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Review

Recent Developments in Sea-Level Rise and Its Related Geological Disasters Mitigation: A Review

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Abstract: With the rapid development of urbanization around the world, the sea-level-rise problem is gaining more and more attention in the 21st century. Sea-level rise is the result of a combination of climate-related factors, structural factors and human activities. Recent studies related to the contributions of these factors to sea-level rise are reviewed and analyzed in this paper. The results suggest that the melting of glaciers and ice sheets have contributed the most to sea-level rise and will continue to be the dominant factor in sea-level rise for the following decades. As sea-level rise becomes an increasingly serious problem, geological disasters related to sea-level rise are also gaining more attention. To better understand the effect of sea-level rise on geological disasters, relevant issues including storm surges, seawater intrusion, the loss of coastal wetland, seismicity, seismic liquefaction and submarine mass failure are further reviewed and highlighted. In response to the risks of those disasters caused by sea-level rise, some disaster mitigation measures are proposed, and in the end, the quantitative disaster assessment concept based on resilience is introduced to the coastal urban system, to assess its ability to resist and recover from geological disasters due to the sea-level rise.

Keywords: sea-level rise; factors leading to sea-level rise; geological disasters; risk mitigation; resilience

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1. Introduction

Sea-level rise is one of the most significant phenomena affecting future human development. Sea-level rise threatens to submerge island countries and coastal regions in which approximately 44% of the world's population lives [1]. Sea-level rise can not only submerge coastal areas, but also lead to some geological disasters, which usually result in loss of life and properties [2–4], and thus some coastal zone residents have been forced to move away from places threatened by the seawater [5]. Between 1901 and 2010, various scholars have used different models to measure the rate of sea-level rise over different time scales, and the average rate of sea-level rise is about 1.7 mm/year with a fluctuation range of 0.5 mm/year to 3 mm/year despite these differences [6]. Since the end of the last century, more precise devices, such as the altimeter satellite, have been used to measure the rate of sea-level rise, showing rates up to 3.3 mm/year from 1993 to 2010 [6]. With the passage of time, the value of sea-level rise observed from the tide gauge and altimetry has become approximately 3.6 mm/my per year from 2006 to 2015 [7]. In recent years, satellite altimetry shows that the global average sea level is rising at an increasing rate along with the disappearance of glaciers in some places (Figure 1) [8,9]. These findings indicate that the rate of sea-level rise is higher compared with previous rates shown in Figure 2. Affected by a variety of reasons, the sea-level rise shows different trends globally, but overall, it has an upward trend globally in densely populated coastal cities and only a downward trend in local areas scattered in the Russian Far East and northern Europe (Figure 3). Thus, sea-level rise has become an urgent issue that warrants more attention.

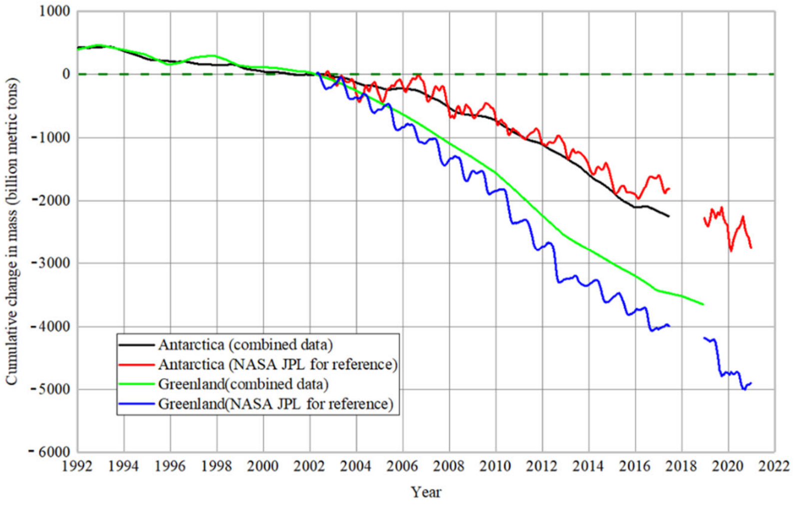


Figure 1. Cumulative mass balance of Greenland and Antarctica, 1992–2020.

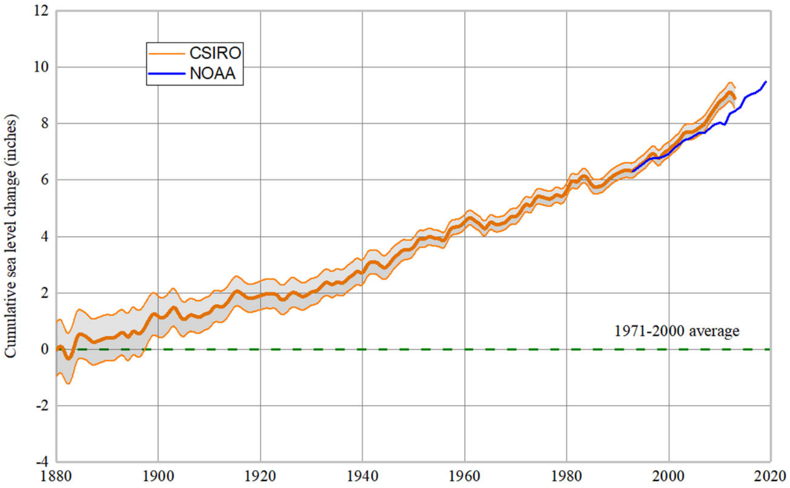


Figure 2. Global absolute sea-level change, 1880–2019.

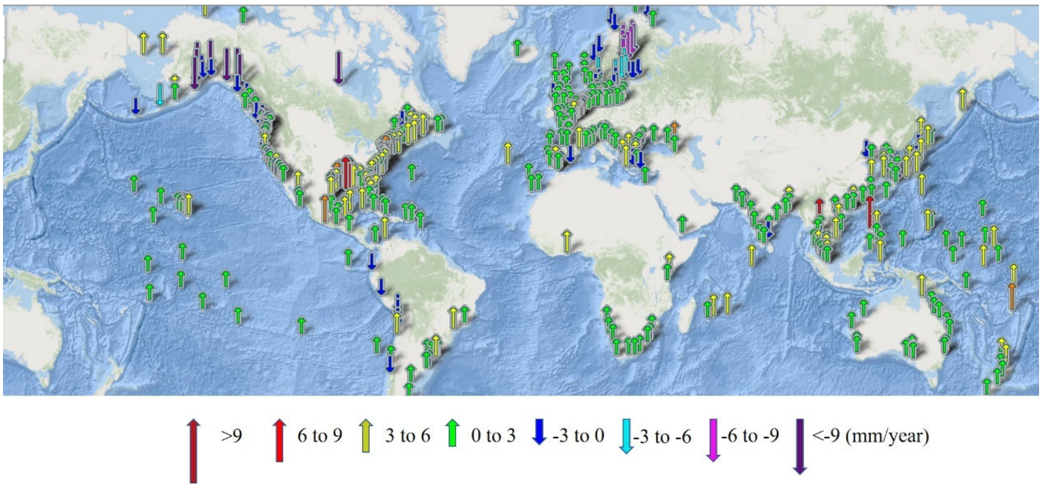


Figure 3. Global sea-level rising trend.

With the continuous change of climate, the rise of the sea level has led to various geological disasters worldwide, and their frequency may increase in the future. Some impacts of sea-level rise are well known, such as the submergence and flooding of coastal land [10–12], the destruction of wetlands, salt marshes, and mangroves [13–15], increased storm surges [16,17], seawater intrusion [18,19] and the destruction of port and harbor facilities [20]. Besides this, sea-level rise can also induce seismicity, seismic liquefaction and submarine mass failure, which are rarely discussed comprehensively in the literature. Sea-level rise may also lead to higher sea surface wave heights, increasing the operational risks of marine engineering and marine energy investment [21–24]. Thus, comprehensive research on recent developments in sea-level rise and relevant geological disasters is needed. As the sea level continues to rise in the future, the frequency of geological disasters associated with sea-level rise will increase accordingly, so it is necessary to conduct necessary disaster assessment and management for coastal cities. In recent years, with the proposal of the concept of resilient cities, which emphasized the need to assess the ability of city systems to resist and recover from disasters, people pay more attention to the resilience of cities nowadays. Therefore, we introduce the concept of resilience to the field of evaluation and prevention of geological disasters caused by sea-level rise in coastal cities, to realize effective risk control.

In this paper, we summarize recent studies on sea-level rise and related geological disasters. The contributions of climate-related and human-related factors to sea-level change are discussed. Geological disasters, including the decrease in coastal wetlands, seawater intrusion, storm surges, submarine landslides, earthquakes and seismic liquefaction, are also discussed. Some recommendations and mitigation methods are further proposed. In addition, from the perspective of disaster management, the new resilience-based concept is introduced to the prevention and control of related disasters caused by the sea-level rise in coastal cities.

2. Factors Contributing to Sea-Level Rise

The ongoing rise in sea level is the result of many factors, including climate factors, structural factors and human-related factors [16]. Climate change is the main cause of the sea-level rise, which can be classified into three categories [25], namely thermal expansion of the oceans, the melting of glaciers and small ice caps and the melting of the Greenland and Antarctic ice sheets. In recent decades, many studies have discussed glacier and ice sheet melt and their contribution to sea-level rise [9,26–29]. However, several human-related factors also contribute to sea-level change, such as underground water and oil mining, deforestation [30] and dam construction along rivers [31], even if the impact on the sea-level rise is not as great as glaciers and ice sheets. Finally, in some coastal areas at a low altitude, such as Venice in Italy, the degree of sea-level rise caused by tectonic factors may be greater than the degree of sea-level rise caused by glaciers, and this kind of geological movement will also bring disasters as a result of the sea-level rise [32]. Here, we summarize and analyze these factors (Figure 4).

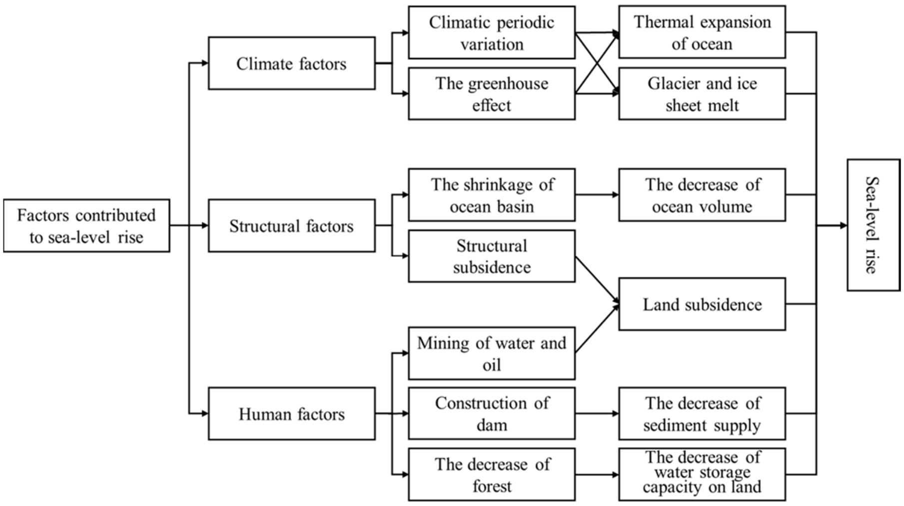


Figure 4. Factors affecting sea-level rise and their mechanisms.

2.1. Major Factors

2.1.1. Thermal Expansion of the Ocean

Assuming that the mass of seawater is a constant value, the density of seawater changes inversely with the increasing ocean temperatures, caused by the emission of greenhouse gases [33]. As a result of the rising temperature, the volume of seawater gradually becomes larger, which leads to the rise of the sea level to a certain extent. From 1950 to 2020, the temperature trend of the seawater surface temperature was almost the same as the change trend of the carbon dioxide concentration, and especially in recent years, the surface temperature of seawater has shown a clear upward trend (Figure 5). In the last century, scholars used limited time-series data and different models to analyze the effect of oceanic expansion on sea-level rise, and different results and conclusions have been drawn. Based on the self-developed measuring apparatus and additional data collected from recent decades, Levitus, Antonov [34] revealed that thermal oceanic expansion has increased considerably. Thermal expansion has contributed to approximately 25% of the sea-level rise since 1960 [35]. From 1993 to 2009, Cazenave and Llovel [36] concluded that the ocean temperature rise has contributed to approximately 30% of the global sea-level rise. Under the conditions of RCP 8.5, IPCC analyzed the trend of sea-level rise due to thermal expansion using the Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models, and they believe the potential sea-level rise will be greater than 12 cm by 2100 [6]. Judging from the results of these studies, the change in the volume of seawater itself caused by the rising climate cannot be ignored.

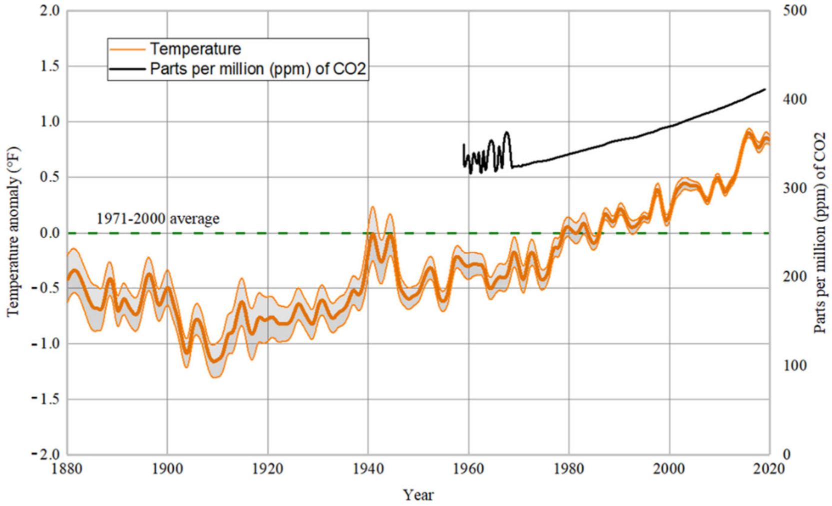
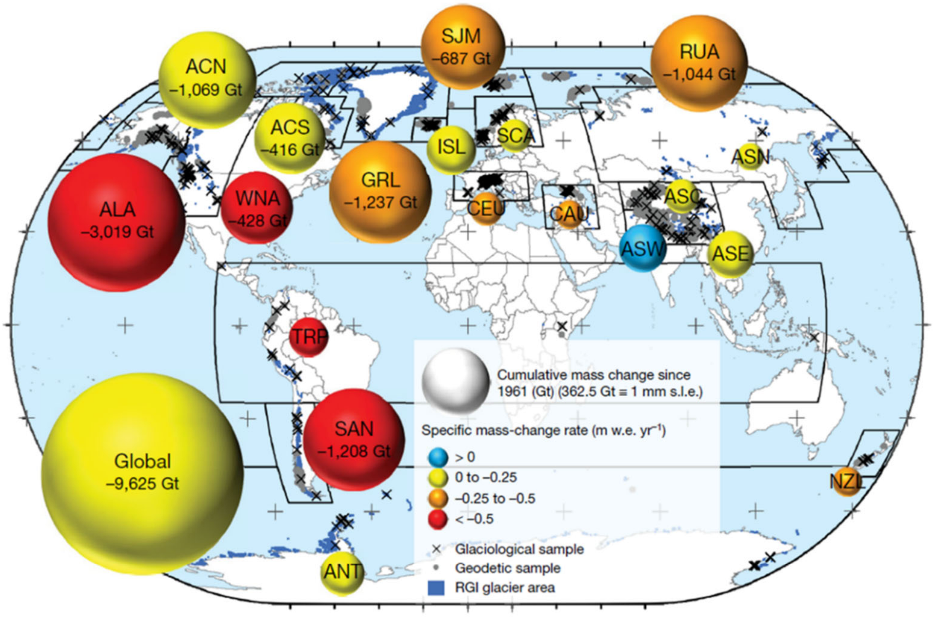


Figure 5. Ocean surface temperature (1880–2020) and the concentration of carbon dioxide in the air (1950–2020).

2.1.2. Glacier and Ice Sheet Melt

Global climate change has also affected the melt of glaciers and ice sheets, which may cause the sea level to rise more than 2 m [20,37,38]. Due to the limitations of measuring apparatus early in the last century, only a few scholars measured the contributions of glacier and ice sheet melt to sea-level rise. Meier [39] used sparse data to study the contribution of retreating glaciers and found that it contributed 2.8 cm to the sea-level rise in 1900–1961 (0.46 ± 0.26 mm/year). With the development of science and technology, different remote sensing tools, including airborne sensing tools, satellite radar, altimetry, InSAR and space gravimetry, were applied to measure the mass change of polar ice sheets since the 1990s [40]. Since then, more attention has been paid to glacial and polar ice sheet melt to estimate its primary contributions to sea-level rise [26,41–43], and the contribution of glaciers in each region to the rise of the global picture is shown in Figure 6. In general, ice sheet melt led to approximately 15% of the sea-level rise between 1993 and 2003, and this contribution has nearly doubled since 2003 [44]. As the melting of continental glaciers increases, Jacob, Wahr [27] showed that glacial and ice cap mass decreased by approximately 148 ± 30 Gt/year from 2003–2010, and its contribution to sea-level rise is about 0.41 ± 0.08 mm/year. Although people realize that climate change is behind the fact the sea has risen, and corresponding energy-saving and emission reduction measures have been adopted, sea-level rise still continued after 2010. During the period from 1992 to 2018, the average sea-level rise was about 10.8 mm due to the melting of Antarctic glaciers [43], which was essentially consistent with the rate estimated by Jacob, Wahr [27]. To date, as greenhouse gas emissions increase, the melting of glaciers and ice sheets caused by climate change has become the main factor of sea-level rise, which has contributed around 50% in the process of the sea-level rise [45,46], and this situation, accompanied by huge uncertainty, is likely to be sustained or increase in the future [26,47,48], so we should focus on the changes in glaciers and climate through more advanced observation methods while observing sea-level rise. In addition to this, the effective control of climate change and the reduction in greenhouse gas emissions is also one of the measures to control sea-level rise. For example, the G7 pledged in 2021 to halve collective emissions by 2030, and they will halt international funding for any coal projects that lack technologies to capture and store carbon dioxide emissions. Similarly, the EU's 2021 proposal for the second part of its climate change plan, which covers areas such as building renovations, methane emissions regulation and greener gas fuels, aims to accelerate progress towards the goal of zero emissions by 2050.



ACN, Arctic Canada North;
ACS, Arctic Canada South;
ALA, Alaska;
ANT, Antarctic and Subantarctic;
ASC, Central Asia;
ASE, South Asia East;
ASN, North Asia;
CAU, Caucasus and Middle East;
CEU, Central Europe;
GRL, Greenland;
ISL, Iceland;
NZL, New Zealand;
RUA, Russian Arctic;
SAN, Southern Andes;
SCA, Scandinavia;
SJM, Svalbard and Jan Mayen;
TRP, Low Latitudes;
WNA, Western Canada and USA;

Figure 6. The contribution of glaciers to sea-level rise from 1961 to 2016 (revised from Zemp, Huss [9]).

2.2. Secondary Factors

Some anthropogenic activities, such as groundwater extraction and oil extraction, cause subsidence in some coastal cities resulting in the elevation of the ground being lower relative to the elevation of the sea level [49–51]. Variations in in-land water are another factor related to sea-level rise, including the aforementioned groundwater extraction and other human activities, such as irrigation and deforestation. The mechanism of their effect on the sea-level rise is almost the same as that of groundwater extraction, that is, the head of the freshwater area in the coastal area is significantly lower than that of seawater. Bennett [30] suggested that these factors contribute little (< 10%) to sea-level rise. In addition, the intensive building of dams during the second half of the last century along rivers also affected sea-level change, lowering overall levels by 0.5 mm/y [31]. Dam building also reduced the sediment supply to river deltas, increasing the effect of sea-level rise in these areas. Although these factors have an impact on the rise of sea level, the degree of impact is not easy to determine. Structural factors mainly include the decrease in ocean volume and land subsidence caused by tectonic movement, and their contribution to sea-level rise is approximately 10% in addition to the contribution of ocean thermal expansion, glacier melting and human activities. However, from a local perspective, such as Italy and the Mediterranean, the relative rise of the sea level caused by vertical geological movement far exceeds the impact of glacier melting and ocean thermal expansion [7,52–54], so the contribution of vertical geological movement to sea-level rise deserves to be further determined.

In different historical periods, the contribution of various reasons to the rise of the sea level can be determined to vary. So far, we can only determine approximately 30%, 50%, 10% and 10% of the contribution to sea-level rise to be the result of ocean thermal expansion, glacial ice melting, human activities and geological movements. However, this can only be a vague number, because there are differences in different places, which can reach more than 30% on a global scale. If specific contribution values for each cause are required, this needs to be explored on a local scale rather than a global scale.

3. Sea-Level Rise Influences on Geologic Hazard

With the increase in sea levels, geological disasters have struck low-lying areas, affecting many cities and people. The frequency and magnitude of these geological disasters have been increasing due to sea-level rise. In this section, traditional disasters resulting from sea-level rise, as well as sea-level rise-related seismic liquefaction, seismicity and submarine mass failure are reviewed.

3.1. Storm Surge

Storm surges are serious marine disasters that seriously affect local residents, infrastructure and ecosystem including various types of marine structures and foundations used in marine energy development [21,55,56], and with the change in storm climatology, coastal flooding caused by this kind of disaster has attracted global attention [57–60]. To mitigate the effects of storm surges, quantitative analyses on the influence of sea-level rise on storm surges are of great importance. Karim and Mimura [61] used a hydrodynamic model to investigate the influence of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh and found that flood-risk areas and flood depth will increase by 15.3% and 22.7%, respectively, with a 0.3 m sea-level rise. A GIS-based approach was applied by Shepard, Agostini [62] to study the effects of sea-level rise on the storm surge risk in Long Island, New York. The research shows that the exposure risk to seawater of these areas has increased, which is basically consistent with the results of Arns, Wahl's [63] study on coastal storm surges caused by sea-level rise in the northern part of German Bight. In recent years, based on the finite-volume coastal ocean model, Lippmann, Simpson [64] argued that a 10–30% rise in the sea level of New Hampshire Estuaries will cause a 23–52% increase in storm surges in the area. It is easy to determine from past research that the intensity of storm surges caused by the sea level has increased [65,66], which will cause great changes to the appearance and deposition process of coastal areas or islands, with continuous changes in climate in the future [67]. In view of the severe adverse effects of storm surges on infrastructure and ecosystems, especially in the case of sea-level rise, it is important to study the impact of storm surges caused by sea-level rise on the infrastructure and ecological environment for the purpose of disaster prevention.

3.2. Seawater Intrusion

Seawater intrusion is a process in which seawater moves from the ocean to land, and cities located along coastal areas are adversely affected by seawater intrusion [68]. Sea-level rise influences seawater intrusion in different ways. Seawater can flow over the sea wall to land during a storm surge that can be intensified by sea-level rise, thus increasing the salinity of land and surface water. In addition, the water pressure increases oceanside as a result of sea-level rise, which aggravates the seawater-intrusion risk in underground aquifers [18]. Seawater can also travel upstream along rivers, thereby increasing the salinity of river water. Under the conditions of sea-level rise, the sea level, flow velocity and tidal strength increase, which exacerbates seawater intrusion in river areas [69]. In recent studies, more attention has been paid to research on the effect of sea-level rise on seawater intrusion. Loaiciga [70] used a developed method to evaluate the effect of sea-level rise and groundwater extraction on seawater intrusion in an area near Monterey, California. They found that groundwater mining was the main factor influencing seawater intrusion in the study aquifer, and sea-level rise should also not be overlooked. In order to further verify the impact of sea-level rise on seawater intrusion, Langevin and Zygnerski [71] developed a model to analyze seawater intrusion in a municipal supply well field in southeastern Florida and found that saltwater intrusion is aggravated by sea-level rise. However, the quantitative assessment of seawater intrusion caused by sea-level rise has not yet been realized, which has an important impact on the groundwater in coastal cities when the sea level continues to rise in the future [72].

3.3. Decrease in Coastal Wetland

Coastal wetlands, mainly salt marshes and mangrove forests, play a significant role in ecosystems, economic development and the reduction or alleviation of floods and storm surges [13]. Sea-level rise may reduce the area of wetlands in some coastal areas, leading to land salinization, and, of course, it may also increase the area of wetlands in some places [73]. However, in recent decades, the effects of human activities and the degree and consequences of sea-level rise have become more serious [74]. Under these circumstances, the submergence and erosion of coastal wetlands are aggravated, leading to a sharp reduction in wetland areas [24,75,76]. Many scholars have carried out research on this issue, for example, Craft, Clough [77] studied the influence of sea-level rise on coastal wetlands in the Georgian coast with different scenarios (mean and maximum rise until the end of 2100) by means of field and laboratory measurements, GIS and numerical modeling. The authors of that study estimated that salt marshes will decrease by 20% and 45% under mean and maximum sea-level rise, respectively. Akumu, Pathirana [78] used the Sea Level Affecting Marshes Model (SLAMM) to predict the potential influence of sea-level rise on coastal wetlands in northeastern New South Wales, Australia, and found that coastal wetlands will decrease from about 225.67 km^2 in 2009 to about 168.04 km^2 by the end of the century in these areas with a 1 m sea-level rise, which is equivalent to a 26% reduction in area. Even worse, Kirwan, Guntenspergen [79] predicted that almost half of the global coastal wetland will be submerged by the end of this century owing to accelerated sea-level rise. Nowadays, the average rate of global sea-level rise is accelerating, and seawater poses a growing risk to intertidal wetlands [80–82]. Some studies argue that up to 78% of the global coastal wetlands may be submerged by 2100 with a high vertical accretion, which causes severe survival pressure on the growth of mangroves [6,83]. The loss of coastal wetland would lead to various economic and social effects and, thus, increased vulnerability to extreme storm events. For these reasons, vulnerability assessments of coastal wetlands are urgently needed in the case of continuous sea-level rise.

3.4. Seismicity

On land, there are many records of earthquakes caused by reservoir filling, which indicates that water loading has an effect on seismicity [84–86]. The same situation may occur in the ocean with the progression of sea-level rise. In recent decades, more attention has been paid to the causal relationship between sea-level rise and seismicity [87–90]. Sea levels have risen over 120 m since the Last Glacial Maximum, which may create differential loading in coastal areas globally and thus change the original stress state and induce earthquakes [91]. To explore the impact, Luttrell and Sandwell [92] calculated the perturbations of sea-level rise to stress after the Last Glacial Maximum using 3D and semi-analytic models in coastal regions. They pointed out that these stress perturbations may markedly change the seismic cycle of some major boundary faults. Brothers, Luttrell [88] also examined the influence of sea-level rise on non-glaciated passive margins with the conclusion that there is an increase of over 1 MPa in coulomb failure stress in fault systems during rapid late Pleistocene–early Holocene sea-level rise, which can trigger fault reactivation and rupture. In addition, Neves, Cabral [93] studied the influence of sea-level change on seismicity in west Iberia, and the results showed a 0.5~1 MPa increase in coulomb stress along the Manteigas–Vilariça–Bragança and Lower Tagus Valley fault systems, which is sufficient to change the seismic cycle of the Manteigas–Vilariça–Bragança fault. These studies have shown that the rise of sea level will indeed change the original stress state near the fault and thus increase the risk of earthquake occurrences. At the same time, seawater may also play a role in softening the fault. Under the combined action of these two effects, sea-level rise may easily induce earthquakes.

3.5. Seismic Liquefaction

Seismic liquefaction is a common phenomenon associated with earthquakes, which causes serious building and infrastructure damage [94], as well as loss of life and property.

The degree of saturation is a decisive factor that influences the liquefaction potential. With the rise of sea levels, the groundwater level may increase in some coastal areas, causing unsaturated sand soil and silt layers to become saturated. In this case, the effective stress of the sand would thus decrease, leading to an increase in the excess pore water pressure, which is needed to achieve a liquefaction state [95,96]. For this reason, areas with higher groundwater levels are more easily liquefied compared with areas with lower groundwater levels when they experience the same-intensity earthquake. Sea-level rise can influence underground water levels in two ways. Firstly, when sea levels rise, the water head of underground water to seawater decreases, thus leading to an underground runoff decrease. Second, sea-level rise also increases the intensity of tidal action in estuary areas, which also decreases the underground runoff. When the tidal level surpasses the underground water level, a great deal of seawater flows back into the underground water and increases underground water levels.

As the sea level rises, the original site conditions are changed, resulting in an increased risk of liquefaction of sand in coastal cities. In this case, it is necessary to consider the risk of liquefaction in coastal areas [97,98]. By comparing liquefaction hazard maps before and after the sea-level rise, Murakami, Yasuhara [99] described a procedure for liquefaction hazard mapping, which shows that sea-level rise can expand the liquefaction areas. Taking the influence of sea-level rise on liquefaction into account, Murakami, Yasuhara [99] presented liquefaction vulnerability maps for earthquakes of varying magnitudes with 0.5 m and 1.0 m sea-level rise in Christchurch, New Zealand, and found that sea-level rise leads to an increased number of devastated areas. Similarly, Abueladas, Niemi [100], using three models, evaluated the probability of the Aqaba-Elat region after the seawater rose by 0.5 m, 1 m, and 2 m, and concluded that the risk of seismic liquefaction in this area would increase by 26% to 49%. For coastal cities, if land subsidence occurs, the risk of seismic liquefaction in this area will increase significantly under the dual effects of land subsidence and sea-level rise [101]. Therefore, coastal cities that frequently experience earthquakes need to pay special attention to this issue.

3.6. Submarine Mass Failure

Numerous submarine landslides occur and are detected annually around the world, which can cause considerable damage to offshore drilling platforms and submarine pipelines [102–104]. There are many factors that contribute to submarine mass failures, such as seismicity, gas hydrates and rapid sedimentation. However, sea-level rise is one factor that should not be neglected, which may cause continuous destruction of coastal slopes (Figure 7). For one, as mentioned above, sea-level rise can influence seismic activities triggering slope failure. In addition, Trincardi, Cattaneo [105] found that sea-level rise can aggravate the effects of overpressure caused by rapid sedimentation (Figure 7a,b). As the sea level rises, hydrostatic pressure on the bottom of high-permeability layers increases (Figure 7c), and this may cause the flow of liquid into high-permeability layers and the draining of liquid, which may lead to submarine mass failure [106]. There are some examples that have testified to the effect of sea-level rise on submarine mass failure. Georgiopoulou, Masson [107] asserted that the Sahara Slide occurred during a period of high sea levels and high pore-water pressure. Smith, Harrison [106] mentioned that Holocene sea-level rise might have contributed in large part to the Holocene Storegga Slide in Norway.

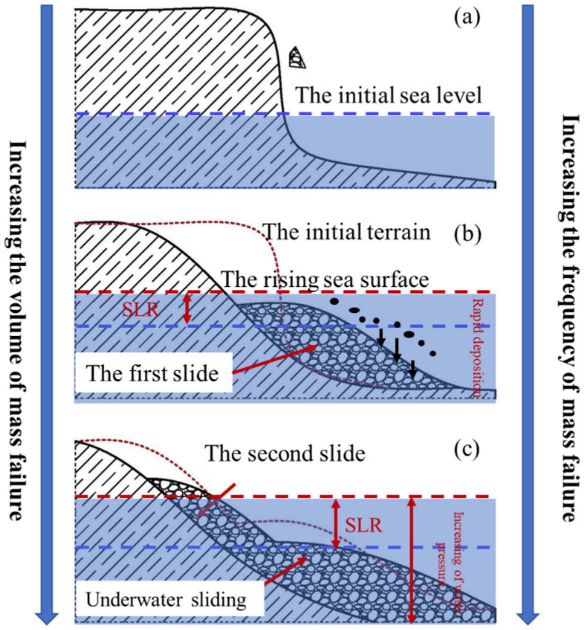


Figure 7. Coastal and submarine material instability model induced by sea-level rise.

Storm surges can also affect submarine mass stability. It is reported that Hurricane Camille resulted in a 20 m storm wave, which triggered a large-scale submarine landslide [108]. It is also believed that some submarine landslides in the Yellow River Delta were caused by storm surges [109]. Considering these circumstances, Zhang, Huang [110] analyzed the mechanism of submarine landslides triggered by storm surges. With the rise in sea levels, the intensity and frequency of storm surges also increase, and thus, the occurrence of submarine land failure is also likely to increase.

4. Disaster Projection and Mitigation Measures

Sea-level rise has influenced human beings in many aspects, including the economy, society and ecosystems. As human activities continue to increase and the climate continues to change, the risk of disasters related to sea-level rise in coastal cities may continue to rise. Therefore, we must take measures to mitigate sea-level rise and its associated geological disasters for coastal cities on the basis of the projection of sea level. In this section, we first review recently reported projections of sea-level rise. Second, some useful mitigation measures are proposed.

4.1. Projection of Sea-Level Rise

The projection of future sea-level rise is a process with many difficulties and uncertainties [111–114]. These uncertainties stem from many factors, such as future climate change [115,116], changes in glaciers and ice sheets [117,118], groundwater extraction and water storage on land. Despite the huge uncertainty, many scholars still make predictions on the future sea-level rise or extent based on reasonable assumptions. Rahmstorf [98] proposed a semi-empirical relation that could be used to project the future sea-level rise and predicted a 0.5–1.4 m increase in sea level by 2100. The Intergovernmental Panel on Climate Change projected global sea-level rise under different representative concentration pathway (RCP) emission scenarios in 2100 and estimated a 0.29–0.59 cm increase under a scenario where the concentration of greenhouse gases is very low (RCP 2.6) and a 0.61–1.10 m increase under the condition of unmitigated growth of emissions (RCP 8.5) [7]. In recent decades, more attention has been focused on the contribution of glacial and ice sheet melt to future sea-level rise. DeConto and Pollard [42] estimated that Antarctica might contribute to more than 1 m and 15 m of sea-level rise by 2100 and 2500, respectively. Slater, Hogg [119] believe that the temperature-driven melting of glaciers will cause sea-level rise at the end of the century to be between 28 cm and 98 cm. From the above research, we can only predict a relatively reliable interval based on the current trend, and it is difficult to specifically determine the actual height of the sea-level rise in the future.

Sea-level rise is a common result of multiple factors, including ice melting, thermal expansion of the oceans, vertical tectonic movements and glacio-hydro isostasy and anthropic subsidence [6]. However, in some areas, only some factors play a key role in the process of sea-level rise, which leads to the difference of degree of sea-level rise globally in the future. For example, the relative sea-level rise in Shanghai is mainly caused by land subsidence caused by artificial pumping, while the sea-level rise in Venice is caused by vertical ground motion [32,120]. In this case, different regions should pay more attention to the relative sea-level change caused by the local main control factors and make a differential projection of the local sea relative value according to the historical observation data. This sea-level prediction in local areas will contribute to the drawing of local flood maps and future coastlines, which will provide strong guidance for reducing flood disasters in coastal cities in the future.

Different projection models and influencing factors are usually selected in the process of projecting sea-level rise, and the uncertainty of project models and influencing factors often leads to huge differences in the projected sea-level rise values. Projected uncertainty ranges are, however, widely divergent as a result of different methodological choices [121]. In terms of projection models, model uncertainty has dominated most of the 21st century. Locally, model uncertainty dominated during 2100, with maxima in the North Atlantic and Arctic Oceans [122]; in addition, an ensemble of models is often used in sea-level rise projection, and inter-model uncertainty is also worth considering [123]. In terms of influencing factors, the uncertainty of century-old global sea-level rise is mainly affected by ice sheets. Geographical changes in projected sea-level change are largely driven by dynamic patterns in ocean responses and other geophysical processes. Finally, the uncertainty of short-term sea-level extreme events is controlled by near-coastal processes, storms and tides [124]. There are three hypothetical relationships between influencing factors, namely independent, non-independent and in-between, and the uncertainties of these three situations are also hugely different [111]. Faced with so many uncertainties, the forecast value should be corrected in time to ensure that the projected value is as consistent as possible with the actual situation.

In the IPCC report, a forecast was made for the future by 2100, but the long-term forecast value is highly uncertain, so they provide a mean value and a range value [7]. To reduce the uncertainty of projection and determine the actual value of the sea-level rise, monitoring networks such as Buoy, GPS monitoring systems and satellite measurements, should be constructed and the existing systems should be further improved to provide accurate data for future forecasts, which can be used as a guide for the construction of protection systems of coastal cities. For example, if the height of the sea-level rise due to various reasons in the next 100 years is roughly 98 cm, then the existing protection system of coastal cities should be increased by 98 cm at least. Moreover, satellite remote sensing monitoring systems could also be used. The combined analysis of satellite altimeter data and tide gauge data can yield precise measurements of sea-level rise on which mitigation and prevention measures can be devised. In addition, different departments within one country or across different countries can share their resources with one another to establish a comprehensive resource sharing system, resulting in better prediction and verification of global sea-level rise.

4.2. Mitigate Measures

To mitigate the risk and the consequences of sea-level rise, effective mitigation measures should be taken immediately. One way to reduce these impacts is to control climate change, the main source of sea-level rise. Greenhouse gas emission is the main driver of global warming [125,126], and the reduction or control of the content of greenhouse gases in the atmosphere can mitigate the effects of global warming. We can develop new energy sources, change our energy structure and discontinue or minimize human activities exacerbating global warming. Replacing traditional fossil energy with cleaner energy, such as wind energy, nuclear energy, tidal energy and bioenergy, would make an important difference to this end [127–129]. Large-scale afforestation and reforestation are also effective because increased forest coverage will result in decreased atmospheric CO_2 levels through photosynthesis. Forests can also store water inland, which can help in reducing the rate of sea-level rise. Carbon sequestration is an important technology for balancing CO_2 levels in the atmosphere. Reducing CO_2 content in the atmosphere by sequestering it in a geological body or the ocean has tremendous potential. Tschakert [130] proposed sequestering CO_2 in degraded agricultural land, which has enormous potential in developing countries. Increasing CO_2 land sink through biochar production and mixing it with soil is another method with good potential [110]. Chemical weathering of silicate rocks can reduce atmospheric CO_2 concentrations over a long geological timescale. Oelkers, Gisiason [131] proposed increasing weathering processes by increasing carbonic acid reaction rates artificially. Now, some new biological technologies for CO_2 reduction have been proposed, which use microorganisms to convert CO_2 into minerals and store them in the desert [132]. In addition to reducing CO_2 emissions, it can also reduce the temperature by absorbing less external heat energy. For example, Zhang, Moore [133] discussed global warming mitigation measures based on increasing planetary albedo. They reviewed several measures, such as the white roof method, stratospheric aerosols and cloud albedo enhancement.

For coastal cities, another way to alleviate the effects of sea-level rise is to implement specific measures according to different geological disasters (Table 1). In addition, making good use of underground water, reasonably restricting the mining of underground water via rules and laws and artificial recharge groundwater are all effective ways to control land subsidence, so as to decrease regional sea-level rise. Flood prevention standards need to be revised in some coastal areas according to the increased height of the local storm surges as a result of sea-level rise. Coastal habitats can protect people from the effects of sea-level rise and reduce the intensity of storms surges [134], so the protection and rehabilitation of coastal habitats, including the planting of mangroves, are of great importance to mitigate losses from sea-level rise for coastal cities.

Table 1. Specific mitigation measures for different geological disasters.

Geological Disasters Related to Sea-Level Rise	Mitigation Measures
Seawater intrusion	Control the mining of underground water Freshwater injection in coastal zone Seawater intrusion barriers Long-distance water transfer
Decrease in coastal wetland	Make good management of sediment Develop rational land use plans Rehabilitation and re-creation of wetland habitat Forbid or restrict the use of hard defenses in some areas
Storm surge	Strengthen the construction of early-warning forecast system and emergency response Construct high-level seawall and floodgates Grow plants that can dissipate waves in coastal areas
Seismicity	Increase the level of seismic fortification in some coastal areas Enhancement of monitoring
Seismic liquefaction	Strengthen the assessment of liquefaction vulnerability in coastal areas Use some remedial measures against soil liquefaction in coastal areas
Submarine mass failure	Reasonable selection of offshore engineering field Use some bank protection and slop reinforcement measures Strengthen the deformation monitoring of coastal slope

5. Future Research Perspectives

At present, the predictability of disasters is low, and they are easily observed when there are obvious signs caused by sea-level rise. Moreover, as the climate changes drastically, the frequency of various geological disasters related to sea-level rise has an upward trend [6]. These disasters are prone to causing serious damage to the coastal urban system, and it takes a long time to recover [135]. Under such circumstances, there is an increasing demand for post-disaster loss assessment and restoration assessment, namely resilience, which can be used as a means to deal with the disaster risk of urban systems from the perspective of disaster reduction and management [136–139]. As appeared in ecology in the 1970s, the concept of resilience is to describe the ability of a system to resist and recover from disasters [140]. Now, resilience-based thinking has been extended to various fields, especially disaster management and prevention [141–144].

In terms of coastal disaster management and prevention, engineering measures were always used to deal with the disasters caused by the sea-level rise from one or several aspects, such as dams, storm surge barriers and tide gates, but hardly considered its resilience in response to disasters [145]. In recent years, with the proposal of the concept of resilient cities, disaster prevention concepts based on resilience have been gradually applied to urban systems to assess and improve the ability of urban systems to mitigate disasters [146–148]. After years of continuous research, the coastal city system is still inadequate in resisting disasters caused by rising sea levels, especially in groundwater intrusion, storm surges, induced earthquakes and other disasters. The quantitative assessment concept of the resilience of coastal city systems has not been achieved. Therefore, it is necessary to introduce the resilience-based disaster prevention concept to coastal cities to assess their ability to mitigate disasters caused by sea-level rise and recover from them [46]. The concept of resilience mainly emphasizes two concepts of the system as shown in Figure 8. The first is robustness, that is, resistance to disasters, which mainly corresponds to P_1 in Figure 8 when the system is suddenly hit by a disaster related to sea-level rise. The second is restorability, that is, the ability to return to the original state, which mainly corresponds to the increase in functionality during the period t_1 to t_i in Figure 8 under the condition of artificial repair. During the recovery process, disasters may occur again, and the system may be destroyed again, which corresponds to the disaster event at time t_i in Figure 8. For catastrophic events, we usually use the probability density function (PDF) to describe its probability of occurrence in the future, and of course, PDF can also represent the loss probability of the system itself after a disaster. The assessment method based on the concept of resilience realizes the quantitative assessment of the whole process of disaster, disaster-bearing structure response and disaster recovery. Due to the different impacts of induced disasters, the definition of the resilience of an urban system to such disasters is also different.

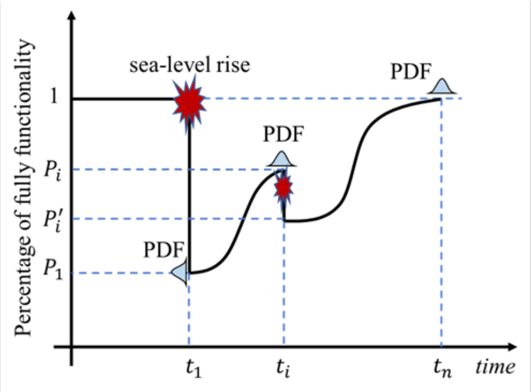


Figure 8. Resilience assessment of coastal cities affected by disasters related to sea-level rise (revised form Xiong and Huang [149]).

The resilience of the coastal city system against groundwater intrusion can be defined as a function of groundwater pumped, injected water, the saltwater and freshwater interface location and time in a certain area. The resilience value is 1 when seawater intrusion does not occur, and it is 0 when seawater intrudes into the urban planning area. For those cities where groundwater has intruded into urban areas, freshwater as a recovery medium should be properly injected into aquifers to control the location of the brackish–freshwater interface. In this case, in order to avoid secondary disasters, the amount of water injection, recovery rate and recovery time should be reasonably calculated. The resilience of the coastal city system against storm surges can be defined as a function of storm surge intensity, water volume, building structure strength and urban elevation. The coastal cities are classified into different research zones according to the distance from the coastline and relative elevation. The robustness of different buildings in these areas to deal with storm tides is discussed, and then the robustness of the area to resist storm tides is evaluated based on the robustness of single buildings. In those areas with less robustness, some weak buildings can be reasonably strengthened to increase the ability of the urban system to resist disasters. The sea-level rise-induced earthquake resilience of the coastal city system can be defined as the dynamic stability probability P_i of different building types under different site conditions, which can be expressed as the expected robustness achieved after a period of recovery with a corresponding probability (e.g., PDF). This probability can not only characterize the randomness of disasters, but also characterize the randomness of the disaster recovery process of the engineering structure. These random parameters can be used as random variables in the recovery model to control the recovery time. In addition to considering the disasters of the coastal city system from the above-mentioned single-disaster perspective, it is necessary to quantitatively evaluate the robustness and resilience of coastal cities under the influence of multiple disasters further, as well as the response and recovery strategies under existing conditions. This resilience-based evaluation method can not only link disasters with the functional status of urban structures and their protection system, but also link the prevention and control measures to mitigate these disasters related to sea-level rise.

After the evaluation is completed, various related guidance maps are drawn according to the evaluation results, which provide a theoretical basis and basic data for the development, utilization and management of coastal cities. For example, for flood disasters in coastal cities, the spatial distribution characteristics of key disaster parameters such as the future coastline changed by the rise of the sea, flood inundation area, inundation depth, main flood channels and flood water levels are visually presented on the flood map. Other maps, such as wetland vulnerability maps and potential liquefaction zone risks corresponding to sea-level rise are in coastal cities, should also be produced.

6. Conclusions

In this paper, we summarized the recent developments in sea-level rise and associated geological disasters; some mitigation measures were also proposed. Based on our review, the following conclusion may be drawn.

Since 1880–2019, the global average cumulative sea level has shown a rising trend, and especially in recent years, the rising trend of sea level has been more severe than before. From a regional perspective, except for northern Europe and parts of the Russian Far East, the sea level in other regions has shown a rising trend, but the degree of sea-level rise in various places showed huge differences in space.

The rise of sea level is mainly affected by climate-related factors, structural factors and human activities. The contribution of climate factors to sea-level rise is now approximately 80%; that is, climate-related factors, such as melting glaciers and the thermal expansion of oceans, have become the most important factors affecting sea-level rise, so it is necessary to control greenhouse gas emissions to mitigate rising sea levels.

As sea levels rise, geological hazards will hit coastal areas, including seawater intrusion, storm surges, coastal wetland degradation, massive seafloor destruction, seismic activity and seismic liquefaction. The frequency and magnitude of associated geological hazards will increase due to rising sea levels. Considering that sea-level rise is not the only factor affecting the increase in these geological disasters, further research should quantitatively study the relationship between sea-level rise and related disasters and should also analyze the comprehensive risk of different disasters.

To strengthen the management of geological hazards caused by sea-level rise, it is necessary to carry out the necessary monitoring and prediction of sea-level rise, and to take reasonable engineering measures based on the results of monitoring and prediction. In addition, a new generation of disaster assessment methods, such as resilience-based disaster quantitative assessment and prevention techniques, should be introduced to the field of coastal urban disaster management. This is not only conducive to giving full play to a building's own ability to deal with disasters, but also helping city managers to predict the severity of disasters and formulate reasonable disaster relief strategies.

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