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Climate-Related Vulnerability and Risk Assessment of Main Ocean Uses: An Overview

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Vulnerability and risk analyses have been increasingly used in a wide variety of contexts to support ocean management and planning processes. Depending on the context, such analyses may focus on different dimensions, spatial scales, and hazards. In the particular context of climate change, the variability inherent to the developed assessments has led to the emergence of numerous methodological frameworks, allowing for advances in the field while raising uncertainties on applied concepts, definitions, and approaches. In the present study, we developed a systematic literature review to analyze and discuss the key concepts, methodologies, and limitations of existing vulnerability and risk assessments of main ocean uses to global climate change. We analyzed over 314 scientific references regarding the elements considered in the analysis (e.g., exposure, sensitivity, adaptive capacity), dimensions (e.g., ecological, economic, social), type of indicators (e.g., quantitative, qualitative), maritime activities, climate-related drivers of change, and spatial scales. Results show that most vulnerability and risk assessments address fisheries and marine conservation, and that sea-level rise and extreme events are the most frequently considered climate-related drivers of change. The main identified limitations pertain to the level of subjectivity and the tremendous variety of concepts, areas of expertise, and systems addressed in such studies. We highlight that further research is needed particularly on the development of cross-sectoral studies and integrative approaches, using multiple indicators and frameworks. There is also a need for assessments explicitly designed to support ocean planning and integrated marine management processes. Review processes such as the present one provide a "big picture," allowing for a global view on complex topics, and contributing to advances in the field.

Keywords: climate change, maritime activities, blue economy, marine spatial planning, vulnerability analysis, systematic literature review

INTRODUCTION

The concepts of vulnerability and risk have long been applied in a variety of contexts, including the assessment of anthropogenic and natural hazards to human, health, nature, or economic growth (Adger, 2006; Bernard and Ostländer, 2008; Moreno and Becken, 2009; Salim et al., 2014). More recently, vulnerability and risk analyses have been increasingly used to address climate change effects on the ocean (Brugère and Young, 2015; Avelino et al., 2018; Wabnitz et al., 2018; Comte et al., 2019). However, finding definitions of vulnerability and risk that are consistently applied and accepted is not straightforward, due to the myriad of existing designations and interpretations, and the variety of fields in which they are applied (e.g., environmental, social, economic) (Brugère and Young, 2015; Bennett et al., 2016; Weis et al., 2016; Weißhuhn et al., 2018; Comte et al., 2019). In effect, depending on the context, studies may focus on particular species and habitats, human populations, economic activities (e.g., fisheries, tourism, maritime transport), specific locations (e.g., open ocean, coastal areas), or different climate-related hazards (e.g., warming, acidification) (Brugère and Young, 2015). As well, while some frameworks define vulnerability as the result of a system's sensitivity, exposure, and ability to adapt to a given hazard (IPCC, 2007), others consider exposure to be external to vulnerability (IPCC, 2014). At the same time, climate-related vulnerability and risk assessments are limited by several factors, such as the uncertainty in predicting long-term climate trends, difficulties in recognizing cause-effect relationships, limitations to existing knowledge on social-ecological systems, and challenges in assessing the combined effects of climate change and other local human stressors (Brugère and Young, 2015; Fawcett et al., 2017; Gissi et al., 2021).

Still, these analyses—particularly when developed in a spatially explicit way (Weis et al., 2016)—allow for a deeper understanding of how environmental goods and services, dependent economies, and human communities are impacted by climate change effects, together with their ability to respond and adapt (Brugère and Young, 2015). They are, therefore, fundamental tools to properly inform and support marine spatial management processes (Frazão Santos et al., 2020), thus contributing to the conservation and sustainable use of the ocean (Hodgson et al., 2019). Of particular importance, is the relevance of these tools to marine spatial planning (MSP). Recognized as a vital process to achieve global ocean governance goals and currently expanding worldwide, MSP initiatives organize the spatial use of the ocean, striving to balance multiple human needs and nature conservation (Ehler, 2021). In order to be sustainable and relevant under a changing climate, MSP requires information on where changes in ocean uses and ecosystems are most relevant—a type of information that is typically acquired through spatial assessments of vulnerability and risk (Frazão Santos et al., 2020). However, few studies take an integrated approach to assess the climate-related vulnerability and risk of main ocean uses to support MSP (Fernandes, 2020). In such context, a key question arises: What are the main trends, challenges, and limitations of existing assessments, and what are the potential pathways to overcome them?

In this Mini Review, we summarize evidence from 314 scientific articles and reports published until 2020, aimed to assess the vulnerability and risk of main ocean uses to different climate-related drivers of change (see **Supplementary Material**). We explore obtained results, identifying key concepts, methodologies, and limitations of retrieved assessments. We further discuss current research needs to provide guidance for the development of future analyses.

METHODOLOGY AND RESULTS

Methodological Approach

A detailed description of the methodological approach followed, including specific information on the different phases of the systematic literature review (e.g., identification, screening, eligibility), is provided in **Supplementary Material** (see also **Supplementary Figure 1** for the methodological approach diagram). The primary source of data used was the Web of Science (WoS) collection (Web of Science, 2021), a well-established database for carrying sound literature reviews (e.g., Falagas et al., 2008; Zhu and Liu, 2020). In order to investigate trends in climate-related vulnerability and risk assessments of main ocean uses, and their integration in MSP and other marine management initiatives, a combination of topics were searched in the WoS database (see **Supplementary Material** and **Supplementary Table 1** for details). Studies available in a language other than English were translated with Google Translate prior to being processed. After screening and eligibility phases, a total of 314 publications were kept and further submitted to full content analysis. Selected publications were analyzed regarding the main ocean uses and climate-related drivers of change addressed (cf. Frazão Santos et al., 2016; European Commission, 2021), and existing references to ocean planning and management or the blue economy. The latter terms were included as proxies of an integrated vision for ocean use (MSP being a public process that manages the spatial and temporal distribution of ocean activities, and blue economy being the "range of economic sectors and related policies that together determine whether the use of oceanic resources is sustainable"; World Bank, 2017). For "case study-based" publications– that is, studies developing an explicit assessment for a particular area resulting in specific risk/vulnerability values (instead of only discussing conceptual aspects, in which case they were considered as "conceptual" publications)—an in-depth analysis was carried based on: spatial scale (local to global); elements considered in the analysis (e.g., exposure, sensitivity, adaptive capacity); dimensions focused by the analysis (ecological, social, economic); and type of indicator used (qualitative, quantitative) (see details in **Supplementary Material**).

Results

A total of 77 conceptual publications and 237 case study-based publications were identified (**Supplementary Tables 2**, **3**). Initial assessments date back to the 1990s, with numbers increasing significantly from 2007 onward, especially for case study-based publications (**Figure 1A**). Indeed, the year 2020 showcases the highest number of case study-based publications (n = 35), and 2019 presents the highest number of conceptual publications (n = 12). Trends for both types of publications are very similar regarding the addressed ocean uses and climate-related drivers, as well as references to ocean planning and management or the blue economy (**Figures 1B–D**)—although with less dispersion of results for conceptual publications.

Regarding references to particular ocean uses, studies pertaining to fisheries, marine conservation, and coastal and marine tourism were by far the most frequent (respectively, 197, 195, and 178 publications, that is c. 60% of all references for both conceptual and case study-based publications; **Figure 1B**). On the contrary, marine renewable energy was the least addressed use in vulnerability and risk assessments (n = 31, c. 10%). Aquaculture, ports, maritime transport, and seabed mining presented intermediate values (**Figure 1B**). Curiously, only two publications addressed all ocean uses simultaneously. One of them focused on the modeling of the Great Australian Bight ecosystem (Fulton et al., 2018), while the other pertained to the use of open-source data for coastal risk assessments (Rumson and Hallett, 2018). As for references to ocean planning and management, or the blue economy, they were found only in a small subset of publications, corresponding to c. 18% and 28% of the total number of studies, respectively (**Figure 1C**). Regarding climate-related drivers, studies addressing sea-level rise and extreme events were the most frequent ones (respectively, 216 and 208 studies, that is almost 70% of references; **Figure 1D**). By contrast, ocean acidification, ocean deoxygenation, and shifts in currents and winds were the least mentioned drivers (under 14%). Ocean warming, species distributional shifts, and diseases and harmful algae blooms presented intermediate values (**Figure 1D**). While several studies addressed multiple climate-related drivers at the same time—e.g., Crozier et al. (2019) address all but deoxygenation; Cochrane et al. (2019) address all but ocean acidification; Gutiérrez et al. (2016), Vivekanandan et al. (2016), and Reid et al. (2019) address all but shifts in currents and winds—only one publication mentions all eight climate-related drivers simultaneously. This pertains to Whitney et al. (2020), which focused on communicating climate impacts to inform adaptation planning.

As for case study-based publications only, the majority was carried at the local scale (n = 122; **Figure 2A** and **Supplementary Table 4**), focusing on a specific area within a country—e.g., Copenhagen, Nova Scotia, or Quy Nhon (Hallegatte et al., 2008; Barnett and Eakin, 2015; Nguyen et al., 2017). Regional studies, that is, studies carried out at a supra-national scale (encompassing more than one country or a region), were the second most frequent ones (n = 67), with examples of assessments including the Mediterranean Sea or the Arctic region (Khan et al., 2014; Danovaro, 2018). Studies focused on a particular nation, such as Australia or the United States (Ekstrom et al., 2015; Pethybridge et al., 2020), and studies carried out at a global scale (e.g., Hanson et al., 2011; Albouy et al., 2020) were the least common (c. 8 and 12% of references, respectively; **Figure 2A**). Regarding the elements considered in the assessments, "risk" (n = 217) and "vulnerability" (n = 184) themselves were the most frequently identified ones (appearing in over 77% of the studies; **Figure 2B**). These were followed by studies that addressed specific vulnerability and risk-related elements, such as "exposure" (n = 130), "sensitivity" (n = 123), and "adaptive capacity" (n = 97) (e.g., Tompkins et al., 2008; Stevens and Collins, 2011; Clarke et al., 2020). It is important to note that c. 22% of the studies (n = 53; **Supplementary Table 3**) addressed all elements simultaneously (e.g., Soto et al., 2019). Most assessments focused on all dimensions—ecological, economic, social—simultaneously (n = 133, c. 56% of references; **Figure 2C**). These were followed by socioeconomic studies (n = 45) and studies on economic and ecological features (n = 17). Purely ecological studies (n = 15), economic studies (n = 13), or social studies (n = 4) were found in a more limited number, as were social-ecological ones (n = 10) (each category under c. 7%; **Figure 2C**). As for the type of indicators, a mix of qualitative and quantitative indicators was by far the most frequent (n = 113, c. 48%; **Figure 2D**), with quantitative studies and qualitative studies alone presenting similar values.

DISCUSSION

The present mini review highlights the large variety of frameworks and approaches—resulting from different combinations of elements, dimensions, and spatial scales included in the analyses—that can be used to develop climate-related vulnerability and risk assessments. Different methods exist, for example, to assess the vulnerability to climate change of a fishing community, a marine renewable energy facility, or a marine protected area, making it extremely difficult and subjective to decide on the methodologies and indicators to use (Brugère and Young, 2015; Monnereau et al., 2017; Avelino et al., 2018; Wabnitz et al., 2018; Zhang et al., 2018). In effect, given the myriad of fields (e.g., environmental sciences, economics, health) that use such assessments, together with the range of possible interpretations and meanings (e.g., Bennett et al., 2016; Weißhuhn et al., 2018; Comte et al., 2019), and variety of objectives and models to be used (Patwardhan, 2006), it is extremely challenging to find a one-size approach to fit all cases. Still, the present review found that the most commonly used and accepted definition of vulnerability was the one from the fourth assessment report by the Intergovernmental Panel on Climate Change (IPCC)—where vulnerability is defined as the result of the interaction between exposure, sensitivity, and adaptive capacity (IPCC, 2007; Okey et al., 2015; Bennett et al., 2016). Reinforcing the use of such definition could further reduce the variability of frameworks and approaches (Bennett et al., 2016), although new tendencies may arise with the publication of new assessment reports and corresponding methodologies (e.g., sixth IPCC assessment report; IPCC, 2021, 2022).

The analyzed body of literature highlights the great focus of assessments on particular ocean uses such as fisheries, marine conservation, and marine and coastal tourism, and specific drivers of change, such as extreme events and sea-level rise. Fisheries is one of the most traditional uses of the ocean space, increasingly studied in a climate context due to the growing awareness of the relevance of climate

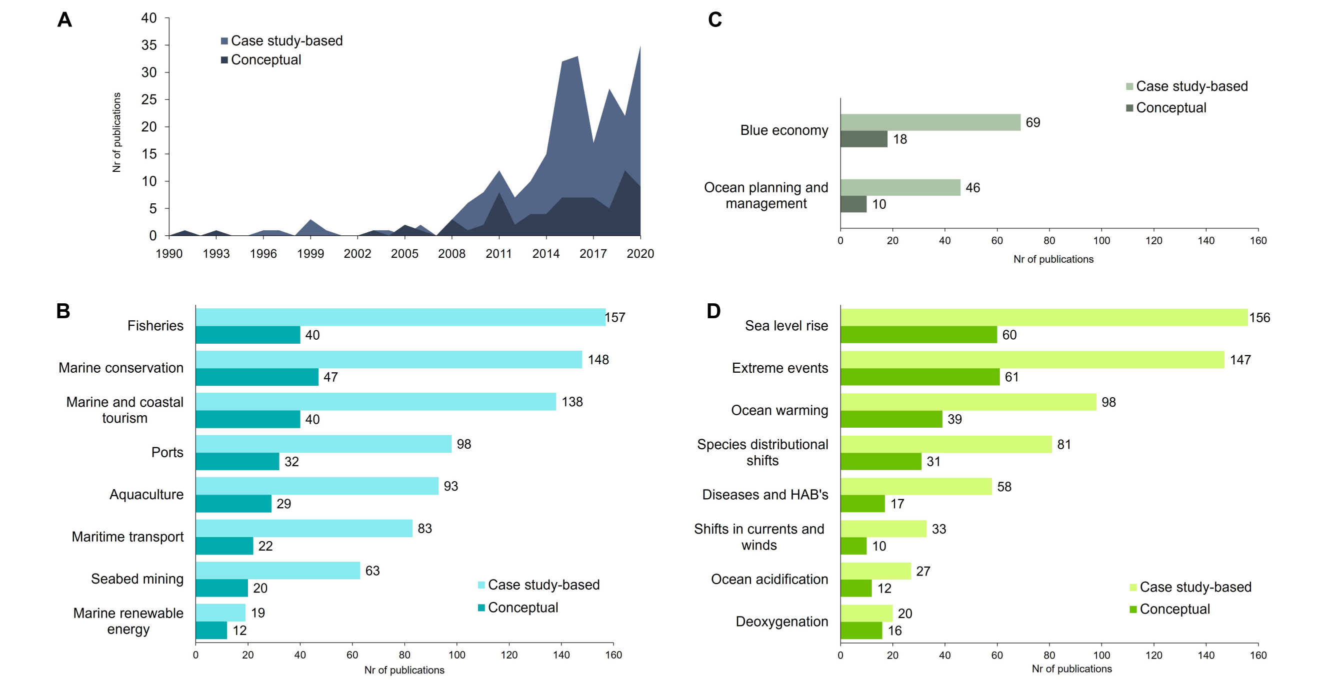

FIGURE 1 | Number of publications included in the analysis according to the year of publication **(A)**, ocean uses addressed **(B)**, references to ocean planning and management, or the blue economy **(C)**, and climate-related drivers of change addressed **(D)**. Case study-based publications (n = 237) pertain to those developing a clear assessment for a particular area resulting in specific risk/vulnerability estimates; conceptual publications (n = 77) pertain to the ones discussing conceptual aspects only. See **Supplementary Tables 2**, **3** for details. Nr, number; HABs, harmful algae blooms.

impacts on fish stocks, local human communities, and dependent economies (e.g., Hollowed et al., 2013; Pecl et al., 2017; Barange, 2018; Pinsky et al., 2018). Studies on the effects of climate change on marine protected areas and other conservation-related management tools are also expanding worldwide (e.g., Bruno et al., 2018; Duarte et al., 2020). Still, obtained results are likely underestimated, as conservation is not generally perceived as an ocean use by most authors (as it is not a maritime activity but a use of the ocean space; e.g., European Commission, 2021). Tourism is a major economic driver in many coastal areas around the world, one that will be significantly affected by climate effects with multiple social and economic consequences (e.g., Jones and Phillips, 2017; Scott et al., 2019), which explains the strong focus on related assessments. By contrast, the limited number of studies on marine renewable energy is potentially related to the limited exploitation of these resources until now (Melikoglu, 2018). However, due to the increasingly recognized relevance of developing ocean renewable energy to mitigating climate impacts (UNGC, 2021), related vulnerability and risk assessments are likely to increase in upcoming years.

The focus on extremes events and sea-level rise is consistent with trends found in other areas, namely in the context of climate-related urban vulnerability assessment (Zhang et al., 2018), given the proximity of main cities to the coast and potential impacts to the society. Interestingly, studies addressing ocean warming and acidification were far less frequent in the present review, while these drivers tend to be constantly referred to in climate-related studies on the ocean (IPCC, 2018, 2019), being integrated into the "deadly trio" (Sampaio et al., 2021). This limited focus on warming and acidification is potentially related to the numerous assessments focused on ocean uses that are less affected by these drivers (Frazão Santos et al., 2016), such as ports or marine and coastal tourism. Moreover, different ocean uses tend to be analyzed individually, on a sector-by-sector basis, which explains the observed little reference to multi-objective, holistic management approaches, including MSP or the development of a sustainable blue economy. In fact, only two out of 314 studies analyzed the impact of climate change for all ocean uses simultaneously (Fulton et al., 2018; Rumson and Hallett, 2018) which highlights the need for further research applying systemic, integrative, and cross-sectoral approaches. Developing such integrated assessments is vital to support MSP and promote the sustainable use and conservation of the ocean (European Commission, 2020; Frazão Santos et al., 2020). The difference found in ratios between case study-based and conceptual publications for the different sectors and drivers of change considered (c.f. **Figures 1B,D**) mirrors the increased relevance of developing site-based analyses (i.e., focused on particular areas) in recent years (**Figure 1A**). Indeed, it has been argued that when carried out at the local level, studies allow for a more robust assessment of vulnerability and risk (Comte et al., 2019).

Particularly for case study-based assessments, the extensive focus on local and regional scales appears to be linked to recent improvements in tools and approaches to assess climate-related

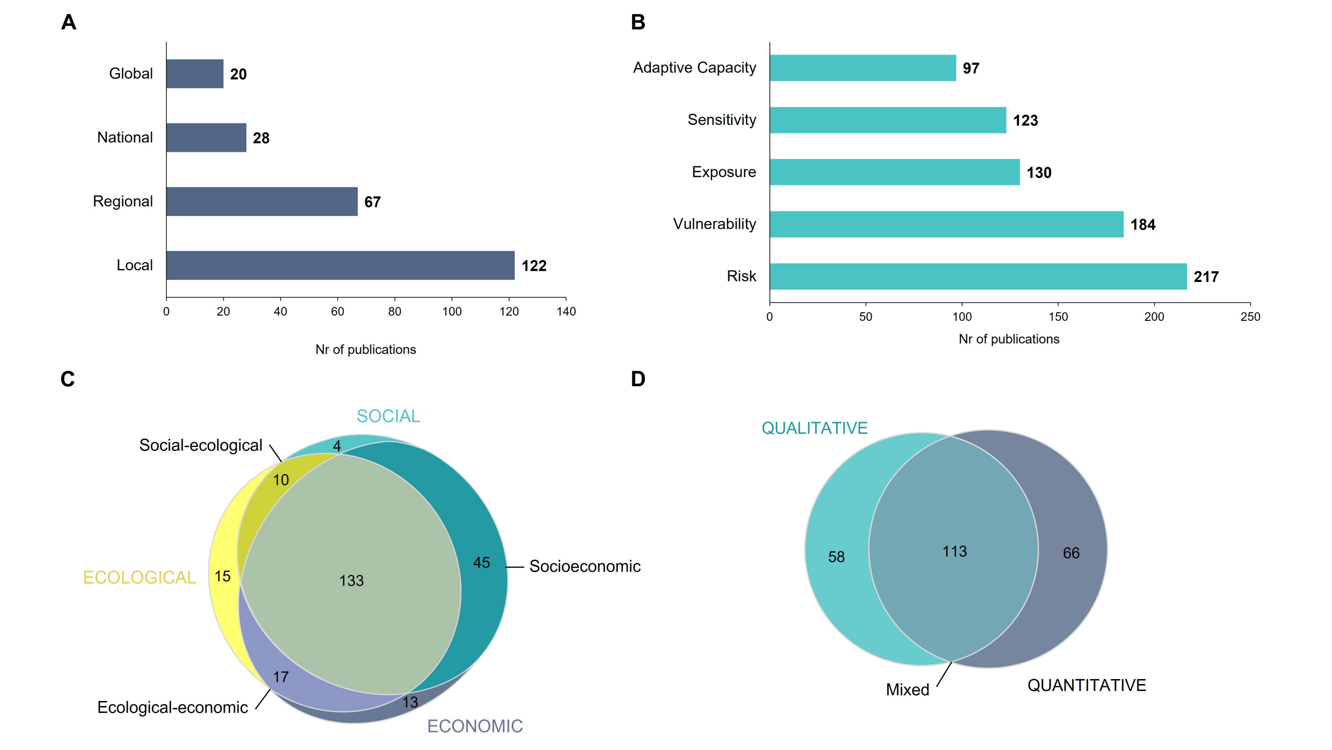

FIGURE 2 | Number of case study-based publications according to the spatial scale of the publication **(A)**, risk and vulnerability-related elements considered in the analysis **(B)**, dimensions focused by the analysis **(C)**, and type of indicator used **(D)**. Proportional Venn diagrams **(C,D)** were developed using R Statistical Software. See **Supplementary Tables 3**, **4** for details.

vulnerability and risk—e.g., InVEST, climate modeling, Bayesian Belief Networks, expert knowledge (e.g., Wyatt et al., 2017; Stelzenmüller et al., 2018; Thiault et al., 2018; Willaert et al., 2019). This is especially evident for studies focusing on small island developing states (e.g., Mcleod et al., 2015; Schmutter et al., 2017). National studies do not benefit from these advances in the same way, likely because of the difficulties in integrating detailed information from different sources and metrics at the national level or because of a lack of data and funding to implement these studies (Brugère and Young, 2015; EEA, 2018). As well, national reports that are not of a scientific nature (e.g., reports on vulnerability and adaptation to climate change developed nationally by several European Union member states) are often not identified by scientific search engines and platforms such as WoS (EEA, 2018; Zhang et al., 2018). Developing vulnerability and risk assessments at the global scale is challenging, either because of difficulties in finding relevant and sound databases or due to limitations in obtained results [cf. Comte et al. (2019) for a discussion on global assessments of adaptive capacity], which is in line with global studies being the less frequent. However, it is important to bear in mind that analyzing studies for their spatial scale is nevertheless a generalization, as some national contexts (e.g., United States, Australia) are geographically more similar to supra-national ones, including different biogeographic regions and a broad range of socioeconomic settings.

Regarding the type of indicator and dimensions included in the analysis, the majority of purely social studies, economic studies, and socioeconomic studies used a mix of qualitative and quantitative indicators (c. 46–75% of the studies; **Supplementary Table 3**). The same applied to social-ecological studies (c. 60%). By contrast, purely ecological studies and ecological-economic studies tended to use quantitative indicators only (over 60% of the studies). This is in line with an ongoing transition from purely quantitative studies focused on ecological vulnerability (e.g., using climate simulation models), to more integrated studies focused on assessing adaptive capacity, social resilience, or the vulnerability of social-ecological systems as a whole, and considering various stress factors and exploring combined effects (Oulahen et al., 2018; Zhang et al., 2018). Such holistic approaches allow for a better understanding of the multidimensional nature of complex systems, and the existing interconnections among communities, sectors, and dependent economies—which is essential to tackle better the challenge of climate change (Brugère and Young, 2015). When analyzed for individual ocean uses, tendencies remained the same; mixed approaches (qualitative/quantitative) were still the most frequently observed ones, being found in c. 42–53% of the studies (**Supplementary Table 3**). Only maritime transportation depicted a different pattern, with studies using quantitative indicators alone being the most frequent (c. 37%). At the same time, there was an equitable distribution of studies per dimensions across all ocean uses.

The increase in publication numbers from 2007 onward is likely linked to the publication of the fourth and fifth IPCC assessment reports (IPCC, 2007, 2014). As previously observed by Zhang et al. (2018), who described an abrupt growth of climate-related vulnerability assessments between 2001–2017 following the publication of the third IPCC assessment report (IPCC, 2001). In fact, these reports raised significant awareness on the importance of developing vulnerability and risk assessments to support climate adaptation actions (Weatherdon et al., 2016; Zhang et al., 2018). With the upcoming launch of the complete sixth IPCC assessment report in 2022 (IPCC, 2021, 2022), and a future increasingly pressured by climate-related challenges, expectations thus are that these assessments will continue to expand (Zhang et al., 2018). In such context, literature reviews like the one presented here are key to inform future assessments since it allows to identify main existing gaps and limitations (e.g., the multiplicity of concepts, low representativeness of some sectors, and lack of focus on holistic public processes like MSP in vulnerability and risks assessments) and recommendations (e.g., transparency and clarity in the concepts used in each assessment, and development of local cross-sectoral and integrative approaches, that combine qualitative and quantitative indicators).

When conducting review studies, we must bear in mind that there is an inherent level of subjectivity to the process due to the multiple interpretations that are possible for each analyzed article (Zhang et al., 2018), and the non-inclusion of potentially relevant documents (e.g., gray literature, non-English studies) from commonly used search engines (Nederhof, 2006; Kim et al., 2016). Nevertheless, literature reviews are essential to provide general overviews on complex topics, helping the scientific community to better recognize such complexity, highlighting areas in need of attention, and further contributing to future research (Zhang et al., 2018).

AUTHOR CONTRIBUTIONS

MF, CVS, and CFS designed the study. MF conducted the literature search and developed the first draft of the manuscript. CVS and CFS commented on initial drafts and all authors contributed to the final version of the article.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.787882/full#supplementary-material

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