Università di Genova

DICCA DIPARTIMENTO DI INGEGNERIA CIVILE, CHIMICA E AMBIENTALE

Master Degree Course

ENGINEERING FOR NATURAL RISK MANAGEMENT

Evaluate the effect of the phenomenon of the sea level rise on the environmental and coastal area

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Accademic year ham 2023-2024

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Abstract

These two simultaneous processes comprise the melting of ice due to global warming and thethermal expansion of seawater. The sea level of earth has undergone changes. It has gone up anddown according to glacial and interglacial periods, while enormous changes took place during the periods of tens of thousands of years. Where there were glacial periods, the sea levels were lower because of immense ice sheets holding enormous volumes of water, while during interglacial periods, the melting of ice brought about higher sea levels. During the Holocene epoch to date, the sea level reached stability about 7,000 years ago, but human activities since the late 19th century have disrupted this stability. Combustion of fossil fuel, deforestation, and industrialization have altogether contributed much to an increase in the atmospheric concentration of greenhouses gases [CO_2, CH_4, N_2O], which further enhanced the greenhouse effect, hence further accelerating global temperatures. For such reason, sea levels rose in the 20th century by 15-20 cm, with a recent acceleration about 3.3 mm/year.

Future projections under high-emission scenarios indicate that global sea levels are likely to rise between 0.5 and 1.2 meters by 2100, while over longer timescales, the range could be much larger owing to the melting of polar ice sheets. In fact, such a rise would pose severe hazards in coastal ecosystems, human settlements, and infrastructure through increased flooding, erosion, andsaltwater intrusion, further threatening biodiversity and displacing communities. Regional variability in Sea Level Rise (SLR), due to issues such as land subsidence, ocean currents, and ice sheet dynamics, among others, further complicates impact assessments and development of adaptation strategies. In this thesis, the rise of sea level and its challenges under different emission scenarios using climate models and the coastal vulnerability index are addressed. Climate models simulate various greenhouse gas emission pathways into the future to project global and regional future sea levels. The vulnerability of a particular coastline is given by the conditions: the geomorphology, the slope ofthe coast, the exposure to waves, and the existence of natural or artificial barriers. The present thesis aims to put together all the above-mentioned tools into one comprehensive framework that could provide insight into the spatial and temporal dimensions of the rise in sea level. It basically provides insight into identifying high-risk

areas and informs targeted adaptation strategies to reduce socio-economic impacts and environmental degradation due to SLR.

1. Introduction

SLR is probably one of the most severe impacts of climate change to coastal communities and ecosystems throughout the world. The continued increase in global temperatures arising from rising levels of greenhouse gases triggers seawater thermal expansion and increases the rate of melting of ice sheets and glaciers, adding more to SLR. It has been obvious that this phenomenon threatens to inundate low-lying coastal areas and further worsens the problems of flooding, and saltwater intrusion that collectively cause massive only loss of land. Indeed, recent estimates suggest that more than 1,000 square kilometers of land are lost every year because of rising seas, causing severe damage to habitats, agriculture, and human settlements. The relation of climate change to SLR is based on the so-called enhanced greenhouse effect wherein heattrapped in Earth's atmosphere by greenhouse gases such as CO_2 and CH_4 raises Earth's temperatures thus causing polar ice to melt and seawater to expand. These changes are now occurring at a rate never experienced before in the last few millennia of geological history. Because the rate of change is accelerating, now and in the future impacts are going to be increasingly difficult to predict, with the consequence that it will also become more and more difficult to formulate effective adaptation strategies. In this respect, the risk due to SLR will continue to increase, fed by the subtle interplay now between causes and effects [1, 2].

Climate modeling, vulnerability assessments, and geographic analyses all are complementary in understanding SLR as a problem from a global perspective. Climate models can model projected sea level changes into the future under different greenhouse gas emission scenarios, while a vulnerability analyzes the area's susceptibility to these changes in sea level. The present geographic analysis is, therefore, very well evidenced with the help of those tools, such as Geographic Information Systems (GIS) and satellite imagery, in order to paint a very detailed picture not only about spatial impacts of SLR but also respecting land lost. The data of current trends draws valuable insights into the magnitude of SLR and implicationsin coastal regions. This inherently will be a very fundamental approach toward the informing of policies and strategies aimed at mitigating the effects of SLR and building resilience withinvulnerable communities. Knowledge acquired through climate modeling, vulnerability assessment, and geographic analysis would assist in the formulation of targeted measures of adaptation with prioritized resource allocations for locations with the highest risk. The more time it takes, the higher the risk of SLR. Proactive management will be required by strategies informed by methods of protection for both the coastal environments and societies [3-5].

1.1 Natural Hazards

Natural hazard, in general, is considered various types of geophysical, atmospheric, and hydrological events generated by the complex and interactive Earth systems that act across a wide range of spatial and temporal scales. The examples are flood, drought, heat waves, cyclones, volcanic eruptions, earthquakes, landslides, avalanches, and rockfalls-all have disastrous economic, social, and environmental impacts. These events mentioned above have increased, by a wide margin, in both frequency and intensity within the last decade. In those ten years, from 2010 to 2019, the average annual economic loss exceeded $187 billion, and a total economic loss reached $2.98 trillion-an increase in value of $1.19 trillion more compared to losses recorded during the past decade between 2000 and 2009. These hazards displaced, on average, 24 million people annually. Natural disasters in the end of 2020 contributed to an economic toll of approximately 268 billion dollars. This is clearly indicated through the increase in extremes that include prolonged droughts, intense heatwaves, and flooding in the coastlands as global climatic change increases the frequency and intensity of natural hazards. Interest in the mitigation of natural hazards globally also becomes a growing area of concern. Understanding natural hazards and coming up with workable ways of risk management have been a topic of considerable research. It would aim at defining the mechanism constituting the natural hazard, undertaking the risk assessments, improving the prediction and warning systems and preparing the plans for emergency response before, at the time of and following such hazards. Ishta Howell, The foundation of the very process of mitigation of risk is deep understanding of the natural hazards through proper attribution of causes [6, 7].

In turn, consideration of the non-stationarity multivariate process will allow better estimation of the risk-for example, owing to compound coastal flooding because of SLR impelled by climate change. The risk assessment, therefore, forms an integral part involving the probable consequences of those hazards. The landslide susceptibility assessment will be able to give an idea about the amount of risk that may be present and forms a framework within which mitigation measures are implemented. Forecasting, in this context, is the prediction of the physical characteristics of future hazard events in terms of well-specified aspects including magnitude, duration, and spatial extent. In volcanoes, forecasting contains unrest monitoring and eruption forecasting. Storm surge forecasting can thereby visualize the future trends of water level and surge height. It could be in the early warning systems, those that release information vital for reducing risks from an event before a hazard occurs. One probable example is the earthquake early warning system, which might provide seconds to minutes warning before seismic activity arrives at a place of vulnerable exposure. Assessment of the magnitude of the disasters through appropriate emergency responses during hazard events and thereafter, therefore, promotes effective rescue operations, which also include evacuation. Sometimes with the help of change detection technologies, damage assessment after an event allows one to map and identify areas affected by the disaster [8-10].

1.2 Risk Definition

Risk is influenced by the decisions we make. From climate change to poor urban planning, it is critical to understand and address risk drivers to curb disaster risk. Risk, in the context of SLR and climate change in general, is considered the potential consequence, damage to a coastal area, people, infrastructure, and ecosystems. It is any way in which one describes the vulnerability a place or a community is under due to the threats imposed by rising sea levels and other climate-related impacts [11]. In Fig 1.1, Natural hazard risk triangle is shown [12]. The risk can be divided into three factors, which are:

1. Hazard: hazard is the actual danger such as rising sea level per se. This is particularly owing to the melting of glaciers and ice sheets, also due to warming up and expansion of ocean water. SLR increases other dangers such as storm surges, coastal erosion, and flooding [13].
2. Exposure: exposure concerns that which is in harm's way. Quite naturally, the coasts are above average regarding exposure, with the low-lying ones even more so. This is becausemillions of people have set up homes on the coast, with much critical infrastructure in areasthat would be covered by a SLR. Hence, these places and assets have a high vulnerability to destruction [14].
3. Vulnerability: Susceptibility to be affected by the hazard and capability of recovery. On alarge scale, vulnerability relates to both physical conditions-for instance, a coastlinewithout significant defenses-and to social aspects, such as a community being prepared toadjust. Poor governance, missing infrastructure, and low economic resilience could all contribute to heightened vulnerability [15].

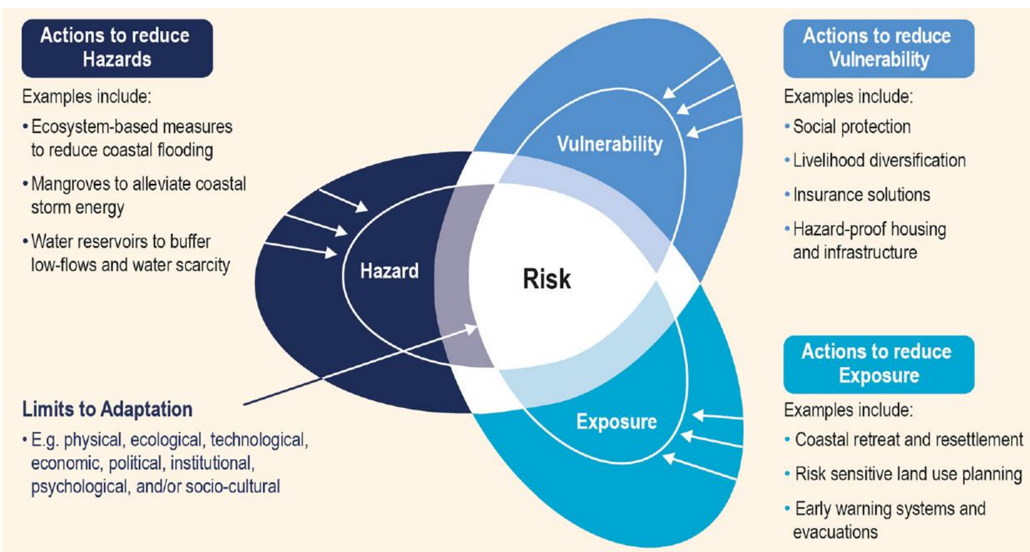

Fig 1.1: Natural hazard risk triangle

These risks together provide the extent of danger for a particular coastal area due to SLR and other climate issues. Where and how these three factors interact is a determinant of Risk. A highly exposed coastal area with weak resilience will have a much greater risk than one that had strong protective measures in place. Take for instance, a highly-populated low-lying area whose flood defenses are scant will fall into a much higher risk category [16].

1.2.1 Risks Linked to SLR

The risks of SLR can be categorized by following types:

1. Physical: Land erosion and other forms of loss, increased flooding along coasts, salt water intrusion of fresh water supplies. Some of the mechanisms could result in permanent flooding of entire regions which would necessitate the migration of human and natural habitats [17].
2. Risks of an economic nature: Rising sea levels can easily sweep away entire economies dependent on coastal infrastructures, such as tourism, fisheries, and trade. Repair costs,the replacement of infrastructures, and the cost related to the relocation of affected populations sometimes high. Climate-related hazards include rising sea levels that could wipe out wetlands, mangroves, and coral reefs-not just natural barriers to storms but also contributors to biodiversity. Loss of these means' loss of protective and ecological functions [18].
3. Social Risks: Currently, the displacement of communities is fast becoming a common feature in the case of loss of homes and livelihoods, especially in small island nations and low-lying coasts. This may, over time, lead to chaotic conditions socially, force migration, and further increase inequity, especially for vulnerable groups that may not quite possess adequate resources to adapt or migrate [19].

These risks of SLR are multivariate and interrelated. It is not only about the physical hazard presented by the actual rise of the water. Rather, it also involves coping and protecting assets and recovering from disasters under varying regional conditions. It would require several mitigating tracks, including reinforcement of coastal defenses and fostering socio-economic resilience.

1.3 Costal vulnerability

It is the predisposition of coastlines to adverse effects, brought about by various environmental hazards, which recently have turned intense due to the action of climate change: SLR, storm surges, erosion, and others. It goes without saying that understanding how to map out the costal vulnerability (Fig 1.2) has turned out presently to be a particularly important task for practical policy formulation regarding the protection of ecosystems, infrastructures, and people who dwellin these areas [12]. This involves analyzing a set of diversified physical, environmental, social, and economic parameters combined in a way to make some areas more vulnerable than others [20].

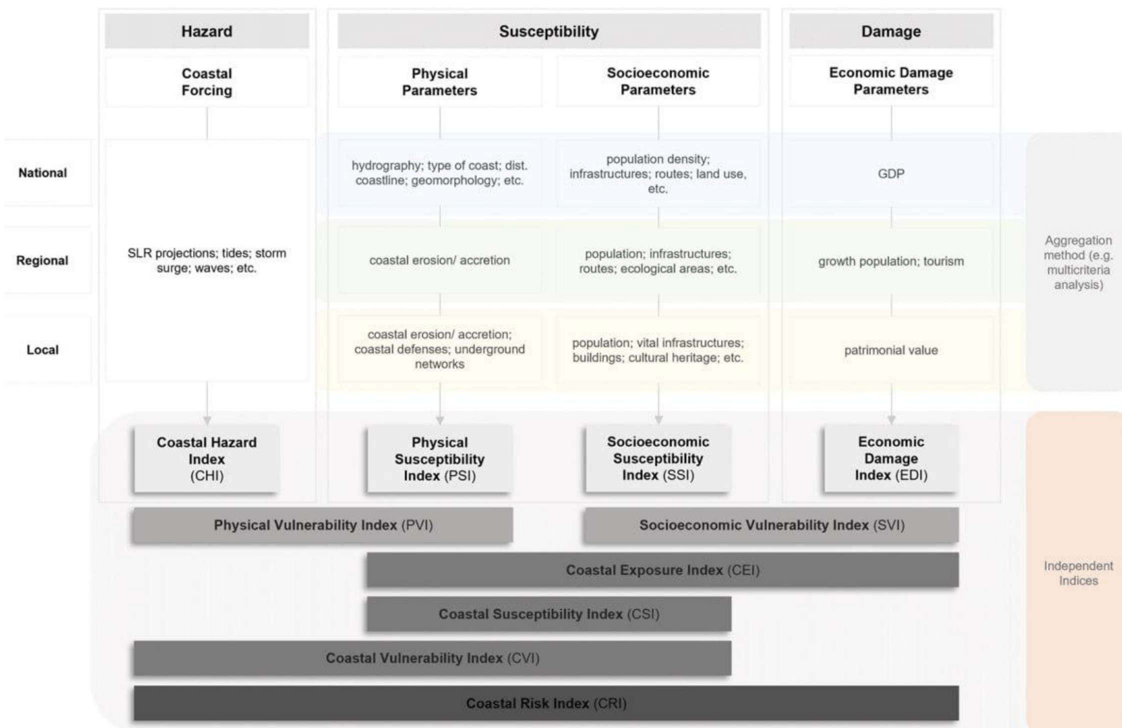

Fig 1.2: The costal the vulnerability.

1.3.1 Key Factors Affecting Coastal Vulnerability

The key factors that affect coastal vulnerability are:

1. **SLR:** SLR is due to global climate change from the thermal expansion of seawater, melting of glaciers, and ice sheets. There is a rise in sea levels

whereby areas along the coast get exposed to flooding erosion, and saltwater intrusion. Low-lying coastal areas will be highly more vulnerable because a small increase in the sea level has resultedin massive loss of lands and habitat destruction [21]. Fig. 1.3 shows the height of the SLR globally [22].

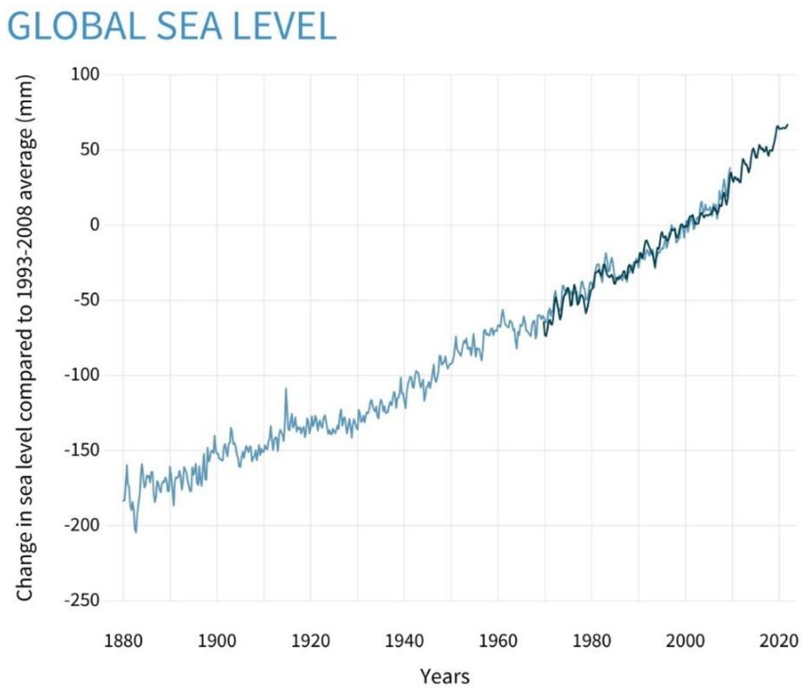

Fig 1.3: Global SLR.

2. **Storm Surges and Extreme Weather Events:** These categories of storms, hurricanes, andtyphoons are each likely to be increasing with climate change. These severe storm surges pose a much greater risk for the majority of coastal areas, especially those areas that can easily experience high tides and waves. Such events may cause infrastructure damages, displaced people, and even changes in the topography of the coast [23].
3. **Coastal Erosion:** Erosion may be explained as the breaking away of the Earth's surface layer constituting soil and rock by natural causes such as wind, waves, and water. Human activities in areas such as deforestation, construction, and sand mining amplify erosion rates as sea levels continue to rise. As a result of the loss of land in the coastal areas with time, the land deteriorates in its natural

ability or power to act as a shock absorber against storms. It reduces the area left for human habitation, agriculture, and wildlife in general [24].

4. **Shoreline Morphology and Coastal Type:** However, there is considerable variation in the vulnerability of shore types: the sandy beaches are quite vulnerable to erosion and may retreat faster due to wave action but on rocky coasts the resistance may be higher though not complete resulting in cliff falls. Generally, coastal plains, deltas, and estuaries are flat and lie low and are more vulnerable on account of proximity to sea level [25].
5. **Sediment Transport and Deposition:** In the coastal system, there is a sensitive balance between sediment supply and erosion. Human beings disrupt this natural flow of sedimentsto the coast through artificial dams and river channelization, adding to the speed of erosion and land loss. Starvation for sediments makes coasts, in most instances, particularly vulnerable to the tidal wave of the rising sea level and other extreme events of weather [26].
6. **Social-Cultural and Economic Factors:** This problem exceeds simple physical effects and embraces some very important socio-economic issues. Coasts are often the most densely populated areas in many countries, and valuable infrastructure, tourism, fisheries,and agriculture contribute significant amounts to local economies. In developing countries,communities located along the coast are often among the poorest and least capable of adapting to or recovering from coastal hazards. These communities are further disadvantaged by social inequalities, poverty, and a lack of access to technology and early warning systems [27].
7. **Ecological Vulnerability:** Wetlands, mangroves, and coral reefs all serve as a nature-made barrier to SLR and storms through dissipating wave energy. Hence, it reduces the power of storm surges. These are among the most vulnerable ecosystems to the effects of SLR, pollution, and habitat destruction. The loss of these natural barriers because of degradation increases the vulnerability in human settlement quite significantly in coastalareas [28].

1.3.2 The Coastal Vulnerability Index

Among the most common assessment tools used is the risk level for a place, using the CoastalVulnerability Index (CVI). It gives out a numerical value stipulating the degree of its vulnerability due to analysis for some key factors listed below [29-31]:

- SLR Rate: Places facing a faster SLR are generally considered to be more vulnerable.
- Shoreline Erosion/Accretion Rate: Vulnerability would be correspondingly higher where erosion rates are high, in places with substantial deposition of sediment, vulnerability could be relatively low.
- Coastal Slope: Where the slope is steeper, the impact of SLR and flooding is reduced.Thus, flat coasts would be relatively more vulnerable.
- Geomorphology: The type of coast in terms of its physical form-for instance, beaches,cliffs, and mangroves determines the resilience of an area to different kinds of coastalhazards.
- Wave Height: Higher the wave energy exposures, higher are the vulnerabilities relatedto erosion and flooding.
- Tidal Range: The range between high and low tides controls the potentials for floodingand saltwater intrusion.

The combination of these into the CVI allows the identification of hotspots of vulnerability and informs priorities for mitigation and adaptation. CVI uses the geometric average of different biophysical parameters, including geomorphology, shoreline change rate (i.e., erosion and accretion), coastal slope, regional SLR, mean significant wave height, and mean tidal range. Thus, it can be calculated by following equation [32]:

$$\text{CVI}=\frac{\sqrt{x_1 \times x_2 \times x_3 \times x_4 \times \ldots\ldots \times x_n}}{n}$$

where x represents a parameter and n refers to the total number of parameters used in the CVI assessment.

1.3.3 Limiting Coastal Vulnerability

Limitation to coastal vulnerability can be considered one of the emerging aspects of protection for natural and human systems against SLR and meteorological extreme events due to coming climate change. Very large parts of the world's population and infrastructure, as well as economic ventures, are concentrated on coasts which often face hazards unique in type. In this respect, the development and realization of the mitigation strategies will have much greater significance within the frame of long-term certainty concerning resilience and sustainability of such regions. These will involve the coastal defense structures engineered in protection against SLR, erosion, storm surges, and other hazards related to climate change. By providing a growth in protection against these increasing risks for human settlements, infrastructure, and ecosystems due to rising sea levelsand more frequent/intense weather events, these systems will play an increasingly important role.Indeed, there is great variety in the types of coast protection structure, each performing different duties and appropriate for different coastal regimes [33, 34]. These protection structures can be categorizedby:

- **Sea walls**: this furthered the rise of coastal protection structures, such as seawalls. Seawalls are solid barriers parallel to the shoreline, constructed for protection against waveaction, storm surges, and SLR. They can be made of concrete, steel, or stone and are designed to absorb and reflect the energy of waves so as to avoid flooding anderosion. In addition, sea walls can often be applied in the protection of highly urbanized coastlines boasting high infrastructural and population values. Seawalls can provide reliable wave-damage protection instantaneously, thus considerably reducing the possibility of flooding along the coastlines. In addition, this structure will safeguard the shoreline and protect very valuable infrastructure like roads, buildings, and ports [35, 36].
- **Breakwaters:** The offshore structure of the breakwater acts as a barrier for coastline protection through dissipation of wave action before reaching the shore. They can eitherbe fixed or floating and are made of materials such as rock, concrete, or somespecialized geotextile materials. They are common in

harbors or marinas for still water.However, they also protect coastlines against erosion and storm surges. Breakwaters aresaid to exude a 'protected' atmosphere, that could avoid erosion and might also preserve the infrastructure. They provide much calmer waters inshore, better suited for boating,fishing, and other tourist-related activities. On the other hand, they interfere with the natural processes along the coast, like seawalls do, sometimes creating erosion elsewhere. They tend to be costly to build and maintain, especially in most places withrough seas or generally bad weather [37, 38].

- **Levees and Dikes:** Levee and dikes refer to artificial earth or rock embankments created for the purpose of saving low coasts from flooding or inundation. They form abarrier between the sea and a part of land area to prevent an inland water area from thesea at high tide or during storm surges. These constructions are very common in countries whose greater parts of the areas lie below sea level, for example the Netherlands, who faces the threat of flooding daily. These are most extended length areas along coasts protected by levees and dikes. They are hence quite vital in protecting agricultural lands, towns, and infrastructures that are at low elevations. Theyare one of those tested ways of flood control management that would result in a minimum risk of catastrophes involving water [39].
- **Gabions:** In coastlines, different methods of erosion control are undertaken by gabions,wire mesh baskets of rocks or other materials, appropriately attached together to forma barrier in the shoreline area. This prevents wear and tear due to erosion, protects cliffs, and it stabilizes shorelines. Gabions represent an alternative option for different coast protections, quite elastic compared with other structures, adaptable to environmental conditions. Coastal defense structures are a dire need for any vulnerable shoreline in order to protect them from increasing threats due to climatic change, specifically because of rising sea levels, storms, and erosion. Each has its different advantages and challenges, and it all depends on the local environmental setting, economic consideration, and long-term goals of sustainability. More hard defenses used

intraditional times-seawalls, levees, and breakwaters-offer protection directly, while in recent times, there is more emphasis placed on more flexible ecosystem-based approaches which, over time, build greater coastal resilience. This would involve hardand soft engineering solutions, besides continuous monitoring and adaptive management for the effective mitigation of vulnerability to come into play [40, 41].

1.4 SLR: Definition and Cause

SLR is that gradual increase in the general level of the world's oceans and is generally ascribed to climate change. The process, which has been measured for decades and centuries, is one of continuously changing coastlines and reconfiguring ecosystems. The rising sea levels create territories highly susceptible to flooding, erosion, and habitat losses. Monitoring the variation in sea level can help in clearly understanding the effects of climate change in the long term on human populations and natural environments [42]. Fig. 1.4 illustrates the main reasons of the SLR [43].

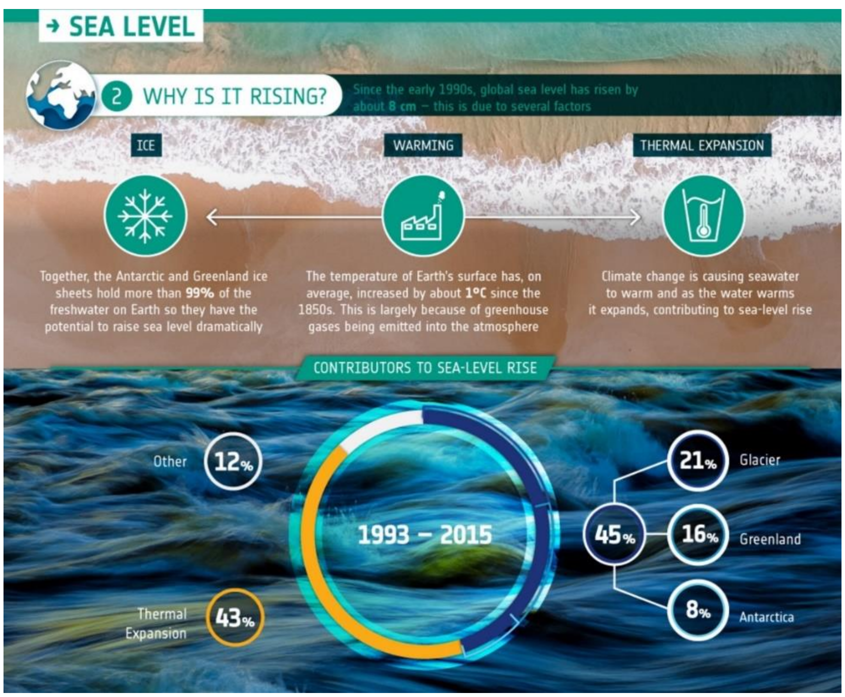

Fig 1.4: The main causes of sea level rising.

1.4.1 Causes of SLR

SLR is driven by multiple factors that are primarily related to climate change [44]. In Fig.1.4 the classification of SLR aspects is demonstrated. The following are the main causes of SLR:

- Heat and Thermal Expansion of Water: This module explores how, with temperatures rising all over the world, a result of climate change, oceans absorb a great deal of this added heat. As water heats up, it expands. This is known as thermal expansion, wherein the volume of the ocean increases. For this reason, thermal expansion is responsible for about half of SLR in the past century. This is a gradual effect, but over time, eventhe slightest rise in temperature leads to great differences in ocean levels [21].
- Melting of Ice Sheets: The other major causes of SLR are melting glaciers. Glaciers are huge masses of ice and are confined in mountainous regions and polar areas.Because of the increasing temperature of the world, the glaciers start to melt at an alarming rate and leak fresh water into the ocean. In addition to the increased sea levels, other resultsof the lost ice include less fresh water coming from those glaciers for certain areas, and that also reflects on the water supply feeding millions of people. The Greenland and Antarctic ice sheets are about 99% of the Earth's 2 largest masses of ice. Their melting isconsidered a very real potential threat to global sea levels. While the Greenland Ice Sheet is melting at an accelerating rate with rising temperatures, adding freshwater to the ocean,the Antarctic Ice Sheet is losing its ice from surface melting, with much of its glaciers being destabilized from underneath. Combined, these two sheets hold enough water to raise sea levels by many meters if completely melted. Although the melting of sea ice-icethat floats in the ocean-does not directly raise sea levels, the loss of sea ice does indirectlyimpact the process. Sea ice reflects sunlight, cooling the planet. When the sea ice melts, there is more darker ocean water exposed that absorbs a lot more heat, and that acceleratesocean warming and thermal expansion. In addition to the ice sheet retreats, anthropogenic

climate warming has been causing the retreat of mountain glaciers around the world. Fig. 1.5 shows SLR of Greenland melt and Antarctica melt for 2003–2008 [45]. Also, the classification of SLR aspects is illustrated in Fig. 1.6. Glacial retreat has occurred concurrently with historic storage of immense volumes of water in mountain ranges such as the Alps, Andes, and Himalayas [46]. Those lost volumes contribute directly to SLR. Mountain glacier meltwaters provide particularly keyheadwater sources for river systems supplying water to billions of people [47-49].

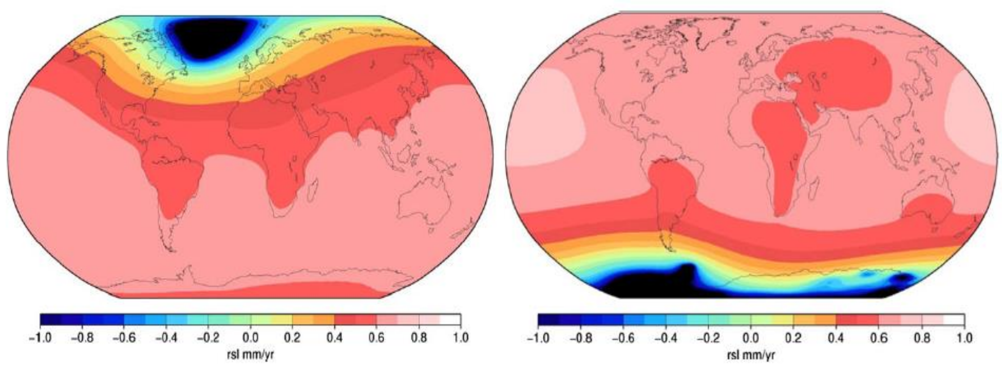

Fig 1.5: SLR of Greenland (left) and Antarctica (right) melts for 2003–2008.

- Land Subsidence: This is when the ground has slowly settled, increasing the effect of sea-level rise in some regions. It could either be natural because of the geological processes or human-made, such as extracting groundwater, drilling for oil, and developing urban areas. While the land settles, SLR is often more dramatic in such areas, increasingthe vulnerability of flooding and erosion [50].
- Groundwater Extraction and Reservoir Storage: Human activities, including the extractionof groundwater for use in agriculture, industry, and at home, further contribute to SLR. Such large-scale extraction from aquifers eventually finds its way into the ocean. Similarly, reservoirs and dams change the natural hydrologic cycle, affecting the quantity of water feeding into the seas and consequently the levels of sea rise that are experiencedlocally [51].

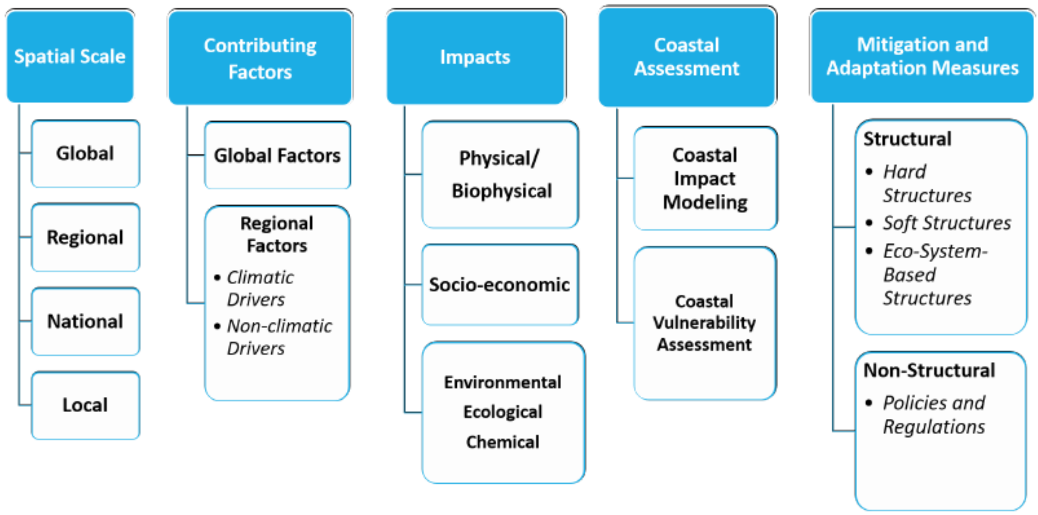

Fig 1.6: Classification of SLR aspects.

1.4.2 Historic Changes in Sea Level

Sea level has always gone through natural ups and downs since Earth's temperature and climates have fluctuated throughout historical times. The Earth went through periods of accumulation and melting during periods called respectively glacial and interglacial cycles, to which it owed so much of the change in sea level. Glacial periods have been those when huge partsof the world had been smothered by ice sheets, holding tremendous volumes of water. Consequently, sea levels were as low as 120 meters below their current levels. Conversely, duringan interglacial period, temperatures get warmer and ice sheets as well as glaciers start melting andreturn water to the oceans, consequently raising the sea levels. These cycles occurred over tens ofthousands of years and were primarily forced by natural variations in the Earth's orbit and axial tiltthat altered the amount of solar radiation the planet received-and thus global climate [21].

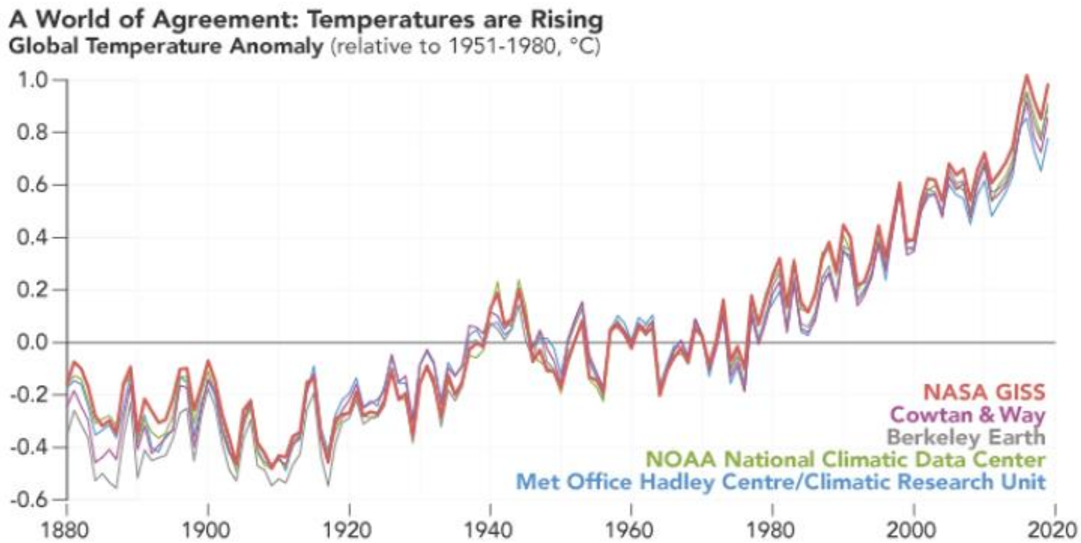

Fig 1.7: Annual global surface temperature 1850–2019. Source: NASA.

During the current interglacial-which is called the Holocene-the sea levels finally reached a stable level some 7,000 years ago. Through much of human history, sea levels have stayed about the same, and beach settlements and ecosystems have formed. These human activities caused sea levels to rise more strongly than usual since the late 19th century-an interruption of the relativelysteady state of the past few millennia. Also, in the 20th century, sea level rose some 15-20 centimeters due to both thermal expansion of seawater and melting of glaciers. In more recent times - since the late 20th century - this rise has accelerated to an average of about 3.3 mm/yr in the early 21st century. Fig. 1.7 shows annual global surface temperature 1850–2019 [52]. The line plot below shows yearly temperature anomalies from 1880 to 2019 as recorded by NASA, NOAA, the Berkeley Earth research group, the Met Office Hadley Centre (United Kingdom), and the Cowtan and Way analysis. NASA's temperature analyses incorporate surface temperature measurements from more than 20,000 weather stations, ship- and buoy-based observations of sea surface temperatures, and temperature measurements from Antarctic research stations. Credits: NASA's Earth Observatory, global-temperatures, accessed on 1 August 2021 [53]. Fig 1.8 shows changes of global sea surface height between 1992 and 2019 based on satellite altimetry data [54]. Most of this has been attributed to the melting of the polar ice sheets, thoseof Greenland and Antarctica in particular. Indeed, recent projections using state-ofthe-art modelsshow up to a meter or two of additional SLR by the end of the century under business-as- usual conditions, with grave implications for coastal communities and ecosystems. It is the swiftness and uniqueness of such a rise that underpin the necessity to understand the historic context of sea-level change and preparation for the future in that respect to climate change [55].

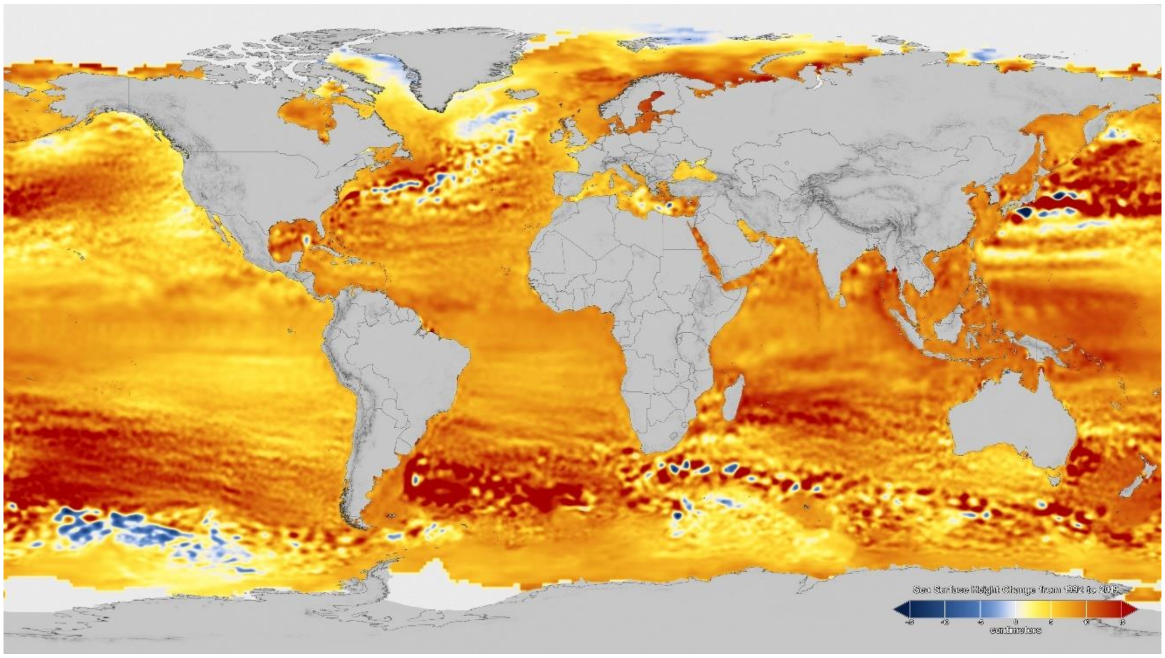

Fig 1.8: Changes in global sea surface height between 1992 and 2019 based on satellite altimetry data. Source: NASA.

1.4.3 Future Sea Levels

In other words, future SLR is mostly dependent on global climate policy and the dynamics of greenhouse gas emissions. Future projections of sea levels, as identified above, indicate that with significant mitigation, the levels will continue to increase throughout this centuryand even far beyond. For instance, by 2100, scientists estimate that global sea levels could rise byas much as 0.5 to 1.2 meters under high-emission scenarios. On truly long timescales, the most significant risk involves the Greenland and Antarctic ice sheets, the total melting of which wouldraise sea levels by many meters over the course of a few millennia. If left unmitigated, such changes would have disastrous implications for coastal cities and low-lying ecosystems [55, 56].

The combination of global and local factors at work does not make sea level uniformly rise around the world. Globally, these are major causes: thermal expansion and melting of ice. Other factors affect the rise in sea levels in some particular area, such as ocean currents, wind patterns, and land subsidence. There are areas, like the western Pacific Ocean, that is showing higher-than-average rates of SLR. For example, areas such as the eastern U.S. Coast also become prominent with relative increases due to land subsidence, besides the rise in sea levels. The gravitational pulling from melting ice sheets can push water towards some areas, causing differential SLR to take place in different parts of the world. Regional differences in exposure to SLR exist due to the fact that. Subsidence-a sinking of the land surface due, for example, to groundwater extraction-can also be added to the encroaching seas as the land falls and sea levels rise, areas experiencing tectonic uplift may face the opposite situation. This sort of knowledge about regional SLR is key to helping municipalities and communities devise effective adaptation strategies that protect the vulnerable areas [55].

Among the many varied coastal ecosystems, wetlands, mangroves, and coral reefs, all face anelevated degree of risk with rising sea levels. These systems provide a wide array of services thatinclude shoreline protection, support for biodiversity, and water filtration. Rising seas can lead tosaltwater intrusion into freshwater systems, drowned wetlands, and eroded beaches. This will disrupt habitat and threaten the species dependent on such areas. Already, warming and acidification of the ocean degrade coral reefs, while a rising sea is adding the final straw that maycollapse these natural barriers. While natural barriers keep weakening, the number of coastlines becomes increasingly vulnerable to storms and flooding [57].

1.5 Impacts of SLR

The rise in the sea level because of climate change is boundlessly altering the current conditions in the coasts, ecologies, and human groups. These changes, which are immediate as well as continuous, involve natural physiognomies, economic orders, and social relations. In Fig. 1.9 the impact of SLR on costal zones are shown [58]. A few basic aspects in which noticeable SLR has managed to elicit critical changes are being appended [59].

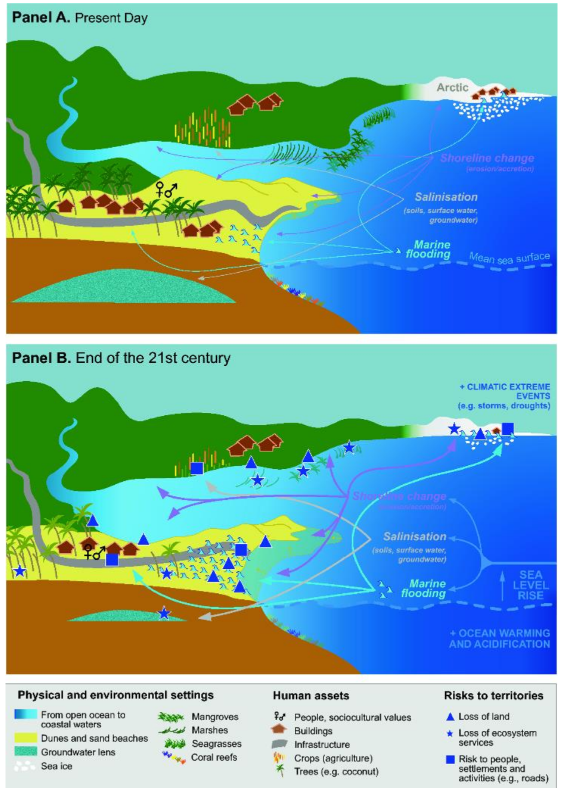

Fig 1.9: Sea level rise impacts on coastal zones.

1.5.1 Flooding of Coasts-Increased Vulnerability to Floods

One of the most direct results of rising sea levels is the increase in frequency and severity of coastal flooding. Where sea levels are higher, what used to be high ground floods far more often after smaller storms or even at high tide. More formally referred to as nuisance flooding, or "sunnyday flooding," this has become increasingly common in many cities along coastlines, such as Miami and Jakarta. These floods disrupt the regular life of individuals, cause the destruction of properties, and result in heavy economic losses. In addition, storm surges associated with extremeweather conditions such as hurricanes and typhoons become more destructive when sea levels increase. Higher seas mean that these surges push water further inland, inundating more extensiveareas. Storm events have brought cities and communities along the coast to such a vulnerable position that billions of dollars in damages have resulted, such as in recent Hurricanes Katrina and Sandy [60].

1.5.2 Coastal Erosion and Loss of Land

SLR is responsible for coastal erosion, which arises because of the higher levels of water that allow waves and storm surges to encroach on the shoreline at an accelerated rate. As theocean advances inland, beaches, cliffs, and dunes disappear. This is a situation where less land is available either for use by people or available for habitats. In some places, these erosion rates arealarming, with homes and infrastructures in their wake being lost. Most of the coasts are guardedby barrier islands, which protect against storms and higher tides through their protective nature. Incases where sea levels rise higher, these islands stand to be submerged and, in effect, diminish in their buffering on areas from flooding and erosion on the mainland. Elimination of barrier islandsexposes coastlines to more storm damage and increases vulnerability in interior areas [61, 62].

1.5.3 Impacts on Coastal Ecosystems

Wetlands, mangroves, and salt marshes provide the protection against flooding, habitats for several species of wildlife, and store carbon. They will go underwater with rising sea levels, whichwill thereby disturb the normal balance within them. When seawater intrusion happens inland to freshwater wetlands, whole ecosystems can be overwhelmed. This may reduce species' habitat andweaken the natural barrier against floods. Coral reefs are sensitive to changes in sea level and temperature. Rising seas can drown shallow reefs that depend on sunlight, while warmer water temperatures promote coral bleaching. While a higher sea level can drown shallow reefs reliant onsunlight, warmer waters promote coral bleaching. It is not only marine biodiversity that stands tosuffer if this demolition of coral reefs continues, but also the natural barrier that such ecosystemsprovide for coastlines against storms and erosion [63].

1.5.4 Social and Economic Impacts

In fact, SLR has already put many coastal communities at risk of displacement. While sometimes entire neighborhoods and towns are in danger, particularly those in very low-lying areas, such as the Pacific islands and parts of Bangladesh, are relocated to higher ground. This results in climate refugees-persons who become displaced due to changes in the natural environment due to shifts in climate. This is a problem socially and politically because it becomeshard for governments to find solutions to relocate people who have been displaced. Coastal infrastructure in the form of roads, bridges, and even ports is extremely susceptible to rising sea- level elevations. Flooding, erosion, and saltwater intrusion destroy or damages infrastructure withresultant expensive repairs and disturbances in economic activities. This makes particularly criticaland airport facilities around the world critical to global trade and transportation non-operational with persistent flooding. Some of the world's megacities-New York, Tokyo, London, and Shanghai-are located on coastlines. For such urban centers, rising sea levels pose severe risks to more than billions of dollars in real estate and economic activities that could be at stake.Companies deal with higher insurance premiums, lower property values, and a higher chance of future business disruptions owing to flooding and infrastructure damage [64, 65].

1.5.5 Saltwater Intrusion and Water Supply Problems

Salt water seeps into the aquifers as the seas rise and contaminates the sources of freshwater supplies communities depend on for drinking water and agriculture. Once the sources of the watersupply are invaded by saltwater, it can be very difficult to reverse the process, long-term in nature, and chronic shortages can develop. Agriculture in the surrounding area is equally vulnerable because salt water intrusion also reduces soil fertility and crop yield. Saline intrusion of coasts increases the level of salinity in the soil of agricultural land lying right at coasts, leading to poor productivity of crops. Rice paddies, dependent on fresh water, become highly prone to intrusion by salty water. Hence, food security in those areas, such as Southeast Asia, which gain a major part of their food grain from the rice crop, becomes endangered. Changes in productivity of this order have economic losses and migrations away from such places as consequences [66].

1.5.6 Threats to Cultural and Historical Sites

Many cultural and historic places are sited on coastlines, and the rise in seas presents a currentthreat through higher sea levels that could cause flooding and erosion to these unique landmarks. Such places include the Venice Lagoon in Italy, the Statue of Liberty in the U.S., and the Sundarbans in India and Bangladesh, which have all been placed in jeopardy of flooding and erosion by higher sea levels that could cause them to damage or even destroy the heritage sites. Generally, conservation efforts at these places involve expensive intervention from seas that are still rising. For many communities, loss of this landscape means a great deal in the way of culturalidentity and livelihoods. SLR displaces land and destroys habitat, thus affecting ways of life dependent on fishing. Relocation from customary homelands has produced a breakdown of community structures, traditions, and social cohesion [67, 68].

1.5.7 Increased Risk to Human Health

The floodings resulting from the rising sea are likely to increase waterborne diseases. Normally, the floodwaters are mixed with sewage and chemicals, adding more misery to the already deplorable situation. Poor sanitations in flooded areas make the propagation of cholera, typhoid, and other diseases active. High populations in the low-lying coasts, especially in developing countries, are the great risks to these health hazards. Apart from flooding, a higher temperature and increased relative humidity due to climate change may cause heat stress and respiratory problems in a coastal area. Increased temperature, along with stagnant air and increasedpollution, might cause respiratory diseases in the low-lying cities that usually affect children and elderly people [69, 70].

1.5.8 Increased Costs for Adaptation and Mitigation

As a result of these rising seas, governments and communities in today's world have to investin costlier means of adaptation: building seawalls, levees, floodgates, and other types of protectiveinfrastructure. Coastal cities, including New York and Rotterdam, have already pledged billions toward developing defenses, but it is not clear how long-term such measures would be practical orpossible as sea levels continue to rise. Sometimes, it is cheaper to apply managed retreat-that is, moving communities away from the most susceptible coasts-than continue to spend on flood defenses. In Fig 1.10, methodolody for developing SLR scenarios for impact, mitigation and adaptation assessments are shown [46]. Relocation efforts are usually politically and socially very contentious, as communities will fight against leaving their homes or might find adapting to new areas difficult. Such strategies would certainly have to be balanced against long-term costs for the benefit of life and property preservation. Adapting to climate change and a rise in sea levels is a balancing act between taking immediate protective measures and planning for the long term. Short-term solutions-like building flood defenses and storm barriers-are needed to protect vulnerable coasts from imminent dangers. However, those measures in the future will not be sufficient if they are not part of an overarching, long-run adaptation strategy. Adaptation strategies in the future should be flexible and resilient because of the uncertainty associated with prospective climate change. That means infrastructure is adaptable to change in conditions, modification, or upgrade. It involves investment in natural defenses, preparing for sea level rise that may exceed scientific projections at present. By considering the present needs in balance with the long-term view, coastal communities are in a position to be resilient while minimizing future risk and cost [71].

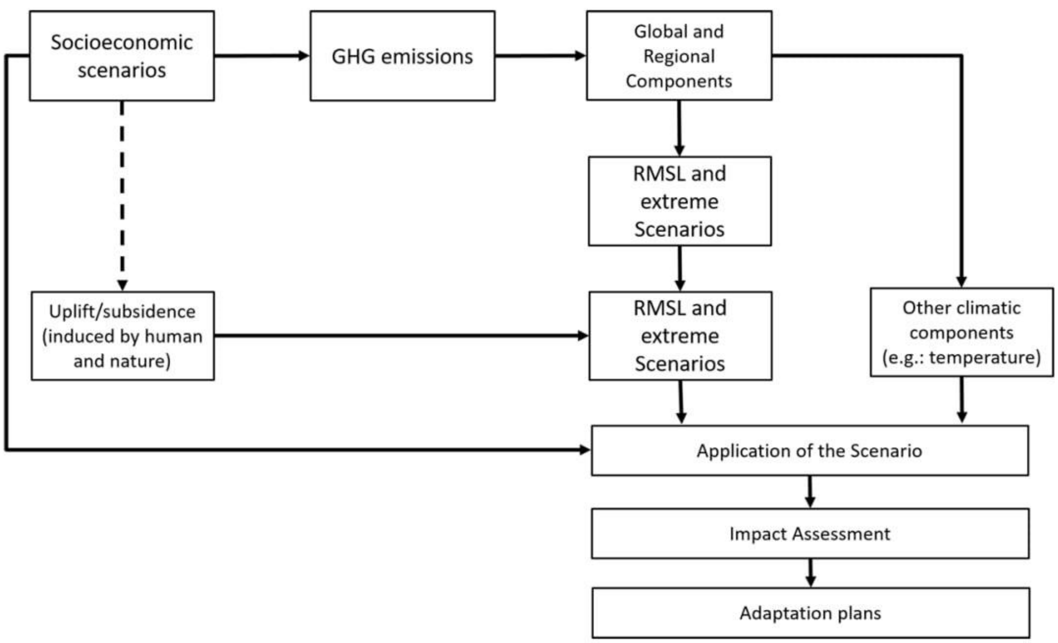

Fig 1.10: SLR scenarios for impact, mitigation and adaptation assesments.

1.5.9 Short-Term Coastal Hazards and Long-Term SLR

These impacts of climate change and SLR come both in the very real short-term hazards and as long-term gradual changes. Contrasting to acute damages from short-term coastal hazards, usually during extreme events, long-term SLR is a chronic threat that will reshape coastlines, ecosystems, and human settlements over decades. The relationship between the two dynamics in the context of coastal management and planning should be understood. Some of the short-run and long-term risks associated with SLR are discussed below [72].

1. **Short-Term Coastal Hazards** [73, 74]

- **Storm Surges:** Heavy winds from tropical storms and hurricanes are commonshort-run hazards in the coasts, whereby seawater is pushed onto land by the heavy winds. Surges could raise water levels several meters higher and flood the coastal areas to cause destruction on a large scale. With higher sea levels, the storm surges would be more dangerous since the base water level would be much higher and allow the storm to push more water ashore.
- **Coastal Flooding:** Coastal flooding is the inundation of an area that usually is dry land, happening in consequence of high tides, storm surges, heavy rainfall overtopping coastal defenses or natural barriers. Even without major storms, regularly occurring nuisance flooding-sometimes called "sunny day flooding"-has become so common in many places because of SLR. Presently, flooding at high tide is a common event in many low-lying cities-especially those with rudimentary infrastructure and drainage systems. Over time, this type of nuisance flooding can begin to contaminate the transportation systems and private property and eventually degrade local economies.
- **Erosion:** Waves, currents, and storms take their toll during this process that generally involves erosion of sand and soil from shores. Accelerated by storms,especially the hurricane season, in which land is lost in so short a time in someareas, with the rise in sea levels instances of erosion increase that cause beachesand wetlands to disappear, including other coastal environments that protect against violent weather.
- **Tsunamis:** Tsunamis: Less frequent but another of the short-term coastal hazards are tsunamis, which can be very destructive. Usually

triggered by underwater earthquakes or volcanic activities, tsunamis are large waves inundating land and causing destruction. SLR does not contribute directly to tsunamis occurring but higher sea levels allow the destructive wavesto reach farther inland thus increasing the amount of potential damage.

2. **Long-Term SLR** [75, 76]

- **Gradual Inundation of Coastal Areas:** Long-term SLR describes a process of submergence whereby large low-lying areas are gradually submerged. Over the period of decades, the sea level will rise irrecoverably and some of the area will become completely submerged for good. Small islands and communities in the coastal areas may just disappear, most especially those without the protection of weak defenses. SLR planning is problematic, mainly because the long-term nature of changes occurs very gradually but is permanent
- **Changes to Shorelines and Coastal Landscapes:** With the rise in sea level, shorelands get pulled further inland and coasts shift. Wetlands, estuaries, and salt marshes will be different and can get completely devastated as they are crucial for ecology and natural protection against flooding. The coasts face shifting of habitats with loss of biodiversity due to the loss of a home for the native species. The barrier islands, which have protected the mainland shores against storms, will become submerged or fragmented.
- **Saltwater Intrusion:** Obviously, SLR has a number of long-term effects, one intrusion into the freshwater system. As the seawater pushes inland, this could eventually seep into freshwater aquifers relied on by many in coastal communities for drinking water and agriculture. This will reduce the amount of potable water supply and agriculture and increase wetland and river salinity. This process will, over time, drastically undermine the freshwater resources of many coastlines and pose a major challenge to food security and human health.

1.6 Background about Climate Change and Its Link to Rising Seas

Logically, the mechanism of rising sea levels would involve climate change wherein global warming itself initiates processes that displace and dilate water on Earth's surface. A number of the most thought-provoking elements considered to cause global warming include increasing concentrations of CO2, CH4, and N2O in the atmosphere. Fig. 1.11 shows the states of these three gases in 2021 [77]. These gases trap heat in the Earth's atmosphere, serving to intensify the greenhouse effect and drive-up global temperatures. This, in turn, warms the pole ice sheets and glaciers directly, causing acceleration in their melting. Meanwhile, the rising temperature of the ocean is thermally expanding the water, adding to sea- level rise [78, 79].

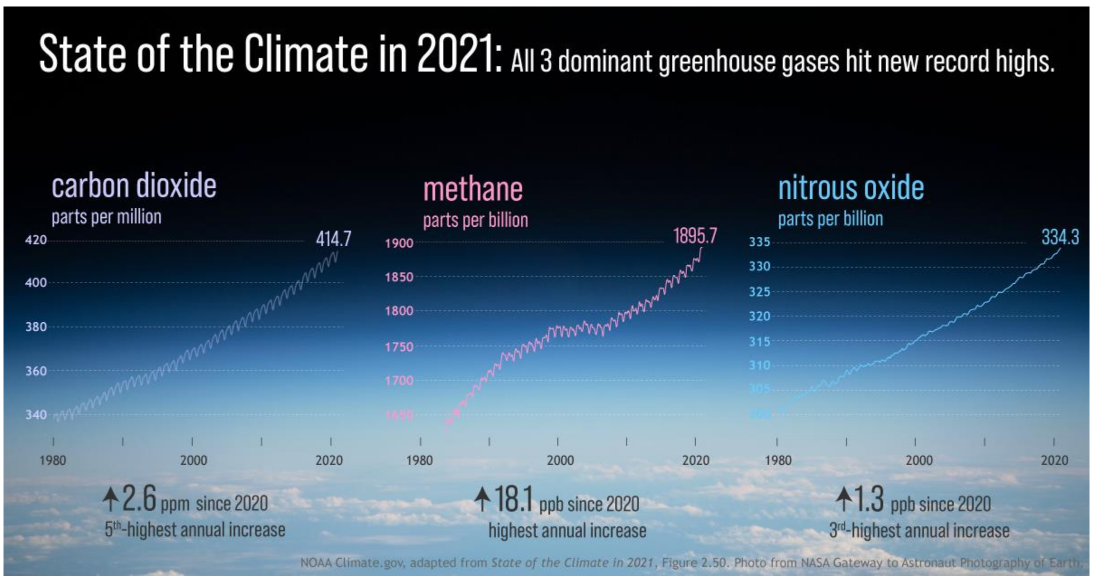

Fig 1.11: State of CO2, CH4 and N2O.

General global warming best manifests climate change through changes in the polar regions, where Arctic and Antarctic ices are showing an unprecedented rate of meltdown. Indeed, huge extents of ice lost annually in Greenland and Antarctica contribute much to the rise in sea levels of the world's oceans. Other contributing factors include mountain glaciers melting-those which, in themselves, are very big sources of fresh water, like the Himalayas and the Andes. This in turn,when the ice melts and finally drains into the ocean, adds volume to the seawater and helps raise its level further. This thus is an effect not confined to polar locations but which has its consequences worldwide for coastlines everywhere. This, in turn, presents a greater risk of coastsin relation to the rise of the seas because of the linkage of climate change. This in return increasesthe rate of flood hazards of the coast and erosion, salt water intrusion, which in turn endangers human settlement, infrastructure, and ecosystems. Places most at risk from these catastrophes include lands which may be below 1 meter of sea level, hosting many small island nations and coastal cities. This implies that an understanding of the drivers of SLR and its future trajectory identifies a fundamental input to the elaboration of adaptation strategies that reduce the socio- economic and environmental impacts of this global challenge [80, 81].

1.6.1 Drivers of Climate Change Overview

While anthropogenic activities enhance atmospheric concentrations of GHGs, it is from thesethat the drivers for climate change generally come. It is mainly in the combustion of fossil fuel- such as coal, oil, and natural gas-for energy, transportation, and industrial processes that the mostcommon GHGs especially emerge from. Large volumes of CO2, named as the most common greenhouse gas and among the major reasons behind global warming, are given off from such activities. While industrialization and energy use continued to rise well into the past century, so too did levels of CO2. Acting like a blanket, this additional CO2 and other greenhouse gases further enhance the greenhouse effect allowing more heat to remain trapped in Earth's atmosphere [79].

On the other hand, methane is another potent GHG released in large amount owing to agricultural activities, livestock, landfills, and extraction of fossil fuels. Methane is said to stay inthe atmosphere for a much shorter period compared to CO2. However, methane's potential to trapheat is much stronger. Nitrous oxide is also released from major sources such as agricultural fertilizers, industrial activities, and combustion of fossil fuels, further increasing global warming.These gases put together act to disrupt the Earth's natural energy balance, a process which, over time, changes temperature, precipitation patterns, and sea levels. Land-use change-mostly due to deforestation-reduces the ability of the planet to absorb CO2 [82].

Forests have become an indispensable depository for the absorption of carbon, while CO2 absorbed from the atmosphere is in large quantities. Heavy deforestation reduces its ability to absorb it and releases the stored carbon at the same time during the felling and burning of trees, considering that the largest part lies in the tropical regions of the Amazon rainforest. Other humanactivities, like urbanization, industrial development, and the change in the practice of agriculture,further alter the natural cycling of carbon that has resulted in an increasingly intense greenhouse effect and rapid rates of global climate change [83].

1.7 Summary of Methodology and Approach

The methodology integrates climate modeling, CVI assessments, and geographic analysis using GIS and satellite imagery to examine the effects of SLR on coastal, and a discussion about them is reviewed in the following. Also, Fig. 1.12 presents the CVI model of world wide [84].

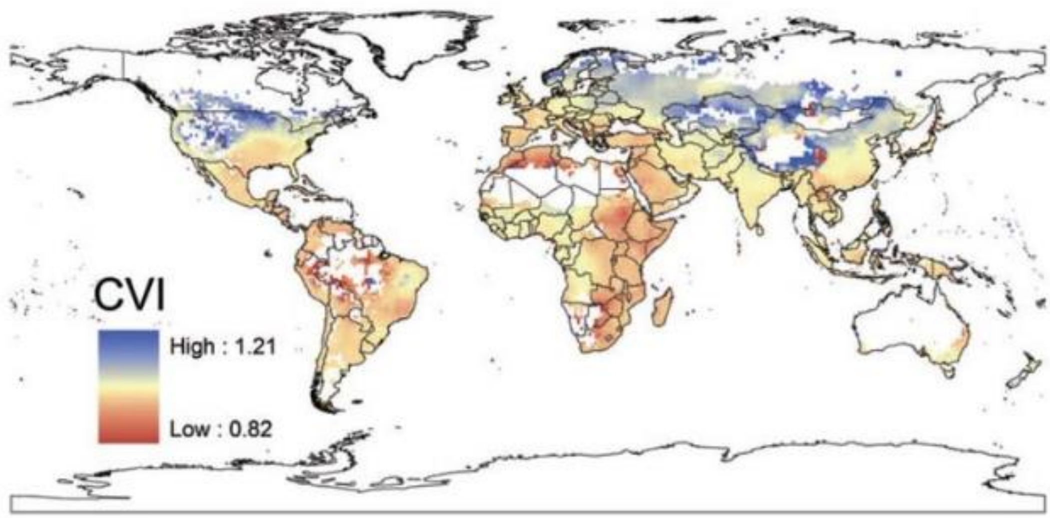

Fig 1.12: The model of CVI.

1.7.1 How Data Will Be Collected: Climate Models and CVI

In this respect, the present study will rely on climate models simulating the complex interactions between the atmosphere, oceans, and ice sheets that allow one to make reasonable projections about future SLR. Climate models are singled out as useful in the determination of how different greenhouse gas-emissions scenarios will affect the rise in global temperatures-and accordingly, sea level-in the future. These models synthesize a set of factors related to temperature increase, ice melt rates, and the thermal expansion of seawater in their projections of sea level change. Different ways of pathways of emissions will allow researchers toestimate the wide range of SLR possible outcomes and timescales for both low- and high-emission scenarios. This would further allow the definition of the magnitude of risks presented tocoastal areas under different global warming scenarios [85].

Again, the CVI, in concert with climate models, will be utilized to provide a quantitative assessment regarding the comparative vulnerability of certain coastlines. The CVI is an index of multiple variables that define the susceptibility of a coastline to SLR. Examples include but are not limited to: geomorphology, coastal slope, wave exposure, tidal ranges, and the presenceof natural or man-made defenses such as dunes or seawalls. With the resulting ranking of the vulnerability score on these aspects, the CVI will indicate which of those factors has a high rate ofexperiencing severe impacts resulting from SLR. Those high-risk areas pinpointed by the CVI will then be priorities for further analysis and adaptation planning, putting resources into theregion's most needy areas [86].

The combined application of climate models and the CVI affords a framework that completesboth the magnitude and the geographical distribution of risks due to rising seas. Climate models predict general rise in sea-level, while the CVI provides a more localized understanding about howdifferent coasts will react based on their physical characteristics. Along with these tools, it will beable to perform a detailed multiscale analysis that informs the formulation of tailored adaptation strategies for vulnerable communities and ecosystems [87].

2. Understanding the Concept of Risk in the Context of Climate Change

2.1 Notions of Risk Along Coastlines

Coasts are on the frontline of the impacts of climate change in that SLR, intensification of storms, and acceleration of erosion are considered serious threats. "Risk" concerning coasts is a wide notion that consists of exposure to hazards, vulnerability of ecosystems and communities, and adaptive capacity in areas. Risk, in the framework of coastal risk, will involve not just probabilities of hazard events, but also possible catastrophic consequences across spheres of social, economic, and ecological importance. Quantification of risk commonly involves a probability of a hazardous event, such as a flood or storm surge, along with the size of potential damages. The possible serious threats that might be posed to the long-term viability of coastal cities are due to global warming-induced SLR and polar ice caps melting. Permanent flooding results in the loss of land to the lowest-lying lands, with dislocations of communities. In addition, higher seas lead to increased storm surges and higher frequency and magnitude of coastal flooding. More shorelines get washed away as they erode, thus threatening homes, infrastructure, and natural habitats [88, 89].

The resultant hazards are more heightened in areas of highly concentrated populations, lack of coastal defenses, or those places that may be fragile in terms of ecosystems. Other economic costs of these hazards include those dealing with tourism, fisheries, agriculture, and infrastructure. These impacts of coastal risks run from immediate physical damages to social, economic, and cultural dimensions. Communities lining coastlines can suffer livelihood disruptions, noticeably among people dependent upon industries like tourism, fishing, or agriculture, while further heightening the risks with damaged infrastructure, loss of property, and population displacement create serious socio-economic problems. It becomes all the more critical in areas where adaptation to climate change is either not proposed or grossly underfunded, hence testing how well-prepared one is for timely interventions as part of proactive risk management strategies. The coasts that are vulnerable might go through irreversible changes which have long-lasting implications in the absence of timely intervention [90].

2.2 Social, Economic, and Environmental Vulnerability

Here, vulnerability is defined as the condition or state in which communities, economies, and ecosystems are made susceptible to sustaining harm from climate variability and associated hazards. Social vulnerability considers the capacity of the population to resist all the different impacts of SLR, among other climate hazards, in a coastal setting. This will reflect the degree to which heterogeneous elements of resource, social network access, and coping, responding, and recovering capability from hazardous events create differences among the populations of individuals and social groups. Communities with little financial input, or with poor infrastructure or social safety nets, are those that are most likely to become more vulnerable in case of sea flooding rather than turning it around and bounding it back. These include the poor, the elderly, and ethnic minorities who are somewhat helpless in coping and adapting with climatic risks. Others are economic susceptibility, particularly with natural resource-dependent economies [19]. A few of such sectors to the impacts of climate change include fisheries, tourism, and agriculture. Flooding along coastlines, intrusion of salt water, erosion, disruption to industries leads to economic losses with unemployment. For example, tourist-dependent areas see beaches get eroded or damage to coast facilities. Such instances, tourists will avoid them and revenues are lost. Moreover, the destruction of ports, transport systems, and industrial estates weakens economic opportunities much more where trade and commerce are prevented [91].

In return, the potential for environmental vulnerability may give the ecological perspective in terms of the extent of absorption and adaptation by the coastal ecosystems where they are hit by the impacts of climate change. Other salt-tolerant ecosystems include mangroves, wetlands, coral reefs, and dunes that offer a number of essential services such as protection against storms and flood control, habitat to biodiversity. These, too, however, are being rendered increasingly vulnerable systems in the rise of seas, warming waters, and human activities. For example, mangroves-natural barriers against storm surges-are under threat from both SLR and coastal development. Degradation of such ecosystems reduces low levels of natural resilience that might have been along coastlines and increases exposure of the human population and infrastructure to climate hazards [12].

2.3 Coastal Vulnerability Assessment

Assessment of coastal vulnerability captures the degree of susceptibility of the SLR coasts, erosion, flooding, storm surges, and saltwater intrusion. So, it considers a wide set of problems initially taken from physical ones-like elevation and shoreline stability-up to social, economic, and environmental ones. In fact, all give the general picture of how various areas could be possibly affected by climate change. While this in itself is a very important objective, the major intention of such assessments tends to make sure that those areas are pointed out which are peculiarly vulnerable, in order to assist in the formulation of plans regarding mitigation and adaptation. A review in this light will hence allow for prioritization of areas that need concerted attention and resources, in order to safeguard vulnerable communities and ecosystems from the ever-increasing hazard posed by climate change [92].

Coastal vulnerability deals with the susceptibility of a coast to possible harmful impacts brought about by SLR and other risks due to climate change. Whatever concerns its natural features, such as geomorphology, elevation, and the presence of natural barriers like dunes or wetlands, is taken into consideration in the study of coastal vulnerability. In general, a low-lying part of coastlines, normally fronting steep slopes and giving very little protection from nature, is always highly susceptible to erosion, flooding, and other hazards. A location like this does not have the physical capacity to absorb any rise in sea level without huge damages either to ecology, infrastructure, or human population. Adding to physical characteristics, human activities were observed to contribute a lot to coastal vulnerability. Activities that destroy such natural barriers, like sand mining or building, further degrade the coast's resilience against environmental stressors. It is also highly exposed because of being highly populated and much endowed with infrastructure, massive losses in economic value through damages to homes, and roads and public services that result in the long-term displacement of the people. Other driving factors among others are economic dependence on vulnerable coastal resources, such as fisheries and tourism, whose environmental change would affect [93, 94].

It therefore requires, in integrative form, an account of the natural and human-induced factor of vulnerability for a complete assessment of vulnerability within the coastal zone. The areas that represent highest risk on account of their vulnerability may be identified with the help of tools such as CVI, with the researchers and policy makers developing focused strategies for adaptation or mitigation. This is not only in the physical aspects, concerning building sea walls and the restorations of natural barriers but also socio-economic factors of increased vulnerability, such as poverty and lack of planning in infrastructural systems. Holistic Coastal Vulnerability Assessments consider human and environmental factors in the development for solutions to protect coastal communities through various SLR impacts. A variety of vulnerability assessments has been employed to understand and quantify the various ways in which different coastal regions are at risk from these environmental changes. These different types of assessments can be explained in the following [95].

2.3.1 Communication Vulnerabilities

Communication vulnerabilities refer to the challenges of communicating risk and impacts from SLR and other hazards to the respective communities. The simple principle of communication would be that residents, along with local governments and stakeholders, are well-informed about the potential risks they face and the steps they can take in order to reduce their vulnerability. It is, in fact, usually geographical isolation, combined with language barriers and socio-economic disparities, that continues to maintain communication gaps at coastal locations. This might be an obstacle to sharing important information pertaining to climate risks in many cases. The most vulnerable communities often do not have reliable sources of information on weather warnings, disaster warnings, and educational materials related to climate change and SLR. This is especially problematic in places with poor infrastructure or thin internet connectivity, where radio or print-based forms of outreach may not be able to reach all residents. Moreover, cultural differences and different levels of education add to barriers to comprehension of complicated climate science and adaptation strategies, increasing vulnerabilities within communications [96].

It would thus be important that communication vulnerabilities are dealt with through the development and implementation of appropriate, inclusive, and accessible communication strategies to cater to various needs within the diverse coastal population. Communication will involve various channels, such as community meetings, social media, and local radio stations, to guarantee access to information by all community members. This would encompass the development of messages relevant for different cultural contexts and in various languages, using visual aids to explain information that is a bit complex. The last important thing is that reduction of vulnerabilities in communication is one of the necessary steps toward the empowerment of these coastal communities for proactive adaptation measures against the challenge posed by SLR [20].

2.3.2 Cultural Vulnerability

Cultural vulnerability addresses the way in which, through events like SLR, climate change threatens to destroy the cultural heritage, traditions, and identity of communities along coastlines. Often, unique cultural practices, historical sites, and a traditional way of life may be found within coastal regions-things to which the community or people are attached and could, therefore, be jeopardized with rising sea levels and the changing coastal ecosystems. For example, the indigenous communities relying on coastal resources for livelihood, food, and herbal medicines may find livelihoods disrupted with an altered environment. In fact, many cultural heritage sites exist along coastlines, threatened by submersion or damage from coastal erosion and flooding. These sites often hold historical and spiritual significance and, as such, cannot be replaced. The loss of these sites thus brings with it a massive sense of identity loss within a community. Moreover, traditional knowledge systems passed from generation to generation may no longer be relevant in changing environmental circumstances and thus leave communities bereft of the cultural frameworks they have managed natural resources with for centuries [97].

This therefore calls for the integration of cultural preservation into climate adaptation strategies as a way of mitigating cultural vulnerability. This can be done through relocation of the cultural heritage site, conservation of oral histories, and facilitation of traditional practices for sustainability at new sites. Simultaneously, adaptation policies should be elaborated with the participation of local communities in order to make sure that adaptation measures respect and preserve cultural values. As policymakers can address cultural vulnerability, they can help safeguard the life of coastal communities from physical harm, as well as their cultural identity and heritage with regard to climate change [98].

2.3.3 Social Vulnerability

Social vulnerability is ascribed to the predisposition of individuals and communities to the adverse consequences of climate change, which is underpinned by social factors like poverty, age, and sex, influencing access to resources. Communities on coasts where poverty or inequality is high are more likely to suffer more severe damage from SLR because their ability to adapt and recover from environmental hazards is substantially low. Most of the poor cannot invest in measures like house elevation or voluntary migration to higher grounds that could reduce their risk, hence they are highly susceptible to different consequences of coastal flooding and erosion. Demographic factors contribute to social vulnerability apart from economic disparities. The elderly population, people with disabilities, and children have always been considered more vulnerable in climate-related calamities just because they might need additional care in case of evacuation or during recovery processes [19, 99].

Apart from this, there is also gender vulnerability in the social sphere because, factually, women in most coastal communities face higher risks related to climate change as a result of their traditional roles related to caregiving and managing resources. These traditionally gendered roles may constrain the ability of women to participate in decision-making processes and to access support services. Additionally, addressing the social vulnerability necessitates an approach along many dimensions: enhancing resource availability, building community resilience, and ensuring that the vulnerable groups are represented in adaptation planning. These are targeted social programs, such as financial assistance to poor families and community-based initiatives that better engage the most marginal in climate resilience. The lower the social vulnerability, the more resilient the community will be to the impacts of SLR. No section within the community will disproportionately suffer from the consequences of climate change [100]. Social vulnerability can be calculated by the following equation:

Social Vulnerability *= 0.5 population density + 0.4 percentage of specific categories at risk + 0.1 percentage of females.*

Population density *= Total of residents / Area of the census block.*

Percentage of specific categories at risk *= (Residents < 5 years + Residents > 65 years) / Total of Resident.*

2.3.4 Physical Vulnerability

Physical vulnerability is the relative potential for buildings, infrastructure, and other physical assets to be damaged or destroyed through SLR and related hazards. Coastal areas contain a great deal of infrastructure, such as roads, bridges, ports, and power plants, related to the normal economic function of operation. Higher sea levels easily flood, erode, or storm-sweep these infrastructures and require costly repairs and disruptions of valuable services. Physical vulnerability depends on geographical features like elevation above sea level, distance from the shoreline, and natural barriers. In general, flooding commonly affects low-lying areas along coasts, while erosion is more frequent in areas with unstable shorelines. Age and quality of buildings and infrastructure also play a major role in determining their vulnerability. The older structures, which were not designed to stand up against the rising sea level and frequently occurring extreme weather conditions, would suffer greater damage [101].

Mitigation of physical vulnerability includes not only retrofitting existing infrastructures to future conditions but also forward-looking planning strategies for new developments. Such adaptation will involve elevation of buildings, sea wall construction, and resilient design standards for building codes. Protection and restoration of wetlands and mangroves can reduce the physical vulnerability of coastlines by absorbing storm surges and preventing erosion. Treatment of symptoms of physical vulnerability enables the protection of infrastructure investment by a coastal community and the sustenance of vital services in the face of climate change [29]. Physical vulnerability can be calculated by the following equation and the term physical vulnerability connects the characteristics of Relative Buildings (RB) refers to the relative distribution or proportion of buildings categorized by the number of floors they possess based on building density and number of floors they possess.

Physical Vulnerability *= 0.4 Building Density + 0.6 number of floors*

Building Density *= Total of Residential Buildings / Area of the census block.*

Number of floors *= (RB 1 floor0.4 + RB 2 floors 0.3 + RB 3 floors 0.2 + RB > 4 floors 0.1) / (Total RB).*

2.3.5 Environmental Vulnerability

The vulnerability of the environment will include the inherent susceptibility of a coastal ecosystem to damage by SLR and climate change. These coastal ecosystems protect extremely long lengths of coasts against storm surges and erosion through wetlands, mangroves, coral reefs, and estuaries acting as a natural barrier. On the contrary, these ecosystems face rising sea levels, increased salinity, among other environmental impacts attributed to global warming. In addition, once these ecosystems are destroyed, their buffering capacity reduces, biodiversity is threatened, livelihoods within the communities relying on the ecosystem for food security and tourism are reduced. Habitat degradation due to human activities is among the leading factors of environmental vulnerability. It is also known that the role of coastal development, pollution, and overfishing weakens the resilience of ecosystems to adapt to the impacts brought about by climate change [91].

For example, mangroves lost to urbanization reduce the coast's storm surge absorption capacity, while agriculture runoff pollutes and destroys coral reefs-all of which are highly valued for marine biodiversity and fisheries. A coast may reduce part of the environmental vulnerability by focusing on the conservation and restoration of ecosystem services. This will also involve protection against further degradation, restoration, and attainment of sustainable management that would balance the needs of growing human populations with the health of the environment. Application of ecosystem-based approaches to plan adaptation will enhance resilience in coastal areas through the natural protective functions of ecosystems, such as wetlands and mangroves, thereby reducing impacts of SLR [102].

2.3.6 Holistic Vulnerability Assessment

Holistic vulnerability assessment encompasses the entire gamut of vulnerabilities the areas on the coast are subjected to. These integrated approaches allow for inclusion of such factors as physical, social, economic, and environmental ones. Such studies will provide comprehensive information on risks related to SLR because the intersections and the exacerbating relations among various forms of vulnerability are taken into consideration. For instance, an area that has high physical vulnerability because of poor infrastructure may equally experience high social vulnerability due to poverty or limited access to resources that hampers recovery from disasters. Holistic assessments are thus quite central to any effective disaster risk management, since they provide a full overview of how different types of vulnerabilities add up to create overall risk. Currently, scientists can combine several data sets and methods, including those from GIS and satellite imaging, to produce highly detailed maps that actually show the most vulnerable areas. The same assessments also enable policymakers to determine the areas where intervention is needed, thereby ensuring resource allocation is based on the actual need, with the ultimate aim of reducing general vulnerability in coastal communities. One of the main problems with holistic vulnerability analyses is that such an analysis requires a fair amount of reasonably reliable data and a great deal of time. While comprehensive assessments provide significant added value, they can be quite time-consuming and require extensive regional data collection where information has hardly been documented. To this end, quick but trustworthy assessment methods have been developed for disaster risk management purposes-as shown in relation to the Copernicus Emergency Management Service (EMS)-ensuring timely and actionable information when needed [103].

2.3.7 Rapid Vulnerability Assessment Approaches

The need for timely decisions also suggests that the issues demand quick assessments of vulnerability, which becomes necessary in cases like natural disasters. It is intended to provide prompt information on the risk in each coastal area, with no need for extensive collection or any prolonged analysis. Central to this method of approach is the use of GIS-based tools, enabling rapid collection, treatment, and analysis of geospatial data. This is useful in terms of emergency management, especially when one considers evacuation routes, man-made or structural vulnerabilities, and even social vulnerabilities regarding populations. The Copernicus Emergency Management Service developed a methodology that offers a very functional means of carrying out a rapid vulnerability assessment. It integrates a number of indicators representative of different types of vulnerability-for example, social, physical, and environmental-scaled to a 0-10 scale to obtain an estimate of the level of risk. These indicators are combined into an overall score of vulnerability, thereby making it easier for a decision-maker to identify immediately those areas that require urgent intervention. The resultant outputs are normally depicted in risk maps applicable for disaster response and recovery planning [104].

While rapid assessments are meant to be timely, they also have to be reliable and address complexity. For example, weights have to be assigned for population density and critical infrastructure, as highly concentrated urban centers are particularly vulnerable to both direct and indirect disaster losses. The updates should also occur on a regular basis for rapid assessments in order to reflect the changes in conditions experienced so that the decision-makers are able to get hold of the most up-to-date and precise information if they have to make any response to emerging threats [105].

2.3.8 Cultural Heritage and Vulnerability

Cultural heritage is inextricably linked to the identity and history of communities within coasts. Indeed, many coasts host key cultural sites, traditions, and knowledge systems evolved over several centuries. Irreversible destruction or damage of these irreplaceable parts of cultural heritage is threatened by SLR, coastal erosion, and flooding. Examples are submergence or erosion of ancient temples, historical monuments, and traditional fishing villages due to higher sea levels-an act that results in irretrievable loss of cultural landmarks. Losses in cultural heritage have important social and psychological effects on communities. Such eviction may be deemed to foster displacement and loss of identity, especially in indigenous or long-settled communities reliant on land and sea for their customary practices. Additionally, in most coastal contexts, economic activities induced by tourism are dependent on the latter. In this regard, other economic consequences of cultural site destruction include reduced revenue from tourism and impacts on livelihoods dependent on the survival of cultural heritage [98, 106].

These would consist of pre-impacting measures that account for cultural heritage: documentation of those sites that would be engulfed by water, translocation of those artifacts that might be easily affected by change in their locations, and formulation of a community-based action plan for their preservation. To this end, cultural preservation must be done in collaboration with local governments, international organizations, and local communities so that the strategic approaches for cultural preservation will respect traditional practices and knowledge systems. It will be very important for the coasting regions to include cultural considerations in their climate adaptation and disaster risk management plans to protect their heritage and create resilience against SLR [107].

2.3.9 Social Vulnerability and Adaptation Strategies

Social vulnerability in regard to the coastal zone includes everything from differential income and resource access to social networks. Low-income families, ethnic minorities, and the elderly might be more susceptible to SLR impacts because of their limited capacity for adaptation. These populations cannot afford the cost of relocation or protection measures. Hence, they are always at a heightened state of vulnerability in cases of displacement, health, and economic collapse during disasters. Adaptation strategies from a social vulnerability standpoint have to be specific in intent and policy to elevate the needs of those very vulnerable populations. These may include the development of affordable housing in safer areas, financial assistance to low-income families, and community-based resilience programs that engage residents in participating in the planning process of climate adaptation. This also includes inclusive governance through which the voices of marginalized communities are included in decision-making processes so that responses to adaptation address particular vulnerabilities and needs [108].

Social vulnerability is, however, not fixed but could change either for worse or better in environmental conditions. It is, therefore, incumbent on governments and organizations to monitor indicators of social vulnerability such as poverty rates and access to basic services to ensure adaptation strategies remain responsive to evolving conditions. This way, the potential reduction in social vulnerability can further enhance resilience in coastal communities to long-term SLR impacts while nurturing social equity and justice [109].

2.3.10 The Role of Demographic Factors in Vulnerability

Demographic factors include age, gender, and health status, which are highly important in a person's or community's vulnerability to SLR and its associated hazards. For example, elderly people are more vulnerable during extreme weather events because of difficulties in mobility and probably reliance on medical assistance. Children and those with disabilities need supplementary support in case of evacuation or recovery. Hence, they are also more vulnerable. Another important influencing factor of vulnerability, particularly in communities that hold female individuals responsible for care and housekeeping-related tasks, is gender. Women in many coastal communities may not have adequate rights to resources, education, or opportunities to make decisions [64].

This consequently impacts the potential for adaptation to environmental change. Such a limited ability could increase their vulnerability, especially to increased sea levels and accompanying socio-economic disruption. These demographic vulnerabilities will have to be taken into consideration through adaptation strategies by targeting specific responses with particular needs. For example, disaster preparedness plans should address elderly care services, accessible transport, and child protection services. In addition to this, resource access, education, and leadership opportunities will enhance community-wide resilience by reducing gender-based vulnerability. Through this process, the consideration of differential demographic needs allows coastal adaptation to make resilient all members of its communities to the various effects of SLR [96, 110].

2.3.11 Environmental Vulnerability and Ecosystem-Based Adaptation

The rate at which natural barriers to SLR are lost is hugely increased. Wetlands, mangroves, and other ecosystems offer protection to shores from surge, flooding, and erosion impacts. These have been being weakened by human activities through urban expansion, pollution, and overfishing, hence making coasts vulnerable to environmental threats. Ecosystem-based Adaptation (EbA) addresses this issue through the ecosystem powers themselves. Hence vulnerability decreases, while resilience increases against climate change.

Equally disturbing are the higher sea levels. Wetland and mangrove ecosystems act as part of the storm surge barriers. Much of the surge impact is soaked up, hence lessening the impact of flooding and erosion of forces [111].

However, in many instances, such defenses have been weakened by urbanization, pollution, and overfishing. EbA works in the restoration and conservation of those ecosystems in a bid to offset rising sea levels but also in giving additional benefits in terms of biodiversity enhancement, carbon sequestration, and livelihood support for the local communities. For example, the restored mangrove forests would have the potential to dampen the oncoming waves, thus eroding the coastline no more, hence protecting the surrounding communities due to extreme weather. Successful EbA requires government, local communities, and conservation organizations working together and continued responsible management of land and natural resources. This will help policymakers make ecosystems and human communities more resilient through the integration of EbA principles into coastal management strategies. This ensures that coastlines continue their services amidst a changing climate while protecting vulnerable areas from the growing dangers at hand due to SLR [112].

2.4 Modeling Approaches for SLR Projections

Understanding and modeling SLR is important for projecting its future impacts on coastal communities, ecosystems, and infrastructure. Because SLR itself is driven by several interacting factors-from increases in global temperature through changes in regional oceanography-a range of modeling approaches are undertaken to capture these complexities. This section provides a deeper look into some of the main approaches used in SLR projections, each one playing an important role in building a full understanding of future risk. The types of modeling approaches for SLR projections are explained in the following [113].

2.4.1 Global Climate Models (GCMs)

Global Climate Models takes into account the Earth's simulation of climate under different scenarios of greenhouse gas emission. The GCMs involve the physics of the atmosphere, ocean, and cryosphere in order to represent global climate change processes. These models run on supercomputers and are able to project climate change decades or centuries into the future. The backbone of international climate assessments, such as those performed by the IPCC, is done by GCMs. That's where the utility of the GCMs lies: in depicting large-scale features of climate change-things such as the thermal ocean expansion due to warming, which is the major contributor to SLR. While the oceans absorb the excess heat from the atmosphere, the water expands and nudges the global mean sea level uphill. Another complication to sea-level projections comes from the melting of ice from the Greenland and Antarctic ice sheets, which GCMs also take into consideration. In contrast, while GCMs are very robust for global applications, they are limited in predicting the variations in sea level variability on the local scale, as they run on coarse spatial scales [114]. Fig 2.1 demonstrates the projection of global SLR from years 1700 to 2100 based on IPCC report.

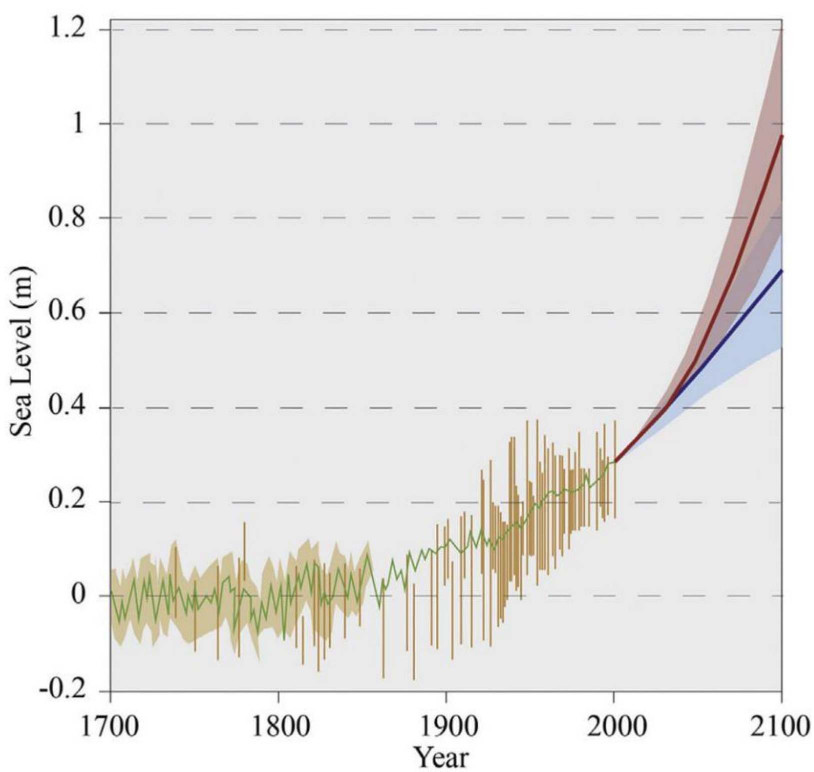

Fig 2.1: Projection of global SLR based on IPCC report.

2.4.2 Regional Climate Models (RCMs)

The RCMs provide more focused projections, through the down scaling of GCM outputs to capture the regional and local processes that contribute to SLR. Regional Climate Models are location-specific, with higher spatial resolution. Hence, they are ideal for localized coastline impact studies. This is important in areas where local topography, ocean currents, and wind patterns essentially modify the rate of SLR. RCMs are applied, for example, to make very high-resolution projections of SLR at specific coastlines in Europe and the U.S. These models take into account regional precipitation, wind stress, and storm surges, hence allowing a more precise evaluation of risks in areas that may not be given by global projections. This regional ocean dynamics might be due to the Gulf Stream in the Atlantic or El Niño events in the Pacific, in which the coastal areas may show SLR variations for which RCMs are better positioned than GCMs [115].

2.4.3 GIS-Based Tools for SLR Mapping

It is with GIS that the translations of output from complex SLR models into actionable visual data are realized. Tools based on GIS allow climate model projections-with all important topographic and infrastructural information-to create in-depth spatial maps that outline areas most susceptible to rising sea levels. This can include how different levels of SLR will alter and shift under different scenarios for specific locations, from major urban areas to rural coastal communities. Tools of a GIS also broaden access to scenario planning. For instance, a decision-maker may use a GIS tool to model scenarios of interest, say, a 1-meter or 3-meter rise in sea level, and determine how different parts of the city would be inundated. This will help planners understand where is at risk, which populations are most vulnerable, and what infrastructure needs protection or relocation. That flexibility within GIS tools lets the addition of real-time data to continuously update any assessment of risk as conditions change, which is vitally important in an evolving climate [116].

2.4.4 Ice Sheet and Glacier Dynamics in SLR Models

Of the more complicated features to model in SLR projections, ice sheet and glacier dynamics play a crucial role. The Greenland and Antarctica ice sheets are both expected to have a major contribution toward future SLR. However, predicting precisely the exact melting rate of such huge ice formations involves very high uncertainty due to the complexity of the interaction occurring between the systems of ice, atmosphere, and ocean involved. Such melting of the ice sheets can accelerate SLR-especially from underneath, where the ocean water is warm and thus particularly effective at eroding the ice-in ways that are difficult to model with precision. Recent advances in satellite technology have allowed more precise monitoring of the loss of ice mass, and data shows that both the Greenland and Antarctic ice sheets are losing ice at an accelerating rate. Not considered yet for ice sheet models are basal ice flow, albedo of ice sheets, and other feedback that could either be dampening or speeding up the rate of the loss. Models tend to provide a range of plausible results due to uncertainties, considering scenarios depicting the best and worst cases [117].

2.4.5 Probabilistic SLR Projections

Because climate modeling is an inherently uncertain business, probabilistic approaches to SLR have gained increasingly wide acceptance. Instead of a single deterministic result, probabilistic models represent the possible future sea level as a probability distribution, reflecting the uncertainty of different emissions pathways and ice melt rates. These models employ statistical techniques that integrate uncertainties in a number of factors—such as future global temperatures, ice melt dynamics, and ocean responses—into a range of projected outcomes. This enables in particular planners and policymakers to contemplate scenarios from the most optimistic-with aggressive climate mitigation-to the most pessimistic-with continued high emissions and rapid melting of ice sheets. The probabilistic models will finally allow decisions that take account of low-probability, high-consequence events that are crucial for long-term infrastructure planning for coastal protection [118]. In Fig. 2.2, the probabilistic projections of global sea-level rise are shown [119]. In this figure, for each time point, the color intensity reflects the probability density function (PDF), while the solid and dashed black lines indicate the median and likely ranges, respectively. The dotted lines represent the minimum and maximum values [120].

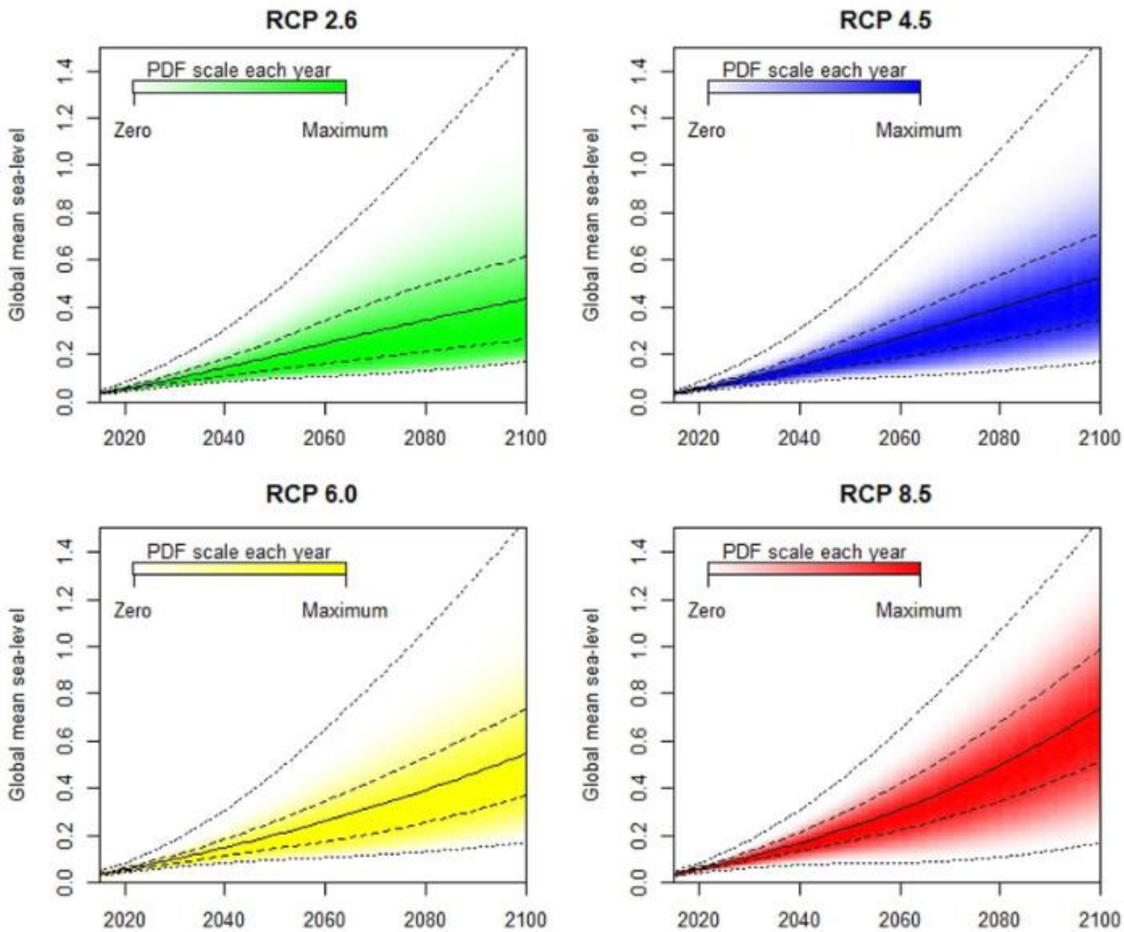

Fig. 2.2: Probabilistic projections of global sea-level rise.

2.4.6 Coupled Models for Coastal Processes

Coupled models, which incorporate SLR with coastal processes, are usually used in predicting the rise in sea levels affecting coastlines. These coupled models simulate the interaction of SLR and coastal processes such as erosion of coastlines, transport of sediment along coasts, and storm surges. Essentially, these models are applicable in predicting varied coastline responses, such as sandy beaches, rocky shores, and wetlands, to SLR. For example, SLR can be projected to raise storm surges and high tides along low-lying coasts, flooding more often and more seriously. Coupled models can also simulate how the coastal ecosystems-such as mangroves, coral reefs, and barrier islands-may dampen or increase these effects through their action as natural buffers. These models contribute equally to the assessment of the long-term evolution of shorelines and allow determination of coasts that might retreat, accrete, or remain stable in the face of rising sea levels [121, 122].

2.4.7 Scenario-Based Projections Using Representative Concentration Pathways (RCPs)

The most common projection frameworks on SLR are through the use of scenario-based modeling, characterized by Representative Concentration Pathways, or RCPs. These refer to a set of emission scenarios that represent different trajectories for greenhouse gas concentrations in the atmosphere. For example, RCP 2.6 is a low-emission future where significant mitigation efforts are taken to hold global warming at 1.5°C. The RCP 8.5 represents a high-emissions scenario with little or no mitigation and thus is a much warmer world. Scientists can model SLR under different RCPs and, by doing so, project a range of possible outcomes based on human behavior and policy choices. In order to make more informed decisions, scenario-based modeling will not only illustrate the potential consequences of different climate actions but also dictate how natural processes respond to human perturbation. As a result, urban coastal planning is done under the most likely SLR scenario but also prepares for the possible extreme consequences by considering the high-end projections under RCP8.5 [123, 124]. Fig. 2.3 shows global sea level changes for RCP2.6, RCP4.5 and RCP8.5 [125]. Fig 2.4 presents the relative change of national GDP in 2100 due to SLR under the SSP5 – RCP8.5 [126].

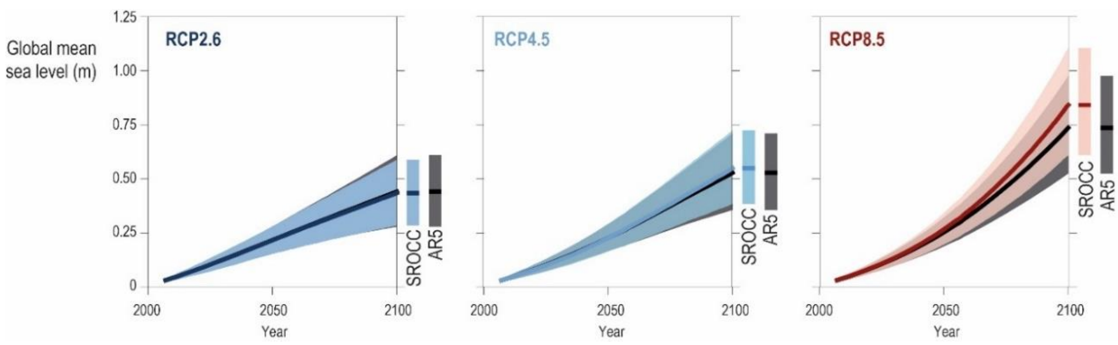

Fig 2.3 Global mean sea level changes for RCP2.6, RCP4.5 and RCP8.5. Source: IPCC 2013 fifth assessment report.

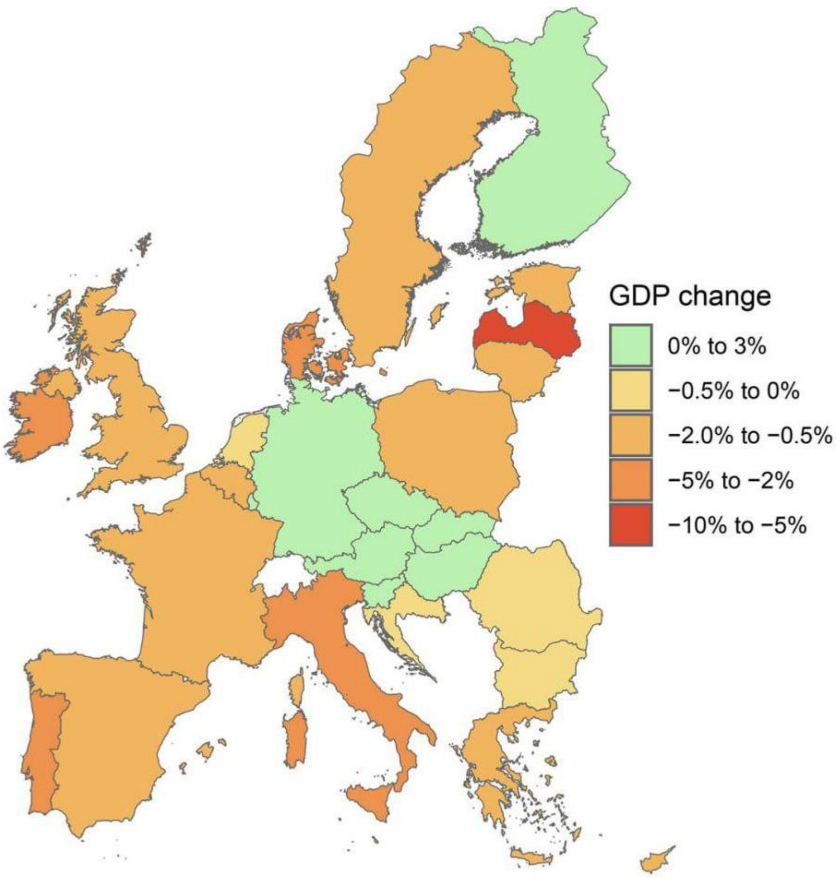

Fig 2.4: Relative change in national GDP.

2.4.8 Dealing with Uncertainty in SLR Modeling

Any projection about climate, therefore, necessarily contains some level of uncertainty, and that extends to SLR modeling. In fact, there is not just one source of uncertainty in SLR models-from the unpredictability of the dynamics of the ice sheets to the regional variations in the behavior of the oceans. Besides, uncertainties associated with future human actions, like levels of emission, technological development, and climate policy, further complicate making any precise long-term projection. These are accounted for in research by stating a range of outcomes and updating models as new data become available. For example, if future satellite data indicates that the rate of ice melt in Antarctica is happening much faster than previously thought, models can be updated to reflect this. In such scenarios, adaptive management strategies help decision-makers prepare for a range of possibilities, other than reliance on one projection alone [127].

2.4.9 Continuous Monitoring and Model Refinement

Models of SLR are continually updated and refined, as more and better data arrives, in particular from satellite observations. Satellite missions like NASA's ICESat and ESA's CryoSat provide key data on ice sheet thickness, glacier flow rates, and sea surface height to further raise the accuracy of these models. Long-term tide gauge records and remote sensing of coastal changes provide further information on the response of local and regional sea levels to global warming. Continuing refinement of the models of SLR ensures that the projections remain as accurate as possible. As technology progresses continuously, new tools such as machine learning algorithms are integrated into models for better predictions [55].

Continuous monitoring of the same is, therefore, a necessity at this stage not only to the researchers but also to the policymakers, as that would facilitate dynamic response to the evolving threats posed by the SLR. Modeling of SLR has been an intricate yet urgent affair that meets the global response to one of the striking impacts caused by climate change. The combination of GCMs, RCMs, GIS tools, and probabilistic models allows scientists to generate highly detailed projections that capture global and local dimensions of SLR. Coupled coastal process models further enable this. Considering the still existing uncertainties, satellite data and modeling of the ice sheets are becoming increasingly important for improving these projections. These models are key tools for the understanding of coastal communities and the policies and planning of developing effective adaptation and mitigation strategies in the light of increasing sea levels [128].

3. Impacts of SLR

3.1 Coastal Erosion

3.1.1 Long-term Impacts on Coastal Ecosystems

Coastal erosion has enormous repercussions, impacting the human and natural world greatly. The retreat in shorelines brings erosion of the key habitats: beaches, dunes, and wetlands are shrinking or disappearing altogether. These ecosystems form an important part for the support of biodiversity. For instance, beaches provide the fundamentally essential nesting habitat for sea turtles and shorebirds, while dunes and wetlands have quite various plant and animal life. Losses of these areas threaten species survival dependent on the same, with decreases in wildlife populations, some already being endangered. The loss of coastal ecosystems exceeds mere biodiversity: dunes and wetlands provide natural barriers by absorbing excess water during storm surges, hence protecting inland areas from flooding. In their degradation, coastal communities become more vulnerable to extreme weather events and rising sea levels due to hurricanes. These protective features have undergone erosion in the majority of cases, therefore putting many places at greater risk of flooding and extremely costly destruction of infrastructure and homes [129].

Besides, erosion of coastal habitats means loss of carbon sequestration. Wetlands, mangroves, and other coastal ecosystems retain so much carbon in mitigating some climate change impacts. Degradation of such an ecosystem will reduce their capacities for continued carbon sequestration and may also release part of the stored carbon into the atmosphere, adding to global warming. In fact, it has created a very vicious circle: climate change quickens coastal erosion, which, in turn, contributes more to climate change. Viewed in their entirety, the effects on ecosystems and human settlements, let alone its contribution to and interaction with the global climate, render it an issue of the highest importance that needs to be addressed without further ado. Mitigation of long-term effects of such a continuing threat is related to processes of restoration and protection of such environments: dune stabilization, wetland restoration, and coastal defenses [130].

3.1.2 Erosion Hotspots and Example Global Case Studies

That is to say, certain regions around the world are more prone to coastal erosion, sustained by peculiar geographic and environmental attributes. To illustrate this, in Louisiana, its coasts were among the fastest disappearing in the world, and for that matter, have been suffering from rapid land loss within the U.S. These are basically driven by a combination of rising sea levels, subsidence of the land, and reduced flow of sediment from the Mississippi River - which previously served as replenishment to the wetlands at the coast. Consequently, Louisiana loses about an expansive field of land every hour-a rapid process with significant impacts on communities, industries, and ecosystems dependent on the protective and productive potential of these coasts [131].

Bangladesh also consists of very densely populated coasts that are fast eroding due to a very high risk of displacement for millions of its people. This is enhanced by the low-lying deltaic geography of the country, in addition to monsoon rains, river flooding, and storm surges. Having minimal resources to fight against these hazards, most Bangladeshis have to migrate inland or abroad, adding to the numbers of climate refugees - people or communities who are displaced from their homes by environmental changes such as sea-level rise and coastal erosion, and who seek safer living environments elsewhere. Small island countries like the MALDIVE and Tuvalu also face an existential threat due to coastal erosion. With rising seas and stronger storm surges, beaches and atolls are being eroded, and put entire islands on the brink of becoming uninhabitable. For these countries, in any case, the economic base will be threatened by the coastal erosion, their ecology, or even their cultural identity and survival [132].

3.1.3 Economic Impact of Erosion on Coastal Communities

The effects of coastal erosion are predominantly financial in nature in those communities whose livelihood depends on the coastline. Tourism is, arguably, one of the largest industries in most coastlines, while beaches lost and infrastructural damage greatly affect such industries. Most coastal resorts, hotels, and recreational facilities are normally situated very close to the shore, which makes them very susceptible to erosion. As beaches erode and properties get destroyed or damaged, the tourism dollars dwindle, devastating local economies relying on visitors. The cost of rebuilding and reinforcing coastal infrastructure is added to the extra financial burden on the communities. Erosion seriously threatens the livelihoods of fishermen along the coasts. The loss of important fish spawning areas like estuaries, mangroves, and coral reefs means depleted fish stocks and adversity to the traditional fishing industry. The implications are not just economic, affecting the economic status of fishing communities, but also affect food security within societies where fish is a staple source of protein. Further, agricultural land erosion and saltwater intrusion increase food insecurity because of the retreat of coastal agricultural lands, particularly in developing countries dependent on coastal farming to feed both the local markets and for subsistence. In many cases, the combined economic pressures from declining tourism, fisheries, and agriculture force migration as people are compelled inland in search of better opportunities [133, 134].

3.1.4 Community-Led Adaptation Efforts

Community adaptation strategies target the issues of coastal erosion in development, whereby opportunities are being taken advantage of by the lead agency in most areas along the coast. Examples of such local efforts include natural barriers: building and reinforcing dune systems that serve to protect the shorelines from erosion and storm surges. This would help hold soils in place and reduce the rate of erosion by planting vegetation like grasses or trees on coastlines. Generally, these are more sustainable and less costly than traditional engineering solutions such as sea walls and contribute to the long-term health of the coastal environment. Communities are also heavily into the restoration of degraded ecosystems forming a natural barrier to erosion. This covers the rehabilitation of mangrove forests that anchor coastal soils and absorb wave energy, now underway for those most at risk of erosion and SLR. Similarly, coral reef restoration protects the shoreline from strong waves and storm surges while sustaining biodiversity simultaneously. This often focuses on the local adaptation plans in keeping the cultural heritage and ways of life preserved amidst livelihoods such as fishing and tourism that are still intact. These community-level initiatives call for upscaling with external support by the governments and international organizations by way of financial resources, technical expertise, and policy frameworks that enhance resilience at the coasts [135, 136].

3.2 Flooding, Storm Surges, and Increased Inundation

3.2.1 Urban Flooding in Coastal Megacities

Coastal flooding has indeed emerged as one of the major threats for every megacity that is near an ocean, including major cities such as New York, Tokyo, and Jakarta. The vulnerability in the infrastructure, along with growing populations and increasing exposure to rising sea levels, gives rise to some unique challenges. Regular flooding during tides causes heavy stress on urban systems, coupled with worst storm surges. Coastal flooding also extends its impacts to main infrastructures such as transport networks, electric supplies, and housing. Thus, it is of great concern to city planners and governments. For example, the impact of storm surges created by storms such as Hurricane Sandy on urban infrastructure calls for comprehensive flood management in New York. Issues are also compounded in cities like Jakarta due to rising sea levels and land subsidence. Over-extraction of groundwater, together with the weight of heavy urban infrastructure, has already made Jakarta sink so fast that parts are regularly flooded. Large investments in flood defense structures such as sea walls and flood gates have yet to hold back the scale of the problem. These steps are many times necessary but not sufficient to address this escalation of risks, as these nature-based measures will largely play catch-up with the upward spiraling of risks in so many cases. What is urgently needed is coming up with holistic solutions for mega coastal cities: better urban planning, natural flood buffers, and even often relocation strategies for particularly vulnerable areas [137].

3.2.2 Health Risks Associated with Flooding

The major public health risks of coastal flooding include direct impacts of saltwater, sewage, and industrial contaminants on sources of drinking water. Contaminated drinking water can cause the spread of waterborne diseases like cholera, dysentery, and typhoid in highly populated or squalid areas with an undeveloped sanitation system. Moreover, the flood water covers the ground from local sewage systems and mixes untreated waste with drinking water, therefore increasing the rate of infection. Clean water is of prime importance once normal services are disrupted in the case of floods. These threats are even more heightened when natural calamity reduces health infrastructure to rubbles or overwhelms it. Medical responses get delayed and timely treatment of various ailments and injuries becomes difficult when floods or power losses are recorded in hospitals and clinics. These health hazards particularly affect the vulnerable populations of the elderly, children, and informal settlement residents as they have limited access to health care and can mobilize few resources for recovery from such disasters. Assuring preparedness and resilience in the health systems is an important part of minimizing public health impacts from coastal flooding [138].

3.2.3 Long-term Economic Disruption from Flooding

Flooding and storm surges have the potential to cause long-term economic disruption due to damage to fundamental infrastructure, displacement of firms, and erosion of property values in flood-prone areas. In nearly every major flood event, basic infrastructure such as roads, bridges, airports, and public transportation systems sustains significant damage, requiring very expensive repairs and taking a very long period of time to rebuild. The financial burden on local governments can be crushing, with recovery often measured in years. Further, the frequent flooding disrupts the normal activity of doing business, which in the end leads to its closure and a reduction in the incomes of local economies. For businesses relying on the steady flow of visitors and residents, such as tourism, hospitality, and retail, these disruptions create ripple economic effects. Ports, commonly located in coastal flood, are also among those highly vulnerable sectors to sea storms. Thus, consequently, any kind of damage or shutdown of ports cascades into the global economy in an instant. Hold-ups flood the supply chains, decelerating the speed of cargo traffic, and raising shipping costs – a worldwide problem aggravated by the dependency of international supply chains on coastal megacities and their infrastructure. Property values dip in places exposed to increased flood risk. Selling or insuring property in such places costs homeowners and businesses time and money. Personal wealth decreases and local real estate markets become rocky.

These areas will be able to insure property. Insurance is a financial instrument that spreads climate-related risk over time and across space, enabling investment and helping capitalise recovery in case of disaster. While any risk transfer works best when supported by a strong system of state support, taxes and regulations, insurance coverage provides a critical floor for climate risk. Homeowners and businesses that are uninsured, or underinsured when disaster strikes, are forced to bear larger financial costs, making them less likely to rebuild or invest in climate resilience. Over time, this reduces the incentives for new investments in coastal areas. [137, 139].

3.2.4 Insurance and Financial Markets' Response to Coastal Flooding

The increasing frequency and severity of coastal flooding are driving major changes in the insurance industry, as insurance companies reassess the financial risk from insuring properties in flood-vulnerable areas. In response, after the rising frequency of expensive claims subsequent to a flooding incident, many insurance companies raise premiums for the coast properties, or in some places, completely withdraw coverage in high-risk areas. For both homeowners and businesses, finding affordable flood insurance is increasingly difficult. This makes properties more vulnerable in cases of financial loss. In some places, as the flood risks go higher, areas of the coast could become "uninsurable"-a situation where property owners are left without protection and further lower property values, adding to the financial burden after disasters. However, beyond insurance firms, financial markets are also reflecting the long-term risks to coastline erosion and flooding. A rising number of institutional investors are showing more aversion to funding property developments in areas at risk from the sea with less robust flood defenses and climate adaptation. In fact, the financial world is increasingly using climate risk as a reason to decide against investment, given that properties vulnerable to extreme flooding are significantly riskier assets. Growing awareness of such climate-related risks begins to change how investments are made, with more emphasis on sustainable and resilient real estate and infrastructure development while encouraging divestments away from high-risk coasts [140, 141].

3.3 Environmental, Ecological, and Chemical Impacts

3.3.1 Mangroves as Natural Defenses

Mangroves protect the coasts from SLR as a physical barrier by absorbing wave energies and preventing erosion, thus helping to trap sediments. These trees, resistant to salt, have thick networks of subterranean roots which stabilize shorelines and protect inland areas from the destructive powers of storm surges and tidal waves. Besides the physical protection, the resilience of mangroves to coastal ecosystems depends on the improvement in water quality, their pollution-filtering capacity, and a barrier protecting the marine-terrestrial boundary. Also, their sediment-trapping capacity supports the elevation of land along the coast, which could help mitigate some of the impacts of SLR. However, it is very ecosystems that mangroves support which are threatened by the rising sea levels and human development. Reciprocally, so many mangrove forests are turning drowned as waters intrude into the coastal zones, especially where their inland migration is hindered by urban development and other forms of agriculture. This also means the loss of mangroves leaves the coasts most prone to erosion and flooding, hence increasing vulnerability to climate change. Most importantly, mangrove forests do host some of the most valuable ecosystems for a number of species, which include fish, birds, and crustaceans. These destructions will surely destroy the biodiversity because so many species depend on these ecosystems for their breeding, feeding, and sheltering purposes. Degradation of mangroves disrupts these ecological relationships, diminishes carbon sequestration potential, and thus plays into the current global climate crisis [142, 143].

3.3.2 Impact of SLR on Coral Reefs

Included among systems highly vulnerable to a rise in sea level are the coral reefs, which are very important for marine biodiversity and as protection against storms in coasts. Whereas such fringing ecosystems can grow up and out in a gradually rising sea level, their further survival is already compromised by a range of impacts related to climate change, particularly those imposed by ocean acidification and increases in water temperature. It is acidic, and as long as the ocean remains in the course of taking up more and more greenhouse gases, it will continue to acidify. This results in further dissolution of the calcium carbonate structures which give corals their skeletal strength, thereby weakening them against damage. On the other hand, increased temperatures warm ocean water temperatures, which can prompt coral bleaching, the expulsion of symbiotic algae that normally provides corals with energy and vibrant colors, thereby causing mortalities reef-wide [144]. Further, SLR exacerbates the issues by cutting down the light reaching the coral reefs, particularly in deeper waters. The symbiotic relationship between the corals and algae is based on photosynthesis, which essentially requires sunlight, though extreme intensities or levels are poor regarding coral health and development. Consequences can be far-reaching once the reefs degrade. As a result, populations of reef-dependent fish shrink due to the loss of shelter and breeding grounds. Aside from this, coral reefs protect coasts from storm surges and erosion by dissipating wave energy. Destruction of coral reefs leaves all coasts more exposed to such threats, while on coasts, artificial defenses are also rendered necessary. As a result, this disrupts the livelihood of communities dependent upon the reef ecosystems for fishing and tourism [145].

3.3.3 Estuarine Ecosystems and Salinity Changes

Estuarine ecosystems are amongst the most biologically productive environments where freshwater rivers meet the ocean. They host a staggering array of plant life and animal species. As sea levels rise, however, this sensitive balance of freshwater and saltwater is increasingly threatened by rising salinity levels in affected areas. Higher sea levels rise make the intrusion of seawater into freshwaters more intense. Already, rising sea levels alter ecological balances that take salt concentrations into account. Freshwater plants, fish and invertebrates that have adapted to low salt concentrations will increasingly face unsuitable habitats. This lowers the diversity of species in marine estuaries, changing their composition. New, salt-tolerant species might be welcomed by the higher salt loads. Freshwater-dependent species may become endangered or even disappear because of SLR-induced habitat conditions. The domination of such ecosystems by more saltwater species may contribute to reduced biodiversity in general, given that these ecosystems have complex implications for food webs and ecosystem services. Besides ecological degeneration that it may cause, increased salinity in the estuaries might also have very significant impacts on agriculture and fresh water supply [59]. Saltwater intrusion into the rivers and groundwaters has caused depuration of fresh-water supplies, thus affecting the cultivability of lands for crops by farmers. Soil salinization reduces agricultural yield, and sometime it leads to the abandonment of farmland as farming becomes more unreliable, especially in lower-lying areas where the effect is most serious. This threatens not only local food security but also livelihoods in agricultural communities dependent on estuarine regions. More generally, loss of fertile land and freshwater through increased salinity epitomizes one of the complex and far-reaching natural and human-system consequences of SLR [146].

3.3.4 Ocean Acidification and Its Connection to SLR

It cannot be disentangled from ocean acidification, both being a function of an increased atmospheric concentration of carbon dioxide. In turn, when atmospheric concentrations of CO2 increase more of this gas diffuses into the ocean, where it forms carbonic acid, thereby lowering the pH of seawater. This acidification interacts directly with marine life, particularly those which have a reliance on calcium carbonate for building shells and skeletons, such as mollusks, corals, and certain plankton species. Weakening of such structures compromises the health and survival of key species, which serve foundational positions in marine food webs and ecosystems. For example, acidification exacerbates the stress that higher sea levels already impose on coral reefs. It makes their growth and recovery from bleaching events even more difficult. SLR and ocean acidification are therefore interwoven in a threat both to the coastal ecosystem and to those who depend on it [147]. As sea levels rise, natural barriers like coral reefs and oyster beds become particularly more prone to ruin. These are some of the natural protective areas, along with many others, that have helped buffer coastlines from wave action and erosion. With acidification degrading these habitats, their effectiveness at providing natural barriers against coastal flooding and erosion increasingly degrades. This can lead to drastic decreases in marine biodiversity, impacting fisheries and tourism that depend on these species, and even the protection of shores-a suite of activities on which the economic and social lives of coastal communities depend. Both are becoming more extreme. Therefore, the resilience of marine ecosystems and their ability to continue providing life support will be further eroded [147].

3.4 Land Loss, Structures, and Infrastructure

3.4.1 The Threat to Coastal Cities

As sea levels rise, coastal cities around the world are facing significant threats. Also, coastal cities worldwide are facing unparalleled threats from infrastructure to land itself. Major metropolitan hubs like Miami, Venice, and Shanghai are already experiencing record flooding, a harbinger that presages an ominous future likely only to worsen over the coming decades. In fact, large swathes of them are underwater in some projections before the turn of this century. This has manifested in increased frequency of flooding events, including "sunny-day flooding" in Miami, where rising groundwater levels spill onto the streets on a clear day and disturb daily life, causing millions in property damage. Coastal cities have fought this reality by investing billions of dollars into sea walls, levees, and drainage systems [148, 149]. These measures are extremely costly and may not bring more than temporary respite in the face of sea levels that seem to rise relentlessly. Efficiency of such infrastructure is also usually bound by the rate of rise in sea levels, as well as the increased ferocity of storms and other events related to climate change. This brings with it a number of concerns that an over-reliance on engineered solutions may detract from any longer-term plans and adaptation strategies, such as habitat restoration and managed retreat, which could well be the only avenues to allow resilient living by coastal communities in light of continued environmental change [150].

3.4.2 Impact on Critical Infrastructure

With the sea levels going up pretty well, most coastal cities around the world are conscious of the enormous threats that their infrastructures and soils face. Cities include big metropolitan cities such as Miami, Venice, and Shanghai, who have already become accustomed to regular flooding and portend a crisis likely to worsen over the next several decades. As seen from projections, with these trends continuing, large areas of those cities will be submerged underwater before the close of this century. For example, flooding in Miami is increasingly common. This also includes "sunny-day flooding," whereby higher groundwater contemplates and floods the streets even on otherwise dry days, affecting human activity and causing property damage. Because of the challenges that are posed, there is a high interest by the coastal cities in implementing flood protection infrastructure such as sea walls, levees, and drainage systems. These may save people for some time, but the costs are high, and the relief might be temporary as sea levels rise unabated. It is also often restricted to the increasing rate of rise in sea levels and the intensification of storms and other climate-related events. There is also the fear that this will result in an over-reliance on engineered solutions and will distract policy and decision-makers from taking necessary long-term planning and adaptation measures, such as habitat restoration and managed retreat, which might be inevitable for securing the future resilience of coastal communities against ongoing environmental change [151].

3.4.3 Climate Adaptation for Coastal Infrastructure

New ways are being uncovered by cities to adapt to these changes with the SLR by devising innovative climate adaptation strategies that will save not just the infrastructure but also the communities. A prime focus is designing "resilient infrastructure" that will be able to resist the impacts of flooding and other climate-related hazards. Other ways may include building the foundations of new buildings in flood regions on stilts or piers to reduce incidences of water damage due to flooding. Besides that, the structures can be made with materials which are more resistant to water so as to minimize long-term damage and reduce maintenance costs. Beyond typical engineering solutions, many cities are also investing millions in green infrastructure strategies that utilize natural processes to stem and absorb floodwaters. This has entailed the development of rain gardens designed to capture and filter runoff from stormwater and the use of permeable pavements, which would allow water to seep into the earth rather than merely pool on the surface. Such green infrastructure manages flooding but also beautifies the urban landscape, supports biodiversity, and contributes to improved air quality. By embedding such adaptive approaches into their plans, cities strive for more sustainable coastal infrastructure which would be resilient against unabated struggles brought about by a rise in sea levels and climate change. To build stronger and more resilient coastal adaptation strategies, it’s important to combine natural defenses with traditional infrastructure, such as seawalls, levees, and breakwaters. By integrating hard infrastructure with natural ecosystems, we create a more comprehensive approach. This combination allows engineered solutions to provide immediate protection while natural ecosystems enhance long-term resilience and adaptability. Over time, this blended strategy can help lower costs, offer sustainable protection, and preserve ecological health, especially as climate change intensifies the vulnerabilities of coastal regions. [152].

3.4.4 Financial Challenges of Adaptation and Relocation

The financial cost to adapt to SLR or to relocate important infrastructures is huge and states a core challenge for any government at all levels. In most developing nations, resources needed in pursuing major adaptation efforts like building seawalls, restoring natural barriers, or relocating whole communities, are simply out of reach in most instances. These countries are usually experiencing competing priorities and limited budgets, making really hard choices as regards funding for climate resilience activities. Protection from SLR may cost as much as trillions of dollars over coming decades, even for the wealthiest nations. As such, funding adaptation will likely be complex, with international collaboration and public-private partnerships serving as a foundation for such funds. There is definitely a need for innovation in funding mechanisms, like climate bonds and insurance, that can spread financial risk around and therefore unlock investment in infrastructure upgrades needed under changing climate scenarios. This would help communities develop more sustainable and resilient approaches to the financial impacts of SLR, drawing from a variety of sources and encouraging collaboration between governments, the private sector, and international organizations. In some cases, managed retreat—relocating communities and infrastructure away from high-risk coastal areas—may be the most practical and cost-effective option. This strategy recognizes the limitations of relying on protective infrastructure, particularly in regions where continuously reinforcing defenses becomes either too costly or environmentally damaging. Managed retreat involves carefully planning the abandonment of areas at high risk, which ultimately reduces the long-term expenses associated with maintaining infrastructure in these vulnerable locations.

Additionally, managed retreat can create opportunities for environmental restoration. For example, allowing floodplains to return to their natural state can help create buffers that protect against future climate impacts. However, this approach also brings significant social and political challenges, as relocating communities requires careful planning, financial resources, and public support. Policymakers must carefully weigh the long-term benefits of retreat against the potential disruption to livelihoods and the cultural identities of affected communities [139, 153].

3.5 Socioeconomic Impacts

3.5.1 Impact on Housing and Real Estate Markets

SLR presents one of the current major threats to most of the housing markets along coastlines, as properties in areas vulnerable to flooding are more and more likely to see their values fall with the increased chance of flooding. In many of the coastal areas, insurance agencies have been raising premiums or refusing to insure homes considered most susceptible to flooding. This shift in insurance practices alone can have a great impact on property owners, forcing down property values and also discouraging the reselling of their homes or recouping their investments. It escalates the perception of risk, and potential buyers may shy away from such properties, further driving down the prices. As this happens gradually, it could spread through a whole neighborhood, where the cost of staying in a neighborhood that floods out on a regular basis outweighs any benefit of staying in those locations. As the property values plummet further and further, the local governments might suffer from declining revenues due to this, which impede their capabilities for infrastructure and service maintenance. This becomes a vicious circle in which reduced investment in community resources hastens the demise of the area. Ultimately, all coastal real estate markets face a multidimensional future in terms of economic slowdowns and exacerbation of environmental hazards. There is a pressing need, therefore, for strategic plans and adaptation measures up against these challenges [154, 155].

3.5.2 Displacement and Climate Refugees

With the further rise in sea levels, a rapid acceleration of displacements in coastal areas is foreseen, along with an unprecedented rise in the number of climate refugees. Countries with low-lying islands, such as the Maldives, Kiribati, and Tuvalu, are more likely to be at greater risk, with possible cases of complete submersion in a few decades. The people who inhabit such regions might find forced migration an ever-increasingly harsh reality, as they might not have any option but to run from their homes to some other land considered safer. The onus of this migration is going to be not just upon the people who get displaced but also upon the host nations that will have to accommodate them [156]. Large-scale displacements caused by the rise in sea level can pressurize resources of the receiving areas and thus result in conflicts over land, housing, and access to basic services. The new residents coming together strain infrastructure beyond present capacity, which increasingly, therefore, heightens a great deal of simmering social and economic tension. On the other hand, cultural integration of climate refugees into new communities may be very complex, with various discriminations, barriers to employment, and social services. For this reason, the governments would have to estimate and be prepared not only for internal displacement within their territories but also for international migration due to their long-term climate adaptation strategies. Policies that respond to the needs of the displaced and host communities will be of utmost essence in response to rising seas and their effect on vulnerable populations [157].

3.5.3 Loss of Cultural Heritage and Identity

These impacts of SLR well transcend economic impacts and pose serious threats to the cultural heritage and identity of communities with coastlines. Centuries-old coastal cities, villages, and historical sites may be inundated or significantly damaged through flooding and erosion. This loss is poignantly experienced by Indigenous and local people for whom their ancestral lands and native site areas have profound significance in cultural terms. Such places can be wiped out, and such erasing inflicts painful cultural displacement and trauma on people who have to come to grips with losing their historical connections. Rising seas pose an existential threat to various Pacific Island countries, for instance, whose cultures are attached to the land dating back thousands of years. It is not only their physical existence that is under threat but also the cultural identity and heritage. In face of such challenges to communities, the safeguarding of cultural heritage in view of the effects of climate change is increasingly innovative and creative in nature-from digital preservation of cultural practice and sites to initiatives of cultural adaptation that help communities hold on to their sense of identity even while physical landscapes shift. Addressing loss of cultural heritage in the context of SLR, building resilience must ensure that very rich histories and identities of concerned communities are allowed to endure [158, 159].

3.5.4 Challenges in Governance and Policy Implementation

Governance for SLR adaptation is replete with challenges that complicate successful policy implementation. On the whole, governments must balance a number of competing priorities related to economic interests, ecological conservation, and human vulnerability. For decision-makers, difficult decisions often arise regarding where protective infrastructure should be built, when managed retreat must be initiated in places vulnerable to flooding, and how resources can best be used. It involves weighing not only current risks but also long-term sustainability and resilience when decisions are made. Furthermore, the fragmentation of climate policy at the local, national, and international levels might impede the building of harmonious and comprehensive solutions. Priorities, resources, and dedication to climate adaptation may differ across jurisdictions, hence causing irregularities to arise in the implementation of policy. The resultant fragmentation can create gaps in protections and services, especially for those communities who may not have the political power to advocate for their needs. Global SLR effects will need coordination in countries that have different levels of government and also across borders. Cooperative strategies involving government, community, and private stakeholders will be crucial in developing integrated methods able to stand up to the challenge presented by rising seas [160, 161].

3.5.5 Global Inequality in Response Capacity

A big complicating factor in addressing the socioeconomic impacts of SLR is the very pronounced inequality between different countries and regions regarding the ability to respond. Richer countries, such as the United States and many European ones, have the financial wherewithal and technical expertise to invest in solid adaptation measures. These countries can afford to build sea walls, move key infrastructure inland, and implement less prevalent, more sophisticated early warning systems that reduce the impact of flooding. It is here that planning and response enable them to avoid the worst effects of rising seas and save their people and economies. On the other hand, developing nations in general, but especially small island states and low-lying coastal countries, usually lack the resources to implement such adaptation strategies. In fact, financial costs of protective infrastructure, community relocations, or enhancement of climate resilience are impossible for these countries to meet without outside help. The lack of capacity for responding makes it crystal clear that there is great inequality in the world, and simultaneously this issue worsens this inequality. Poor countries, which have contributed relatively very little to worldwide greenhouse gas emissions, are found to be disproportionately vulnerable to the impacts of climate change and hence bear an unusually greater burden. Closing this gap will take increased international cooperation and support through climate finance and technology transfer to make sure the most vulnerable nations are not left behind in the global response to SLR [162].

3.5.6 The Role of International Aid and Climate Finance

International aid and climate finance have emerged as key drivers for closing the adaptation capacity gap between the rich and the vulnerable. Institutions such as the Green Climate Fund were specifically created to provide financial assistance to developing countries on how to respond to the challenges of climate change through adaptation and mitigation activities. These funds are needed by countries that can't afford to build sea defenses, relocate communities, or install disaster preparedness systems. All too often, though, disbursement of climate finance has been slow and the sums pledged too meager in view of the scale of the problems faced in so many countries. More and more, developing countries want action on commitments over loss and damage compensation, too. It holds that countries rich in economic history and emissions should financially support those suffering the most from a changing climate's impacts-SLR, for example. To many small island states and low-lying countries, loss and damage financing is one non-negotiable mechanism to address irreparable impacts such as land loss and dislocation. Approaches meant to reinforce international finance mechanisms and increase contributions to climate funds will be critical in ensuring that resources arise to help the most vulnerable nations tackle the rising seas. It is only through addressing this growing demand for financial support-coming up with appropriate adaptation strategies-that collaboration among governments, international organizations, and private sectors shall take center stage [163, 164].

3.5.7 Psychological and Social Impacts

The impacts of SLR go beyond physical destruction of homes and infrastructure but also affect psychosocial well-being of the affected populations. The potential loss of a home, livelihood, or even community may be emotionally grave-to say the least-and is referred to as climate anxiety. This building sense of helplessness and uncertainty, particularly from vulnerable coastal areas, may further lead to chronic stress, anxiety disorders, and depression in people coming to terms with the indeterminate nature of their futures. In areas where flooding and hurricanes occur more frequently, the burden on mental health increases. This is especially true for those people who may also be vulnerable because of economic or social reasons. In addition to the psychological burdens of SLR, it can also strain the social fabrics within communities [165].

When whole communities have to move because of flooding or coastal erosion, the loss of well-developed social contacts can lead to increased loneliness, weaker community ties, and social friction. Outplacement of communities into other areas may involve integration problems that can result in potential frictions between homeless people and host communities. Moreover, the cultural dislocation related to people who must relocate from their ancestors' lands or other places of historical significance can heighten feelings of loss and disconnection. The psychological and social impacts of SLR should be considered in developing comprehensive adaptation strategies. The support services for mental health will play a very important role in supporting individuals to cope with the emotional impact of climate change, whereas building community resilience and social cohesion may reduce social disruptions among displaced people. As people begin to experience the long-term consequences of SLR, embedding mental health care within disaster response and developing programs that strengthen community ties will provide necessary supports [17, 166].

3.5.8 Opportunities for New Economies and Resilience Building

While SLR presents one of the major sets of challenges, there are indeed opportunities for innovation in resilience building and the development of new economic sectors. It is because of these changing environmental conditions that some of the pioneering coastal cities and regions develop adaptive strategies which mitigate not just the risks but also open up economic opportunities in green and sustainable industries. All these initiatives include several innovative architectural designs, from floating buildings to adaptive infrastructure that will help sustain the impact of the rising seas, through indeed cities like Amsterdam that are already working on floating housing projects, where the urban plan fits in and shows adaptation with the shifting water level. These will be adaptive structures that would bend and shock-absorb the shocks, while offering ease into adapting to the environment of the future [167].

The further effect will involve the creation of new jobs, which are related to environmental conservation, rehabilitation, and restoration, added to tourism in a sustainable manner. Rehabilitation of mangrove forests creates more biodiversity, protects coasts, and builds ecotourism to feed the local economies. Even sustainable fisheries and aquaculture benefit from healthy coastlines. Those industries will also profit from the preservation of good, quality coastlines. The need for more resilient and greener infrastructure fuels growth in the land-and-water-based industries related to wind, wave energy offshore, among others. Offshore wind farms, in addition to solar projects, constructed along coastlines, have served a dual purpose in helping reduce carbon emissions while diversified economies help those areas especially being battered by SLR. The emerging waves of economic opportunity presented in the shift toward green technologies and sustainability-based industries place coastal communities at the leading edge in adapting to a changing climate. This will allow coasts to transform these challenges into opportunities with much-needed investment in the needed development of such innovative solutions-leading toward a more sustainable and economically feasible future within the context of SLR [168].

3.5.9 Shifts in Population and Economic Centers

As SLR continues to push into coastal areas, the balance of population and economic centers will likely shift inland. In these historically busy commercial, tourist, and cultural hubs that are the coastal cities, depopulation may be seen to occur as residents and businesses alike move to areas with less risk of flooding and erosion. Inland cities generally considered safe may face rapid population increases, putting pressure on housing, infrastructure, and resources. These demographic changes will have to be addressed through urban planning by investing in resilient infrastructure, systems for resource management, and affordable housing to avoid the overcrowding of the receiving area and ensure growth in a sustainable manner. Economically, this could redefine regional economies as businesses and industries migrate from threatened coastal zones to safer inland areas. Fig 3.1 shows the areas which impacted by SLR and the affected percentage of the population. Whereas shipping and tourism industries shrink in the coastal zones, a gain in inland cities through new economic opportunities arising in the form of construction, services, and adaptive industries will be found. Governments will be particularly critical in facilitating this transition by providing investment incentives, retraining workers, and ensuring social services for those dislocated. These changes also have international effects because climate-induced migration across borders is growing, and therefore requires a common effort for the protection of populations and maintaining world stability [169].

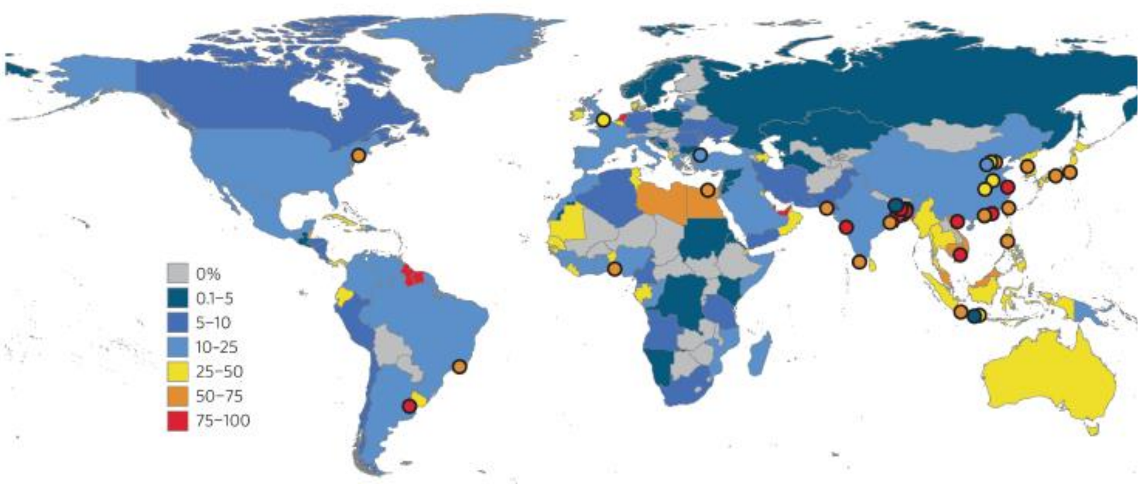

Fig 3.1: Areas impacted by SLR and the affected percentage of the population.

3.5.10 The Future of Coastal Development

SLR is going to make the threats grow dramatically, which in turn will affect how the coasts are developed in the future. Throughout much of the country, the approach to building along coastlines has moved away from expansion and toward adaptation. More and more, governments and developers are finding out that, in places, traditional development can no longer be seen or made in the same way due to the increased risk of flooding and erosion. At these locations, a retreat in the face of climate change might be managed: the communities are moved on, and the land returned to its natural state. Although very social, economic, and politically sensitive, it potentially avoids loss of life and property at locations most prone to rising seas. Elsewhere, developers explore climate-resilient infrastructure and design solutions for coastal developments that would survive episodic flooding and storm surges. The adaptive strategies involved include building elevation, floating structures, and the use of materials impervious to water inundation. Coastal cities like Rotterdam and Singapore are already leading in designing their city waterfronts to coexist with higher water levels. Decisions over the types of coastal development that will or should occur in coming decades-retreat, adaptation, or hybrid-will be central to determining how well coastal communities withstand the challenges presented by SLR [170].

3.5.11 The Role of Technology in Adaptation

Technology is, thus, increasingly becoming an essential tool in the current global adaptation effort against the rising tide. This is because, through improved predictive modeling, scientists and policymakers are able to simulate future, rising seas scenarios that may help them to identify the most vulnerable regions, thereby helping to make priorities for adaptation. Drones and satellite technology that monitor the coastal zone are a game-changer through availing real-time data on erosion, flooding, and other critical changes fundamental for early warning systems and disaster responses. The construction would be about the invention of new materials and engineering techniques to come up with resilient infrastructure which can withstand SLR. Think of elevated buildings, flexible seawalls, and flood-resistant materials. In this way, it can favor much better the challenge presented by rising seas with technological innovation. SLR is a long and complicated battle and generates considerable ecosystems, economic, and societal effects: devastation on coastal ecosystems, economic stability in concerned areas uncertain, and whole communities under threat to be displaced. Undoubtedly, it gives rise to hope against such challenges in innovation, international cooperation, and resiliency-building efforts. What are required now are means whereby, on the one hand, governments have to come together with local communities and international organizations to think out solutions that will bring in an integrated environmental, economic, and social set of approaches. Undeniably, the future is imponderable, but collective forward thinking can blunt the most intense effects of rising sea levels, securing people and the planet for times to come [150, 171].

4. Common Challenges Between Europe and Asia (Example Italy and Bangladesh)

Italy and Bangladesh are among the countries most vulnerable to climate change, but under different geographical, economic, and social contexts. Italy is a European country with a Mediterranean climate and an advanced economy, while Bangladesh is a low-lying country in South Asia, highly flood-prone with a majority of its people surviving below the poverty line. Despite such differences, both countries share a common challenge in adapting to impacts stemming from climate change, namely the rise in sea levels and extreme weather conditions. Both of these countries' coasts are exposed to the highest degrees of vulnerability, as their economies, livelihoods, and ecosystems together are under severe threat of modification. In furtherance of this understanding, this section will take on board how Italy and Bangladesh try to tackle these challenges by perusing the level of vulnerability of impacts of climate change that is quite similar yet different. We will also look at global adaptation efforts under the RCP framework, which gives different scenarios on climate change mitigation and adaptation. Comparison of approaches by the two countries will also make the highly localized nature of climate change understood as a global problem that requires international cooperation [135, 172].

4.1 Geographical and Environmental Vulnerabilities

Although Italy and Bangladesh are both listed among the countries most vulnerable to the changing climate, the nature of the challenges reflects their geographic differences: highly exposed to rising sea levels, erosion, and extreme weather events like storms and heatwaves along its very long Mediterranean coastline. Key cities include Venice, Naples, and Genoa-all very prone to flooding that could bring critical damage to cultural heritage, infrastructure, and tourist industries. Bangladesh is very much a land of lowlands, in contrast. Most of its people either dwell directly on sea coasts or are within river delta regions. Indeed, Bangladesh is a victim of tropical cyclones due to its known geographical position inside the Bay of Bengal, placing it among the most climate-vulnerable countries in the whole world.

Both are geographical vulnerabilities made increasingly serious in both countries by the growing frequency of extreme weather events: flooding and heatwaves in Italy, cyclones and storm surges in Bangladesh. In both, investment in coastal protection and early warning systems will be required, besides resilient infrastructure. It is relatively more of a challenge for Bangladesh due to higher population density in people in vulnerable areas and lower financial ability of adaptation [173, 174].

4.2 Social and Economic Impacts of SLR

SLR further endangers the economic and social structures of both Italy and Bangladesh, though with differently stated impacts. The SLR in Italy threatens vital economic activities related to tourism, agriculture, and urban infrastructures. For example, flooding in iconic cities like Venice could bring the tourism sector to a grinding halt. Similarly, saltwater intrusion and degradation of agricultural soils risk agriculture across coasts. With all these sectors put together, the protection costs are pretty high: high investment in flood defenses, coastal management, and climate-resilient infrastructure. Bangladesh, for one, presents some of the most catastrophic outcomes of SLR. Being predominantly agrarian, rural Bangladeshi people rely heavily upon land and water resources that become increasingly vulnerable with each increasing inch of rising seas. Saltwater intrusion is decreasing the availability of arable land, while frequent flooding displaces thousands and causes mass internal migration. These in turn enhance poverty and social vulnerability, since often the most affected populations have the least resources to adapt to the change. Through targeted adaptation strategies and international cooperation, both countries should try to address such socioeconomic impacts [135, 175].

4.3 Infrastructure and Urban Planning for Coastal Protection

Adaptation strategies for the protection of coastal cities and infrastructure are quite different between Italy and Bangladesh because of the large difference in both economic and geographic contexts: in Italy, for example, some large infrastructure projects have already been initiated, like the MOSE-a flood barrier system that will protect Venice against high tides. Similarly, Italy also focuses on climate-resilient urban planning by incorporating green infrastructures and sustainable urban drainage systems that would help reduce the flood risks in the cities like Naples and Genoa. While Italy has to cope with just a few issues, Bangladesh faces huge challenges in safeguarding the longest coastline and densely populated cities like Dhaka and Chittagong. It has constructed a number of flood protection measures in the country, such as embankments and cyclone shelters. However, most of these solutions are temporary and cannot cope with the ever-increasing threat of SLR. In addition, Bangladesh's financial resources are so limited that it is very hard to invest in large-scale infrastructure projects for long-term coastal protection. It therefore needs to focus on community-based adaptation and cost-effective, scalable responses while seeking international support for financing more extensive infrastructure enhancements [176, 177].

4.4 Ecosystem Loss and Environmental Degradation

Both Italy and Bangladesh contribute to a loss of biodiversity and environmental degradation due to climate change, even though it affects different ecosystems. The SLR and subsidence threaten the coastal wetlands in Italy. Examples of wetlands in Italy include those of the Po River Delta. Wetlands protect against flooding, support biodiversity, and are a carbon sink, yet they are increasingly lost either to development or through climate change impacts. In Italy, Mediterranean biodiversity is also at risk due to temperatures and changed weather patterns that the species cannot adapt to. On the other hand, in Bangladesh, there is the Sundarbans, which represents the most extensive mangrove forest in the world, providing fundamental services such as protection against storms and carbon sequestration. It also hosts rare species like the Bengal tiger, highly endangered by increased salinity and sea-level rise. If the Sundarbans disappeared, it would spell not only catastrophe for local biodiversity but also ruin the livelihood of the communities dependent on the source of that forest. Both Italy and Bangladesh have to develop and institute protection and restoration of the ecosystem that will nurse their biodiversity and help them resist the increasingly turbulent weather [178, 179].

4.5 Public Health Impacts of Climate Change

While the particular health risks differ by geographical and socioeconomic contexts, there are serious impacts on public health currently experienced both in Italy and Bangladesh due to climate change. The increasing trend of extreme weather events in Bangladesh-for example, floods and cyclones-causes outbreaks due to the waterborne disease's cholera and diarrhea. The general vulnerability and that of the coastal areas to nutritional deficiencies are due to losses of crops and absence or limited availability of water. On top of this, the higher temperatures are increasing heat-related pathologies, with increased transmission of vector-borne diseases such as dengue fever [180]. In Italy, besides a few public health issues that are interrelated with climatic change, include heat waves, air pollution, and extreme weather events. Due to the accumulation effect, heat waves are intensifying with regard to the duration and frequency, above all in the towns affected by the urban heat island phenomena. They then present a real threat to the health of that population, vulnerable as it is: elderly people and those with predisposed illnesses. Air pollution, aggravated through climate change, also contributes to respiratory and cardiovascular diseases, particularly in large towns like Rome and Milan. Both countries have to upgrade their public health systems through the implementation of an effective early warning system, improvement in healthcare infrastructure, and enhancement of public awareness of risks to health from climatic factors [181, 182].

4.6 Climate Justice and Equity in Adaptation

Climate change hits the most vulnerable sections of society in both Italy and Bangladesh, representing a critical issue of climate justice and equity. Poor, marginalized, coastal communities in Bangladesh will suffer from the worst impacts of SLR, extreme weather events, and saltwater intrusion. Most of them can hardly afford to move or make any investments in whatever adaptation measures necessary. They therefore are much more likely to get displaced and lose livelihoods. Climate justice in Bangladesh demands adaptation processes that consider rights and roles of the most vulnerable people, including women, children, and indigenous peoples. In Italy, even though the general level of vulnerability is lower, there is a great difference among regions, and especially the southern part is more at risk with climate-related phenomena like droughts and heatwaves. Other marginalized communities in urban areas include migrants and low-income residents who would also become less capable of coping with the increased climate risks. This said, the concern for climate justice in Italy would involve equitably distributed adaptation policies, resources, as well as a voice in decision-making processes within vulnerable communities. Equitable adaptation, therefore, should be at the heart of both countries' strategies to ensure that no one is left behind in the transition towards a more climate-resilient future [183, 184].

4.7 International Collaboration Role in Adaptation

International cooperation supports efforts within countries for the likes of Italy and Bangladesh to deal with the challenges presented by climate change. Membership to the European Union provides financial support and technical support to Italy in climate adaptation projects such as the European Green Deal. This joint EU approach to climate policy supports Italy in the accomplishment of its emission reduction targets and further reinforces the adaptation process in Italy through knowledge sharing and transboundary collaboration [185]. Bangladesh, as one of the developing countries, relies considerably on climate finance and international technical support to finance adaptation projects. It includes collaboration with countries like the Netherlands, which contributes experience in water management and flood protection, and international mechanisms such as the Green Climate Fund that provide vital finance for adaptation projects. Both Italy and Bangladesh have to continuously be involved in global climate diplomacy and make full use of international support to build resilience against climate change. It also helps these countries move towards global climate objectives stronger adaptive actions, as they work together on finding solutions to common problems [186].

4.8 Similarities in Climate Change Impacts

Although Italy and Bangladesh are from very far ends in geographical, climatic, and socioeconomic status, both of them have certain similarities in the way climate change affects their respective regions. The direct influence of SLR threatens both countries due to its effects on coastal communities, agricultural productivity, and biodiversity. Countries such as Italy are experiencing larger 'flood-prone' areas now, such as Venice, while in Bangladesh, the large plains along its coasts make it exposed to storm surges and erosion that could make the majority parts of this population in danger of displacement. Moreover, extreme weather conditions have been experienced quite frequently in both countries, with Italy's extreme heatwaves being more usual and Bangladesh's pattern of cyclones increasing in ferocity.

These events turn grave with the effects of global warming, hence affecting the livelihood, health, and infrastructure. In both countries, these impacts are especially affecting the most vulnerable populations in low-income groups or those living in coastal or rural areas, creating a common challenge to mitigate social inequalities exacerbated by climate change [187, 188].

4.9 Differences in Climate Change Impacts

Though both Italy and Bangladesh are similarly affected by the vagaries of climate change, the nature and extent of risks vary significantly. Italian coastal cities are mainly at risk from flooding, erosion, and heat island effects. Impacts compromise, among others, tourism and agriculture, generalized loss in the quality of life, especially in southern regions. Italy has the high level of economic development, meaning flood barriers and climate-resilient urban planning can be more realistically brought into existence [172, 175]. In Bangladesh, the problems to be surmounted are much greater: low-lying geography, dense population, and economic limitations make its plight worse. Indeed, much of its land lies just a few meters above sea level. Hence, Bangladesh is highly prone to disastrous flooding, cyclones, and loss of arable land due to saltwater intrusion. Bangladesh, unlike Italy, enjoys neither financial nor technological capability to protect its population fully against such impacts, which in turn has been accentuating poverty, food insecurity, and internal displacement [135].

4.10 Global Adaptation under RCP Frameworks

The RCPs supply a framework for assessing the possible future impacts of climate change under various scenarios of greenhouse gas concentration. Both Italy and Bangladesh will have to face reduced emissions and mitigation strategies that result in the decrease of climate risks according to the RCP framework. Taking into consideration one of the high-emission scenarios-RCP 8.5-it would leave both countries at the mercy of disastrous SLR, extreme weather conditions, and an increased frequency of natural disasters with the adaptation possibility that will be increasingly difficult and expensive. The changes in climate, under the lower-emission scenarios like RCP 2.6, would be pretty insignificant in their effects on Italy and Bangladesh while allowing more scope for adaptation to the changed climate in the long run for both the countries. For instance, fewer cases of heatwaves and coastal flooding could occur in Italy, while Bangladesh might feel the impact of the slackened SLR and reduced intensities of storms, making the adaptation more possible. In any case, global cooperation in emission reduction will be relevant for both countries in trying to avoid worst-case scenarios under the RCP framework [124, 189].

4.11 Shared Socioeconomic Pathways and Global Adaptation (SSP)

The SSP framework supplements RCP with various future scenarios based on global development trends in socioeconomic pathways. In SSP1, which is a development pathway that is sustainable, there is increased international cooperation, technological innovation, and equitable resource distribution that would prevail in both Italy and Bangladesh. This would naturally result in more adaptation efforts in the two countries through investments in climate-resilient infrastructure and stronger social safety nets that truly protect the vulnerable [190]. SSP3 is characterized by regional rivalry and a lack of global cooperation, while under this pathway, the inability of both countries to adapt to the increasing impacts of climate change would be real. Fig 4.1 shows probabilistic 2100 global mean SLR projections for SSP marker scenarios. showing medians and minimum/maximum 66% ranges for the individual pathways pooled by their radiative forcing targets (FTs) and the SSP baseline scenarios [191]. Fig 4.2 illustrates the fractions of 2050 primary energy (PE) from non-CCS fossil fuels and 2050 PE from non-biomass renewable energy of 2050 total PE in panels (*a*) and (*c*), their relative changes between 2010 and 2030 as percentage from 2010 levels in panels (*b*) and (*d*). This figure also shows that the carbon price percentage in 2050 change carbon intensity relative to 2030 levels in panel (*f*). PE is expressed using the direct energy equivalence method. The SSP scenarios are listed with colors indicating the SSP category and symbols referencing the specific FT. The highlighted pathways represent the marker scenarios for each SSP category. SSP and FT bars on the sides of the panels show corresponding min/max ranges [191]. Vertical boxplots with 90% range whiskers, 50% range boxes and black medians subsume SLR trajectories falling under the individual SSP indicator categories. Dashed vertical gray lines indicate the category bounds in each panel. Global mean SLR is provided in centimeters relative to the 1986–2005 mean. In this case, Italy would be caught in economic stagnation and political fragmentation, thus having limited capability to invest in urgent adaptation measures. Bangladesh would get very limited access to international climate finance and technology, increasing their vulnerability to SLR and extreme weather events. Global socio-economic development, as projected within the framework of SSPs, makes the crucial difference in the effectiveness of adaptation strategies of both regions [192, 193].

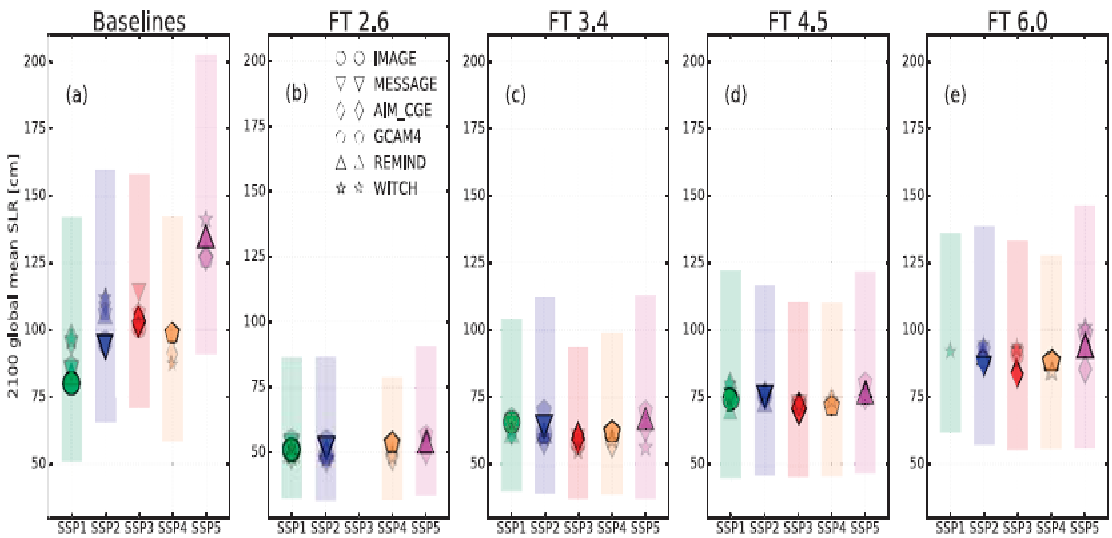

Fig 4.1: Probabilistic 2100 global mean SLR projections for SSP marker scenarios.

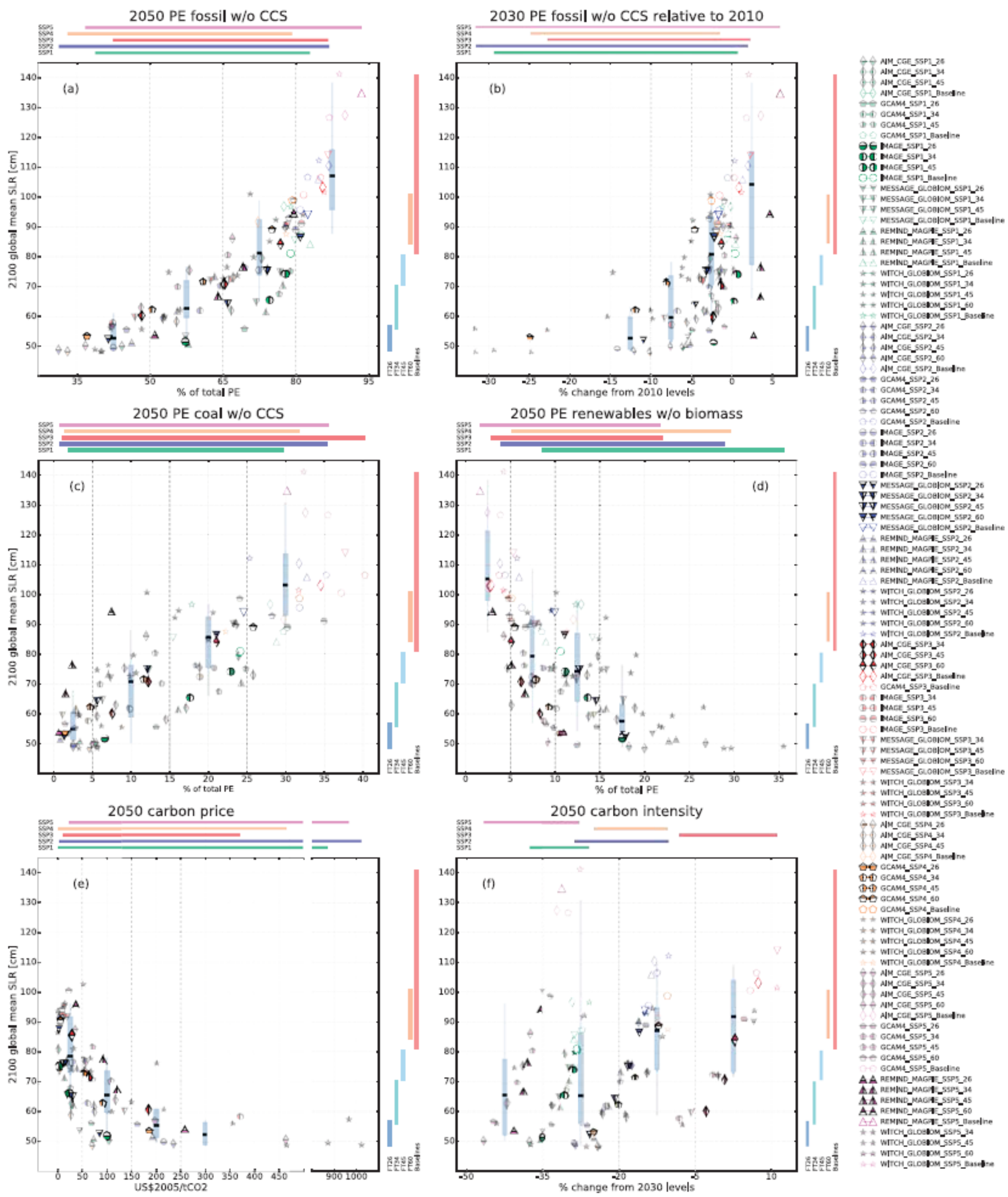

Fig 4.2: Selected SSP indicators plotted against 2100 globalmean SLRmedians relative to 1986–2005 for every available SSP scenario.

4.12 Strategies toward Adaptation: A Comparative Perspective

Both Italy and Bangladesh have built up their adaptation strategy at the national level to cope with climate change impacts. Their scales, scopes, and focuses are turning out to be peculiarly different, considering the basic socio-economic and geographical contexts. The Italian adaptation strategy will be designed in such a way as to aim at making urban planning, infrastructure development, and natural resource management more climate-resilient. This has been evidenced in the flood defense systems like that MOSE system in Venice and the green infrastructures installed in various cities with the objective of reducing the country's vulnerability against extreme heat and flooding. Italy enjoys institutional capacity that is well-developed and hence permits articulated interventions by different regional and local governments. Adaptation strategies most prevalent in Bangladesh include disaster risk reduction owing to its high exposure to cyclones and flooding. Other Bangladeshi adaptation measures involve community-based approaches: the construction of cyclone shelters, early warning systems, and climate-resilient housing. Upscaled measures are however beset by huge financial and institutional barriers. Hence, the adaptation strategies that are commonly adopted by this country usually hang on foreign support and finance. While countries have indeed done these adaptation initiatives, the striking difference in resources and capacity contributes differently towards long-term resilience [194-196].

4.13 The Role of Technology in Climate Adaptation

Technology is nonetheless one of the most relevant roles in adaptation strategies in both countries, even though technology is at different advancement stages between the two. The very foundation of adaptation in Italy consists of high engineering solutions related to flood barriers, early warning, and smart city initiatives. Similarly, Italy is investing in renewable energies, such that solar and wind powers are increasingly integral to its energy mix, reducing dependence on fossil fuels, hence increasing its general climate resilience. In the case of Bangladesh, although the access to advanced technology has been limited, technological innovation in the fields of early warning systems of cyclones and flood forecasting has helped the country. Mobile technology is increasingly distributing climate-related information to the most isolated communities, hence enabling people to take quicker action against extreme weather events. Bangladesh is, on its part, studying innovative and low-cost solutions to adapt its agriculture with the shifting climate, such as floating farms or climate-resilient crops. Both countries benefit from technological advancement, but scaling up remains the challenge for Bangladesh due to resource constraints [197, 198].

4.14 Cultural and Historical Considerations in Climate Adaptation

In developing a climate adaptation strategy, both countries have to take into consideration cultural and historical factors. For Italy, with heritage cities like Venice and Rome, adaptation becomes quite complicated. These cities are both at risk due to rising sea levels and extreme weather conditions, but also need special attention to protect historical landmarks and unique urban landscapes. A delicate balance needs to be found between climate resilience and the preservation of Italy's great cultural heritage. In Bangladesh, deep-seated cultural traditions and historical experiences in a life with floods and cyclones have formed the country's approach to climate adaptation. Traditional knowledges and practices such as building houses on stilts and daily commutes via boats have been developed by flood-prone communities to cope with extreme weather. However, the increasing severity of climate impacts necessitates that modern adaptation strategies complement such indigenous practices. Understanding the cultural context is an important influence in designing adaptation measures socially acceptable and effective in both countries [199-201].

4.15 Climate Change and Migration: Italy vs. Bangladesh

While migration is indeed an important issue related to climate change in both Italy and Bangladesh, the dynamics are very different. Climate-induced migration is already a fact in Bangladesh, as thousands of people are displaced yearly due to either flooding, SLR, or river erosion. The most common internal migration flows are from inland and particularly from coastal rural areas to large cities, such as Dhaka, placing further pressure on already overpopulated cities. This internal migration does create immense problems for Bangladesh in terms of housing, employment, and public services. In contrast, Italy has to face international migration. Climate change acts as one of many drivers behind migration inflows from Africa and the Middle East. It nurtures droughts, food insecurity, and conflict in these areas, which pushes people towards refuge in Europe. Italy, although one of the primary entry points for Mediterranean crossings, is thus faced with humanitarian and social challenges within the context of this migration. It has therefore balanced its climate adaptation needs. Both countries illustrate how climate change acts as a driver of migration, albeit in different ways [64, 202].

4.16 Education and Public Awareness in Climate Adaptation

Public awareness and education are highly instrumental in raising resilience in both Italy and Bangladesh. Greater public consciousness of the reality of climate change has grown through media coverage, scientific research, and the advocacy of environmental organizations in Italy. Public campaigns on reducing carbon footprints, conserving water, and preparing for extreme weather events have become more common. Furthermore, climatic change inclusion in the school curriculum has been done, hence assuring a new generation that will be environmentally conscious. In Bangladesh, different kinds of awareness among the general public have been conducted, mainly on disaster preparedness and risk reduction due to its vulnerability to cyclones and floods. Thus, community-based organizations are taking the lead in educating people on early warning systems, evacuation plans, and climate-resilient agricultural practices. However, long-term adaptation strategies still need to be extended further in education, especially in the rural areas where access to information is low. Therefore, both countries realize the potential of education and public awareness for a resilient culture and preparation of their populations for the impacts of climate change [203, 204].

4.17 Economic Costs of Climate Adaptation

These economic costs are clearly high both for Italy and Bangladesh in adapting to climate change, but they differ in a number of manifestations based on their different development statuses: protecting infrastructure and retrofitting buildings for energy efficiency in Italy are highly cost-inclusive, as well as large-scale engineering projects such as flood barriers. These are matters requiring huge public and private investments. Still, the strong economy of Italy, in addition to its access to European Union funding, offers partial financial stability to all such efforts. In Bangladesh, on the other hand, the economic costs of climate adaptation are extremely acute since the country has limited financial resources. Adaptation needs to SLR, flooding, and extreme weather events call for investments in infrastructure, agriculture, and public health systems that are just too expensive for the country's budget. Therefore, Bangladesh is highly dependent on international climate finance, grants, and loans in order to realize its plans for adaptation. The sharp economic resource contrast of the two cases-Italy and Bangladesh-further raises questions on equitable global financial mechanisms that will allow the most vulnerable countries to adapt to climate change [175, 205].

4.18 Challenges in Institutional Capacity and Governance

The most influential factors that would, therefore, shape adaptation strategies in Italy and Bangladesh are the institutional level capacity, coupled with governance. Italy is a developed country and has relatively strong institutional frameworks in terms of climate adaptation at both national, regional, and sub-national levels. The Italian Government has integrated the aspect of resilience in climate into the current policy, and hence coordination from various sectors such as urban planning, environmental protection, and disaster risk management increases poised response toward climate challenges. Bangladesh has done remarkably well in climate governance. However, there is a number of challenges faced concerning institutional capacity and coordination. These are the country's climate resilience policies, at least as stated in the country's national adaptation plan. In most cases, however, their actual implementation falls prey to limited resource allocation, bureaucratic inefficiencies, and a lack of coordination among the different agencies. Moreover, corruption and political instability might undermine efforts at adaptation, especially at the level of local self-government. This would surely enhance their capacity of institution and governance, which is much crucial for Bangladesh and Guyana for implementing their adaptation strategies correctly, but Bangladesh needs more international support to overcome challenges [206-208].

4.19 Looking Forward: A Shared Vision for Global Adaptation

Italy and Bangladesh both continue to grapple with the impacts of a changing climate. While there is an increasingly intense realization that responses need to be framed in their specific contexts, the broader context enacted by climate change presents one where responsibility is shared. These two countries are part of an international community that has to make efforts toward a reduction of emissions, enhancement of climate resilience, and assurance of protection for the most vulnerable among the population. The success of climate adaptation both in Italy and Bangladesh is going to depend on international cooperation, equitable access to resources, and adherence to the principles of climate justice. Where Italy should be playing the role of a developed nation, Bangladesh stands in need of its financial and technical support. In turn, Bangladesh's experiences can offer lessons in community-based adaptation and building resilience. Eventually, a collaborative action for global climate resilience calls for a shared vision concerning a common future: sustainable [209].

5. Summary and Conclusion

This thesis encompasses the now-very-relevant concern of SLR and its impacts to the coastal areas around the world. Being one of the major effects of climate change, SLR is not just a product of ocean water thermal expansion but also glacier and ice sheet melting. The process has been going on for the last two centuries with great acceleration due to anthropogenic factors. Changes in sea levels viewed from a historical perspective to present and into the future are discussed, while various drivers of SLR are also outlined. The discussion of SLR vulnerability deserves due weight in this paper by providing an overview that identifies many factors adding up to exposure in relation to coastal hazard vulnerability. This is where the CVI plays an important role in assessing how much coastlines are likely to stand up to a rise in sea level. These take into consideration shoreline characteristics, wave exposure, and regional sea level rise trends. Since the vulnerability of such regions is on the rise, the approach towards hazard assessment as well as adaptation should, therefore, be multi-faceted in nature.

Other focuses involve setting the risk in the context of the SLR. In this respect, the thesis explores an increase in risks of see storms, erosion of the coastline, and saltwater intrusion. The foregoing factors have their severity increased by increasing storms and storm surges that have been increasing with intensities heightened by climate change. Indeed, unprecedented threats face the coastal communities who need urgent attention and actions. Historical records of SLR suggest that the rate has accelerated from 1.4 mm/yr between 1901 and 1990 to 3.4 mm/yr between 1993 and 2020. The rate is also increasingly an accelerating trend that threatens major coastal ecosystems and human settlements. About 10% of the world's population inhabits low-lying lands less than 10 m above sea level, most of whom are especially the most vulnerable, while effects of SLR may last for many decades to come. Probably one of the most dangerous SLR consequences is an increase in coastal flooding.

Both the actual flooding-either through gradual sea level rise or more violent storm events-threatens to destroy homes, infrastructures, and ways of life. Flooding of lands can dislocate populations and create "climate refugees"-one of the growing anxieties from a governmental and international point of view. Coastal flooding causes economic losses in industries such as tourism, fishing, and agriculture.

Another crucial manifestation of SLR is the erosion of coasts, which befalls the land to get lost and causes possible degeneration in an ecosystem. Consequently, with eroded shorelines, beaches, wetlands, and numbers of habitats have started to appear underwater. Nevertheless, natural barriers such as mangroves and coral reefs still protect from surge storms and erosion. SLR has great effects on water resources. For example, saltwater intrusion into freshwater supplies from higher sea levels and reduced access to clean drinking water for the people in a coastal community can be particularly problematic in areas reliant on groundwater supply as a source of water for agriculture and human uses. Loss of freshwater resources through saltwater intrusion can have cascading impacts on food security and public health. Impacts of SLR, therefore, besides being purely social and economic, are much more pervasive. Beyond the loss of land and infrastructure, cultural and historic sites along coastlines are under threat from rising seas. Heritage sites are often an integral part of the local identities and economies that get destroyed by erosion and flooding. The economic costs of adapting to SLR are still quite high, especially in developing countries which lack the wherewithal to put in place extensive protective measures. Moreover, SLR also increases health risk. In cases of coasts flooding, this can lead to a general proliferation of waterborne diseases alongside breeding sites for insects carrying diseases. In some areas, the dislocation from rising seas may be exacerbating health problems in terms of the lack of access to medical treatment and stresses on health services.

The thesis has tried to give weight to SLR adaptation at traditional coastal defense frontiers. A number of countries have, for many years, been committed to the prevention of flooding and erosion by means of "hard" interventions represented by seawalls and levees. These interventions are becoming ever more inefficient and expensive, with the impacts of climate change making themselves felt with ever greater intensity. However, there is an increasing realization that these need to be supplemented with "soft" measures. Ecosystem-based adaptation has now become an attractive alternative wherein natural systems are being tapped to help in coastal resilience. Mangroves, wetlands, and coral reefs protect coasts against surge storms erosion and flooding. These ecosystems protect the shoreline but also provide a number of other services around carbon sequestration, habitat for wildlife, and livelihood support. This integration of ecosystem-based adaptation into coastal management plans empowers communities to develop sincerely more sustainable and cost-effective adaptation approaches, relative to the challenges posed by SLR, and preserves valuable natural resources. It hence reflects the idea of a dual approach: on one side, ecosystem-based solutions must be combined with traditional infrastructure in order to develop holistic and more resilient strategies of coastal adaptation to climate change. This sort of system would be a barrier against storm surges and flooding, among others. Other ecological services that would also result from such a system include carbon sequestration and habitat for marine species. Investment in the protection of such natural defenses lowers coastal communities' vulnerability to SLR. Besides adaptation to the environment, the policy frameworks also play a vital role in managing the risks of SLR. It has to be ensured that governments establish detailed planning for coastal management based on both short-term hazards and long-term trends. These integrate scientific data of SLR with inputs from the community to make sure that whatever adaptation measures are indeed effective and equitable. SLR is a problem that requires international cooperation, at the very least. The adaptation costs are huge, ranging from re-designing and reinforcing coastal infrastructure such as roads, bridges, and ports against a higher sea and frequent storms. In many cases, managed retreat may be the most economically suitable option; it involves removing communities and infrastructure from the vulnerable coastlines. These steps have tough political and social ways, needing careful planning and large amounts of economic investment. On the other hand, it encapsulates opportunities for innovation: new technologies such as GIS-based tools for SLR mapping and advanced climate modeling; improving the capability for forecasting and managing coastal risks. These new capabilities provide the ability for policymakers and planners to make more strategic decisions on where and how to invest in adaptation measures. Climate finance opens new sources of funding for SLR adaptation projects.

International efforts, such as the Paris Agreement, give important pathways to address the global nature of SLR and climate change. Most countries of the world have committed themselves through a course of reduction in greenhouse gas emissions, building up climate resilience within their national adaptation plans. However, how all that plays out depends on sustained commitment and availability of financial resources to support vulnerable regions, especially in the Global South. A case study between Italy and Bangladesh highlights the very different challenges and opportunities presented by SLR around the world. While both countries are highly vulnerable to a rising sea, approaches toward adaptation diverge on account of reasons relating to economic resources, governance structures, and environmental conditions. The common messages emanating from these case studies bring into focus the tailored solution needed in keeping with local needs and capacities. This thesis therefore summarizes causes and impacts, as well as prospective solutions to SLR by incorporating scientific research, policy analysis, and case studies in a holistic approach to some of the most challenging environmental problems of the modern world. The urgency for proactive, innovative, inclusive adaptation strategies for SLR is real and is continuous. It would be tough to save the coastal communities and ecosystems from worst damages due to SLR unless a good score of coordination is achieved at a global level.

Based on the information that thesis provided, it can be concluded the natural variability and anthropogenic factor together at present promote SLR at a global scale, which presents an unparalleled challenge to coasts. This paper has highlighted the acceleration of SLR trends, the attendant flooding and erosion hazards, and the widespread implications for ecosystems, infrastructure, and human society. Sea level rise in the 21st century will continue to accelerate, with the result that all types of risks to the well-being and livelihoods of millions of people who stay in low-lying areas along coastlines. These call for an all-inclusive approach to be considered-from fortifying coastal defense and conservation of natural systems to the efficient use of available policy frameworks. Adaptation strategies are a delicate balancing act between immediate protective measures and long-term planning. Considerations should be based on projected estimates in terms of sea level rise. What is required now is international cooperation and financial assistance, particularly to those regions which are most vulnerable and thus far are unable to cope with the effects of SLR due to the lack of means. Ultimate responses to SLR will require capability both technological and scientific, complemented by a strong commitment to global cooperation and equity. A set of environmental, social, and economic problems link the coasts throughout the world that can only be approached effectively through common action toward a resilient future of human and natural systems.

Acknowledgements

I want to express my gratitude to my thesis advisor Prof. Angela Celeste Taramasso, for their support and invaluable guidance, throughout this thesis.

Special thanks are due, to the professors and staff at the University of Genova, for their guidance and assistance that enabled me to earn my Master’s degree.

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