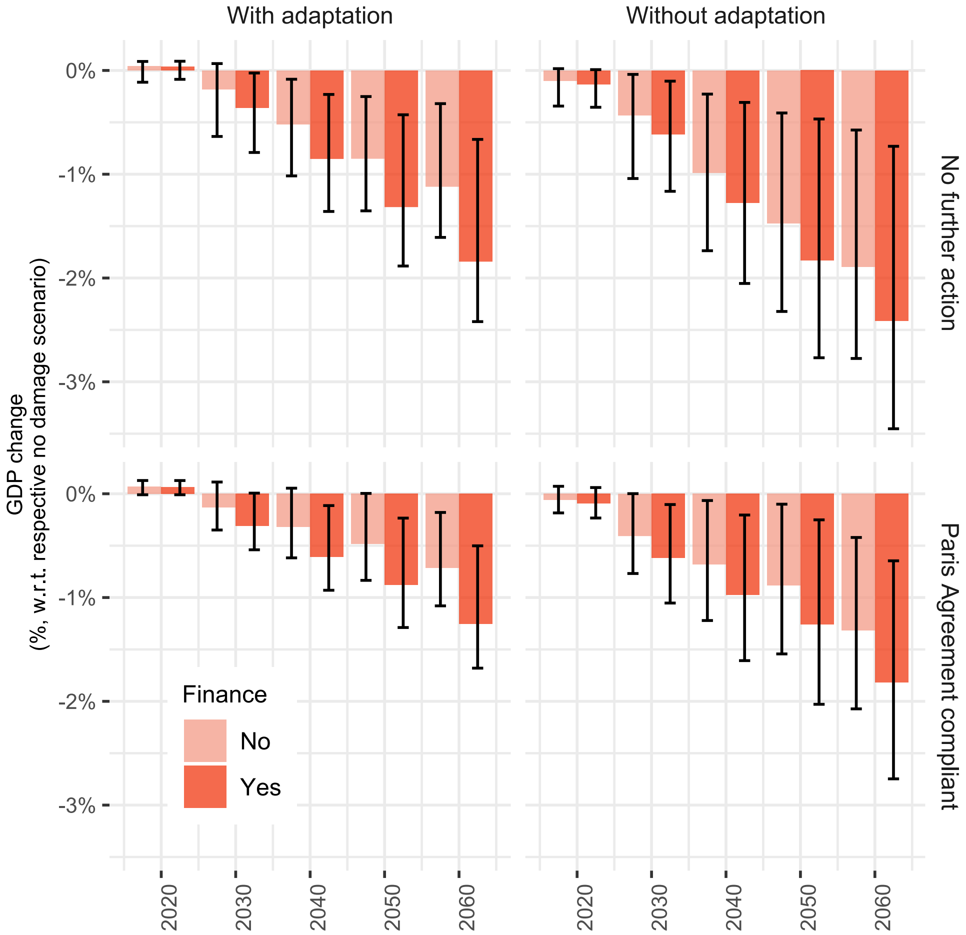
To summarise how the addition of the "climate-related risk premium" will act in our scenarios: the inclusion of the damages from climate change will reduce the firms profitability and increase the risk premium, whereas the implementation of adaptation measures will improve the profitability, but it will also raise the financial leverage of firms that support the investments, leading to a mixed impact on the risk premium.

Before presenting the results of this sensitivity on firms financing, we must clarify that this methodology is exploratory and the results must be considered with caution. We based our work on the methodology developed by Emambakhsh et al. (2023) from the European Central Bank, but in this study, Emambakhsh et al. (2023) assessed the transition risks, and their analysis and estimates have been done at firm-level and up to 2030, whereas we assess the physical risks and adaptation measures at macro-sectoral level up to 2060.

Once again, EU GDP is negatively impacted in all scenarios, and these GDP losses are even larger when considering the addition of the climate risk premium (Figure 77). Indeed, the losses induced by the different climate impacts reduce the profitability of European firms, leading to a higher probability of default that is materialised in higher interest rates in our modelling. In 2050, when this layer on firms' financing is not considered, the EU GDP is -1.5% and -0.9% lower in the "No further action" and "Paris agreement compliant" with all damages than in the respective reference scenarios, and these losses are limited to -0.85% and -0.5% respectively when implementing adaptation. For the same scenarios, with the addition of the climate-related risk premium, the EU GDP losses are of -1.8% and -1.3% in 2050 without adaptation, and -1.3% and -0.9% with adaptation respectively.

Firstly, these numbers indicate that the inclusion of the climate-related risk premium, as modelled here, raises the economic losses in all cases. Nevertheless, this impact is weaker, in relative terms, when the expected GDP losses are the highest like in the "No further Action" scenario without adaptation. In fact, the reduction of the EU GDP implies, *ceteris paribus*, a decline of the macro-economic investment that downwards the capital cost, because of the reduction of the demand for capital. This effect counterbalances partially the negative effect coming from the decline of firms' profitability induced by the climate change damages. Secondly, the inclusion of the climate-related risk premium reduces partially the benefits of the implementation of the adaptation measures to mitigate the economic impacts of the climate damages. Indeed, even if EU GDP losses are still lower with adaptation, when including the climate-related risk premium, the gains are lowered –from the 40-55% of the economic impacts avoided by adaptation measures, the inclusion of climate-related risk premium, limits it benefit to 25-35%. Thus, the negative impacts of the additional investment for adaptation on the leverage of firms overcome the positive impacts coming from the improvement of their profitability.

Figure 77: EU GDP variation due to climate damages without or with adaptation measures and with or without the addition of firms' financing



Source: NEMESIS model.

The results presented are referring to the case in which all climate damages quantified in section 3.3 are included and, when adaptation is implemented, in which adaptation measures are applied to the following impacts: coastal and river floodings, labour productivity and droughts. "No" for finance means that the addition of the climate-related risk premium is not considered, as for results in section 3.4 and 3.6, and "Yes" for finance when it is added. The error bars indicate the lower (25%) and upper (75%) bounds when all damages and all adaptation measures, when implemented, are included.

4. Summary and concluding remarks

In this study, we apply a modelling approach in several steps, starting from the literature review, used thereafter to quantify the shocks introduced in the model. We also explain how we implement the input into the model. We finish with the analysis of the results and the performing of some sensitivity analysis either on some inputs and parameters or on the model' mechanisms.

We defined two reference scenarios that are thereafter used as reference scenarios to assess the economic impacts of the climate change damages and of the adaptation measures. These scenarios represent two different contexts. The first, called **"No further action", draws a high GHG emissions pathway in which current trends on emissions remain and no additional climate mitigation actions are engaged in the rest of the world** (outside of the EU). We base this scenario on the SSP3-7.0 illustrative scenario of the IPCC AR6 WGI (2021) that leads to a temperature rise of about 3.6°C [2.8-4.6°C] in the long term and 2.1°C [1.7-2.6°C] in the mid-term.

The second, called **"Paris Agreement Compliant", depicts a low climate change scenario, in which a rapid and large action to mitigate GHG emissions is realised worldwide in line with the Paris Agreement**. We tie this global context to the SSP1-1.9 illustrative scenario from IPCC AR6 WGI (2021) in which global mean temperature rise about 1.4°C [1.0-1.8°C] in the long-term and 1.6°C [1.2-2.0°C] in the mid-term.

On each of these global climate contexts, we applied a particular EU climate action: **in the "No further action" context, we assume that the EU energy system and GHG emissions evolve as described in the EU Reference Scenario 2020**whereas **in the "Paris Agreement Compliant" context, the EU commits to a deep decarbonisation**, following the European Green Deal GHG reduction target of at least -55% in 2030 with respect to 1990 and applying the "Fit for 55" policy package for the EU-ETS and ESR sectors (European Commission, 2021c). After 2030, GHG emissions decline regularly to reach net zero emissions in 2050, as stated in the European Long-term Strategy (European Union, 2020) and remain at net zero thereafter.

The transformation of the energy system required in the EU in the "Paris Agreement compliant" scenario delivered by the NEMESIS model is relatively similar to the PRIMES projections. Nevertheless, the NEMESIS model relies more after 2040 on negative emission technologies (namely biomass with carbon capture and storage in power generation) than PRIMES, allowing lower GHG mitigation efforts in final energy sectors. Renewable energy sources are also largely mobilised to decarbonise the EU economy in both models, but NEMESIS uses more bio-energy resources than PRIMES.

The macro-economic assessment by **the NEMESIS model emphasises the important role of investments that positively contribute to the EU GDP in the "Paris Agreement compliant" scenario, but that also push up capital costs, leading to inflationary pressures in the EU** and then a decline of the EU competitiveness compared to the rest of the world, in which we assume no particular impact. This leads, in 2050, to a decline of EU GDP by -0.7% compared to the "No further action" scenario. This GDP loss is on the lower bound of European Commission's macro-economic impact assessment (European Commission, 2018), between -1.3% to +2.2% in comparable scenarios that may be explained by some limitations in available mitigation options in NEMESIS (no hydrogen, no e-fuels, etc.) and by the assumptions of limited availability of credit to finance these additional investment needs –an assumption that can significantly influence the economic impact of deep decarbonisation (Pollitt and Mercure, 2019; Boitier et al., 2022).

For the next step, we selected from the literature review **10 different impact areas** of climate change that will affect the European economy in the coming decades, and we identified quantitative figures usable for the macro-economic modelling. These impacts are: **coastal floodings, labour**

productivity, agriculture, energy demand and supply, droughts, forestry, fisheries and river floodings. The availability of quantitative studies for each of these impacts is heterogeneous in terms of geographical or sector details as well as in terms of number: from five and seven studies for coastal floods and labour productivity respectively to one for forestry and fisheries. We excluded the studies that assess the economic impacts of future climate change on the EU tourism and ecosystem services because these are too segmented in their scope for tourism and too aggregated and very scarce for ecosystem services.

After processing the data, collected in the synthesis of the literature review (section 3.3), to frame them with both general climate contexts, we introduced the climate change damages into the NEMESIS model. **The implementation of the impacts of climate change downwards the projected EU GDP without these damages. In 2050, the EU GDP loss is of -1.5% and -1.9% in 2060 in the "No further action" scenario, and of -0.9% and -1.5% respectively in the "Paris Agreement compliant" scenario**. When using the upper bound of the literature on the potential climate change impacts, the EU GDP losses increase to -2.3% in 2050 and -2.8% in 2060 in the "No further action" scenario, and to -1.5% and -2.1% respectively in the "Paris Agreement compliant" scenario.

The expected effects of the climate change damages on employment follow similarly those on the EU GDP. **In 2050, in the "No further action" scenario, the total potential employment loss is of 1.4 million persons in comparison with the same scenario without climate damages. These losses are about 675 000 employments in the "Paris Agreement compliant" scenario**. Among the ten impacts analysed, four contribute significantly to the EU GDP reduction. On the -1.5% of GDP losses expected in 2050 in the "No further action" scenario, -0.67% of GDP is due to river flooding, -0.48% to lower labour productivity, -0.25% from droughts, and -0.18% from coastal flooding. At the opposite, climate change impact on the energy demand and agriculture could have moderated and even positive consequences on the EU economy.

At Member States level, the projected economic impacts of climate change are relatively heterogeneous, with the largest GDP losses in Greece, Cyprus, Hungary and Romania with: -3.8%, -2.75%, -3.7% and -3.3% respectively in 2050 in the "No further action" scenario. Globally, European Mediterranean countries (Portugal, Spain, Italy, Malta, Slovenia, Croatia, Greece and Cyprus) face a two-fold GDP loss compared to other EU countries, with in the "No further action" scenario and in 2050, -2.3% of GDP compared to -1.2% in the rest of EU countries**. In the strong case, these impacts on GDP are larger, with, in the "No further action" scenario, GDP losses reaching up to -5.6% in Greece, -5.1% in Romania, -5% in Hungary and -4.8% in Cyprus in 2050**. Besides these numbers, the results show an increase trend in the impacts on the EU economy and the projection of these impacts after 2060 would continue to grow in the "No action scenario", whereas they are expected to stabilise in the "Paris Agreement compliant" scenario, as the increase in the global temperature would also stabilise in this scenario.

In the next step, as for the climate damages, we identified in the literature the effects of the adaptation measures, focusing on four impacts (coastal and river floods, labour productivity and droughts), that have shown the largest impacts on the EU economy. For each impact, we collected the annual expected damages reduction rate and the benefit-cost ratio, to calculate the extent of the mitigation of the climate change damages achieved by adaptation measures and their related costs.

The implementation of adaptation measures on top of climate damages mitigate the EU GDP losses induced by these damages. **In the "No further action" scenario, in 2050, without adaptation the EU GDP declines by -1.5%, whereas it is -0.9% with adaptation. Similarly, in the "Paris Agreement compliant" scenario, the EU GDP loss is of -0.9% without adaptation and of -0.5% with adaptation**. The employment gains coming from the implementation of the adaptation measures are also important, of 115 000 in the "No further action" scenario and of 73 000 in the "Paris Agreement compliant" scenario.

At Member States level, there are no major differences, in relative terms, across Member States in the benefit of adaptation measures, but the countries that are most impacted in absolute terms are also the ones benefiting the most from adaptation, and inversely. **The extent of these investments to mitigate the climate change damages on the EU economy, corresponding to €69 billion (constant 2020) in 2050 in the average case (0.33% of EU GDP), is important, but represents a moderate share of the total investment in 2050**, of 1.5% in the "No Further Action" scenario. Nevertheless, these investments will be added to other important investment needs for the EU economy in the coming decades, such as for the digital economy and the achievement of carbon neutrality, and will continue to grow after 2060, particularly in a "No Further Action" scenario.

Finally, we ran different sensitivity analysis on different parameters for which the literature does not deliver enough information, namely, the share of insured damages and on the value of the cost-benefit ratio of adaptation measures for damages impacting labour productivity (section 3.6). Both sensitivity analyses do not modify our conclusions from the previous results, however the sensitivity analysis on the firms' financing shows more marked impacts. We add on the top of existing modelling of the interest rates a climate-related risk premium at country and sectoral level, following Emambakhsh et al. (2023). **In 2050, when this layer on firms' financing is considered, the EU GDP declines by -1.8% and -1.3% in the "No further action" and "Paris agreement compliant" scenarios without adaptation, and by -1.3% and -0.9% with adaptation, whereas these EU GDP losses are of -1.5% and -0.9%, without adaptation and of -0.9% and -0.5% with adaptation in the "No further action" and "Paris agreement compliant" scenarios respectively, when the climate-related risk premium is not included.** The economic losses induced by climate change damages reduce firms' profitability, pushing up the risk perceived by investors, while the implementation of adaptation measures mitigates this reduction of firms' profitability, but the financing of the related adaptation investments increases their debt, therefore partially counterbalancing the positive effects on their profitability.

To summarise, the impacts of climate change on the EU economy in the middle of the century are expected to be significant (-1.5% of EU GDP and up to -2.3%), even if deep decarbonisation, compliant with the Paris Agreement, is achieved (-0.9% and up to -1.5%). In case of no additional GHG mitigation effort worldwide, the upward trend on the economic impacts of climate change damages would continue, while it would stabilise in a Paris Agreement compliant scenario. Adding potential additional climate-related risks on firms' financing reinforce the negative impacts on the EU economy (-1.8% instead of -1.5% EU GDP in the "Paris Agreement Compliant" scenario and up to -2.8% instead of -2.3% EU GDP in the "No Further Action" scenario). These economic losses can be mitigated with appropriate adaptation measures in both scenarios.

All these results must be considered with caution, in particular the sensitivity of firms' financing which is based on an exploratory approach, but also for climate change damages and adaptation measures. Our modelling exercise is limited to 2060, and the extent to which climate damages would continue to grow up with temperature raise thereafter. We do not include tipping points that may exacerbate economic losses, and some potential snowball effects cannot be considered in macro-economic modelling. Finally, we must also mention that the benefits from implementing adaptation measures are important because our methodology selected the efficient ones, but there might exist important maladaptation lowering their expected benefits, or even increasing the economic losses.

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