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EDITORIAL

Ocean politics and governance: between complexity and necessity

Oceanopolítica y gobernanza de los océanos: entre la complejidad y la necesidad

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Jaime Orlando López de Mesa C.[1]

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Around the 1970s, a new phase of globalization began, which intensified after the fall of the socialist bloc and the Berlin Wall, rapidly increasing economic, political, and cultural exchange. This led to a growing interdependence between countries, a phenomenon fueled by various sources, including technological changes driven by the third industrial revolution from the 1950s and the fourth industrial revolution, whose onset is marked by the emergence of the internet, according to historians of science. It seems that we are witnessing a moment of backtrack, or an ebb in globalization, after a long period of its flow or growth (Fazio, 2002).

During the growth phase of globalization, economic diplomacy predominated, despite all the ups and downs, invasions here, and wars there. It was a moment when geopolitics seemed to diminish in relevance compared to the momentum of economic globalization, widespread economic treaties, and the use of economic instruments to achieve strategic objectives; that is, geoeconomics and the deepening of the financialization process, characterized by the dominance of the interests of the financial sector and the imposition of its logic on other sectors.

However, the rise of phenomena of global impact, such as China's proposal for the New Silk Road, and the emergence or resurgence of wars in Ukraine, Syria, or Yemen, has marked the revival of geopolitics as a central phenomenon in contemporary international relations. This highlights the central role played by oceans and seas in 21st-century scenarios, both as peaceful means for the transportation of people and goods (Orempüller do Nascimento, 2019) and for the transit of troops and war supplies, as well as a source of strategic resources, such as oil.

They are, therefore, a means and a potential scenario for combat operations and the struggle for control of maritime routes. In this way, the oceans are a fundamental resource and a strategic objective. These transformations suggest a transition from a predominantly geoeconomic moment to one that is eminently geopolitical.

Nevertheless, the advances made in the boom phase of globalization, as happened in the past, are never entirely lost, and there are always advances that survive moments of setback. Among them are the experiences accumulated in the management of international trade, the progressive consolidation of international law in its various manifestations, including the Law of the Sea, or strategies of consensual and participatory governance, from the highest international levels to local spaces and territories, known as multilevel governance. In other words, there are surviving lessons for dialogue.

Among these achievements, two can serve as a catalyst for the development of populations and the achievement of lasting and secure global peace. These achievements have matured in recent decades and, due to their characteristics, encompass aspects of geopolitics, geoeconomics,

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and diplomacy, presenting an exemplary opportunity to help overcome the challenging panorama of contemporary global geopolitics.

They are ocean politics and ocean governance, the former as a source of knowledge and the latter as the foundation of agreements, which both provide an opportunity for dialogue and peace. Ocean politics is based on the conception of the ocean as a complex system, in which multiple actors with heterogeneous interests interact, and a plurality of factors intervene at various levels (Martínez, 1996). Based on this perspective, ocean politics is:

> "The concept that acknowledges the existence of the ocean in the geographical environment and the influence it has on political decisions. Its fundamental purpose is to ensure that political management regards the ocean as the natural space for the development and future growth of the State" (Martínez, 1993).

In this line of thought, ocean politics emerges as a science whose objective is to integrate maritime spaces into development processes through the "territorialization" of the seas (Dávalos, 2018). Due to its complexity, and global geopolitical and geoeconomic dynamics, ocean politics faces challenges that can be summarized in five areas (Unesco, 2021), namely:

Climate change and its strong impact on seas and oceans, manifested in polar ice melt, rising sea levels, ocean acidification, and the loss of marine biodiversity. Vital marine ecosystems for human activities are at risk as a result.

Another challenge lies in the growing marine pollution that already affects numerous species, reaching such a level that islands of floating waste composed of plastic waste and chemicals have formed in the oceans. This, along with the discharge of wastewater, forms a critical scenario that is beginning to have effects on the sustainability of island communities.

The competition for marine resources is another central component of the issue facing ocean politics, as the oceans have been a fundamental source, from time immemorial, of both food and energy resources that rely on threatened biodiversity. Demographic growth, the increasing scarcity of these resources, and the strategic demands of various powers are exacerbating the competition for maritime resources, generating tensions and conflicts.

Illegal, unreported, and unregulated (IUU) fishing characterizes one of the most pressing elements, as it is estimated to represent at least 30% of global fishing, jeopardizing species that are fundamental for the balance of nature in the sea (Unesco, 2021).

Finally, piracy and terrorism constitute a growing threat to maritime security, creating even greater tensions and risks for maritime conservation and ocean governance.

Addressing this issue requires forms of governance that allow for the recognition of the rights of all parties, within a framework of constructive dialogue and on equal terms for all actors. This is in the context of the enormous complexity of the oceans from social, political, cultural, ecological, and environmental perspectives. To this end, ocean governance has been developed as the fundamental tool that enables the search for solutions to the pressing problems facing ocean politics.

Ocean governance includes the idea that the oceans are the basis for the survival of humanity, and therefore, their prosperity is a central component for future development and the conservation of the planet. Thus, a comprehensive perspective of ocean governance has been progressively built, including norms, laws, institutions, policies and strategies, and the economic interests involved in them. It also addresses security issues aimed at managing ocean resources, including formal and informal institutions with increasingly horizontal processes of discussion, design, and solution-seeking on a consensual basis (Singh & Ort, 2020). It is a macro-process that is far from perfect but represents significant progress (Blythe, Armitage, Bennett, Silver, & Song, 2021).

Various studies have pointed out the challenges facing ocean governance. Perhaps the most significant was produced by the United Nations Educational, Scientific and Cultural Organization (Unesco) in 2021, identifying four major challenges for ocean governance with a total of eleven components.

The first challenge is the fragmentation of governance derived from political, sectoral, stakeholder and knowledge segmentation, and territorial and institutional fracture. Capacity and awareness issues are another obstacle to ocean governance, represented by a lack of awareness of the issues concerning the seas and a lack of capacity to develop global policies due to various obstacles. Scale issues constitute another element that ocean governance faces, particularly in spatial, temporal, and representational dimensions. And finally, uncertainty and change, through emerging issues and complex problems, complete the panorama identified by Unesco as the greatest challenges for ocean governance (Unesco, 2021).

In any case, progress in ocean governance stands as a small oasis in the desert of growing global bellicosity, paving the way for the development of ocean politics that, in a process of mutual feedback, allows the creation of channels for dialogue. Its preservation, conservation, and maturation should be a central focus of states, international politics, and intergovernmental organizations.

Therefore, ocean politics is a discipline that faces the complexity of the seas and, hand in hand with ocean governance, constitutes a field for the study of the problems facing water bodies around the planet, the search for solutions, and the implementation of policies to mitigate their pressing issues.

In fact, there is a widespread consensus on the direct relationships among the main risks faced by the oceans directly related to governance, such as:

> “(1) the impacts of the overexploitation of marine resources... (2) inequitable distribution of access to and benefits from marine ecosystem services... (3) inadequate or inappropriate adaptation to changing ocean conditions” (Haas *et al*., 2022).

Colombia, with its enormous water wealth, the privilege of having coasts on two oceans, and having advanced in recent decades with the efforts of the Colombian Navy, constitutes a country that, like few others, has enormous potential to emerge as a regional power in ocean politics and with sufficient authority to propose ocean governance schemes on the global stage. While the task has begun, there is still a long way to go.

Given its complex characteristics, delving into the understanding of ocean politics and its governance is a necessity for the country’s development.

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CIOH Sci. Bull. 2023; 42(2): 7-24

SCIENTIFIC AND TECHNOLOGICAL RESEARCH ARTICLE

Co-participatory identification of the impacts of climate change on the maritime cultural heritage of Tierra Bomba Island, Cartagena de Indias, Colombia

Identificación coparticipativa de los impactos derivados del cambio climático sobre los patrimonios culturales marítimos en la isla de Tierra Bomba, Cartagena de Indias, Colombia

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ABSTRACT

Climate change currently represents one of the greatest risks for the development of biodiversity and the social and cultural sustainability of human beings throughout the planet. This paper presents the partial results of the pilot phase of research which developed a space designed for community actors interested in generating a proposal for identifying the effects of climate change on the maritime cultural heritage of the island of Tierra Bomba, in Cartagena de Indias (Colombia). This project, called "Colaborartorio Azul", is a co-participatory laboratory interested in articulating the different community, institutional and academic knowledge on Climate Change and its impact on the natural-cultural heritage of the maritime and coastal landscape of the city and some of its population centers.

KEYWORDS: Climate change, cultural heritage, knowledge co-production, Tierra Bomba, Cartagena de Indias, Colombia.

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RESUMEN

El cambio climático representa en la actualidad uno de los mayores riesgos para el desarrollo de la biodiversidad y la sostenibilidad social y cultural de los seres humanos en todo el planeta. En este trabajo se presentan algunos de los resultados de la fase piloto de una investigación en la cual se desarrolló un espacio diseñado para actores comunitarios interesados en generar una propuesta para la identificación de los efectos que produce el cambio climático en los patrimonios culturales marítimos de la isla de Tierra Bomba, en Cartagena de Indias (Colombia). Dicho proyecto, denominado "Colaborartorio Azul", es un laboratorio coparticipativo interesado en articular los diferentes saberes comunitarios, institucionales y académicos sobre el cambio climático y su impacto en el patrimonio natural-cultural del paisaje marítimo y costero de la ciudad, y algunos de sus centros poblados.

PALABRAS CLAVES: *cambio climático, patrimonio cultural, coproducción del conocimiento, Tierra Bomba, Cartagena de Indias, Colombia.*

INTRODUCTION

Climate change is generating impacts in all areas of contemporary society. As it is a threat to human well-being, social sciences play a key role in understanding and mitigating these impacts (Rivera-Collazo, 2021). In relation to cultural heritage, at the international level, some reports have been published in recent years. In 2005, the World Heritage Committee focused attention on climate change, understood as a threat to global heritage assets, by adjusting the application form for inscription on the World Heritage List, which must now list the changes and impacts caused by climate change, such as floods, earthquakes, and other natural disasters (Unesco, 2005). Subsequently, in 2014, the United Nations Educational, Scientific and Cultural Organization (Unesco) supported the development of a practical guide on climate change adaptation at four heritage sites in Kenya and India, providing theoretical and practical examples for planning a climate adaptation strategy.

However, this remains a recent and underexplored topic (Morel *et al*., 2022). Most of the work has highlighted the risks and threats (Barba, Díaz, & Luna, 2010; Ezcurra & Rivera, 2018; ICOMOS, 2020; Unesco, 2005, 2022; Reeder-Myers, 2015), but also the possibilities and potential of maritime and underwater cultural heritage in the face of climate change (Guiao, 2020; Unesco, 2021). It is worth noting that with the Paris Agreement (UN, 2015), the importance of intangible cultural heritage in adaptation actions to climate change is recognized.

In this sense, decisions should:

> *"[...] be based on and inspired by the best available scientific information and, where appropriate, traditional knowledge, indigenous peoples' knowledge, and local knowledge systems, with a view to integrating adaptation into relevant socio-economic and environmental policies and measures, as appropriate"* (UN, 2015, p. 10).

Therefore, community participation and cultural heritage play a fundamental role in the formulation and implementation of climate change adaptation actions, as they could increase effectiveness, efficiency, sustainability, and inclusivity (Guiao, 2020).

On the other hand, climate change can have negative impacts on maritime and underwater cultural heritage, causing both direct and indirect damage to material assets and intangible practices, whether viewed from a physical or social context (Unesco, 2015). Particularly, in a survey conducted by the World Heritage Center in 2005, the impacts of climate change on sites designated as world heritage were assessed. Based on responses received from 83 participating countries, the most recurrent climate-related threats identified were hurricanes and storms, rising sea levels, wind or water erosion, floods, increased precipitation, drought, desertification, and rising temperatures (Unesco, 2007). Thus, it becomes a priority to implement short-term research and management models that integrate communities and their traditional knowledge with the scientific sector, given the urgency of the impacts and losses to cultural heritage (Figueira & Howard, 2019). In addition to displacing a culture from the land where its physical heritage is located, climate change can irreversibly transform its traditions and knowledge (Henriksen, 2007).

For the specific case of Cartagena de Indias, due to environmental issues such as coastal erosion, rising sea levels, and flooding affecting the cultural heritage on Tierra Bomba Island (Del Cairo *et al*., 2022; Riera & Báez, 2022), and more broadly in the city of Cartagena (Distrito de Cartagena de Indias, 2016; Villarreal, 2019), it is necessary to establish protection mechanisms that incorporate multiple community, institutional, and academic perspectives. According to research by authors such as Andrade (2008); Andrade, Ferrero, and León (2017); Rangel and Montealegre (2003); Pabón (2003a; 2003b); Pabón and Lozano (2005); Torres and Tsimplis (2013), it has been shown that the upward trend in relative sea level in Cartagena is two to three times greater than in Cristóbal (Panama), Magueyes (Puerto Rico), and Lime Tree (Florida Keys). While for these cities, the relative sea level rise trend ranges between 1.3 mm and 1.9 mm per year, in Cartagena, it varies between 4.5 mm and 5.3 mm per year. This represents a risk to the conservation of cultural heritage located on the city's coastline, as the accelerated rise in sea levels can lead to structural damage and eventual disappearance over time.

Thus, the inter-institutional approach must be accompanied by an interdisciplinary perspective that can establish a support network for this collaborative space where shared participation is a cross-cutting axis for generating knowledge about climate change and its impact on cultural heritage, and designing solutions and alternatives for its mitigation. Building on the above, the project 'Colaborartorio Azul: Effects of Climate Change on Cultural Heritage Sites in Cartagena de Indias, Colombia' (Del Cairo *et al*., 2023) was born as a study that, from an archaeological, anthropological, and historical perspective, aims to identify, investigate, and analyze the impacts of climate change on cultural heritage. This is done through a participatory approach alongside the communities of Cartagena de Indias, providing valuable data for current and future risk reduction measures and contributing to the identification of different response strategies for protecting cultural heritage from the impacts of climate change.

This co-participatory approach aims to establish networks of exchange between public and private stakeholders, academia, and the community for the continuous development of protection mechanisms and concerted decision-making that make community participation in public heritage protection both viable and sustainable (Forero, Hernández, & Zafra, 2023). A lack of awareness or coordination of impacts from the community's perspective increases the likelihood of producing maladaptive plans and actions that can result in irreversible changes or greater losses (Moshenska, 2014). In this regard, this article presents partial results from the "Colaborartorio Azul" project in its pilot phase (Del Cairo *et al*., 2023), which analyzes the impacts of climate change based on historical documentation and cartography, as well as the integration of local knowledge through community participation regarding climate change and its impact on the cultural heritage of Tierra Bomba Island.

STUDY AREA

Tierra Bomba Island is located south of the urban area of Cartagena de Indias and north of the Barú Peninsula. The island is divided into four townships: the eponymous Tierra Bomba, Punta Arenas, Caño de Loro, and Bocachica, all of which have a rich cultural potential resulting from historical and territorial processes related to the sea (Villa, Cáceres, & Arrieta, 2019). In terms of maritime cultural heritage (Fig. 1), this area encompasses various tangible expressions of the daily life of the local residents, which interact with immovable heritage (fortifications, wells, cisterns, among others).

They contain a diversity and richness of intangible and material maritime-coastal cultural heritage within themselves (Rubio-Ardanáz, 2014; Rozo-Pinzón, 2020; Del Cairo *et al*., 2022; 2023). Particularly, we worked with the communities of Bocachica on the forts of San José, San Fernando, and San Luis; with the inhabitants of Tierra Bomba at the San Bernabé tile- and brickworks, and with the residents of Caño de Loro on the structures near the old leprosy hospital.

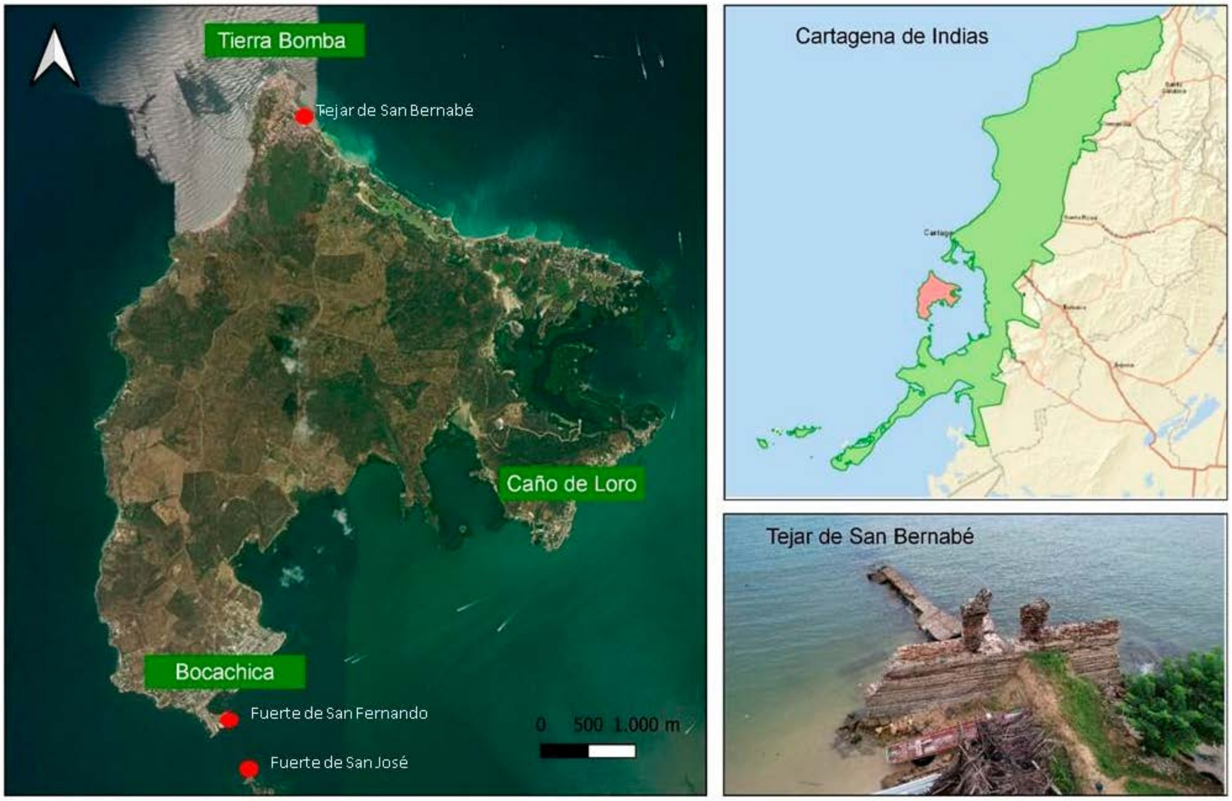

Figure 1. Location of the study area and aspects of cultural heritage (San Bernabé tile and brickworks). The map shows the analyzed sectors: Tierra Bomba, Bocachica, and Caño de Loro.

Despite the rich cultural and heritage assets of the island, the community of Tierra Bomba finds itself in a state of neglect by certain national institutions due to their limited presence in the area. This is reflected in the living conditions of the residents and their access to essential services (Picó *et al.*, 2013). For example, 96.7% of the 12 207 inhabitants in 2019 lives in extreme poverty conditions: they lack sewerage, drinking water, and landline telephone services. Natural gas was installed only in 2016, and electricity in 2003. Additionally, there are problems with inadequate housing and overcrowding (Del Cairo *et al.*, 2023).

Regarding environmental vulnerability, despite the island's abundant natural resources, factors such as rising sea levels, flooding, improper solid waste management, coastal erosion, and the use of fuels like wood make it susceptible to climate change (Cáceres & Romero, 2017; González & Torres, 2019), affecting both its residents and the material cultural heritage of the area (Parra & Anaya, 2017). There are also serious issues related to pollution, drug addiction, gangs, and violence, leading to an environment of insecurity and division within the community. This has resulted in fragmented and individualistic communities (Caraballo, 2020).

Current trends such as the privatization of coastal areas on the island for the construction of exclusive hotels and tourist sites have exacerbated these social issues on the island. While these activities contribute to tourism development, they have led to the neglect of local communities and created barriers within the territory, limiting the mobility of locals and, consequently, access to archaeological and natural sites (Iregui &

García, 2016; Rozo-Pinzón, 2020). Bocachica, the township with the most archaeological and historical sites on the island, provides a clear example of territorial division due to the pressure emanating from the exclusive hotel industry, which has been privatizing the coastal area of the district. These exclusive services have gradually taken over the coastal zone and displaced locals (Rozo-Pinzón, 2020).

METHODOLOGY

A preliminary mapping of actors and stakeholders was carried out to build a support network that strengthened the capacities of the "Colaborartorio Azul" project from various social, academic, economic, and technological perspectives. A methodological proposal with a co-participatory approach was implemented to identify the impacts of climate change on maritime cultural heritage on Tierra Bomba Island. This approach horizontally integrated local communities into the activities carried out to achieve the project's objectives. In this sense, the island's residents became the key players in identifying the impacts of climate change on cultural heritage. This was achieved by valuing and recognizing the traditional knowledge and practices of communities in relation to changes in weather patterns, which were then integrated where there were gaps in the scientific information.

Thus, through the development of working groups, workshops, surveys, and visits to cultural resources (Fort San Fernando, the San Bernabé tile- and brickworks, Fort San José, and the leprosy hospital) during the last quarter of 2022, communities engaged in the co-creation of knowledge and the development and strengthening of research capacities to enable governance and the protection of the territory and its heritage at different temporal scales of analysis. The information encompassed quantitative and qualitative data:

- First, the "long-term" scale was addressed through primary and historical sources such as historical maps, travelers' notes, and navigation diaries. These sources allowed the definition of natural features, along with perceptions and events that helped characterize the climate and heritage, and their transformations over time.
- Secondly, the "medium-term" scale was addressed through practical exercises with the community. Tools such as field diaries, audiovisual records, social mapping, the Mandala methodology[9], and other participatory dynamics were used to reconstruct a landscape memory that led to the identification of alterations caused by climate change in relation to the physical environment and the traditional practices of the current community.
- Finally, the "short-term" scale involved a practical component including monitoring, recording climate conditions, and establishing recording points, among others. The purpose of this exercise was to design measurement mechanisms and tools for assessing the effects of climate change on the cultural heritage of the area.

Analysis of the impacts of climate change according to historical documentation

This research reviewed cartographic sources (Table 1) and satellite images, which formed the basis for a historical characterization of transformations in the local maritime and coastal cultural landscape. This allowed us to register the environmental processes that have occurred in Cartagena de Indias, particularly on Tierra Bomba Island. The analysis of historical cartography involved three phases: *(i)* Collection and selection of historical cartography: After obtaining an initial database with information for each of the analyzed sites, specific historical cartographic references were chosen for the overlay. *(ii)* Overlay of historical maps with aerial photography using ArcMap (utilizing ArcGIS software): To perform georeferencing, reference points that had remained constant over time, such as the fortifications in Cartagena Bay, were used, preferably in locations from different parts of the map to maintain the image's proportional relationship. *(iii)* Tracing and vectorization of different coastlines on the maps: Some maps displayed coastlines from different years, and these coastlines were traced and vectorized.

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[9] Framework that allows for the systematic gathering of both general and specific information aimed at identifying the socio-cultural universe of the community through various activities and objects associated with daily life.

Table 1. Primary Cartographic Sources Consulted.

Title	Year	Author	Source
Map of the City of Cartagena de Yndias, located at 10 degrees and 26 minutes of northern latitude and 304 degrees of longitude.	1716	Anonymous	AGI MP-PANAMA,123
Map of the Bay of Cartagena de las Yndias, surveyed by Field Marshal Don Juan de Herrera y Sotomayor, Military Engineer of this Town, and outlined by Captain of Horses Don Carlos de Briones Hoyo y Abarca, Lieutenant Military Engineer and Castellan of the Castle of San Felipe de Barajas.	1721	Juan de Herrera y Sotomayor	Biblioteca Digital Hispánica No. bdh0000031660
Island of Tierra Bomba: Map of the Peninsula of Tierra Bomba and Carex, which explains the division of a land cavalry of the College of the Society of Jesus with the lands of Captain Don Alberto de Sucre according to the Commitment.	1734	Anonymous	AGI MP-PANAMA,261
Grundriss Cartagena in Indien, 1735.	1735	Ulloa, Antonio de Arévalo	Bibliothèque nationale de France, GED-2372 (VII)
Map of Cartagena de Indias [General map of the square of Cartagena de Yndias, part of its bay, and the surrounding land to understand the location of the Bocagrande opening, a dangerous threat to this square and the Isthmus square that lies between them...].	1769	Antonio de Arévalo	Biblioteca Virtual de Patrimonio Bibliográfico MN — Signatura: 28-A-14
Map of the Bocachica channel, the only entrance for ships to the bay of Cartagena de Yndias and the adjacent land on its northern and southern sides, created in accordance with the order of His Majesty on October 18, 1768. This map is intended to show the impact the sea has had on this area from October 1757 until the present day, as well as the necessity of providing the boats called "betas", as provided for in the aforementioned Royal Order to extract the sand deposited by tides and winds.	1792	Antonio de Arévalo	Cartografía y relaciones históricas de ultramar; Servicio Histórico Militar, Servicio Geográfico del Ejército Tomo V
Map of the port of Cartagena de Indias, the city situated at a latitude of 10° 26 '07'' N and a longitude of 69° 20' 01'' W of Cadiz. [Nautical chart] by the Spanish Directorate of Hydrographic Works.	1809	Anonymous	Institud Caartografic i Geologic de Catalunya
Cartagena	1885	Anonymous	CO.AGN.SMP.4,REF.X-71
Map of the Port of Cartagena de Indias, the city located at a latitude of 10° 26' 07'' N and a longitude of 75° 33' 10'' W of Greenwich.	1910	Vergara y Velasco, Francisco Javier 1860-1914	Biblioteca Nacional de Colombia fmapoteca_1332_fbnc_110
Aids to navigation in service in Cartagena Bay	1973	Anonymous	Acero Rangel, J. A. (2019). Sistema de ayudas a la navegación de Colombia: del acetileno al monitoreo remoto "Una luz para arribar seguro a puerto"

Articulation of knowledge about climate change

In order to generate horizontal knowledge about the impacts of climate change on Tierra Bomba Island and, in general, on Cartagena de Indias, workshops were held to build the general foundations about the impacts of climate change on maritime cultural heritage, bringing together the main social actors from the townships and institutional entities (Fig. 2). These workshops were attended by representatives of the Tierra Bomba Island community, members of the foundations Vigías de Karex and Los Jagüeyes, the General Maritime Directorate (Dimar), the Institute of Cultural Heritage of Cartagena, the University of Cartagena, the Cartagena de Indias School Workshop (ETCar), and the Naval Museum of the Caribbean.

In the first workshop (Fig. 3), held at the University of Cartagena in November 2022, an introductory activity focused on discussions about six key aspects: climate change, its impact on the community, the maritime coastal environment, heritage, climatic variables, and the units of observation for these impacts. To do this, readings from 20th-century newspapers were used to explore topics related to floods, rainfall, cyclones, storms, and other effects on coastal areas and heritage sites (Fig. 3).

Figure 2. Participants and activities of the first working group.

Inundaciones en casi todos los barrios

Intensifican campaña

Figure 3. Workshop discussion around 20th-century newspaper articles.

Participants were also consulted on their perspectives, reflections, and perceptions regarding the effects of climate change and their connection to maritime and coastal cultural heritage. Once the information provided by the community was compiled and digitized, it was analyzed in the context of scientific research conducted in the area.

Diffusion and dissemination strategy

As part of the measures to capture and disseminate the research results, a strategy was implemented to catch the interest of the target audience and create a virtual community that offers training and builds community capacities in theoretical and practical skills that would allow for the diagnosis of the impacts of climate change on regional heritage (Del Cairo *et al*., 2023).

RESULTS AND DISCUSSION

As a result of the preliminary mapping activities of the target audience and actors, a support network was built to strengthen the capabilities of the "Colaborartorio Azul" project from various social, academic, economic, and technological fronts. Among the entities identified with the greatest potential were: the Naval Museum of the Caribbean, Dimar, the Port Captaincy of Cartagena, the Center for Oceanographic and Hydrographic Research of the Caribbean (CIOH), the Cartagena School Workshop, Cartagena City Hall, the Cartagena Institute of Cultural Heritage, the Conservar Group, and the Community Museum of Tierra Bomba. Organizations like Vigías de Karex, Cartagena Divers and the University of Cartagena, and international actors, especially the University of California and the University of Panama, were also highlighted (Del Cairo *et al*., 2023).

Impacts of climate change according to historical documentation

By overlaying historical information, it was possible to identify how the island of Tierra Bomba has undergone significant transformations over the centuries (Fig. 4), attributed to both human and natural actions. For instance, in the case of human actions, in the northern sector of the island, during the 17th and part of the 18th century, it was connected to the Bocagrande peninsula by a land bridge. However, starting in the second half of the 18th century, with the opening of the channel and, consequently, the construction of the submerged breakwater, the morphology of the northern part of the island changed.

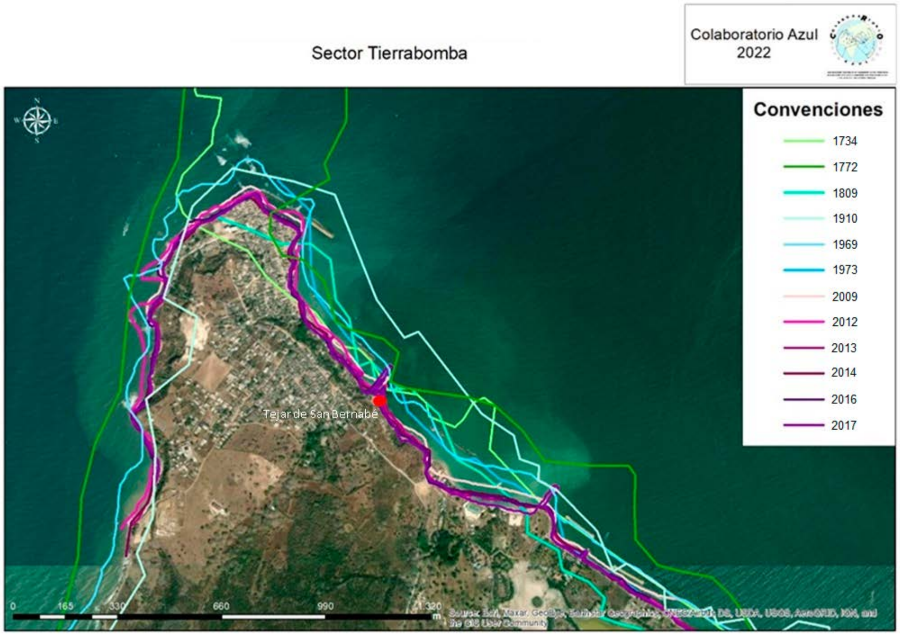

Figure 4. Evolution of the coastline in the Tierra Bomba sector from the 18th century to the 21st century.

This fact serves as an important precedent to consider for the analysis of the coastline. However, starting in the 20th and 21st centuries, coastal erosion of up to 265 m is identified in the northern part of the island. When examining temperature changes in Cartagena de Indias over a 42-year period from 1979 to 2021, a gradual increase was observed, with the highest temperatures recorded during the years 2015 and 2016, exceeding 28°C. Therefore, through the cartographic superposition exercise conducted in the framework of the project (Fig. 4) and data collected by other researchers (Andrade *et al*., 2017; Mora *et al*., 2018), it becomes evident that in the last 100 years, more coastline has been lost compared to previous centuries, raising the possibility that this behavior is associated with the effects of climate change.

In the Bocachica sector (Fig. 5), during the late 17th century and the 18th century, several transformations of the coastline are observed, with an increase in sediment deposition, especially in the southern area between San Fernando Fort and Castilletes. The sediment deposition reached up to 94 m between 1698 and 1721 and up to 127 meters between 1721 and 1792 in front of Castillo de San Luis de Bocachica. During the period from 1809 to 1910, a marked trend of coastal erosion is observed, although it is important to note that additional data verification with topographic and bathymetric studies, for instance, is required to obtain more precise measurements of elevation and depth.

Finally, in the Caño del Loro area (Fig. 6), there is a complex morphology that has remained relatively similar over the centuries. This complexity made the cartographic superimposition from the 17th century more challenging. Overall, the Caño del Loro area has shown a tendency toward erosion, as evidenced by wear and retreat of the coastline over the 18th and 19th centuries. Some areas, such as the hospital complex and the Lazaret, have experienced significant erosion in the past 120 years. During the 20th century, there is variability in coastal dynamics in this region.

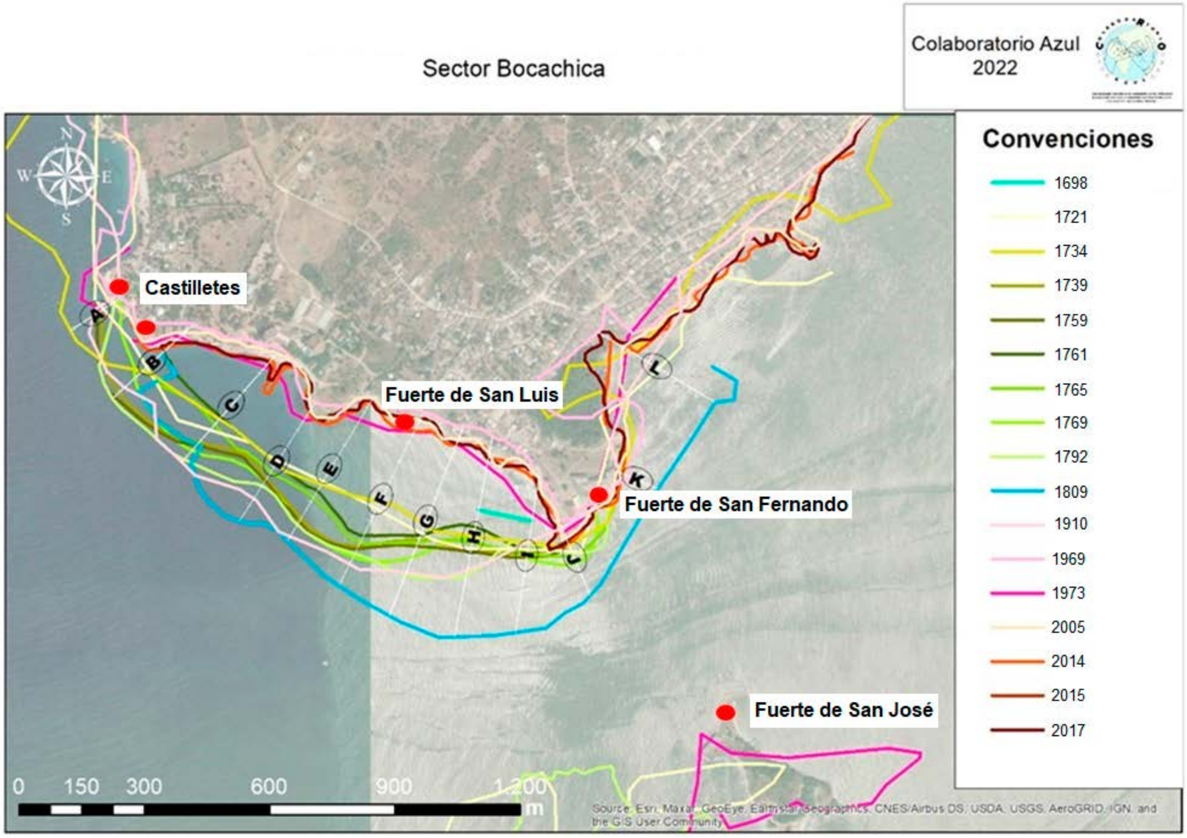

Figure 5. Evolution of the coastline in the Bocachica sector from the 17th century to the 21st century.

Figure 6. Evolution of the coastline in the Caño de Loro sector from the 18th century to the 20th century.

According to Posada, Henao, and Morales (2011), the township of Caño del Loro is subject to flooding caused by storm surges and strong waves generated by merchant ships passing through the area. These activities also lead to erosion, which has necessitated the relocation of some homes. The first line of houses on the northern side of the settlement is heavily affected due to the low-lying terrain, as it is situated on intertidal marshes with anthropogenic fill. Along the coastline, blocks have been positioned and walls built to protect against storm surges.

For the recent period, studies on changes in the coastline of Tierra Bomba Island are scarce, and existing studies are related to human activities. Afanador *et al*. (2008) mentioned that a significant part of its beaches is affected by coastal erosion, and only in some areas has the construction of a series of irregularly distributed groins slightly reduced the retreat of the coastline. Recently, Ricaurte *et al*. (2018) showed that Tierra Bomba is at a high level of threat from coastal erosion on the side facing the bay and very high on the side facing the sea. This is attributed to the lack of natural protective structures guarding it against the waves, which constantly and directly impact the coast, gradually degrading the existing rocky material. However, although the part facing the bay is sheltered from the incident waves (produced by the wind), it may still be affected by waves produced by the passage of boats, which could be one of the significant factors leading to erosion (Amell *et al*. 2012).

Based on the above, it is necessary to consider various hypotheses to confirm whether coastal erosion and sea-level rise are solely indicators associated with climate change. Factors beyond climate change, such as anthropogenic modifications to the environment made during colonial times to ensure the strategic defense of the bay, may have led to variations. For example, dredging in the 18th century in the area of the old military channel of Bocachica, or the construction of the submerged breakwater in the Bocagrande channel. Additionally, integrating factors associated with geological dynamics, to combine them with the factors described, will help understand the causes of the transformations of the coastline of Cartagena de Indias.

Articulation of knowledge about climate change

As a result of the discussion groups, some environmental variables associated with climatic events were identified (Table 2), not only for Tierrabomba but for other areas of Cartagena. The most representative variables mentioned include rainfall, strong winds, and flooding.

Table 2. Climate variables identified during the workshop that was part of the methodology of this study.

Variables	N° mentions
Rain	17
Wind	16
Flooding	13
Hurricanes	10
High tides	11
Diseases	6
Storms	3
Drought	2
Coastline change	2

Additionally, the community pointed out that the areas most affected by the mentioned phenomena were those located closest to the coastline and in intertidal spaces. Among other territories affected by these same issues, beyond Tierra Bomba, there were other areas that could serve as inputs for new studies, such as El Laguito, Bocagrande, Castillo Grande, the Historic Center, Getsemaní, San Diego, Marbella, and rural areas surrounding the Ciénaga de la Virgen, as well as the rural sectors of Tierra Bomba, Bocachica, and Barú (Fig. 7).

The perceptions of the community (Table 2) can be grouped into atmospheric and marine categories. The atmospheric category includes rainfall, winds, hurricanes, storms, and droughts, while the marine category encompasses high tides and changes in the coastline. Flooding could fall into either category, depending on whether its origin is due to excessive precipitation or variations in sea level.

Furthermore, during visits to three cultural heritage sites, the San Bernabé tile- and brickworks, San Fernando Fort, and the leprosy hospital, which are at higher risk of flooding and the loss of structures caused by erosion and pollution from waste, we identified various factors associated with climatic variables and administrative actions that have contributed to their continuous deterioration.

At the San Bernabé tile- and brickworks, located in the Tierra Bomba district, the decomposition and disappearance of some structural elements were observed. For example, there was evidence of concretions, alterations caused by marine fauna, and erosion. Additionally, it was possible to observe alterations in the sites due to small roots, various insects such as earthworms, spiders, and even dogs. Finally, terrain erosion has resulted in losses of archaeological contexts and the deterioration of artifacts.

Regarding San José Fort, located in the Bocachica district, there were observations of alterations due to the waves impacting the fort's walls. Furthermore, moisture-related deterioration has affected graffiti, and sea level changes have led to the fort being flooded, converting it into a habitat for fauna and flora.

As for the leprosy hospital, located in the Caño del Loro district, vegetation growth, areas inundated by rainfall, and rising sea levels have led to increased damage to the infrastructure.

Considering these contexts, damages to properties, ecosystems, and social systems, including cultural heritage sites, have been mainly attributed to changes in air and water temperature in the atmosphere, which are the primary drivers of the destruction of stone and brick structures (Vyshkvarkova & Sukhonos, 2023). Sesana *et al*. (2021) reviewed the literature investigating the impacts of gradual changes in temperature, precipitation, humidity, and wind on the mechanisms causing the degradation of exposed heritage. According to Sabbioni, Cassar, and Brimblecombe (2009), water is the most important deterioration factor for buildings and especially for historic environments, as it poses a higher risk of moisture penetration into historical materials, including masonry, which, in turn, leads to corrosion and biological colonization.

Figure 7. Areas affected by climatic phenomena identified by the local community. These areas include other places not considered for this case study, although they are useful for final considerations and for planning the continuity of this research.

Regarding sea level variations, the most recent report by the Intergovernmental Panel on Climate Change (IPCC, 2021) shows that, on a global scale, the mean sea level increased by 0.20 m between 1901 and 2018. Locally, the outlook is not encouraging, as coastal subsidence in Cartagena de Indias is occurring at a higher rate than the global sea level rise driven by climate change (Restrepo-Ángel *et al*., 2021).

These authors show that, in a simulated scenario for the year 2100, the eastern side of Tierra Bomba (facing the bay) would be more affected than its western side (facing the sea), with the northeast zone being the most affected. This area falls within the areas defined as flood-prone by Castillo and Gamarra (2014), who refer to marshes and swamps that change in size (opening and closing) depending on the climatic season. The results of these authors also reveal that communities will have different perceptions depending on which side of the island they inhabit.

The meetings and dialogues during "Colaborartorio Azul" with communities, academia, and institutions allowed for understanding, from various perspectives, which climatic factors are currently present and how their transformation and increase over time contribute to the effects and damage present in the environment (landscape) and in the dynamics and quality of life of the communities that inhabit these territories. The most mentioned and recurrent factors were tides, water currents, and winds, followed by heavy precipitation, rising sea levels, and high temperatures. The community also expressed the need to be aware that the behavior of each factor affects the others. Thus, if one is out of balance, it causes the same effect in the others, which is reflected in the daily life of the people on the island, as expressed in one of the excerpts from the interview with the community:

> *"The sea used to be different from how it is now, the sea was calmer. There used to be a breeze like in January, but now it has increased, but now, with the high tides, it brings a different dynamic, I believe the sea is much fuller."* (Excerpt from an interview with Eligio Guerrero, 73 years old, from the Tierra Bomba township; Del Cairo *et al*., 2023).

Diffusion and dissemination

A communication plan was developed, focusing on two main stages. The first stage involved creating a WhatsApp group where the community and institutions could share real-time information about the impacts of climate change in their areas of residence. They were also able to share other relevant posts and all of this helped strengthen inter institutional support networks.

In the second stage, the focus shifted to using digital platforms such as StoryMaps and social media networks like Instagram, Facebook, and LinkedIn. This aimed to create an informative and dynamic online space accessible to interested stakeholders.

The establishment of this virtual network led to discussions and proposals for co-creating strategies to eventually protect maritime cultural heritage. The goal was to help these connected communities understand the effects of climate change and generate mechanisms for mitigating and safeguarding their tangible and intangible cultural legacies (Del Cairo *et al*., 2023).

CONCLUSIONS

In Colombia, as the only country in South America to have coasts on two oceans, and one with highly variable geographical characteristics, there is a growing recognition of the need to raise awareness and take action aligned with international policies and guidelines aimed at developing a mitigation strategy for the effects of climate change. The need to structure intersectoral adaptation measures in response to adverse scenarios that may pose risks to both the population and the territories has become increasingly evident. For example, some of the institutions participating in inter-institutional working groups, such as Dimar and its research center CIOH, have developed mechanisms for monitoring and protecting maritime scenarios and marine-coastal ecosystems through scientific research (Vallejo & Pico, 2022; Del Cairo *et al*., 2023).

As a solution to this global issue, various national development plans in Colombia have incorporated actions, causes, and prevention measures for natural disasters. CONPES document 3990 "Sustainable Bioceanic Potential", published by the National Planning Department, sets the framework for maritime development and discusses the technical weaknesses in managing risks resulting from coastal natural phenomena, including the effects of climate change. For coastal settlements, this implies increased participation in confronting the challenges posed by climate change, as one of its primary impacts is the significant rise in sea levels.

As reflected in multiple primary and secondary sources of information, climate change represents one of the greatest risks to biodiversity, social sustainability, and human culture on Earth. This phenomenon creates a new reality in which environmental factors, such as rising sea levels and atmospheric pollution driven by greenhouse gasses, underscore the urgent need for action. In most cases, industrialized countries are disproportionately responsible for the changes, and developing countries are the hardest hit (Vallejo and Pico, 2022).

Based on the information provided throughout this article and the research conducted, it is evident that the effects of climate change have led to tangible and measurable impacts on the coastal environments of Tierra Bomba. Transformations in natural and cultural resources, as well as impacts on archaeological heritage, traditions, knowledge, and community quality of life, have persisted over time and space due to a lack of education, job opportunities, and access to information. Therefore, the dialogues in horizontal discussion spaces have highlighted the need to find solutions to these challenges given the consequences that affect the communities' living environment. Furthermore, it is crucial to enable the co-production of knowledge within the framework of sustainable local risk management, while preserving the community's past.

With this initial phase of climate change impact assessment, analytical tools have been developed to facilitate comprehensive information conceptualization and provide better management and analysis capabilities. This also serves as a mechanism for environmental monitoring. An indirect impact is the expectation of increased awareness regarding the relationship between climate change and the past, as a natural phenomenon with diachronic anthropogenic influence, through participatory approaches. This aims to empower local communities to deal with its effects, protect their heritage, and address the evident and constant threats they have historically faced and continue to face in the short, medium, and long term.

In conclusion, Colombia is highly vulnerable to the effects of climate change. Given its privileged geographic position, oceanic conditions, and natural resources, it is imperative to develop strategies and policies aligned with international guidelines to strengthen mitigation and adaptation measures for this phenomenon (Cancillería, 2022). As highlighted, climate change is a critical issue that should be the focus of all entities at all levels. Adaptation is key in the search for appropriate strategies to address the impending climate crisis in the coming years, as it will undoubtedly change how nations prepare to face adverse events in a resilient manner.

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AUTHORS' CONTRIBUTIONS

Conceptualization: C. DelC., G. C., L. R., L. B.; methodology: C. DelC., G. C., J. A., L. B.; analysis: C. DelC., G. C., L. R., S. V., J. A., J. C., L. B.; software: L. R., L. B.; research: C. DelC., G. C., G. H., L. R., J. A., L. B.; validation: C. DelC., G. H., S. V., J. C.; writing and original draft preparation: C. DelC., G. C., L. R., L. B., S. V., J. A., L. B.; proofreading and editing: C. DelC., G. C., G. H., L. R., J. A., J. C., L. B.; supervision, C. DelC., G. C.; project administration: C. DelC.; funding acquisition: C. DelC. All authors have read and agreed to the published version of the manuscript.

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SCIENTIFIC AND TECHNOLOGICAL RESEARCH ARTICLE

Analysis of wave climate and energy potential of intermediate waters in the marine sphere of influence of the main ports of the Colombian Caribbean

Análisis del clima marítimo de aguas intermedias y su potencial energético en la zona de influencia de los principales puertos del Caribe colombiano

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ABSTRACT

This paper presents a study of the wave climate of the Colombian Caribbean Sea, between coordinates 8° N and 16° N latitude and 84° W and 70° W longitude, and the energy potential at intermediate water points within the area of the Colombian Caribbean, which serve as inputs for the country's maritime interests. It was carried out based on the analysis of wave propagation simulations for 30 years developed at the Center for Oceanographic and Hydrographic Research of the Caribbean (CIOH), using the SWAN (Simulating WAves Nearshore) model, forced with the winds of the North American Regional Reanalysis (NARR) from 1979 to 2010 and validated with directional buoy data from the Colombian General Maritime Directorate (Dimar) and the United States National Oceanographic and Atmospheric Administration (NOAA) in the Caribbean. The results show four regions of similar wave height, period, and directional characteristics in the Colombian Caribbean. The first is the region around the islands of San Andrés and Providencia, and the second is a southern region between Urabá and Cartagena. A third comprises the central region around Barranquilla and Santa Marta, and the fourth, between Riohacha and Puerto Bolivar, occupies the northern part. The highest wave height values are observed for Barranquilla and Santa Marta, while the lowest are at Urabá. Furthermore, we evaluated the renewable wave energy capacity by studying the potential energy spectrum for virtual buoys in the primary ports. We observed that the energy was concentrated between 4 s and 6 s, with wave heights ranging from 0.5 m to 3 m for buoys in Barranquilla, Santa Marta, Puerto Bolivar, and Providencia. Amongst these, Barranquilla displayed the highest potential, with a period of 7 s and a wave height of 4m, followed by Santa Marta with values of 6 s and 3.8 m. The annual pattern of average energy potential revealed high values between December and March, medium values from June to August, and low values in May and between September and November; demonstrating that there is greater energy in the dry seasons and lower energy in the wet seasons. The wave conditions detected surpass the necessary threshold for energy generation via a Wave Energy Converter (WEC) alternative energy system, offering highly promising yield potentials, which could be magnified through the use of energy parks.

KEYWORDS: wave climatology, SWAN model, Colombian Caribbean Sea, wave potential energy

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RESUMEN

Este trabajo presenta un estudio del clima de oleaje para el mar Caribe colombiano, entre las coordenadas 8° N y 16° N de latitud y 84° W y 70° W de longitud, y su potencial energético en los puntos de aguas intermedias en el área de influencia marítima en los principales puertos del Caribe colombiano, que sirven de insumo a los intereses marítimos del país. Se realizó con base en análisis de simulaciones de propagación de oleaje de un período de 30 años elaborado en el Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe, utilizando el modelo Simulating Wave Nearshore, forzado con los vientos del Reanálisis Regional de América del Norte de 1979 a 2010, y validado con información de boyas direccionales de la Dirección General Marítima y de la Administración Nacional Oceanográfica y Atmosférica en el mar Caribe. Los resultados muestran cuatro regiones del Caribe colombiano con características similares de altura, período y dirección de ola. La primera es la región insular de San Andrés y Providencia; la segunda, una región sur entre Urabá y Cartagena; una tercera es la región central, entre Barranquilla y Santa Marta; la cuarta corresponde a la parte norte, entre Riohacha y Puerto Bolívar. Los valores más altos de altura de ola se observan en Barranquilla y Santa Marta y los más bajos en Urabá. Adicionalmente, se evaluó la capacidad de energía renovable obtenida por medio del oleaje a partir del espectro de energía potencial para boyas virtuales en los principales puertos. Se encontró que la energía se concentra entre 4 s a 6 s de periodo, y entre 0.5 m y 3 m en alturas de ola, para las boyas de Barranquilla, Santa Marta, Puerto Bolívar y Providencia; siendo Barranquilla el sitio de mayor potencial que se encuentra entre 7 s y 4 m, seguida de Santa Marta entre 6 s y 3.8 m. El potencial energético promedio anual presenta valores altos entre diciembre y marzo; medios, entre junio y agosto; valores bajos, en mayo, y entre septiembre y noviembre, correspondientes a las épocas seca y húmeda. Las condiciones del oleaje encontradas superan el umbral necesario para generar energía con un sistema de energía alternativa tipo Wave Energy Converter, con potenciales de rendimiento aceptables que podrían multiplicarse mediante la instalación de parques energéticos.

PALABRAS CLAVE: *climatología de olas, modelo SWAN, Caribe colombiano, potencial energético del oleaje.*

INTRODUCTION

The richness and diversity of marine energy resources in the Atlantic and Pacific basins are a privilege for Colombia, which has about 892 118 km2 of marine territory between the two basins (Invemar, 2015). Additionally, due to Colombia's subscription to different international maritime agreements, it is necessary to carry out maritime studies that provide knowledge of the territorial waters for purposes such as navigation, the exchange of goods, passenger transportation, vessel design and tourism, among others (Dimar, 2023).

Dimar, as Colombia's national maritime authority, has led oceanographic, meteorological and hydrographic studies that provide knowledge regarding the conditions of the seas and coasts under Colombian jurisdiction, through its marine scientific research centers located in the Caribbean and Colombian Pacific (González, 1987; Andrade, 1992; Molares, Vanegas, Bustamante & Andrade, 2004; Bastidas, 2011; Grisales, Salgado & Molares, 2014; Monroy & Zambrano, 2017; Casanova, Zambrano, Latandret, Guerrero, Suárez & Albán, 2019). To this end, different oceanographic campaigns and research projects have been carried out to contribute to the knowledge and understanding of the maritime dynamics of Colombia's territorial waters (Rueda, 2017; Dagua, Torres & Monroy, 2018; Moreno & Báez, 2021).

In 2006, Dimar began implementing a system for field monitoring of meteorological and oceanographic conditions along the Colombian coasts, with a project called Red de Medición de Parámetros Oceanográficos y de Meteorología Marina (RedMpomm), which includes meteorological stations, tide gauges and wave buoys on the Colombian Pacific and Caribbean coasts. This system offers support for maritime activities and provides information on in situ conditions in real time.

In addition to the information collected by Dimar, different authors have focused their attention on waves towards the construction, expansion and adaptation of port structures which improve the flow of the maritime and river transport necessary for the coordination of logistics, using visual and instrumental data (Agudelo, Restrepo, Molares, Torres & Osorio, 2005), satellite databases (Thomas, Nicolae & Posada, 2012), as well as numerical modeling and reanalysis data (Mesa-García, 2009; Osorio, Mesa, Bernal & Montoya, 2009; Vega, Alvarez, Restrepo, Ortiz & Otero, 2020; Orejarena, Restrepo, Correa & Orfila, 2022).

Similarly, for more than a decade, specific studies evaluating wave energy potential have been carried out in Colombia. These have been performed at Isla Fuerte, located off the coast of Córdoba (Ortega, Osorio & Agudelo, 2013), the north of the peninsula of La Guajira, and Bocas de Ceniza in Barranquilla (Torres & Andrade, 2006), as well as for the entire Caribbean Sea, with special interest in the area of the Caribbean Low Level Jet (Appendini, Urbano, Figueroa, Dagua, Torres-Freyermuth, Salles, 2015). There studies have identified that, in the area including the Gulf of Mexico and the Caribbean Sea, the most energetic areas are found on the Colombian coastline.

Ocean energy has a key role to play in the sustainable development of coastal regions, as it can be integrated into local energy grids to supply, in addition to electricity, services such as water (from seawater desalination) and it can power electric transportation (Shadman *et al*., 2023). Colombia is advancing in an energy transition that will lead the country towards a green economy (DNP, 2023), supported by the National Development Plan (PND) 2023-2026 and the National Council for Bioceanic Economic and Social Policy (Conpes 3990) (DNP, 2020), which will contribute to the sustainable development of the country through the integrated and sustainable use of its strategic location, oceanic conditions and natural resources. Diversifying the country's energy matrix requires a broad knowledge of its resources. For this reason, and in order to study the maritime climate of the Colombian Caribbean and learn about its energy potential, in 2011 the Center for Oceanographic and Hydrographic Research of the Caribbean (CIOH) generated continuous synthetic wave time series, using a third generation numerical spectral wave model.

The hindcast employed made use of the SWAN (Simulating WAves Nearshore) model (Booji *et al*., 2004), which is based on the conservation of wave energy and winds from the North American Regional Reanalysis (NARR) project (Messinger, DiMego, Kalnay, Mitchell, Shafran & Ebisunaki 2006), from 1979 to 2010. The model was calibrated and validated using the data available from RedMpomm and it was verified that the model adequately reproduced the measurements (Dagua, Lonin, Urbano & Orfila, 2013). In this sense, this work aims to characterize the wave regime of the Colombian Caribbean based on the information generated, and calculate its energy potential. The work has been divided into sections on the maritime climate and energy potential; the former covers Colombia's jurisdictional waters in the Caribbean Sea and the latter uses specific points in the vicinity of the different harbor master's offices.

Study area

The Caribbean Sea begins at the Yucatan Peninsula and extends to Panama, bordered to the east by the Lesser Antilles and to the north by the Greater Antilles, ending at the island of Cuba. The predominant wind during most of the year comes from the east (known as trade winds) (Vernette, 1985; Nystuen & Andrade, 1993) and it is frequently affected by tropical waves, mainly between May and November (Sosa & Hernández, 2002). It is also affected by global-scale meteorological phenomena such as the North Atlantic Oscillation and the Southern Oscillation (Poveda, 1998; Amador, 2008).

There are two climatic seasons: a dry season between December and February, with higher wave heights, and a wet season between September and November, when wave height decreases. In addition, there is a transition period known as the Veranillo de San Juan (Bernal, Poveda, Roldán, Andrade, 2006) between June and August, with a peak wave height increase in July, after which it weakens until a low point in the wet season. The study area is located within Colombian jurisdictional waters in the Caribbean Sea, within which we selected the data point in intermediate waters ranging between 125 m and 250 m that is closest to the main ports of the Caribbean coast.

METHODOLOGY

In order to establish the characteristic parameters of waves and their effects in the region, it is essential to know their spatio-temporal evolution with sufficiently long time series, for which the CIOH's 30-year wave simulation database was chosen. Its domain in the Caribbean Sea is between latitudes 8° N and 18.7° N, and longitudes 84.5° W and 59.4° W (Fig. 1), with a spatial resolution of 12 km and a 1-hour temporal resolution. The output variables correspond to the integral wave parameters at each node: significant height (Hs), peak period (Tp) and predominant direction (Dir). The data were validated and calibrated with information measured by Dimar and National Oceanographic and Atmospheric Administration (NOAA) buoys, given that the numerically obtained data deviate from the instrumental data (Dagua *et al*., 2013), thus making it necessary to adjust the model parameterizations.

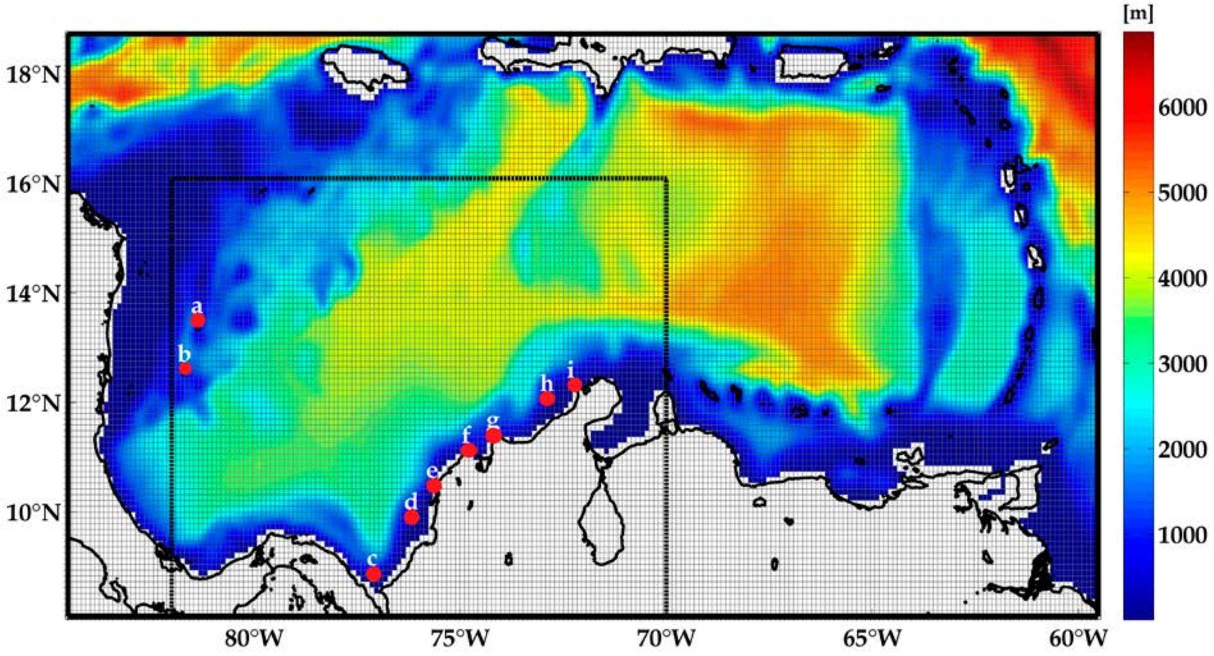


Figure 1. Computational domain of the wave modeling. The study area (--) with the location (red dots) of the virtual buoys: Providencia **(a)**, San Andrés Island **(b)**, Urabá **(c)**, Coveñas **(d)**, Cartagena **(e)**, Barranquilla **(f)**, Santa Marta **(g)**, Riohacha **(h)** and Puerto Bolívar **(i)**.

The data used to force the SWAN model were: bathymetry from ETOPO1 (Amante & Eakins, 2009) and winds from the NARR reanalysis (1979-2010), obtained from the Eta model of the US National Center of Environmental Prediction (NCEP); we used the zonal and meridional components of the wind at 10 m height, with a time step every three hours and a spatial resolution of 32 km.

For the analysis of the marine climate, a subdomain focused on Colombian jurisdictional waters was selected (Fig. 1, dotted line) between latitudes 8° N and 16° N, and longitudes 84° W and 70° W, and nine nodes were selected as virtual buoys located within 80 km of the main Colombian ports (Table 1).

Table 1. Coordinates of the virtual buoys from the SWAN model.

ID.	Region	Latitude (° N)	Longitude (° W)	Depth (m)
a	Providencia	13°31.98′	81° 19.98′	125
b	San Andrés	12° 38.82′	81° 40.38′	500
c	Urabá	08° 55.44′	77° 03.60′	250
d	Coveñas	09° 56.76′	76° 10.14′	250
e	Cartagena	10° 31.38′	75° 37.68′	250
f	Barranquilla	11° 09.66′	74° 45.60′	125
g	Santa Marta	11° 26.58′	74° 10.08′	250
h	Riohacha	12° 06.30′	72° 52.26′	250
i	Puerto Bolívar	12° 21.06′	72° 13.08′	125

Wave climate

Mean and extreme conditions of the sea state variables were calculated via a statistical analysis of the integral parameters for the study region. Mean conditions were obtained with the time average of each Hs and Tp series for all nodes in the study region. The probability of the joint density function was estimated using histograms of height and period in specific directions, providing monthly information on the propagation values for each wave period in a given direction.

For the extreme regime, although there is no single criterion to determine the wave conditions, it has been observed that distributions that consider two or three parameters are more appropriate (Ruiz *et al*., 2009). The distribution used corresponds to the Peaks Over Threshold (POT) method, following the methodology of Cañelas, Orfila, Méndez, Gómez-Pujol and Tintoré (2007). At the sites associated with the virtual buoys near the harbor master's offices, wave roses were produced to provide the predominant direction and associated wave height.

Calculation of power potential

To calculate the power potential using the integral wave parameters, an adjustment was made over the period (Booji *et al*., 2004) modeled in the 30-year historical wave analysis, which corresponds to:

$$T_{m,p-1,p} = 2\pi \frac{\iint \omega^{p-1} E(\omega,\theta)\,d\omega\,d\theta}{\iint \omega^{p} E(\omega,\theta)\,d\omega\,d\theta} \qquad \textbf{(Eq.1)}$$

Where

$p = 0.5$ and $E = (\omega, \theta)$	Is the variation of the spectral power density.
ω	Is the absolute frequency determined by the change in the dispersion relation, bearing in mind the Doppler Effect and the wave direction .

Since the power flux P is a function of the significant wave height H_s (Vicinanza, Constetabile & Ferrante, 2013; Akpinar & Kömürcü, 2012; Rusu & Guedes, 2012; Aydogan, Ayat & Yüksel, 2013), the significance of the energy period is associated with a sine wave with the same energy as the sea state. For this reason, the energy period is the period parameter used to estimate wave energy in deep water:

$$P = \frac{\rho g^2 H_s^2 T_e}{64\pi} \qquad \textbf{(Eq.2)}$$

Where,

ρ	is the density of seawater.

Meanwhile, in the SWAN model (Booji *et al*., 2004) T_e corresponds to another definition of the wave period, in the sense of the weighting factor for the spectral power in phase space:

$$RT_{m-10} = 2\pi \frac{\iint \sigma^{-1} E(\sigma,\theta)\,d\sigma\,d\theta}{\iint E(\sigma,\theta)\,d\sigma\,d\theta} \qquad \textbf{(Eq.3)}$$

Where,

$E = (\sigma, \theta)$	is the spectral energy density.
σ	is the relative frequency of the wave and the wave direction θ.

Based on the methodology described by (Cahill & Lewis, 2014), which estimate the relationship between T_e and the zero-crossing period T_{02} for a Bretschneider and JONSWAP spectrum; the latter more adequately represents the waves in the Caribbean with a constant α (Torres & Lonin, 2007).

$$T_e = \alpha T_{02} \qquad \textbf{(Eq.4)}$$

According to the spectral moments, Equation 4 can be written as:

$$\frac{m_{-1}}{m_0} = \alpha \sqrt{\frac{m_0}{m_2}} \qquad \textbf{(Eq.5)}$$

By rearranging this equation in terms of H_{m0}, peak frequency f_p and the peak shape parameter γ, making the respective substitutions and simplifications, it is possible to rewrite the term α in terms of γ:

$$\alpha = \left(\frac{4.2+\gamma}{5+\gamma}\right) . \left(\frac{11+\gamma}{5+\gamma}\right)^{\frac{1}{2}} \qquad \textbf{(Eq.6)}$$

The values of the constant can vary according to the peak fitting parameter of the spectrum, γ, as shown in Table 2.

Table 2. Wave period ratio for the JONSWAP spectrum (Cahill & Lewis, 2014).

α	γ
1	1.22
2	1.20
3.3	1.18
5	1.16
7	1.14
10	1.12

The sensitivity of α to the shape of the spectrum indicates that the relationship is transient and that the values can fluctuate significantly at a site, depending on the conditions and the composition of the wave spectra; therefore, the constant cannot be defined if it is not corroborated with local information and a sufficiently long data series.

To make the fit between T and T_e, the correlation between the two variables was calculated. For this purpose, a year of wave propagation was simulated, in which the model was configured to calculate the two variables. It is assumed that in a one-year period the correlation between these two variables is statistically representative for the climatological conditions of the Caribbean.

For the simulated year, the time series was extracted for a node located east of Bocas de Ceniza, which is a zone with strong waves (-74.76° W and 11.16° N), and the respective correlation was made (Fig. 2) between the variables T and T_e.

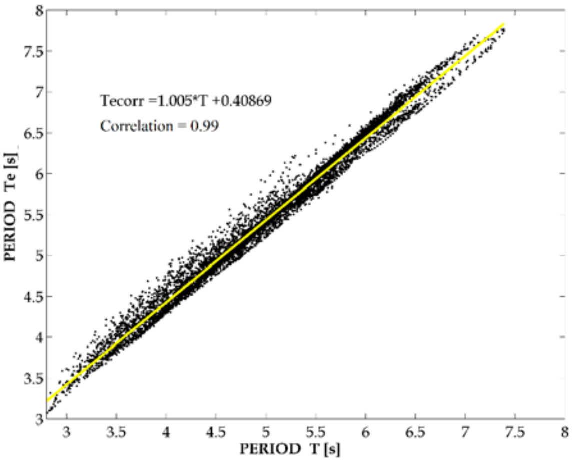


Figure 2. Correlation between the modeled variables T and T_e

The correlation coefficient is 0.99; however, was adjusted using the following equation obtained from the line of best fit, where is the calculated energy period:

$$T_{ec} = 1.005 * T + 0.4087 \qquad \textbf{(Eq.7)}$$

The period T_{ec} was replaced and calculated. This adjustment was applied to the energy period for the nine virtual buoys and it was replaced in Equation 2 to obtain the power potential. The value of the constant used to adjust the period, α, is underestimated compared to the calculations presented in Table 2. This is because the period equation for performing the calculations by Cahill and Lewis (2014) is the zero crossing period, different from the average absolute period used for this case in the SWAN model.

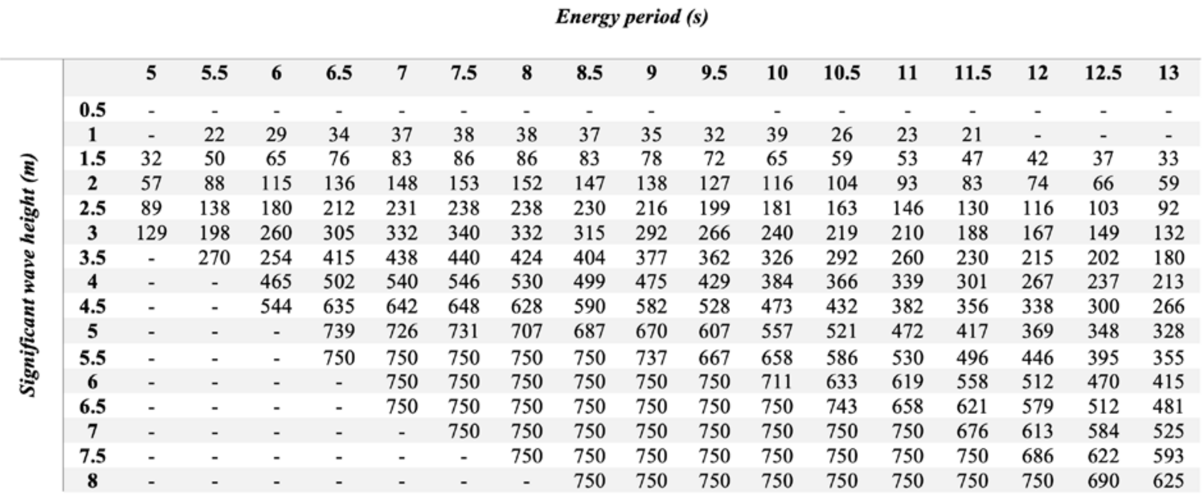
Wave energy converter systems

The points in Table 1 were used to select a device to capture the wave energy of the Colombian Caribbean in the area of influence of the ports. Because depths range from 125 m to 250 m, the technology that can be used is the so-called offshore system (mounted at depths greater than 40 m) (Rodríguez-Abal, 2019; Pozos, 2019) or it is possible to explore a combination with nearshore technology (systems mounted at depths between 20 m and 30 m).

Next, we present some options of wave energy converter (WEC) devices that could be used to harness the energy, taking into account their power matrix (a diagram giving the power produced under certain wave conditions). This makes it possible to identify the maximum power generated by an instrument and to know its optimum performance:

- Pelamis: this device is versatile and can be adapted to a variety of depths (offshore wave energy harvesting system). It consists of a cylindrical structure, divided into several sections, that is located semi-submerged; its shape allows it to have two degrees of freedom, giving it horizontal and vertical mobility. The relative movement between the hinged parts pumps oil through a hydraulic system that feeds a pressurized cylinder which, in turn, drives an electricity generator and allows the capture of energy (Rodríguez-Abal, 2019; Vergaray, 2008). The orientation and shape allow power generation to be maximized when the waves are small. Table 3 presents the equipment's power matrix.

Table 3. Pelamis power matrix. Source: Rodríguez-Abal (2019).



Energy period (s)

Significant wave height (m)	**5**	**5.5**	**6**	**6.5**	**7**	**7.5**	**8**	**8.5**	**9**	**9.5**	**10**	**10.5**	**11**	**11.5**	**12**	**12.5**	**13**
0.5	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-
1	-	22	29	34	37	38	38	37	35	32	39	26	23	21	-	-	-
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	254	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4	-	-	465	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	582	528	473	432	382	356	338	300	266
5	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

- OSWEC (nearshore wave energy capture system): This device is anchored to the seabed, therefore, its depth cannot exceed 30 m and it is located at a distance of 1 km from the coast (Morales, 2016). The system consists of a main paddle that receives the impact of the waves, and its dimensions depend on the bathymetry of the area where the equipment is installed. The paddle is mounted on a pivot which allows rotational movement induced by the interaction with the waves, using the power to drive a set of pistons that deliver pressurized water to the energy transformer unit. Table 4 presents the device's power matrix.

Table 4. OSWEC power matrix (OYSTER 800). Source: Rodríguez-Abal (2019).

	Energy period (s)												
Significant wave height (m)	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	27	39	57	76	87	104	109	100	101	92	94	94	87
1.5	63	92	126	168	201	213	201	239	207	198	183	150	154
2	75	160	233	301	380	408	383	399	239	365	319	265	259
2.5	-	254	378	467	568	623	616	601	519	523	481	390	428
3	-	368	503	693	799	824	876	792	759	704	546	579	554
3.5	-	-	655	934	1032	1085	1241	1075	973	925	862	747	688
4	-	-	843	1093	1352	1427	1430	1390	1158	1224	1139	1138	863
4.5	-	-	1219	1408	1644	1677	1807	1641	1662	1562	1404	1370	1191
5	-	-	1247	1670	1965	1952	2097	2002	1833	1798	1814	1459	1442
5.5	-	-	-	1979	2339	2308	2115	2389	2120	2012	1940	1518	1587
6	-	-	-	2406	2713	2776	2344	2705	2451	2396	2182	2414	2133
6.5	-	-	-	2778	3044	3001	2989	3211	2986	2896	2716	2455	2309
7	-	-	-	2871	3119	3131	3127	3176	3332	2877	2925	2676	2658

Therefore, if we want to know the amount of power that can be generated with WEC (Wave Energy Converter) systems, it is necessary to correctly define the energy period and significant wave height in order to use the power matrix of the instrument. The power matrix defines the threshold value to activate the system and, in turn, gives the effective power for the wave characteristics.

The performance of the device is measured by the plant factor, which corresponds to the ratio between the effective power and the nominal power of the equipment. With this ratio, it is possible to know the percentage of the maximum possible power delivered by a WEC.

Plant factor = (effective power generated) / (nominal power) ×100 **(Ec.8)**

RESULTS AND DISCUSSION

From the calculation of the average deep water wave regime for the Colombian Caribbean Sea (Fig. 3a), it is evident how the waves are directly influenced by the wind (Fig. 3c), where the pattern of the wave and wind maxima are concentrated around the 75° W meridian with 12° N, north of the Colombian coasts, as a result of the Caribbean Low Level Jet, in agreement with what has been presented by other authors (Appendini *et al*., 2015; Wang & Lee, 2007). The maximum values for average Hs oscillate around 2 m, with wind speeds of 8 m/s.

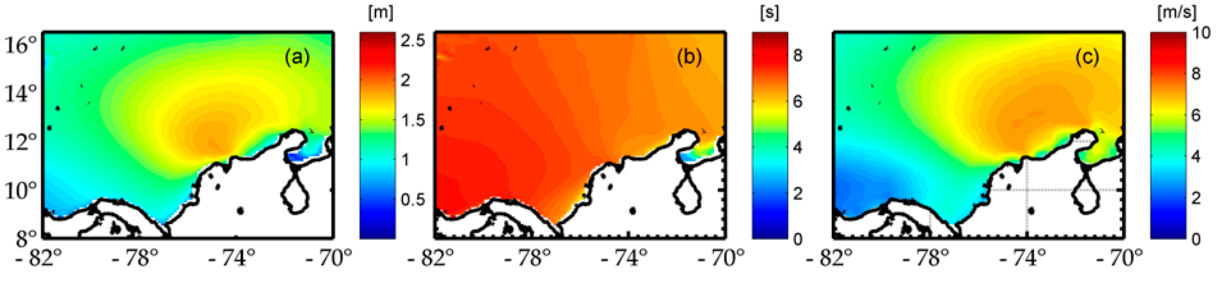


Figure 3. Mean values calculated from the 30-year database of CIOH reanalysis data: significant wave height **(a)**, peak period **(b)** and NARR reanalysis wind speed **(c)**.

The behavior of the peak period (Fig. 3b) is characterized by an east-west increase associated with the fetch, ranging from 6 s to 8 s. Although the winds over the Caribbean are not uniform (Fig. 3c), the wind sea waves increase their period depending on the fetch.

From Figure 3c, the values of moderate winds of U = 4 m/s (outside the La Guajira maximum) were used in the formula of Van Rijn (1994). The peak period is defined as $Tp = 0.286F^{*0.33}U/g$, where g is gravity and F* is the dimensionless fetch ($=gF/U^2$). It is calculated from this equation that a fetch of 546 km is required to reach the peak periods of 8 s (Fig. 3b). This coincides with the distance between the maximum winds (greater than 4 m/s) and the isthmus of Panama. It is important to mention that the wave height also depends on the fetch, but for the area of maximum wind the distribution of wind sea waves depends more on their intensity (Figures 3a and 3c).

Wave Climate in the Colombian Caribbean

The average regime allows us to characterize the wave behavior that will affect the coast on average. Figure 4 shows the average behavior of the significant wave height for each month of the year. This information is indispensable for studies for maritime works, bearing in mind that for a site near the coast it is necessary to propagate the deep water waves up to the point of interest.

From Figure 4, it can be observed that the wave behavior in the study area is, throughout the year, strongly influenced by the Caribbean Low Level Jet and the Intertropical Convergence Zone (ITCZ). Thus, during the months of December to March, during the dry season, the ITCZ is located further south, the trade winds are more intense, and the wave height is greater compared to the rest of the year.

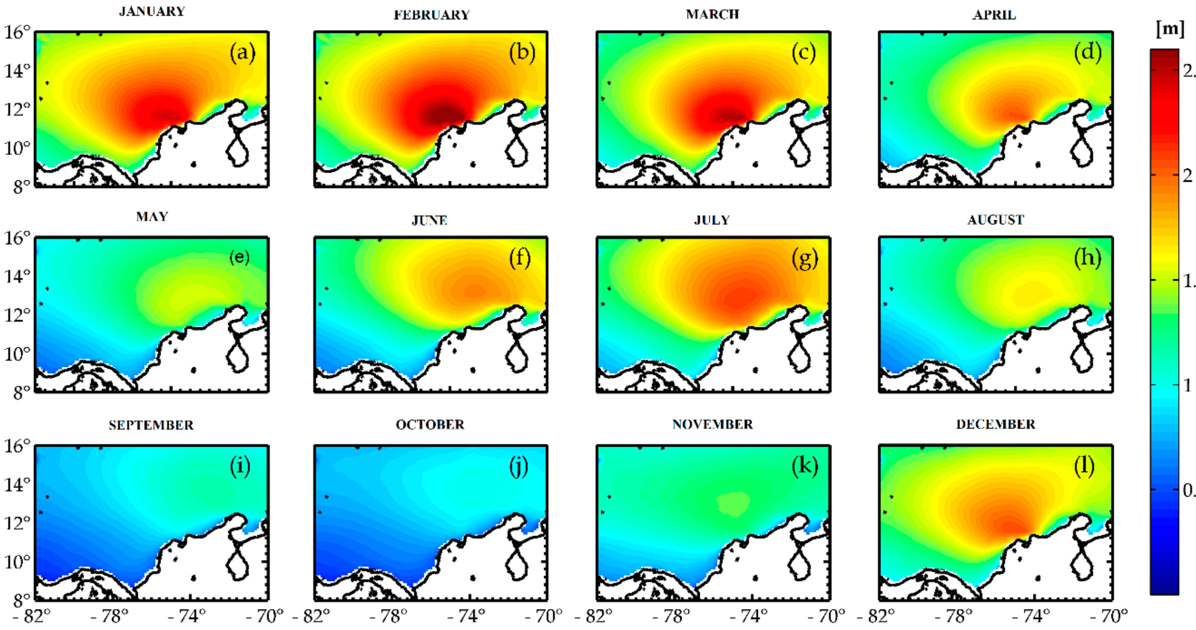


Figure 4. Monthly averages for significant wave height, based on the reanalysis information generated by the CIOH.

The opposite occurs during the months of September to November, which is the wet season and when the ITCZ is further north (Pujos & Mesa, 1988; Mesa, Poveda & Carvajal, 1997; Bernal *et al*., 2006). Likewise, Figure 4g (July) shows the influence of the San Juan dry season, with an increase in wave height compared to June and August (Figures 4f and 4h).

These results agree with those presented by Mesa-García (2009), who states that, in addition to spatial variability, the waves in the region have a temporal variation that manifests in the variability in the magnitude of the significant wave height in the different periods of the year.

In order to know in detail the wave behavior and its predominant direction in the vicinity of the main ports of the country, wave roses were produced for the locations of the virtual buoys given in Table 1 (Fig. 5).

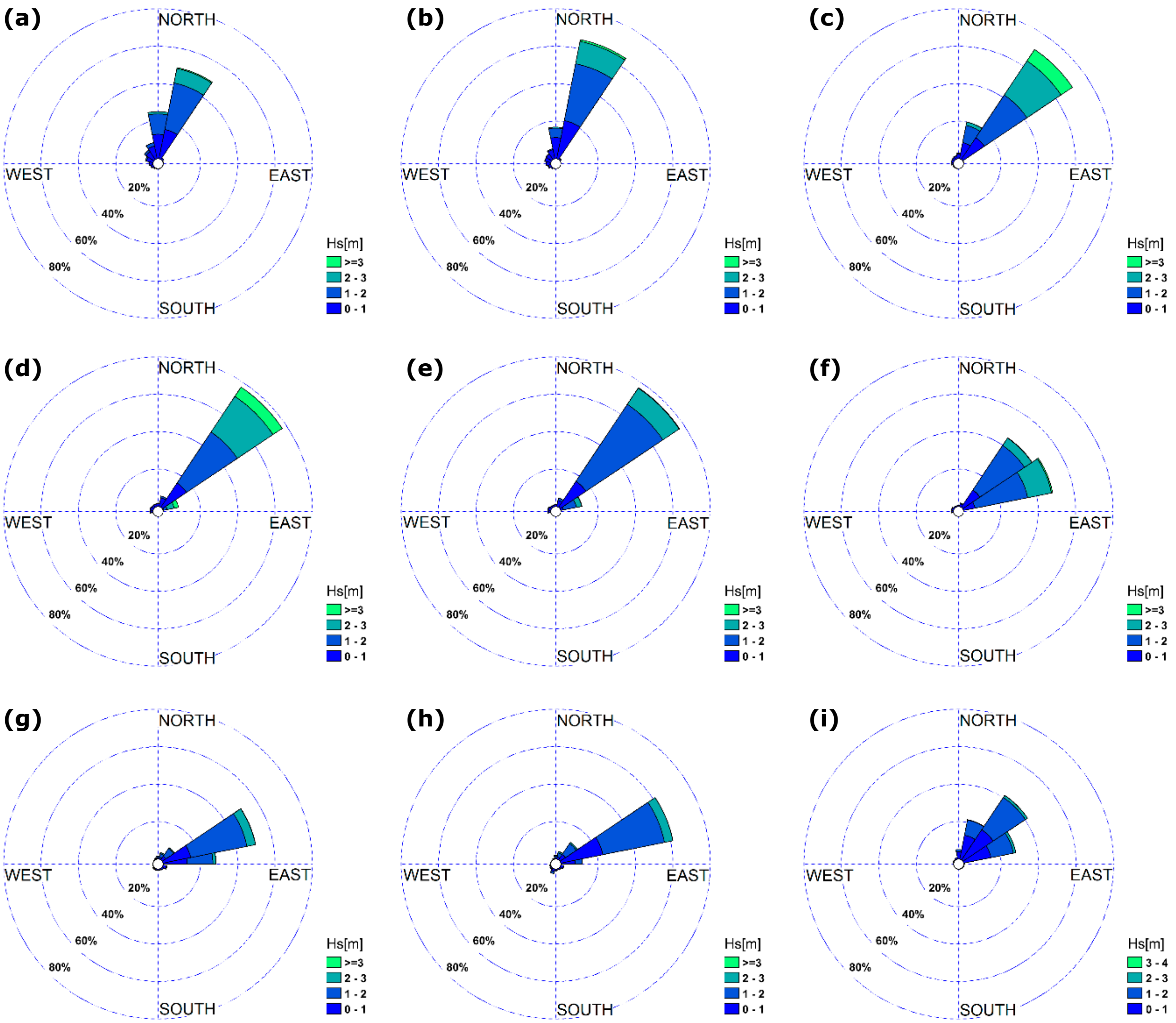


Figure 5. Wave roses for the study points, with associated wave height (color indicates Hs magnitude). Providencia **(a)**, San Andrés **(b)**, Urabá **(c)**, Coveñas **(d)**, Cartagena **(e)**, Barranquilla **(f)**, Santa Marta **(g)**, Riohacha **(h)**, Puerto Bolívar **(i)**.

For all the cases studied, it can be observed that wave directions are predominantly in the northeast (NE) quadrant. This behavior agrees with the wind climatology for the Caribbean described in (Vernette, 1985; Nystuen & Andrade, 1993), confirming a clear influence of the trade winds in the region.

The basic parameters of each virtual buoy are presented in Table 5, which shows the predominant direction and the proportion of time in which it occurs, as well as the significant wave height that is not exceeded 50% and 99% of the time for each location. It is observed that, for both the 50% and 99% occurrences, the maximum wave height value is for Barranquilla and the lowest is for Urabá, something which is corroborated both in the calculated mean regime (Fig. 3) and in the monthly averages (Fig. 4).

Table 5. Description of the predominant direction and wave height for each virtual buoy.

Virtual buoy	Direction	Direction Probability (%)	Hs50%	Hs99%
Providencia	NEE	50.60	1.275	2.613
San Andrés	NEE	61.24	1.174	2.542
Urabá	NE	41.45	1.047	2.290
Coveñas	NNE	49.63	1.311	3.044
Cartagena	NNE	64.82	1.338	3.104
Barranquilla	NE	70.69	1.777	3.953
Santa Marta	NE	77.32	1.700	3.770
Riohacha	NE	76.92	1.419	2.754
Pto. Bolívar	NEE	48.77	1.677	3.067

Figure 6 shows the results of the extreme regime, with different return periods.

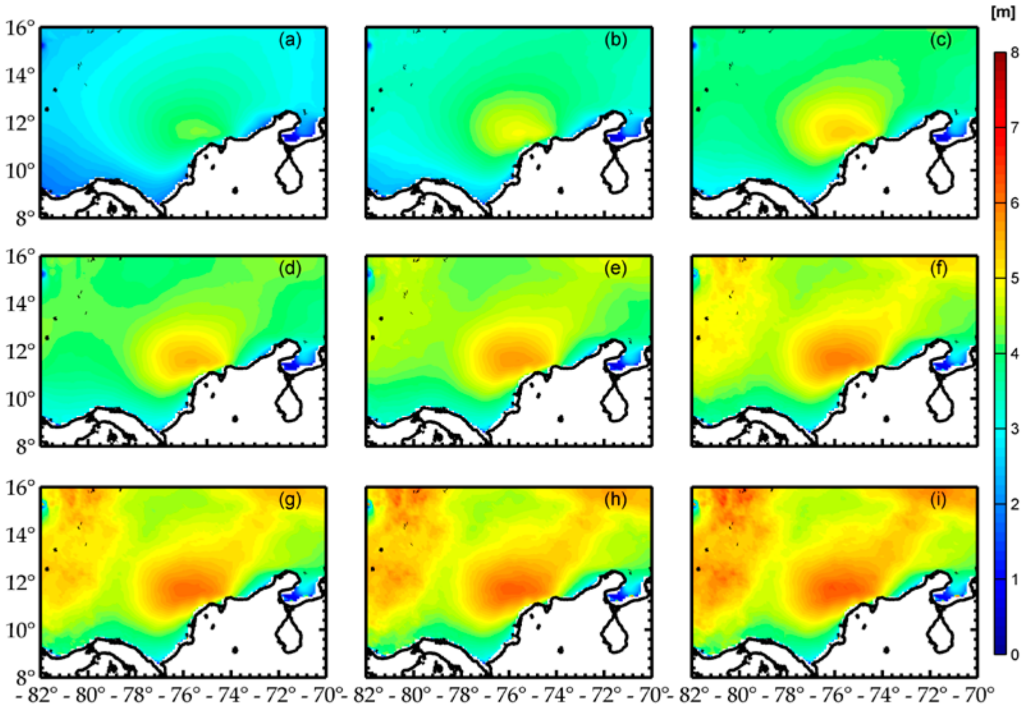


Figure 6. Extreme waves for deep water in the study area. Wave height for the 99% threshold **(a)**, 1-year return period **(b)**, 3-year return period **(c)**, 5-year return period **(d)**, 10-year return period **(e)**, 20-year return period **(f)**, 30-year return period **(g)**, 50-year return period **(h)**, 100-year return period **(i)**.

The waves associated with extreme events has their lowest heights in the Urabá region in the southernmost area of the Caribbean Sea, as well as in Coveñas, which, given its position, is less exposed to the strongest storms coming from the east. The regions of Providencia and San Andres have high wave values in the different return periods, but the highest extreme wave height values occur in deep waters in the regions of Barranquilla and Santa Marta, with associated wave heights of around 6 m.

Although the results presented in this study agree with the mean values of height and predominant direction presented by other authors (Agudelo *et al*., 2005; Osorio *et al*., 2009; Thomas, Nicolae, Durand, Posada, García & Andrade 2011), the extreme values differ for different return periods and regions. This is attributed to the fact that the databases used are different (data from traveling ships or satellite altimetry), as well as the methodologies used for their calculation (annual maximum, GEV, POT).

In this sense, it is clear that wave statistics (through wind reanalysis) should better reflect these values compared to the observations from traveling ships: (*i)* due to visual observation errors and subjective experiences; *(ii)* because they occur in different locations when there is a need to group the data in a grid; *(iii)* as ships avoid severe adverse phenomena, such as tropical cyclones, in the shipping lanes.

Potential of wave energy for points close to the harbor master's offices

The expressions for calculating power described in the methodology were used to obtain scatter and energy diagrams in terms of Hs and Te (Fig. 7). These describe the average power potential of a year, for intervals of 0.25 m and 0.25 s, respectively.

According to these results, the power potential is concentrated between 4 s and 6 s and between 0.5 m and 3 m, similar to the figures reported by Appendini *et al*. (2015) for the Barranquilla, Puerto Bolivar and Providencia buoys. The highest potential is observed for the Barranquilla buoy, at around 7 s and 4 m; followed by Santa Marta, around 6 s and 3.8 m, taking into account that the power lines vary according to the period and wave height.

It should be noted that the frequency of these values is low, considering that the color bar establishes the proportion of time (in hours) that a certain amount of megawatts is available or generated, calculated for an average year. Therefore, although Barranquilla's maximum potential is around 50 kW/m, these conditions will only generate less than 0.1 MWh per year. Finally, to establish the most favorable conditions of energy flow, the seasonal variability of the potential was calculated, giving averages over the year for each virtual buoy (Fig. 8).

In general, high values of power potential in the annual cycle are observed from December to March, in the dry season, and the lowest values in May and between September and November, months that correspond to the wet seasons, respectively (Bernal *et al*., 2006). But there is also an increase in July, related to the Veranillo de San Juan or transitional season (Andrade & Barton, 2000; Curtis & Gamble, 2007).

As in the potential energy diagrams, the virtual buoys of Barranquilla and Santa Marta have higher values than the other buoys. This is explained due to their geographical location close to the Caribbean Low Level Jet (Appendini *et al*., 2015; Ruiz & Bernal, 2009; Bernal, Ruiz & Beier, 2010; Andrade & Barton, 2005). This affects the waves as recorded in the pattern of the mean significant wave height value (Fig. 3) and confirmed in its monthly variability (Fig. 4).

Effective potential calculated for the points near the harbor master's offices

According to the study, the points with the greatest potential are located near Barranquilla and Santa Marta, where between 55 Kw/m and 43 Kw/m, respectively, could be obtained. However, this is not the real potential achieved with WEC systems.

Considering the wave characteristics of Figure 7, it is possible to define the Hs intervals and energy periods that are maintained throughout the year. With this information the real power (effective power) generated with the Pelamis and Oyster instruments, described earlier, was

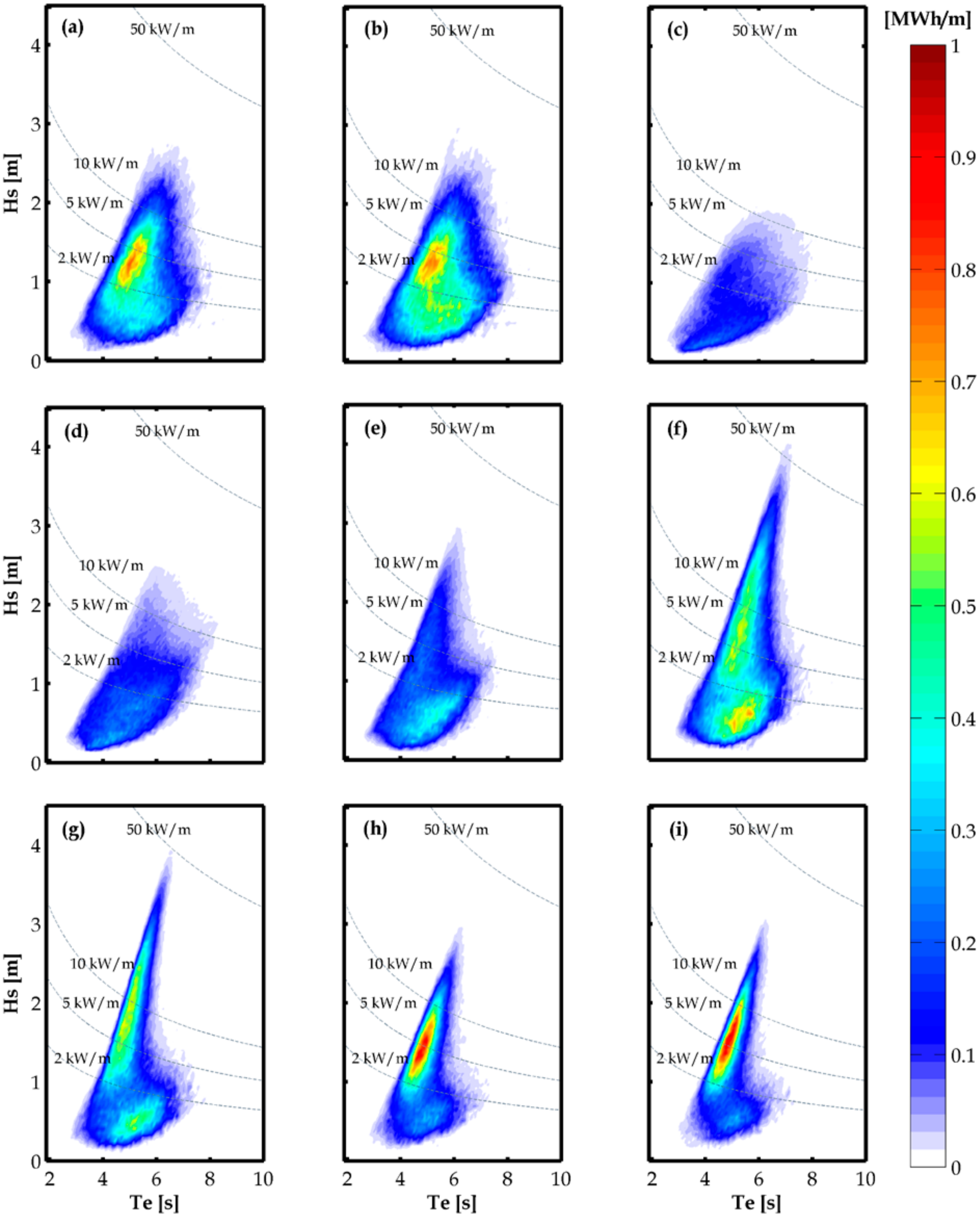


Figure 7. The combined scatter and energy diagrams of Hs and Te for the virtual buoys near: Providencia **(a)**, San Andrés **(b)**, Urabá **(c)**, Coveñas **(d)**, Cartagena **(e)**, Barranquilla **(f)**, Santa Marta **(g)**, Riohacha **(h)**, Puerto Bolívar **(i)**. The dotted line indicates the potential power (per meter of wave front) and the colors give the power per unit of time

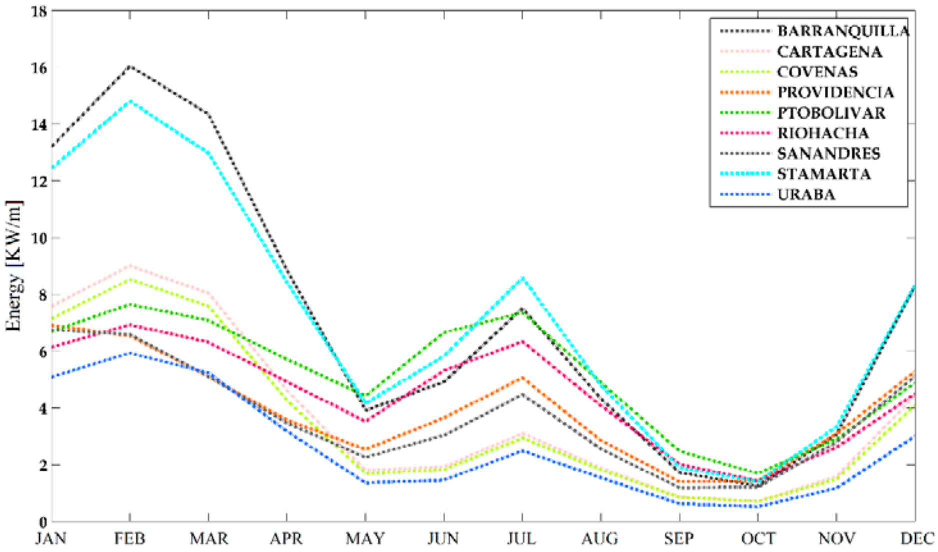
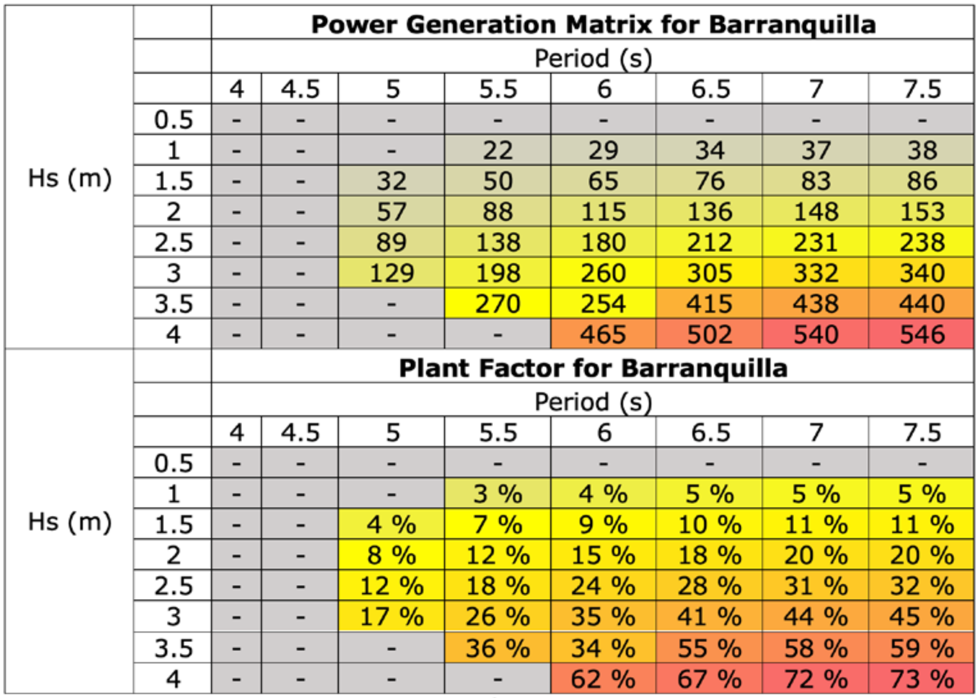


Figure 8. Average annual power potential for the virtual buoys near Providencia, San Andrés, Urabá, Coveñas, Cartagena, Barranquilla, Santa Marta, Riohacha and Puerto Bolívar.

calculated for each of the study areas. In addition to the real potential, it is possible to generate the plant factor and define the percentages of the energy that each instrument would capture (Eq. 8). Tables 6, 7, 8 and 9 present the performance of the Pelamis and Oyster instruments for the Barranquilla and Santa Marta areas, in which the color variations (gray-lower to red-higher) reflect the power and yield of each of the devices considered, depending on the wave conditions.

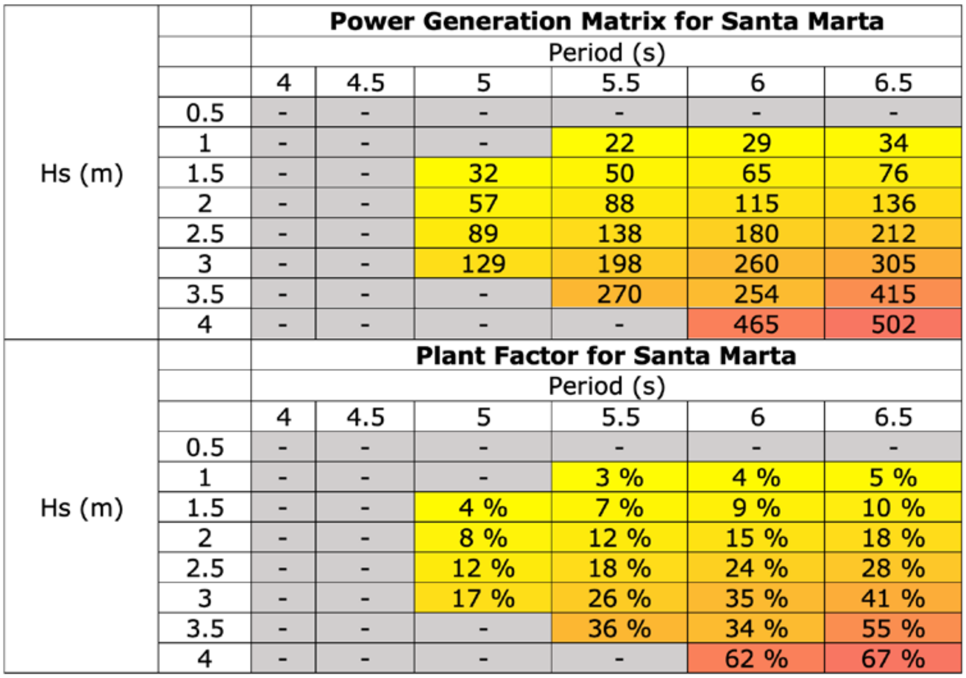
Table 6. Power matrix and plant factor for Barranquilla with Pelamis technology



		Power Generation Matrix for Barranquilla							
		Period (s)							
		4	4.5	5	5.5	6	6.5	7	7.5
Hs (m)	0.5	-	-	-	-	-	-	-	-
	1	-	-	-	22	29	34	37	38
	1.5	-	-	32	50	65	76	83	86
	2	-	-	57	88	115	136	148	153
	2.5	-	-	89	138	180	212	231	238
	3	-	-	129	198	260	305	332	340
	3.5	-	-	-	270	254	415	438	440
	4	-	-	-	-	465	502	540	546

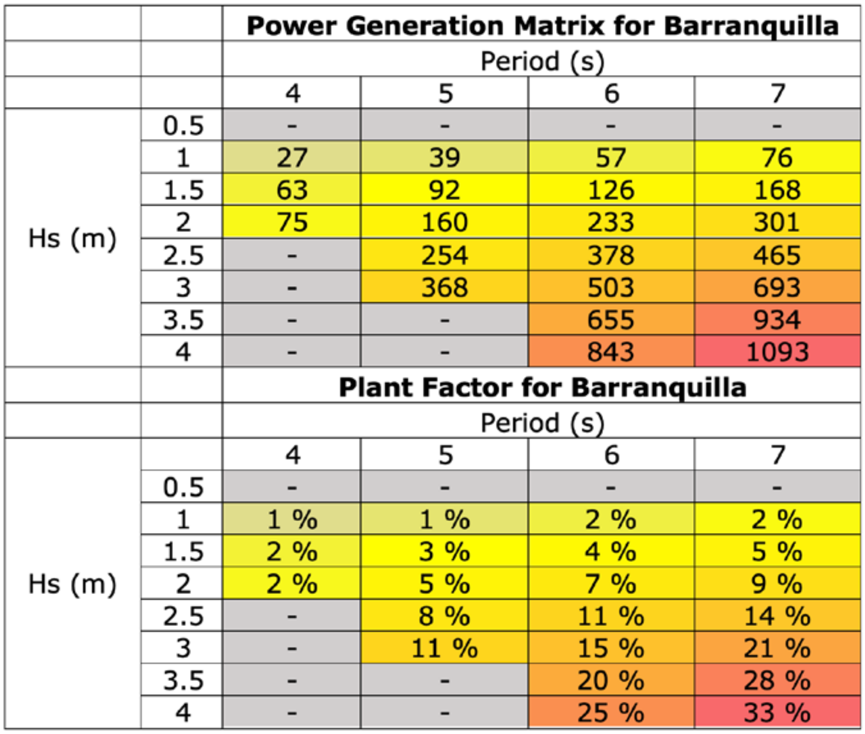
		Plant Factor for Barranquilla							
		Period (s)							
		4	4.5	5	5.5	6	6.5	7	7.5
Hs (m)	0.5	-	-	-	-	-	-	-	-
	1	-	-	-	3 %	4 %	5 %	5 %	5 %
	1.5	-	-	4 %	7 %	9 %	10 %	11 %	11 %
	2	-	-	8 %	12 %	15 %	18 %	20 %	20 %
	2.5	-	-	12 %	18 %	24 %	28 %	31 %	32 %
	3	-	-	17 %	26 %	35 %	41 %	44 %	45 %
	3.5	-	-	-	36 %	34 %	55 %	58 %	59 %
	4	-	-	-	-	62 %	67 %	72 %	73 %

Table 7. Power matrix and plant factor for Santa Marta with Pelamis technology



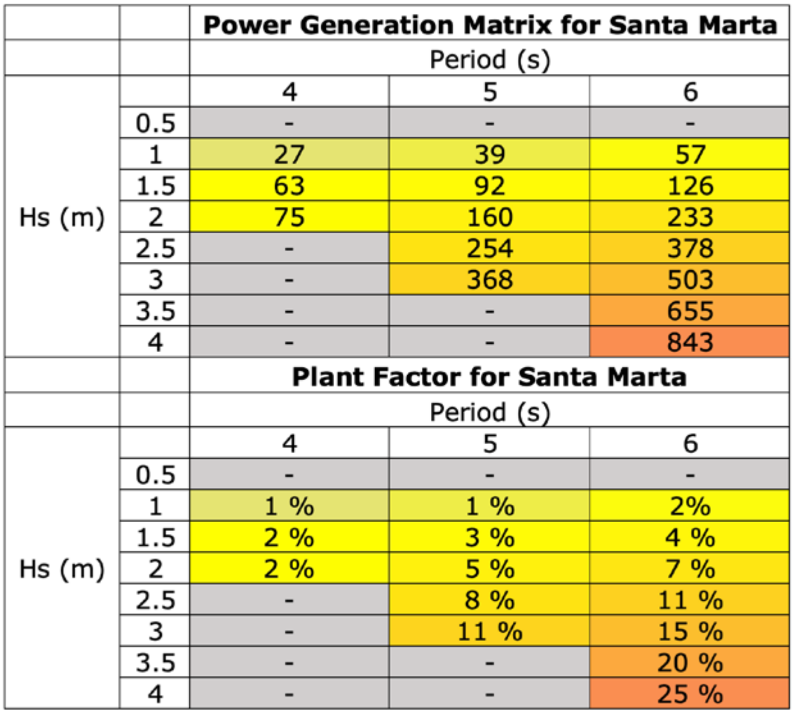
		Power Generation Matrix for Santa Marta					
		Period (s)					
		4	4.5	5	5.5	6	6.5
Hs (m)	0.5	-	-	-	-	-	-
	1	-	-	-	22	29	34
	1.5	-	-	32	50	65	76
	2	-	-	57	88	115	136
	2.5	-	-	89	138	180	212
	3	-	-	129	198	260	305
	3.5	-	-	-	270	254	415
	4	-	-	-	-	465	502
		Plant Factor for Santa Marta					
		Period (s)					
		4	4.5	5	5.5	6	6.5
Hs (m)	0.5	-	-	-	-	-	-
	1	-	-	-	3 %	4 %	5 %
	1.5	-	-	4 %	7 %	9 %	10 %
	2	-	-	8 %	12 %	15 %	18 %
	2.5	-	-	12 %	18 %	24 %	28 %
	3	-	-	17 %	26 %	35 %	41 %
	3.5	-	-	-	36 %	34 %	55 %
	4	-	-	-	-	62 %	67 %

Tabla 8. Power matrix and plant factor for Barranquilla with Oyster technology



		Power Generation Matrix for Barranquilla			
		Period (s)			
		4	5	6	7
Hs (m)	0.5	-	-	-	-
	1	27	39	57	76
	1.5	63	92	126	168
	2	75	160	233	301
	2.5	-	254	378	465
	3	-	368	503	693
	3.5	-	-	655	934
	4	-	-	843	1093
		Plant Factor for Barranquilla			
		Period (s)			
Hs (m)		4	5	6	7
	0.5	-	-	-	-
	1	1 %	1 %	2 %	2 %
	1.5	2 %	3 %	4 %	5 %
	2	2 %	5 %	7 %	9 %
	2.5	-	8 %	11 %	14 %
	3	-	11 %	15 %	21 %
	3.5	-	-	20 %	28 %
	4	-	-	25 %	33 %

Tabla 9. Power matrix and plant factor for Santa Marta with Oyster technology



		Power Generation Matrix for Santa Marta		
		Period (s)		
Hs (m)		4	5	6
	0.5	-	-	-
	1	27	39	57
	1.5	63	92	126
	2	75	160	233
	2.5	-	254	378
	3	-	368	503
	3.5	-	-	655
	4	-	-	843
		Plant Factor for Santa Marta		
		Period (s)		
Hs (m)		4	5	6
	0.5	-	-	-
	1	1 %	1 %	2%
	1.5	2 %	3 %	4 %
	2	2 %	5 %	7 %
	2.5	-	8 %	11 %
	3	-	11 %	15 %
	3.5	-	-	20 %
	4	-	-	25 %

In Barranquilla and Santa Marta, 546 Kw/m and 502 Kw/m respectively can be achieved with a Pelamis WEC, which represents an efficiency of 73% and 67%, in maximum wave conditions. However, these conditions are not constant over time, as shown in Figure 7. Potentials between 115 Kw/m and 88 Kw/m would be obtained with greater frequency, representing an efficiency of 15 % and 12 %. The variability of the conditions means that the system does not maintain maximum generation; therefore, conditions should be sought in which an almost constant electrical generation is achieved as recommended by (Rodriguez-Abal, 2019), thereby achieving a reliable system which generates the power necessary to meet the demand of users.

With an Oyster device, under maximum wave conditions, electricity potentials of 1 093 Kw/m and 843 Kw/m are achieved for Barranquilla and Santa Marta respectively, which reflects plant factors of 33% and 25%. However, as previously mentioned, these conditions are not constant over time. Potentials of 233 Kw/m and 160 Kw/m would be obtained with greater frequency, which indicate a yield of 7% and 5% at the two ports. Compared to a Pelamis system, the Oyster delivers higher electrical potentials, but the performance of the equipment does not reach the percentages shown by Pelamis as a consequence of its higher nominal power.

CONCLUSIONS

Four regions of similar wave height, period and direction characteristics were identified in the Colombian Caribbean. The first is an insular region corresponding to San Andrés and Providencia; there is a southern region located between Urabá, Coveñas and Cartagena; a central region corresponds to the region around Barranquilla and Santa Marta; and a northern region is found between Riohacha and Puerto Bolívar.

The study shows that Barranquilla and Santa Marta have higher wave height values compared to the other regions, in both the 50% and 99% probability calculations, while the lowest values are found at Providencia, San Andrés and Urabá. For the case of extreme regimes, the highest extreme wave height values occur in deep waters in the regions of Barranquilla and Santa Marta, and the lowest in the regions of Urabá and Coveñas.

The spectrum of potential energy for the virtual buoys is concentrated between 4 s to 6 s in period and between 0.5 m and 3 m in wave height, very similar to that reported by (Appendini *et al*., 2015) for the buoys of Barranquilla, Puerto Bolivar and Providencia. The highest potential is observed at the Barranquilla buoy with 7 s and 4 m, followed by Santa Marta with 6 s and 3.8 m.

The annual average of potential energy has high values for the dry months of December to March, while it has low values in May, and between September and November, corresponding to the wet seasons. The statistics and databases produced in this work provide reference information on the process of wave transformation in transitory and shallow waters in the maritime zone of influence of all the port captaincies of the Caribbean.

In this sense, taking into account that most of the research on wave energy in Colombia has focused on characterizing the resource by measuring the height and period of the waves, it is relevant to develop, optimize and characterize equipment to identify the feasibility of this type of technology, and develop devices for generating energy from the resources available in the country.

According to the results of this study, the wave conditions exceed the threshold necessary to activate a WEC system, with possibly acceptable yield potentials, which could be multiplied when setting up energy parks involving more than one or two WEC devices and making a more exhaustive analysis of the topographic conditions of the installation areas. In the end, the viability of these systems will be subject to economic factors, which will mark the cost-benefit ratio of this type of emerging technology.

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Author contributions

Conceptualization, C. U.; methodology, C. U.; data curation: C. D., A. C.; analysis, C. U., C. D., A. C; software: C. U., C. D., A. C.; visualization, C. U.; writing – original draft preparation, C. U.; writing – review and editing, C. U., C. D. All the authors have read and accepted the published version of the manuscript.

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SHORT ARTICLE

User perception of coastal risks. A practical case study on the beaches of Mayapo (Colombian Caribbean)

La percepción de los usuarios sobre los riesgos costeros. Un estudio de caso práctico en las playas de Mayapo (Caribe colombiano)

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ABSTRACT

Tourist beaches are sensitive and complex ecosystems that are constantly subjected to pressures derived from anthropic activities. The presence of natural phenomena increases coastal risks. The research was documentary and descriptive. The object of the study focused on assessing the perception that users have about the existing coastal risks on the beaches of Mayapo, in the department of La Guajira, Colombia. Among the results, it was found that the most frequent threat to the area of the beach comes from floods that occur in the rainy seasons, characterized by strong winds and large waves. It is concluded that the beach area currently suffers flood threats that lead to a reduction in the size of the coastal strip and damage to the present infrastructure, affecting the environmental, economic and sociocultural sustainability of the coastal territory.

KEYWORDS: Coastal risks, perception, tourist beaches, natural phenomena, La Guajira.

RESUMEN

Las playas turísticas son ecosistemas sensibles y complejos que constantemente están sometidas a presiones derivadas de las actividades antrópicas. La presencia de fenómenos naturales incrementa los riesgos costeros. La presente investigación fue de tipo documental y descriptiva. El objeto del estudio se enfocó en valorar la percepción que tienen los usuarios sobre los riesgos costeros existentes en las playas de Mayapo, departamento de La Guajira. Entre los resultados se encontró que la amenaza más frecuente en la zona de playa procede de las inundaciones que se presentan en las temporadas de lluvias, caracterizadas por fuertes vientos y olas de gran tamaño. Se concluye que actualmente la zona de playa presenta amenazas de inundación que generan reducción de la franja costera y daños sobre la infraestructura presente, afectando la sostenibilidad ambiental, económica y sociocultural del territorio costero.

PALABRAS CLAVES: *riesgos costeros, percepción, playas turísticas, fenómenos naturales, La Guajira.*

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INTRODUCTION

The impacts of anthropic activities on marine and coastal ecosystems, along with the absence of a harmonious relationship between human actions and their environment, have affected the natural dynamics of these ecosystems. This has reached a point where the ecosystem services they provide have been jeopardized. Additionally, the presence of natural phenomena associated with the effects of climate change increases the coastal risks that the population may face in these territories (Ferrari, 2011). The risk factor in these natural spaces is represented by the possibility of environmental, social, and economic losses. The occurrence of disasters requires the historical construction of the past and the present in order to understand the changes that have occurred in the coastal territory (Ojeda-Rosero & López-Vásquez, 2017).

For this reason, it is understandable that the threats present in marine and coastal areas alert the population to the potential damages they may cause to a territory. In this regard, the probability of occurrence and the damages caused are fundamental conditions for assessing the level of risk that may arise in a coastal area (Galán-Gaitán & Jiménez-Miranda, 2018). Similarly, beach ecosystems are not immune to the emergence of socio-environmental problems caused by anthropic activities and natural phenomena resulting from climate change (Cantarero, De la Fuente, & Bellido, 2023). In this sense, tourist beaches are considered a space that is sensitive to damages caused by anthropic activities and natural disasters (Daza-Daza, Castellanos-Martínez, & Jiménez-Royeth, 2020).

Regarding coastal management, the perception that users may have of their environment provides vital information to understand the relationships between different actors (Villares, Roca, & Oroval, 2015). Additionally, it makes it possible to determine the position and knowledge of residents about the phenomena and impacts that have occurred in the coastal area over the years (Roca, Villares, Oroval, & Ortega, 2014). Therefore, this work is oriented towards assessing the perception that users have about the existing coastal risks to the beaches of Mayapo, in the department of La Guajira, Colombia.

STUDY AREA

The district of Mayapo belongs to the municipality of Manaure, located in the department of La Guajira. It borders the Caribbean Sea to the north, the community of Garciamana to the south, the communities of Capichiraure and El Chorro to the southwest, and the community of Popoya to the west (Chaux, Márquez, Acero, & Gómez, 2018) (Fig. 1). The tourist beaches of Mayapo are located 30 minutes by land from Riohacha, the capital of the department of La Guajira.

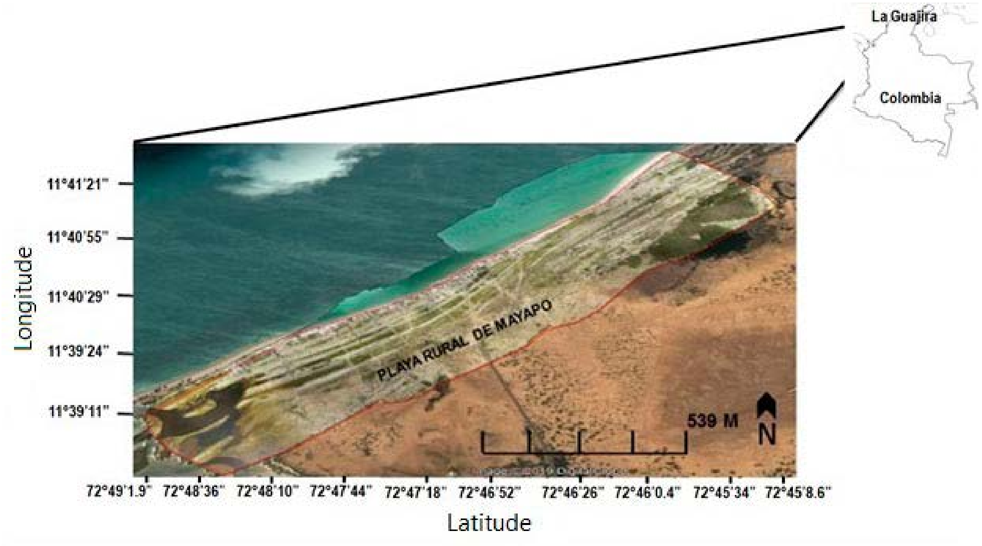

Figure 1. Location of the study area (Taken from: Daza-Daza *et al.*, 2020)

The department of La Guajira is characterized by average temperatures around 28.3°C, with scarce precipitation, mainly concentrated in September and October, when there is an average of 150 mm/month (Fig. 2). This characterizes it as a semi-arid to arid climate. The area is highly influenced by the Northeast Trade Winds, which reach average sustained speeds of 9 m/s at a height of 10 m above ground (Ideam, 2014; Gonzáles & Barney, 2019; CIOH, 2020).

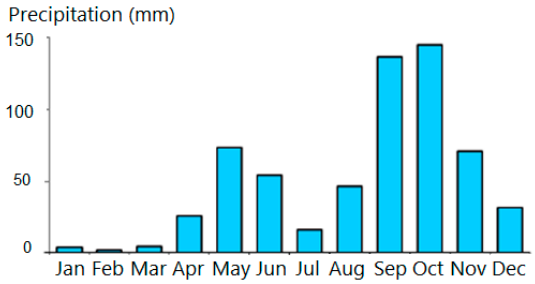

Figure 2. Precipitation in Riohacha, La Guajira (Source: Ideam, 2014)

METHODOLOGY

According to Yáñez-Arancibia and Day (2010), the coastal zone is considered a broad ecoregion with intense physical, biological, and socio-economic interactions, where there is a dynamic exchange of materials and energy between the continent, freshwater, the atmosphere, and the adjacent sea. Regarding coastal risks, Alonso, Vides, and Londoño (2001) define them as the probability of dangerous events occurring in coastal areas and the possible negative consequences that may result from these events.

Threats and vulnerability in coastal areas have been addressed by different authors. González (1990) defines a threat as the probability of the occurrence of a phenomenon to a certain magnitude at which damage can be caused. Vulnerability is defined by Blaikie, Cannon, Davis, and Wisner (1996) as the characteristic of a person or group based on their ability to anticipate, survive, resist, and recover from the impact of a natural threat. According to Alonso *et al*. (2001), threats refer to events or natural phenomena that can cause damage or endanger coastal areas, and vulnerability encompasses the susceptibility of coastal areas to suffering damage or losing resources as a result of dangerous events.

In the context of tourist beaches, the term “user” is defined as a person who uses or enjoys the beaches as a tourist or recreational destination. This includes not only tourists who visit the beach temporarily but also local residents who use it regularly (EPA, 2023). In this sense, according to Sauver, Roca, and Villares (2022), some types of users that can be found in the beach area are:

- Local Residents: Beaches are frequented by residents living near the beaches, who visit them to sunbathe, swim, exercise, or relax.
- Tourists: Beaches are popular destinations, so tourists are frequent users. Tourists visit the beaches for holidays, to explore the natural environment, and participate in water activities.
- Families: Beaches are attractive for families looking to spend quality time together, engaging in activities like building sandcastles, playing in the water, and recreational activities.
- Athletes: Beaches are also used by sports enthusiasts engaging in activities such as surfing, beach volleyball, swimming, scuba diving, etc. These users make use of the natural conditions of beaches to enjoy their favorite sports
- Nature Lovers: Many people visit beaches to appreciate their natural beauty and marine life. They might be interested in bird watching, exploring protected areas near the beaches, and enjoying the natural surroundings.
- Service and Amenity Users: People visiting the beaches to take advantage of services and amenities like restaurants, bars, beach equipment rental, loungers, umbrellas, etc.

This research was documentary and descriptive according to the classification presented by Tamayo (2001). Secondary information sources were used to understand the history of natural phenomena that have impacted the coasts of Mayapo. Additionally, direct field observation was implemented to identify evidence validating the current risks to which beach users are exposed. Subsequently, the zone was described to characterize the problems in the beach sector, and guided interviews were conducted with residents to understand their perception of existing risks (Daza-Daza *et al*., 2020). To achieve this and following the criteria of the United States Agency for International Development (USAID, 1991), the qualitative assessment matrix in Table 1 was implemented.

Table 1. Variables considered for qualitative risk assessment (Modified from: USAID, 1991)

Variable	Description
Water conditions	The visual quality of the water was assessed, including the presence of contaminants, transparency, odor, and the presence of algae or other organisms harmful to health.
Presence of warning signs	It was checked whether there were visible signs or indicators warning about possible dangers, such as strong currents, presence of sharks, rocky areas, or presence of dangerous marine life.
Terrain conditions	The condition of the terrain was assessed, including the presence of undulations, slopes, or unstable areas that pose risks to users.
Presence of emergency services	The availability and proximity of emergency services that might be needed such as lifeguards, rescue equipment, and access to medical services were verified.
Evaluation of human activity	The number of people present on the beach was observed, as well as how they interact with the environment, and whether they follow the established safety rules.

Semi-structured interviews were conducted using intentional sampling (Otzen & Manterola, 2022), with the criteria of selecting individuals of legal age who have a longer period of residence in the beach area, and who possess extensive knowledge of the threats present in the area (Fig. 3). During the execution of the field activities, a total of 20 residents meeting these criteria were identified.

The fieldwork was supported by tenth-semester students of the Environmental Engineering Program at the Universidad de La Guajira - Fonseca Campus, during the course of the subject Emphasis III - Assessment and Management of Natural and Anthropic Risks in Marine Coastal Areas 2022-II (Fig. 4). Microsoft Excel for Windows, version 2016, was used to tabulate the information.

Figure 3. Conducting interviews in the study area

Figure 4. Field observation activities

Finally, to determine the perception of local residents about the threats, the following questions were formulated:

- Have you experienced any natural threats in the area of Mayapo beach?
- What has been your reaction after the occurrence of a natural threat?
- What measures have been taken to mitigate and/or prevent the threats in Mayapo beaches?
- Have you received information from any authority about what to do in the event of a natural threat?
- Do the beaches of Mayapo have any plan or measures to be implemented in the event of a natural threat?
- What is your opinion on the use of native vegetation as a strategy to mitigate natural threats in the beach area?

RESULTS AND DISCUSSION

Background of natural phenomena that have impacted the coasts of Mayapo

The La Guajira Peninsula and the islands of San Andrés and Providencia are the areas in Colombia with the highest risk to the threat of storms coming from the East (Ortiz-Royero, 2007). In the 1980s and 1990s, the department of La Guajira was affected by the outer edges of around 25 hurricanes in the Caribbean Sea (Corpoguajira & Invemar, 2012). The report of threatening marine meteorological events for the department of La Guajira in the period 1966-2016 obtained from the DESINVENTAR database also showed that the most frequent threat is flooding, followed by strong gusts of winds (Invemar & Gobernación de La Guajira, 2018).

Currently, according to comments from local residents, natural threats continue to occur in the beach area. These threats include tidal surges, stream overflow, and torrential rains, which have caused severe flooding and changes in sand transport dynamics (coastal erosion), leading to the destruction of coastal infrastructure (thatched palapas, public bathrooms, kitchens, and supporting walls) and deterioration of mangrove ecosystems.

Research conducted by Rangel and Anfuso (2012), demonstrates that historical records of beach ecosystems in the municipality of Manaure show an accretion of beaches of 33.7 m in 32 years, equivalent to rates of +1 m/year. It is necessary to clarify that while it is true that natural phenomena such as hurricanes have not directly hit the shores of the Mayapo district, La Guajira, due to its geographical position, is the second most likely zone in Colombia to be affected by the outer edges of hurricanes. This is because in the Caribbean, hurricanes move from East to Northwest (Corpoguajira & Invemar, 2012).

Perception of residents about the natural threats present in the area

Based on the responses obtained from the interviews, in general terms, the most frequent threat in the beach area corresponds to floods that occur during the rainy seasons, characterized by strong winds and large waves. These cause damage to existing infrastructure (destruction of thatched palapas, restaurants, and hotel buildings), economic losses due to the inability to offer products to tourists (crafts, food sales), and a reduction in the beach area due to sediment transport. Likewise, there was evidence of the concern of local residents regarding the periodicity of natural phenomena, as they expressed that "if flood threats occurred regularly, Mayapo would cease to exist."

When assessing the residents' perception of their responsiveness to threats, it was found that after natural events, the local community engages in recovery activities such as salvaging wood from palapas and other useful items. They emphatically stated that they carry out these actions independently, without receiving support from any state institution.

Regarding the question "What measures have been taken to mitigate and/or prevent the threats in the beaches of Mayapo?" It was found that, to mitigate the effects of floods, the local community has extracted sand from the beach itself to build protective barriers (Fig. 5a) and used wheelbarrows to transport beach sand (Fig. 5b) and fill flooded access roads, thus ensuring the entry of tourists with their vehicles. This action may be potentially exacerbating the problem due to the loss of sediment in the beach area.

Figure 5. Management actions by the local population **(a)**, and items used for transporting sand **(b)**

Regarding the awareness of local residents about the existence of any risk management plan, it is apparent that there is no such management tool. Additionally, they stated that institutional presence is low, as institutional actors are only present during vacation seasons.

The perception of local residents regarding the importance of conserving mangrove ecosystems and their use as a mitigation measure against flood threats, revealed that they believe having mangroves on the coastal zone does not prevent the floods that occur. One reason given is that the strong currents in the area would sweep away mangrove species. In this regard, some considered that groins could be a good course of action. It is crucial to note that according to some local residents, back in the days when the beaches were untouched and there was no road, the Mayapo area was blanketed with mangroves and boasted an extensive stretch of beach. However, with the construction of the road, tourism made its way to the area, prompting locals to clear mangroves, construct palapas, and establish access roads.

In this sense, it is clear how the impacts resulting from natural phenomena and anthropic activities have affected not only tourism, but also the scenic quality of the beach ecosystems. Regarding this, the study on the perception of beach landscapes in the Colombian Caribbean conducted by Botero, Anfuso, Williams, and Palacios (2013) found that users who visit rural beaches prefer them for their clean sand, clear waters, natural vegetation, and morphological characteristics such as cliffs, rocky platforms, caves, arches, and dunes.

Anthropic activities, and the associated effects and risks in the beaches of Mayapo

During the study, anthropic activities were identified, and their effects can have a negative impact on tourism, the health of coastal ecosystems, and the protection of the coastline. Among these activities is the extraction of sand and seashells (Fig. 6a), used to fill in flooded roads, with the main effect being the reduction of the width of the beach (Fig. 6b). The accumulation of solid waste from restaurants, hotels, and hostels (Fig. 6c) leads to the contamination of mangrove ecosystems and areas with stagnant water (Fig. 6d), becoming breeding grounds for vectors.

Manual raking of the sand and constant foot traffic from tourists and residents affect the natural regeneration processes of mangrove propagules (Fig. 6e) and hinder their natural growth. Meanwhile, the transit of motorcycles and vehicles (Fig. 6f) causes soil compaction and loss of vegetative cover. All of this is in addition to the absence of environmental authorities and disaster risk management institutions.

Based on the above, Pérez (2021) suggests that anthropic activities in coastal areas can increase risks in beach areas. He states that the activities with the greatest impact are: increased tourism, material extraction, domestic waste, and poorly planned tourism.

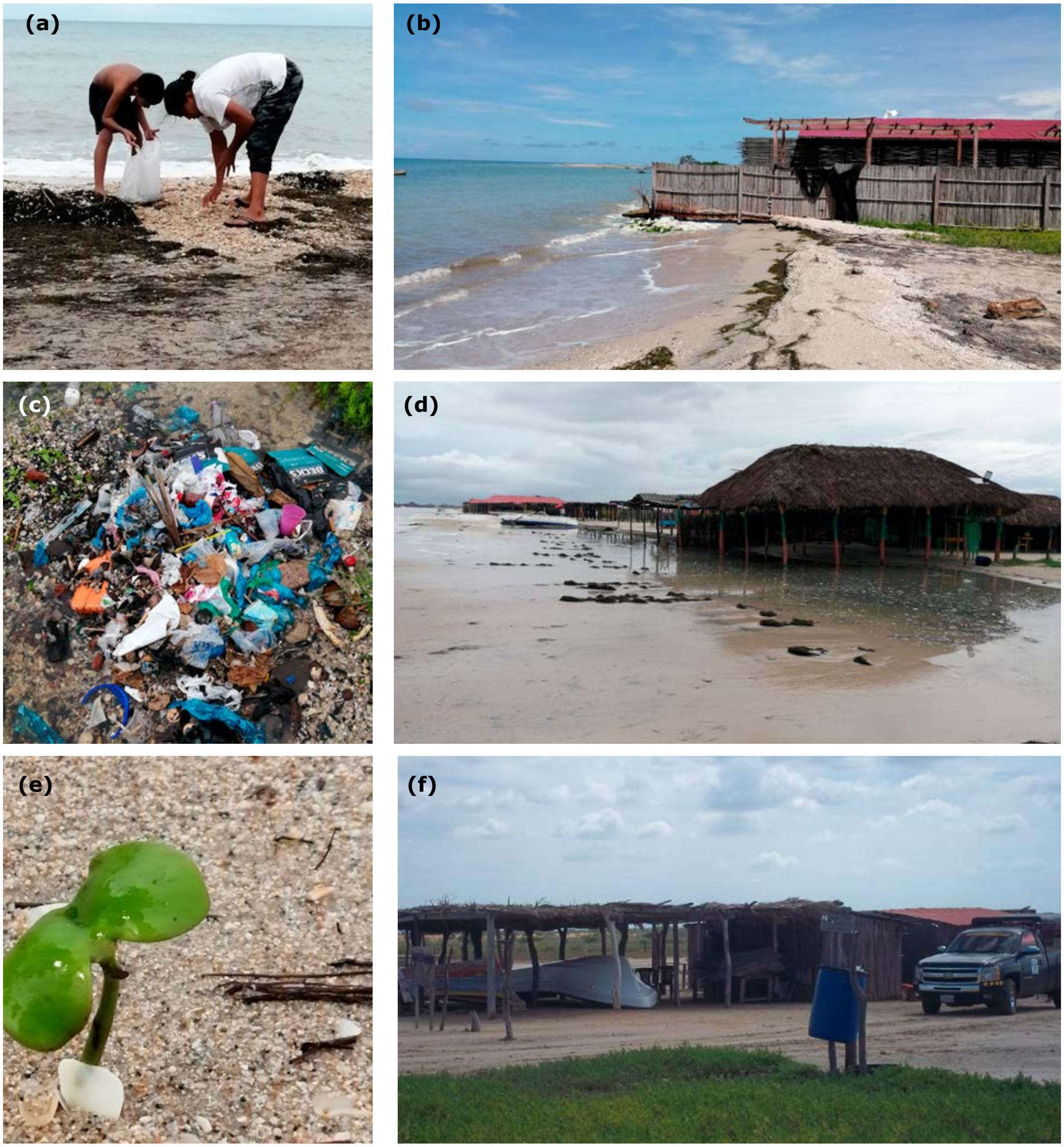

Figure 6. Anthropic activities and effects identified in the beach area. Extraction of seashells **(a)**, reduction of the coastal strip **(b)**, accumulation of solid waste **(c)**, flooding of infrastructure **(d)**, mangrove propagules **(e)**, and vehicle traffic **(f)**

CONCLUSIONS

The beaches of Mayapo currently pose risks to users, stemming from threatening marine meteorological events and anthropic activities that negatively impact the coastal ecosystem.

The extraction of sand from the beach by local residents, as a mitigation measure against flooding processes, can affect the stability of the coastline due to sediment loss. Additionally, the construction of containment walls with sandbags from the beach disrupts natural sedimentation processes, affecting the natural dynamics of the beaches and their ability to provide protection against extreme weather events.

The lack of a risk management tool for Mayapo beach has negative effects on its state and conservation. Moreover, institutional absence in the coastal area can lead to inappropriate use of the current ecosystems, jeopardizing their sustainability.

The negative perception among local residents regarding the effectiveness of mangroves as a mitigation measure demonstrates the need to create spaces for dialogue with the population to enhance understanding of disaster risk management. This includes knowledge about threats, reduction strategies, and response and recovery activities, which have no negative consequences for the ecosystems of Mayapo beach and its users.

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SHORT ARTICLE

Oceanographic factors as modulators of biodiversity in the La Guajira upwelling system: a systematic review

Factores oceanográficos como moduladores de la biodiversidad en el sistema de surgencia de La Guajira: una revisión sistemática

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ABSTRACT

In the northern part of Colombia is the department of La Guajira, a marine-coastal area influenced by different oceanographic and atmospheric processes that give it unique characteristics. Various investigations have focused on describing the oceanography of La Guajira, in which the environmental variables respond differently according to the climatic season; however, there are few works that contrast the oceanographic processes of the area of interest with the biodiversity. The objective of this systematic review was to determine the main environmental factors that modulate the oceanography of La Guajira and to establish whether the authors link them with aspects of biodiversity. To achieve this, a search was carried out for scientific articles related to the climatology and oceanography of La Guajira, for which three world-renowned databases were consulted: Scopus, ScienceDirect, and Web of Science. Finally, it was concluded that, although several investigations have analyzed the behavior of the Caribbean Sea and the way in which its temperature, salinity and chlorophyll vary at different scales, few investigations have focused on relating these characteristics with the biodiversity of the zone; a key aspect to take into account if we think that species and ecosystems respond to the way the climate and the ocean behave.

KEYWORDS: La Guajira, upwelling, oceanography, biodiversity.

RESUMEN

En la zona norte de Colombia se encuentra el departamento de La Guajira, un área marino costera influenciada por diferentes procesos oceanográficos y atmosféricos que le atribuyen características únicas. Diversas investigaciones se han centrado en describir el comportamiento oceanográfico de La Guajira, en la cual las variables ambientales responden de manera distinta de acuerdo con la época climática; sin embargo, son pocos los trabajos que contrastan los procesos oceanográficos del área de interés con la biodiversidad. La presente revisión sistemática tuvo como objetivo determinar los principales factores ambientales que modulan la oceanografía de La Guajira, y establecer si los autores los vinculan con aspectos de biodiversidad. Para lograrlo se realizó una búsqueda de artículos científicos relacionados con temas de climatología y oceanografía de La Guajira, para lo cual fueron consultadas tres bases de datos mundialmente reconocidas: Scopus, Sciencedirect, y Web of Science. Finalmente, se

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concluyó que, a pesar de que varias investigaciones han analizado el comportamiento del mar Caribe y la manera en la que su temperatura, salinidad y clorofila varían a diferentes escalas, pocas investigaciones se han enfocado en relacionar estas características con la biodiversidad de la zona; un aspecto clave para tener en cuenta si se considera que las especies y los ecosistemas responden a la manera en la que se comporta el clima y el océano.

Palabras clave: *La Guajira, surgencia, oceanografía, biodiversidad.*

INTRODUCTION

La Guajira is a peninsula located in the northern part of Colombia (Fig. 1), characterized by being an area of desert and xerophytic ecosystems, which is also highly influenced by the Caribbean upwelling system, driven by the Northeast Trade Winds (Martínez, Goddard, Kushnir, & Ting 2019) and the Caribbean Low-Level Jet (CLLJ) (Muñoz, Busalacchi, Nigam, & Ruiz-Barradas, 2008; Wang, 2007; Andrade & Barton, 2005).

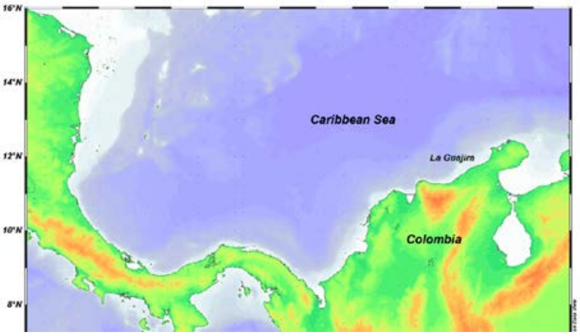

Figure 1. The department of La Guajira and its adjacent marine area

Additionally, it is influenced by the movement of the Intertropical Convergence Zone (ITCZ), which is responsible for precipitation in the area, ranging between 218 mm and 532 mm per year (Toro-Tobón, Alvarez-Flórez, Mariño-Blanco & Melgarejo, 2022). The sea surface temperature (SST) ranges from 20 °C to 30 °C, with an average of 25 °C (Rueda-Roa & Muller-Karger, 2013, Chollet *et al*., 2012). These attributes lead to an upwelling of organic matter that attracts a diversity of species such as fish, marine reptiles, and sharks (Andrade & Barton, 2005; Vásquez & Sullivan, 2021).

There are few studies in this area that address marine biodiversity or its relationship with climatology or oceanography, among which Muller-Karger (2023), Ayala, Gutiérrez, and Montoya (2022), Dorado-Roncancio, Medellín-Mora, Mancera-Pineda and Pizarro-Koch (2022), Invemar (Eds. 2010), Páramo *et al*., (2003) and Bernal *et al*., (2016) stand out, as it is a zone in which mainly social, cultural, and economic aspects are addressed (Bonet-Morón & Hahn-De-Castro, 2017; Colorado & Moreno, 2017).

In this sense, it is relevant to discuss not only social issues but also climatological and oceanographic topics in the area, as their variation over time could jeopardize indigenous populations and the associated biodiversity (Vásquez & Sullivan, 2021). Therefore, this study aimed to identify research trends in the maritime area of La Guajira through a bibliometric analysis, and based on this, determine the main environmental factors that modulate the oceanography of La Guajira and establish whether authors link it to aspects of biodiversity or not.

STUDY AREA

The region of La Guajira, in oceanographic and ecological terms, is characterized by the presence of a seasonal upwelling system with low productivity (Gómez & Acero, 2020). Consequently, there is high variability in oceanographic and atmospheric structure. Using satellite reflectances and standardized empirical orthogonal functions, Bastidas-Salamanca, Ricaurte, Santamaría del Ángel, Ordóñez, Murcia and Romero (2017) identified 9 oceanographic regions in the Colombian Caribbean with high variability in the annual cycle, one of which was named the La Guajira System. This system was described by Murcia, Ricaurte, Ordóñez and Bastidas-Salamanca (2017) as an area of high oceanographic dynamism, where the main fertilization mechanism is advection rather than Ekman transport. This advection varies depending on the dominant season, either through mesoscale eddies from the east transporting nutrients from the Gulf of Venezuela or from the west through continental discharges from the Magdalena River carried by the Caribbean counter-current.

The area is inhabited by different indigenous groups, including the Wayúu, Koguis and Arzarios, known for their culture and tradition, with a total population exceeding 1 000 000 inhabitants, according to the Chamber of Commerce of La Guajira (Cámara de Comercio de La Guajira, 2017). The economy is centered around the mining of salt, gas, and coal, as well as agriculture involving the cultivation of sesame, rice, sorghum, cotton, cassava, sugarcane, and tobacco. Additionally, there are some tourism activities. However, La Guajira is the third poorest department in Colombia, following Chocó and Vichada (Otero-Cortés, 2013).

METHODOLOGY

A search for scientific articles related to climatology and oceanography in La Guajira, Colombia was conducted. The search was performed using three databases available at Nueva Granada Military University: Scopus, ScienceDirect, and Web of Science (WoS). The information was obtained based on the search criterion of articles published in the last 20 years (2003 to 2021) related to the biodiversity, ecology, oceanography, and climatology of the region (Fig. 2).

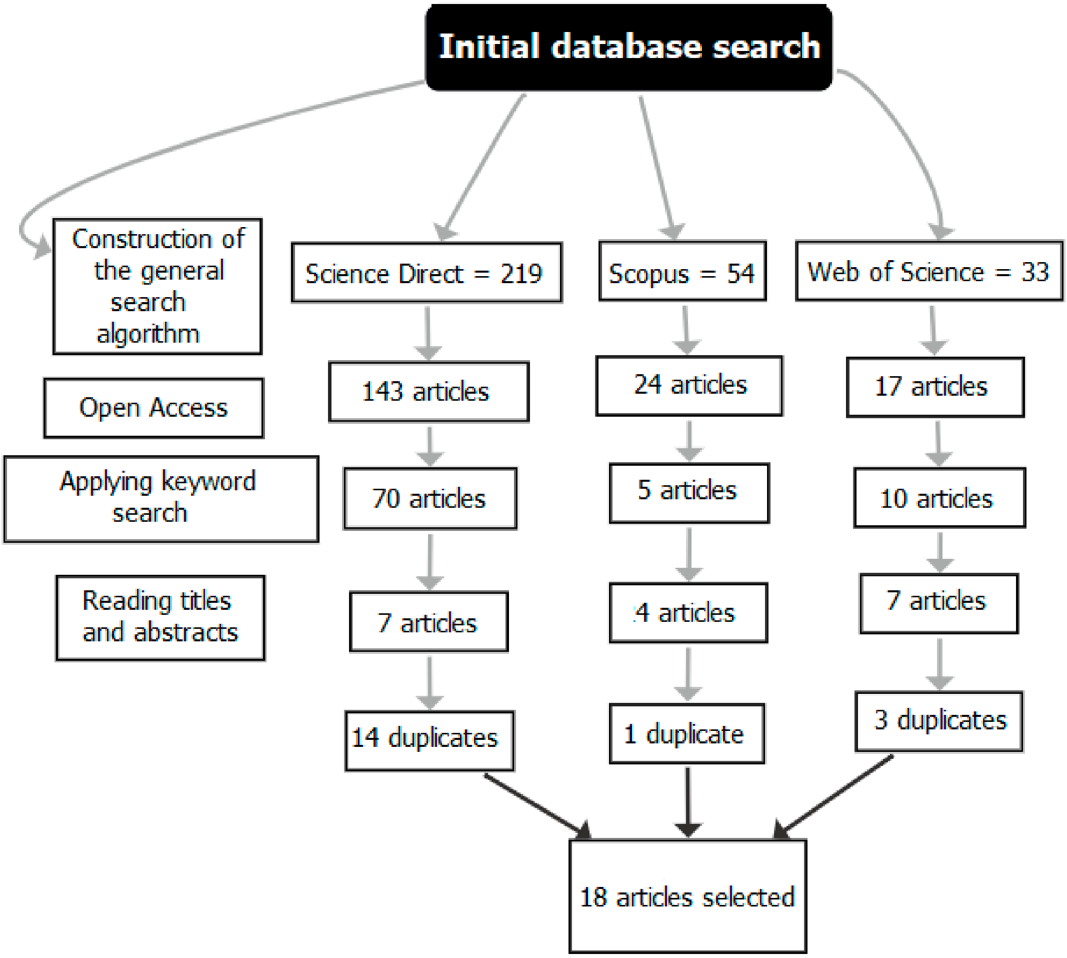

Figure 2. Flowchart of the filtering process applied to the documents found in the databases before the systematic review

The database search followed the following search algorithm: Caribbean Sea OR Guajira AND oceanographic, Guajira AND upwelling, Guajira AND Caribbean Jet, Guajira AND Climatology. The selection of documents was based on those that strictly met the search algorithm, and were available in English and Spanish. Duplicate documents in each database were not considered. Subsequently, a matrix was created with the selected articles, allowing for a comparison of publication years, databases, and topics addressed. Additionally, a bibliometric analysis of the selected articles in the Scopus database was conducted using the VOSviewer software, a freely available tool for analyzing and visualizing scientific literature through bibliometric networks.

RESULTS AND DISCUSSION

Bibliometric Analysis

The systematic search yielded a total of 306 publications related to climatological and oceanographic processes in the Colombian Caribbean and La Guajira. After applying the selection criteria, a total of 85 publications were obtained from the three selected databases. Finally, these publications were carefully reviewed to assess their relevance to the objective of this study, resulting in the selection of a total of 18 publications (Table 1).

Table 1. Selected articles after the filtering process

Author	Year	Title of the Publication	Data base
Alonso del Rosario, J. Vidal, J.; Blázquez, E.	2021	The Upwelling of the Colombian Caribbean Coasts: Remote Sensing, Morphology, and Influence on the Lake Maracaibo	Scopus
Torregroza-Espinosa, A. Restrepo, J.; Escobar, J. Pierini, J.; Newton, A.	2021	Spatial and temporal variability of temperature, salinity and chlorophyll-a in the Magdalena River mouth, Caribbean Sea	ScienceDirect
Orfila, A.; Urbano, C.; Sayol, J.; González-Montes, S. Cáceres-Euse, A.; Hernández, I.; Muñoz, A.	2021	On the Impact of the Caribbean Counter Current in the Guajira Upwelling System	WoS
Correa-Ramírez, M.; Rodríguez, A.; Ricaurte-Villota, C. Paramo, J.	2020	The Southern Caribbean upwelling system off Colombia: Water masses and mixing processes	Scopus
Alonso del Rosario, J; Vidal, L.; Blázquez, E.	2019	On the prediction of upwelling events at the colombian caribbean coasts from modis-SST imagery	Scopus
Montoya-Sanchez, R.; Devis-Morales, A.; Bernal, G.; Poveda, G.	2018	Seasonal and intraseasonal variability of active and quiescent upwelling events in the Guajira system, southern Caribbean Sea	ScienceDirect
Beier, E.; Bernal, G.; Ruiz-Ochoa, M.; Barton, E.	2017	Freshwater exchanges and surface salinity in the Colombian basin, Caribbean Sea	WoS
Bastidas-Salamanca, M.; Ordóñez-Zúñiga, A.; Ricaurte-Villota, C.	2016	Events of wind intensification and relaxation in the Bay of Santa Marta (Colombian Caribbean): Oceanographic implications	Scopus
Santos, F.; Gómez, M.; Varela, R.; Ruiz☐Ochoa, M.; Días, J.	2016	Influence of upwelling on SST trends in La Guajira system	WoS
Bernal, G.; Osorio, A.; Urrego, L.; Peláez, D.; Molina, E.; Zea, S.; Montoya, R.; Villegas, N.	2016	Occurrence of energetic extreme oceanic events in the Colombian Caribbean coasts and some approaches to assess their impact on ecosystems	ScienceDirect

Author	Year	Title of the Publication	Data base
Alonso del Rosario, J. Blázquez, E.; Isaza-Toro, E.; Vidal, J.	2015	Internal structure of the upwelling events at Punta Gallinas (Colombian Caribbean) from modis-sst imagery	ScienceDirect
Sarmiento-Devia, R.; Vásquez, Á.; Mejías, M. Dávila, P.; Franco-Herrera, A.	2014	Variabilidad intra-anual del régimen climático en sectores de surgencia en el sudeste del Mar Caribe, usando ERA Interim.	WoS
Jouanno, J.; Sheinbaum, J.	2013	Heat Balance and Eddies in the Caribbean Upwelling System	WoS
Ruiz-Ochoa, M.; Beier, E.; Bernal, G.; Barton, E.	2012	Sea surface temperature variability in the Colombian Basin, Caribbean Sea	ScienceDirect
Lonin, S.; Hernández, J. Palacios, D.	2010	Atmospheric events disrupting coastal upwelling in the southwestern Caribbean	WoS
Arévalo-Martínez, D. Franco-Herrera, A.	2008	Características oceanográficas de la surgencia frente a la ensenada de Gaira, departamento de Magdalena, época seca menor de 2006	ScienceDirect
Andrade, C.; Barton, E.	2005	The Guajira upwelling system	ScienceDirect
Páramo, J.; Quiñones, R.; Ramírez, A.; Wiff, R.	2003	Relationship between abundance of small pelagic fishes and environmental factors in the Colombian Caribbean Sea: an analysis based on hydroacoustic information	WoS

For the search conducted in the Scopus database, the bibliometric analysis included the representation of keyword co-occurrence in the VOSviewer program (Fig. 3).

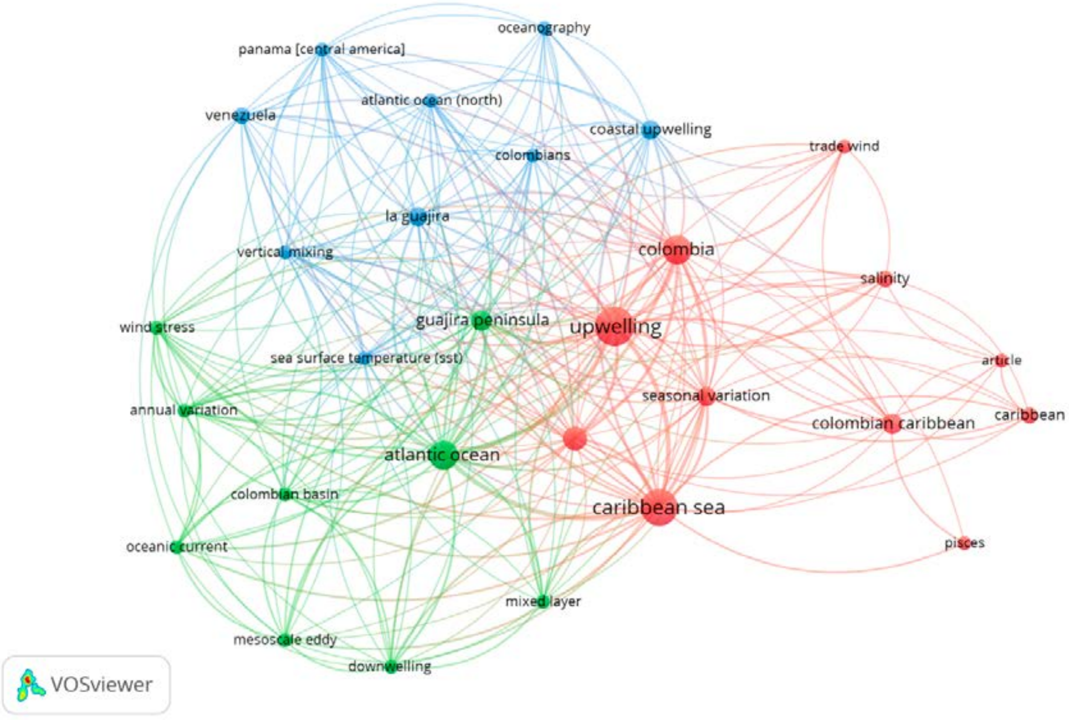

Figure 3. Keyword co-occurrence network, part of the bibliometric analysis of the results from Scopus

In this graph, the nodes (colored circles) represent the selected feature (keywords). The location and size of the nodes have meaning; for example, a larger-sized node represents a greater presence of that keyword, indicating that it has been more extensively researched than others among the articles found in the database. For this specific search, the largest nodes correspond to "upwelling," "Caribbean Sea," and "Colombia," which refer to the study area.

Additionally, three colors are identified in the figure (green, blue, and red). This color grouping is called a cluster and corresponds to a set of nodes that have been commonly investigated, representing large grouped themes that can be studied simultaneously. For the Scopus database, excluding words associated with geographical areas, the blue cluster encompasses themes of coastal upwelling, vertical mixing, and sea surface temperature; the green one includes wind stress, annual variation, circulation (eddies and currents), and the mixing layer, and the red one includes winds, salinity, seasonality, and fish. From this graphical analysis, it is possible to identify the predominance of studies in physical topics associated with oceanography and meteorology, and few or almost none associated with biological aspects, representing an initial indication of research opportunities.

It is important to note that the Scopus database includes scientific articles published in indexed journals and does not include gray literature (reports, theses, books, event proceedings), which may potentially contain research contributing to oceanographic, climatic, and biodiversity knowledge that is beyond the scope of this analysis.

Oceanographic Factors Modulating Biodiversity

La Guajira Upwelling Process

Upwelling is an oceanographic phenomenon where the interaction of coastal winds and currents causes the rise of deep waters, bringing nutrients from the ocean floor to the surface, where they are utilized by photosynthetic organisms. Therefore, this upwelling process of productivity favors different pelagic species (Andrade & Barton, 2005). This process generally occurs on the western edges of continents; however, there are specific conditions in certain other areas that allow this phenomenon to happen (Albuquerque *et al*., 2014).

In addition to its importance in maintaining the oceanic food web and, consequently, establishing areas of high biodiversity (Arévalo-Martínez & Franco-Herrera, 2008), on a large scale, it can even regulate local, regional, and global thermal balance (England *et al*., 2014; Jouanno & Sheinbaum, 2013). In the case of the La Guajira upwelling, it is driven by the Trade Winds, the CLLJ, and the Caribbean Current (Alonso del Rosario *et al*., 2019). The Caribbean upwelling system has been studied in two main areas: the western basin (La Guajira, Colombia) and the eastern one (Cariaco, Venezuela). Oceanographic behavior is different in the two areas, and sea surface temperature (SST) and salinity values vary notably (Montoya-Sánchez, Devis-Morales, Bernal & Poveda, 2018). Also, in both coastal upwelling zones, fish production is very uneven (Gómez & Acero, 2020).

Some authors consider that, compared to other coastal upwelling processes, La Guajira's is weak and has low productivity due to a mixing process occurring in the Panama-Colombia Gyre (Correa-Ramírez *et al*., 2020). There, the influence of the mouth of the Magdalena River causes dilution of the nutrient-rich Caribbean Sea by freshwater, leading to a reduction in salinity values and nutrient concentration, thereby contributing to the low productivity of this upwelling system (Beier *et al*., 2017). However, another author suggests that the upwelling process is strong thanks to the mouths of the Magdalena and Orinoco Rivers and the outlet of Lake Maracaibo. Additionally, there is an aeolian contribution of dust from the La Guajira desert, which also enriches the Caribbean waters (Andrade & Barton, 2005).

The upwelling in La Guajira is strong during the months of December to March and July, as these are the dry seasons and wind intensity is high. In the rainy season from October to November, the winds weaken, as does the upwelling (Andrade & Barton, 2005; Montoya-Sánchez *et al*., 2018). This aligns with Alonso del Rosario *et al*. (2019) and Alonso del Rosario *et al*. (2015), who consider that the upwelling in the zone is mainly coastal, not evident in the open sea, and strongly influenced by the ITCZ. When this is located to the south (December to April-May), the Trade Winds predominate, the CLLJ intensifies, and so does the upwelling. On the other hand, it weakens around June-August when the ITCZ is located to the north, and the rainy seasons occur.

Thus, it is determined that the Caribbean region is strongly influenced by the Trade Winds that induce the CLLJ, even though two upwelling episodes occur around the La Guajira Peninsula during the year. The first is the strongest and occurs from October-November to March-April. The second occurs between May and July, when the ITCZ is in the northern zone and is much weaker (Alonso del Rosario *et al*., 2021).

Temperature

Ruiz-Ochoa *et al*. (2012) found that the influence of the La Guajira upwelling was observed throughout the evaluated period (1985-2009) but was more intense between December and February. During this period, the temperature ranged between 25.5 °C and 29.5 °C, with no difference between La Niña and El Niño years. This aligns with Lonin *et al*. (2010), Bastidas-Salamanca *et al*. (2016) and Santos *et al*. (2016), who found that during the first three months of the year, SSTs fluctuate between 25 °C and 28 °C, associated with the upwelling process. In the weakened upwelling season, SSTs rise above 28 °C. However, Alonso del Rosario *et al*. (2019) found different values. These authors suggest that during upwelling processes, the temperature varies from 22 °C to 23 °C, and when upwelling weakens, the temperature fluctuates between 28 °C and 29 °C. This discrepancy may be associated with the studies being conducted in different years, during which the El Niño or La Niña phenomena occurred, which led to different values being measured.

Chlorophyll

Chlorophyll values are usually measured in the sea through satellite images from spectroradiometers. Chlorophyll is associated with higher primary productivity, indicating greater nutrient availability for the first links in the marine food chain (Roberts *et al*., 2017). For example, Orfila *et al*. (2021) found that between June and October, when the wind is weakened, chlorophyll values were close to 3 mg m^{-3}. However, Arévalo-Martínez and Franco-Herrera (2008) found that during the dry season when the winds are strong, the Caribbean waters have SSTs between 21 °C and 24 °C, salinity between 36.5 and 37.2, and chlorophyll values of 0.59 mg m^{-3}. Therefore, the months of higher productivity correspond to the rainy season, between June and October. In contrast, when the ITCZ is located to the north, chlorophyll concentrations decrease during April and May (Orfila *et al*., 2021).

The Colombian Caribbean is influenced by river discharge, causing variations in salinity, temperature, and chlorophyll values. Torregroza-Espinosa *et al*. (2021) found that at the mouth of the Magdalena River, salinity has values close to 28, the average temperature is 27.6 °C, and chlorophyll values are 1.5 mg m^{-3}. This aligns with the mixing processes described by Correa-Ramírez *et al*. (2020), which cause the oceanographic conditions in this area to be different compared to areas without river mouths, affecting upwelling processes.

Salinity

In the Panama-Colombia Gyre zone, freshwater dilution from rivers and runoff occurs throughout the year, causing salinity values to decrease (Torregroza-Espinosa *et al*., 2021). In contrast, to the north of La Guajira, salinity increases from December to May due to upwelling processes, as a result of which values can reach around 36.5 (Sarmiento-Devia *et al*., 2013). When the El Niño phenomenon is present, the increase in salinity values occurs in the dry season from December to February. In La Niña periods, when the rainy season begins (between September and November), dilution processes are elevated near the La Guajira coastal zone (Beier *et al*., 2017), and consequently, salinity decreases.

Biodiversity

Some authors mention the relationship between the oceanographic processes in the area of interest and the abundance and distribution of different species such as the Atlantic herring (Opisthonema oglinum), scaled sardine (Harengula jaguana), and round sardinella (Sardinella aurita). These species have a preference for certain salinity and temperature conditions that are favored by upwelling processes (Páramo *et al*., 2003). Some planktonic organisms usually leave the continental margin to develop in open sea areas, depending strictly on the upwelling processes occurring on the coasts to obtain food in their early life stages (Andrade & Barton, 2005). On the other hand, Bernal *et al*. (2016) mention the importance of understanding these oceanographic processes in relation to coastal ecosystems such as mangroves, reefs, and beaches, to understand how they behave and respond in the face of these processes.

Recently, Dorado-Roncancio *et al*. (2022) analyzed the distribution of copepods between 2013 and 2018, finding that it responds to local oceanographic patterns regulated by dissolved oxygen variability and temperature in the water column. Using data collected on a cruise in 2008, Lozano, Vidal, and Navas (2010) reported spatial differences in the Colombian Caribbean regarding the composition and percentage abundance of phytoplankton species. Meanwhile, Medellín and Martínez (2010), using data from the same cruise, described the distribution of mesozooplankton, indicating that the highest concentrations of biomass and abundance were found in the northeastern and southwestern zones of the Colombian Caribbean, and that they are related to upwellings and continental discharges, as well as the pattern of surface currents and cyclonic circulation events.

The conditions of the seafloor are also relevant to the biodiversity of the Colombian Caribbean. Regarding echinoderms, Benavides-Serrato and Borrero-Pérez (2010) identified a clear bathymetric distribution pattern, with four clusters of stations that could be explained by the structure of water masses, marine currents, and sediment type. For their part, Trujillo, Sosa, and Linero (2009) showed a weak effect of the size of the grains which make up the physical substrate on the spatial distribution of La Guajira's macrofauna.

Currently, there is a growing interest in the potential for renewable energy in the La Guajira area, both on the mainland and in the sea. Studies on wind resources have been conducted along the entire coastal zone of the Colombian Caribbean with high (Gil, Cañón, & Martínez, 2021) and low temporal resolution (Bastidas-Salamanca & Rueda-Bayona, 2021), and for specific locations such as La Guajira (Ochoa, Álvarez, & Chamorro, 2019). However, as mentioned by Garavito-Téllez (2020), these types of projects generate environmental impacts on the biotic environment, including connectivity loss or fragmentation, habitat loss, or collisions with structures, which require special attention from environmental authorities and will require, in the short term, specific studies on biodiversity.

CONCLUSIONS

Based on this review, it is evident that there is a comprehensive understanding of how the La Guajira upwelling system functions and behaves. The influence of this upwelling can be identified in terms of variations in salinity, temperature, and chlorophyll during the year. The upwelling is driven by the Trade Winds, the Caribbean Low-Level Jet (CLLJ), and the Caribbean Current. Additionally, it is influenced by the Intertropical Convergence Zone (ITCZ) and its position, which varies during the year in concert with the dry and wet seasons.

Various authors have been able to establish the values of key variables and how they change in the annual cycle using satellite images. The temperature during upwelling processes is cold, ranging between 25°C and 28°C; when upwelling weakens, sea surface temperatures (SST) increase to values above 28°C. Chlorophyll values are generally higher during upwelling processes but can also vary depending on whether it is the dry or wet season. Salinity values are high (36.5 to 37.2) but decrease in the wet season or in areas with river mouths due to the mixing and dilution process.

However, there is a gap in understanding regarding the upwelling and its impact on the biodiversity of the area and the ecosystems associated with it. While some articles briefly mention the importance of the upwelling process for marine diversity, it is crucial to recognize that climate and oceanography modulate how species are distributed. Moreover, many species associated with upwelling zones have high economic value, making it even more imperative to conduct research in this regard.

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