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Review

Exploring GIS Techniques in Sea Level Change Studies: A Comprehensive Review

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Abstract: Sea level change, a consequence of climate change, poses a global threat with escalating impacts on coastal regions. Since 1880, global mean sea level has risen by 8–9 inches (21–24 cm), reaching a record high in 2021. Projections by NOAA suggest an additional 10–12-inch increase by 2050. This paper explores research methodologies for studying sea level change, focusing on Geographic Information System (GIS) techniques. GIS has become a powerful tool in sea level change research, allowing the integration of spatial data, coastal process modeling, and impact assessment. This paper sets the link with sustainability and reviews key factors influencing sea level change, such as thermal expansion and ice-mass loss, and examines how GIS is applied. It also highlights the importance of using different scenarios, like Representative Concentration Pathways (RCP), for accurate predictions. The paper discusses data sources, index variables like the Coastal Vulnerability Index, and GIS solutions for modeling sea level rise impacts. By synthesizing findings from previous research, it contributes to a better understanding of GIS methodologies in sea level change studies. This knowledge aids policymakers and researchers in developing strategies to address sea level change challenges and enhance coastal resilience. Furthermore, global analysis highlights the pivotal roles of the United States and China in sea level change (SLC) and GIS research. In the Gulf Cooperation Council (GCC) region, rising temperatures have substantial impacts on local sea levels and extreme weather events, particularly affecting vulnerable coastal areas.

Keywords: sea level change; Geographic Information Systems (GIS); climate change; coastal vulnerability; Representative Concentration Pathways (RCP); impact assessment

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1. Introduction

Sea level change is a critical global challenge with significant implications for coastal regions and populations. It is a consequence of climate change and has been accelerating over the past century. Since 1880, global mean sea level has risen about 8–9 inches (21–24 cm) due to melting glaciers and ice sheets, as well as the warming of seawater [1,2]. In 2021, the global mean sea level reached a record high of 97 mm (3.8 inches) above 1993 levels [1]. According to NOAA [2], sea levels along the coastline are projected to increase by an additional 10–12 inches by the year 2050, with regional variations. This alarming trend highlights the urgency of studying sea level change and its potential impacts on coastal communities and ecosystems. Understanding the complex dynamics of sea level change is crucial for developing effective strategies to mitigate its impacts. It is also essential for devising effective mitigation and adaptation strategies to address its impacts. Therefore, this research paper aims to explore and analyze the methodologies employed in the study of sea level change, with a specific focus on the application of Geographic Information System (GIS) techniques.

In recent years, GIS has emerged as a powerful tool in sea level change studies due to its ability to integrate and analyze spatial data, model coastal processes, and assess the potential consequences of sea level rise (SLR). Instead of only relying on terrain data and measurements, GIS provides tools to create models and predictions automatically by integrating the use of data like vectors or rasters, including satellite imagery or LiDAR (Light Detection And Ranging), for instance. The ability to visualize 2D maps and even render them in 3D has brought a whole new dimension to the way sea level change is studied. Nowadays, it is possible to render coastal flooding and make predictions. Automatic computation of the potential consequences of coastal flooding on entire cities or environments is also feasible very quickly, based on terrain elevation. The incorporation of GIS techniques allows researchers to examine intricate geospatial relationships and gain valuable insights into the patterns and drivers of sea level change. This research paper delves into various aspects of sea level change, including its context, sustainability aspect, and the key factors influencing its fluctuations, such as thermal expansion, ice-mass loss, and changes in terrestrial water storage. By reviewing the existing literature and previous research studies, a comprehensive overview of sea level change research and its progression over time is presented. Furthermore, the paper explores the specific GIS methodologies utilized in monitoring and predicting sea level change. Diverse data sources employed in such studies, the index variables utilized to assess coastal vulnerability, and the GIS solutions used to model sea level rise impacts on coastal areas are examined.

By synthesizing the findings from previous research and analyzing the role of GIS in sea level change (SLC) studies, this paper contributes to a deeper understanding of the methodologies used in this field. It also participates in establishing the spatial distribution and chronological evolution of the SLC field. A focus on temperature parameters will also allow us to better understand their consequences. The knowledge gained from this investigation can assist policymakers, researchers, and stakeholders in making informed decisions to address the challenges posed by sea level change and enhance coastal resilience in the face of a changing climate. Through this research, it is hoped to provide valuable insights that can inform future research and contribute to the development of sustainable and effective strategies to tackle sea level change and its impacts.

2. Materials and Methods

This literature review adopted a structured approach to comprehensively explore sea level change research and its interplay with GIS. Key academic databases, including PubMed, Web of Science, Scopus, and Google Scholar, were systematically searched using tailored search queries to identify pertinent studies published from 1992 to 2023. The inclusion criteria encompassed studies directly related to sea level change, GIS applications, climate change impacts, or coastal vulnerability assessment. After the initial screening of titles and abstracts, full texts were examined to determine eligibility. The review also applied snowball sampling by scrutinizing reference lists of selected papers. Data were extracted systematically, covering publication details, methodologies, key findings, data sources, and key variables, to facilitate a comprehensive analysis of the literature.

3. Sustainability

As per the Intergovernmental Panel about Climate Change, sustainable development is defined as "seeking to meet the needs of people living today without compromising the needs of future generations, while balancing social, economic and environmental considerations" [3]. Sustainable development goals have been defined by the United Nations, and climate action falls within their scope. Sea level rise is a part of the process that is closely studied to mitigate its effects on coastal cities and mangroves, for instance. The consequences lead us to formulate adaptive measures to mitigate loss and damage [4].

Dube et al. [5] showed its potential impacts on coastal tourism and activities. Sea level rise can also have important consequences on coastal ecosystems like mangroves, as highlighted by Rogers [6]. Saintilan et al. [7] drew attention to the potential impact of relative sea level rise (RSLR) on mangrove evolution, as it could stop their vertical accretion if its rate per year is too high. Acting as important carbon sinks, they constantly evolve and increase their accretion. This emphasizes the necessity of mitigating the effects of RSLR for sustainable management of mangroves and coastal areas.

4. Sea Level Change (SLC) Context: A Review of Sea Level Change Studies

Frederikse et al. [8] presented a comprehensive overview of sea level evolution since 1900, identifying three main parameters influencing sea level change: thermal expansion, ice-mass loss, and changes in terrestrial water storage. Glacier-induced ice-mass loss emerged as a dominant factor, exceeding the impact of thermal expansion since 1900. Global and basin-scale variations in sea level were observed, and the study highlighted that no additional processes were needed to explain observed changes in sea level since 1900. Consequently, it is evident that global mean sea level (GMSL) is significantly influenced by these three key parameters. Various studies [9–11] have projected future sea level changes to assess their potential impact on coastal areas.

At a global scale, this work has been applied by Dangendorf et al. [12] between 1900 and 2015 to understand past variations and contextualize global mean sea level changes. Their study showed a persistent acceleration of GMSL, which is mostly linked to Indo-Pacific and South Atlantic sea level fluctuations. This was done using Kalman Smoother (KS) and Reduced Space Optimal Interpolation (RSOI) techniques. This methodology was applied to tide gauge data, including gaps, which is one of the important issues faced in research related to SLR. This could imply inaccuracies or uncertainties related to the projected variations. In continuation, future sea level changes are projected by De Conto et al. [13], showing the loss of ice shelves in relation to global temperature increases and their contribution to sea level change over the long term, using a calibrated ice sheet shelf model. The results show the potential contribution of Antarctic ice melting to sea level change and the future retreat of glaciers linked to increasing temperatures if nothing is done to prevent estimations going further than existing ones. For instance, estimations of a 1 m contribution to GMSL by 2100 with RCP 8.5 show the urgency of understanding the potential impacts of such events on coastal areas in the near future. Such estimations may be different, as this paper only tests a single model, while multiple ice-sheet models are yet to be tested. For instance, in this model, the role of ice-cliff calving is still not well-known and would require further testing to understand how much it impacts projections.

Similar work was conducted by Edwards et al. [14], with similar results projecting the potential land ice contribution to GMSL, utilizing emulation created by several models. They revealed that glaciers represent half of the most important contributors to global mean sea level change, with a median's sea level equivalent (SLE) dropping from 25 to 13 cm by the year 2100. However, there are still uncertainties regarding the exact links between melting land ice and climate change, as all the processes at stake are complex to understand.

At a regional scale, the impact of various SLR scenarios derived from predictions, such as those mentioned previously, is assessed by Griggs [15]. His report states the potential vulnerability of California's coast to SLR. The main contributors mentioned are ocean thermal expansion, land ice, glaciers, and Greenland and Antarctica's great polar ice sheets. The last contributor is emphasized due to its capacity to raise sea levels by "7.4 m and 57 m, respectively". Both poles are locally impacted by this phenomenon due to the presence of polar ice sheets. Projections show that California's relative and global sea levels could increase by nearly 1 m under the RCP (Representative Concentration Pathway) 8.5 and around 75 cm with the RCP 2.6. These scenarios were created by the IPCC (Intergovernmental Panel for Climate Change) to provide a common international scale to measure the impact of SLR [16,17]. They are important as nowadays, stakeholder decisions are based on them at a political scale to decide future policies. Using these scenarios has become commonplace for predicting precise, potential future sea level changes and making decisions accordingly. GIS-based sea level change research helps researchers as well as policymakers develop strategies through advancements such as the development of new methodologies, algorithms, indices, or the use of higher spatial and temporal resolution data. Improved predictions based on these advancements yield refined conclusions of greater precision for decision-makers and the scientific community. Future investigations, like those conducted in California [15], recommend merging newly acquired satellite images and observations with models to bridge different fields, such as meteorology, glaciology, computer science, and oceanography. Some feedback from decision-makers could also make a difference in improving the planning of future projections about sea level change. This paper [15] offers a great summary of the context of California in facing SLR and is an example of existing reports dedicated to informing about potential risks and providing insights to decision-makers. The outcomes are projections based on models and imply uncertainty about the future of California's coastal areas because the scenario that will unfold cannot be predicted, only anticipated.

On the contrary, in another report, which is based on tide gauge data, Gesh [18] mapped potential inundated areas in eastern North Carolina, this time comparing different datasets to show which one is most efficient. This is done by assessing vertical accuracy, which is a key component when using LiDAR (Light Detection and Ranging) data, and measuring the uncertainty of the data before mapping and estimating impacts on land cover and population. This methodology was applied to an outdated dataset for one of the data sources, but as the original goal was to compare them, the results confidently show that LiDAR is the best one to use for studying SLR when available.

Some papers also assess countries regarding their exposure to SLR. For instance, Raey [19] highlighted the high vulnerability of each country in the Arab region to sea level rise using a SWOT analysis. This provided information about the UAE's context, for example, and outlined the strategies envisioned by the country for coastal protection. However, because this study was published in 2010, the data mentioned are outdated.

At a local scale, Chow and Sun [11] focused on one of the Arab countries, the United Arab Emirates, especially the city of Abu Dhabi. They created a new model combining a hydrodynamic model (DELFT3D), a spectral wave model (SWAN), and wave run-up to assess the impact of SLR, tidal flooding, and extreme events. They showed that with an SLR of 0.5 m, most of the Abu Dhabi coastline would be inundated, considering the horizontal resolution of the water level data used is 30 m. This estimation doubles when including the impact of tidal flooding, wind, and shamal-induced waves.

Instead of assessing the potential impact of SLR, Fraile-Jurado et al. [20] focused on evaluating the flooding probability due to sea level rise in two areas in Spain. They used four probability models based on the IPCC and Hunter models, which is not an often used methodology. The approach of spatializing the probability of inundation is very interesting in comparison with classical methods, as it includes multiple possibilities. However, the results would require performing a complementary and more in-depth analysis of the probability approach.

At each scale, projections can be made. However, most of them are affected by data gaps, uncertainties, or inaccuracies related to the use of models or the data type used.

5. Scenario Choice

5.1. RCP

Studying sea level change implies understanding which areas it will impact. To do so, several sea levels are generally defined to compare the consequences between them. They are usually associated with climate change, as the IPCC (Intergovernmental Panel for Climate Change) created four Representative Concentration Pathways (RCPs): 2.6, 4.5, 6.0, and 8.5 scenarios, each linked to different estimations of rising temperatures and sea level change. These RCPs correspond to different levels of elevation and are widely used in the literature [10,13–15,20]. They have been applied at local, regional, and world scales (Table 1), even though these types of scenarios would better fit the world scale, as local and regional scales are impacted by local variations that often differ from general sea level trends. For instance, Griggs [15], in addition to SLR scenarios, created an extreme scenario called the H++ scenario to fit the California coast context. RCP scenarios are used for multiple purposes, such as mapping the probability of inundation due to SLR [20], studying the impact of SLR on coastal areas [15], assessing the impact of SLR on port operability [10], and assessing Antarctica's or land ice's impact on future GMSL projections [13,14].

Therefore, RCP scenarios are interesting to employ as a basis, as they are used by a lot of studies in predicting future sea level change.

5.2. Other Scenarios

Ollila [21] shows that, based on IPCC results, some scientists do not agree with the values established within the RCP scenarios. Other reasons such as the chosen scale, as mentioned previously, can also explain this choice. Consequently, other scenarios are used [9–11,15,18,20,22–26], which are not climate-based but are related to specific locations, taking topography into account. These scenarios are more interesting to use as they take into account all possibilities, including the most pessimistic scenarios. For instance, Weiss et al. [22] used six different sea levels: 1, 2, 3, 4, 5, and 6 m, and Sahin et al. [25] applied four scenarios: 2 mm or less, 3 mm, 4 mm, and above 5 mm/year. These two papers are good examples of completely different scenarios, as their numbers and measurement units differ. The advantage of using different scenarios lies in taking into account different levels of submersion, thereby fitting better with local scales and facilitating the identification and implementation of advanced, adaptive solutions to build more resilient cities in the long term for future generations.

Table 1. Sea Level Rise scenarios.

Paper	SLR Scenario	Temperature Projections	Estimated SLR by 2100
Albedwawi (2021) [26]	LS *	/	1, 2, 3, 4 m
Chow and Sun (2022) [11]	LS	/	0.5 m
Cooper et al. (2012) [9]	LS	/	0.75, 1.9 m
De Conto, et al. (2021) [13]	RCP 2.6, 4.5, 8.5	+1.5 °C, +2 °C, +3 °C	0.08, 0.09, 0.15 m (SLR)/0.09, 0.09, 0.34 (Temperature)
Edwards, et al. (2021) [14]	RCP 2.6, 4.5, 6.0, 8.5	SSP 1–19, SSP 1–26, SSP 2–45, NDCs, SSP 3–70, SSP 5–85	/
Elkabbany (2019) [24]	LS	/	1, 2, 3 m
Faour et al. (2013) [23]	LS	/	0.6, 0.9, 1.3, 1.9, 2.5, 5 to 7.5 m
Fraile-Jurado et al. (2017) [20]	RCP 2.6, 6.0, 8.5 and Hunter	/	0.4, 0.47, 0.63, 1 m
Gesh (2009) [18]	LS	/	1 m
Gracia et al. (2019) [10]	RCP 8.5	/	0.88 m
Griggs (2021) [15]	RCP 2.6, 4.5, 8.5 and H++	/	/
Sahin et al. (2019) [25]	LS	/	2 or less, 3, 4, above 5 mm/year
Weiss et al. (2011) [22]	LS	/	1, 2, 3, 4, 5, 6 m

* LS = Localized scenario.

6. Review of GIS Techniques to Study Sea Level Change

6.1. Data

Data sources for these types of studies often include the USGS (United States Geological Survey), NOAA (National Oceanic and Atmospheric Administration), or other official institutions contingent on the countries where the research is conducted. Different data, notably from these various sources, are used to monitor the impact of sea level variations, depending on the technique used. For instance, Dangendorf et al. [12] used a combination of sea level data and information to reconstruct past variations in global mean sea level between 1900 and 2015. This method combines the efficiency of reconstructing sea level changes over the long term with the ability to model them accurately over shorter periods using tide-gauge records. Frederikse et al. [8] also used tide-gauge records to understand the evolution of sea level rise since 1900. However, using this type of data is complicated as it implies data gaps, which can be avoided, for instance, by selecting specific time frames based on data availability [8]. In cases where gaps cannot be resolved, this could imply inaccuracies or uncertainties in the projected variations [12].

Other methods, such as those using satellite imagery, have been employed. For instance, Aldogom et al. [27] used Landsat 1, 5, 7, and 8 to measure the rate of change between dates to assess coastal land dynamics (erosion and accretion) in the UAE. Albedwawi's [26] thesis also used Landsat 8 along with SRTM (Shuttle Radar Topography Mission) and DEM (Digital Elevation Model) to assess the impact on land use in the north-eastern part of the UAE. DEMs, derived from SRTM data, were also used by Elkabbany [24] in his research. Landsat 8 data were also utilized as the main data. However, these studies obtained a DEM with a spatial resolution of 30 m, which is considered low resolution when the purpose is to study sea level rise with differences between scenarios of 1 m or less. The same issue applies to Landsat imagery.

Usually, DEMs are derived from SRTM or LiDAR data. This is also the case in Gracia et al.'s [10] paper, which used LiDAR-derived DEM. Additionally, the study mentions that using a DEM is more efficient than using TIN as it is more efficient space-wise [10]. Cooper et al. [9] utilized the same process for DEM creation to assess the potential impacts of future sea level rise in Hawai'i.

LiDAR data have very high spatial and vertical resolution, which is a clear advantage in spatial analysis studies. They were used by Fraile-Jurado et al. [20] and Gesh [18] too. To obtain an accurate analysis of sea level change, LiDAR is the most interesting as it provides high spatial and vertical resolution [18]. When using LiDAR data, a vertical accuracy measurement is nearly always performed to account for uncertainties.

So, LiDAR-derived DEMs are great data often used to monitor sea level change and its consequences. However, a vertical accuracy assessment should be performed before using them to understand the uncertainty of outcomes.

6.2. Indexes/Variables

It is also possible to study SLR and its potential impacts using indexes and variables (Table 2), like the Coastal Vulnerability Index (CVI), which is widely used in the literature [23,26,28]. The CVI provides a value to rank the level of impact of sea level change. Depending on this, the potential consequences of sea level rise can be deduced in a specific area where the CVI is computed. Based on this number, it is possible to infer zones that are more at risk and prioritize further actions to be taken. The index is derived based on an equation including variables such as geomorphology, geology, soil, tidal height, wave height, land use/land cover, coastal slope, land use, and shoreline change.

Table 2. Indexes and variables used in the literature.

Paper	Indexes/Variables	Calculation	Significance
Albedwawi (2021) [26]	CVI (Coastal Vulnerability Index)	Based on elevation values	Highlight the degree of vulnerability of a zone to sea level change
Faour et al. (2013) [23]	CVI/Geomorphology Class, Coastal slope (%), SLR Change (mm·year^{-1}), Shoreline Erosion/Accretion (m), Mean Tide (m), Wave Ranges (m)	$CVI = \sqrt{(a \times b \times c \times d \times e \times f)/6}$ a = geomorphology, b = coastal slope, c = relative SLR change rate, d = shoreline erosion/accretion rate, e = mean tide range, f = mean wave height	Assess the degree of vulnerability of the coast to sea level change

Table 2. *Cont.*

Paper	Indexes/Variables	Calculation	Significance
Gracia et al. (2019) [10]	MWL (Mean Water Level)	MWL = mean water level + mean astronomical tide + SLR	Defines four operability statuses: maximum operability, minimum operability, not operable, and flooded
Hastuti et al. (2022) [29]	CVI/Geomorphology, Shoreline change rate (m/year), Elevation (m), Sea level change rate (mm/year), Tidal range (m), Significant wave height (m)	$CVI = \sqrt{(a \times b \times c \times d \times e \times f)/6}$ a = geomorphology, b = shoreline change rate, c = elevation, d = sea level change rate, e = tidal range, and f = significant wave height	Highlight the degree of vulnerability of a zone to sea level change
Sahin et al. (2019) [25]	Relative Sea Level Rise (RSLR) (mm/year), Coastal slope (Cs) (%), Tidal range (Tr) (cm), Wave height (Wh) (m), Geomorphology (GS), Presence of CR (coral reef) or artificial structures	$\text{Coastal slope} = \left(\frac{y_1 - y_2}{d}\right)$ y_1 = height of the vegetation line, y_2 = height of the waterline and d = horizontal distance between y_1 and y_2	Used to predict the probability of shoreline change rate
Subraelu et al. (2021) [28]	CVI/Geomorphology, Coastal slope (%), Shoreline change (m/year), Land use/Land cover, Mean spring tide (m) and Significant wave height (m)	CVI = 4 g + 4 s + 3 lulc + 2 c + t + hs g = geomorphology, s = coastal slope, c = shoreline change, lulc = land use/land cover, t = spring tide range and hs = significant wave height	Used for coastal vulnerability classification

Other variables such as relative sea level rise, coastal slope, tidal range, wave height, geomorphology, and the presence of coral reefs or artificial structures can be used with other methodologies, like the one developed by Sahin et al. [25]. They used a Spatial Bayesian Network approach to predict sea level change-induced coastal erosion. This approach predicts the evolution of the coast but does not provide spatial information, only mentioning if erosion or accretion is expected. However, this approach requires further testing to understand its advantages, disadvantages, and limitations.

6.3. GIS Solutions

The studies mentioned before in the review of SLR studies did not use GIS techniques. In effect, there are several ways to study SLR, which is the focus of this paper (Table 3). In effect, GIS is increasingly used to monitor or assess sea level change.

6.3.1. Hydrological Connectivity in ArcGIS

The first common method consists of using hydrological connectivity to deal with increasing sea levels on DEMs. This is usually performed using ArcGIS software. Sahin et al. [25], for instance, predicted shoreline change by combining Bayesian Network with GIS using this tool. However, as mentioned before, this approach still needs to be validated. Cooper et al. [9] also used hydrological connectivity to assess the vulnerability in Hawai'i, employing LiDAR data. The vertical accuracy of the data was assessed before the process, which allows us to know the real accuracy of the outcomes, even if there were still commission errors despite filtering. This method, often called the "bathtub" method, has also been utilized by Elkabbany [24] and Weiss et al. [22]. However, their studies both use data with low spatial resolution, preventing precise results. Gesh [18] also referred to this approach, using 8-way connectivity to map potential inundation areas and assess the impact on land cover and population. By comparing four datasets, he shows that LiDAR is the most efficient for studying SLR due to its spatial resolution. However, his results are based on outdated datasets regarding population, infrastructures, and economy, which is not an issue, as the original aim was to compare datasets. However, updating the analysis with recent datasets would be required to ensure the validity of the outcomes.

6.3.2. Other GIS Applications

Concerning the papers that do not use hydrological connectivity, several other applications exist to monitor and predict the impact of sea level rise. Aldogom et al. [27] and Abd-Elhamid et al. [30] extracted coastline delineation using the DSAS tool in ArcGIS, which allows for providing automatic insights into if erosion or accretion occurred over long-term variations. The spatial resolution of 30 m could be improved, especially for shoreline analysis. Faour et al. [23] used the same software to classify and perform change detection analysis to assess the degree of vulnerability of the Syrian coast and the impact of future sea level change on the Syrian coast. Improving the accuracy of the DEM and the interpolation method would enhance the morphological representation of the area. Subraelu et al. [28] had a similar approach by creating a vulnerability ranking map based on the CVI and using remote sensing, like Albedwawi [26], who assessed the impact of sea level rise on land-use in the northeastern parts of the UAE. To have a more comprehensive analysis, the first study could include more social, economic, and environmental characteristics. The second study could also improve its methodology by creating more classes to increase detection and have more precise classification. Gracia et al. [10] also used ArcMap software to compute the potential impact of sea level rising on port infrastructure by 2100 along the Catalan coast. After defining the characteristics of each part of the port, a level of freedom was created. Data were crossed to produce cartography of the impacts of sea level change on different parts of the ports, considering four levels of freedom overlapping topographic and DEM layers. The results show accurate and precise cartography of the ports and the impacts of SLR on them under different RCPs. Other effects that could slightly impact SLR have not been taken into account, as they were considered negligible. Therefore, the results should be taken as indicative of potential impacts.

Table 3. GIS techniques.

Paper	GIS Techniques/Tools	Software	Data	Methodology
Albedwawi (2021) [26]	Classification (Semi-Classification Plugin)	QGIS 3.16 Hannover with GRASS 7.8.4	Landsat 8 images + SRTM + DEM	Create SLR scenarios, classify the area's land use, and compute CVI to assess the impact of SLR on land-use
Abd-Elhamid et al. (2023) [30]	DSAS (Digital Shoreline Analysis System)	ENVI 5.3, ArcGIS 10.8	Landsat 1 MSS, 2 MSS, 5 TM, 8 OLI/TIRS	Preprocessing of data, shoreline extraction, mapping of shoreline change
Aldogom et al. (2020) [27]	DSAS	ArcGIS	Landsat 1 MSS, 5 MSS, 7 ETM+ and 8 TIRS	Preprocessing of data, coastline extraction using an algorithm, and analysis of coastline evolution
Cooper et al. (2012) [9]	Reclassify, Intersect	ArcGIS	LiDAR, Geodetic Reference System of 1980 (GRS80) ellipsoid elevations	DEM generation, assess vertical accuracy, identify vulnerable areas
Elkabbany (2019) [24]	Extraction, Region Group, Overlay, Extract by Attribute, Extract by Mask, Convert	ArcGIS Desktop 10.5 ArcGIS Pro 2.0.1	SRTM, Landsat 8, World Imagery, Country borders, land-use, Roads, Streets and 13 others	Create SLR scenarios, evaluate potentially inundated areas, assess the impact of inundation, visualize using a dashboard
Faour et al. (2013) [23]	Classification, inundation model	ArcGIS	Topographic map, DEM, Ground Control Points, ASTER, LUC (Land use/cover) map, Landsat TM and ETM+, IKONOS, topographic, geologic, soil, and geomorphologic maps	A geometric correction of data is made before classifying land use, applying the model, and computing the CVI

Table 3. *Cont.*

Paper	GIS Techniques/Tools	Software	Data	Methodology
Fraile-Jurado et al. (2017) [20]	Spatial analyst tools	ArcGIS 10.2 GRASS	DSM, DTM, LiDAR, tide gauge	Use two probability models: Gaussian model IPCC and raised cosine model (Hunter) to compute future SLR, define probability, and compute inundation probability
Gesh (2009) [18]	Intersection, overlay	/	LiDAR, NED, STRM, GTOPO30, LandScan global gridded population dataset and National Land Cover Dataset	Assess vertical accuracy, measure of uncertainty, mapping of potential inundation areas, and estimate the impact on land cover and population
Gracia et al. (2019) [10]	Vector (Polygon) creation, Reclassify	ArcMap®	LiDAR, Topographic Cartography	Building DEM, land-use identification, mean water level change assessment, and port operability map creation
Sahin et al. (2019) [25]	Convert to raster file	ArcGIS 10.3	High-resolution Raster, Coastal slope, Wave height, Tide range, Sea level rise, Shoreline change	Combine Bayesian Network with GIS: Spatial Bayesian Network
Subraelu et al. (2021) [28]	Classification, compute CVI and fill attribute table, Spatial Join, Overlay	ArcGIS 10.6	Sentinel 2A, SRTM, Landsat ETM, UKHO	Create vulnerability ranking map based on CVI
Weiss et al. (2011) [22]	Compute overlap	ArcGIS Desktop™	National Elevation Dataset (NED), municipal boundaries, tidal wetlands	Create a geoprocessing algorithm, apply to NED, define land area with elevation at or below 1–6 m

6.3.3. 3D to Model SLR Using Game Engines

GIS can also be associated with game engines to help with better visualization of SLR or flooding. Other software can be used, like Blender, to obtain a 3D or photorealistic view, as demonstrated by Giannakidis et al. [31]. However, the 3D outcomes are not the same as what game engines allow, as game engines enable the computation of statistics about the environment while Blender specializes in graphics. The modeling of SLR or flooding can be applied to any environment type, as game engines enable their modeling and even create fantastic ones using real physics. Two famous game engines used for the creation of video games are Unity and Unreal Engine [32].

Unity has been used to model the effects of flooding on museums by Khoury et al. [33], Mercantini and Charpentier [34], and on a city by Presa Reyes et al. [35]. Virtual environments can also be projected for the same purpose using Unity [36,37]. The creation of scenarios in Unity depends on the factors implemented but allows a high degree of freedom with C# programming. However, their similarity to reality depends on the factors implemented. The simulation by Mercantini and Charpentier [34], for instance, only includes the museum without exterior factors, and the inundation is modeled only by elevating the water level from a flat surface, which differs from a real scenario.

Unreal Engine also enables the modeling of flooding in a city, as demonstrated by Lee et al. [38]. The simulation is based on real topography, and the advantage of this game engine in comparison to others is that it allows for much more powerful visualization with effects. However, it required knowledge of the C++ programming language and high computing capacities. This game engine can only be applied to computers or mobile devices, as it does not work online [38].

However, despite producing great visual results, these new techniques are rarely used, as shown by the little amount of literature found on this topic. They lack one principal element: the direct extraction of statistics from the visualization. They also do not always offer the possibility to move freely or provide access to a computer-based experience, as some of them create a physical terrain for simulation, which is usually not real.

7. Worldwide SLC and GIS Studies

It appears that a lot of SLC articles have been published, using several different methodologies and datasets in different areas around the world. Hence, having a general idea about the repartition and evolution of these articles published about SLR would help in understanding the dynamics of SLC publications. Here, the focus is on SLC- and GIS-based studies.

Figure 1 shows the proportion of empirical method-based SLC studies worldwide to highlight their spatial extent. Based on 200 articles (Supplementary Materials), it offers an overview of the places where SLR studies have mainly been conducted, whether GIS-based or not.

At first, it is striking that, of the 48 countries inventoried, the United States and China hold the highest numbers, with a total of 42 and 26 articles, respectively. Sea level rise is a global issue that impacts coastal regions. In the U.S., states like Florida and Louisiana are already experiencing increased flooding and coastal erosion. In China, cities like Shanghai and Guangzhou are vulnerable to rising sea levels. Both countries have active scientific communities dedicated to understanding and mitigating the effects of sea level rise. Moreover, both the U.S. and China, as signatories to international agreements like the Paris Agreement, are required to monitor and report their efforts to combat climate change, including addressing sea level rise. Scientific research and publications are instrumental in ensuring transparency and accountability in meeting these commitments. This highlights the importance of conducting SLC studies in these areas, given the number of people involved and the urgency to know the potential impacts. Budget may also be another parameter to take into account, as these two countries are world powers [39,40], which could explain the outstanding number of publications. However, they depict two opposite tendances: a majority of applied GIS articles in the United States and a majority of non-applied GIS articles in China. It is clear that applied GIS articles are predominant on a global scale for most countries (29 out of 42).

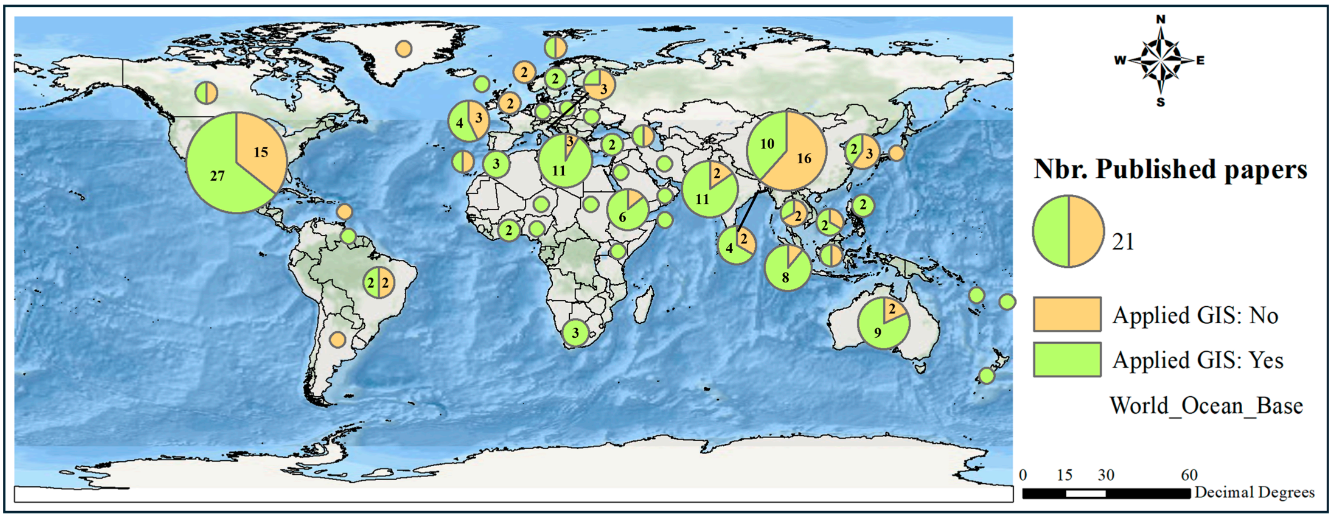

Figure 1. Spatial distribution of the number of SLC journal articles published between 1992 and 2023 by country (when the number is not mentioned, there is one). (Credits: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors. The list of 200 articles is provided in the Supplementary Materials).

The tendency observed in China is predominant in Eastern Asia and North Europe. This means that GIS-applied studies are more commonly published in the literature compared to non-GIS ones, which shows the development of this field in research from 1992 to 2023.

India, Australia, and Egypt also show a significant number of publications, with 13, 11, and 12 published articles, respectively. These countries are also well-represented in the literature because of the risks they face due to SLR and the important coastal population impacted. Australia's predominantly coastal population, the vulnerability of inhabitants in the Nile delta in Egypt, and India's great population are all factors contributing to the observed numbers of published articles.

In the Middle East, nearly all countries are covered by SLC studies, with a clear predominance shown in the United Arab Emirates, with seven articles, which surely shows a growing interest in this field. In effect, this country has a plan to reduce emissions by 2050 in line with climate change actions. As this country will be strongly impacted by sea level change and rising temperatures, it has become important to study the potential consequences and mitigate them.

Not all continents are fully represented by published articles related to SLC (Table 4). Antarctica, for instance, has not been studied at all, according to the 200 articles reviewed. The selection of papers mainly focused on English articles, which may have led to not considering papers in other languages. Another reason for the absence of studies in other countries could be attributed to the number of papers selected. In this review, 200 articles were considered a sufficient sample to represent the repartition of SLC studies worldwide since 1992.

Table 4. Number of published articles and countries studied per continent.

Region	Countries	Published Articles	Applied GIS: No	Applied GIS: Yes
Asia	18	85	31	54
America	7	52	21	31
Europe	11	25	12	13
Africa	8	24	1	23
Oceania	4	14	2	12
Antarctica	0	0	0	0

Figure 1 and Table 4 show that there is publication inequality in a topic that is one of the most discussed relating to climate change and the future of coastal cities. The number of published papers is highest in Asia, followed by America, Europe, Africa, and Oceania. The countries count is also the highest in Asia, followed by Europe and Africa, before America and Oceania. Overall, the number of articles with GIS applications is always higher than those without GIS applications.

From a temporal point of view, Figure 2 reveals a striking increase in the number of GIS-based articles published in 2008. Before this, the number of articles was not as high, which may correspond to the release of the IPCC synthesis report about climate change impacts in 2007 [41]. In 2008, the Climate Change Act [42] was passed in the United Kingdom, which also represents a starting point for realizing the impact of climate change. It was created to implement a vision for 2050 aimed at reducing greenhouse gas emissions. For non-applied GIS, there is also a less important peak in publications in 2011. After this, GIS-based papers decrease before going up again. The fact that there are not a lot of articles mentioned in 2023 can be linked to the publishing time, as papers about this topic might still be published later at the time of the review.

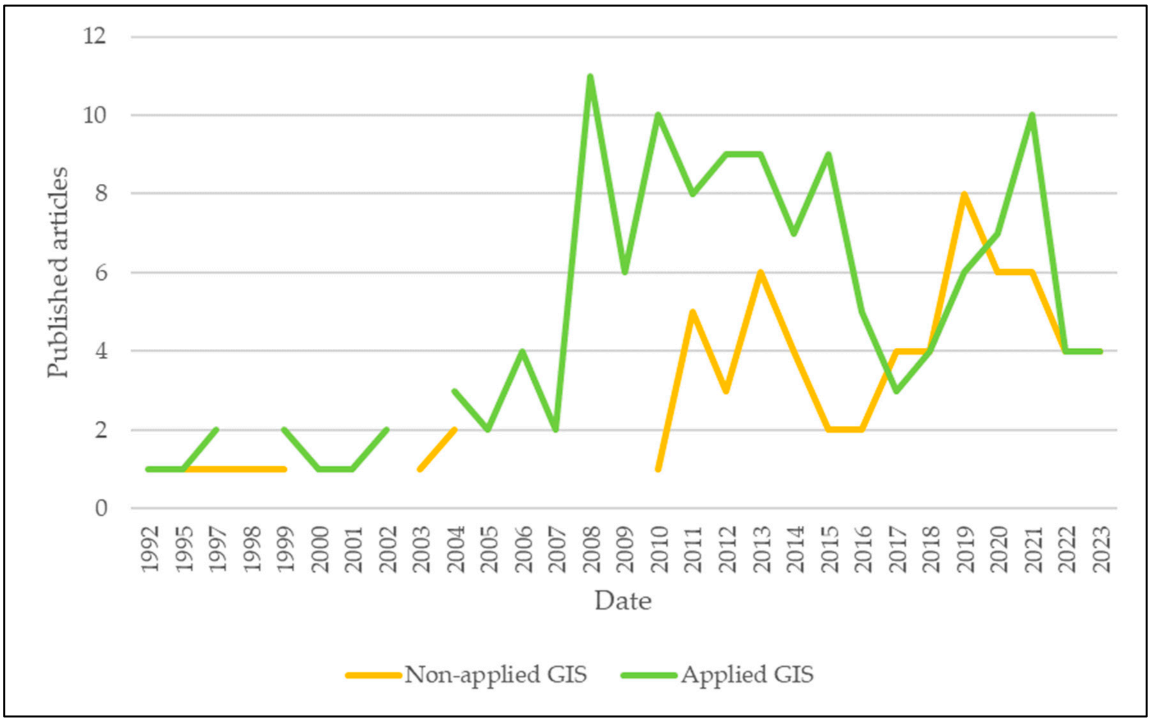

Figure 2. Evolution of the number of applied and non-applied GIS published articles since 1992.

8. Relationship between Temperatures and Sea Level Change

8.1. Global Overview

On a global scale, surface air temperatures are rising (Figure 3). As the United Nations (UN) Secretary General said in July 2023, "the era of global warming has ended" and "the era of global boiling has arrived" [43] (p. 1), which highlights and stresses the impacts of it. Since the 1970s, after the ECMWF (European Centre for Medium-Range Weather Forecasts), there has been a continuous increase in the evolution of these temperatures. From that moment onwards, there has been a gain of more than 1 °C. The last few years, especially 2023, highlight particularly warmer years than average. A correlation can be observed between the variation of surface air temperature and sea surface temperature between 60° S and 60° N (Figure 4). In effect, sea surface temperature shows the same evolution, with an increase of 1 °C from 1970–1980 until 2023, with an exceptionally high value for 2023. The same conclusion is highlighted by the evolution of surface air temperature. Focusing on the ongoing year 2023, there appears to be a tendency that suddenly breaks from previous variations, as seen in 2016.

The role of anthropogenic processes is often mentioned to explain these variations. However, Dangendorf et al. [12] in 2019 also mentioned the role of steric changes leading to thermal expansion, notably related to changes in westerlies, to explain the acceleration of global mean sea level. Steric changes, which involve changes in temperature, are depicted in Figure 4, showing an evolution towards even more significant thermal expansion and consequent rise in global sea level. This is also explained by Frederikse et al. [8], who mentioned that this is linked to a combination of thermal expansion of the ocean and increased ice-mass loss from Greenland [8] (p. 1). Such changes are observed at a time when catastrophic events like tsunamis or storm surges happen and are becoming even more violent and dangerous. Hence, studying these parameters is closely related to studying the evolution of sea level.

8.1.1. Asia and America

As mentioned earlier, Asia and America are the two leading continents, with China and the United States, countries near the ocean, publishing the most articles related to sea level rise. Several articles have been published in the United States regarding surface air temperature [44–47], mainly studied on a local scale. In China, there is a very high number of publications [48–54], appearing to surpass those of the United States. This shows the specific concern of this country with the question of surface air temperature. In effect, China conducts several studies related to climate change as it has consequences for this country, as evidenced by the number of publications concerning sea level rise. Asia also includes India, Indonesia, and the United Arab Emirates, three countries that have published 13, nine, and seven articles, respectively. For instance, Chowdary et al. [55] showed that surface air temperature is locally influenced by sea surface temperature and El Niño in India. This highlights a link at a local scale that could also be applied at a global level, aligning with results obtained by the Copernicus Climate Change Service [56].

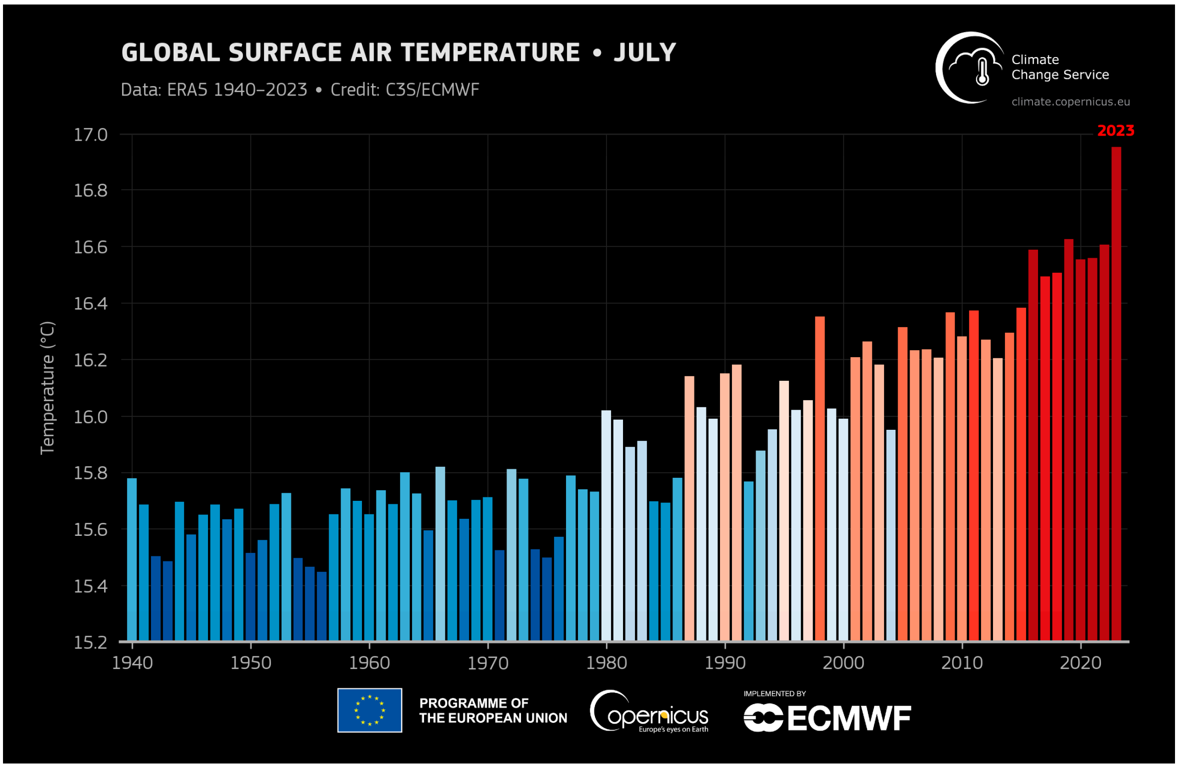

Figure 3. Globally averaged surface air temperature for all months of July from 1940 to 2023. Shades of blue indicate cooler-than-average years, while shades of red show years that were warmer than average. Data: ERA5. Credit: ECMWF, Copernicus Climate Change Service (C3S) [56].

Only two studies have been performed in Indonesia mentioning surface air temperatures. As this type of study is rare in Indonesia after Rohman et al. [57], the decision to work on it was made because Indonesia is vulnerable to climate change due to its important agricultural sector. Rohman showed an increase in air temperatures at different sites in Indonesia. In the United Arab Emirates, this question has also been assessed, with global trends showing a global increase in surface air temperatures from a local point of view [58–60] and a regional one at the scale of the Arabian Peninsula [61].

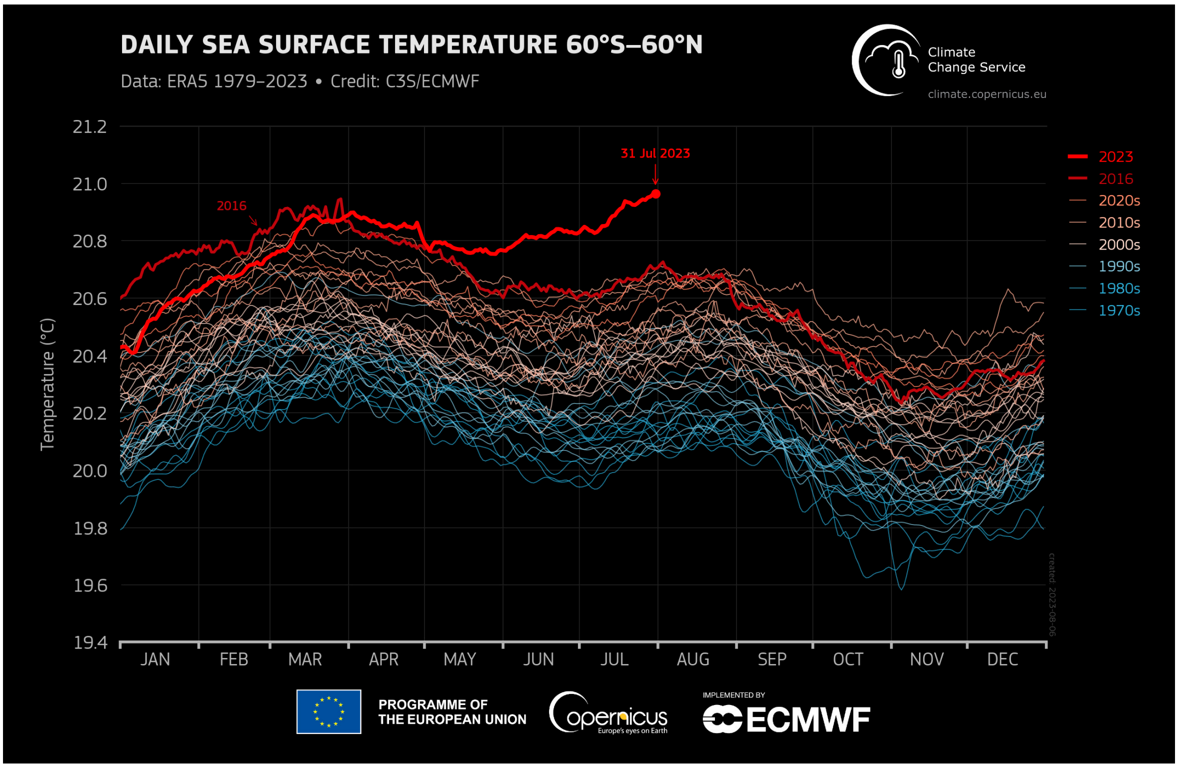

Figure 4. Daily global sea surface temperature (°C) averaged over the 60° S–60° N domain, plotted as a time series for each year from 1 January 1979 to 31 July 2023. The years 2023 and 2016 are shown with thick lines shaded in bright red and dark red, respectively. Data: ERA5. Credit: ECMWF, Copernicus Climate Change Service (C3S) [56].

8.1.2. Europe and Africa

The two other continents that have a smaller number of articles published, are Europe and Africa. These continents include, notably, Egypt and Spain. In Egypt, Hasanean and Basset [62] studied surface air temperatures and linked them to climate variations, including El Niño too. This shows that it is possible to understand variations in sea level rise by studying surface air temperatures. In effect, El Kenawy [63] explained that atmospheric patterns could explain temperature variations in a study area in Spain. Italy, the Netherlands, Sweden, and the United Kingdom are also coastal countries that are impacted by these fluctuations. Despite their underrepresentation in the literature on sea level rise, the Netherlands is a great example of vulnerability due to the presence of polders, as a part of the country is located at sea level. Coastal parts of Italy are also endangered, like Venice. A potential acceleration of sea level rise could have important consequences for this city.

8.1.3. Oceania and Antarctica

The two last continents with the least number of publications are Oceania and Antarctica. Oceania has a lot of islands that are vulnerable to sea level rise, like Fiji [64]. For instance, in line with previous papers, Xue et al. [65] showed that surface air temperature is locally influenced by sea surface temperature in Australia and El Niño, when studying during the austral summer. However, there are no papers on Antarctica, as research in this region mainly focuses on glacier melting.

All these areas mostly highlight the same outcome: sea surface temperatures influence surface air temperatures. Overall, no matter what area is selected, surface air temperatures appear to increase over time with a speed related to the location studied. The more arid the climate of the area, the quicker the temperature rises. These temperature changes impact sea surface temperatures over time through winds on a global scale, which is significantly responsible for sea level rise [12].

8.2. Case of GCC (Gulf Cooperation Council)

After a general overview, the decision was made to focus on GCC countries. The United Arab Emirates is one of them, and previous sections have demonstrated that it is one of the countries that has published several papers about sea level rise. Moreover, there is a link between the intensity of climate events and temperatures. In regions like the GCC, because of its overall arid climate, temperatures are usually high, especially in the summer. The more desertic the area, the more pronounced the climate events are. Also, recent extreme weather conditions in the Middle East, like snowfall in the desert in Saudi Arabia and significant episodes of rain and hail in the UAE, have highlighted the importance of focusing on this region.

Several catastrophic events happened regularly in the GCC, such as cyclones. Sandstorms and dust storms are also frequent. Francis et al. [66] showed that there is a correlation between temperature rise and the recurrence of cyclones in the Arabian Peninsula. Because of the growing importance of these events in this area, it is important to focus on them, as the literature on this subject is limited. The cities in the GCC are vulnerable, and stakes are high with important business and touristic hubs. Environmental awareness and recent sport events, like COP28 in Dubai or the Qatar World Cup Final, raise questions about the vulnerability of such events in the future in this region, considering the risks of sea level change or natural hazards they face, using network analysis, for instance [67]. The preservation of the environment, including mangroves, is also an important challenge, as already addressed by several studies [7,68], mostly using models.

It has been decided to focus on average summer temperatures as it is the warmest season of the year. This way, it will be possible to see how this season, which is the most extreme, evolves.

To explore the spatial distribution pattern of summer temperatures in the GCC and neighboring countries, average temperature data spanning 60 years were used, from June and July 1963 to 2023. These data come from the ECMWF ERA5 open-source dataset produced by the Copernicus Climate Change Service (C3S) and are analyzed using the GrADS application on a Linux-based system.

Figure 5 presents the average summer season temperature in °C for the months of June and July, from 1963 to 2023, across the GCC region. Over this 60-year timeframe, it is apparent that the maximum temperature values remained stable, while their geographical coverage expanded significantly.

Between June and July 1963 and 1983, the region experienced maximum temperatures averaging between 39 and 43 °C, confined to a relatively small part of Saudi Arabia and the northern part of Yemen. Temperature levels gradually decreased as one moved away from this central area.

In contrast, during June and July 1983–2003, the area characterized by maximum temperatures within the same range (39–43 °C) expanded significantly, covering nearly all of Saudi Arabia, parts of Yemen, and a small portion of Oman. The rate of temperature decreases in surrounding regions exhibited a gentler gradient.

Moving into the period of June and July between 2003 and 2023, distinctive temperature changes come into focus. In June, an increase in maximum temperatures is observed, with values ranging from 41 to 43 °C, primarily in the central region of Saudi Arabia. However, in July, the temperature range remains consistent at 41 to 43 °C. What is noteworthy is that this temperature range expands its coverage, extending beyond the borders of Saudi Arabia and encompassing a broader geographical area that includes neighboring countries like Kuwait, the UAE, Iraq, and Iran. These temperature dynamics in the 2003–2023 period highlight the intriguing variations in thermal conditions experienced during these two summer months across the Gulf Region.

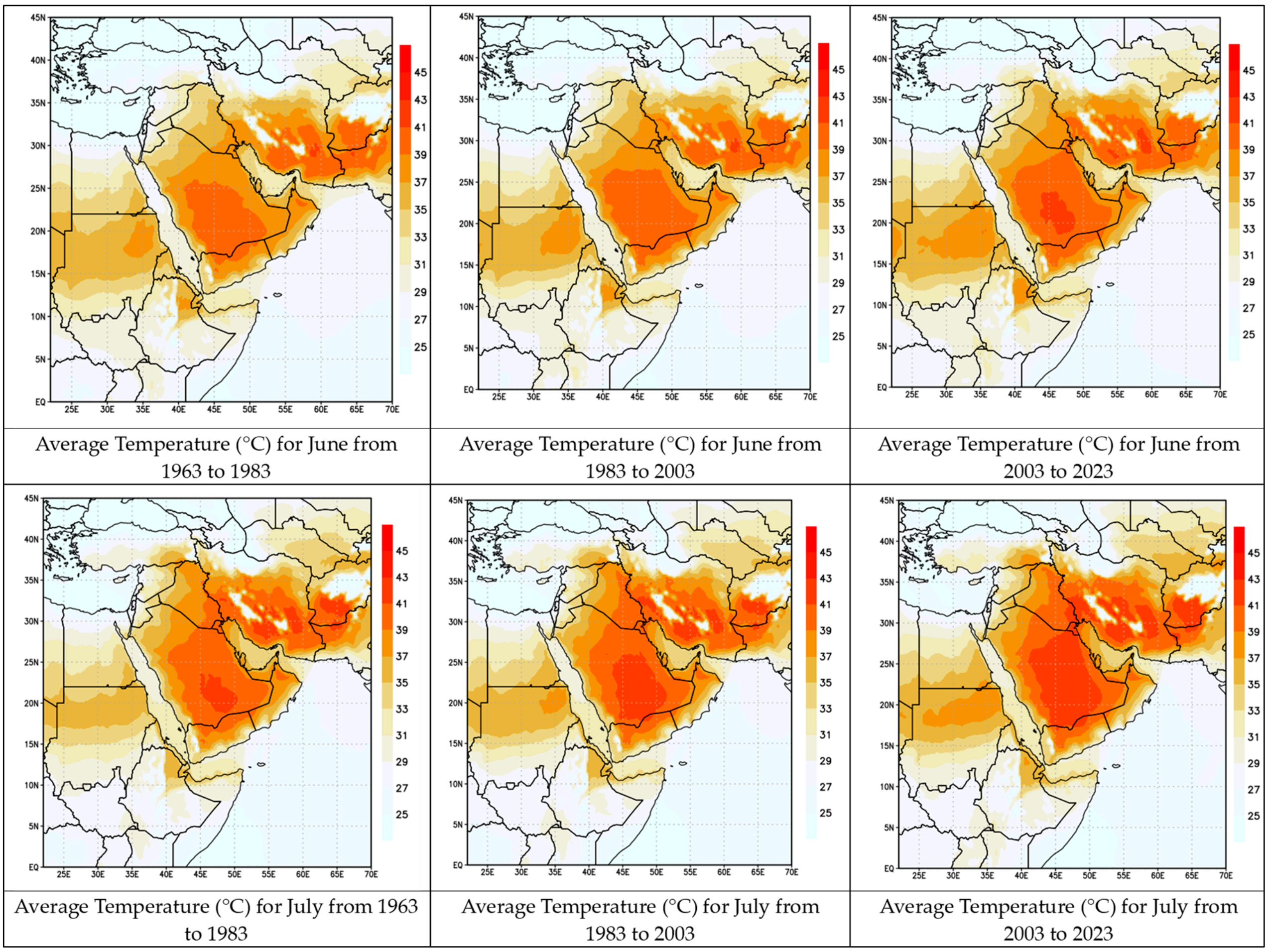

Figure 5. Average summer season temperature in °C for June and July, from 1963 to 2023, in GCC countries.

The observed increase in temperature patterns, especially during the summer months of June and July in the GCC region, can have significant implications for long-term for sea level rise in the area. In effect, steric changes can happen due to increasing temperatures, leading to expanding sea volume locally and causing sea level rise [69]. Higher temperatures can also lead to more frequent and severe weather events, as highlighted by the IPCC [70] and mentioned by Ebi et al. [71]. For example, a cyclone or hurricane in the Arabian Sea can bring intense rainfall and storm surges, leading to temporary but significant increases in sea levels. An example is Cyclone Gonu in 2007, which caused coastal flooding in Oman and the UAE [72]. Moreover, rising sea levels intensify coastal erosion, particularly in Qatar, posing a significant threat to coastal infrastructure and property [72]. These instances demonstrate the various ways in which rising temperatures and their consequences, including sea level rise, affect the GCC region, highlighting the need for ongoing monitoring, adaptation, and mitigation measures.

9. Important Gaps Addressed by the Methods

Despite the advances made in research related to sea level rise, major gaps still remain to be addressed (Figure 6), as outlined in the following subsections.

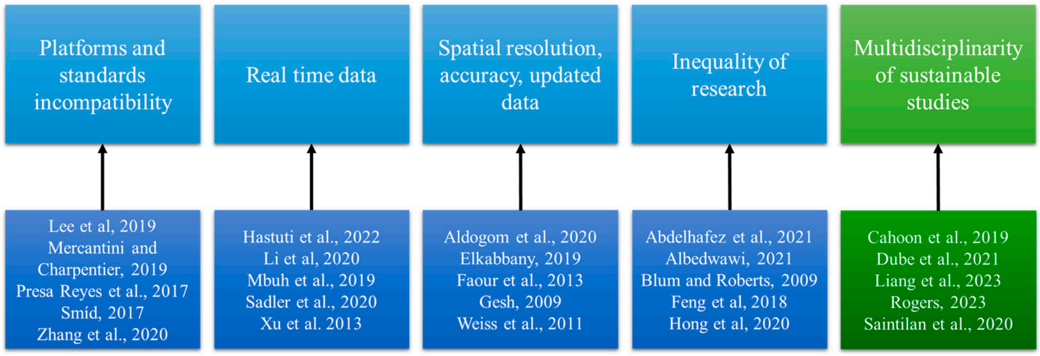

Figure 6. Gaps addressed in function of the articles mentioned in this review [5–7,18,22–24,26,27,29,32,34,35,37,38,73–82].

9.1. Platforms and Standards Incompatibility

This critical gap addresses the issue of GIS data formats being incompatible with game engine software [32,34,35,37,38] due to a lack of interoperability. Complex conversions are required when using geospatial data, which prevents easy access to these new promising technologies. In effect, the new appearance of game engines in the research scene highlights and supports an already existing problem faced with GIS. Not all geospatial formats are compatible with other software, like architecture (Sketchup, AutoCAD) or design (Blender). Some plugins or extensions have been created to facilitate compatibility, but they are not embedded originally and may not include or consider all the formats that could be imported. BIM (Building Information Modeling) is a great example of the number of recent advances made in this field [83].

To solve this problem, the creation of common standards or the development of software to ease integration between GIS and game engines could be considered, as is already beginning to be the case. Another solution could be inspired by ArcGIS, which integrated a link with Unreal Engine to resolve this issue and transfer data directly from one to another. However, using it to its full extent would require more than a free ArcGIS developer account due to the limitations of such accounts. Standardization is also a key method to achieve this, as presented by Malinverni et al. [84]. Standardization would be beneficial for research, including sea level rise and decision-making related to sustainable development, for instance. The reason for this lies in these softwares' great graphic performance and in creating easy visualization tools understandable by anyone.

This method is as accurate as the data it uses, as visualization and computation only rely on the implemented data inside. These softwares use more complex models that take into account more parameters than a usual GIS application, as they implement 3D, but they have the advantage of providing a realistic overview of a given situation.

9.2. Real-Time Data

Real-time data has already been implemented in several GIS studies and has shown its advantages [73–76]. It definitely improves the precision of data collected, ensures that data are up to date, enables quick reactions to any changes, facilitates continuous monitoring of phenomena using captors, and even allows for data analysis in real time. However, this approach has not been frequently used for studying sea level rise. One study was found using real-time information to mitigate flooding in a coastal city [76] facing sea level rise, but its use is not widespread. Not a single study mentioned previously used real-time data, which shows that this type of information is not used in the field of sea level rise, despite its widespread use in GIS. The same conclusion can be drawn regarding applications in smart cities [74,75] and fires [73], for instance, but the field lacks extensive literature about this topic related to GIS [29], despite its proven efficiency.

9.3. GIS Studies

The spatial resolution of data is an important gap. Studies using hydrological connectivity methods or other GIS techniques use low spatial resolution data [22,24], which shows a gap in the availability of high-resolution spatial datasets. This prevents the attainment of accurate and precise results. Additionally, the accuracy of the DEMs [23,27] used is not high as well, which presents the same issue. In addition, some datasets used are outdated [18], which highlights a gap in the availability of updated data to ensure the validity of the results.

Some studies voluntarily do not consider some variables that could impact sea level rise, as in the case of Mercantini and Charpentier [34], who did not include external factors to model their museum flooding scenario. Taking these variables into account would lead to a more comprehensive analysis for further research.

9.4. Inequality of Research Related to Sea Level Rise

As seen previously, there is inequality about the number of papers published by each country regarding sea level change in general. For instance, China and America are leaders [77–80] in comparison to other countries like the United Arab Emirates [26]. This inequality can be explained by economic disparities, research capacities, access to data, national priorities, information diffusion, or national politics, all of which can influence the finances available to conduct research.

The most important inequality is related to whether a country has a coastal border or not, which is logical. However, not all coastal countries have the same number of publications, which is an important gap. In effect, countries that experience sea level rise might not be able to publish the results of their research or conduct research on this phenomenon in comparison to other countries.

It would be interesting to apply sea level rise studies to coastal countries that do not have extensive literature on this subject to uncover areas that would be vulnerable to this risk.

9.5. Multidisciplinarity of Sustainable Studies

Another gap addressed by sustainability is the lack of research that studies all aspects of sustainability in one paper. Usually, papers only focus on one aspect related to sustainability [5,81]. However, understanding it in its entirety should help highlight the multiple processes that are at stake to make the causes and consequences of a situation clearer. For instance, in the case of the impact of sea level rise on mangroves [6], only the sustainability of coastal area management is usually addressed [7]. However, this occurs within the broader context of protecting coastal cities. Therefore, it would be interesting to diversify the points of view to better understand the different aspects that impact a specific context, like Liang [82] began to do by adding land use in the analysis.

10. Conclusions

In summary, this review provides a comprehensive overview of the diverse methodologies and tools available for the study of sea level change, emphasizing the interconnections among these fields [8,12,25]. However, there is a lack of interest of sustainability regarding sea level rise field. Sea level change is predominantly assessed through predictive modeling at various spatial scales. Methodological approaches vary, with the use of different scenarios, including the commonly employed Representative Concentration Pathways (RCP) from the Intergovernmental Panel for Climate Change (IPCC), as well as localized scenarios tailored to specific regional or local contexts [15,22].

The integration of Geographic Information Systems (GIS) has emerged as a pivotal advancement in sea level change research, owing to the increased availability of satellite imagery and LiDAR data [24,27]. Furthermore, researchers have introduced additional variables and indices, such as the Coastal Vulnerability Index (CVI), to enhance the understanding and quantification of this complex phenomenon [23,26]. These developments have led to the adoption of innovative techniques like hydrological connectivity analysis, which facilitates assessments of potential future sea level rise (SLR) impacts on coastal areas [9,18]. Furthermore, the emerging use of gaming technology for 3D simulations offers exciting prospects for immersive visualization and public engagement in understanding the consequences of sea level change and the need for proactive policies and actions [33,34]. Additionally, a global analysis of SLC and GIS research highlights the prominent roles of the United States and China in this field. Furthermore, our examination of rising temperatures in the GCC region reveals the profound impact of climate change on local sea levels and extreme weather events. Coastal regions in the GCC are particularly vulnerable, necessitating ongoing monitoring and adaptive measures.

A common constraint of the articles reviewed is their spatial resolution, which is usually not high. Moreover, the methodologies employed are not always validated and may need to be improved. The outcomes of the review of 200 papers are one of the main limitations addressed here. In effect, the decision not to deepen the analysis was made because this number of papers was accessible and selected at the time of the study, and it was considered a representative sample of the state-of-the art regarding the SLR field.

The findings from this review have critical policy implications for coastal management and climate adaptation strategies. Policymakers should prioritize the incorporation of localized sea level rise scenarios to inform region-specific mitigation and resilience efforts. Investments in advanced GIS technology and high-quality data sources are essential for making informed decisions about coastal development and protection.

Further research could explore more articles and find new data, variables, or methodologies that are applied to the SLR field. SLR articles are often focused on the impact of SLR on the coast. However, it also has consequences for coastal cities, transportation, and the environment. A future paper could examine these components through the lens of SLR due to the lack of research in this field. A focus on the GCC region could also be planned in continuation of this review.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16072861/s1.

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