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Review

Review of the Impacts of Climate Change on Ports and Harbours and Their Adaptation in Spain

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Abstract: Climate change is one of the issues of greatest concern to today's society. The increase in temperatures has affected sea levels, polar masses and extreme events, among others. There are many scientific studies that analyze the impacts of climate change on coastal communities, but most of them focus on beach erosion and coastal recession. Scientific literature on the effects of climate change on ports and harbors and their adaptation is much less abundant. Ports are essential for the economy and society of their cities, so studying the impact of climate change on them is an urgent need. The Mediterranean and the Spanish Mediterranean coast is one of the areas that will be most affected by climate change in the future. In addition, the Spanish economy depends a lot on its tourism and, thus, on its coastal cities. Therefore, the study of the impact of climate change on Spanish ports and coastal communities is essential. This article presents a review of the studies carried out until now on the effects of climate change on Spanish ports, and it identifies research gaps and weaknesses and suggests new research lines.

Keywords: climate change adaptation; Mediterranean Coast; sea-level rise; ports adaptation; Spanish coast adaptation

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1. Introduction

Climate change has always existed, but since the industrial revolution the amount of greenhouse gases (GHG) emitted to the atmosphere has increased considerably. The greenhouse effect is a natural effect and without it, Earth would have freezing temperatures (around 33 °C less than today). When humans emit greenhouse gases, what they are producing is an "overeffect" that causes global warming. There are four main greenhouse gases: carbon dioxide (CO_2) (accounting for 80% of the emissions caused by humans), methane (CH_4), oxide of nitrogen (N_2O) and fluorinated gases [1].

The increase of emissions of these GHG is causing global warming, which is affecting the ocean and cryosphere. This increase of temperatures is provoking sea level rise (SLR) due to the thermal expansion of the ocean and the thaw of polar regions and high mountain areas. Another consequence of the rising temperatures is the increment of both the magnitude and frequency of extreme events. This is causing, at the same time, negative impacts in water quality, ecosystems and cultures of different ethnicities, great damages in human infrastructures and social and economic losses [2–6].

To avoid climate change effects there are two main strategies: mitigation and adaptation. Mitigation strategies focus on the reduction of emissions, while adaptation strategies focus on the adjustment of the existing systems to the expected effects caused by these emissions [7]. Even if the world stopped emitting GHG today, the sea will continue rising and extreme events will continue increasing. Therefore, defining proper and adequate adaptation plans is key for the future.

One of the systems most threatened by global warming is coastal systems. A significant percentage of world's population and infrastructures are located next to the coast; around 40% of global population lives within 100 km (km) of the coast. In addition, in 2050 this value is expected to increase to 75% [8,9]. On the other hand, the impact of climate change will not be the same in all countries. There are areas that will be most affected by the effects of climate change and one of these areas is the Mediterranean basin. It has been calculated that temperatures in the Mediterranean will increase by 1.4 °C with respect to preindustrial levels, which is 20% more than in the rest of the world [10]. The Mediterranean coast is located between the North of Africa, whose climate is arid and dry and central Europe, which has a rainy and humid climate. Therefore, it is affected by atmospheric and oceanic interactions, which makes it very vulnerable to climate change [11]. In fact, it has been defined as one of most worrying hot-spots when referring to the climate change problem [12]. Therefore, scientific literature on climate change and the Mediterranean is extensive.

However, most of the literature about climate change and coastal management focuses on the effect of climate change on shoreline evolution. Some examples are Mentaschi et al., 2018 [13] who concluded that a total of 28,000 km^2 of land has been lost due to coastal erosion or Luijendijk et al., 2018 [14] that found that one out of four beaches in the world is eroding.

Although many scientists studied the effect of climate change in beaches and coastal ecosystems, there is much less research on the effects that climate change will have on ports and their operability. Seaports are one of the infrastructures most threatened by climate change, and given their key role in global supply chains, adapting and protecting ports against climate change is crucial for the future of our society [15]. Navigation is one of the main modes of transport, especially in the transport of goods; 80–90% of goods worldwide are traded by sea [16,17], and it is forecasted to annually increase by 4% over the next five years [18]. Therefore, to avoid economic and social losses, it is crucial to study the impact that climate change will have on ports and to propose adaptation plans.

The aim of this article is to collect up-to-date knowledge about how climate change will affect the port infrastructure of the Spanish Mediterranean. For the first time, a regional, temporal, methodological and thematic analysis has been carried out. It has been identified in which areas of the Spanish Mediterranean there is a lack of specific studies. The main methodologies used in these studies have also been analyzed and compared. In addition, a thematical analysis of these studies has been conducted, identifying which topics have been the most dealt with in scientific literature and which are the most important for the future and need more attention and resources, as well as what future lines of research should be focused on.

2. Materials and Methods

For the present research, a structured literature review based on the methodology of Adebisi et al., 2019 [19] was conducted. As explained in Adebisi et al., 2019 [19], the structured literature review has three stages: planning, review and information synthesis. In the first stage, planning, search criteria and databases were defined. The databases used were mainly Web of Science (WOS), Scopus and PubMed. The search criteria was the topic of the articles, and the keywords used were "Levante climate change," "Mediterranean climate change" and "Spain climate change." In the second stage of the review, the articles were searched and filtered. A total of 14 articles coincided with the search of "Levante climate change," 9875 with "Spain climate change" and 30,896 with "Mediterranean climate change."

The distribution of the major concepts of all the studies obtained is presented in Figure 1. The great majority of studies were related to environmental sciences, followed by climatology, ecology environmental sciences, marine ecology and computational biology.

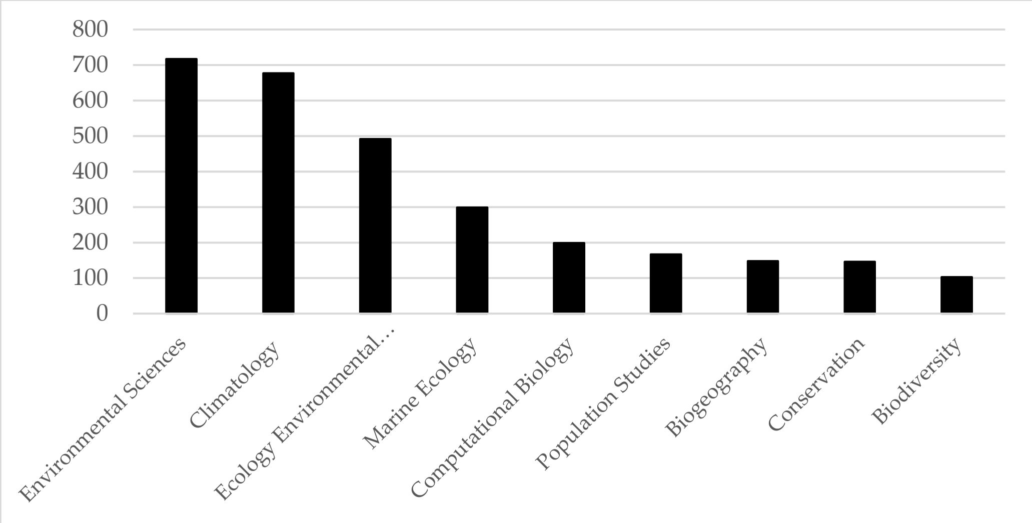

Figure 1. Major concepts of the studies from WOS.

All these articles were filtered by study area, selecting only the ones related to oceanography, maritime infrastructures and ocean and maritime engineering, which gave a total of 272 articles. Further, 21 articles were about Mediterranean climate, 63 about SLR and flooding, 41 about coastal erosion and shoreline projections, 32 about extreme events and 115 about adaptation and vulnerability (Figure 2). Finally, in the third stage, all the information of these 272 articles was analyzed and synthesized.

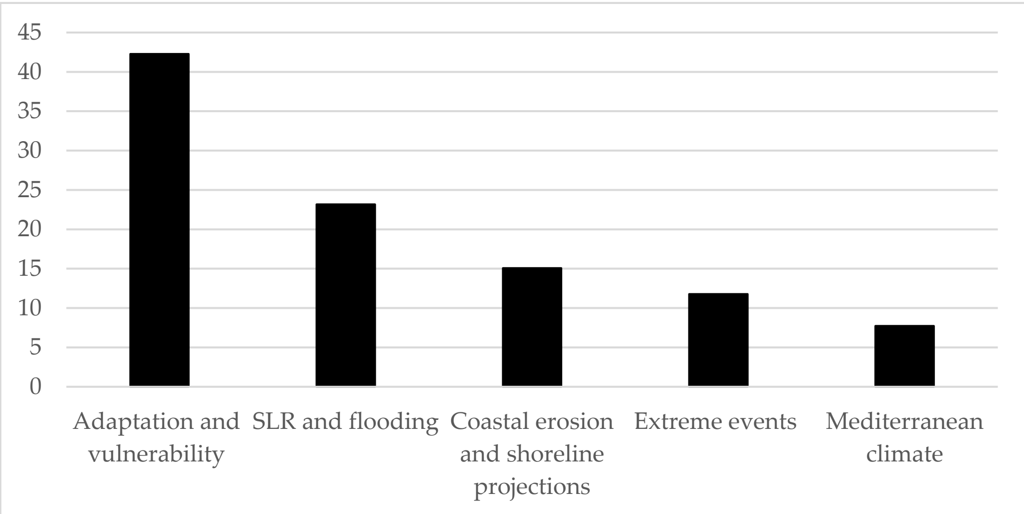

Figure 2. Classification of reviewed articles by topic.

3. Results and discussion

3.1. Sea Level Rise (SLR) and Flooding

As was explained in Section 1, one of the direct consequences of climate change and the increment of Earth's temperature is the increase of sea level (SL). Total water level of the sea can be divided into mean sea level (MSL), wave setup and storm surge [20]. An increase of any of these three components will cause an increase in SL.

The elements that cause SL changes are usually divided into mass component (due to mass changes, such as ice thaw) and steric component (due to density changes); the steric component can also be divided into thermosteric and halosteric components [21].

All the causes of changes in SL can be summed up in: ice sheets (Greenland, West Antarctic and East Antarctic), glacier and ice cap, global mean thermal expansion, land water storage, regional ocean steric and dynamic effects, surface mass balance, glacial isostatic adjustment (GIA), sediment compaction and tectonics [22].

This increase can cause negative impacts on environmental systems, social communities, infrastructures, etc. Therefore, much scientific effort has been put into its estimation. To know the MSL of a region, there are different databases, and the most-used one is the Permanent Service for Mean Sea Level (PSMSL) [23]. Apart from SL databases, scientific literature about SLR is abundant. The number of studies of SLR has increased since 1997 due to the necessity to develop climate change adaptation strategies. Figure 3 presents the evolution in time of the number of studies of SLR presented in this section (Table 1).

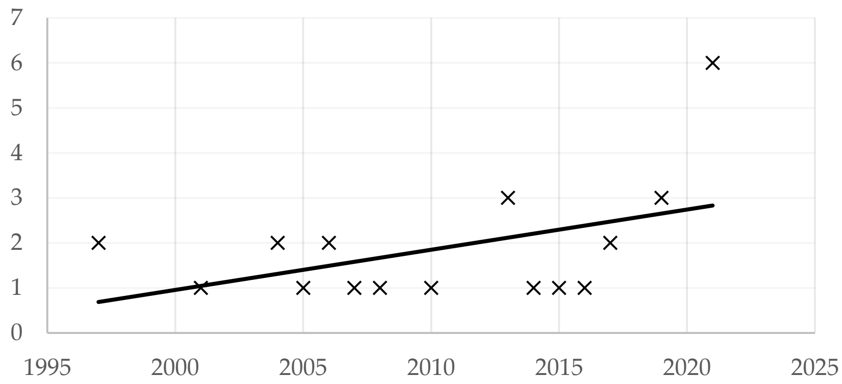

Figure 3. Evolution in time of the number of studies concerning SLR.

For the twentieth century, the value of global SLR estimated by most research is 1–2 mm/year [24–26]. For the period 1993–2010 the global SLR estimated is around 3 mm/year [27–30]. Apart from estimating SLR from altimetry measures, tide gauges, satellites, etc., it is important to project future SLR. Some of the most relevant estimations and projections of SLR from the scientific literature are presented in Table 1 [31].

In general, the global SLR projection has increased with time. Studies between 2005–2015 estimated a SLR around 75 cm for 2100 under RCP8.5, while studies between 2015–2020 estimated a SLR around 85 cm.

Although global SL estimations are important, regional variability is huge. Vacchi et al., 2021 [32] studied this variability along the central and Western Mediterranean with a Bayesian spatio-temporal statistical model with 401 sea level index points and pointed out that, to study the effects of SLR, regional studies are necessary.

Some of the most important regional studies in Spain are presented in Table 1. Apart from these studies, Marcos et al., 2021 reconstructed sea-level historic series in Alicante and Santander [33] and studied the SLR of Cadiz during the period 1880–2018 [34]; they obtained different values of SLR (0.7 mm/year) from those of Vargas-Yanez, 2021 [35] (1.28 mm/year); these differences may be due to the influence of the methodology followed to fill the measure gaps. Table 1 also presents regional studies that project SLR for the future.

Table 1. SLR review.

Author	Region	Time Frame	Scenario	SLR	Methodology
Peltier, 2001 [26]	Global	20th century	Present estimations	1–2 mm/year	Tide gauges and GIA model
Miller and Douglas, 2004 [25]					Tide gauges with observations of temperature and salinity
Church and White, 2006 [24]				1.1 mm/year	Tide gauges
Church and White, 2006 [28]		1993–2010		3.1 mm/year	Satellite altimeter and island sea-level measurements
Hay et al., 2015 [29]		1993–2010		3 mm/year	Tide gauges and physics-based and model-derived signals (Probabilistic)
Tsimpilis et al., 2013 [30]		1993–2011		2.8–3 mm/year	Altimetry, temperature, salinity and gravity measurements
Cazenave et al., 2004 [27]		1993–2003		2.8–3.1 mm/year	Satellite altimeter
IPCC 2013 [36]		2100	RCP8.5	53–97 cm	Numerical models
IPCC 2019 [6]				61–110 cm	Numerical models
IPCC 2021 [37]				63–101 cm (SSP5–8.5)	Numerical models
Rahmstorff et al., 2007 [38]				50–140 cm	Semi-empirical model
Horton et al., 2014 [39]				50–150 cm	Experts survey
Kopp et al., 2016 [40]				52–131 cm	Statistical synthesis of regional sea-level reconstructions
Mengel et al., 2016 [41]				57–131 cm	Semi-empirical model
Bamber et al., 2019 [42]				21–163 cm	Structured expert judgement (Probabilistic)
Ibañez et al., 1997 [43]	Ebro Delta	20th century	Present estimations	3 mm/year	Measure rates of sedimentation, accretion, vertical elevation and subsidence
Jiménez et al., 1997 [44]					Tide gauges and Bruun's rule
Vázquez et al., 2021 [45]	Cádiz	1960–2020		3.5 mm/year	Tide gauges, linear regression and global records
Vargas-Yanez, 2021 [35]		1880–2018		1.28 mm/year	Tide gauges and statitical linear models
Marcos et al., 2021 [34]				0.7 mm/year	Tide gauges and near records
Chust et al., 2019 [46]	Basque Coast	2nd half of 20th century		2–2.5 mm/year	Tide gauges and LiDAR (altimetry)
Marcos et al., 2005 [47]					Tide gaguges and Empirical Orthogonal Function analysis
Leorri et al., 2008 [48]					Foraminifera-based transfer function
Vousdoukas et al., 2017 [49]	Europe	2050	RCP8.5	21–24 cm	Numerical models
Luque et al., 2021 [20]	Balearic			18–36 cm	Numerical models
Chust et al., 2010 [50]	Basque Coast	2100		28.5–48.7 cm	Temperature projections and LiDAR (altimetry)
Vitousek et al., 2017 [51]	Europe			53–77 cm	Numerical models

Luque et al., 2021 [20]	Balearic	46–103 cm	Numerical models

As it can be seen from the table above, most SL predictions are global, but to develop efficient climate change studies these global estimations must be translated to regional studies. Figure 4 shows the number of regional studies of SLR in Spain; the colour green means that a considerable number of regional studies have been conducted and the colour red that zero studies have been conducted. Most SLR studies of the Mediterranean coast are conducted in the Maresme and Delta del Ebro areas because they are the most problematic zones on this coast. However, the rest of the Mediterranean coast is also a hotspot for climate change and has a need of specific regional studies to accurately predict SLR. In addition, as it can be seen from Table 1, all the studies obtained similar results, except those by Marcos et al. [34] and Vargas-Yanez et al. [35], whose differences could be due to the different methodologies applied.

Referring to the methodology followed to estimate SLR, a large number of the studies presented used tide gauges records with different supplementary techniques. In previous years, numerical models have been the most used methodology to predict SLR because they have improved enormously and have become one of the most accurate tools to forecast sea level rise. Figure 5 shows the main methodologies used to estimate SLR.

Figure 4. Number of SLR studies in the coast of Spain.

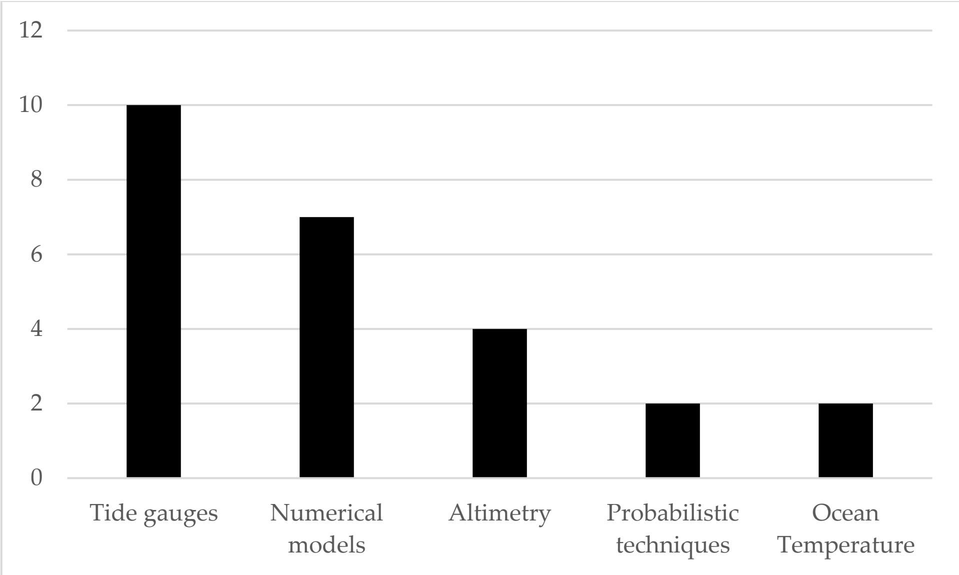

Figure 5. Frequency of methodologies used to estimate SLR.

One of the main direct impacts of SLR is the flooding of coastal cities, ports, dunes and any coastal system. Hence, many scientists have studied the flooding of different areas.

Hinkel et al., 2014 [52] studied flood damage globally and highlighted that under a SLR of 25–123 cm, 0.2 to 4.6% of the population would be flooded annually in 2100, and annual losses of Gross Domestic Product (GDP) would be of 0.3 to 9.3%. Focusing on the Mediterranean coast, Jorda et al., 2013 [21] studied the Mediterranean basin and predicted an increase of its salinity due to the increase of evaporation and decrease of precipitation. Galassi et al., 2014 [53] also studied SLR projections in the Mediterranean by 2050, and concluded that in the near future the mass component will clearly exceed the steric component.

In Spain, Guil-Guirado et al., 2021 [54] conducted a study on the Spanish Mediterranean coast and concluded that the worst seasons for flooding were autumn and winter and the worst months September to November. The cities most affected were Valencia, Barcelona and Alicante, and the worst sector was the tertiary sector. Pérez-Morales et al., 2018 [55] stated that the increase in flood exposure in Murcia and Alicante was linked to two construction peaks, one between 1978–1982 and the other between 1997–2007. Two years later, Ribas et al. [56] reached the same conclusion for Catalonia, Valencia, Alicante and Murcia, and stated that the urbanization in areas with a high risk of flooding significantly increased the exposure of these cities.

Chust et al., 2010 [50] studied the effects of SLR on the Basque coast and pointed out that 15.6% of sandy beaches will be affected by 2099.

Vinet et al., 2019 [57] mapped the mortality related to floods in Catalonia and the Balearic Islands and obtained a fatality rate of 0.407 and 0.623, respectively. This rate means that one person per million people dies every 1/F years due to floods.

Sayo et al., 2018 [58] and Grasses et al., 2020 [59] studied the effects of SLR in the Ebro Delta. López-Dóriga et al., 2020 [60] developed a pseudo-dynamic to evaluate the response capacity of active shorelines to Relative Sea Level Rise (RSLR) and applied it to low-lying coastal areas of Catalonia.

Ballesteros et al., 2018 conducted a multicomponent flood-risk assessment of the Maresme coast [61]; they developed a source-pathway-receptor-consequence model and concluded that in this area, the risk of flooding was low, except in some areas such as the Tordera delta.

Finally, Hernández-Mora et al., 2021 [62] developed a flood model using LISFLOOD and S-Beach in Tossa de Mar, Catalonia.

As happens with the prediction of SLR, most of the studies about the impact of SLR are focused on very specific points of the Spanish Mediterranean coast, more specifically in Catalonia, and they are mainly the Maresme coast and the Delta del Ebro hotspot. Figure 6 illustrates this lack of studies of the rest of the Mediterranean coast.

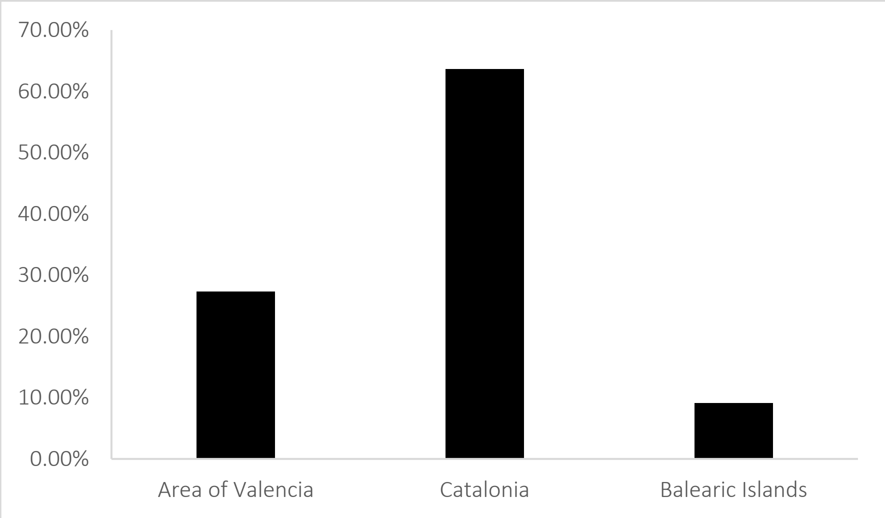

Figure 6. Distribution of studies of SLR impacts in the Spanish Mediterranean coast.

3.2. *Impacts on Ports and Harbours and the Need to Adapt*

Coastal cities and ports are key for the current society and global economy. Their importance as economic hubs is increasing and they are becoming places where large parts of the population congregate and create economic and social value. In fact, in 2005, thirteen out of the twenty most populated cities in the world were port cities [63]. Ports also play a strategic role for economic growth and development in all scales, whether global, regional or local. They are also key transportation nodes for goods, they link local and national supply chains to global markets and are responsible for 80–90% of transportation of goods [64]. Therefore, if ports are affected by any problem that prevents their operation, there will be significant social and economic consequences [65]. Protecting them and developing proactive plans is essential and is a current priority.

Port cities will be one of the most affected systems under high-emissions scenarios and under climate change effects. Nursey-Bray et al., 2013 [66] affirmed that there are five main areas in ports that will be affected by climate change: Infrastructure, environment, population, safety and occupational health, and supply chains. Nicholls et al., 2008 [63,67] studied 136 port cities with more than one million inhabitants and assessed that in 2005 about 40 million people were threaten by a 100-year return-period coastal flood and that a total of 3000 billion USD was also exposed. This means that around 5% of global GDP is exposed to coastal flooding and this exposure could grow by the 2070s to 35,000 billion USD, which means that a 9% of projected global GDP will be at risk.

As it has been said in Section 1 Introduction, despite ports being one of the systems most affected by climate change, the majority of scientific studies focus on erosion and flooding events, not on the effects that climate change can have on port cities or the derived consequences. In this section, a review of the most relevant studies about the impact of climate change in ports is presented.

3.2.1. Global Studies

Globally, Australia, USA and Japan are pioneers in studying the effects of climate change in port cities. Australian and American authors mostly focused on developing manuals to define adaptation strategies and much of their work was done between 2010–

2015. On the other hand, Japanese authors focused on structure stability. Some of the most relevant studies are explained below.

In America, Haveman and Shatz, 2006 [68] compiled a standard reference manual for understanding the issue of port security in the USA and particularly in California. Messner et al., 2013 [69] developed a methodology to evaluate vulnerability and risk in San Diego Port. In Australia, Nursey-Bray et al., 2013 [66] studied vulnerabilities and the adaption of Australian ports and Mcevoy et al., 2013 [70] wrote a document to test and refine assessment methodologies. In Japan, Takagi et al. [71–73] and Mase et al., 2013 [74] studied the stability of breakwaters under new climate change conditions (SLR and increase in wave heights and storm surge).

Becker et al. [75,76] presented the effects of climate change in ports at a global scale and conducted a survey to detect port risks. They specifically highlighted the need for more awareness about the complex implications that climate change may have on ports and related transport networks. Finally, Mutombo et al., 2017 [77] conducted a survey to analyze port risk over 29 countries.

In Europe, Prahl et al., 2018 [78] analyzed the economic loss due to coastal flood height in 600 European cities, and the adaptation costs that it will have. They did this by defining damage and protection cost curves. After this, Abadie et al., 2019 [79] studied the distribution of the damage curves using the Generalized Extreme Value (GEV) distribution model. Another relevant study at the European level is one conducted by Reckien et al., 2015 [80], who exanimated the barriers and drives of adaptation and mitigation measures. They pointed out the unemployment rate of a city and low values of GDP as key barriers to the development of urban plans. Christodoulou et al., 2019 [81] also studied the impacts of SLR in European ports and concluded that in the Black Sea and the Mediterranean, the effects of climate change will be less aggressive, but much more frequent.

The problem of these general studies is that climate change impacts have a huge regional variability and to develop an efficient adaptation pathway, each case must be studied in detail and no general rules can be applied. Therefore, all these studies must be complemented with regional and site-specific studies, and to apply all the general guidelines, they have to be adapted to each case.

3.2.2. Spanish Studies

Focusing on Spain and in the Mediterranean, the most relevant studies are presented below.

Sánchez-Arcilla et al., 2016 [82] studied the effects of climate change on the Mediterranean. They noted that SLR will affect the water depths of ports and inevitably affect wave propagation patterns, and it may have consequences on infrastructure stability.

Sierra et al., 2015 [83] studied harbor agitation, and the results obtained showed a gentle descent in harbor agitation in the majority of the ports of the Catalan coast. In 2017 [84], they modelled the impact of climate change on Barcelona and concluded that it will remain safe and maintain operability levels under climate change. SLR represents a small percentage of the water depth of Barcelona port (around 10%). Therefore, the relative increase is small, and it will not significantly affect wave patterns and diffraction coefficients. Casas-Prat and Sierra [85,86] also conducted studies on the Catalan coast in which they analyzed the trend of wave storminess and direction. They highlighted the importance of also including directional studies in climate change assessments because most coastal infrastructures are designed with directional records of wave height, and changes in the direction of the waves could affect their stability.

León-Mateos et al., 2021 [15] criticized the lack of quantitative and validated studies in port adaptation research. To address this problem, they defined a Port Resilience Index and validated it using the port of A Coruña. López et al., 2015 [87] applied artificial neural networks (ANNs) to assess operability in the port of Ferrol.

The studies above-presented are focused on the impacts that climate change can have on ports. However, another important part of research is to study possible adaptation measures to mitigate these impacts. The United Nations Conference on Trade And Development (UNCTAD) [88] stated in the Meeting on Climate Change and Adaptation that adaptation was critical, and that adaptation and mitigation should be dealt with simultaneously. In the section below, studies that are more focused on the adaptation process than on the impacts produced by climate change are presented.

Becker et al., 2012 [76] defined three main options for port adaptation: update storm defenses, elevate to compensate and relocate entirely. Foti et al., 2020 [89] performed a review on coastal defense techniques and called for an improvement of existing structures and the combination of different types of solutions. Tanik et al., 2017 [90] studied and compared the adaptation measures in Germany, France, Spain, Italy, Denmark, USA and Kenya.

Sánchez-Arcilla et al., 2016 [91] studied different pathways to adaptation on the Catalan coast, criticized the reactive management followed in Spain and called for active and sustainable interventions. López-Dóriga et al., 2020 [92] studied the investment in adaptation on the Spanish coast. The investment in coastal adaptation between 2010–2018 was estimated at 56 M €, and they concluded that it was not enough to face climate change. Abadie et al., 2020 [93] studied 62 main coastal cities in Portugal and Spain under RCP 2.6, 4.5 and 8.5., and calculated the estimated costs if no adaption measures were taken and if adaption strategies were implemented. They concluded that the investment in adaptation will be much smaller than the economic damage caused by inaction.

Sierra et al., 2017 [94] studied the effect of seagrass meadows in two harbors on the Catalan coast. These meadows were found to be a great measure to reduce wave height. Velasco et al., 2018 [95] conducted an assessment of the effectiveness of structural and nonstructural measures in Barcelona with a 1D/2D-coupled model that used depth-damage curves, detailed flood depth maps and land-use maps.

There are also different research studies concerning adaptation and administrative and governance issues in Spain.

Salvia et al., 2021 [96] studied the mitigation policies within Mediterranean Europe and saw that France and Spain were the most active in terms of climate-mitigation planning. Losada et al., 2019 [97] also studied the adaptation strategy of Spain to climate change. In 2020, Izaguirre et al. [98] developed a methodology to assess climate change impacts in seaports. Sauer et al., 2021 [99] studied the actors that participate in the management of the port of Barcelona and its adaptation.

In addition, it has to be said that the port of Valencia is part of the ECCLIPSE European Project, of which the main objective is to develop a common framework for assessing the impacts associated with climate change and the adaptation to such impacts of ports in the southwest of Europe [100].

Table 2 presents a summary of the main conclusions and methodologies of the studies presented in this section.

Table 2. Summary of Spanish studies of climate change and ports.

Type of Study	Authors	Region	Main Conclusions	Methodology
Impacts of climate change on Spanish ports	Sánchez-Arcilla et al., 2016 [82]	Mediterranean	Overtopping and flooding are the main direct impacts of SLR.	Review of previous studies.
	Sierra et al., 2015, 2017 [83,84]	Catalan ports	Small ports will be affected by SLR because the relative increment of depth is high.	SWAN and Boussinesq models and linear wave theory.
	Casas-Prat and Sierra, 2010, 2012 [85,86]		Directional changes will cause a mean increase of about 50% in harbor agitation.	Statistical and linear regression analysis and Boussinesq model.

	León-Mateos et al., 2021 [15]	A Coruña	Port Resilience Index to identify the areas in which improvement is necessary.	Identification of critical processes, risk scenarios and resilience indexes. Crossing of the datasets.
	López et al., 2015 [87]	Ferrol	Implementation of ANNs, more efficient and less data needed than traditional methods.	Collection of the data from buoys, training and validation of the ANN.
Adaptation of Spanish ports	López-Dóriga et al., 2020 [92]	Spain	Investment in adaptation directly related to the regional GDP. Andalusia invests much more.	Data collection and correlation and statistical analysis.
	Abadie et al., 2020 [93]	Iberian Peninsula	Using median values can underestimate coastal risks. Invest in adaptation measures is needed.	Stochastic approach. Define SL cities percentiles and damage functions.
	Sierra et a., 2017 [94]	Catalan ports	Seagrass meadows can attenuate 40% of wave-height. Higher density, higher attenuation.	SWAN and Boussinesq models.
	Sánchez-Arcilla et al., 2016 [91]		Resilience is higher for energetic coasts. Sustainable practices are long-term practices.	Comparative analysis.
	Velasco et al., 2018 [95]	Barcelona	Nonstructural strategies are better than structural. Structural are more efficient, but more expensive.	1D/2D coupled model (Infoworks ICM).
Adaptation and governance issues	Salvia et al., 2021 [96]	Mediterranean Europe	The west of Europe is more active in mitigation policies (stronger governance and regulation).	Data and plans review at regional level. Statistical analysis.
	Losada et al., 2019 [97]	Spain	Cooperation between stakeholders and policymakers, public and private sector, and at regional level is key.	Development of Spanish Strategy for Coastal Adaptation.
	Sauer et al., 2021 [99]	Barcelona	Lack of diversity, vertical coordination and communication in climate change adaptation.	Social Network Analysis, quantitative metrics and semi-structured surveys.

From all the scientific articles analyzed in this paper, most of them focused on the damage that climate change could cause on ports (Figure 7). However, only a few of them studied the relationship of the agents implied in the operation of ports, which has proven to be a weakness. The operation of ports is very complex; it involves public and private agents and for the development of an efficient strategy to adapt ports to climate change, an effort to study the relationships between these agents is needed. The number of studies that focus on the development of adaptation strategies is also scarce. The first step to deal with climate change is to improve the collaboration between the agents implied in port operations, and to do that, future research lines should focus on the study of port networks and how to improve the collaboration between the public and private sector and the academics.

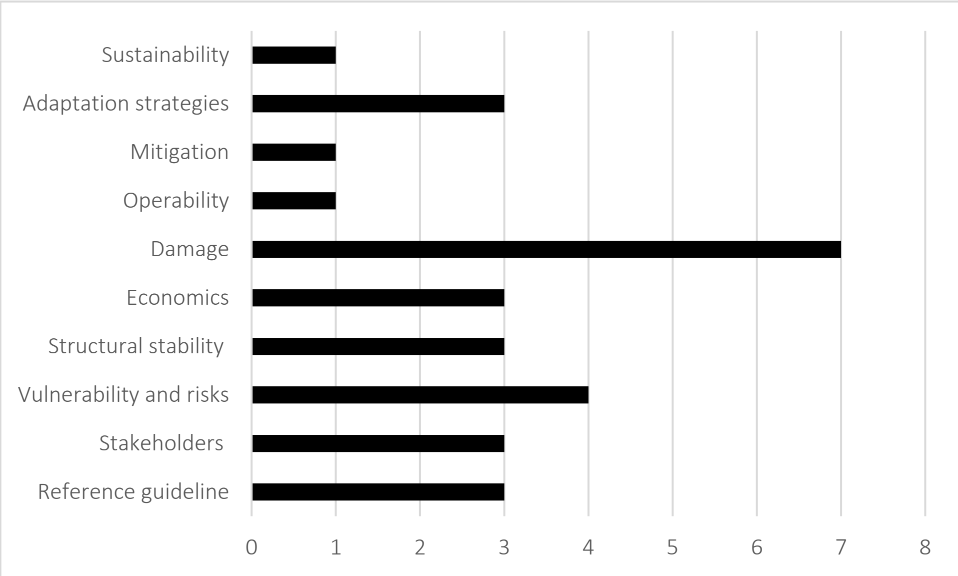

Figure 7. Topic of the main studies focused on climate change and ports.

Referring to the methodology, the majority of the studies used numerical models, more specifically, SWAN for wave propagation and Boussinesq models to study harbor agitation; SWAN models cannot solve diffraction problems and Boussinesq models are very computationally expensive, so they can only be applied in very small areas. The main problem of these numerical models is that they need a great amount of high-quality data, so when this data is not available, other techniques such as linear theory or analytical models have to be applied. Moreover, ANNs have proved to outperform traditional models and they are becoming more popular, so future studies should use this methodology to improve the accuracy of the results when numerical models cannot be applied, and even as an alternative to them.

On the other hand, all of the studies presented focus on big ports because they have a higher economic and social value. There are almost no scientific papers in the Spanish Mediterranean coast that study the impact of climate change on small ports and, as stated by Sierra et al. [83], these will be the ports most affected by climate change because the SLR will represent a high percentage of each depth. Therefore, more studies on small ports are needed.

Finally, as detailed in Section 3.1, most of the studies about port adaptation are located in very specific areas of the Mediterranean coast, though there are thousands of km of the Spanish Mediterranean coast and ports without specific regional studies.

4. Conclusions

Ports are key spaces in coastal cities. They are not only crucial for logistic chains and the transport of goods nationally and internationally, but also, they are essential for the economic and social functions of their cities. Around ports, spaces of great social and economic value are generated for a city. Many coastal cities have taken advantage of the port area to develop street markets, bars, discotheques and even amusement parks for children. Ports concentrate many activities, both social and economic, and generate a lot of value. They create employment and contribute to the GDP of coastal cities, promoting urbanization and industrialization.

Ports are one of the systems most threatened by climate change. To face climate change impacts, mitigation and adaptation policies are key. However, mitigation policies take too long to work and there are climate change effects that do not have solutions even with the implementation of mitigation policies. Therefore, the development of adaption plans is key for the future of coastal cities. The scientific community agrees on this (Becker et al., 2013 [76]; Sánchez-Arcilla et al. [91,101]; Sierra et al. [83,84,94]; Casas-Prat et al. [85,86]; Toimil et al., 2017 [102]; Camus et al., 2019 [64]; Abadie et al., 2020 [93]) and calls on countries to develop active measures.

Spain and the Spanish Mediterranean coast is one of the hotspots of climate change. If no adaption measures are taken, huge economic and social losses will occur in future scenarios, such as the ones that happened with Gloria or Emma squall. To avoid these losses, the adaption of the coastal defense structures and adaption strategies are needed.

Although scientific literature about climate change is abundant, there are only a few articles that focus on the effect that climate change will have on ports and on their operability. Much more effort has been put into studying how coastlines are going to change with climate change, such as in the study of beach erosion and of the flooding of cities by rainfall events.

However, ports and their adaptation to climate change have received much less attention and most of the studies that exist concerning climate change and its effects on ports focus on the damage and impacts that SLR and extreme events will have. Nonetheless, it has been proven that one of the reasons that makes the study of ports very difficult is the complexity of the network of the agents implied in the operation of ports. There are very few articles that study these relationships and how to improve coordination and cooperation between the actors involved in the operation of a port. Until this is improved, all studies and efforts will be in vain. Therefore, future research lines should focus on this topic.

Referring to the methodologies used in these studies, the most common methods used are numerical models (in both sea level prediction and impacts and adaptation assessments). However, in recent years, ANNs have been proven to provide more accurate results, be less computationally expensive and have the capacity to model processes even with less-quality data. ANNs have become a widely used tool in water resources research and should also be applied in ocean and coastal engineering.

In the case of Spain, the scientific papers that exist concerning ports and climate change focus on very specific hotspots, most of them in the Catalan coast (the Ebro Delta, Maresme, etc.), but there is still a lack of studies in most of the ports along the coast. Therefore, more studies should be carried out in these geographical gaps (Balearic Islands and the area of Valencia).

In addition, most studies focus on ports of general interest, but the ports that will be most affected by climate change are small fishing ports and marinas, because due to their dimensions, changes in SL and wave height are much more significant and their relative importance is higher. Therefore, future research lines should also focus on the study of small harbors, even if they are not as important as ports of general interest, as they are the ports most threatened by climate change.

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