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Europe

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Executive Summary

Where Are We Now?

Our current 1.1°C warmer world is already affecting natural and human systems in Europe (*very high confidence*[1]). Since AR5, there has been a substantial increase in detected or attributed impacts of climate change in Europe, including extreme events (*high confidence*). Impacts of compound hazards of warming and precipitation have become more frequent (*medium confidence*). Climate change has resulted in losses of, and damages to, people, ecosystems, food systems, infrastructure, energy and water availability, public health and the economy (*very high confidence*) {13.1.4;13.2.1;13.3.1;13.4.1; 13.5.1;13.6.1;13.7.1;13.8.1;13.10.1}.

As impacts vary both across and within European regions, sectors, and societal groups (*high confidence*), inequalities have deepened (*medium confidence*). Southern regions tend to be more negatively affected, while some benefits have been observed, alongside negative impacts in northern and central regions. Traditional lifestyles, for example in the European Arctic, are threatened already (*high confidence*). Poor households have lower capacity to adapt to, and recover from, impacts (*medium confidence*) {13.5.1;13.6.1;13.7.1;13.8.1.;13.8.2;13.10.1;Box 13.2}.

The range of options available to deal with climate-change impacts has increased in most of Europe since AR5 (*high confidence*). Growing public perception and adaptation knowledge in public and private sectors, the increasing number of policy and legal frameworks, and dedicated spending on adaptation are all clear indications that the availability of options has expanded (*high confidence*). Information provision, technical measures and government policies are the most common adaptation actions implemented. Nature-based Solutions (NbS) that restore or recreate ecosystems, build resilience and produce synergies with adaptation and mitigation are increasingly used. Many cities are taking adaptation action, but with large differences in level of ambition and implementation (*high confidence*) {13.2.2;13.3.2;13.4.2;13.5.2;13.6.2;13.7.2;13.8.2;13.10.2; 13.11.1;13.11.2;13.11.3}.

Observed adaptation actions are largely incremental with only a few examples of local transformative action; adaptation actions have demonstrated different degrees of effectiveness in reducing impacts and feasibility of implementation (*high confidence*). For example, adaptation actions such as flood defences and early warning systems have reduced flood damages and heat-related mortality in parts of Europe. Despite progress in adaptation, impacts are observed. Adaptation actions in the private sector are limited, with many businesses and regions remaining under-prepared. A gap remains between planning and implementation of adaptation action (*high confidence*) {13.2.2;13.5.2;13.6.2;13.7.2;13.11}.

What Are the Future Risks?

Warming in Europe will continue to rise faster than the global mean, widening risk disparities across Europe in the 21st century (*high confidence*). Largely negative impacts are projected for southern regions (e.g., increased cooling needs and water demand, losses in agricultural production and water scarcity) and some short-term benefits are anticipated in the north (e.g., increased crop yields and forest growth) {13.1.4;13.2.1;13.3.1;13.4.1;13.5.1;13.6;13.7.1;13.10.2}.

Four key risks (KR) have been identified for Europe, with most becoming more severe at 2°C global warming levels (GWL) compared with 1.5°C GWL in scenarios with low to medium adaptation (*high confidence*). From 3°C GWL and even with high adaptation, severe risks remain for many sectors in Europe (*high confidence*). Key risks are: mortality and morbidity of people and ecosystems disruptions due to heat (KR1: heat); loss in agricultural production due to combined heat and droughts (KR2: agriculture); water scarcity across sectors (KR3: water scarcity); impacts of floods on people, economies and infrastructure (KR4: flooding) {13.10.2}.

KR1: The number of deaths and people at risk of heat stress will increase two- to threefold at 3°C compared with 1.5°C GWL (*high confidence*). Risk consequences will become severe more rapidly in Southern and Western Central Europe and urban areas (*high confidence*). Thermal comfort hours during summer will decrease significantly (*high confidence*), by as much as 74% in Southern Europe at 3°C GWL. Above 3°C GWL, there are limits to the adaptation potential of people and existing health systems, particularly in Southern Europe, Eastern Europe and areas where health systems are under pressure (*high confidence*) {13.6.1;13.6.2;13.7.1;13.7.2;13.8.1;13.10.2.1}.

KR1: Warming will decrease suitable habitat space for current terrestrial and marine ecosystems and irreversibly change their composition, increasing in severity above 2°C GWL (*very high confidence*). Fire-prone areas are projected to expand across Europe, threatening biodiversity and carbon sinks (*medium confidence*). Adaptation actions (e.g., habitat restoration and protection, fire and forest management, and agroecology) can increase the resilience of ecosystems and their services. Trade-offs between adaptation and mitigation options (e.g., coastal infrastructure and NbS) will result in risks for the integrity and function of ecosystems (*medium confidence*) {13.3.1;13.3.2;13.4.1;13.4.2;13.10.2.1; Cross-Chapter Box SLR in Chapter 3; Cross-Chapter Box NATURAL in Chapter 2}.

KR2: Due to a combination of heat and drought, substantive agricultural production losses are projected for most European areas over the 21st century, which will not be offset by gains in Northern Europe (*high confidence*). Yield losses for maize will reach 50% in response to 3°C GWL, especially in Southern Europe. Yields of some crops (e.g., wheat) may increase in Northern Europe if warming does not exceed 2°C (*medium confidence*).

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[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium or robust; and for the degree of agreement: low, medium or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and is typeset in italics (e.g., *medium confidence*). For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

While irrigation is an effective adaptation option for agriculture, the ability to adapt using irrigation will be increasingly limited by water availability, especially in response to GWL above 3°C (*high confidence*) {13.5.1;13.5.2;13.10.2.2}.

KR3: Risk of water scarcity will become high at 1.5°C and very high at 3°C GWL in Southern Europe (*high confidence*), and increase from moderate to high in Western Central Europe (*medium confidence*). In Southern Europe, more than a third of the population will be exposed to water scarcity at 2°C GWL; under 3°C GWL, this risk will double, and significant economic losses in water- and energy-dependent sectors may arise (*medium confidence*). For Western Central and Southern Europe, and for many cities, the risk of water scarcity will be strongly increasing under 3°C GWL. Adaptation becomes increasingly difficult at 3°C GWL and above, due to geophysical and technological limits; hard limits are *likely*[2] first reached in parts of Southern Europe {13.2.1;13.2.2;13.6.1;13.10.2.3}.

KR4: Due to warming, changes in precipitation and sea level rise (SLR), risks to people and infrastructures from coastal, riverine and pluvial flooding will increase in Europe (*high confidence*). Risks of inundation and extreme flooding will increase with the accelerating pace of SLR along Europe's coasts (*high confidence*). Above 3°C GWL, damage costs and people affected by precipitation and river flooding may double. Coastal flood damage is projected to increase at least tenfold by the end of the 21st century, and even more or earlier with current adaptation and mitigation (*high confidence*). Sea level rise represents an existential threat for coastal communities and their cultural heritage, particularly beyond 2100 {13.2.1;13.2.2;13.6.2;13.10.2.4;Box 13.1; Cross-Chapter Box SLR in Chapter 3).

European cities are hotspots for multiple risks of increasing temperatures and extreme heat, floods and droughts (*high confidence*). Warming beyond 2°C GWL is projected to result in widespread impacts on infrastructure and businesses (*high confidence*). These impacts include increased risks for energy supply (*high confidence*) and transport infrastructure (*medium confidence*), increases in air conditioning needs (*very high confidence*) and high water demand (*high confidence*) {13.2.2;13.6.1;13.7.1;13.10.2}.

European regions are affected by multiple key risks, with more severe consequences in the south than in the north (*high confidence*). These risks may co-occur and amplify each other, but there is uncertainty about their interactions and their quantifications. There is *high confidence* that consequences for socioeconomic and natural systems will be substantial: the number of people exposed to KRs and economic losses are projected to at least double at 3°C GWL compared with 1.5°C GWL (*medium confidence*); and increased risks are also projected for biodiversity and ecosystem services, such as carbon regulation. The risks resulting from changes in climatic and non-climatic drivers in many sectors is a key gap in knowledge (*high confidence*). This gap prevents the precise assessment of systemic risks, socio-ecological tipping points and limits to adaptation {13.10.2;13.10.3;13.10.4}.

Climate risks from outside Europe are emerging due to a combination of the position of European countries in the global supply chain and shared resources (*high confidence*). There is emerging evidence that climate risks in Europe may also impact financial markets, food production and marine resources beyond Europe. Exposure of European countries to inter-regional risks can be reduced by international governance and collaboration on adaptation in other regions (*medium confidence*) {13.5.2;13.9.1;13.9.2;13.11; Cross-Chapter Box INTEREG in Chapter16}.

What Are the Solutions, Limits and Opportunities of Adaptation?

There are a growing range of adaptation options available today to deal with future climate risks (*high confidence*). Examples of adaptation to the key risks include: behavioural change combined with building interventions, space cooling and urban planning to manage heat risks (KR1); restoration, expansion and connection of protected areas for ecosystems, while generating adaptation and mitigation benefits for people (KR1: heat); irrigation, vegetation cover, changes in farming practices, crop and animal species, and shifting planting (KR2: agriculture); efficiency improvements, water storage, water reuse, early warning systems and land-use change (KR3: water scarcity); early warning systems, reserving space for water and ecosystem-based adaptation, sediment or engineering-based options, land-use change and managed retreat (KR4: flooding). Nature-based Solutions for flood protection and heat alleviation are themselves under threat from warming, extreme heat, drought and SLR (*high confidence*) {13.2.2;13.3.2;13.4.2;13.5.2;13.6.2;13.7.2;13.8.2;13.9.4;13.10.2;13.11}.

In many parts of Europe, existing and planned adaptation measures are not sufficient to avoid the residual risk, especially beyond 1.5°C GWL (*high confidence*). Residual risk can result in losses of habitat and ecosystem services, heat related deaths (KR1), crop failures (KR2), water rationing during droughts in Southern Europe (KR3) and loss of land (KR4) (*medium confidence*). At 3°C GWL and beyond, a combination of many, maybe even all, adaptation options are needed, including transformational changes, to reduce residual risk (*medium confidence*). {13.2.2;13.3.2;13.4.2;13.5.2;13.6.2;13.7.2;13.8.2;13.9.4;13.10.2;13.11}.

Although adaptation is happening across Europe, it is not implemented at the scale, depth and speed needed to avoid the risks (*high confidence*). Many sectors and systems, such as flood risk management, critical infrastructure and reforestation, are on self-reinforcing development paths that can result in lock-ins and prevent changes needed to reduce risks in the long term and achieve adaptation targets. Forward-looking and adaptive planning can prevent path dependencies and maladaptation, and ensure timely action (*high confidence*). Monitoring climate change, socioeconomic developments and progress on implementation is critical in assessing if and when further actions are needed, and evaluating whether adaptation is successful {13.2.2;13.10.2;13.11.1;13.11.2;13.11.3; Cross-Chapter Box DEEP in Chapter 17}.

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[2] In this Report, the following terms are used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10% and exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100% and extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics (e.g., *very likely*).

Systemic barriers constrain the implementation of adaptation options in vulnerable sectors, regions and societal groups (*high confidence*). Key barriers are limited resources, lack of private-sector and citizen engagement, insufficient mobilisation of finance, lack of political leadership and low sense of urgency. Most of the adaptation options to the key risks depend on limited water and land resources, creating competition and trade-offs, also with mitigation options and socioeconomic developments (*high confidence*). Europe will face difficult decisions balancing these trade-offs. Novel adaptation options are pilot tested across Europe, but upscaling remains challenging. Prioritisation of options and transitions from incremental to transformational adaptation are limited due to vested interests, economic lock-ins, institutional path dependencies and prevalent practices, cultures, norms and belief systems {13.11.1;13.11.2;13.11.3}.

Several windows of opportunity emerge to accelerate climate resilient development (CRD) (*medium confidence*). Such windows are either institutionalised (e.g., budget cycles, policy reforms and evaluations, infrastructure investment cycles) or open unexpectedly (e.g., extreme events, COVID-19 recovery programmes). These windows can be used to accelerate action through mainstreaming and transformational actions (*medium confidence*). This CRD is visible in European cities, particularly in green infrastructure, energy-efficient buildings and construction, and where co-benefits (e.g., to health, biodiversity) have been identified. Private-sector adaptation takes place mostly in response to extreme events or regulatory, shareholder or consumer pressures and incentives (*medium confidence*) {13.11.3; Box 13.3; Cross-Chapter Box COVID in Chapter 7}.

Closing the adaptation gap requires moving beyond short-term planning and ensuring timely and adequate implementation (*high confidence*). Inclusive, equitable and just adaptation pathways are critical for CRD. Such pathways require consideration of SDGs, gender and Indigenous knowledge and local knowledge (IKLK) and practices. The success of adaptation will depend on our understanding of which adaptation options are feasible and effective in their local context (high confidence). Long lead times for nature-based and infrastructure solutions or planned relocation require implementation in the coming decade to reduce risks in time. To close the adaptation gap, political commitment, persistence and consistent action across scales of government, and upfront mobilisation of human and financial capital, is key (high confidence), even when the benefits are not immediately visible {13.2.2;13.8;13.11; Cross-Chapter Box GENDER in Chapter 18}.

13.1 Point of Departure

13.1.1 Introduction and Geographical Scope

This regional chapter on climate-change impacts, vulnerabilities and adaptations in Europe examines the impacts on the sectors, regions and vulnerable populations of Europe, assesses the causes of vulnerability and analyses ways to adapt, thereby considering socioeconomic developments, land-use change and other non-climatic drivers. Compared with AR5 and in the context of the Paris Agreement (2015), we place emphasis on the planned and implemented solutions, assess their feasibility and effectiveness, and consider the Sustainable Development Goals (SDG) and shared socioeconomic pathways (SSPs). Global warming level (GWL) refers to global climate-change emissions relative to pre-industrial levels, expressed as global surface air temperature (Section 1.6.2; Chen et al., 2021).

The chapter generally follows the overall structure of AR6 WGII. We first present our point of departure (the present section) followed by the key sectors, starting with water, as water is interconnected and of fundamental importance to subsequent sections (Sections 13.2–13.8). For each section, we assess the observed impacts and projected risks, solution space and adaptation options, and knowledge gaps. The solution space is defined as the space within which opportunities and constraints determine why, how, when and who adapts to climate risks (Haasnoot et al., 2020a). Section 13.9 discusses impacts and adaptation beyond Europe, followed by the key risks for Europe (Section 13.10). The chapter ends with an assessment of the adaptation solution space, CRD pathways and SDGs (13.11), although recognising that scientific literature on these aspects is only slowly beginning to emerge.

With the rapidly growing body of scientific literature since WGII AR5 (Callaghan et al., 2020), our assessment prioritises systematic reviews, meta-analyses, and synthesis papers and reports. Feasibility and effectiveness assessments use revised methods developed for the Special Report of Global warming of 1.5°C (de Coninck et al., 2018; Singh et al., 2020). Protocols, as well as supporting material for figures and tables, can be found in the Supplementary Material.

The geographical scope and subdivision of European land, coastal and ocean regions is largely the same as in WGII AR5 Chapter 23 (Kovats et al., 2014): Southern Europe (SEU), Western Central Europe (WCE), Eastern Europe (EEU) and Northern Europe (NEU). Note that WGI assesses a larger region for the Mediterranean (MED) which includes North Africa and the Middle East compared with the assessment in this chapter (SEU). The European part of the Arctic region is not

Geographical subdivision of land and ocean regions of Europe

Polygon delineations represent the boundaries used for the regional synthesis of historical trends and future climate change projections used in the Assessment Reports of the IPCC WGI.

- 🟪 **(a) Northern Europe (NEU)**
- 🟨 **(b) Eastern Europe (EEU)**
- 🟧 **(c) Western and Central Europe (WCE)**
- 🟩 **(d) Southern Europe (SEU)** *

European marine sub-regions

- 🟦 **(i) Northern European Seas (NEUS)**
- ▨ **(ii)Temperate European Seas (TEUS)**
- ☐ **(iii) Southern European Seas (SEUS)**

* Different from the WGI Mediterranean (MED) which includes also the eastern and southern countries bordering the Mediterranean.

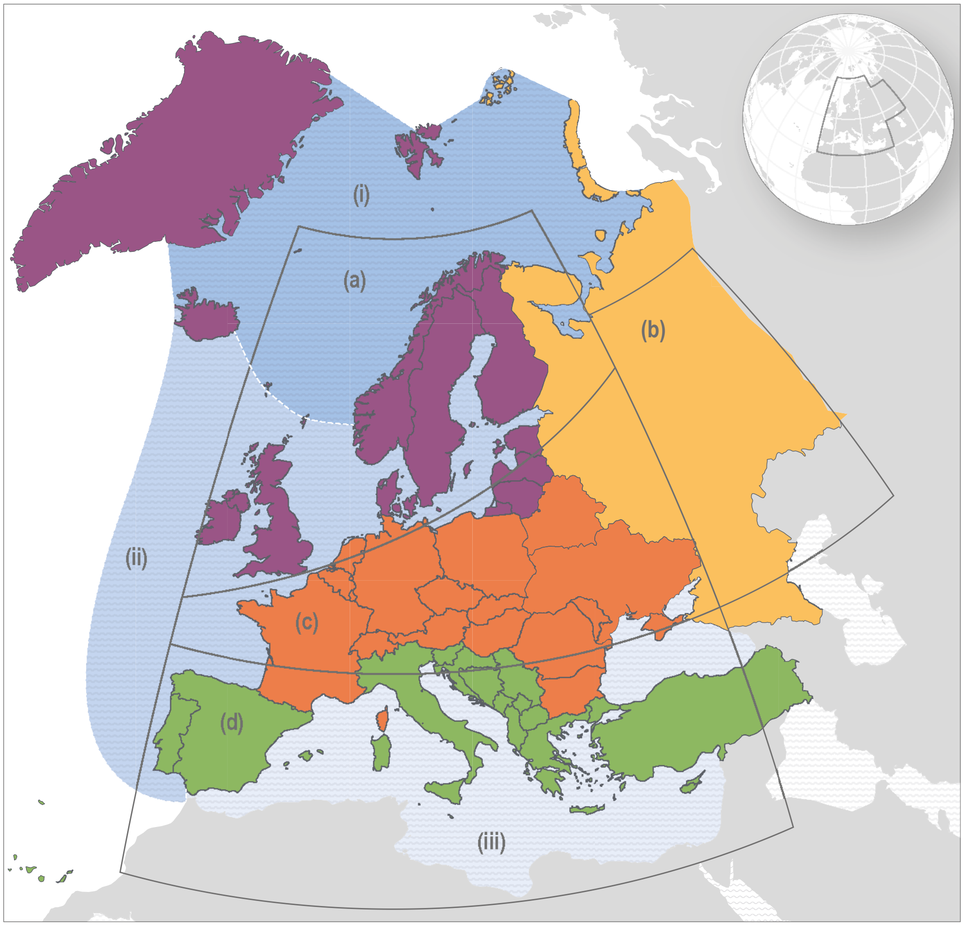


Figure 13.1 | Geographical subdivision of land (a,b,c,d) and ocean (i,ii,iii) regions of Europe. The overlay represents the WGI AR6 (IPCC, 2021) subdivisions for climate-change projections of land, while the colour coding indicates the European countries (or, in case of the Russian Federation, the European part of the country, EEU, used for this chapter). Note that in the WGI AR6 report, MED includes both Southern Europe and Northern Africa, while this chapter includes only the northern (European) part of the MED region. To distinguish between the two the region is called SEU here.

systematically assessed here, as it is extensively captured in Cross-Chapter Paper 6. Information relevant to Europe is also synthesised in the CCPs (Cross-Chapter Papers), including European biodiversity hotspots (Cross-Chapter Paper 1), coastal cities and settlements (Cross-Chapter Paper 2), Mediterranean regions (Cross-Chapter Paper 4) and mountains (Cross-Chapter Paper 5). European seas are broadly divided by latitude into (i) European Arctic waters (NEUS), (ii) European temperate seas (TEUS) and (iii) southern seas with the Mediterranean and the Black Sea (SEUS) (Figure 13.1).

13.1.2 Socioeconomic Boundary Conditions

The adaptive capacity, as measured by the GDP per capita, tends to be higher in northern and western parts of Europe (Figure 13.2a). In recent decades, climate change has led to substantial losses and damages to people and assets across Europe, mostly from riverine flooding, heatwaves and storms (Figure 13.2b). Public concern about climate change, which is an indicator of the intention to mitigate and adapt, is particularly high in parts of SEU and WCE (Figure 13.2c). Current vulnerability to extreme weather and climatic events in European countries is low to moderate compared with the rest of the world (Figure 13.2d).

13.1.3 Impact Assessment of Climate Change Based on Previous Reports

The main findings of previous reports, particularly the WGII AR5 (Kovats et al., 2014) and the IPCC Special Report on 1.5°C (Hoegh-Guldberg et al., 2018), highlighted the impacts of warming and rainfall variations and their extremes on Europe, particularly SEU and mountainous areas. At 2°C GWL, 9% of Europe's population was projected to be exposed to aggravated water scarcity, and 8% of the territory of Europe were characterised to have a high or very high sensitivity to desertification (UNEP/UNECE, 2016). These impacts are driven by changes in temperature, precipitation, irrigation developments, population growth, agricultural policies and markets (EEA, 2017a). Heat is a main hazard for high-latitude ecosystems (Kovats et al., 2014; Jacob et al., 2018; Hock et al., 2019). The majority of mountain glaciers lost mass during the past two decades, and permafrost in the European Alps and Scandinavia

Damages to people and assets, vulnerability and adaptive capacity across Europe

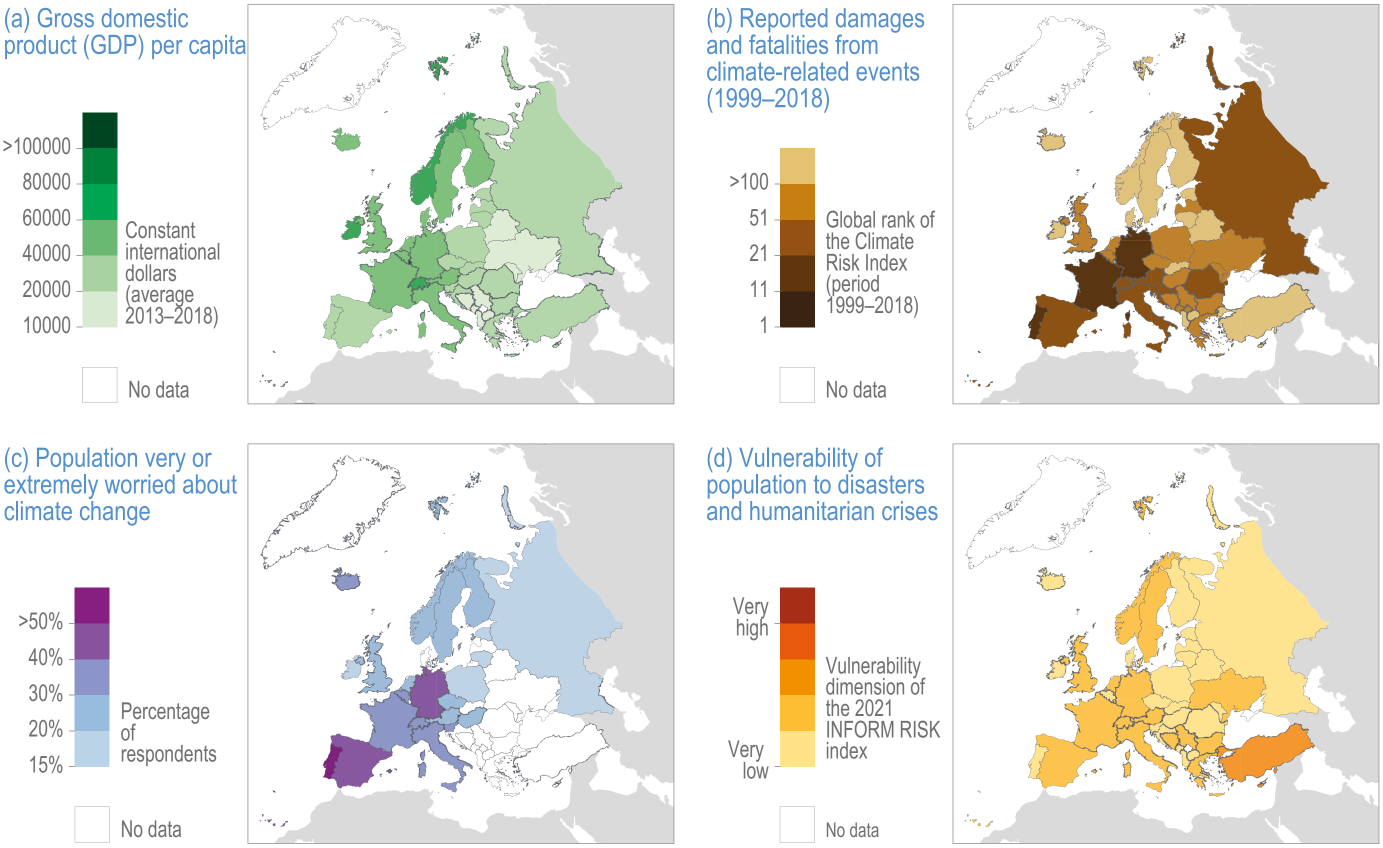


Figure 13.2 | Indicators of reported damages to people and assets, vulnerability and adaptive capacity across European countries:

(a) GDP per capita (average 2013–2018), in constant 2011 international dollars (World Bank, 2020);

(b) exposure as measured by the global rank of the Climate Risk index, which is based on economic damages and fatalities due to climate-related extreme weather events between 1999 and 2018 (Germanwatch, 2020);

(c) level of climate-change concern among a representative weighted sample of residents 15 years and older in private households (European Social Survey, 2020); and

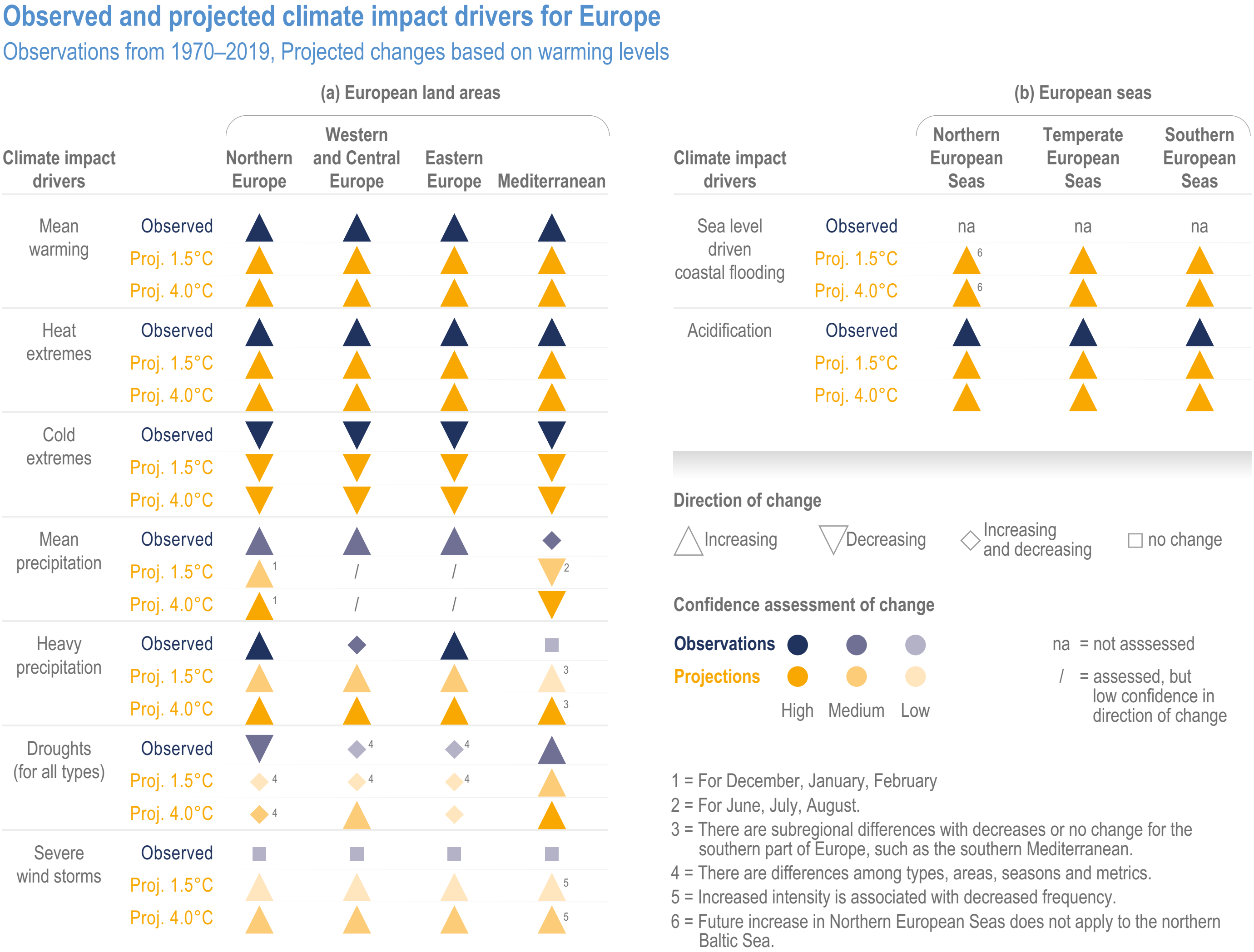
(d) vulnerability to disasters and humanitarian crisis in 2021. The index is based on socioeconomic factors (development, inequality and aid dependency) and vulnerable groups (DRMKC, 2020).

is decreasing (Hock et al., 2019). In Central Europe, Scandinavia and Caucasus, mountain glaciers were projected to lose 60–80% of their mass by the end of the 21st century (Hock et al., 2019). The combined impacts on tourism, agriculture, forestry, energy, health and infrastructure were suggested to make SEU highly vulnerable and increase the risks of failures and vulnerability for urban areas (Kovats et al., 2014). Previous reports stated that the adaptive capacity in Europe is high compared with other regions of the world, but that there are also limits to adaptation from physical, social, economic and technological factors. Evidence suggested that staying within 1.5°C GWL would strongly increase Europe's ability to adapt to climate change (de Coninck et al., 2018).

13.1.4 European Climate: Main Conclusions of WGI AR6

Changes in several climatic-impact drivers have already emerged in all regions of Europe: increases in mean temperature and extreme heat, and decreases in cold spells (Ranasinghe et al., 2021; Seneviratne et al., 2021). Lake and river ice has decreased in NEU, WCE and MED, and sea ice in NEUS (Fox-Kemper et al., 2021; Ranasinghe et al., 2021). With increasing warming, confidence in projections is increasing for more drivers (Figure 13.3). Mean and maximum temperatures, frequencies of warm days and nights, and heatwaves have increased since 1950, while the corresponding cold indices have decreased (*high confidence*) (Ranasinghe et al., 2021; Seneviratne et al., 2021). Average warming will be larger than the global mean in all of Europe, with largest winter warming in NEU and EEU and largest summer warming in MED (*high confidence*) (Gutiérrez et al., 2021; Ranasinghe et al., 2021). An increase in hot days and a decrease in cold days are *very likely* (Figure 13.4a,b). Projections suggest a substantial reduction in European ice glacier volumes and in snow cover below elevations of 1500–2000 m, as well as further permafrost thawing and degradation, during the 21st century, even at a low GWL (*high confidence*) (Ranasinghe et al., 2021).

The assessment of climate change in WGI AR6 concludes that during recent decades mean precipitation has increased over NEU, WCE and EEU, while magnitude and sign of observed trends depend substantially on time period and study region in MED (*medium confidence*) (Douville et al., 2021; Gutiérrez et al., 2021; Ranasinghe et al., 2021). Precipitation extremes have increased in NEU and EEU (*high confidence*) (Seneviratne et al., 2021), vary spatially in WCE



Observed and projected climate impact drivers for Europe

Observations from 1970–2019, Projected changes based on warming levels

(a) European land areas

Climate impact drivers		Northern Europe	Western and Central Europe	Eastern Europe	Mediterranean
Mean warming	Observed	▲	▲	▲	▲
	Proj. 1.5°C	▲	▲	▲	▲
	Proj. 4.0°C	▲	▲	▲	▲
Heat extremes	Observed	▲	▲	▲	▲
	Proj. 1.5°C	▲	▲	▲	▲
	Proj. 4.0°C	▲	▲	▲	▲
Cold extremes	Observed	▼	▼	▼	▼
	Proj. 1.5°C	▼	▼	▼	▼
	Proj. 4.0°C	▼	▼	▼	▼
Mean precipitation	Observed	▲	▲	▲	◆
	Proj. 1.5°C	▲ 1	/	/	▼ 2
	Proj. 4.0°C	▲ 1	/	/	▼
Heavy precipitation	Observed	▲	◆	▲	■
	Proj. 1.5°C	▲	▲	▲	▲ 3
	Proj. 4.0°C	▲	▲	▲	▲ 3
Droughts (for all types)	Observed	▼	◆ 4	◆ 4	▲
	Proj. 1.5°C	◆ 4	◆ 4	◆ 4	▲
	Proj. 4.0°C	◆ 4	▲	◆	▲
Severe wind storms	Observed	■	■	■	■
	Proj. 1.5°C	▲	▲	▲	▲ 5
	Proj. 4.0°C	▲	▲	▲	▲ 5

(b) European seas

Climate impact drivers		Northern European Seas	Temperate European Seas	Southern European Seas
Sea level driven coastal flooding	Observed	na	na	na
	Proj. 1.5°C	▲ 6	▲	▲
	Proj. 4.0°C	▲ 6	▲	▲
Acidification	Observed	▲	▲	▲
	Proj. 1.5°C	▲	▲	▲
	Proj. 4.0°C	▲	▲	▲

Direction of change

△ Increasing ▽ Decreasing ◇ Increasing and decreasing ☐ no change

Confidence assessment of change

	High	Medium	Low
Observations	●	●	●
Projections	●	●	●

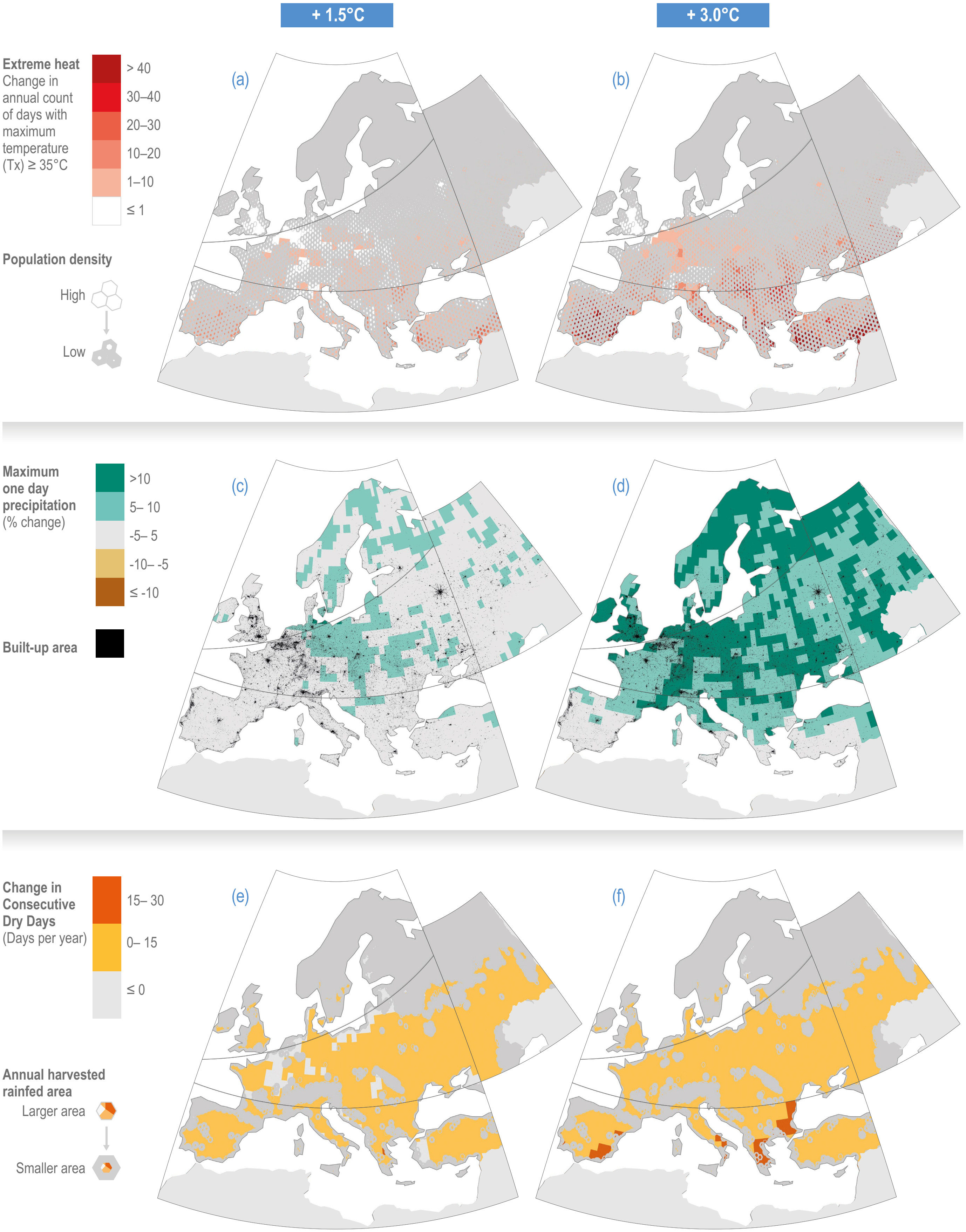
na = not asssessed

/ = assessed, but low confidence in direction of change

1 = For December, January, February
2 = For June, July, August.
3 = There are subregional differences with decreases or no change for the southern part of Europe, such as the southern Mediterranean.
4 = There are differences among types, areas, seasons and metrics.
5 = Increased intensity is associated with decreased frequency.
6 = Future increase in Northern European Seas does not apply to the northern Baltic Sea.

Figure 13.3 | Observed and projected direction of change in climate-impact drivers at 1.5°C and 4°C GWL for European sub-regions and European seas. (Assessment from Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021).

Climate impacts drivers and socio-ecological vulnerabilities



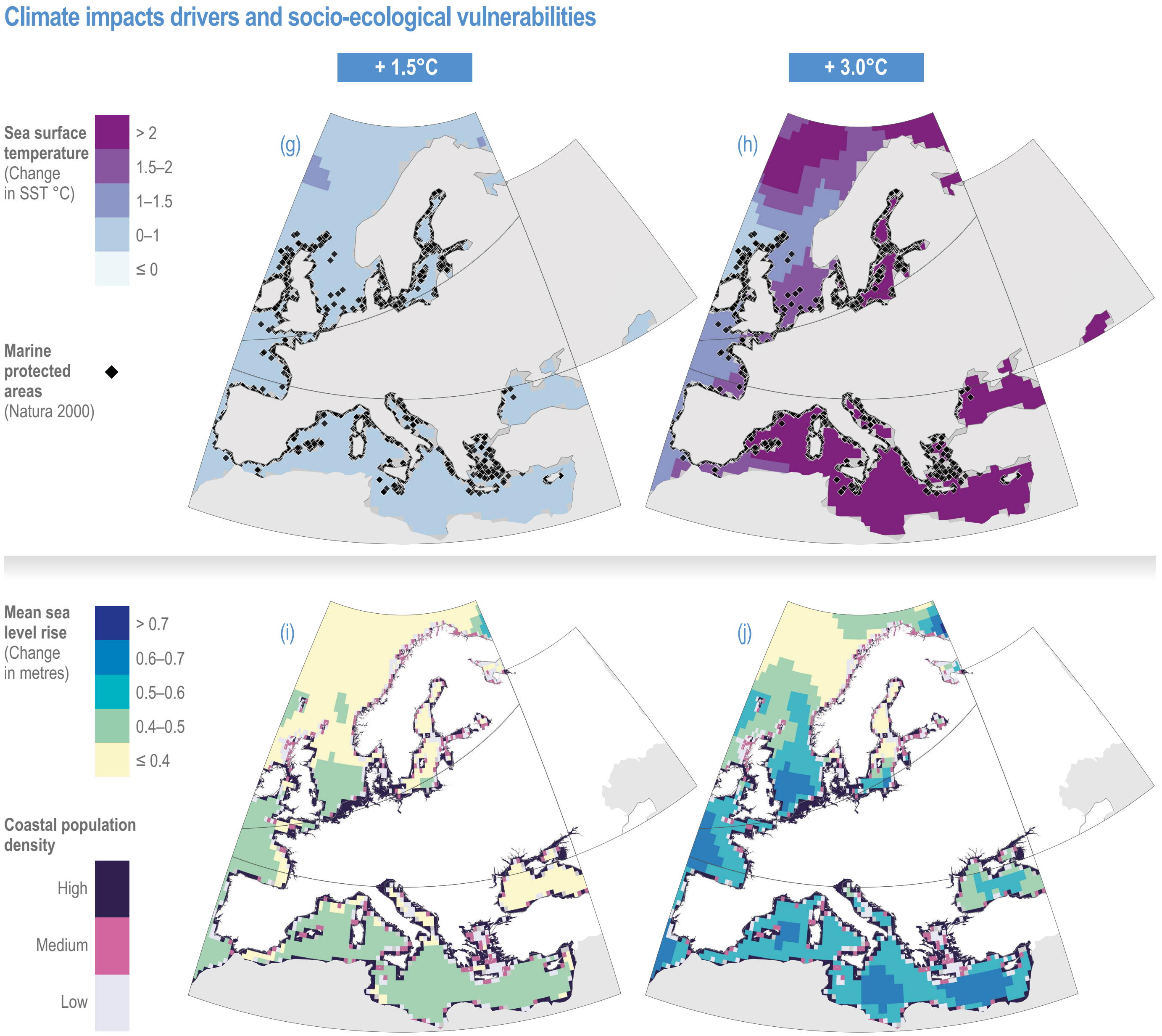


Figure 13.4 | Changes in climate hazards for global warming levels of 1.5°C and 3°C based on the CMIP6 ensemble (Gutiérrez et al., 2021) with respect to the baseline period 1995–2014, combined with information on present exposure or vulnerability:

(a,b) number of days with temperature maximum above 35°C (TX35) and population density (European Comission, 2019);

(c,d) daily precipitation maximum (R × 1 d) and built-up area (JRCdatacatalogue, 2021);

(e,f) consecutive dry days and annual harvested rain-fed area (Portmann et al., 2010);

(g,h) sea surface temperature and marine protected areas (EEA, 2021b); and

(k,l) sea level rise (SLR) and coastal population (Merkens et al., 2016). The SLR data consider the long-term period (2081–2100) and SSP1–2.6 for (i) and SSP3–7.0 for (j).

(*medium confidence*) and have not changed in MED (*low confidence*). For >2°C GWL, of mean precipitation in NEU in winter is increasing and decreasing in MED in summer (*high confidence*). A widespread increase of precipitation extremes is projected for >2°C GWL for all sub-regions (*high confidence*), except for MED where no change or decrease is projected in some areas (Figure 13.4c,d; Gutiérrez et al., 2021; Ranasinghe et al., 2021). WGI assessed projections for meteorological, agricultural/ecological and hydrological drought (Ranasinghe et al., 2021) with *low confidence* in the direction of change in NEU, WCE and EEU at 1.5°C GWL. MED is projected to be most affected within Europe with all types of droughts increasing for 1.5°C (*medium confidence*) and 4°C GWL (*high confidence*). At 4°C GWL, hydrological droughts in NEU, WCE and EEU will increase (*medium confidence*). Projections for the 21st century show increases in storms across all of Europe (*medium confidence*) for >2°C GWL with a decrease in their frequency in the MED (Ranasinghe et al., 2021).

Sea surface warming between 0.25°C and 1°C has been observed in all regions over recent decades (*high confidence*) (Ranasinghe et al., 2021) and are projected to continue increasing (*high confidence*), particularly in the SEUS and at the NEUS (Figure 13.4g,h; Gutiérrez et al., 2021). Salinity has increased in the SEUS and decreased in NEUS and is projected to continue (*medium confidence*) (Fox-Kemper et al., 2021). European waters have been, and will continue, acidifying (*virtually certain*) (Eyring et al., 2021; Szopa et al., 2021), resulting in a mean decrease of surface pH of about 0.1 and 0.3 pH units at 1.5°C and 3°C GWL with the largest changes at high latitudes (Gutiérrez et al., 2021).

Relative sea level has risen along the European coastlines (Ranasinghe et al., 2021), regionally mitigated by post-glacial rise of land masses in Scandinavia (Fox-Kemper et al., 2021). This SLR will *very likely* continue to increase during the 21st century (Figure 13.4k,l) (*high confidence*), with regional deviations from global mean SLR (*low confidence*). Extreme water levels, coastal floods and sandy coastline recession are projected to increase along many European coastlines (*high confidence*) (Ranasinghe et al., 2021).

13.2 Water

13.2.1 Observed Impacts and Projected Risks

13.2.1.1 Risk of Coastal Flooding and Erosion

Almost 50 million Europeans live within 10 m above mean sea level (Vousdoukas et al., 2020; McEvoy et al., 2021). Without further adaptation (Section 13.2.2), flood risks along Europe's low-lying coasts and estuaries will increase due to SLR compounded by storm surges, rainfall and river runoff (*high confidence*) (Mokrech et al., 2015; Arns et al., 2017; Sayol and Marcos, 2018; Vousdoukas et al., 2018a; Bevacqua et al., 2019; Couasnon et al., 2020). The population at risk of a 100-year flood event starts to rapidly increase beyond 2040 (Vousdoukas et al., 2018a) reaching 10 million people under RCP8.5 by 2100, but it stays just below 10 million people under RCP2.6 by 2150 (Figure 13.5; Haasnoot et al., 2021b) assuming present population and protection. The number of people at risk is projected to increase and risk to materialise earlier especially in response to increasing population under SSP5 (Vousdoukas et al., 2018a; Haasnoot et al., 2021b). Under high rates of SLR resulting from rapid ice sheet loss from Antarctica, risks may increase by a third by 2150 (Haasnoot et al., 2021b). Expected annual (direct) damages due to coastal flooding are projected to rise from 1.3 billion EUR today to 13–39 billion EUR by 2050 between 2°C and 2.5°C GWL and 93–960 billion EUR by 2100 between 2.5° and 4.4°C GWL, largely depending on socioeconomic developments (Cross-Chapter Box SLR in Chapter 3; Vousdoukas et al., 2018a) (*high confidence* in the sign; *low confidence* in the numbers). UNESCO World Heritage sites in the coastal zone are at risk due to SLR, coastal erosion and flooding (Section 13.8.1.3; Cross-Chapter Paper 4; Marzeion and Levermann, 2014; Reimann et al., 2018b) as are coastal landfills and other key infrastructures in Europe (AR6/SROCC; Brand et al., 2018; Beaven et al., 2020).

Observations indicate that soft cliffs and beaches are most affected by erosion in Europe with, for example, 27–40% of Europe's sandy coast eroding today, without climate change being identified as the main driver so far (Pranzini et al., 2015; Luijendijk et al., 2018; Mentaschi et al., 2018; Oppenheimer et al., 2019). SLR will increase coastal erosion of sandy shorelines (*high confidence*) (Ranasinghe et al., 2021), but there is *low confidence* in quantitative values assessment of erosion rates and amounts (Athanasiou et al., 2019; Le Cozannet et al., 2019; Thieblemont et al., 2019). Without nourishment or other natural or artificial barriers to erosion, sandy shorelines could retreat by about 100 m in Europe at 4°C GWL; limiting warming to 3°C GWL could reduce this value by one-third (Vousdoukas et al., 2020).

13.2.1.2 Risks Related to Inland Water

13.2.1.2.1 Riverine and pluvial flooding

Precipitation has raised river flood hazards in WCE and the UK by 11% per decade from 1960 to 2010 and decreased in EEU and SEU by 23% per decade (Douville et al., 2021; Ranasinghe et al., 2021). The most recent three decades had the highest number of floods in the past 500 years with increases in summer (Blöschl et al., 2020). Economic flood damages increased strongly, reflecting increasing exposure of people and assets (Visser et al., 2014; Hoegh-Guldberg et al., 2018; Merz et al., 2021).

Projections indicate a continuation of the observed trends of river flood hazards in WCE (*high confidence*) of 10% at 2°C GWL and 18% at 4.4°C GWL, and a decrease in NEU and SEU (*medium confidence*) with, respectively, 5 and 11% in NEU and SEU for a 100-year peak flow, making Europe one of the regions with the largest projected increase in flood risk (Di Sante et al., 2021; Ranasinghe et al., 2021). While there is disagreement on the magnitude of economic losses and people affected, there is *high agreement* on direction of change, particularly in WCE (Alfieri et al., 2018). New research increases confidence in AR5 statements that without adaptation measures, increases in extreme rainfall will substantially increase direct flood damages (e.g., Madsen et al., 2014; Alfieri et al., 2015a; Alfieri et al., 2015b; Blöschl et al., 2017; Dottori et al., 2020; Mentaschi et al., 2020). With low adaptation, damages from river flooding are projected to be three times higher at 1.5°C GWL, four times at 2°C GWL and six times at 3°C GWL (Alfieri et al., 2018; Dottori et al., 2020). At 2°C GWL, the incidence of summer floods is expected to decrease across the whole alpine region, whereas winter and spring floods will increase due to extreme precipitation (Gobiet et al., 2014) and snowmelt-driven runoff (Coppola et al., 2018).

Pluvial flooding and flash floods due to intense rainfall constitute most flood events in SEU and a substantial risk in other European regions (Cross-Chapter Paper 4; Llasat et al., 2016; Rudd et al., 2020). The majority (56%) of flood events between 1860 and 2016 were flash floods (Paprotny et al., 2018a). These floods had considerable impacts including danger to human lives, for example, causing total economic damage of 1 billion USD in Copenhagen (Denmark) in 2011 (Wójcik et al., 2013), damage to private households of more than 70 million EUR in Münster (Germany) in 2014 (Spekkers et al., 2017) and during the 2021 floods in Belgium, Germany and the Netherlands over 200 deaths, damage to thousands of homes and disrupted water and electricity supply (Kreienkamp et al., 2021). The intensity and frequency of heavy rainfall events is projected to increase (*high confidence*) (Figure 13.3; Ranasinghe et al., 2021). Combined with increasing urbanisation, the risk of pluvial flooding is projected to increase (Westra et al., 2014; Rosenzweig et al., 2018; Papalexiou and Montanari, 2019). Small catchments, steep river channels and cities are particularly vulnerable due to large areas of impermeable surfaces where water cannot penetrate (Section 13.6).

13.2.1.2.2 Low Flows and Water Scarcity

The frequency and severity of low flows are projected to increase, making streamflow drought and water scarcity more severe and persistent in SEU and WCE (*medium confidence*) (Figure 13.3; Ranasinghe et al., 2021), but decreases are projected in most of NEU except the southern UK (Forzieri et al., 2014; Prudhomme et al., 2014; Schewe et al., 2014; Roudier et al., 2016; Ranasinghe et al., 2021). In EEU, uncertainty about changes in water scarcity pose distinct challenges for adaptation (Greve et al., 2018). At 1.5°C GWL, the number of days with water scarcity (water availability as opposed to water demand) and drought will increase slightly in SEU (Schleussner et al., 2016; Naumann et al., 2018), resulting in 18% of the population exposed to at least moderate water scarcity, increasing to 54% at 2°C GWL (Byers et al., 2018). Moderate water scarcity is emerging in some parts of WCE (Bisselink et al., 2018) increasing to16% of the population under 2°C GWL and SSP2 (Byers et al., 2018). Under 4°C GWL, areas in WCE experience water scarcity, especially in summer and autumn. Future intensive water use can aggravate the situation, in particular in SEU (Sections 13.5.1, 13.10.3). Groundwater abstraction rates reach up to 100 million m^3 yr^{-1} across WCE and SEU, and exceed 100 million m^3 yr^{-1} in parts of SEU (Wada, 2016). Low recharge rates lead to a depletion of groundwater resources in parts of SEU and WCE (Doll et al., 2014; Wada, 2016; de Graaf et al., 2017), increasing the impacts on water scarcity in SEU. Groundwater pumping and declines in groundwater discharge already threaten environmental flow limits in many European catchments, especially in SEU, extending to almost all basins and sub-basins within the next 30–50 years (de Graaf et al., 2019).

The combined effect of increasing water demand and successive dry climatic conditions further exacerbates groundwater depletion and lowers groundwater levels in SEU but also WCE (Goderniaux et al., 2015). Declines in groundwater recharge of up to 30% further increase groundwater depletion (Aeschbach-Hertig and Gleeson, 2012) especially in SEU and semiarid to arid regions (Moutahir et al., 2017). Even in WCE and NEU, projected increases in groundwater abstraction will impact groundwater discharge, threatening sustaining environmental flows under dry conditions (de Graaf et al., 2019).

The risks for soil moisture drought are projected to increase in WCE and SEU for all climate scenarios (Grillakis, 2019; Tramblay et al., 2020; Ranasinghe et al., 2021). At 3°C GWL compared with 1.5°C GWL, the drought area will increase by 40% and the population under drought by up to 42%, especially affecting SEU, and to a lesser extent in WCE (Samaniego et al., 2018).

Box 13.1 | Venice and Its Lagoon

Venice and its lagoon are a UNESCO World Heritage Site. This socio-ecological system is the result of millennia of interactions between people and the natural environment. It is exposed to climatic and non-climatic hazards: more frequent floods, warming, pollution, invasive species, reduction of salt marshes, hydrodynamic and bathymetric changes, and waves generated by cruise ships and boat traffic.

The elevation of the average city pedestrian level and of its inner historic area are, respectively, 105 and 55 cm above the present relative mean sea level (RMSL). Consequently, even small surges and compound events cause floods when they coincide with high tide (Lionello et al., 2021a). During the 20th century, RMSL rose at about 2.5 mm yr^{-1} due to SLR and land subsidence (Zanchettin et al., 2021). The frequency of floods affecting the city has increased from once per decade in the first half of the 20th century to 40 times per decade in the period 2010–2019 (Figure Box 13.1.1a).

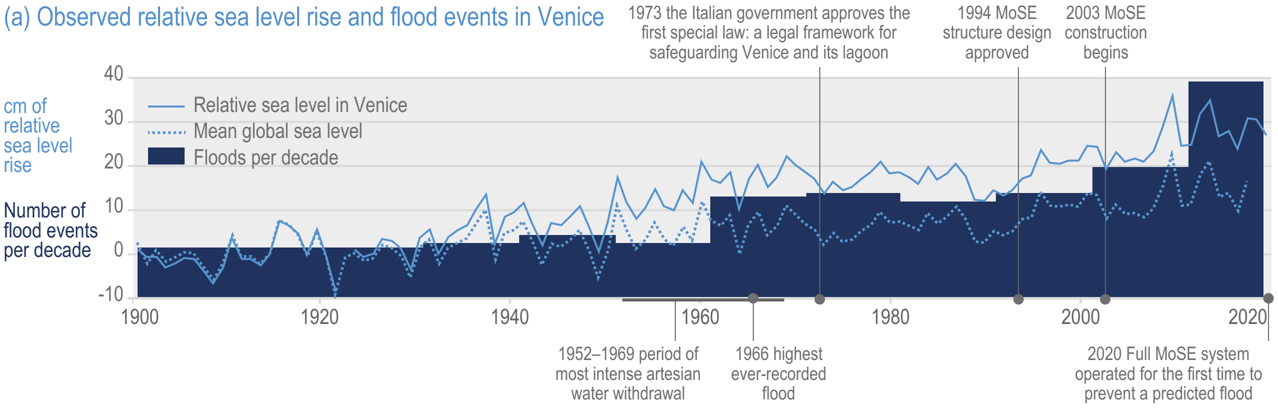
In 1973, the Italian government established a legal framework for safeguarding Venice and its lagoon. Construction of the flood protection system started in 2003 and was used for the first time in October 2020 (Lionello et al., 2021b). This system of mobile barriers (MoSE) closes the lagoon inlets to avoid floods when needed, while under normal conditions they lay on the seabed, thus allowing ship traffic and the exchange between the lagoon and the sea (Molinaroli et al., 2019). To prevent flooding of the central monument area, additional measures have been proposed including inlets, expansion of salt marshes and pumping seawater into deep brackish aquifers to raise the city's level (Umgiesser, 1999; Umgiesser, 2004; Teatini et al., 2011).

Without adaptation, potential economic damages between 7 and 17 billion EUR have been estimated for the next 50 years (Caporin and Fontini, 2016). Additionally, the ecosystem is vulnerable to warming (Solidoro et al., 2010) and SLR (Day Jr et al., 1999; Marani et al., 2007). The duration of the closure of the lagoon inlets is expected to increase from 2 to 3 weeks yr^{-1} for RMSL rises of 30 cm, to 2 months yr^{-1} for 50 cm and 6 months yr^{-1} for 75 cm (Figure Box 13.1.1b; Umgiesser, 2020; Lionello et al., 2021b), resulting in disconnection from the sea for most of the time for RMSL rise exceeding 75 cm. Frequent closures of the inlets would prevent ship traffic and in/outflow of water. For Venice, adaptation pathways considering the full range of plausible RMSL (Figure Box 13.1.1c) levels are not available, indicating a long-term adaptation gap. As planning and implementation of adaptation of this extent can take several decades (Haasnoot et al., 2020b; Cross-Chapter Box SLR in Chapter 3), this increases the risk that the city will not be prepared in case of rapid SLR.

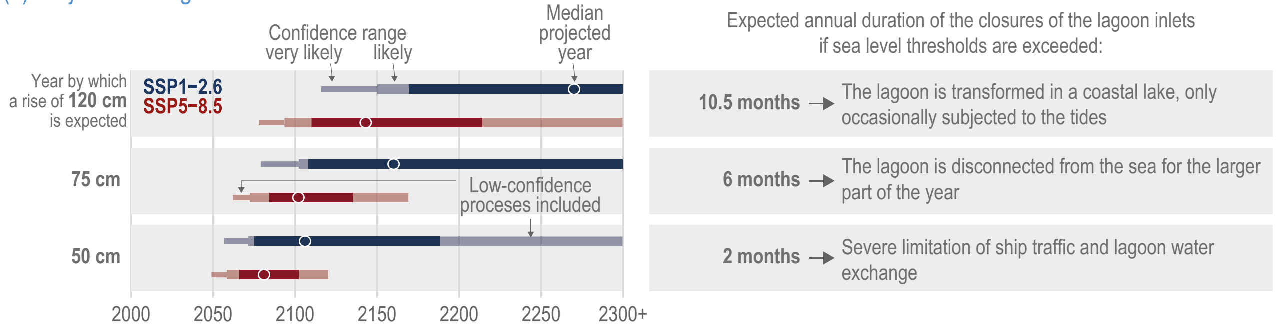
Box 13.1 (continued)

Protecting Venice from sea level rise and coastal flooding

(a) Observed relative sea level rise and flood events in Venice



(b) Projected timing of sea level rise milestones



(c) Projected sea level rise in Venice

(d) Venice and its lagoon

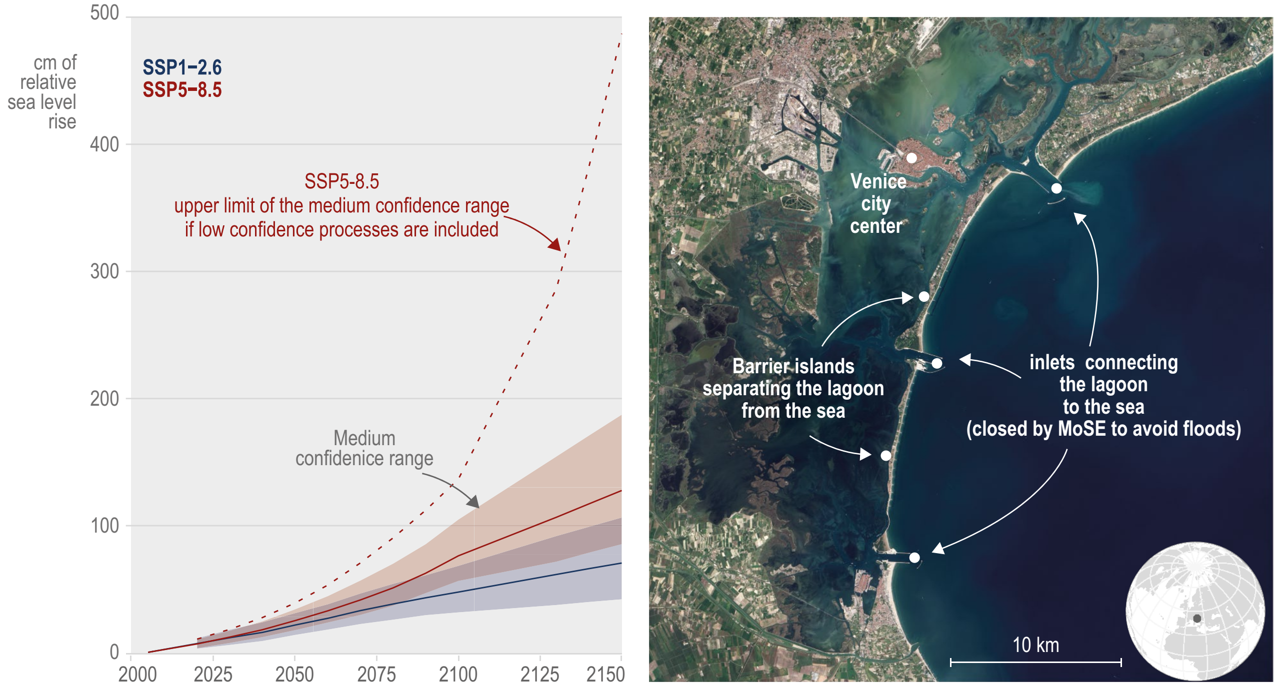


Figure Box 13.1.1 | Venice sea level rise (SLR) and coastal flooding: (a) evolution of relative and mean sea level in Venice and decadal frequency of floods above the safeguard level in the city centre (Frederikse et al., 2020; Lionello et al., 2021a; Lionello et al., 2021b; Zanchettin et al., 2021); **(b)** projected relative SLR at the Venetian coast (Fox-Kemper et al., 2021); "very likely" corresponds to 5–95th percentile range, "likely" to 17–83rd percentile range; **(c)** timing when critical relative sea level thresholds will be reached depending on scenarios and confidence level (Lionello, 2012; Umgiesser, 2020; Lionello et al., 2021a), the upper limit of the medium confidence range under SSP5–8.5 represents a low-likelihood, high-impact storyline, low confidence processes include ice sheet instability; **(d)** Landsat view of Venice and its lagoon with the three inlets connecting it to the Adriatic Sea.

13.2.1.2.3 Water Temperature and Quality

Water temperatures in rivers and lakes have increased over the past century by ~1–3°C in major European rivers (CBS, 2014; EEA, 2017a; Woolway et al., 2017). Warming is accelerating for all European river basins (Wanders et al., 2019) increasing by 0.8°C in response to 1.5°C GWL and 1.2°C for 3°C GWL relative to 1971–2000 (van Vliet et al., 2016a) aggravated by declines in summer river flow.

(Ground)water extractions or drainage have caused saltwater intrusions (Rasmussen et al., 2013; Ketabchi et al., 2016). During summer, seawater will also penetrate estuaries further upstream in response to reduced river flow and SLR, resulting in more frequent closure of water inlets in the downstream part of the rivers in a period when water is most needed (*high agreement, low evidence*) (e.g., Haasnoot et al., 2020b).

13.2.2 Solution Space and Adaptation Options

In recent decades water management in Europe has increasingly shifted towards integrated and adaptive strategies, with the most noticeable shifts in WCE (*high confidence*) (e.g., Kreibich et al., 2015; Bubeck et al., 2017). While adaptive strategies are increasingly considered as an approach to strengthen flexibility and implement climate-change adaptation actions, given deep uncertainty about the future (Ranger et al., 2013; Klijn et al., 2015; Bloemen et al., 2019; Hall et al., 2019; Pot et al., 2019), more traditional water management approaches still dominate across Europe (OECD, 2013; OECD, 2015; Wiering et al., 2017). Current measures focus on structural flood protection and water resources supply and play an important role to preserve present land use and development patterns. The long-term effectiveness of such measures is increasingly challenged by their reinforcing path dependency (e.g., flood defence and water supply attract developments which require further protection and supply). This path dependency limits the solution space and may hamper implementation of transformative measures, such as land-use change, to accommodate the water system (*medium confidence*) (Cross-Chapter Paper 2; Di Baldassarre et al., 2015; Kreibich et al., 2015; Alfieri et al., 2016; Gralepois et al., 2016; Welch et al., 2017; Di Baldassarre et al., 2018; Haer et al., 2020).

Water laws, policies and guidance documents increasingly mainstream climate impacts and adaptation options (Runhaar et al., 2018; Mehryar and Surminski, 2021), though not everywhere. Differences are apparent, for example, in coastal adaptation where most, but not all, countries are planning for SLR (Figure 13.5; McEvoy et al., 2021). Although the planning horizon of 2100 and 1-m SLR are most common (adjusted for local conditions), there are significant differences between countries (e.g., the high-end SLR value in 2100 ranges from 0.3 to 3 m), which may lead to unequal impacts over time (McEvoy et al., 2021).

13.2.2.1 Flood Risk Management

Across Europe a range of measures have been implemented to address flood risk (Figure 13.6), with protection as the most used strategy (*high confidence*). Early warning and flood protection have been successful in reducing vulnerability to coastal and riverine flooding (Jongman et al., 2015; Kreibich et al., 2015; Bouwer and Jonkman, 2018). Consequently, fatalities due to river flooding have decreased in Europe, despite similar numbers of people exposed (1990–2010 compared with 1980–1989) (Jongman et al., 2015; Paprotny et al., 2018a).

13.2.2.1.1 Coastal flood risk management

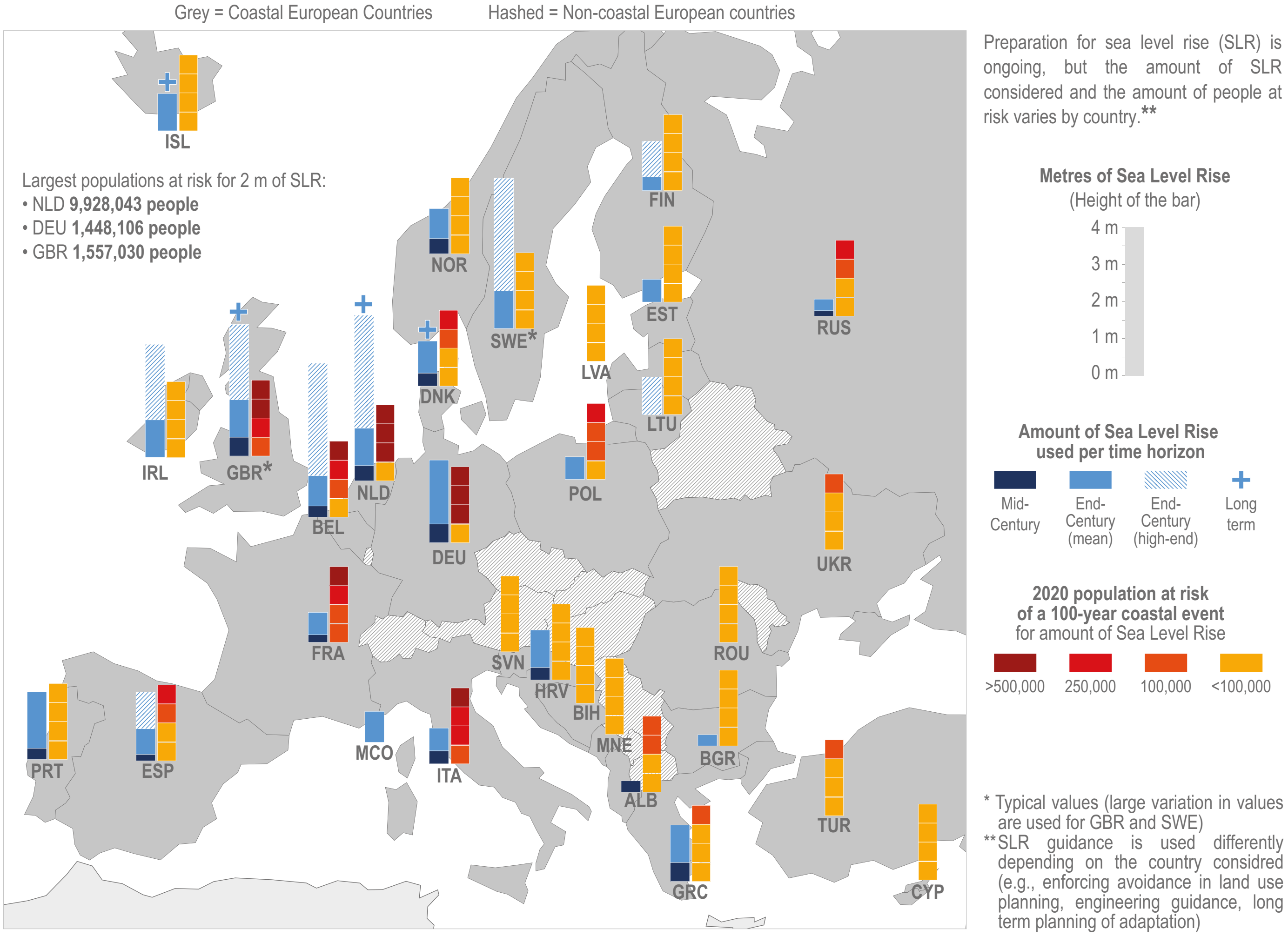
Further protection against coastal flooding is considered economically beneficial for densely populated areas (Lincke and Hinkel, 2018; Tiggeloven et al., 2020). At least 83% of flood damages due to coastal flooding could be avoided by elevating dykes along ~23–32% of Europe's coastline by 2100 (RCP4.5-SSP1, RCP8.5-SSP5) (Vousdoukas et al., 2020). Limitations of building flood defences include cost–benefit considerations in rural areas, available land and social acceptability in densely populated areas (Haasnoot et al., 2018; Hinkel et al., 2018; Meyerhoff et al., 2021).

Nature-based Solutions (NbS) (e.g., wetlands) and sediment-based solutions (e.g., sand nourishment) are increasingly considered for environmental, economic and/or societal reasons (Cross-Chapter Box NATURAL in Chapter 2; Stive et al., 2013; Pranzini et al., 2015; Pinto et al., 2020; de Schipper et al., 2021). Coastal wetlands can be effective to reduce wave height and form habitats, but their feasibility and effectiveness is limited for densely populated areas with competing land use, runoff of pollution, sediment-starved deltas like the Rhine Delta (Edmonds et al., 2020) and rapid SLR (Kirwan et al., 2016; Oppenheimer et al., 2019; Haasnoot et al., 2020b). While losses of wetlands could be minor if warming stays below 1.7°C GWL, at high warming or SLR above 0.5 m large-scale losses of these habitats will impact their ecological importance, ecosystem function (Section 13.4; KR 1, Section 13.10.2) and their ability to protect coastlines (Roebeling et al., 2013; van der Spek, 2018; Wang et al., 2018; Xi et al., 2021). A combination with structural defences could reduce risk in urbanised coastal regions (*high confidence*). Accommodation through elevated or floating houses have been implemented and proposed locally within cities as part of a hybrid strategy together with protection and as a way of innovative urban development (Section 13.6.2; Cross-Chapter Paper 2; Penning-Rowsell, 2020; Storbjörk and Hjerpe, 2021).

Avoidance through restricting new developments in flood prone areas is applied along the coast of WCE and SEU (Harman et al., 2015; Lincke et al., 2020) and is considered a low-cost alternative to coastal defence at lower SLR. In SEU, an integrated coastal zone management (ICZM) protocol has been developed which requires a setback zone of 100 m from the coast in unprotected areas. Setback zones are projected to reduce impacts considerably in urbanised regions (Lincke et al., 2020). Planned relocation is increasingly considered as a realistic adaptation option in cases of extreme SLR (Haasnoot et al., 2021a; Lincke and Hinkel, 2021; Mach and Siders, 2021), for example, UK Shoreline Management Plans (Nicholls et al., 2013; Buser, 2020). Retreat is rarely applied in Europe (*medium confidence*), though it can have greater benefit-to-cost outcomes than protection, particularly in less populated parts of Europe (Lincke and Hinkel, 2021). Along parts of the coast in the UK (e.g., The Wash), Germany (e.g., Langeoog Island) and the Netherlands (e.g.,

Risk and national adaptation planning to sea level rise in Europe

(a) Amount of sea level rise used in national level planning per country and population at risk by amount of sea level rise per country

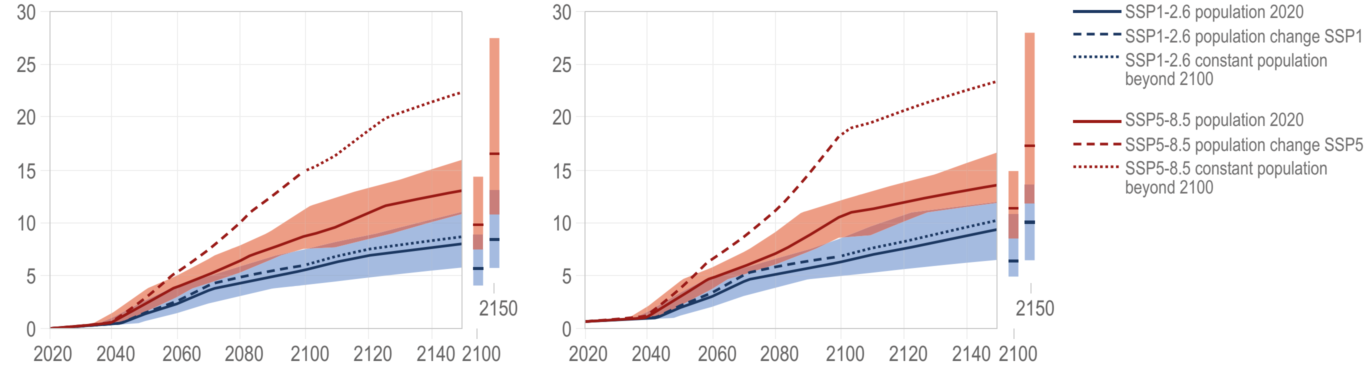


Largest populations at risk for 2 m of SLR:
- NLD **9,928,043 people**
- DEU **1,448,106 people**
- GBR **1,557,030 people**

Preparation for sea level rise (SLR) is ongoing, but the amount of SLR considered and the amount of people at risk varies by country.**

* Typical values (large variation in values are used for GBR and SWE)

**SLR guidance is used differently depending on the country considred (e.g., enforcing avoidance in land use planning, engineering guidance, long term planning of adaptation)


(b) Millions of people at risk of a 10-year flood event

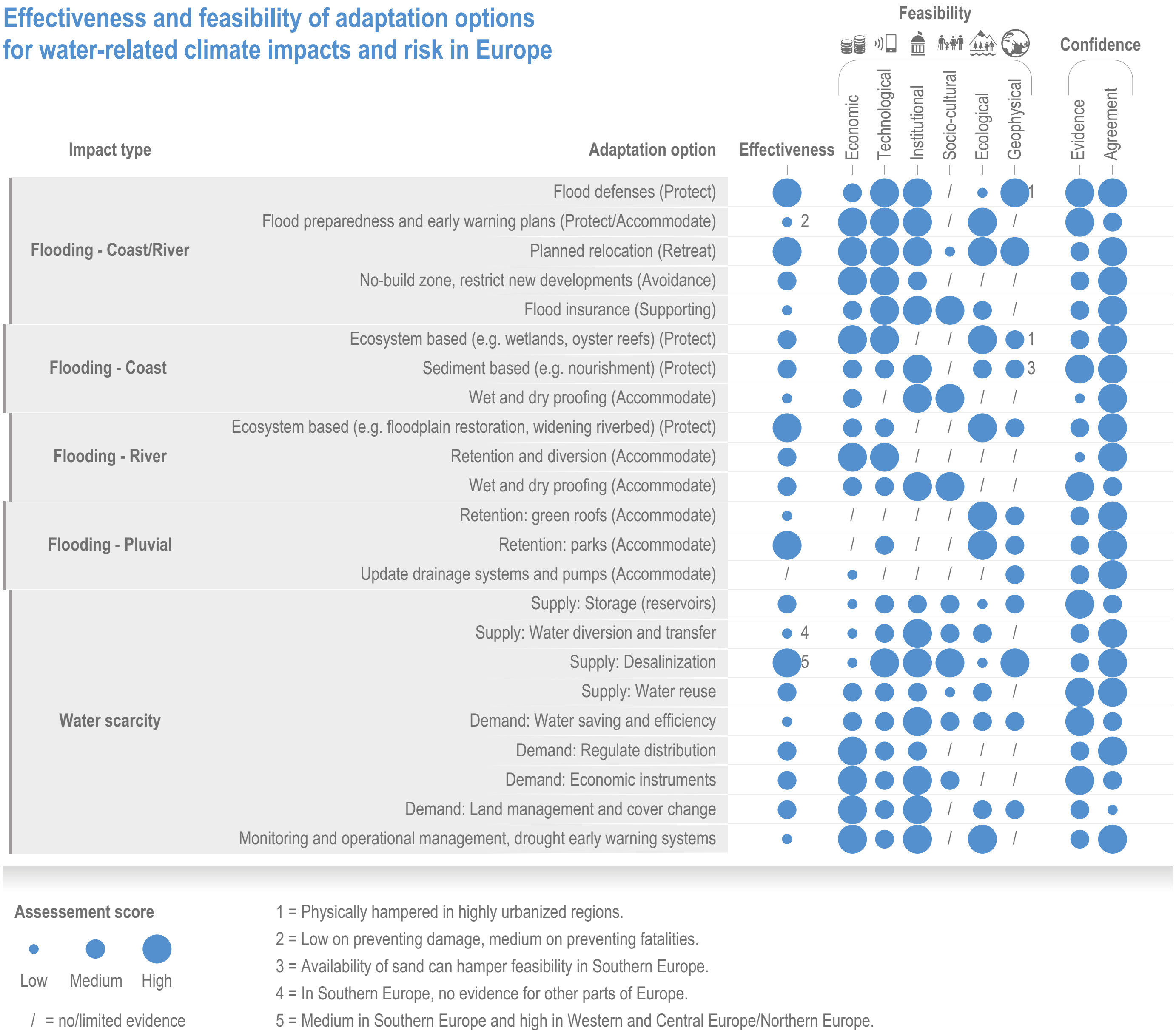
(c) Millions of people at risk of a 100-year flood event

Figure 13.5 | Sea level rise (SLR) vulnerability and national planning in Europe:

(a) map of countries in Europe summarising the amount of SLR each country is planning for, at different time horizons (blue bars), and the present population (2020) at risk of a 100-year coastal flood event (orange bars) (Haasnoot et al., 2021b). The amounts of SLR and time horizons reflect national guidance or planning (local or project-based levels may differ) (McEvoy et al., 2021);

(b) projected population at risk to experience a 1-in-10-year coastal flood event under RCP2.6-SSP1 and RCP8.5-SSP5 assuming present protection and population levels, as well as population change according to, respectively, SSP1 and SSP5, based on Merkens (2016);

(c) projected population at risk to experience a 1-in-100-year coastal flood event under RCP2.6-SSP1 and RCP8.5-SSP5, assuming the present protection and population levels, as well as population change according to, respectively, SSP1 and SSP5, based on Merkens (2016) (based on Haasnoot et al., 2021b).



1 = Physically hampered in highly urbanized regions.
2 = Low on preventing damage, medium on preventing fatalities.
3 = Availability of sand can hamper feasibility in Southern Europe.
4 = In Southern Europe, no evidence for other parts of Europe.
5 = Medium in Southern Europe and high in Western and Central Europe/Northern Europe.

Figure 13.6 | Effectiveness and feasibility of water-related adaptation options to achieve objectives under increasing climate hazards (Section SM13.9; Table SM13.1)

Westerschelde) retreat has been applied to restore salt marshes and to aid coastal defence (Haasnoot et al., 2019; Kiesel et al., 2020; Lincke and Hinkel, 2021).

13.2.2.1.2 Riverine and pluvial flood risk management

Structural flood protection (e.g., levees) is considered economically beneficial in densely populated areas (Alfieri et al., 2016; Dottori et al., 2020) and could reduce flood damage by ~45% as estimated under 1.5°C GWL and ~70% under 3°C GWL (Dottori et al., 2020).

Providing more room for water through NbS is increasingly considered (Kreibich et al., 2015) as they can reduce risk effectively at lower costs, except in places with limited space or in areas with large protection. Such measures include (forest) restoration for upstream retention, restoration of river channels and widening riverbeds for natural flood retention (Kreibich et al., 2015; Barth and Döll, 2016; Wyżga et al., 2018). Natural retention areas are estimated to be the most effective option to reduce riverine flood risk across Europe in the 21st century, followed by protection (*low evidence*) (Dottori et al., 2020).

Wet and dry proofing of buildings can be applied at household level. While measures taken at household level can reduce the risk of flooding, there is often insufficient investment (*medium confidence*) (Bamberg et al., 2017; Aerts et al., 2018). Reasons include low awareness or under-estimation of the risk (Kellens et al., 2013), low perceived efficacy of adaptation measures (van Valkengoed and Steg, 2019) and lack of financial support (Kreibich, 2011). In the long term, risk reduction measures by governments are projected to outweigh floodproofing at household level, in particular in WCE, while for near-term household adaptation or regionally in SEU this could reduce risk more effectively (Haer et al., 2019). Relocation of households has occurred in response to river flood events (e.g., the 2013 flood events along the Danube River in Austria), with financial compensation playing a crucial role (Mayr et al., 2020; Thaler and Fuchs, 2020; Thaler, 2021).

Urban drainage infrastructure is designed based on historical rainfall intensities, and thus may not have sufficient capacity for increased future intensities (Dale et al., 2018). Adaptation options to pluvial flooding include large retention ponds, local green spaces and green roofs within cities (Zölch et al., 2017; Maragno et al., 2018; Babovic and Mijic, 2019; Ribas et al., 2020).

Early warning systems, insurance and behaviour change can complement protect and accommodate measures to limit residual risk (*high confidence*). Early warning systems have high monetary benefits (Pappenberger et al., 2015). Behavioural adaptation to flooding relies on recognition of the threat and capacity to respond, both of which are often lacking (Section 13.11.2.2; Bamberg et al., 2017; Haer et al., 2019). Flood risk insurance and compensation systems vary across European countries, ranging from post-disaster payments by governments and compulsory flood insurance, to public–private partnerships where the state acts as reinsurer (Keskitalo et al., 2014; Surminski et al., 2015; Hanger et al., 2018). Risk-based insurance premiums can induce risk-averting behaviour but may become unaffordable to poor households and some households in high-risk zones (Hudson, 2018; Surminski, 2018). Increasing future flood risks due to both climatic and socioeconomic change could overburden government budgets (*medium confidence*) (Section 13.11.2; Paudel et al., 2015; Mysiak and Perez-Blanco, 2016; Schinko et al., 2017; Mochizuki et al., 2018), resulting in unavailable or unaffordable insurance for private customers (Section 13.8.3; Hudson et al., 2016; Surminski, 2018), and underfunding and insufficient solvency of insurance companies (Section 13.6.2.5; Lamond and Penning-Rowsell, 2014). Local knowledge about disastrous flood events in the past can be lost across generations, leading to (re)-settlement in flood-prone areas (Fanta et al., 2019).

Limits to adaptation to extremely high SLR scenarios have been identified for coastal defences, such as the Venice MoSE barrier (see Box 13.1), Thames Barrier in the UK (Ranger et al., 2013) and the Maeslant Barrier in the Netherlands (Kwadijk et al., 2010; Haasnoot et al., 2020b). However, the scale and pace of adaptation required to face high-end SLR scenarios along all coasts of Europe has been poorly studied. Given the lead and long lifetime of large critical infrastructures, there is a growing need to look beyond 2100 to support the design of new infrastructures (Cross-Chapter Box SLR in Chapter 3).

13.2.2.2 Water Resources Management

Planning adaptation to water scarcity has centred on increasing the availability and supply of freshwater through water storage, diversification of sources and water diversion and transfer (*high confidence*). Reservoirs are costly, have negative environmental impacts and will not be sufficient under higher warming levels in every place (Papadaskalopoulou et al., 2015a; Di Baldassarre et al., 2018; Garnier and Holman, 2019). Wastewater reuse is considered a low-cost and effective measure where wastewater is available (Lavrnic et al., 2017; De Roo et al., 2020), but public acceptance for domestic reuse is presently limited (*high confidence*) (Papadaskalopoulou et al., 2015b; Morote et al., 2019). Increasing desalination capacity is used particularly in SEU but has high energy demands and produces brine waste (Garnier and Holman, 2019; Jones et al., 2019; Morote et al., 2019).

Adaptation measures on the demand side include monitoring (e.g., water meters, early warning systems of drought) and regulating demand, for example, water restrictions, water pricing, water saving and efficiency measures, and land management and cover change (Papadaskalopoulou et al., 2015b; Varela-Ortega et al., 2016; Manouseli et al., 2018; Garnier and Holman, 2019). Prolonged water restrictions and prioritising sectoral supply could result in economic losses (e.g., for irrigated agriculture) (Section 13.5.2; Wimmer et al., 2014; Salmoral et al., 2019). Economic instruments, such as water pricing, can be effective when combined with incentives for water saving and efficiency (Kayaga and Smout, 2014; Esteve et al., 2018; Crespo et al., 2019). Water saving and efficiency measures, such as leakage repair, education and improved irrigation, could limit conflicts across sectors but necessitate technological advances and changes in practice together with a willingness to cooperate (Garnier and Holman, 2019; Papadimitriou et al., 2019; Teotónio et al., 2020). Increased irrigation efficiency has reduced water scarcity, particularly in SEU (Section 13.5; De Roo et al., 2020), and occur at farm level in WCE and NEU (Papadaskalopoulou et al., 2015b; van Duinen et al., 2015; Rey et al., 2017) but come with increasing path dependency on supply and trade-offs which may not be sustainable in the long term (*high confidence*) (Di Baldassarre et al., 2018).

The assessment of the effectiveness and feasibility of adaptation options shows that a portfolio of supply-and-demand measures is needed to reduce water scarcity (Key Risk 3, Section 13.10.3), although locally demand-side measures could be sufficient (Kingsborough et al., 2016). Under high warming levels, adaptation to drought and low flows by water saving and efficiency measures may not be sufficient to counteract reduced availability (*medium agreement, low evidence*) (Collet et al., 2015; De Roo et al., 2020). Successful adaptation in the water sector depends on integrating water considerations into sectoral policies (Collet et al., 2015; Papadaskalopoulou et al., 2016). Inclusive and participatory approaches where (local) stakeholders are actively involved in the initiation and execution of water management can enhance problem ownership, the quality and democratic legitimacy of processes and decisions, enhance support and accelerate decisions (Edelenbos et al., 2017; Begg, 2018).

13.2.3 Knowledge Gaps

An assessment of the full solution space of adaptation options and pathways under low to high GWL, including the long term, is lacking. A quantification of the effectiveness of measures in reducing risk is limited in the scientific literature. The available assessments consider adaptation by incremental measures. Transformative options, such as land-use changes, planned relocation from exposed areas or restricting future development, are rarely considered. While high-end scenarios describing *low confidence* processes and scenarios beyond 2100 are considered to be useful for risk-averse decision making, in particular coastal adaptation (Hinkel et al., 2019; Haasnoot et al., 2020b), they are rarely considered in practice.

13.3 Terrestrial and Freshwater Ecosystems and Their Services

13.3.1 Observed Impacts and Projected Risks

13.3.1.1 Observed Impacts on Terrestrial and Freshwater Ecosystems

European land and freshwater ecosystems (Figure 13.7) are already strongly impacted by a range of anthropogenic drivers (*very high confidence*), particularly habitats at the southern and northern margins, along the coasts, up mountains and in freshwater systems (Cross-Chapter Paper 1). Interacting with climate change are non-climatic hazards, such as habitat loss and fragmentation, overexploitation, water abstraction, nutrient enrichment and pollution, all of which reduce resilience of biotas and ecosystems (*very high confidence*). Peatlands in NEU and EEU and other historically important cultural landscapes in Europe are overexploited for forestry, agriculture and peat mining (Page and Baird, 2016; Tanneberger et al., 2017; Ojanen and Minkkinen, 2020). Inland wetland RAMSAR convention sites in Europe, which constitute 47% of the global sites have lost area in WCE and gained in SEU from 1980 to 2014 (Xi et al., 2021). Forests in WCE were impacted by the extreme heat and drought event of 2018, with effects lasting into 2019 (Schuldt et al., 2020) and losses in conifer timber sales in Europe (Hlásny et al., 2021).

Extirpation (e.g., local losses of species) have been observed in response to climate change in Europe (*medium confidence*) (Wiens, 2016; EEA, 2017a; Soroye et al., 2020). Strong climate-induced declines have been detected in thermosensitive taxa (Hellmann et al., 2016), including many freshwater groups, insects (Habel et al., 2019; Harris et al., 2019; Seibold et al., 2019; Soroye et al., 2020), amphibians, reptiles (Falaschi et al., 2019), birds (Lehikoinen et al., 2019) and fishes (Myers et al., 2017a; Jarić et al., 2019). The loss of native species, especially specialised taxa,

Köppen-Geiger climate classification and biodiversity hotspots in Europe

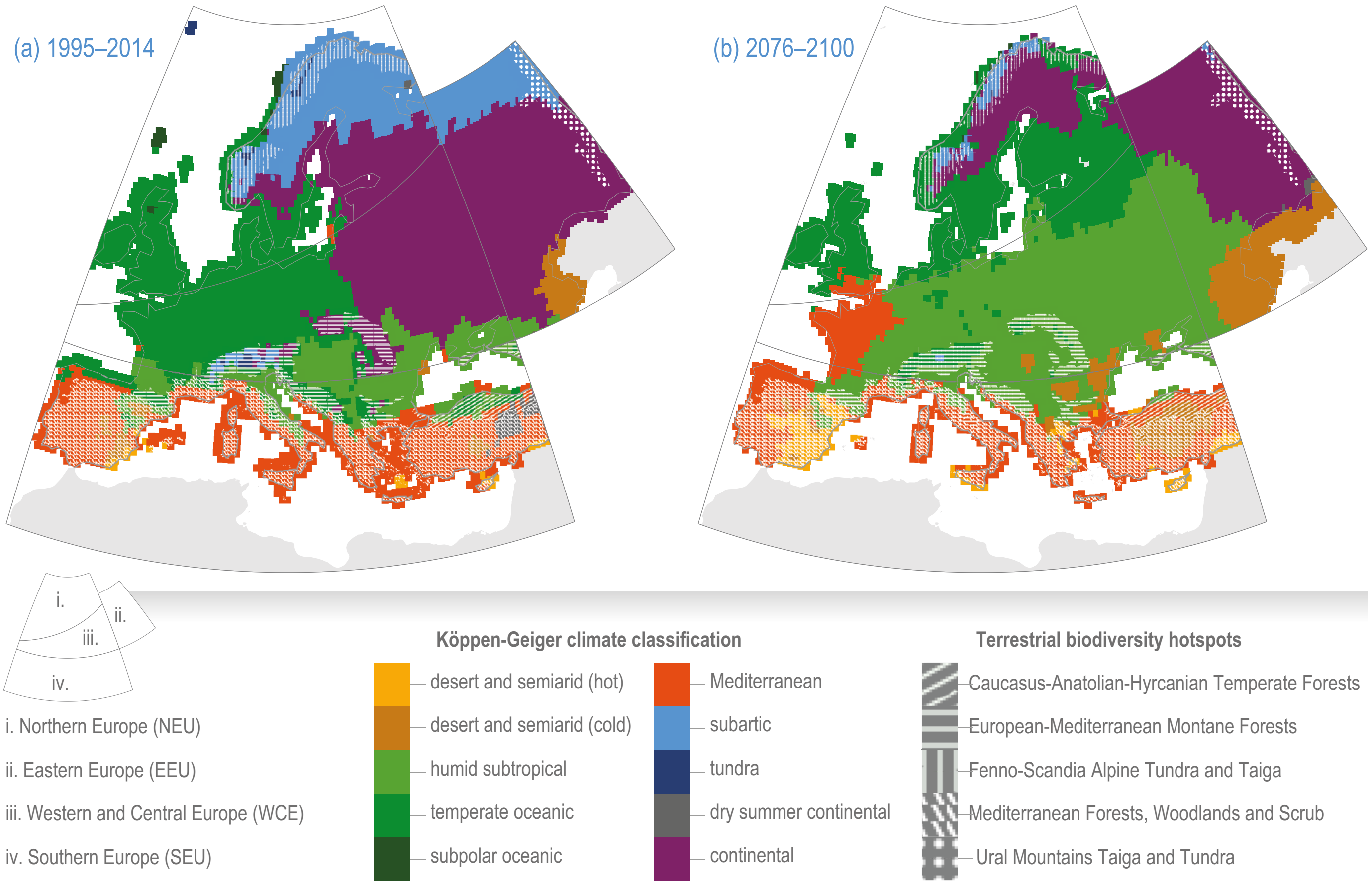


Figure 13.7 | Köppen-Geiger climate classification and biodiversity hotspots in Europe. Boundaries are of the

(a) Northern European (NEU),

(b) Western–Central European (WCE),

(c) Southern European (SEU) and

(d) Eastern European (EEU) regions for 1985–2014 (left) and 2076–2100 (right, A1FI scenario, ~4°C GWL), based on Rubel and Kottek (2010).

is changing biodiversity; however, overall biodiversity could remain stable because losses may be offset by range shifts of native, and the establishment of non-native, species (Dornelas et al., 2014; McGill et al., 2015; Hillebrand et al., 2018; Outhwaite et al., 2020).

Range shifts are leading to northward and upwards expansions of warm-adapted taxa (*very high confidence*) (Figure 13.8; Chapter 2). These shifts have altered species living in the boreal and alpine tundra (Elmhagen et al., 2015; Post et al., 2019; Mekonnen et al., 2021) and are greening the high Arctic tundra with shrubs and trees (Myers-Smith et al., 2020). Plants display more stable distributions at low than at higher mountain altitudes (Rumpf et al., 2018). Microclimatic variability in some locations can buffer warming impacts (*medium confidence*) (Suggitt et al., 2018; Zellweger et al., 2020; Carnicer et al., 2021). Northward shifts of tree species distributions is documented in north-western Europe (Bryn and Potthoff, 2018; Mamet et al., 2019) but not consistently detected (Cudlín et al., 2017; Vilà-Cabrera et al., 2019).

The timing of many processes, including spring leaf unfolding, autumn senescence and flight rhythms, have changed in response to changes in seasonal temperatures, water and light availability (*very high confidence*) (Chapter 2; Szabó et al., 2016; Asse et al., 2018; Peaucelle et al., 2019; Menzel et al., 2020; Rosbakh et al., 2021), resulting, for example, in earlier arrival dates for many birds and butterflies (Karlsson, 2014; Bobretsov et al., 2019; Lehikoinen et al., 2019). The largest increase in length of growing season in plants has been detected in WCE, NEU and EEU, but shortening in parts of SEU driven by later senescence (Garonna et al., 2014), increasing population growth for butterflies and moths (Macgregor et al., 2019) and birds (Halupka and Halupka, 2017), and residence time for migrant birds (Newson et al., 2016).

13.3.1.2 Projected Risks for Terrestrial and Freshwater Ecosystems

Risks for terrestrial ecosystems will increase with warming (*very high confidence*) with high impacts at >2.4°C GWL and very high impacts >3.5°C GWL (*medium confidence*) (Section 13.10.3.1). Land-use changes will increase extirpation and extinction risk (*very high confidence*) (Vermaat et al., 2017). In NEU, biodiversity vulnerability is projected to be lower as new climate and habitat space is becoming available (Warren et al., 2018; Harrison et al., 2019). Warming <1.5°C GWL would limit risks to biodiversity, while 4°C GWL and intensive land use could lead to a loss of suitable climate and habitat space for most species (*low confidence*) (Warren et al., 2018; Harrison et al., 2019).

Disruption of habitat connectivity reduces resilience and is projected to impact 30% of lake and river catchments in Europe by 2030, through drought and reduced river flows (*medium evidence*) (Markovic et al., 2017). Average wetland area is not projected to change at 1.7°C GWL across Europe, while for >4°C GWL expanding sites in NEU are not sufficient to balance losses in SEU and WCE (*high confidence*) (Xi et al., 2021). At 3°C GWL the alpine tundra habitat and its associated species are projected to be lost in the Pyrenees and shrink dramatically in NEU, WCE and EEU (Anisimov et al., 2017; Barredo et al., 2020).

Population range shifts (Figures 13.7, 13.10) are projected to continue (*medium confidence* at 1.5° GWL, *high confidence* at 3.0°C GWL) (Figure 13.8). The largest losses of suitable climatic conditions are projected for plants and insects, with different taxon-specific regions of highest risk, while proportions of species projected to lose suitable climates are lower for other groups (*medium confidence*) (Figure Box 13.1.1; Table SM13.3; Warren et al., 2018). Temperatures >1.5°C GWL will lead to a progressive subtropicalisation in SEU, expanding into WCE at >3°C GWL, a northward shift in the temperate domain into NEU (*medium confidence*) (Feyen et al., 2020) and an expansion of desert biomes in EEU (Sergienko and Konstantinov, 2016). Changes in distribution are projected for major tree species in all European regions at 1.7°C GWL (Dyderski et al., 2018; Leskinen et al., 2020), with economic implications for managed forests (Section 13.5.1.4). The longer growth season in NEU and WCE will support the establishment of invasive species (Cross-Chapter Paper 1). Temperatures <1.5°C GWL would limit expansion and novel appearances of pests, while >3.4°C GWL would make large parts of SEU and WCE suitable for pests, for example, wood beetles (Urvois et al., 2021), and increase economic losses due to lower harvest quality of timber (Toth et al., 2020).

Risks emerging from climate change for phenology are uncertain, given asynchrony between species, taxa and trophic responses (Thackeray et al., 2016; Posledovich et al., 2018; Keogan et al., 2021) and the complexity of phenological events and their cues (*medium confidence*) (Delgado et al., 2020; Ettinger et al., 2020). Spring events may continue to occur earlier (Gaüzère et al., 2016), but reduced chilling may decrease this temporal shift (Wang et al., 2020). Projections for autumn are mixed, with continuing delays (Prislan et al., 2019) or earlier onset of leaf senescence (Wu et al., 2018), but reduced chilling may also decrease these developments (Wang et al., 2020). Advancement, combined with longer autumn growth, may extend the growing season of trees by two days per decade in SEU (Prislan et al., 2019). Warming to >3°C GWL will impact forest planning in NEU (Caffarra et al., 2014).

13.3.1.3 Observed Impacts and Projected Risks of Wildfires

Fires affect over 400,000 ha every year in the EU (San-Miguel-Ayanz et al., 2019), with 85% of the area located in SEU (Khabarov et al., 2016; de Rigo et al., 2017; Gomes Da Costa et al., 2020), where 'fire weather' conditions (determined by temperature, precipitation, wind speed and relative humidity) are most pronounced (Figure 13.10). Fire hazard conditions, including heatwaves (Boer et al., 2017), increased throughout Europe from 1980 to 2019 (Figure 13.10), with substantive increases in SEU and WCE (*high confidence*) (Urbieta et al., 2019; Di Giuseppe et al., 2020; Fargeon et al., 2020). Extreme wildfires have been observed in recent years, including 2017 in Portugal, 2018 in Sweden (Krikken et al., 2021) and 2021 in south-eastern Europe. In SEU, WCE and NEU human activities have caused more than 90–95% of the fires, while natural ignition accounts for a substantial portion of burned areas in EEU (Wu et al., 2015; Filipchuk et al., 2018).

Except for Portugal, burned area in SEU has shown a slightly decreasing trend since 1980, with high interannual variability (Cross-Chapter Paper 4; Turco et al., 2016; de Rigo et al., 2017). In SEU, burned terrestrial biomass declined from 2003 to 2019 (Turco et al., 2016), despite increasing fire risks. This trend is parallel to increasing fire management measures implemented (Fernandez-Anez et al., 2021). The slight increase in burned biomass in WCE and NEU is associated