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STATE OF THE PLANET Discussions

# Sea Level Rise in Europe: Summary for Policy Makers

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## Abstract

The European Knowledge Hub on Sea Level Rise (KH-SLR), an initiative by JPI Climate and JPI Oceans, has developed its first Assessment Report to address the challenges posed by sea level rise (SLR) in Europe. This report, preceded by a series of targeted surveys and workshops with researchers and stakeholders (e.g. coastal decision makers), has synthesized the current scientific knowledge on SLR drivers, impacts and policies at local, national, and European basin scales. It provides additional value by more in-depth and region-specific analyses on local sea level changes, compared to relevant global assessments such as by the Intergovernmental Panel on Climate Change (IPCC). In addition, it identified critical knowledge gaps supporting the development of actionable information. The Summary for Policy Makers (SPM) distills the key findings of the report, presenting information specific to each European basin (Mediterranean and Black Sea, North Sea, Baltic Sea, Atlantic and Arctic basins). It highlights region-specific trends, vulnerabilities, and potential impacts, while also orienting future requirements.

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# 1. Assessment Scope and Stakeholder Needs on European SLR drivers, impacts, and policies

## 1.1 Scope of the assessment

Despite the global threat of sea level rise (SLR), Europe faces disparities in understanding and applying sea level science, evaluating its impacts, and devising effective adaptation strategies. The European Knowledge Hub on Sea Level Rise (KH-SLR), a joint effort between JPI Climate and JPI Oceans, compiled a first assessment report based on an extensive scoping process defining its outline, identifying critical knowledge gaps, aiming to provide easy access to usable knowledge on regional-local sea level change in Europe and enabling policy makers to make well-informed decisions regarding protective and adaptive measures. The assessment of ~~regional SLR for Europe~~ is intended to provide ~~additional~~ value that complements global (e.g., IPCC) and national assessments (see also Pinardi et al., 2024, this volume).

## 1.2 Stakeholder consultation on available and requested information

### 1.2.1 Online Survey

An online survey targeting stakeholders involved in coastal planning and research was conducted to assess the availability and ~~usage~~ of SLR information, impacts ~~induced by~~ SLR, and adaptation strategies and policy implications of SLR. Responses were received from 200 ~~participants~~, with 94% from 23 European and 6% from 8 non-European countries~~, with participants' professional backgrounds separated into~~ two groups: government (about one third of respondents) and research (about two third of respondents) (see Figure 2, Jiménez et al., 2024, this volume). ~~Major~~ outcomes of the survey are summarized below (also see Jiménez et al., 2024, section 3.1, this volume).

~~**SLR Information**~~

Approximately 32% of respondents indicated a lack of essential regional to local information and data ~~on SLR~~, with disparities across different sea basins and stakeholder groups. Global sea level projections were most accessible and ~~utilized~~. Information gaps primarily revolve around regional SLR projections, uncertainties and ice sheet mass loss contributions, highlighting the need for better projections related to long-term SLR and comprehensive understanding. Both government and scientist respondents identified similar gaps with slight variations in perspectives and priorities. Government respondents prioritize precise regional projections as the ultimate product, crucial for fulfilling their responsibilities, with uncertainty estimation being a significant concern. Scientists, however, prioritize a comprehensive understanding of factors influencing regional projections~~, considering these insights as the final goal~~, with a strong focus on the factors contributing to uncertainty. Improving local SLR projections, understanding the impact on extreme water levels, and addressing coastal erosion ~~are~~ all deemed important.

~~**SLR Impacts**~~

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Shoreline erosion emerged as ~~a dominant~~ concern in all basins except the Arctic, highlighting the critical role of beaches in regional economies. Due to this, other significant impacts are outlined, such as increased flooding, damage to infrastructure, and groundwater salinization, with notable disparities across sea basins. Challenges persist due to the absence of high-quality impact assessments, particularly in the Black Sea and Arctic basins.

**~~Adaptation~~ to SLR**

Many ~~existing adaptation plans are deemed inadequate, with scientists exhibiting a more critical perception than government respondents~~. Flexibility of existing adaptation strategies ~~in the face of SLR induced~~ impacts is considered insufficient, highlighting the need for adaptive planning approaches. ~~Neglected considerations in decision making include SLR impacts~~ on coastal ecosystems, coastal urban planning frameworks, river discharge characteristics, and freshwater management.

**Policy Support and Implications**

~~Respondents unanimously agree on the usefulness of IPCC reports~~ for informing policy and decision-making. ~~Identified needs encompass~~ periodic updates to SLR projections, comprehensive impact assessments, and enhanced exploration of adaptation strategies to mitigate SLR impacts on coastal communities and ecosystems. Additionally, allocating resources for research and data collection to improve evidence-based and adaptive policymaking ~~is~~ deemed necessary. Collaboration among government agencies, research institutions, and stakeholders to develop and implement effective adaptation measures ~~is~~ emphasized.

Policy implications include the recognition of the value of incorporating Nature Based Solutions (NBS) in coastal adaptation plans, although their implementation requires rigorous evaluation and evidence of long-term sustainability under site-specific circumstances.

### 1.2.2 Online Workshops

Four online scoping workshops focusing on specific European sea basins gathered insights from stakeholders, policymakers, and experts, furthering the understandings from the survey. ~~Major outcomes of the workshop are listed below~~ (also see Jiménez et al., 2024, section 3.2, this volume).

**North Sea and Arctic Basins**

Locally specific reconstructions and projections of extreme sea levels, along with comprehensive guidance on existing models, are needed to address the demand for SLR information. Additionally, a thorough understanding of compound processes contributing to sea-level extremes and mutual learning among regions are required to tackle hazards and impacts effectively. To facilitate adaptation and decision-making, a comprehensive overview of adaptation options, policy comparisons across countries, and active stakeholder engagement is necessary.

**Eastern Atlantic Basin**

In terms of SLR information, gaps have been identified in SLR scenarios tailored to estuaries, the limited spatial resolution of climate models, and the monitoring of key processes like ice sheets. There is a need to assess the

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combined impact of waves, surges, tides, and SLR, as well as to protect cultural heritage from SLR impacts. Regarding adaptation and decision making, emphasis is placed on practicing stakeholder engagement, community-focused adaptation planning, and building confidence in SLR projections.

**Mediterranean and Black Sea Basins**

Gaps have been identified in data management, sea level projections, coastal vulnerability data, and multidisciplinary data integration. Erosion, flooding, and salt-water intrusion are recognized as critical impacts requiring attention, along with the need for 'what if' scenarios feeding into the design and implementation of coastal adaptation policies. Emphasis is placed on integrating SLR-related policies within an Integrated Coastal Zone Management framework as part of Marine Spatial Planning, community engagement, and effective communication strategies.

**Baltic Sea Basin**

In the Baltic Sea Basin, there is a need for high-resolution projections of future sea level extremes and improved characterization of drivers triggering natural hazards. Erosion, flooding, salt-water intrusion, and compound events are identified as significant risks, along with the role of critical infrastructure in adaptation. Also, here emphasis is placed on integrating SLR-related policies with Marine Spatial Planning, addressing conflicts of interest, and assessing the effectiveness of adaptation measures. In this regard, it was recommended combining short- and long-term planning as part of an adaptive planning approach.

## 2. Past, present and future sea level

The ~~Assessment Report~~ delves into observed and projected SLR and extreme sea level (ESL) in European basins. Despite some variability in SLR trends between European basins, satellite altimetry shows a consistent upward trend in ~~basin averaged sea level~~, slightly above global mean SLR. Relative sea level rise (RSLR), which considers human-induced subsidence and vertical land motion due to the glacial isostatic adjustment and to the contemporary land ice mass loss, present more contrasted trends across European seas, including a relative sea level fall in the uplifting northern Baltic Sea.

Relative sea level will rise throughout the 21st century ~~over European Seas~~, except in the northern Baltic Sea and parts of the European Arctic. Under a very high emission scenario, a 1-m SLR is projected to occur ~~over~~ most European coasts south of 60°N during the first half of the 22nd century. Because of the large inertia of ice sheets and of the deep ocean, sea level is committed to rise for centuries to millennia, in European seas. ~~A major uncertainty for SLR projections relates to the Greenland and Antarctic ice mass loss and related tipping points~~.

The frequency at which historical centennial water levels are reached is projected to amplify along most European coasts in the coming decades, especially in the southern European Seas, implying the need for more adaptation measures. Higher-resolution ~~Sea level~~ projections are needed, together with information on local drivers of extreme sea levels (including tides, waves, storm surges). European wide drivers of past mean and extreme sea level, as well as future projections of these are provided for each of the assessed basins.

## 2.1 Eastern Atlantic

### Drivers of Past Mean and Extreme Sea Level

The north-eastern Atlantic Ocean basin, encompassing Portugal, Spain, France, the UK, and Ireland, features strong bathymetric gradients, energetic tides, waves and storm surges notably due to the North Atlantic mid-latitude storm track. Rates of SLR have accelerated over the past century. Regional patterns of relative SLR are mostly explained by ocean dynamics and gravitational patterns associated with mass loss from Greenland ice sheet and mountain glaciers. Climate modes of variability such as the North Atlantic Oscillation (NAO) significantly affects regional sea level trends and extremes, impacting storm surges along western Europe. Changes in storminess and atmospheric pressure patterns associated with NAO influence the frequency and intensity of extreme sea level events, particularly storm surges. The highest extreme water levels (50-yr return period) of European Seas are reached in the north-eastern Atlantic (see Melet et al., 2024, section 6.1.2, this volume).

### Projections on Mean and Extreme Sea Level

Projections for the 21$^{st}$ century suggest that relative sea level over European seas will rise (close to) the fastest along the coasts of the north-eastern Atlantic (see Table 3, Melet et al., 2024, this volume). Relative SLR in this region will closely track the global mean, with some variations in rates across geographical regions. Sterodynamic SLR, driven by global mean thermal expansion, steric and ocean circulation changes, remains the primary contributor to relative SLR along the European Atlantic coast. Changes in ocean circulation patterns, such as the intensification of currents, are projected to influence mean and extreme wave conditions, affecting coastal flooding and erosion. Projections indicate a decrease in significant wave height and period along European coasts, leading to a reduction in wave setup and runup, with the potential exception of the Baltic Sea. Non-linear interactions between SLR, tides, and storm surges can be substantial in the north-eastern Atlantic and are anticipated to have substantial impacts on coastal water levels, with implications for coastal resilience and adaptation measures (see Melet et al., 2024, section 6.1.3, this volume).

## 2.2 North Sea

### Drivers of Past Mean and Extreme Sea Level

The North Sea, bordered by several European countries, experiences a predominant cyclonic ocean circulation due to prevailing westerly winds. It receives warm, saline water from the North Atlantic and cooler, fresher water from the Baltic Sea, resulting in complex dynamics. Relative SLR in the North Sea is largely driven by sterodynamic sea level changes. Spatially varying rates of relative SLR are also substantially influenced by factors such as the glacial isostatic adjustment, ice mass loss, and subsidence, with the highest rates of relative SLR found in the south-eastern North Sea. Interannual variations of sea level are mostly driven by variability

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in local winds and surface atmospheric pressure. Sea levels in the North Sea experience a large temporal variability. Astronomical tides significantly influence water levels, with the largest tidal ranges observed along the UK east coast. Large non-linear interactions between the tidal and non-tidal components of water level are especially important in the southern North Sea. Changes in waves, tides and storm surges have been observed, influenced by historical trends in mean sea level, changes of ocean stratification, and non-linear interactions between water level components (see Melet et al., 2024, section 6.2,2, this volume).

**Projections on Mean and Extreme Sea Level**

Projections suggest that 21st century relative SLR in the North Sea will vary spatially, with higher rates in the southern regions, with spatial differences influenced by factors like glacial isostatic adjustment. Sterodynamic SLR is projected to be relatively uniform across the North Sea. However, projections acknowledge the uncertainty stemming from factors like the resolution of global climate models (GCMs) and local dynamics. Amplification of Extreme Sea Level (ESL) frequencies due to SLR are expected, with implications for coastal communities, but the increase in frequency of ESL is smaller than in other European Seas. The impact of SLR on storm surges, tides, and waves is significant, particularly in shallow areas, necessitating adaptive coastal management strategies. While the effect of changes in storminess on ESLs remains uncertain, studies agree that mean SLR itself is the primary driver of change in the North Sea (see Melet et al., 2024, section 6.2,3, this volume).

### 2.3 European Arctic

**Drivers of Past Mean and Extreme Sea Level**

Vertical land motion (VLM) is a significant driver of relative sea level change in the European Arctic, bordering Iceland and parts of Norway, attributed to past ice mass loss and glacial isostatic adjustment (GIA). Ongoing ice mass loss on Iceland, Svalbard also contributes to local land uplift. Recent studies highlight widespread non-negligible elastic VLM in the European Arctic due to ice mass loss from Greenland, and an overall rising trend in sea level. Sea level observations are challenging due to the remote location of the European Arctic and limited number of tide gauges, and to hampered satellite measurements (see Melet et al., 2024, section 6.3.2, this volume).

**Projections on Mean and Extreme Sea Level**

Projections suggest that the European Arctic will experience a below than global average SLR, mainly due to GIA and gravitational, rotational, and deformational (GRD) effects, particularly from Arctic glaciers and the Greenland ice sheet. Consequently, a 0.5 or 1.0 m SLR will be reached later in the future in the European Arctic than in other European seas (see Figure 11, in *Melet et al., 2024,* this volume). However, sterodynamic SLR in the Arctic is expected to be larger than the global average, primarily due to ocean freshening. Projections indicate uncertainties regarding changes in storm surges and waves, but future wave climate projections generally indicate a lower mean significant wave height in the northeast Atlantic sector. Receding sea ice cover

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will result in higher waves in the northwestern part of the Norwegian and Barents Seas (see Melet et al., 2024, section 6.3.3, this volume).

## 2.4 Mediterranean Sea and Black Sea

### Drivers of Past Mean and Extreme Sea Level

The Mediterranean Sea, connected to the Atlantic Ocean via the Strait of Gibraltar, experiences sea level changes driven primarily by mass contributions at basin scale, while the steric component explains a significant portion of variance at sub-basin scale. Interannual to decadal basin averaged sea level variability correlates with the nearby Atlantic, while regional deviations result from ocean circulation, heat redistribution, and air-sea momentum fluxes. Storm surges, due to North Atlantic atmospheric cyclones and to medicanes, and seiches are especially important for ESL in the microtidal Mediterranean Sea. VLM can be locally important.

The Black Sea, receiving freshwater from the Danube, Dnieper and Don river basins primarily, presents much lower salinity than the Mediterranean. Most of the steric SLR in this basin appears primarily related to salinity reduction rather than temperature increases. Coastal VLM is a relatively minor contributor to relative SRL in the Black Sea compared to other regions (see Melet et al., 2024, section 6.4.2, this volume).

### Projections on Mean and Extreme Sea Level

Multi-model ensemble projections for the Mediterranean Sea suggest basin-average rates of SLR by 2100 that are amongst the highest for European Seas (see Table 3, in Melet et al., 2024, this volume). The Black Sea's projected relative SLR has been scarcely assessed but is expected to be within a range of ±20% of global mean SLR. Mean SLR will be the dominant driver of increasing coastal ESLs during the 21$^{st}$ century. Storm surges and wind waves are projected to undergo small and mostly negative changes in southern Europe by 2100. Additionally, future changes in medicanes (extratropical cyclones), and meteotsunamis (high-frequency oceanic waves), are anticipated due to increased sea surface temperatures and altered atmospheric circulation patterns, with potential implications for coastal hazards. The projected increase in the frequency at which ESL are reached (amplification factor of ESL) over European Seas is the largest in the Mediterranean Sea (see Figure 12, in Melet et al., 2024; also see Melet et al., 2024, section 6.4.3, this volume).

## 2.5 Baltic Sea

### Drivers of Past Mean and Extreme Sea Level

The Baltic Sea is characterized by its semi-enclosed and shallow nature. The North Atlantic Oscillation plays a significant role in the climate variability of the region, impacting wind patterns and sea level fluctuations. The Baltic Sea experiences pronounced seasonal variations in sea level. At time scales longer than a month, mean sea level in the Baltic Sea approximately follows the sea level in Kattegat, outside the Baltic Sea, but with larger variance at the northern and eastern most bays. SLR in the southern Baltic Sea approximately follows the projected global mean SLR (or slightly less) but land uplift due to GIA is particularly significant in northern sub-basins, leading to a relative mean sea level fall there. Storm surges, amplified by westerly winds, pose threats to low-lying coastal areas. Tides have relatively low amplitudes and ESLs in the Baltic Sea are caused by pronounced atmospheric cyclones that sometimes interact with seiches on daily time scales and with volume changes on weekly time scales (see Melet et al., 2024, section 6.5.2, this volume).

**Projections on Mean and Extreme Sea Level**

Projections of 21st century sea levels in the Baltic Sea are requiring high-resolution regional climate models due to the complex coastline and topography of the region. Available projections suggest continued basin mean SLR in the Baltic Sea under medium and high emission scenarios, slightly below global mean SLR. Relative sea level will continue to exhibit a clear meridional gradient during the 21$^{st}$ century, with a relative sea level fall in the northern most Baltic Sea due to GIA-induced effects (see Figure 10, in Melet et al., 2024, this volume Melet et al., 2024). Future changes in ESL will depend on mean SLR, atmospheric circulation patterns, which remain uncertain, and wind changes. Sea ice loss due to warming is expected to increase sea level extremes in previously ice-covered regions, leading to higher wave heights, coastal erosion, and sediment resuspension. While some studies suggest a rise in extreme sea levels beyond mean sea level due to changes in atmospheric circulation, confidence in these projections remains limited due to inconsistencies between global climate model projections. Due to land uplift, the lowest amplification factors of the frequencies of ESL in European seas are found in the northern Baltic Sea (see Melet et al., 2024, section 6.5.3, this volume Melet et al., 2024).

## 3. Coastal flooding, erosion, and saltwater intrusion in Europe

The analysis of the primary impacts of SLR on Europe employs the Source-Pathway-Receptor-Consequence framework and focuses on coastal flooding, coastal erosion, and saltwater intrusion.

### 3.1 Impacts

#### 3.1.1 Flooding

Coastal flooding, influenced by rising sea levels and various factors like storms, has profound impacts across Europe, causing social, economic, and environmental consequences. Despite high flood-defence standards, significant populations and assets remain vulnerable, especially in low-lying coastal flood plains. The risks are further escalated by aging infrastructure, urbanization in these areas and habitat loss. Compound flooding, resulting from combined factors like heavy rainfall, river overflow and storm surge, exacerbates these challenges. The interplay of drivers like extreme coastal water levels, tides, storm surges and waves is receiving increasing attention in development of early warning and decision support tools.

Climate change intensifies coastal flooding, primarily through SLR, altering flood dynamics and increasing the likelihood of compound events. Efforts to address flooding involve a multi-faceted approach, including coastal defences, habitat restoration, and enhanced flood forecasting.

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Policy directives incorporating SLR risk assessments can help to improve flood management strategies. While extensive flood management infrastructure exists, challenges persist, especially with accelerating SLR. Effective adaptation measures and investments in flood resilience are essential to mitigate the growing risks posed by coastal and compound flooding in Europe (see van de Wal et al., 2024, section 4, this volume).

**3.1.2 Erosion**

Extreme waves, storm surges and human activities influence coastal erosion, which governs over 8,200 km of sandy beaches causing shoreline change. SLR and the reduction of river sediment supply due to human developments and dams are main drivers of erosion.

While local sediment budgets and climate patterns determine the specific sign and magnitude of shoreline changes, rising sea levels will negatively impact all coastlines by adding a background erosion rate to existing trends. Coastal erosion poses significant challenges for coastal communities, leading to habitat loss, infrastructure damage, increased flood risk and compromising the sustainability of recreational beach use, thereby impacting the tourism sector.

Europe’s coastline is heavily influenced by human activities and infrastructure. Human development along coastlines exacerbates erosion. Effective coastal management strategies must consider the complex interplay of drivers contributing to erosion and shoreline change (see van de Wal et al., 2024, section 5, this volume).

**3.1.3 Saltwater intrusion**

Saltwater intrusion (SWI) is the encroachment of saltwater into freshwater resources, affecting both surface waters and groundwater. It poses significant challenges to agriculture, freshwater availability and coastal communities' livelihoods due to salt damage to crops and health risks associated with saline drinking water. SWI reduces freshwater storage, impacts soil fertility, vegetation, freshwater species and ecosystem services, especially in deltaic regions and estuaries.

Human activities, including reduced river flows and urbanization, exacerbate SWI. Climate change intensifies SWI drivers, including SLR and reduced freshwater supply, affecting hydrogeological interactions between groundwater, surface water and marine water. SWI's consequences encompass social, economic, and environmental aspects, including reduced drinking water reserves, agricultural losses, habitat degradation, and land subsidence. Anthropogenic interventions, such as flood barriers and managed aquifer recharge schemes, aim to mitigate SWI impacts by limiting saltwater intrusion and enhancing freshwater resources. Challenges persist, including the effectiveness of engineered solutions during extreme events and the need for sustainable groundwater management strategies. Future projections indicate increasing water stress and groundwater salinization, underscoring the importance of integrated coastal management and adaptation measures to address SWI's multifaceted impacts on Europe's coastal regions (see van de Wal et al., 2024, section 6, this volume).

**3.2 <u>Regional impact</u>**

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While not all SLR impacts have been systematically assessed for each basin, an inventory of the main impacts covered within the report are summarized below. The reader is advised not to consider that any impacts not covered for a specific basin are not experienced, but rather a possible scope for future assessments to fill these gaps.

### 3.2.1 Eastern Atlantic

*Flooding*: The Eastern Atlantic coastline is affected by coastal flooding due to SLR. Flood-defence standards in many European countries along the Eastern Atlantic are among the highest in the world, indicating high importance of protection measures in this region.

*Saltwater intrusion*: Along the Atlantic coasts various cases of increased saltwater intrusion in the groundwater system are reported. Specifically, the Minho and Lima estuaries in the northern coast of Portugal are affected by SLR, leading to a transgression of the saltier front over several kilometres.

*Coastal Erosion*: Projections under different emission scenarios indicate a shoreline retreat along the Basque coast from 10-66 meters by the year 2100.

### 3.2.2 North Sea

*Flooding*: The North Sea coastline is significantly affected by coastal flooding due to SLR. Coastal cities such as those of Rotterdam, Hamburg, and London are vulnerable to compound flood events arising from storm surges, waves, river discharge, and heavy precipitation. Port operations may also be negatively affected by SLR.

*Saltwater intrusion*: Enhanced salinization is projected to be induced by SLR and climate change in several coastal locations in the North Sea. The text cites examples such as The Netherlands and Belgium, where coastal locations are facing increased saltwater intrusion due to SLR.

### 3.2.3 Mediterranean Sea and Black Sea

*Flooding*: The Mediterranean Sea coastline is highly vulnerable to SLR-induced coastal flooding. Specific locations such as the Gulf of Valencia, northwest Algeria, the Gulf of Lion, and the Adriatic coast of the Balkan Peninsula present an increased flood risk due to compounding features characterizing hydrometeorological hazards and coastlines.

*Coastal erosion*: Mediterranean beaches are particularly susceptible to the negative effects of SLR due to their relatively narrow width. Studies project significant erosion impacts on Mediterranean beaches, such as those in the Balearic Islands, with projections of at least 20% of beaches losing more than 50% of their surface area by the end of the 21$^{st}$ century.

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*Saltwater intrusion*: There are significant impacts of saltwater intrusion on the Mediterranean region, including through increased seawater infiltration in coastal aquifers. This has pronounced consequences on agricultural productivity and poses a threat to coastal ecosystems, including the potential loss of subtidal seagrass meadows.

### 3.2.4 Baltic Sea

*Flooding*: The vulnerability of coastal subtidal seagrass meadows and intertidal salt marshes to SLR is particularly high in microtidal areas in parts of the Baltic Sea coast.

Despite prior infrastructure investments, increased flood risk and losses are expected, particularly with higher SLR rates.

## 4. Adaptation measures and decision-making principles

### 4.1 Key adaptation strategies

A wide range of adaptation measures and decision-making principles related to sea-level rise and coastal hazards exist. ~~Key strategies include accommodation, protection, advance and retreat.~~ Interventions and measures can be classified in ~~various~~ ~~categories~~ (see Galluccio et al., 2024, section 4.1.1, this volume), as follows:

- **'Accommodation' measures** such as flood-proofing buildings and increasing resilience of critical infrastructure are highlighted as effective responses to reduce the vulnerability of coastal communities to SLR impacts. These measures encompass a range of approaches, from flood-proofed materials to early warning systems and climate risk insurance schemes.

- **'Protect' measures** aim to reduce coastal hazards through hard and soft defence mechanisms, as well as the restoration and management of coastal ecosystems. Examples include dams and seawalls, artificial reefs, restoring marshes and other forms of Nature Based Solutions.

- **'Advance' measures** involve creating or advancing new land to address coastal flooding and erosion, often through conservation and restoration efforts.

- **'Retreat' measures** focus on reducing exposure to coastal hazards by relocating human activities, infrastructure or cities from high-risk to less exposed areas. This may involve planned relocation or managed realignment programs. Relocation strategies involve complex trade-offs between effective risk reduction and societal and economic costs.

### 4.2 Approaches for decision making

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Coastal adaptation decision-making is complex, demanding thoughtful approaches amidst uncertainties. Coastal adaptation decisions involve selection of various options implemented at different moments in the future. Adaptation decision-making methods can be applied to analyse consecutive decision moments in time, including their potential triggers, alternatives and long-term implications. Participatory and analytical methods are crucial in this process, fostering stakeholder cooperation and identifying suitable options.

~~Coastal adaptation decisions share common characteristics such as the existence of multiple measures, multiple objectives and uncertainties regarding both sea level rise and the implications of measures. The consideration of multiple interests is addressed through methods like multi-criteria decision analysis (MCA), which structure decisions and identify preferences.~~ Implementation of low regret measures, such as awareness campaigns and preserving coastal wetlands in rural areas, offers immediate benefits with minimal costs.

Inherent SLR uncertainties require flexibility and adaptability of strategies. Keeping future options open involves postponing long-term decisions where possible and implementing flexible measures that can be adjusted to changing conditions and available information. ~~SLR affects decisions taken currently that, particularly for critical infrastructure and urban planning, have long term outcomes.~~ Iterative revision of decisions and monitoring progress enable timely adjustments and the adoption of new policies as needed. Adopting a systematic approach to coastal adaptation decision-making ensures resilient and sustainable outcomes amidst evolving challenges. Methods like economic analyses, robust decision-making and adaptive policy planning aid in evaluating decision timing and strategic prioritization (see Galluccio et al., 2024, section 4.2, this volume).

### 4.3 Assessment of regional adaptation ~~developments~~

In Europe, adaptation to SLR varies across different sea basins, and includes a combination of ~~the previously described~~ strategies~~:~~ accommodation, protection, advancement and/or retreat. ~~Common~~ trends across all basins include the integration of traditional ("hard") engineering solutions with ecosystem-based ("soft") measures, community involvement in decision-making processes, as well as continuous monitoring and flexible management strategies through coastal and marine planning instruments (see Galluccio et al., 2024, section 4.3, this volume).

#### 4.3.1 Eastern Atlantic

Across the Atlantic Ocean Basin, countries are implementing a variety of adaptation measures, including nature-based solutions and improved spatial planning. Ecosystem-based protection measures such as cliff strengthening, and sand nourishment are prominent, alongside advance strategies like the regeneration of beaches and artificial dune systems. Retreat measures, including the removal of constructions in flood-critical areas, are considered at various locations.

#### 4.3.2 North Sea

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In the North Sea Basin, most countries have integrated SLR information into coastal planning, employing a combination of hard and soft protection measures such as dike upgrading, sand nourishment and managed retreat. Comprehensive strategies combine flood protection with maintaining a healthy freshwater system while enhancing societal and ecological values.

**4.3.3 Mediterranean Sea**

Mediterranean Sea Basin countries have advanced the mainstreaming of SLR information into national adaptation planning, e.g. in Spain and Italy. Soft protection measures, including sand nourishment, and coastal reforestation and the restoration of dunes and marshes, are emphasized along with large-scale adaptation initiatives in major urban areas like Venice (Italy) and Barcelona (Spain). Further, insurance is emerging as an accommodation measure to address SLR, e.g. in Spain and France.

**4.3.4 Black Sea**

In the Black Sea Basin, efforts are directed towards developing monitoring and early warning systems, alongside upgrading coastal infrastructure to manage SLR and associated flood risks. Initiatives combining sand nourishment, cliff stabilization, and artificial reef building are being implemented with the aim of reducing erosion risks and enhancing resilience in the tourism sector.

**4.3.5 Baltic Sea**

In the Baltic Sea Basin, several nations have integrated SLR projections into spatial planning and land-use regulations. Protection measures, including upgrading coastal defences and implementing nature-based solutions are being implemented and contribute to marine environment conservation and enhancing living marine resources.

## 5. ~~Governance Context and Challenges~~

~~Progress in coastal adaptation governance in Europe is assessed in the socio-economic and political contexts by reviewing coastal adaptation relevant policy frameworks in place at regional and national levels within each of the selected sea basins.~~

### 5.1 Eastern Atlantic

**Geopolitical context**

The Atlantic Ocean has transitioned from a zone of peaceful cooperation to one of growing instability, ~~particularly in the Arctic Ocean~~. The region faces militarization and competition over natural resources and trade routes, necessitating strategic engagement and cooperation from the European Union (EU) and its member states (see Bisaro et al., 2024, section 5.2.1, this volume).

**Economic context and governance**

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The Eastern Atlantic basin encompasses several vital economic sectors such as maritime tourism, shipping, and blue economy sectors including renewable energy and green port infrastructure. With the rise in maritime activities, challenges related to sustainable development and resource management emerge. Policy interventions are necessary to balance economic growth with environmental conservation. Atlantic Ocean Basin countries have adopted adaptation policy strategies, but challenges persist in addressing uncertainty in SLR and associated risks. Some countries incorporate SLR into their Maritime Spatial Planning, while others lack specific measures (see Bisaro et al., 2024, section 5.2.2, this volume).

### 5.2 North Sea

**Geopolitical context**
The North Sea region, known for its democratic institutions and environmental standards, is witnessing heightened attention due to its vast energy reserves and potential for renewable energy, notably offshore wind. The EU aims to leverage these resources for its energy transition to enhance economic growth and stability.

**Economic context and governance**
The North Sea region boasts significant economic sectors like shipping, oil and gas and emerging sectors such as offshore wind energy. The North Sea Basin countries have reported SLR as a chronic hazard and adopted adaptation policy strategies. Coastal adaptation measures vary and funding approaches differ substantially among countries. Governance challenges include maintaining environmental sustainability amidst economic growth, while ensuring safe maritime activities and transitioning towards renewable energy sources.

### 5.3 European Arctic Ocean

**Geopolitical context**
The Arctic Ocean has become a geopolitical hotspot due to its rich energy resources and strategic positioning. The EU is actively engaged in Arctic policy, focusing on sustainable development, climate resilience, and cooperation with indigenous populations amidst growing global competition.

**Economic context and governance**
The European Arctic region faces economic opportunities in sectors like oil and gas, fishing as well as emerging sectors including data centres and raw material extraction. Governance challenges include balancing economic development with environmental conservation, addressing demographic shifts and indigenous peoples' rights alongside industrial growth. In the Arctic Ocean Basin, Norway considers mid-range SLR scenarios in planning approaches, highlighting a proactive stance towards coastal adaptation.

### 5.4 Mediterranean Sea and Black Sea

**Geopolitical context**

The Mediterranean and Black Seas present complex challenges, including migration, territorial disputes and energy security concerns. In its policies and recommendations, the EU emphasizes partnership and cooperation to address conflicts, promote stability, and mitigate environmental degradation in these critical basins.

**Economic context and governance**

The Mediterranean and Black Sea regions host crucial economic sectors like tourism, fisheries, mariculture and emerging sectors like offshore energy. Governance challenges include sustainable tourism management, ensuring seafood security and transitioning towards renewable energy sources to mitigate environmental degradation. The Mediterranean Sea Basin has regional instruments addressing coastal adaptation, albeit with limited effectiveness due to the absence of specific measures for SLR. In the Black Sea, regional instruments lack provisions for SLR and coastal adaptation.

### 5.5 Baltic Sea

**Geopolitical context**

The Baltic Sea region faces security challenges exacerbated by the Russia-Ukraine conflict and aggravated by its energy dependence. Efforts focus on diversifying energy sources, enhancing maritime security as well as promoting sustainable development through innovation and cooperation.

**Economic context and governance**

The Baltic Sea region features significant sectors such as shipping, fishing, and emerging sectors like offshore wind energy. Governance challenges involve addressing pollution concerns, sustainable resource management and promoting green technologies to reduce environmental impact. Baltic Sea Basin countries show varying levels of adoption of adaptation policies and measures addressing SLR. Maritime Spatial Planning is enforced across the basin, with some countries incorporating SLR into their plans.

## Competing interests

The contact author has declared that none of the authors has any competing interests.

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