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Sea Level Rise in Europe: Summary for Policymakers

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Abstract. Sea level rise (SLR) is a global concern for low-lying coastal areas, including many European coasts. The European Knowledge Hub on Sea Level Rise (KH-SLR), a collaborative effort by the Joint Programming Initiatives for "Connecting Climate Knowledge for Europe" (JPI Climate) and for "Healthy and Productive Seas and Oceans" (JPI Oceans), has developed the 1st Assessment Report (SLRE1) to address the challenges posed by SLR in Europe. The report's target audience includes national and subnational bodies focused on research and policy advice for coastal management and climate adaptation, as well as European experts who contribute to shaping policy frameworks and collecting information at a pan-European scale. 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 in-depth and basin-specific analyses on local sea level changes, compared with relevant global assessments of the Intergovernmental Panel on Climate Change (IPCC). In addition, it identified critical knowledge gaps needed to support the development of actionable information. The Summary for Policymakers (SPM) distils the key findings of the SLRE1, presenting information specific to the six European basins: Mediterranean Sea, Black Sea, North Sea, Baltic Sea, Atlantic, and Arctic. The SPM highlights basin-specific trends, vulnerabilities, and potential impacts, while also orienting future requirements.

Key statements from the 1st Assessment Report of the Knowledge Hub on Sea Level Rise

- Sea level rise is a chronic hazard that is addressed in the governance of environmental and economic development of European coastal regions in all surrounding sea basins (Sect. 5, 5.1, 5.2, 5.3, 5.4, 5.5).
- The mean rate of European absolute sea level rise slightly exceeds the global mean trend and is accelerating. Regional variability is large, with lower (or negative) relative sea level rise in some Baltic regions due to vertical land movements and the effects of loss of land ice masses. Future sea level rise rates are very uncertain and depend greatly on emission scenarios. Higher relative rates of sea level rise are expected in the southern areas (Sect. 2, 2.3, 2.4, 2.5).
- Sea level rise has several coastal impacts (such as the increased likelihood of floods, shoreline retreat via coastal erosion, and freshwater shortages due to saltwater intrusion). Other human interventions can exacerbate these impacts, such as reduced sediment supplies due to streamflow obstructions, urbanization, and habitat loss in exposed coastal areas; lack of sustainable groundwater strategies; or ageing coastal infrastructure (Sect. 3.1, 3.2).
- Values of sea level rise considered in the management of coastal developments vary across countries and depend on socioeconomic developments in coastal areas, environmental constraints, and options to take measures against negative sea level rise impacts. Many countries have mainstreamed sea level rise in national and regional policies for climate adaptation as well as in (marine) spatial planning and environmental conservation (Sects. 4.3, 5.1)
- Selection of options against adverse sea level rise impacts must usually strike a balance between multiple objectives, available time windows, and long-term implications. Uncertainty in future sea level rise and socioeconomic developments require long-term flexibility by adopting an iterative decision process and monitoring progress in reaching policy objectives (Sect. 4.2, 4.3).
- Many measures to reduce adverse sea level rise impacts exist, classified in broad categories (accommodate, protect, advance, and retreat). They include hard (engineering) and soft (nature-based) infrastructure measures, upgrading or restoring existing coastal assets (such as dikes) or resources (such as aquifer recharge), preventive (such as early warnings) or recovery (such as insurance) measures, and changes in land occupation (such as managed retreat) (Sect. 4.1, 4.3).

1 Assessment scope and stakeholder needs for European sea level rise information

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 "Connecting Climate Knowledge for Europe" (JPI Climate) and " Healthy and Productive Seas and Oceans" (JPI Oceans), has compiled the 1st Assessment Report (SLRE1) based on an extensive scoping process defining its outline and identifying critical knowledge gaps. It aims to provide easy access to usable knowledge on regional–local sea level change in Europe and enable policymakers to make well-informed decisions regarding protective and adaptive measures. The assessment of SLR for the six European basins is intended to provide additional value that complements global (e.g. the Intergovernmental Panel on Climate Change – IPCC) and national assessments (also see Pinardi et al., 2024, in this report).

1.2 Stakeholder consultation

1.2.1 Online survey

An online survey targeting stakeholders involved in coastal planning and in research was conducted to assess the availability and use of SLR information, impacts of SLR, and adaptation strategies and policy implications of SLR. Responses were received from 200 stakeholder participants, with 94 % from 23 European countries and 6 % from 8 non-European countries, and participants were separated into two groups based on their professional backgrounds. The first group (labelled "government") consisted of potential users of SLR information for policy design and implementation, usually professionals in public regional and national governance and in private industry with advisory roles, and was represented by about one-third of the respondents. The second group (labelled "research") consisted of information providers and was primarily comprised of academic research staff (about two-third of the respondents) (see Fig. 2 of Jiménez et al., 2024, in this report). Major outcomes of the survey are summarized in the text below (also see Sect. 3.1 in Jiménez et al., 2024, in this report).

Availability of SLR information

Approximately 32 % of respondents indicated a lack of essential regional–local data and information on SLR, with disparities across different sea basins and stakeholder groups. Overall, global sea level projections were most accessible and most widely used. 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. Government and scientist respondents identified gaps with slight variations in perspectives and priorities. Government respondents prioritized precise regional projections as the ultimate product, crucial for fulfilling their responsibilities, with uncertainty estimation being a significant concern. Scientists, however, prioritized 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 were all deemed important.

Impacts of SLR

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

The survey results show that many stakeholders deem existing adaptation plans to be inadequate, with scientists being more critical 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. SLR impacts that were mostly neglected by stakeholders include those on coastal ecosystems, coastal urban planning frameworks, river discharge characteristics, and freshwater management.

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 (people living, working, and residing in coastal zones) and ecosystems. Additionally, allocating resources for research and data collection to improve evidence-based and adaptive policymaking was deemed necessary. Collaboration among government agencies, research institutions, and stakeholders to develop and implement effective adaptation measures was emphasized.

Policy implications include the recognition of the value of incorporating nature-based solutions (NBSs) 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

The SLRE1 also reports on four online scoping workshops focusing on specific European sea basins that gathered insights from stakeholders, policymakers, and experts, furthering the understandings from the survey. Major outcomes of the workshops are summarized in the text below (also see Sect. 3.2 in Jiménez et al., 2024, in this report).

For all European sea basins, the workshops identified significant data and information gaps, particularly in climate projections that capture local processes and coastline details. Notably, there is insufficient resolution in estuaries and a lack of data on human activities, alongside the need for a robust data delivery and quality control system. The workshops also highlighted the need for a solid methodology to assess the effectiveness of coastal adaptation measures and to develop integrated coastal zone management and/or maritime spatial planning that incorporates sea level rise policies. Additionally, both scientists and policymakers emphasized the importance of community engagement and effective communication strategies. More details on the specific needs for each European basin are given in Jiménez et al. (2024, in this report).

2 Past, present, and future sea level

The SLRE1 delves into observed and projected SLR and extreme sea levels (ESLs) in European basins. Despite some variability in SLR trends between European basins, satellite altimetry shows a consistent upward trend in the basin-averaged sea level for the past 30 years, slightly above the global mean SLR. Relative sea level rise (RSLR), which considers human-induced subsidence, and vertical land motion, due to past and contemporary land ice mass loss, present more contrasting 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, along with information on local drivers of extreme sea levels (including tides, waves, and storm surges). Europe-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

2.1.1 Drivers of past mean and extreme sea level

The north-eastern Atlantic Ocean basin, concerning 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 current changes and mass loss from the Greenland ice sheet and mountain glaciers. Climate variability, such as the North Atlantic Oscillation (NAO), significantly affects storminess and atmospheric-pressure patterns, thereby impacting the frequency and intensity of extreme sea level events, particularly storm surges. The highest extreme water levels (50-year return period) of European seas are reached in the north-eastern Atlantic.

2.1.2 Projections of mean and extreme sea level

Projections for the 21st 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 in Melet et al., 2024, in this report). Relative SLR in this region will closely track the global mean, with some variations in rates across sea basins. SLR, driven by global mean thermal expansion, salinity, 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 set-up and run-up, 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 Sect. 6.1 in Melet et al., 2024, in this report).

2.2 North Sea

2.2.1 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 temperature, salinity, and current changes. Spatially varying rates of relative SLR are also substantially influenced by factors such as ice mass loss and subsidence, with the highest rates of relative SLR found in the south-eastern North Sea. Interannual variations in sea level are mostly driven by variability in local winds and surface atmospheric pressure. Sea levels in the North Sea are known to experience large changes over time. 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 in ocean stratification, and non-linear interactions between water level components.

2.2.2 Projections of mean and extreme sea level

Projections suggest that relative SLR in the North Sea will vary spatially in the 21st century, with higher rates in the southern parts of the basin and spatial differences influenced by factors like past and present terrestrial ice mass loss. Changes in SLR, due to temperature, salinity, and currents, are projected to be relatively uniform across the North Sea. However, uncertainty stemming from factors like the resolution of global climate models (GCMs) and local dynamics are still large. There are likely to be more ESL events due to SLR, which will affect coastal communities, but the increase in frequency of ESLs 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 Sect. 6.2 in Melet et al., 2024, in this report).

2.3 European Arctic

2.3.1 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. Ongoing ice mass loss in Iceland and on Svalbard also contributes to local land uplift. Recent studies highlight widespread 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, the limited number of tide gauges, and hampered satellite measurements.

2.3.2 Projections of mean and extreme sea level

Projections suggest that the European Arctic will experience a below-global-average SLR, mainly due to land uplift effects, particularly from Arctic glaciers and the Greenland ice sheet melting. 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 Fig. 11, in Melet et al., 2024, in this report). However, temperature-, salinity-, and current-driven 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 north-eastern Atlantic sector. Receding sea ice cover will result in higher waves in the north-western part of the Norwegian and Barents seas (see Sect. 6.3 in Melet et al., 2024, in this report).

2.4 Mediterranean Sea and Black Sea

2.4.1 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 temperature and salinity components explains a significant portion of variance at the subbasin 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 ESLs in the microtidal Mediterranean Sea. VLM can be locally important.

The Black Sea, primarily receiving freshwater from the Danube, Dnieper, and Don basins, presents much lower salinity than the Mediterranean. Most of the SLR in this basin appears to be primarily related to salinity reduction, rather than temperature increases. Coastal VLM is a relatively minor contributor to relative SLR in the Black Sea compared with other basins.

2.4.2 Projections of mean and extreme sea level

Multi-model ensemble projections for the Mediterranean Sea suggest basin-averaged rates of SLR by 2100 that are amongst the highest for European seas (see Table 3, in Melet et al., 2024, in this report). The Black Sea's projected relative SLR has been scarcely assessed, but it is expected to be within a range of $\pm 20\,\%$ of global mean SLR. Mean SLR will be the dominant driver of increasing coastal ESLs during the 21st 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 due to rapid atmospheric-pressure changes) 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 and amplitude of ESLs is the largest in the Mediterranean Sea among the European seas (see Fig. 12 in Melet et al., 2024, and Sect. 6.4 in Melet et al., 2024, in this report).

2.5 Baltic Sea

2.5.1 Drivers of past mean and extreme sea level

The Baltic Sea is characterized by its semi-enclosed and shallow nature. The NAO plays a significant role in the climate variability in the basin, impacting wind patterns and sea level fluctuations. The Baltic Sea experiences pronounced seasonal variations in sea level. At timescales longer than a month, the mean sea level in the Baltic Sea approximately follows the sea level in Kattegat, outside the Baltic Sea, but with larger variance at the northernmost and easternmost bays. SLR in the southern Baltic Sea approximately follows the projected global mean SLR (or is slightly lower), but land uplift due to ice mass loss is particularly significant in northern subbasins, 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 timescales and with volume changes on weekly timescales.

2.5.2 Projections of mean and extreme sea level

Projections of 21st-century sea levels in the Baltic Sea require high-resolution regional climate models due to the complex coastline and topography of the basin. Available projections suggest continued basin mean SLR in the Baltic Sea under medium- and high-emission scenarios, slightly below the global mean SLR. Relative sea level will continue to exhibit a clear north–south gradient during the 21st century, with a relative sea level fall in the northernmost Baltic Sea due to the effects of ice mass loss (see Fig. 10 in Melet et al., 2024, in this report). Future changes in ESLs 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 ESLs beyond the 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 ESLs in European seas are found in the northern Baltic Sea (see Sect. 6.5 in Melet et al., 2024, in this report).

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 on low-lying coastal flood plains. The risks are further escalated by ageing 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.

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 Sect. 4 in van de Wal et al., 2024, in this report).

3.1.2 Erosion

Extreme waves, storm surges, and human activities influence coastal erosion, which governs over 8200 km of European 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 (winds and atmospheric-pressure changes) 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, and increased flood risk as well as compromising the sustainability of recreational beach use and, thus, 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 Sect. 5 in van de Wal et al., 2024, in this report).

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 and 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. However, challenges persist, including the effectiveness of engineered solutions during extreme events and the need for sustainable groundwater management strategies. Future projections indicate increasing groundwater salinization and drinking water loss, underscoring the importance of integrated coastal management and adaptation measures to address SWI's multifaceted impacts on Europe's coastal regions (see Sect. 6 in van de Wal et al., 2024, in this report).

3.2 Regional impact

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

3.2.1 Eastern Atlantic

The following SLR impacts are reported for the 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 the high importance of protection measures in this basin.

- *Coastal erosion*. Projections under different emission scenarios indicate a shoreline retreat along the Basque coast of 10–66 m by the year 2100.

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

3.2.2 North Sea

The following SLR impacts are reported for the North Sea:

- *Flooding*. The North Sea coastline is significantly affected by coastal flooding due to SLR. Coastal cities, such as 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

The following SLR impacts are reported for the 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, north-west 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 21st century.

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

3.2.4 Baltic Sea

The following SLR impact is reported for the 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. Interventions and measures can be classified in four main adaptation strategies (see Sect. 2.1.1 in Galluccio et al., 2024, in this report):

- *Accommodation* refers to measures that enable coping with the consequences of sea level rise, such as flood-proofing buildings and increasing resilience of critical infrastructure, which 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 NBSs.

- *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 programmes. Relocation strategies involve complex trade-offs between effective risk reduction and societal and economic costs.

The reader is refer to Table 1 of Galluccio et al. (2024, in this report) listing the relevant adaptation measures, in response to SLR impacts, for different basins.

4.2 Approaches for decision-making

Coastal adaptation decision-making is complex, demanding thoughtful approaches to address uncertainties about future climate and societal developments. Coastal adaptation decisions involve the selection of various options planned for implementation at different moments in the future. Policy analysis methods exist that systematically examine the sequential ordering and timing of adaptation decisions in the future, including their potential triggers, alternatives, and long-term implications. A combination of participatory and analytical methods is crucial in this process, fostering stakeholder cooperation and identifying suitable options.

Coastal adaptation decision processes usually have to strike a balance between multiple objectives, available measures, and uncertainties about future conditions and policy implications. Methods such as multi-criteria decision analysis (MCA) help manage this complex balance by organizing decisions and highlighting preferences and priorities. Potential low-regret measures can be identified that offer immediate benefits with minimal costs, including awareness campaigns and preservation of landscapes with high societal support.

Inherent SLR uncertainties require the 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 current decisions with long-term consequences, particularly in the domains of critical infrastructure and urban planning. Iterative revision of decisions and monitoring progress enable timely adjustments as well as 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 Sect. 2.2 in Galluccio et al., 2024, in this report).

4.3 Assessment of regional adaptation

In Europe, adaptation to SLR varies across different sea basins and often includes a combination of accommodate, protect, advance, and/or retreat strategies. All basins display examples of the integration of traditional (hard) engineering solutions with ecosystem-based (soft) measures, community involvement in decision-making processes, and continuous monitoring and flexible management strategies through coastal and marine planning instruments (see Table 1 in Galluccio et al., 2024, and Sect. 2.3 in Galluccio et al., 2024, in this report).

4.3.1 Eastern Atlantic

Across the Atlantic Ocean basin, countries are implementing a variety of adaptation measures, including NBSs 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 also being considered at various locations.

4.3.2 North Sea

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 upgrades, sand nourishment, and managed retreat. Comprehensive strategies combine flood protection with the maintenance of a healthy freshwater system, while also enhancing societal and ecological values.

4.3.3 Mediterranean Sea

Countries in the Mediterranean Sea basin have advanced the mainstreaming of SLR information into national adaptation planning, e.g. in Spain and Italy. Soft protection measures, including sand nourishment, 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). Furthermore, 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 being 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 NBSs, are being implemented and are contributing to marine environment conservation and the enhancement of living marine resources.

5 Governance context and challenges

The governance of coastal adaptation policies includes institutional organization, stakeholder engagement, and the practice of decision-making, including the management of scientific knowledge, conflicting objectives and interests, and the incorporation of a diversity of perspectives and views. Assessment of coastal adaptation governance does require the incorporation of the socioeconomic and political contexts. In the SLRE1, this is carried out by reviewing relevant European coastal adaptation policy frameworks in place at regional and national levels and their contexts within each of the selected sea basins (see Sect. 5.2 in Bisaro et al., 2024, in this report).

5.1 Eastern Atlantic

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). However, the basin also faces militarization and competition over natural resources and trade routes. This necessitates strategic engagement and cooperation from the European Union (EU) and its Member States. 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 the associated risks. Some countries incorporate SLR into their maritime spatial planning, whereas others lack specific measures.

5.2 North Sea

The North Sea basin hosts significant economic sectors like shipping, oil, and gas and 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.

Countries in the North Sea basin have reported SLR as a chronic hazard and have 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

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

The European Arctic faces economic opportunities in traditional sectors, like oil and gas and fishing, and in emerging sectors, including data centres and raw-material extraction. Governance challenges include balancing economic development with environmental conservation and 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

The Mediterranean and Black Sea regions host crucial traditional economic sectors, like tourism, fisheries, and mariculture, and emerging sectors, like offshore energy. In addition, complex challenges are present, 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.

Governance challenges include sustainable tourism management, ensuring seafood security, and transitioning towards renewable energy sources to mitigate environmental degradation. The Mediterranean 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

The Baltic Sea basin features significant traditional sectors, such as shipping and fishing, and emerging sectors, like offshore wind energy. However, the region also faces security challenges exacerbated by the Russia–Ukraine conflict and aggravated by its energy dependence. Efforts focus on diversifying energy sources, enhancing maritime security, and promoting sustainable development through innovation and cooperation.

Other governance challenges involve addressing pollution concerns, sustainable resource management, and promoting green technologies to reduce environmental impact. Countries in the Baltic Sea basin 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.

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