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PADRÕES METEOROLÓGICOS, DESASTRES NATURAIS COSTEIROS E DANOS: UMA ANÁLISE INTEGRADA PARA O ESTADO DE SANTA CATARINA

Karine Bastos Leal

Porto Alegre
Outubro, 2024

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Tese de doutorado submetida ao Programa de Pós-Graduação em Geografia da Universidade Federal do Rio Grande do Sul como pré-requisito para a obtenção do título de Doutora em Geografia.

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O presente trabalho em nível de doutorado foi avaliado e aprovado por banca examinadora composta pelos seguintes membros:

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Certificamos que esta é a **versão original e final** do trabalho de conclusão que foi julgado adequado para obtenção do título de Doutora em Geografia.

____
Prof. Dra. Lucimar de Fátima dos Santos Vieira
Coordenadora do Programa

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Prof. Dr. Luís Eduardo de Souza Robaina
Orientador

Porto Alegre, 2024.

Este trabalho é dedicado à minha avó, Neiva (*in memoriam*), e à minha mãe, Silvia.

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Esse trabalho é fruto da solitude de uma estudante que, em um quarto emprestado, elaborou, em grande parte, a sua tese de doutorado.
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Josué 1:9
Provérbios 16:3

RESUMO

Na zona costeira brasileira, os desastres naturais estão diretamente relacionados aos fenômenos oceânicos e atmosféricos e potencializados pela ação antrópica. Sabe-se ainda que, as mudanças climáticas estão intensificando os eventos extremos e somados à crescente ocupação, processos como inundações e erosão costeira se tornarão mais frequentes principalmente nas regiões sul e sudeste do Brasil. Diante dessa problemática, este trabalho se propôs a analisar de forma integrada o aumento do registro de desastres naturais costeiros, os danos decorrentes e os padrões meteorológicos associados em Santa Catarina. Na primeira etapa do estudo, realizou-se uma revisão de literatura sistematizada utilizando o banco de dados Scopus e uma análise bibliométrica. O objetivo foi compilar os trabalhos científicos existentes sobre desastres naturais costeiros causados pelas marés de tempestade no contexto das mudanças climáticas. Esta revisão identificou lacunas no estado da arte e estabeleceu a base teórica para as etapas subsequentes. Na segunda fase, foram identificadas e analisadas espacialmente as ocorrências de desastres naturais costeiros em Santa Catarina entre 1998 e 2020. Esta análise revelou os municípios, setores costeiros, anos, meses e estações em que ocorreram mais desastres e destacou a relação entre o crescimento populacional e o aumento nos registros desses eventos adversos. A terceira etapa teve como objetivo identificar os padrões meteorológicos associados aos desastres datados e analisar os danos humanos, materiais e ambientais decorrentes. Isso permitiu uma discussão integrada sobre os padrões meteorológicos predominantes no litoral catarinense, sua relação com os registros de desastres naturais costeiros e os consequentes danos. Por fim, este estudo contribui para a unificação de um banco de dados de desastres costeiros em Santa Catarina e discussão das inconsistências no preenchimento dos formulários oficiais de desastres pelos gestores, que condicionam a análise e os resultados deste trabalho. Além disso, sugere métodos para a previsão de desastres com base nos resultados obtidos, fornecendo suporte para a gestão de riscos costeiros e a implementação de medidas preventivas mais eficazes.

Palavras-chave: Crescimento populacional. Erosão costeira. Marés de tempestade. Subida do nível do mar. Ciclone.

ABSTRACT

In the Brazilian coastal zone, natural disasters are directly related to oceanic and atmospheric phenomena, exacerbated by anthropogenic activities. It is also known that climate change is intensifying extreme events, and when combined with increasing occupation, processes such as floods and coastal erosion will become more frequent, particularly in the southern and southeastern regions of Brazil. In light of this issue, this study aims to conduct an integrated analysis of the increase in recorded coastal natural disasters, the resulting damages, and the associated weather patterns in Santa Catarina. In the first phase of the study, a systematic literature review was conducted using the Scopus database, along with a bibliometric analysis. The objective was to compile existing scientific papers on coastal natural disasters caused by storm surges in the context of climate change. This review identified gaps in the state of the art and established the theoretical foundation for the subsequent phases. In the second phase, the occurrences of coastal natural disasters in Santa Catarina between 1998 and 2020 were identified and spatially analyzed. This analysis revealed the municipalities, coastal sectors, years, months, and seasons with the highest incidence of disasters, and highlighted the relationship between population growth and the increase in records of these adverse events. The third phase aimed to identify the weather patterns associated with the recorded disasters and analyze the resulting human, material, and environmental damages. This enabled an integrated discussion of the predominant weather patterns on the coast of Santa Catarina, their relationship with the records of coastal natural disasters, and the consequent damages. Finally, this study contributes to the unification of a coastal disaster database in Santa Catarina and discusses inconsistencies in the completion of official disaster forms by managers, which influence the analysis and results of this work. Moreover, it suggests methods for disaster forecasting based on the results obtained, thus providing support for coastal risk management and the implementation of more effective preventive measures.

Keywords: Population growth. Coastal erosion. Storm surge. Sea-level rise. Cyclone.

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AA	Análise de Agrupamento
AVADAN	Avaliação de Danos
BRL	Real Brasileiro
COBRADE	Classificação e Codificação Brasileira de Desastres
DCSC	Defesa Civil de Santa Catarina
ECP (SPC)	Estado de Calamidade Pública (*States of Public Calamity*)
FIDE	Formulário de Informações do Desastre
GMSL	*Global Mean Sea Level* (Nível Médio Global do Mar)
Hs	*Significant wave height* (Altura significativa de onda)
IPCC	*Intergovernmental Panel on Climate Change* (Painel Intergovernamental sobre Mudanças Climáticas)
PNGC	Plano Nacional de Gerenciamento Costeiro
NMGM	Nível Médio Global do Mar
S2ID	Sistema Integrado de Informações sobre Desastres (*Integrated Disaster Information System*)
SASH	*South Atlantic Subtropical High* (Alta Subtropical do Atlântico Sul)
SAt	*South Atlantic* (Atlântico Sul)
SC	Santa Catarina
SDG 13	*Sustainable Development Goal* 13 (Objetivo do Desenvolvimento Sustentável 13)
SE (EM)	Situação de Emergência (*Emergencies Situations*)
SIG	Sistema de Informações Geográficas
SNM	Subida do Nível do Mar
WP	*Weather Pattern* (Padrão Meteorológico)
ZC	Zona Costeira
ZCSC	Zona Costeira de Santa Catarina

SUMÁRIO

ESTRUTURA DA TESE

A estrutura da tese é norteada pelas perguntas de pesquisa, pela hipótese e pelos objetivos e, portanto, está organizada em sete capítulos. O embasamento metodológico e parte do referencial teórico estão apresentados separadamente em cada capítulo. O trabalho está organizado da seguinte forma:

PRIMEIRO E SEGUNDO CAPÍTULO: O primeiro capítulo apresenta o tema da tese e todas as questões que nortearam as próximas etapas da pesquisa. O segundo capítulo consiste no referencial teórico, o qual descreve o arcabouço teórico e conceitual que embasa a estrutura da tese. Primeiro desenvolveu-se a base conceitual, que destaca os importantes termos utilizados no decorrer do texto. Em seguida, estão apresentados três tópicos principais, são eles: A dinâmica da zona costeira; Desastres naturais costeiros; Sistema de Informações Geográficas (SIG) aplicado ao estudo de áreas costeiras; Análise de Agrupamento (AA) e Método K-Means. Esses dois primeiros capítulos introduzem o terceiro, quarto e quinto, julgados como os centrais da pesquisa, já que apresentam o desenvolvimento dos objetivos. Cabe salientar que o referencial teórico não se atém somente à esta etapa, o mesmo está dissolvido ao longo de todo o texto. Por fim, as referências bibliográficas referentes aos dois capítulos em questão estão elencadas ao final do segundo capítulo.

TERCEIRO CAPÍTULO: Apresenta a situação atual da informação produzida pela academia na ampla área de pesquisa. Foi realizada uma revisão sistemática da literatura, considerando o banco de dados Scopus, e uma análise bibliométrica. O intuito foi de compilar os trabalhos técnicos e científicos já realizados que consideram os desastres naturais costeiros de erosão e inundação causados pelas marés de tempestade no cenário das mudanças climáticas. A construção do artigo apresentado neste capítulo permitiu o entendimento sobre a relação dos três pontos destacados (desastres, marés de tempestade e mudanças climáticas). Além disso, apresentou lacunas sobre o tema e o atual estado da arte também produzida pelo Brasil nessa temática específica. O capítulo sustenta a revisão bibliográfica para os dois seguintes, o quarto e o quinto.

QUARTO CAPÍTULO: Teve como objetivo identificar, tabelar, mapear e discutir a ocorrência de desastres naturais costeiros e o crescimento populacional nos municípios expostos ao Oceano Atlântico, e pertencentes à zona costeira do estado de Santa Catarina, Brasil, entre os anos de

1998 e 2020. O capítulo apresenta três principais propósitos: unir, em um único banco de dados, todos os desastres naturais costeiros, datados por bases oficiais de dados, que ocorreram na série temporal; e mapear tais desastres. Além disso, é etapa fundamental para a realização do quinto capítulo desta tese. O material suplementar, que apresenta a tabela com a datação de todos os desastres naturais costeiros analisados pode ser acessado através deste link.

QUINTO CAPÍTULO: Apresenta os padrões meteorológicos associados aos desastres costeiros ocorridos em Santa Catarina. Inicialmente, estava prevista a utilização da base de dados com a datação dos desastres, conforme realizada no quarto capítulo. Contudo, atualizações, apresentadas neste capítulo, foram necessárias para assegurar maior confiabilidade das datas. Estão destacados os setores e municípios mais afetados por cada padrão meteorológico e os danos humanos, materiais e ambientais decorrentes de cada desastre, o que propiciou uma discussão sobre a necessidade do correto preenchimento dos formulários de registros de desastres. Este capítulo fornece produtos importantes para a previsão e, como consequência, prevenção dos desastres costeiros futuros no estado de Santa Catarina. O material suplementar, que apresenta a nova tabela com a datação de todos os desastres naturais costeiros ocorridos entre 1998 e 2020 pode ser acessado através deste link.

SEXTO CAPÍTULO: Este capítulo integra os capítulos anteriores e visa apresentar uma discussão abrangente sobre os desastres naturais costeiros ocorridos em Santa Catarina entre os anos de 1998 e 2020. Além disso, propõe métodos para a previsão desses desastres com base nos resultados desta tese, sugere direções para trabalhos futuros e apresenta as conclusões finais.

1 INTRODUÇÃO

As alterações na zona costeira (ZC) brasileira, que impactam tanto o ambiente como a sociedade, estão intrinsecamente ligadas aos fenômenos oceânicos e atmosféricos, sendo potencializadas pela ação antrópica. Os desastres naturais costeiros estão diretamente associados à degradação de áreas frágeis e são intensificados pela ocupação. Esse cenário conduz os pesquisadores a concluir que há uma relação estreita entre o avanço da degradação ambiental, a intensidade do impacto dos desastres e a crescente vulnerabilidade e exposição aos riscos (Herrmann, 2006; Santos, 2007; IPCC, 2022). A vulnerabilidade é entendida como o grau de insegurança intrínseca de um desastre frente a um evento adverso determinado (Castro, 2008).

As projeções para o aumento da temperatura média global indicam um aquecimento de aproximadamente 4,4º até 2100 no cenário mais crítico estabelecido pelo Painel Intergovernamental sobre Mudanças Climáticas (IPCC, 2023). Isso pode levar a uma aceleração do ciclo hidrológico e, consequentemente, intensificar os eventos extremos (Collins *et al*., 2013; Coco; Ciavola, 2017; Oppenheimer *et al*., 2019). Estima-se que, nesse cenário pessimista, o nível médio global do mar (NMGM) pode aumentar 2 metros até 2100 (IPCC, 2021). Como resultado, os sistemas costeiros enfrentarão cada vez mais desastres naturais ao longo do século 21 (Collins *et al*., 2013), com maiores impactos nos países subdesenvolvidos (Neumann *et al*., 2015). No Brasil, os desastres se tornarão mais frequentes e intensos e isso ocorrerá principalmente nas regiões sul e sudeste (Brasil, 2002; Santos, 2007; Short; Klein, 2016; Araújo *et al*., 2018). Dada a potencial magnitude da subida do nível do mar (SNM), a aplicação e o sucesso da adaptação são grandes incertezas que requerem maior avaliação e consideração (Nicholls; Cazenave, 2010).

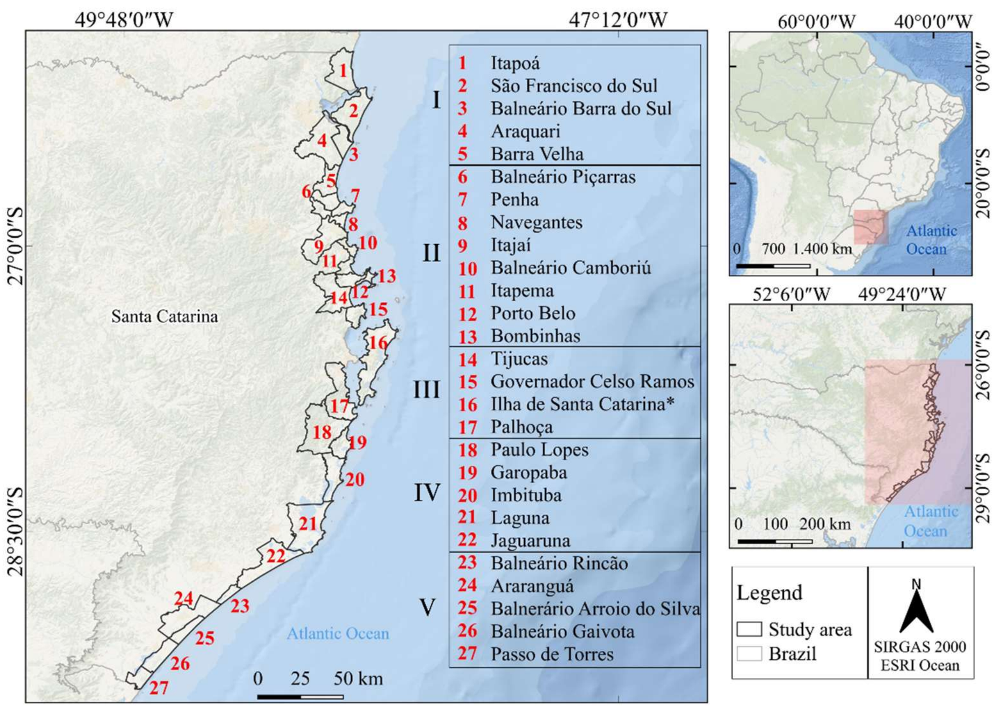
Diante desse cenário, durante as últimas décadas, o interesse nos estudos das zonas costeiras tem se intensificado, motivado pelos conflitos de interesses, uso de recursos naturais, poluição (Corraini *et al*., 2018; Canto *et al*., 2020), economia/turismo (Cristiano *et al*., 2018; Pegas; Castley; Queiroz-Neto, 2018). Além disso, devido ao aumento da ocorrência de eventos extremos atmosféricos e oceânicos (Oliveira *et al*., 2019; Gramcianinov *et al*., 2020; Leal *et al*., 2022) e do crescimento da população em áreas costeiras, que, em conjunto com os eventos extremos, desencadeiam os desastres naturais (Wisner *et al*., 2004; Leal *et al*., 2023).

Portanto, torna-se evidente a necessidade de pesquisas que identifiquem e discutam as possíveis causas do crescente registro de desastres naturais no litoral do Brasil (em particular, neste trabalho, o litoral de Santa Catarina), e apresentem produtos eficazes para a previsão e prevenção dos desastres frente às mudanças climáticas. Este estudo propõe uma análise integrada de três fatores que promovem alterações no setor costeiro de Santa Catarina, relacionando (a) o aumento do registro de desastres naturais costeiros (b) os danos decorrentes desses desastres e (c) os padrões climáticos associados a eles.

1.1 Área de estudo

Adotou-se como área de estudo o conjunto de municípios em contato com o Oceano Atlântico, que pertencem à zona costeira de Santa Catarina (ZCSC), localizada na Região Sul do Brasil (Figura 1-1), devido à sua grande representatividade aos aspectos associados à problemática apresentada. A ZCSC conta com 41 municípios, incluindo os 27 listados na Figura 1-1. A delimitação foi aprovada pela Portaria MMA nº 34, de 2 de fevereiro de 2021, determinada pelo Ministério do Meio Ambiente (MMA) (Brasil, 2021). O litoral de SC se estende de norte a sudoeste por aproximadamente 430 km, e contém 922 km de costa aberta e baias, com 246 praias arenosas ocupando 60% da costa (Klein; Short; Bonetti, 2016).

Figura 1-1 – Mapa da área de estudo



*Foi considerada apenas a Ilha de Santa Catarina, que pertence ao município de Florianópolis. Fonte: Elaboração própria com dados adaptados do Instituto Brasileiro de Geografia e Estatística (IBGE).

No estado, cerca de 1.983.440 (26,06%), do total de 7.610.361 habitantes, residem nos municípios estudados (IBGE, 2022). Essas áreas têm sido frequentemente afetadas por desastres naturais costeiros, especialmente ao longo da última década. O quarto capítulo desta tese aprofunda as discussões acerca da ocorrência dos desastres costeiros em SC. No quinto capítulo estão descritas as características climáticas, geológicas e geomorfológicas da área de estudo.

1.2 Perguntas de pesquisa

A pesquisa foi norteada pelas seguintes perguntas pesquisa:

a. Houve aumento nas publicações científicas que abordam a relação entre desastres naturais costeiros, marés de tempestade e mudanças climáticas? Quais são os trabalhos mais relevantes nessa área, e o Brasil está entre os países com maior número de publicações sobre essa relação?
b. Em quais setores e municípios do litoral de Santa Catarina ocorreram mais desastres naturais costeiros?
c. Qual é a relação entre o crescimento populacional e o aumento no registro de desastres naturais costeiros em Santa Catarina? Os municípios com maior crescimento populacional são os que registraram mais desastres?
d. Existem padrões meteorológicos associados aos desastres naturais costeiros no litoral de Santa Catarina?
e. É possível prever quais municípios serão afetados por cada padrão meteorológico?
f. Quais são os danos decorrentes de cada desastre natural costeiro?
g. É possível indicar qual padrão meteorológico contabiliza os maiores danos humanos, materiais e ambientais?

1.3 Hipótese

Para responder às perguntas, será testada a seguinte hipótese:

Os desastres naturais costeiros registrados em Santa Catarina são condicionados duplamente por padrões meteorológicos e pela crescente ocupação humana no litoral.

1.4 Objetivos

1.4.1 Objetivo Geral

Analisar de forma integrada o registro de desastres naturais costeiros, os danos decorrentes e os padrões meteorológicos associados em Santa Catarina.

1.4.2 Objetivos Específicos

a. Compreender o estado da arte e a relação entre os desastres naturais costeiros, as marés de tempestade, e as mudanças climáticas através da análise da produção bibliográfica.
b. Identificar espacialmente e temporalmente os registros de desastres naturais costeiros que ocorreram nos municípios da área de estudo entre 1998 e 2020.
c. Compreender como o crescimento populacional se relaciona com o aumento do registro de desastres naturais costeiros na área de estudo.
d. Identificar padrões meteorológicos associados aos desastres naturais costeiros.
e. Apresentar os danos humanos, materiais e ambientais decorrentes dos desastres naturais costeiros identificados.

O Quadro 1-1 apresenta uma síntese das perguntas de pesquisa, os seus objetivos específicos e o capítulo da tese em que serão respondidas.

Quadro 1-1 – Descrição de apoio ao estudo

Objetivo geral		
Analisar de forma integrada o registro de desastres naturais costeiros, os danos decorrentes e os padrões meteorológicos associados em Santa Catarina.		
Perguntas de pesquisa	**Objetivos Específicos**	**Capítulos**
Houve aumento nas publicações científicas que abordam a relação entre desastres naturais costeiros, marés de tempestade e mudanças climáticas? Quais são os trabalhos mais relevantes nessa área, e o Brasil está entre os países com maior número de publicações sobre essa relação?	Compreender o estado da arte e a relação entre os desastres naturais costeiros, as marés de tempestade, e as mudanças climáticas através da análise da produção bibliográfica.	Terceiro Capítulo
Em quais setores e municípios do litoral de Santa Catarina ocorreram mais desastres naturais costeiros?	Identificar espacialmente e temporalmente os registros de desastres naturais costeiros que	Quarto Capítulo

Qual é a relação entre o crescimento populacional e o aumento no registro de desastres naturais costeiros em Santa Catarina? Os municípios com maior crescimento populacional são os que registraram mais desastres?	ocorreram nos municípios da área de estudo entre 1998 e 2020. Compreender como o crescimento populacional se relaciona com o aumento do registro de desastres naturais costeiros na área de estudo.	
Existem padrões meteorológicos associados aos desastres naturais costeiros no litoral de Santa Catarina? É possível prever quais municípios serão afetados por cada padrão meteorológico?	Identificar padrões meteorológicos associados aos desastres naturais costeiros.	Quinto Capítulo
Quais são os danos decorrentes de cada desastre natural costeiro? É possível indicar qual padrão meteorológico contabiliza os maiores danos humanos, materiais e ambientais?	Apresentar os danos humanos, materiais e ambientais decorrentes dos desastres naturais costeiros identificados.	

Fonte: Própria do trabalho.

1.5 Justificativa

A ZCSC é impactada, entre outros fatores, pela crescente população, pela ocorrência de desastres naturais costeiros e pelas marés de tempestade. Esse estudo se justifica pela necessidade de identificar as causas do crescente registro desses desastres e de propor produtos eficazes para a previsão e prevenção, além de fornecer subsídios para medidas de mitigação do problema. Para isso, propõe-se analisar a relação entre os desastres naturais costeiros, os devidos danos humanos, materiais e ambientais e os padrões meteorológicos associados aos desastres.

O trabalho se propõe a preencher a lacuna de conhecimento sobre as características oceânicas e atmosféricas relacionadas aos desastres registrados em cada município, o que permitirá previsões mais precisas dos fatores desencadeantes e condicionantes dos desastres. Isso fornecerá aos gestores costeiros ferramentas de apoio à gestão do risco costeiro, que são importantes para a previsão e prevenção dos desastres nos municípios maior ocorrência de desastres costeiros. Além disso, este estudo unifica a base de dados dos desastres costeiros que ocorreram entre 1998, ano do primeiro registro de desastre costeiro em base oficial de dados no Brasil, e 2020, e destaca a importância do preenchimento correto dos documentos de registro de desastres, que contabilizam os danos. Reconhecer a relevância desse preenchimento é crucial para entender quais áreas são mais propensas a danos, o que permite uma prevenção mais eficaz dos desastres.

Esta pesquisa está alinhada com os Objetivos de Desenvolvimento Sustentável 11 (ODS 11) e 13 (ODS 13) da Agenda 2030 da Organização das Nações Unidas (ONU). O ODS 11 prevê cidades e comunidades sustentáveis, visando a redução significativa do número de mortes e de pessoas afetadas por catástrofes e substancialmente diminuir as perdas econômicas diretas causadas por elas. O ODS 13 enfatiza a necessidade de criar mecanismos de estudo e planejamento que considerem os efeitos das mudanças climáticas. Visa reforçar a capacidade de adaptação às mudanças climáticas através da formulação de políticas públicas eficazes e ações de planejamento estratégicas (ONU Brasil, 2015).

A relevância desta pesquisa é sustentada, também, por duas importantes contribuições. Santos (2007) destaca que entender as respostas do ambiente às ações antrópicas que desencadeiam desastres é fundamental para perceber que qualquer intervenção humana deve ser precedida por estudos de impacto cautelosos e planejamentos adaptados a cada realidade. Além disso, é crucial prever medidas que minimizem os efeitos negativos dessas ações. Robaina e Oliveira (2013) argumentam que os pesquisadores devem contribuir para a compreensão dos desastres naturais por meio de monitoramento e diagnóstico, e que essas informações devem ser comunicadas à sociedade para apoiar o desenvolvimento de medidas mitigadoras.

Por fim, uma pesquisa realizada no Sistema Integrado de Informações sobre Desastres (S2ID) revela que Santa Catarina é o estado com o maior número de registros de desastres naturais costeiros entre 1978 e 2022 (S2ID, 2024). Apesar das inconsistências na base de dados do sistema, discutidas no quinto capítulo desta tese, a importância do estado no histórico de ocorrências de desastres costeiros e no reconhecimento de áreas de risco é inegável. Estudos anteriores mostram que SC apresenta uma ZC cada vez mais degradada (Andrade; Scherer, 2014). Diante disso, alerta-se para a necessidade de estudos que abordem essa temática.

2 REFERENCIAL TEÓRICO

Neste capítulo apresenta-se o quadro conceitual (2.1 Base conceitual) utilizado neste trabalho. Adicionalmente, para melhor compreensão dos processos que interferem na ZC, são apresentados os seguintes tópicos: 2.2 A dinâmica da zona costeira; 2.2.1 Ocupação urbana na zona costeira de Santa Catarina; 2.3 Desastres naturais costeiros; 2.3.1 Tempestades costeiras e marés de tempestade. Por fim, propõe-se uma descrição da utilização das geotecnologias para tratamento de dados espaciais como instrumentos de apoio aos estudos costeiros (2.3 Sistema de Informações Geográficas (SIG) aplicado ao estudo de áreas costeiras) e de técnicas e métodos de agrupamentos de dados (2.5 Análise de Agrupamento (AA) e Método K-Means).

2.1 Base conceitual

Desastre natural costeiro: desastre é o resultado de eventos adversos (ocorrências desfavoráveis, que trazem prejuízos), naturais ou provocados pelo homem sobre um cenário vulnerável, causando grave perturbação ao funcionamento de uma comunidade ou sociedade envolvendo extensivas perdas e danos humanos, materiais e ambientais, que excede a sua capacidade de lidar com o problema usando meios próprios. Os desastres naturais são aqueles provocados por fenômenos e desequilíbrios da natureza e produzidos por fatores de origem externa que atuam independentemente da ação humana (Castro, 1998). Em contrapartida, Coppola (2011) argumenta que não existem desastres naturais, uma vez que, para ser considerado desastre é necessária a interação da sociedade e seu ambiente construído. De acordo com o Dicionário Michaelis, o termo “costeiro” refere-se à costa, que se define como a região litorânea próxima ao mar. Portanto, entende-se por desastre natural costeiro o resultado de eventos adversos causados por desequilíbrios da natureza e pela ação humana, capazes de provocar perdas e danos humanos, materiais e ambientais na faixa litorânea.

Ocupação urbana costeira: considera áreas com residências, calçadões, casas de veraneio, quiosques, e outras edificações (Araújo *et al.*, 2007).

Meteoceanográfico: trata das condições atmosféricas e oceânicas e sua interrelação (Lima; Lins de Barros; Cirano, 2021).

Padrão meteorológico (*Weather pattern*): condições sinóticas agrupadas com base em suas características em comum (Laviola-da-Silva, 2024).

Ciclone extratropical[1]: ciclone refere-se aos sistemas de tempo com rotação associada às áreas de baixa pressão na superfície (Petterssen, 1956). O termo extratropical relaciona-se com os ciclones formados nos extratrópicos (Reboita *et al*., 2017). Então, entende-se ciclone extratropical como um centro de baixa pressão atmosférica gerado fora da área delimitada pelos trópicos.

Maré de tempestade (*storm surge*): resulta da sobreelevação do nível do mar causada por forçantes atmosféricas, especialmente pelo arraste do vento na superfície do mar e pela variação da pressão atmosférica na superfície, associadas às tempestades (Carter, 1988; Flather, 2001; Melo Filho, 2017). Pode durar de poucas horas a até 2 a 3 dias e tem grande escala espacial comparada à profundidade (Flather, 2001). Como consequência, pode quebrar diques, causar inundações, destruir construções e erodir as costas (Pullen *et al*., 2007; Staneva *et al*. 2016). Assim como na tese de Melo Filho (2017), esta pesquisa se propõem a utilizar o termo "maré", na definição de maré de tempestade, para identificar flutuações de nível do mar, não necessariamente relacionadas às forças de origem astronômica. Além disso, cabe destacar que "maré de tempestade" é a tradução de "*storm surge"* (termo em inglês), como proposto por autores como Rudorff *et al*. (2014), Melo Filho (2017) e Leal, Bonetti e Pereira (2020). Ainda, pode ser considerado sinônimo de "ressaca" de acordo com o COBRADE (2012).

2.2 A dinâmica da zona costeira

A ZC, considerada como patrimônio nacional pela Constituição Brasileira de 1988, é determinada pelo espaço geográfico de interação do ar, do mar e da terra, incluindo seus recursos renováveis ou não, abrangendo uma faixa marítima e outra terrestre. Foi definida primeiramente pelo Plano Nacional de Gerenciamento Costeiro (PNGC) (Brasil, 1988, 1997) e regulamentada pelo Decreto 5.300/2004 (Brasil, 2004).

A ZC é de grande importância na prestação de diversos serviços ecossistêmicos (Barragán, 2014; Scherer; Asmus, 2016) como, por exemplo, regulação climática, suporte à biodiversidade, recursos alimentares e filtragem de purificação da água. É o ecossistema mais produtivo do planeta, onde as principais cidades estão localizadas (Cabrera; Lee, 2022). No entanto, também é sensível e vulnerável às mudanças ambientais devido à elevada concentração populacional e às interações entre a terra e o oceano. A constante interação de fenômenos provenientes dos compartimentos atmosférico, terrestre e marinho faz dessa área uma dinâmica

[1] Este e outros tipos de ciclones foram amplamente descritos por Reboita *et al*. (2017).

única (Araújo *et al*., 2018). Ela é responsável por uma ampla gama de funções ecológicas, tais como a prevenção de inundações, da intrusão salina, da erosão costeira, a proteção contra tempestades (Brasil, 2002) e serve como filtro, que remove poluentes e outros materiais derivados da terra antes de entrar no oceano (Ferreira, Marques; Seixas, 2017).

Além disso, a ZC possui grandes valores sociais, econômicos e ambientais. São mais densamente povoadas que o interior, concentrando ativos econômicos significativos, infraestruturas críticas e atividades humanas. Suas características físicas, atrativo paisagístico e rica biodiversidade marinha e terrestre propiciam um leque de possibilidades de uso e ocupação, destacando-se atividades econômicas, de transporte, residenciais e recreacionais, sendo lar de recursos marinhos vivos e ecossistemas altamente produtivos (Melet *et al*., 2020). Com isso, grande parte dos investimentos, das infraestruturas e do fluxo econômico preponderante dos países convergem para esses locais (Dalinghaus *et al*., 2018).

De acordo com Williams *et al*. (2021) cerca de 74% da população mundial vive a menos de 50 km do litoral, e estudos revelam que há uma tendência permanente ao aumento da concentração demográfica nessas áreas (Brasil, 1997; Gruber *et al*., 2011; IPCC, 2014). Além de serem áreas mais densamente povoadas em relação ao interior, apresentam taxas mais elevadas de crescimento populacional e urbanização (Neumann *et al*., 2015). Esse aumento se torna um problema, visto que atividades e intervenções antrópicas geram conflitos e pressões, que acabam por comprometer a capacidade de suporte dessas áreas, bem como seu equilíbrio ambiental (Barragán, 2014).

No Brasil, a ZC se estende, na sua porção terrestre, por mais de 8.698 km sobre uma área de aproximadamente 388.000 km². Abrange uma parte terrestre com 17 estados e 440 municípios, distribuídos do norte equatorial ao sul temperado do país (Brasil, 2021). Além disso, contempla uma área marinha, que corresponde ao mar territorial brasileiro, com largura de 12 milhas náuticas a partir da linha de baixa-mar do litoral continental e insular (Brasil, 1993).

No litoral do país, o turismo, o comércio e outras atividades relacionadas às praias e a outros ambientes costeiros são o suporte econômico de um número progressivo de comunidades, o qual tem ocasionado uma ocupação acelerada da costa sem os cuidados necessários (Albuquerque, 2013). Este padrão de ocupação acelerada, é resultado de uma demanda crescente por casas de veraneio, inexistência de licenciamento ambiental e fragilidade do poder público em aplicar a legislação que protege os ambientes naturais. Dessa forma, esses fatores se tornam preponderantes para a perda dos remanescentes dos ecossistemas costeiros nativos (Cohenca; Scherer; Vieira, 2017), que protegem a costa.

Sabe-se que a presença humana torna o ambiente propício à ocorrência de desastres, eventos adversos que não ocorreriam na ausência de ocupações antrópicas (Robaina, 2013). Neste sentido, as construções dentro da faixa de resposta da dinâmica costeira aos fatores meteorológicos, colocam as ocupações em áreas propensas à ocorrência de desastres (Dalinghaus, 2018). Como esperado, os problemas relacionados a esse fenômeno concentram-se em áreas onde a urbanização se situa junto à linha de costa, substituindo ambientes naturais, que em muitos casos são as dunas originais (Klein; Short; Bonetti, 2016) e áreas de restinga. Além disso, nos locais onde o desenvolvimento urbano não é planejado, os ambientes costeiros vizinhos, que são vulneráveis como as baias, estuários, recifes de coral e manguezais, podem ser degradados e fragmentados (Barragán; de Andrés, 2016).

As ocupações em áreas impróprias têm contribuído e até acelerado processos erosivos, desencadeadores de desastres, ao longo da costa (Wisner *et al*., 2004). Mattedi e Butzke (2001) e Robaina e Oliveira (2013) discutem que, apesar da ocupação urbana ocorrer em áreas irregulares, as pessoas costumam atribuir os desastres somente às forças da natureza e não à forma da própria ocupação do espaço. Em suma, a ocupação de áreas com maior suscetibilidade natural e o uso impróprio dos recursos naturais estão entre os principais fatores que potencializam a ocorrência de desastres na ZC do Brasil (Santos, 2007). A ocupação das áreas susceptíveis aos processos da dinâmica da natureza é pautada em fatores econômicos, políticos, sociais e culturais. Neste sentido, é preciso desconstruir a ideia de que o desastre é desencadeado somente pelos fenômenos da natureza, sendo a sociedade apenas o agente afetado (Robaina; Oliveira, 2013).

O processo de ocupação irregular vem ocasionando intensas alterações espaciais ao longo dos anos e está, sobretudo, alterando a vida da população e ampliando a degradação dos ambientes (Carmo, 2023). A omissão do poder público na efetivação das políticas de conservação contribui para que a ocupação ocorra em áreas inadequadas (Foleto; Silva, 2013). Para agravar, a velocidade da ocupação urbana, muitas vezes de forma irregular, é significativamente maior que a implementação de ações de contenção (Robaina, 2013).

Perante este contexto, é necessário planejar a ocupação do espaço, avaliar a existência de áreas a serem protegidas da ocupação humana em função de suas características físicas e naturais (Foleto; Silva, 2013). A alta concentração de cidades e população urbana no litoral define esta unidade como uma área em que os processos de gestão costeira devem estar intimamente relacionados com o desenvolvimento urbano e o desenvolvimento de atividades econômicas (Andrés; Barragán; Scherer, 2018). Além disso, torna-se importante compreender as interações entre os aspectos meteorológicos e as zonas costeiras para construir uma visão estratégica, de modo que medidas possam ser tomadas em resposta a novos cenários de aumento do nível do mar e de desastres costeiros (Nicolodi; Petermann, 2011).

2.2.1 Ocupação urbana na zona costeira de Santa Catarina

A conformação do espaço geográfico resulta da organização social em um processo híbrido de ideias e ações ao longo do tempo (Santos, 2006). O processo social que se refere tanto ao crescimento físico dos artefatos geográficos em suas diferentes configurações quanto às mudanças nas relações comportamentais e sociais desenvolvidas no interior das cidades e das aglomerações urbanas resulta na urbanização (Clark, 1982).

A primeira porção ocupada pelos colonizadores no Brasil foi o litoral. A intensidade, o modelo e a dinâmica espacial de ocupação dos diferentes trechos litorâneos dependeram de conjunturas naturais, geográficas, econômicas e de políticas públicas, que variaram significativamente no tempo e no espaço (Moraes, 2007). O oceano e a zona costeira constituem espaços fundamentais de desenvolvimento econômico e social, e sua exploração exige cuidados e atenção às questões ambientais. No caso brasileiro, os números evidenciam sua importância. Em Santa Catarina, o percentual de habitantes vivendo a menos de 150 km de distância do oceano chega a aproximadamente 75,4% (IBGE, 2022)

O litoral catarinense[2] é um dos mais urbanizados no Brasil (Andrés; Barragán; Scherer, 2018) e isso é resultado de um processo histórico que remonta ao período colonial. No século XVIII, por exemplo, a Ilha de Santa Catarina e áreas próximas já eram vistas como estratégica pelos colonizadores portugueses. Com a construção de fortes e de um porto, a ilha tornou-se um importante ponto de comércio, o que impulsionou o crescimento urbano. Com o passar do tempo, a urbanização se expandiu para outras áreas do litoral, como Itajaí e Balneário Camboriú, que se desenvolveram como importantes centros econômicos (Honório; Rocha, 2020).

A partir da década de 1950, o Brasil experimentou um processo acelerado de industrialização, levando indústrias de diversos setores a se estabelecerem em áreas próximas aos portos. No caso de SC, o desenvolvimento de áreas urbanas foi reforçado, também, nessa década com a construção de uma rodovia ao longo da costa (BR-101), para uma melhor comunicação entre os municípios litorâneos de Santa Catarina e outros estados costeiros brasileiros (Scherer *et al*., 2006).

[2] A descrição mais detalhada da formação sócio-espacial da zona costeira de Santa Catarina pode ser encontrada em Honório e Rocha (2020).

A urbanização do litoral de SC, no entanto, também foi impulsionada por fatores mais recentes, como o turismo e a especulação imobiliária. Almeida e Medeiros (2023) comentam que a partir da década de 1960 o turismo se tornou um dos principais motores da economia catarinense e do litoral em especial. Com isso, houve uma crescente demanda por áreas urbanizadas e infraestrutura turística, o que impulsionou a expansão urbana nas regiões costeiras. Além disso, a especulação imobiliária também teve um papel importante na urbanização do litoral, com investidores comprando terrenos em áreas consideradas de potencial turístico e construindo empreendimentos imobiliários (Pereira, 2011).

Klein *et al*. (2006, 2009) destacam que o uso intenso de áreas da costa para o desenvolvimento urbano e turístico em SC se intensificou ainda mais na década de 1970 e resultou em extensas áreas de perda de *habitat*, incluindo setores de degradação costeira. A instalação de empreendimentos na linha de costa impactou os ecossistemas costeiros de diferentes formas como a supressão de vegetação, poluição, esgotos, erosão e consequentemente a qualidade de vida da população humana e de seu futuro (Silva, 2010).

A ZCSC é uma das áreas mais afetadas pela ocupação humana, apresentando um alto grau de urbanização e atividades econômicas voltadas para o turismo e a pesca. Essa pressão antrópica tem causado um desequilíbrio ambiental e a degradação da ZC. As consequências da expansão urbana refletem-se num aumento da superfície ocupada pelas cidades e centros urbanos, e num crescimento da população urbana e suas atividades econômicas (Andrés; Barragán; Scherer, 2018).

A urbanização das ZC pode apresentar carências no saneamento básico, problemas ambientais, aumento de construções irregulares, favelização e outros problemas (Strohaecker *et al.,* 2006). Fernandes (2012) aponta fatores como causas da degradação ambiental costeira, por exemplo, a especulação imobiliária, loteamentos irregulares, turismo predatório e assentamentos clandestinos. Novaes (2012) sugere que a expansão das segundas residências no litoral, aliada à atividade turística intensificou a ocupação da ZC.

A rápida urbanização resultou em impactos significativos, incluindo problemas ambientais como a erosão costeira (Leal *et al*., 2023) e o assoreamento dos rios (La Corte, 2001). Além de contribuir para a perda de áreas naturais e biodiversidade, aumentar a demanda por recursos naturais, como água e energia, e gerar uma série de conflitos de uso do solo, como a ocupação de áreas de preservação permanente (Scherer *et al*., 2006).

No setor norte do litoral de SC, de acordo com Ferreira e Osako (2021), os municípios de São Francisco do Sul e Itapoá apresentaram um aumento de 3,36% na urbanização entre 1991 e 2019. De modo geral, São Francisco do Sul tem experimentado um desenvolvimento urbano intenso desde 1991, impulsionado principalmente pelo avanço do setor imobiliário residencial e comercial, bem como pela evolução do porto e de suas instalações. Em Itapoá, essa urbanização foi impulsionada principalmente pela instalação do porto. Silveira *et al*. (2019) e Leal *et al*. (2023) mostram que nesse município, parte da urbanização e das estruturas rígidas estão expostas ao mar sem proteção natural.

Originalmente, os municípios do setor sul eram recobertos por restingas formadas sobre campos eólicos de dunas móveis e fixas, banhados e lagoas costeiras (Cordazzo; Seeliger, 1995). Nas últimas décadas, esses ecossistemas têm sido ameaçados pela expansão da ocupação humana, que rapidamente os converte em outros tipos de uso da terra, apesar de grande parte desses ambientes serem protegidos pela legislação ambiental como Área de Preservação Permanente (Cohenca; Scherer; Vieira, 2017). Entretanto, Leal *et al*. (2023) apresentam uma análise comparativa entre o setor norte e sul, revelando que o setor sul de Santa Catarina possui um nível notavelmente elevado de proteção natural, ao contrário do setor norte. As praias nessa região geralmente são classificadas como praias protegidas por dunas, restingas e ambientes naturalmente resilientes, que de forma eficaz mitigam a erosão e as inundações (Bulhões, 2020).

A urbanização da ZCSC representa um desafio para a gestão costeira e para a busca de soluções para a mitigação dos impactos ambientais. Os principais desafios para minimizar essa tendência estão relacionados ao planejamento do uso do espaço costeiro e marinho, especialmente na regulação e monitoramento das atividades econômicas industriais, portuárias, de veraneio e turismo, de exploração de recursos naturais e de desenvolvimento urbano (Asmus; Kitzmann; Laydner, 2004). Nesse contexto, a gestão costeira integrada tem sido discutida como uma estratégia para lidar com os impactos da ocupação costeira. Essa gestão deve considerar a integração dos aspectos ambientais, sociais e econômicos, além de ser baseada em um planejamento participativo e em uma visão de longo prazo (Scherer; Asmus; Gandra, 2018).

Contudo, a implementação de políticas de gestão costeira integrada ainda enfrenta desafios. A falta de capacidade técnica e financeira dos municípios costeiros para implementar as medidas eficazes é um obstáculo importante. Além disso, a falta de integração entre as diferentes esferas de governo, articulação entre estados costeiros e a falta de envolvimento da sociedade civil também são apontadas como barreiras para uma gestão mais efetiva da ZC. É importante que as políticas públicas estejam alinhadas com a realidade local e que haja um esforço conjunto entre governos e sociedade para alcançar um desenvolvimento sustentável da ZCSC (Polette, 2009; Scherer; Asmus; Gandra, 2018; Horovitz, 2019).

Uma significativa contribuição feita por de Andrés, Barragán e Scherer (2018) propõem o Sistema Costeiro Catarinense (SC/CS), que somaria uma superfície de 28.277 km², representando 30% da área do estado e abrangendo 111 municípios. Em contraste, na atual delimitação são 8.871 km² com 38 municípios incluídos no PNGC. A inclusão de outros centros urbanos e atividades econômicas mais distantes do atual limite da Zona Costeira é importante para a delimitação do litoral como sistema. Isso se deve à sua repercussão nos ecossistemas costeiros e marinhos.

2.3 Desastres naturais costeiros

A nível mundial, o aumento dos desastres[3] relacionados às inundações e à erosão, devido às mudanças climáticas, está entre as maiores ameaças a que sistemas costeiros e áreas baixas estão sujeitos (IPCC, 2022; CEPAL, 2018). Essas áreas cada vez mais experimentarão impactos, dado que o aumento do nível médio do mar tornará os eventos extremos mais frequentes (IPCC, 2021). Alguns sistemas serão capazes de se adaptar, no sentido de recuar para o interior para acomodar mudanças no nível do mar. No entanto, outros irão experimentar o chamado *stress* costeiro, que ocorre quando uma costa em erosão se aproxima de estruturas rígidas e imóveis, tais como paredões, falésias ou construções (Jackson; Mcilvenny, 2011), representando risco para a sociedade, para a economia e para os ecossistemas (IPCC, 2014). Para um pior cenário, essas condições adversas, desencadeadora dos desastres, tem resultado em maiores impactos nos países em desenvolvimento (Neumann *et al*., 2015).

Apesar da nomenclatura "desastre natural" utilizada pelo COBRADE, Alcántara-Ayala (2002) considera que os desastres são induzidos pela ação humana. Complementando essa visão, Robaina (2013) argumenta que o aumento da frequência e intensidade dos desastres não pode ser atribuído exclusivamente ao incremento da magnitude e constância de eventos naturais adversos, mas, em grande parte, à ocupação extensiva do espaço geográfico sem considerar as dinâmicas naturais locais.

No Brasil, anualmente, verifica-se um incremento no número de desastres naturais em virtude da ocupação desordenada do território pela omissão do poder público na execução de uma política ambiental para redução da ocorrência de novas catástrofes (Herrmann *et al*., 2014). Fica evidente em situações de desastres, principalmente no caso brasileiro, a inexistência de ações estruturadas que antecedam o evento perigoso, no sentido de diminuir a vulnerabilidade. As estratégias de gestão devem ampliar a capacidade da comunidade para transformar as

[3] O quarto e quinto capítulo desta tese exploram mais profundamente o tema.

condições perigosas e reduzir a vulnerabilidade, para além da mera recuperação pós desastre (Robaina; Oliveira, 2013).

No sul do Brasil, as causas de desastres de erosão costeira são atribuídas a fatores naturais e antrópicos. Aos fatores naturais, são reconhecidos os fenômenos atmosféricos de escala sinótica, como os ciclones e anticiclones, que de forma separada ou conjunta podem resultar em tempestades costeiras intensas, ventos fortes, ondas altas e marés de tempestade[4] (Rocha *et al*., 2004; Bitencourt *et al*., 2011; Gramcianinov *et al*., 2020). Em relação aos fatores antrópicos, os desastres são relacionados, principalmente, à urbanização da orla, destruição de dunas frontais e instalação de estruturas rígidas (diques, quebra-mares, entre outros) paralelas ou transversais ao litoral (Souza *et al.*, 2005).

Bulhões (2020) descreve que a erosão costeira pode ser considerada como a resultante na paisagem da deficiência no balanço sedimentar em determinado segmento da linha de costa, durante determinado intervalo de tempo. O balanço sedimentar determina as perdas e ganhos da praia. Deve ser entendido como a diferença, em volume, entre o suprimento e a supressão de materiais sedimentares em determinado segmento costeiro, também em um intervalo de tempo definido. Quando o balanço for negativo, ou seja, quando houver mais perda do que ganho de sedimentos, a praia é determinada em estado de erosão, logo, quando o balanço for positivo, está em acresção (Souza *et al.*, 2005). Muehe (2005) sugere que a urbanização, quando avança sobre as praias, imobiliza faixas ainda incorporadas no processo morfodinâmico, determinando esses processos erosivos.

Conforme a Classificação e Codificação Brasileira de Desastres (COBRADE, 2012), os desastres naturais costeiros são categorizados de acordo com suas causas atmosféricas, oceânicas e de ocupação do solo. A classificação organiza os desastres por grupos, subgrupos, tipos e subtipos (Quadro 2-1).

Quadro 2-1 – Classificação e Codificação Brasileira de Desastres.

Grupo	**Subgrupo**	**Tipo -- Subtipo**	**Descrição**
Geológico	Erosão	Erosão costeira/marinha	Processo de desgaste (mecânico ou químico) que ocorre ao longo da linha da costa (rochosa ou praia) e se deve à ação das ondas, correntes marinhas e marés.
	Terremoto	Tsunami	Série de ondas geradas por deslocamento de um grande volume de água causado geralmente por terremotos, erupções vulcânicas ou movimentos de massa.

[4] A definição está apresentada no próximo tópico “2.3.1 Tempestades costeiras e marés de tempestade”.

Meteorológico	Sistemas de grande escala/escala regional	Ciclones -- Ventos Costeiros (Mobilidade de Dunas)	Intensificação dos ventos nas regiões litorâneas, movimentando dunas de areia sobre construções na orla.
		Ciclones -- Marés de Tempestade (Ressacas)	São ondas violentas que geram uma maior agitação do mar próximo à praia. Ocorrem quando rajadas fortes de vento fazem subir o nível do oceano em mar aberto e essa intensificação das correntes marítimas carrega uma enorme quantidade de água em direção ao litoral. Em consequência, as praias inundam, as ondas se tornam maiores e a orla pode ser devastada, alagando ruas e destruindo edificações.

Fonte: Adaptado de COBRADE (2012).

Os desastres relacionados às Inundações Litorâneas podem ser definidos de acordo com Castro (2003) como a brusca invasão do mar, normalmente caracterizadas como desastres secundários, podendo ser provocadas por vendavais e tempestades costeiras, ciclones tropicais, trombas d'água, tsunamis e ressacas muito intensificadas.

Numerosos estudos têm documentado os impactos dos desastres costeiros no Brasil (Brasil, 2018), principalmente na Região Nordeste (Paula *et al*., 2021; Leisner *et al*., 2023), Região Sudeste (Muehe *et al*., 2018) e Região Sul do país (Leal, *et al*. 2023). Ademais, pesquisadores e profissionais têm discutido e apresentado ferramentas e estratégias para a previsão, prevenção e mitigação desses desastres (Brasil, 2022; Martins; Bulhões; Gomes, 2022; Lins-de-Barros *et al*., 2023). A contribuição feita por Bulhões (2020), por exemplo, descreve diferentes obras de contenção aos desastres naturais costeiros utilizadas e afirma que,

> "na maioria dos casos tais obras são dimensionadas para conter as consequências da erosão e não propriamente suas causas, ou seja, a erosão não é realmente o problema atacado, e sim os seus impactos negativos para o homem (ex. perda de infraestrutura pública ou privada). Neste sentido, e apesar dos esforços, a erosão costeira continua a ser uma ameaça permanente. Em áreas costeiras expostas, as estratégias estruturais tradicionais de combate à erosão costeira levam a impactos negativos cumulativos que incluem perdas no transporte e estoque de sedimentos e supressão de habitat" (Bulhões, 2020, p. 660).

2.3.1 Tempestades costeiras e marés de tempestade

Mais de 80% dos tipos de desastres naturais que ocorrem no planeta tem sua gênese derivada dos fenômenos e processos climáticos (Herrmann *et al*., 2014). Além das pressões antrópicas, diariamente as zonas costeiras estão sujeitas a processos naturais, exercidos por forçantes meteoceanográficas. A ação desses agentes tem grande capacidade de causar mudanças significativas na paisagem litorânea, principalmente em situações extremas e em áreas com ocupações próximas ao mar (Araújo *et al.*, 2018). De acordo com Foleto e Silva (2013) os eventos extremos têm ocorrido ao longo do tempo, determinando prejuízos econômicos significativos, deixando milhares de desabrigados e, sobretudo, vítimas fatais. Contudo, embora em alguns casos inevitáveis, esses eventos são previsíveis.

Nesse contexto, observa-se o maior interesse na quantificação do aumento de tempestades costeiras em um cenário de mudança climática global e na determinação da ligação com as variações nos sistemas atmosféricos e oceânicos (Ruggiero *et al.*, 2010; Izaguirre *et al.*, 2011; Sénéchal; Castelle; Bryan, 2017). Entende-se por tempestades costeiras

> "as perturbações metorológicas que impactam as condições marítimas locais (ou seja, ondas e/ou nível da água) que tem o potencial de alterar significativamente a morfologia subjacente e expor o *backshore* às ondas, correntes e/ou inundações. São ocasionadas em condições ciclônicas e se forem associadas a ventos fortes podem gerar tempestade severa. Nesses casos, em praias naturais (sem intervenção humana) ocorrerá o processo de recuperação e num período maior do que a duração da tempestade. Por outro lado, em alguns casos, a praia pode se adaptar às condições extremas de alta energia" (Harley, 2017).

Como produto das tempestades costeiras, podem ocorrer as marés de tempestade (Carter, 1988; Flather, 2001; Rudorff, 2014; Melo Filho, 2017). Essas sobre-elevações do mar podem se agravar devido a uma combinação de fatores. Se houver um vento relativamente forte soprando em direção à costa que produza uma sobre-elevação de nível, ele pode eventualmente se superpor a algum episódio de maré meteorológica[5] pré-existente e a uma maré astronômica de sizígia (que ocorre nas fases da lua cheia e lua nova). Isso resultaria em um evento extremo de sobre-elevação de nível de curta duração (escala de horas), que se assemelharia quase a uma maré de tempestade causada por um furacão (Melo Filho, 2017). Harley (2017) acrescenta ainda que, quando relacionadas, principalmente, aos ciclones (em menor grau aos extratropicais) podem causar consequências catastróficas para costas baixas (ou submergentes). Sabe-se ainda que, o grau de impacto de uma maré de tempestade resultante de tempestade costeira dependerá da interação entre os fatores meteorológicos (velocidade do vento, pressão e velocidade do avanço do ciclone) e o cenário costeiro em qual ocorre, dependendo das características ambientais, sociais e econômicas de cada setor costeiro (Harley, 2017; Bonetti *et al.*, 2013).

[5] Definida amplamente por Melo Filho (2017).

No sul do Brasil, as adversidades atmosféricas têm afetado significativamente o estado de Santa Catarina ao longo de sua história. Esses eventos adversos, que podem contribuir para a ocorrência desastres naturais, estão relacionados com diferentes padrões atmosféricos[6] (Marcelino *et al*., 2014). Em geral, na Região Sul do Brasil, os desastres naturais costeiros associados às marés de tempestade ocorrem, principalmente, durante a passagem de sistemas atmosféricos intensos como as frentes polares atlânticas e os ciclones extratropicais (Bitencourt et al., 2011; Campos *et al*., 2018). Além disso, podem se tornar ainda mais intensos quando a tempestade costeira ocorre em condições de maré de sizígia (Rudorff *et al*. 2014; Leal; Bonetti; Pereira, 2020).

Como exemplo, a tempestade costeira de maio de 2001 foi responsável pela ocorrência de 11 registros de marés de tempestade com danos severos no estado de Santa Catarina. Esse episódio esteve relacionado à ocorrência de um ciclone extratropical muito intenso em condição de maré de sizígia entre os dias 5 e 8 de maio (Herrmann *et al*., 2007). Já em 2004 ocorreu o Furacão Catarina com ventos que atingiram velocidade de 180 km/h. O Furacão iniciou como um ciclone extratropical, a aproximadamente 1000 km da costa brasileira, passou pela fase subtropical e se tornou tropical, gradualmente adquirindo características de um furacão, atingindo as costas catarinense e gaúcha com ventos extremamente severos (Marcelino *et al*., 2005).

2.4 Sistema de Informações Geográficas (SIG) aplicado ao estudo de áreas costeiras

"Quase tudo que acontece, acontece em algum lugar. Saber o local onde algo acontece pode ser fundamental", assim Longley *et al*. (2013, p. 4) introduz sobre a importância e a utilidade de um Sistema de Informações Geográficas (SIG). As novas tecnologias de tratamento de dados espaciais digitais (computação gráfica, sensoriamento remoto, geoprocessamento, entre outras) tornaram-se instrumentos indispensáveis ao planejamento e monitoramento à medida que possibilitam, além da espacialização da informação, maior acessibilidade, precisão e velocidade na obtenção e processamento dos dados necessários às análises (da Silva; Zaidan, 2007; Grabski *et al*., 2015).

A estrutura de um SIG é constituída por um *hardware*, um *software*, dados, procedimentos e usuários (Longley *et al*., 2013). Diante disso, as suas funções dependerão do objetivo do estudo e das necessidades do usuário. Em geral, podem ser destacadas a aquisição

[6] Os padrões estão apresentados no quinto capítulo desta tese.

e edição de dados, o gerenciamento de um banco de dados espacial, a análise geográfica de dados e a representação de desses por meio de produtos cartográficos (Fitz, 2008).

Para alguns os SIGs são um meio de automatizar a produção cartográfica, para outros pode servir como apoio à resolução de problemas geográficos e apoio à decisão espacial. Para além disso, um SIG tem o potencial de gerar mecanismos para a análise de dados e revelar novas perspectivas. Esse tipo de sistema pode manter inventários complexos, permitindo controlar e gerenciar recursos espacialmente distribuídos (Longley *et al*., 2013). Como resultado, acabam sendo integrados na organização e armazenamentos de dados relativos às análises e levantamentos ambientais, por apresentarem uma estrutura de banco de dados que propicia uma organização de forma bastante robusta e segura, além de permitir as consultas e a atualização nos dados de forma rápida e fácil. Atualmente, a grande disponibilidade de *software* de SIG, principalmente não comercial, permite que estas ferramentas sejam utilizadas para o mapeamento ambiental. Destaca-se, no âmbito internacional, o *software* QGIS desenvolvido e disponibilizado pela *Open Source Geospatial Foundation* (OSGeo) (Trentin; Bazzan, 2013).

Sabe-se que o uso de SIG para a mitigação de desastres tem aumentado desde a última década (Mohanty *et al*., 2019). Segundo Câmara *et al*. (2001), na perspectiva moderna de gestão do território, toda ação de planejamento, ordenamento ou monitoramento do espaço deve incluir a análise dos diferentes componentes do meio ambiente e o inter-relacionamento destes. Nesse contexto, o uso do geoprocessamento e de suas ferramentas estão se destacando.

No cenário das zonas costeiras, as diversas funcionalidades disponíveis nos SIGs subsidiam o monitoramento e a gestão das áreas por meio da integração, tratamento, armazenamento, manipulação e transformação das informações espaciais, que permitem a geração de diferentes produtos cartográficos (Grabski *et al.,* 2015). Os SIGs permitem o analista (usuário) controlar eventos e, para além disso, identificar onde esses eventos acontecem. Através do cruzamento de informações, o SIG auxilia no planejamento urbano, na definição de políticas públicas e intervenções antrópicas que favoreçam a melhoria da qualidade de vida das populações (Trentin; Bazzan, 2013).

Em particular para a integração dos dados em estudos costeiros, os SIG apresentam, pelo menos, três requisitos essenciais: a eficiência (pela facilidade de acesso e manipulação de grandes volumes de dados), a integridade (pelo controle de acessos por múltiplos usuários) e a persistência (pela manutenção de dados por longo tempo) (Santos, 2004). A análise espacial do território urbano tem contribuído para nortear a tomada de decisões no que diz respeito à gestão do uso e ocupação do solo urbano e à consequente intervenção no espaço na definição de políticas públicas que regulem o uso e ocupação desses espaços (Nascimento; Lima; Santos, 2009).

Theilen-Willige e Wenzel (2019) afirmam que, como se espera que as consequências e os efeitos das mudanças climáticas tenham um impacto crescente na intensidade e na ocorrência de riscos geográficos, como inundações repentinas, o monitoramento sistemático e contínuo desses riscos e áreas afetadas é essencial. Isso pode ser feito utilizando dados integrados em um banco de dados de SIG, o que é uma questão importante para a preparação de perigos e avaliação de riscos. Os autores destacam como alguns métodos utilizados em SIG podem contribuir para a detecção e o monitoramento contínuo e padronizado de riscos geológicos no oeste da Arábia Saudita. Por exemplo, por meio da delimitação de áreas costeiras do Mar Vermelho propensas a inundações de tsunami e marés de tempestade. Para complementar, recentemente autores como Sahoo e Bhaskaran (2018), Leal, Bonetti e Pereira (2020), Pazini *et al*. (2022) e Leal *et al*. (2023) utilizaram métodos e ferramentas em SIG para apresentar problemas ambientais costeiros, como risco, vulnerabilidade e erosão.

2.5 Análise de Agrupamento e Método K-Means

As estatísticas multivariadas, particularmente a análise de agrupamento, permitem identificar similaridades e dissimilaridades em um conjunto de dados ao organizar os elementos em grupos que são internamente homogêneos e externamente heterogêneos. Isso significa que há baixa variação dentro dos grupos e alta variação entre os grupos. A Análise de Agrupamento (AA), também conhecida como clusterização, busca encontrar uma estrutura de agrupamento natural no conjunto de dados, agrupando elementos com base em uma medida pré-definida (Wilks, 2006).

A análise de agrupamento é amplamente utilizada em diversas áreas, como biologia e geografia, para segmentar populações, identificar padrões, e classificar dados complexos. Métodos como K-Means (de Souza *et al*., 2022; Laviola-da-Silva, 2024), hierárquico (Viana, 2014) e DBSCAN (Chefrour, 2022) são comumente empregados, cada um com suas particularidades e adequações dependendo do tipo de dados e do objetivo do estudo. A escolha da medida de similaridade ou dissimilaridade, como a distância euclidiana ou a correlação, é crucial para o sucesso da clusterização e deve ser adequada à natureza dos dados analisados (Mingoti, 2005).

O algoritmo de agrupamento K-Means[7] foi inicialmente proposto por MacQueen *et al*. (1967) e posteriormente aprimorado por Hartigan e Wong (1979). O método particiona um conjunto de dados em K grupos (*clusters*), em que cada ponto de dados pertence ao *cluster* com o centroide mais próximo. A escolha de K (número de *clusters*), é um passo crítico no processo, pois determina a granularidade do agrupamento. Uma abordagem comum para selecionar K, além da possibilidade de ser definido pelo analista, é o método do cotovelo (*Elbow Method* - Thorndike, 1953).

O método do cotovelo é uma abordagem gráfica utilizada para determinar o número ideal de clusters (K) no algoritmo K-Means. Esse método envolve a execução do algoritmo K-Means para diferentes valores de K (por exemplo, K=1, 2, ..., 10) e a subsequente plotagem da soma das distâncias quadráticas dentro dos clusters (inércia) em função de K. A inércia, ou *Sum of Squared Errors* (SSE), é calculada como a soma das distâncias quadráticas entre os pontos de dados e seus centróides. Após calcular a inércia para cada valor de K, esses valores são apresentados em um gráfico com o número de *clusters* K no eixo x e a inércia no eixo y. O ponto onde a inércia começa a diminuir a uma taxa mais lenta indica o "cotovelo", sugerindo o número ideal de *clusters*. Este método ajuda a identificar um equilíbrio entre a redução da inércia e a complexidade do modelo, evitando a escolha de um número excessivo de *clusters* que não proporciona uma melhoria significativa na inércia (Thorndike, 1953).

A utilização de técnicas de *Machine Learning*, como o K-Means, permite a investigação de padrões e variabilidade na circulação atmosférica (Laviola-da-Silva, 2024). A AA é reconhecida como uma ferramenta estatística utilizada para agrupar regiões climatologicamente homogêneas, com base em parâmetros meteorológicos ou períodos, visto que o resultado serão grupos que refletem a similaridade interna e heterogeneidade externa das variáveis (Gong; Richman, 1995).

[7] A utilização do método K-Means está descrita no quinto capítulo desta tese.

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3 COASTAL IMPACTS OF STORM SURGES ON A CHANGING CLIMATE: A GLOBAL BIBLIOMETRIC ANALYSIS

LEAL, K. B.; ROBAINA, L. E. de S.; DE LIMA, A. de S. Coastal impacts of storm surges on a changing climate: a global bibliometric analysis. **Natural Hazards**, v. 114, p. 1455-1476, 2022. https://doi.org/10.1007/s11069-022-05432-6

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Abstract
An increase in the global mean sea level is predicted during the 21st century, as a consequence of global average rising temperature projections. In addition, changes in the strength of atmospheric cyclonic storms may alter the development of storm surges, exacerbating the risks to coastal communities. Based on the fact that the interest and range of papers on this topic are growing, this study aims to present the status of the global scientific production on studies that have correlated climate change and the impact of storm surges on the coastal zone leading to erosion and flooding (inundation) via a bibliometric analysis. We analyzed 429 papers published in journals between January 1991 and February 2021 from the Scopus database. Through the VOSviewer and Bibliometrix R package, we describe the most relevant countries, affiliations, journals, authors, and keywords. Our results demonstrate that there has been an exponential growth in the research topic and that authors from the United States and the United Kingdom are the most prolific. Among the 1,454 authors found, 10 researchers published at least five papers on the topic and obtained at least 453 citations in the period. The most represented journals were the Journal of Coastal Research, Climatic Change, and Natural Hazards. We also found and discuss the lack of standardization in the choice of keywords, of which climate change, storm surge, and sea level rise are the most frequent. Finally, we have written a guide to facilitate the authors' bibliographic review.

Keywords: Scientific production. Climate change. Storm surge. Coastal erosion. Coastal flooding. Sea level rise.

3.1 Introduction

Global predictions project an increase of 4ºC to 6ºC in the global average temperature by 2100 on the most extreme greenhouse gas representative concentration pathway (Collins et al. 2013). This may lead to an acceleration of the hydrological cycle, which consequently increases the intensity and frequency of extreme events, such as coastal storms and storm surges (Coco and Ciavola 2017; Oppenheimer et al. 2019). In this extreme scenario (RCP8.5), it is estimated that the global mean sea level (GMSL) may increase by approximately 1.10 m in the

21st century (Oppenheimer et al. 2019). A recent study conducted by Nicholls et al. (2021) shows that, in the last two decades, the GMSL has increased 2.5 mm yr^{-1} and that the impact in subsiding coastal areas is four times faster with an average relative sea-level rise varying from 7.8 mm to 9.9 mm yr^{-1}. Therefore, as a result, coastal systems will increasingly flood and experience erosion during the 21st century if measures are not taken to adapt or mitigate sea-level rise and extreme events (Nicholls 2002; Nicholls and Cazenave 2010; Wong et al. 2014; Oppenheimer et al. 2019; Nicholls et al. 2021).

A fundamental aspect of coastal storms that distinguishes them from other extreme events is their genetic process, which is driven by atmospheric disturbances over the open ocean. Tropical cyclones and extratropical cyclones are the main synoptic systems responsible for the vast majority of coastal storms worldwide. Depending on several factors, related to both the cyclonic system as well as the coastal setting in which it occurs, these systems may also generate storm surges (Harley 2017). Storm surges refer to an abnormal rise in seawater level caused by low atmospheric pressure and the force exerted on the sea surface by strong winds. By definition, it is measured as the height of the water above the normal predicted astronomical tide (Lowe and Gregory 2005; Harley 2017; NOAA 2021).

During a changing climate, changes in the number, path, and strength of atmospheric cyclonic storms may alter the formation and development of storm surges (Lowe and Gregory 2005). The amplitude and impact at any given location depend on the intensity, size, and speed of the storm, coastline orientation, and local topobathymetric characteristics (Lowe and Gregory 2005; Resio and Westerink 2008; De Lima et al. 2020; Leal et al. 2020; NOAA 2021). Furthermore, hazards and disasters associated with this abnormal rise in seawater level are highly correlated with storm frequency and characteristics (Harley 2017; Lin et al. 2019). Severe coastal flooding usually occurs when wind-induced waves and storm surges coincide with high tides (Resio and Westerink 2008; Kumbier et al. 2017; Chen et al. 2021). In addition, these storms are the main driver of coastal flooding, and are responsible for extensive coastal erosion (Resio and Westerink 2008; Leal et al. 2020). Their impacts can be different and more destructive on densely urbanized coasts, in terms of human and economic losses (Neumann et al. 2015). Although the impacts of sea-level rise and, consequently, storm surges, are potentially strong, the application and success of adaptation are large uncertainties that require more assessment and consideration (Nicholls and Cazenave 2010). Therefore, the scientific community's interest in studies on these impacts and possible adaptations to climate change is growing.

We see a bibliometric analysis as an important tool that can facilitate and expand the capacity of researchers in a given subject. For instance, in some cases, the bibliographic review process can take a long time, since it is essential to select relevant papers for the scientific community; thus the results of the bibliometric study can be a quick solution. In addition to the accelerated production, control, and dissemination of information, the development of computer programs for bibliometrics and the creation of databases facilitates the gathering of data in the same place, streamlining information processing and access to new papers. Furthermore, the synthesis of past research findings is one of the most important tasks in advancing a particular research line. Quantitative analysis for given scientific research, through bibliometric studies, determines the scientific knowledge derived from publications and represents the current research trends, through which the direction of science and related institutions is defined. Besides, bibliometrics can connect published papers, authors, or journals; identify research substreams; and produce published research maps (Davyt and Velho 2000; Zupic and Čater 2015).

Therefore, this study aims to present the status of the global scientific production on studies that have correlated climate change and the impact of storm surges on the coastal zone that lead to erosion and flooding (inundation). Through a bibliometric analysis, we resolve the following fundamental topics: 1) the most relevant countries, affiliations, authors, and journals; 2) the most cited papers; 3) direct scientists to the research area in their bibliographic reviews. To the best of our knowledge, the present study combines, for the first time, climate change and coastal impacts of storm surges to conduct a bibliometric analysis.

3.2 Approach and methodology

The combination between systematic literature review and bibliometric analysis provides a rigorous and formal methodical procedure, which seeks to minimize bias and possible errors when selecting studies to characterize an area of knowledge (Denyer and Tranfield 2009; Zupic and Čater 2015; Keathley-Herring et al. 2016; Carrión-Mero et al. 2020). The methodology for the bibliographic review and bibliometric analysis was adapted from Zupic and Čater (2015). It has been used by several studies from different research areas (Barnes et al. 2019; Ji et al. 2019; Fan et al. 2020; Lima and Bonetti 2020; Feng and Cui 2021; Majeed and Ainin 2021; Maldonado-Erazo et al. 2021). Four main steps were followed to address the research objective (Fig. 3-1).

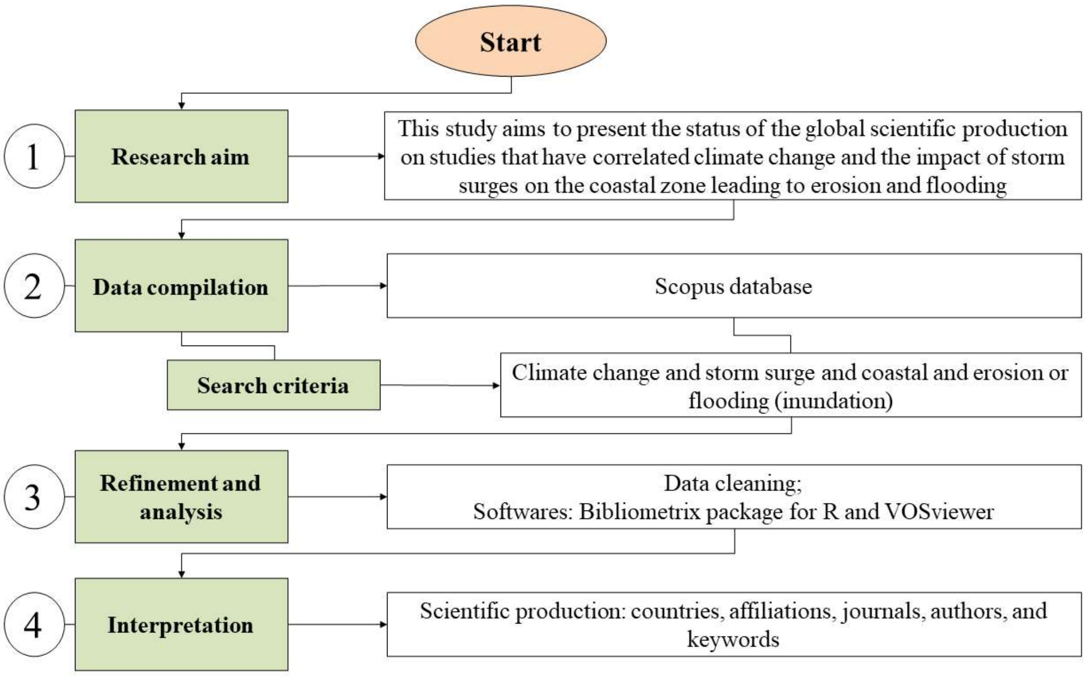

Fig. 3-1 – Main steps of the research process. Adapted from Zupic and Čater (2015)

In the first step, researchers must define their research objective (Zupic and Čater 2015). The main purpose of the bibliometric analysis was to present the status of the global scientific production on studies that have correlated climate change and the impact of storm surges on the coastal zone leading to erosion and flooding (inundation), as well as direct scientists to the research area in their bibliographic reviews.

A bibliographic database was selected and compiled during the second step. First of all, considering the three main databases (Google Scholar, Web of Science, and Scopus), we found out that Scopus is the most relevant database, indexing 25,751 journal titles, and it also has the largest number of publications related to the topic, outperforming the other databases. We found 326, 384, and 486 papers written in English and published in journals between January 1991 and February 2021 in Google Scholar, Web of Science, and Scopus databases, respectively. Therefore, the review was based on the Scopus database. According to Lima and Bonetti

(2020), the selection of a single database is the actual best alternative to performing a bibliometric analysis, although it must be highlighted that it will never cover all the existing information, and limits will always exist on using this approach.

It is necessary to clarify that the present study has only considered papers that have correlated climate change and the impact of storm surges on the coastal zone that leads to erosion and flooding (inundation). Studies that did not consider such disasters (i.e., erosion and flooding) were not included in this paper. Four criteria were defined for choosing the terms to be included in the systematic review: 1) the study area should be impacted by *storm surge* and *flooding (inundation)* or *erosion*; 2) the area must be located along a *coastal* zone; 3) the impact must be associated with *climate change*; 4) papers with biological bias were disregarded. Thus, the query expression applied to the *Advanced paper search* in the Scopus database was:
(TITLE-ABS-KEY ("climat* chang*") AND TITLE-ABS-KEY (coast*) AND TITLE-ABS-KEY (erosion OR flood* OR inundation)) AND TITLE-ABS-KEY ("storm surge*") AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SRCTYPE , "j"))

The terms were searched in the *titles, abstracts*, and *keywords* (TITLE-ABS-KEY) of each indexed paper. We selected only *papers* (LIMIT-TO (DOCTYPE, "ar")) published in *journals* (LIMIT-TO (SRCTYPE, "j")) and written in *English* (LIMIT-TO (LANGUAGE, "English"). Periods (dates) were not determined. Thus, the search has considered all papers in the historical series until February 2021. In the same step, all abstracts were read, using the *Show all abstracts* option. The intention was to select only the papers of interest, based on the four pre-established criteria. Finally, the file with selected papers was exported in two extensions, *.csv* e *.bib*, which are automatically recognized by the bibliometric analysis software.

The third step consisted of data refinement (that is, data cleaning) and analysis. Based on the studies already carried out (Lima and Bonetti 2020; Majeed and Ainin 2021), we opted for a more robust analysis with results generated by both the Bibliometrix package for R version 4.0.4 and VOSviewer version 1.6.16 software. The Bibliometrix package provides various routines for importing bibliographic data from numerous databases (e.g. Scopus and Web of Science), performing bibliometric analysis, and building data matrices for co-citation, coupling, scientific collaboration analysis, and co-word analysis. It is a unique tool, developed in the statistical computing and graphic R language, according to a logical bibliometric workflow (Aria and Cuccurullo 2017). In the same sense, VOSviewer is a software tool for creating maps based on network data and visualizing and exploring these maps (Jan van Eck and Waltman 2020).

In addition, during the third step, the appropriate bibliometric methods were chosen to respond to the first step. Table 3-1 presents the relational and evaluative methods that were generated by using, respectively, the Bibliometrix package for R version 4.0.4 and VOSviewer version 1.6.16. The choice of methods was based on the proposed objective of presenting the global scientific production status on the topic. Furthermore, Zupic and Čater (2015) discuss the pros and cons of presenting each method, contributing to the final results of this study.

Table 3-1 – Relational and evaluative methods generated through, respectively, Bibliometrix package for R version 4.0.4 and VOSviewer version 1.6.16

VOSviewer version 1.6.16				
Relational Methods	**Co-authorship**	**Citation**	**Co-citation**	**Co-occurrence**
Units of Analysis	By country By author	By journal By author	By author	Author Keywords
Bibliometrix package for R version 4.0.4				

Evaluative Method	Annual Scientific Publications	Country Scientific Production	Journal Growth	Affiliations	Keywords Growth

The *co-authorship method* is established when two authors co-publish a paper. It can provide evidence of collaboration and produce the social structure of the field. However, collaboration is not always acknowledged with co-authorship. *The citation method* is used as a measure of influence. If a paper or journal is heavily cited, it is considered important. In addition, it can quickly help to find important works in the research field. On the other hand, newer publications had less time to be cited, therefore, citation count as a measure of influence is biased toward older publications. The *co-citation method* by the author is defined as the frequency in which two authors are cited together. This analysis uses co-citation counts to construct measures of similarity between authors and/or journals. A fundamental assumption of co-citation analysis is that the more two items are cited together, the more their contents are related. The *co-occurrence method* by author keywords connects words when they appear in the same keyword list. The idea underlying the method is that when words frequently co-occur in papers, it means that the concepts behind those words are closely related. However, words can appear in different forms and can have different meanings (White and McCain 1998; Small 1999; Lu and Wolfram 2012; Zupic and Čater 2015; Grácio 2016).

Finally, in the fourth step, all the results generated for scientific production were interpreted by the following units of analysis: countries, affiliations, journals, authors, and keywords. In addition, a table was attached as supplementary material to facilitate the review of the literature review of other researchers. For each paper analyzed, the following information was tabulated: authors, title, year of publication, journal, and DOI.

3.3 Global scientific production status

We found 486 papers written in English and published in journals between January 1991 and February 2021 in the Scopus database. However, 429 papers were selected according to the abstracts and pre-established criteria in the second step of the methodology. The analysis resulted in papers produced in 57 countries, 182 journals, and 660 affiliations, by 1454 authors, who used a total of 1075 keywords. The first and most relevant results for each unit of analysis were listed to make the data presentation clearer.

As shown in Fig. 3-2, the period between January 1991 and February 2021 can be divided into two different analyses. The first paper was written in 1991, and the second in 1992, with no publications in 1993. Since 1996, more than one paper has been published each year, except for 1998, when there were no publications related to the topic. On the other hand, in the period between January 2007 and February 2021, there was an increase in annual scientific publications according to the Scopus database. From 2007 onwards, at least 14 papers per year started to be published (disregarding 2009 and January/February 2021), showing the growth trend. Although a significant decrease in publications was observed between 2012 and 2014, during the following years, it was observed fewer differences in the number of publications, indicating a more balanced scenario (i.e., between 2014 and 2018). The highest number of publications was observed in 2020, when the authors published 60 papers related to the topic. In January and February 2021, 11 papers had already been published, which is more than the whole year of 2009 and the period before 2007. This result demonstrates a recent increase in studies that have correlated climate change and the impact of storm surges on the coastal zone leading to erosion and flooding (inundation).

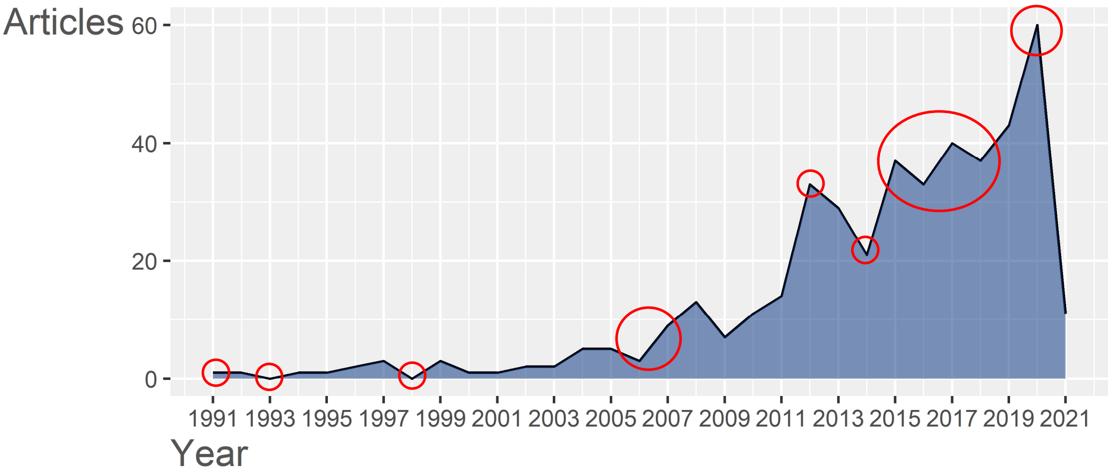

Fig. 3-2 – Annual scientific publications on the impact of storm surges related to coastal erosion and flooding under climate change (red circles highlight the years indicated in the text above). Note that the number of publications in 2021 includes only January/February

3.3.1 Analysis by country

Among 57 countries, at least 10 have 18 papers or more published between January 1991 and February 2021 (Table 3-2). Authors from the United States published 132 papers, that is, 30.77% of the total of 429. Next is the United Kingdom, where 54 papers were published. Authors from unlisted countries have published 36 papers or less. Table 3-2 also highlights the first 10 countries in which the authors were most cited. Among 19,753 citations, the countries listed reached 15,821, which represents 80% of the total citations. Authors from the United States concentrate on 4,844 citations counted until February 2021: this reflects a percentage of 24.52%. Authors from the United Kingdom were cited 3,494 times (17.69%) whereas German researchers were cited 1,586 times (8.03%). In contrast, papers published by the authors from the Netherlands have 78 fewer citations. In France and Australia, citations reach 1,103 and 1,016, respectively. Papers published by researchers from Italy, Canada, India, and Bangladesh reach 11.49% of the total. The unlisted countries have 422 citations or less.

Table 3-2 – Total number of papers and citations according to the 10 most relevant countries

Papers			Citations		
Rank	**Country**	**N. Papers**	**Rank**	**Country**	**N. Citations**
1	United States	132	1	United States	4,844
2	United Kingdom	54	2	United Kingdom	3,494
3	Netherlands	36	3	Germany	1,586
4	Germany	35	4	Netherlands	1,508
5	Italy	33	5	France	1,103
6	Australia	32	6	Australia	1,016
7	China	29	7	Italy	917
8	Canada	22	8	Canada	470
9	India	21	9	India	458
10	Spain	18	10	Bangladesh	425

The Netherlands has more papers than Germany, although fewer citations. France researchers are not on the top of the paper list, but they have 1,103 citations in their 13 papers. Australia has fewer papers compared to Italy but has more citations, 1,016 and 917, respectively. Canada, India, and Spain have fewer papers than China but account for a greater number of citations, 470, 458, and 380, respectively. Finally, Bangladesh has fewer papers (14) than Spain (18) but adds 45 more citations.

In Fig. 3-3 a co-authorship network is listed using a cluster approach. Countries are separated by colors into different clusters of collaboration; the size of the circle represents the number of publications, and the line thickness represents how strong the relationship between countries is. For example, lines between countries with more co-authorships are thicker. The results of co-authorship by countries are represented by 10 different clusters, in which 43 authors have at least two co-authorships. It was observed a larger network among researchers in 39 countries. Researchers from the United States have established co-authorship with 22 different countries. Among them, China, the United Kingdom, Italy, Australia, and India had a high relationship.

Researchers from the United Kingdom have 54 published papers and at least two co-authorships with 24 other countries. Among them, there are Ghana, China, Germany, and the Netherlands. The authors of the Netherlands, Germany, and Italy have 36, 35, and 33 papers (respectively) and at least two co-authorships with researchers from 17 countries. Authors from these three countries have a strong relationship. Both Australia and China had a strong relationship, co-authoring with 11 countries. In Canada, two co-authorships occur with eight countries, and in India, with six, which are represented in the same cluster as Iran. Despite being in tenth place in the publication ranking, Spain has at least two co-authorships with 18 countries. Brazil, which has four published papers, has a strong relationship with Portugal and the United States.

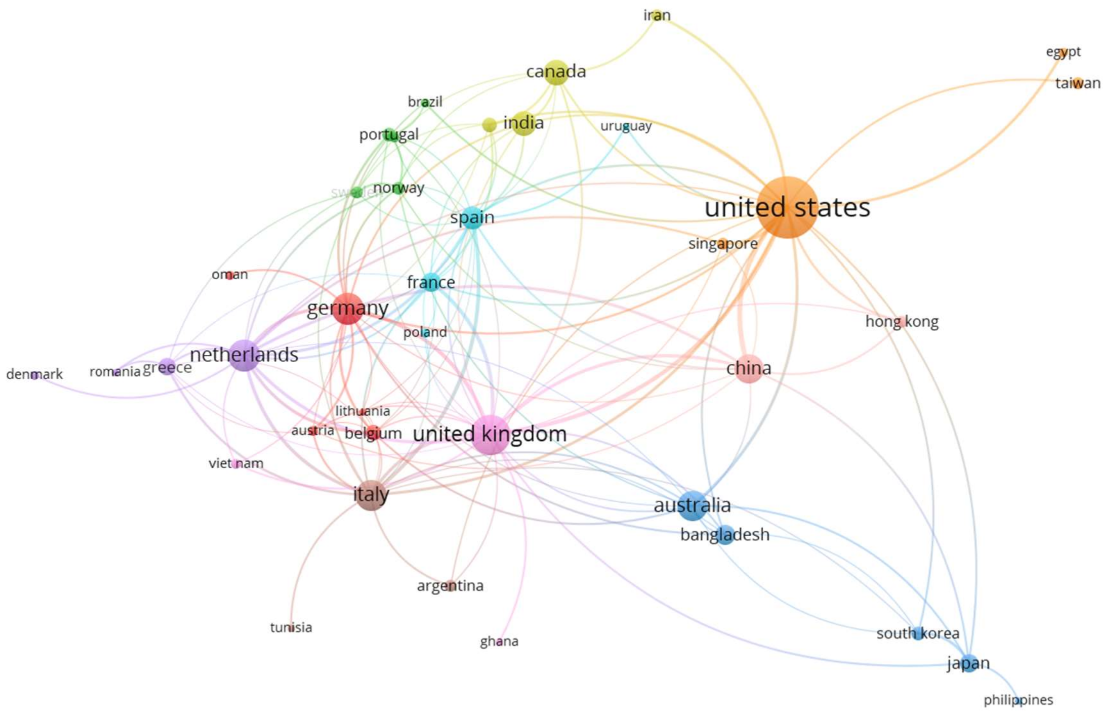

Fig. 3-3 – Co-authorship network by country

3.3.2 Analysis by affiliations

The authors' addresses recorded a total of 660 affiliations. It was found that 490 affiliations (74.24%) published only one paper. In Fig. 3-4 are listed the 12 organizations with which authors were affiliated in terms of the most papers published in the period between

January 1991 and February 2021. Pennsylvania State University is the most prolific affiliation with 20 papers, followed by Deltares and Princeton University, which published 15 papers each. The 12 affiliations represent 29.84%, with 128 papers out of a total of 429 publications on the topic. The other affiliations published six papers or less. Regarding countries, seven affiliations are located in the United States. The Netherlands is the second country that most appeared in the rank, with two affiliations. The United Kingdom, Greece, and Taiwan are host countries for one affiliation.

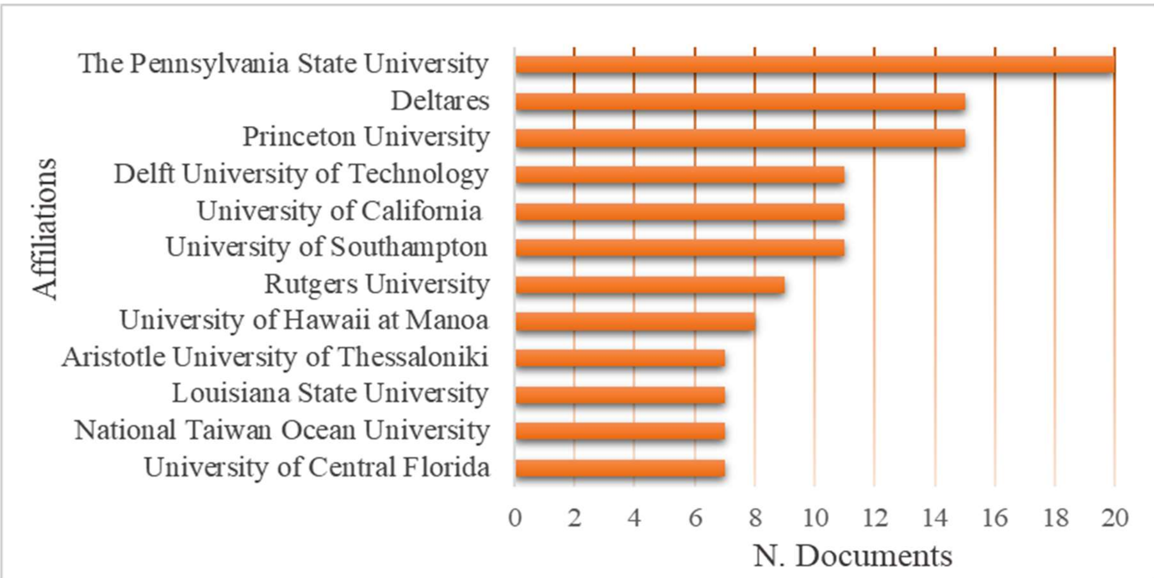

Fig. 3-4 – Number of papers related to the 12 most relevant affiliations between January 1991 and February 2021

3.3.3 Analysis by journals

The 429 selected papers were published in 182 individual journals. In Table 3-3 are shown the first 10 journals that published more papers on the topic in the period between January 1991 and February 2021. The first paper in our time series (Paw and Thia-Eng 1991) was published in Ocean and Coastal Management, which has 16 papers related to the topic and 15 citations. The second and third (Daniels 1992, Toppe and Fiihrboter 1994) were published in the Journal of Coastal Research, in which 21 papers were published subsequently. Natural Hazards has published 20 papers, the first in 2003 (Danard et al. 2003); Climatic Change has published 21 papers the first in 2008 (Kirshen et al. 2008). These first three journals represent 14.69% of the total number of published papers. The remaining seven listed journals total 19.11%, with 82 papers published. Furthermore, 119 journals published only one paper, 24 journals published two, and another 39 published three or more papers in the analyzed period.

Table 3-3 – Number of papers published by the 10 most prolific journals on the subject

Rank	Journal	N. Papers	SJR Index (Scimago 2019)	H-INDEX
1	Journal of Coastal Research	22	0.36	84
2	Climatic Change	21	1.91	175
3	Natural Hazards	20	0.81	96
4	Journal of Coastal Conservation	18	0.4	36
5	Ocean and Coastal Management	16	0.82	77
6	Global and Planetary Change	10	1.76	124
7	Natural Hazards and Earth System Science	10	1.01	90

8	Water (Switzerland)	10	0.66	42
9	Coastal Engineering	9	1.82	100
10	Science of The Total Environment	9	1.66	224

The annual occurrence of papers related to the theme in the seven most relevant journals is presented in Fig. 3-5. Over the years, the journal Natural Hazards set out a significant number of publications related to the vulnerability to and impact of, storm surges. It was the journal that published the most in January and February 2021. Water (Switzerland) also grew exponentially over the period and was the second to publish more related papers in 2021. The Journal of Coastal Conservation published more in the period between 2017 and 2019. On the other hand, Climatic Change published more between 2013 and 2015, and Ocean and Coastal Management obtained the highest number of publications in the year 2017. The Journal of Coastal Research, which took an initial interest in the topic, has maintained it with a relatively consistent since 2009. Global and Planetary Change published less than the other six journals, with the peak between 2011 and 2015. Concerning all the highlighted journals, it can be seen that there has been a marked increase in publications with a focus on the impacts of the storm surges since 2007.

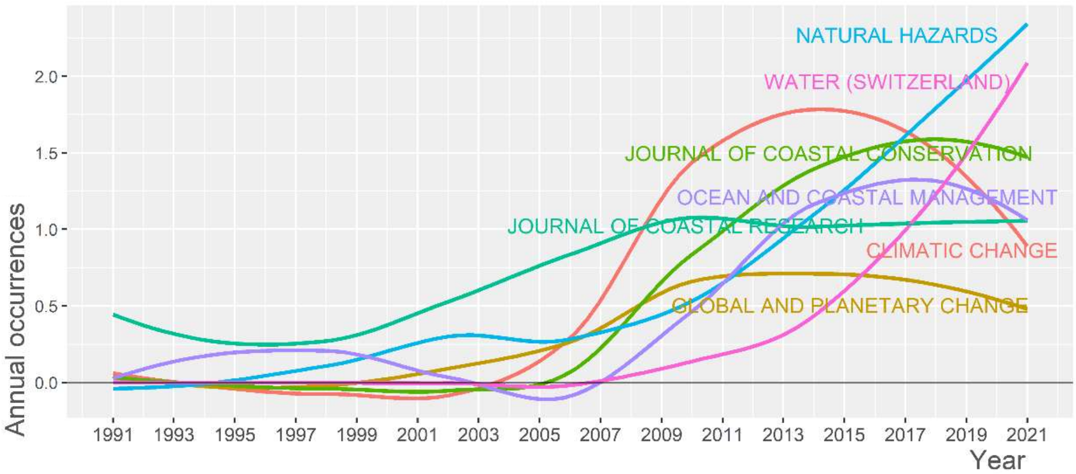

Fig. 3-5 – Annual occurrence of theme-related papers in the seven most prolific journals between January 1991 and February 2021

In Table 3-4 are listed the top 10 journals where the 429 selected papers were cited. Climatic Change, which published 21 papers, is the most-cited journal. On the other hand, the Journal of Coastal Research, with 22 papers, is the fifth most-cited journal (705). Plos One, which has six published papers, obtained 789 citations. Natural Hazards, third in the publications rank, appeared in the tenth position, with 443 citations. Journals, such as Global Environmental Change, Climate Research, Nature Climate Change, also do not appear in the ranking of those that have published more on the topic, but they total 763, 648, and 619 citations, respectively. The other journals, which are not in the top 10, were cited 412 times or less. Among the 13,548 citations, the first 10 journals have 6,778 (50.03% of the total). The results also demonstrate that 16 journals were not cited, 14 had one citation, and 152 were cited two times or more.

Table 3-4 – The first 10 most cited journals by the 429 selected papers

Rank	Journal	Citations	SJR Index (Scimago 2019)	H-INDEX
1	Climatic Change	1,087	1.91	175
2	Plos One	789	1.02	300

3	Global Environmental Change	763	4.3	162
4	Global and Planetary Change	708	1.76	124
5	Journal of Coastal Research	705	0,36	84
6	Climate Research	648	0.8	101
7	Nature Climate Change	619	7.74	160
8	Ocean and Coastal Management	547	0.82	77
9	Coastal Engineering	469	1.82	100
10	Natural Hazards	443	0.81	96

Fig. 3-6 shows 10 journals, in which at least seven papers have been cited 65 times. In three clusters, represented by different colors, some journals have the highest citation network, indicated by the line thickness. The Natural Hazards and Climatic Change have a greater relationship, forming a cluster represented by the color blue. In the green cluster are represented Water (Switzerland), Global and Planetary Change, Journal of Geophysical Research, and Science of the Total Environmental. Finally, the red cluster lists Ocean and Coastal Management, Journal of Coastal Research, Journal of Coastal Conservation, and Coastal Engineering. The size of the circles shows that among the journals with the highest citation network, Climatic Change, Global and Planetary Change, and Journal of Coastal Research were the three most cited journals.

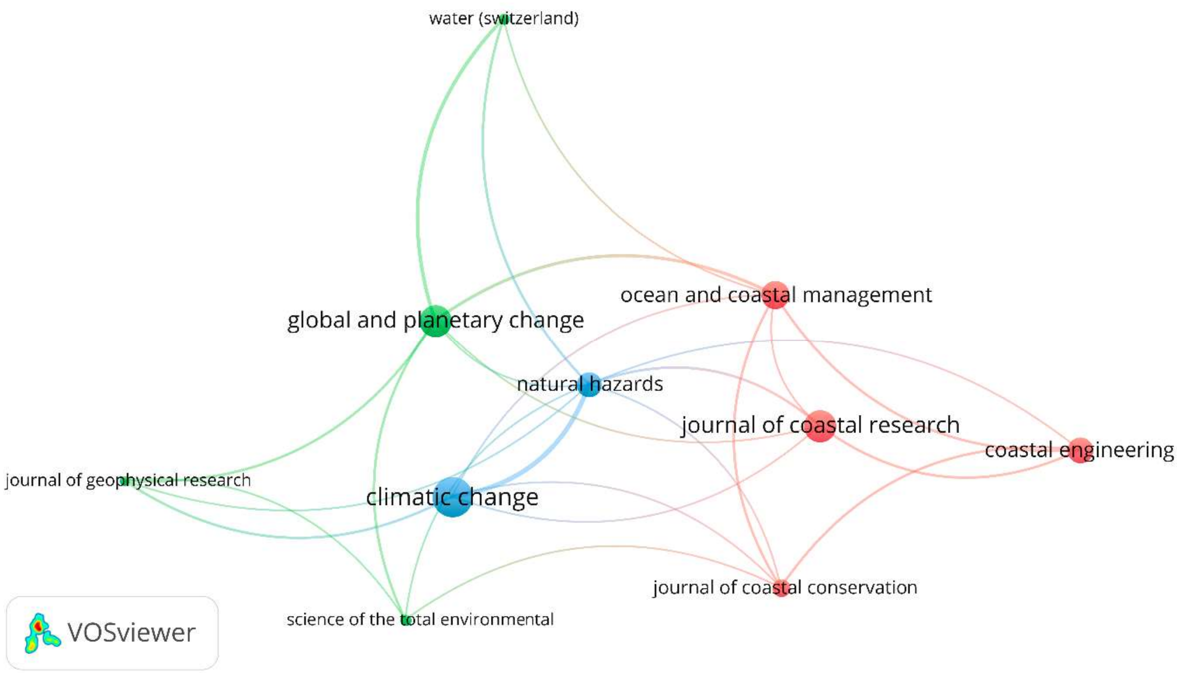

Fig. 3-6 – Citation network by journals

3.3.4 Analysis by authors

The results indicate a total of 1,454 authors. The 10 most productive authors were highlighted, according to the number of publications on the topic. Furthermore, the number of citations, affiliations, country, and gender of the author are presented in Table 5. In our analysis, we have only selected the authors who have correlated climate change and the impact of storm surges on the coastal zone leading to erosion and flooding (inundation) in their papers.

Robert Nicholls published the most papers on the topic; his first paper was published in 1996 in Ocean and Coastal Management Journal (Nicholls and Hoozemans 1996). Until

February 2021, this paper obtained 31 citations of a total of 1,965 citations. The author's most cited paper was published in 2015 in the Plos One journal and obtained 713 citations (Neumann et al. 2015). The second author of the rank is Lin, who has published nine papers. The first paper produced with Lin as the main author was in 2010 (Lin et al. 2010) in the Journal of Geophysical Research: Atmospheres. That paper obtained 161 citations out of the 414 citations reached by the researcher. Other authors are recorded in the database as having published seven or fewer papers in the period.

The affiliations presented were described on the profile of each researcher in Scopus. They were updated according to the last paper published by the author until March 31, 2021. Thus, some authors may have more than one affiliation. According to Table 3-5, two prominent authors are affiliated with the Euro-Mediterranean Center on Climate Change: Critto and Torresan. The other authors are affiliated with different universities/centers. Regarding the countries, three authors develop research in Italy (Critto, Marcomini, and Torresan), and another three in the United States (Lin, Hagen, and Medeiros). Nicholls and Lowe are from the United Kingdom. Belgium and Germany also appear in the rank with the authors Vousdoukas and Weisse, respectively.

The discussion about gender aims to demonstrate that the frequency in which men and women are published in the field is vastly different. Holmam et al. (2018) found that prestigious journals have fewer female authors. Furthermore, the authors estimated that men are invited co-authorship papers at approximately twice the rate of women. Gender equity guarantees women the same opportunities as men in benefiting from the fruits of research, contributing to society, earning a living, and choosing a fulfilling profession (Huyer 2015; Vila-Concejo et al. 2018). In the current times, in which gender equality is sought, it is necessary to present and show that women still do not dominate ranks, such as those presented in Table 3-5 and Table 3-6. Regarding the largest number of publications, Lin (female) occupies the second position. In the same sense, Torresan occupies the ninth position of the rank. However, the results point out that women are the minority compared to men, which account for 80% of the 10 authors in the top ranking.

Table 3-5 – Top 10 most productive authors by the number of papers from January 1991 to February 2021

Author	Papers	Citations	Affiliation*	Country	Gender
Nicholls R.J.	13	1965	University of East Anglia	United Kingdom	Male
Lin N.	9	414	Princeton University	United States	Female
Lowe J.A.	7	529	Met Office	United Kingdom	Male
Hagen S.C.	6	236	Louisiana State University	United States	Male
Vousdoukas M.I.	6	269	European Commission Joint Research Centre	Belgium	Male
Critto A.	5	113	Euro-Mediterranean Center on Climate Change	Italy	Male
Marcomini A.	5	113	Università Ca' Foscari Venezia	Italy	Male
Medeiros S.C.	5	219	Embry-Riddle Aeronautical University	United States	Male
Torresan S.	5	113	Euro-Mediterranean Center on Climate Change	Italy	Female
Weisse R.	5	366	Helmholtz-Zentrum Geesthacht	Germany	Male

* Affiliations were completed according to each author’s profile on Scopus, which considers the affiliation of the most recent paper published until March 31, 2021. Some authors may have more than one affiliation.

The clusters of researchers who are co-authors in at least two papers are shown in Fig. 3-7. Colors separate authors into nine different clusters by collaborations; the size of the circle represents the number of publications, and the line thickness represents the intensity of the relationship between the authors. Among the 1,454 authors, 183 are co-authors on the 429 papers analyzed. Conversely, the largest set of connecting co-authorship consists of 49 authors. In this case, the cluster analysis allows the identification of the co-authors' niches.

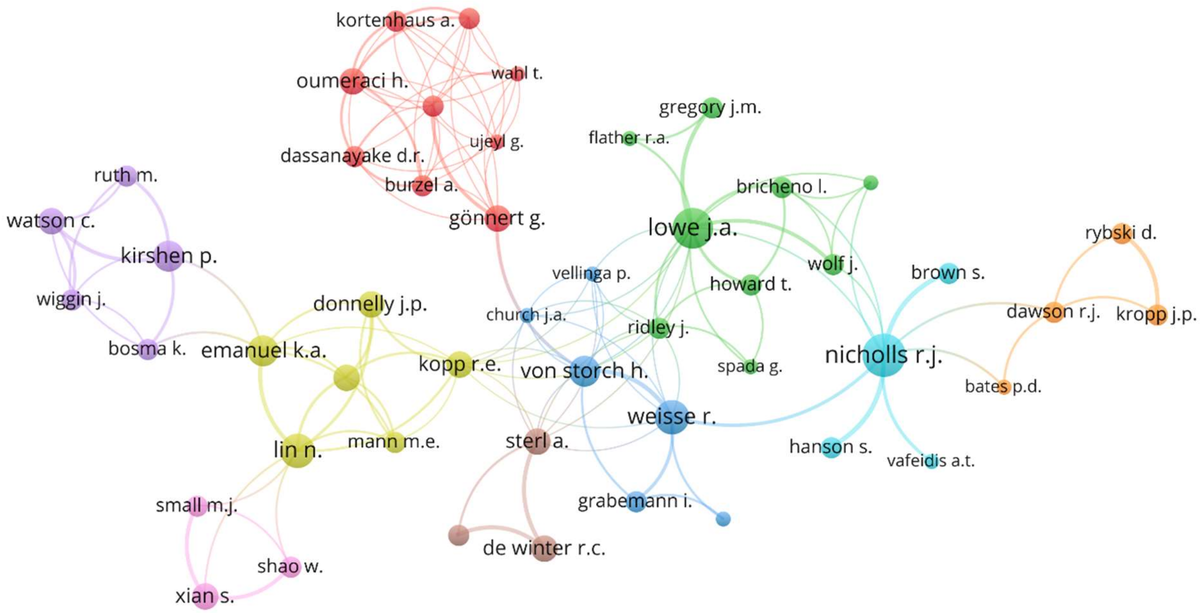

Fig. 3-7 – Co-authorship network by author

In the light blue cluster (Fig. 3-7), Nicholls was the author who published more (13 papers) and he was co-author with 10 other researchers. Among his strongest relationships, there are Brown, Hanson, and Vafeidis. The author has also contributed to papers by Dawson (orange cluster), which has two publications and is co-author with another three researchers. Lowe, who published seven papers, was the researcher with the highest co-authorship number (15). This author also has connections with Nicholls and other light blue cluster authors. In the dark blue cluster, Weisse was the most prolific author with five published papers and is a co-author with 10 researchers. His strongest connection is with Von Storch. Moreover, he is also a co-author with Nicholls and Lowe. Gonnert is the most productive author in the red cluster with three papers published, and he is the co-author with nine other researchers. The red and green clusters are composed of the largest number of researchers who publish dominantly among themselves. Sterl was the most prolific publisher in the brown cluster with three published papers, and he is co-author with nine other authors. Lin published nine papers, thus being the author who has most published in the yellow cluster, co-authoring with eight researchers. She is in the top 10 most productive analyzed authors, like Nicholls, Lowe, and Weisse. In the pink cluster, Xian was the author who has written the highest number of papers (three) and is a co-author with three researchers, including Lin. Finally, in the purple cluster, Kirshen, who published four papers, is co-authored with five researchers.

Table 3-6 presents the first 10 most-cited authors. The first four authors, Nicholls, Vafeidis, Neumann, and Zimmermann are co-authors of the same paper (Neumann et al. 2015), which obtained 713 citations until February 28, 2021. Lowe is the fifth author of the rank, with 529 citations in his seven published papers. Dingman, Ericson, Meybeck, Vörösmarty, and Ward are also co-authors of the same paper (Ericson et al. 2006), which has 453 citations to the same date.

Regarding affiliations, Vafeidis and Zimmermann are affiliated with the Christian-Albrechts-Universität zu Kiel in Germany. Dingman and Ward are part of the University of New Hampshire Durham, located in the United States. The other authors of the rank are affiliated with different universities/centers. The first country in the rank is the United States, with four researchers. Next is Germany, with three authors, and the United Kingdom, with two researchers. France appears only once, in the seventh position in the ranks. As in the analysis of the most prolific authors (Table 3-5), the results related to gender in Table 3-6 also indicate that women occupy only 20% of the rank of most-cited researchers. It is also noteworthy that Neumann and Zimmermann were co-authors of the same work, with Neumann being the first author. Again, it is shown that women are not the majority among the 10 authors on the top ranking.

Table 3-6 – Top 10 cited authors from January 1991 to February 2021

Author	Citations	Papers	Affiliation*	Country	Gender
Nicholls R.J.	1965	13	University of East Anglia	United Kingdom	Male
Vafeidis A.T.	714	2	Christian-Albrechts-Universität zu Kiel	Germany	Male
Neumann B.	713	1	Institute for Advanced Sustainability Studies	Germany	Female
Zimmermann J.	713	1	Christian-Albrechts-Universität zu Kiel	Germany	Female
Lowe J.A.	529	7	Met Office	United Kingdom	Male
Dingman S.L.	453	1	University of New Hampshire Durham	United States	Male
Ericson J.P.	453	1	Virginia Department of Conservation and Recreation	United States	Male
Meybeck M.	453	1	Sorbonne Université	France	Male
Vörösmarty C.J.	453	1	City College of New York	United States	Male
Ward L.G.	453	1	University of New Hampshire Durham	United States	Male

* Affiliations were filled out, according to each author's profile at Scopus, which considers the affiliation of the most recent paper published until March 31, 2021. Some authors may have more than one affiliation.

Fig. 3-8 presents the cluster analysis of the authors, in which at least three published papers were cited four times by other researchers. Divided into six clusters, the authors are associated with other authors, among whom they were cited; the size of the circle represents the number of citations and the line thickness represents how strong the relationship between authors is. Nicholls was the most cited author, among the analyzed researchers. This author also presents a connection with the authors represented by the light blue, red, and purple clusters. This indicates that he also cites a significant number of authors from those clusters. Lowe appears as the second author who obtained at least four citations in three published papers. He was the researcher most cited by the authors of the light blue cluster. Lin was the third most cited author of the 429 papers in the database. The author was a reference, mainly of the works written by Emanuel, Xian, Donnelly, Horton, Kopp, Yin, and McInnes.

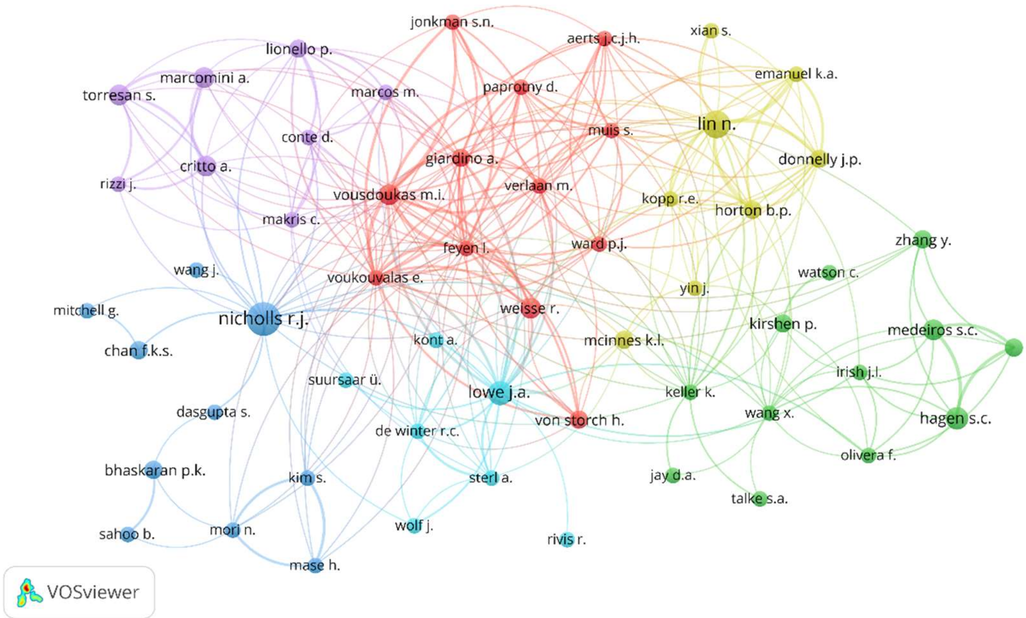

Fig. 3-8 – Citation network by author

The co-citation patterns indicate the history of recognition and academic impact of publications since a publication can be relevant for future research and can, thus, potentially be cited (Hjørland 2013). The co-citation analysis by the author presents the cluster of researchers who are cited by a group of authors. Therefore, it becomes important to demonstrate to the authors that it is also related to the topic. The analysis of co-citation by the author demonstrates, from four clusters, the set of authors that were most cited by the 1454 authors of the 429 papers analyzed. In the selected papers, 24,623 researchers were cited, and the 36 researchers represented in Fig. 3-9 were cited at least 65 times. The authors' proximity to clusters refers to the list of their proposed themes within the general topic of storm surges and climate changes.

Nicholls appears as the most cited author, with 552 citations. In the same papers, authors, such as Woodroffe, Hinkel (the fifth most cited, with 144), Tol, Vafeidis, Hallegatte, and Corfee-Morlot are also cited. It does not exclude the fact that the authors of other clusters are also cited in the same paper, in which Nicholls appears. Emanuel is in the second position, with 247 citations. The authors most cited by the same paper are represented in the green cluster, in which Lin, the fourth-most cited is part, with 146. Church is the third in rank, with 147 citations by base papers. The author is represented by the yellow cluster, in which also appears Cazenave, the sixth most-cited author, with 141 papers. The other researchers were cited 121 times or less.

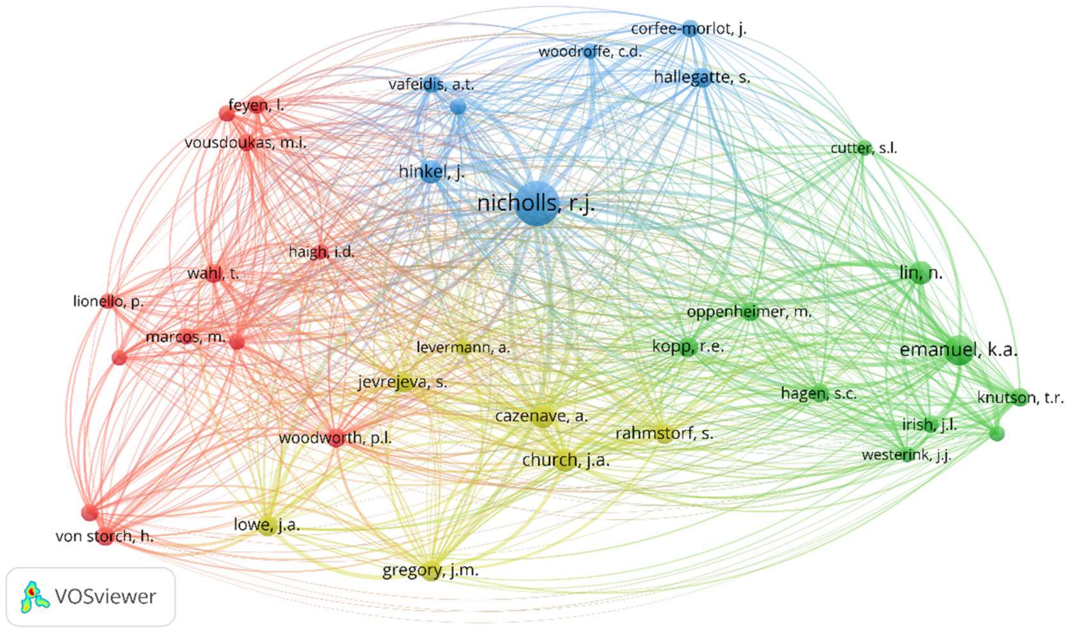

Fig. 3-9 – Co-citation network by author

The paper entitled *Sea-level rise and its impact on coastal zones* (Nicholls and Cazenave 2010) was the most cited by the 429 papers analyzed. The authors discuss important issues in it, such as *Global Sea-Level Rise in the 21st Century, Main Impacts of Sea-Level Rise,* and *Adaptation.* The publication obtained 40 citations among the selected papers. The paper totaled 1,256 citations until April 2, 2021. Between January and April 2, 2021, the paper had already been cited 49 times, as indicated by Scopus.

3.3.5 Keywords' analysis

The evolution of the five most used keywords between January 1991 and February 2021 is shown in Fig. 3-10. The keywords plus (i.e., most commonly used words in titles, abstracts, and keywords list) were represented according to their annual and noncumulative occurrence. The main keywords are highlighted: *Climate Change, Storm Surge, Floods, Sea Level,* and *Sea Level Change*. In general, the terms appeared considerably since 2007. The most used keyword per year was climate change. Between January 2019 and February 2021, the curve is stable, with an annual occurrence of approximately 35. It shows that its use is constant and more elevated, concerning the other highlighted keywords.

Storm surge is the second most used keyword since 2007. Its peak usage occurred between 2017 and 2019. However, it was select papers between January and February 2021, only. Studies related to the topic are growing exponentially until the year 2020, as seen in Fig. 3-2. In addition, only two months in 2021 account for more publications than several other years, such as 2009. The growth occurs due to the current situation of climate change and environmental impacts. *Sea level change* was the most used keyword in the papers since 2007. However, between 2015 and 2018, it remained stable, with a drop in its employment in 2019. After 2016, *floods* started to have a higher annual occurrence in keywords. Its peak was in the first two months of 2021. The use of the term *sea level* in keywords was stable between 2017 and 2019, slightly decreasing in 2020.

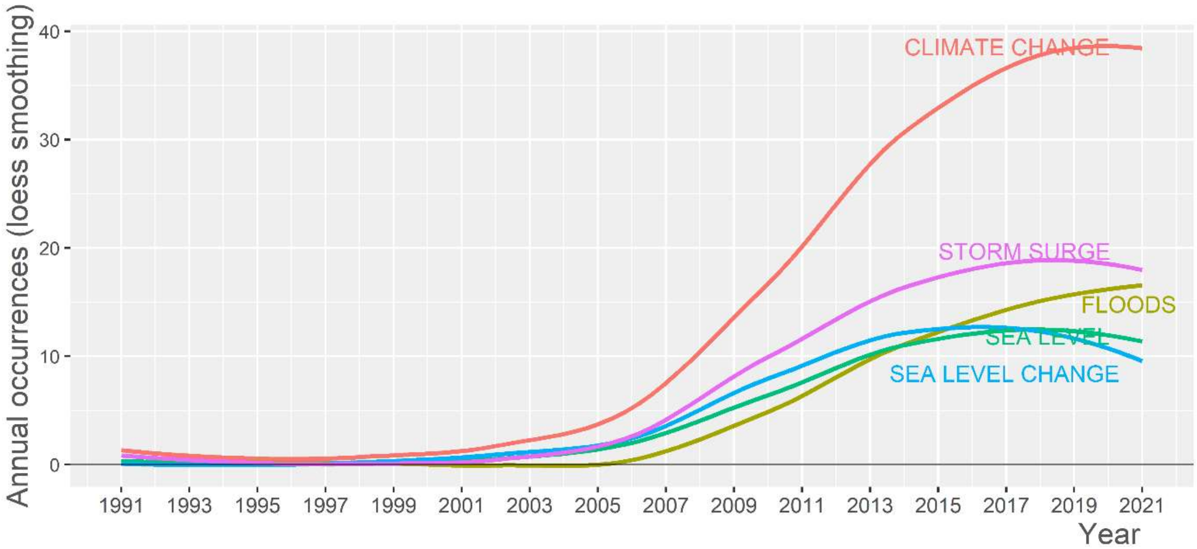

Fig. 3-10 – Keywords usage growth from 1991 to February 2021

Among the 1,075 keywords chosen by the authors, 17 occurred in at least 10 papers out of 429 analyzed. The co-occurrence network based on keyword occurrences in papers is shown in Fig. 3-11. The size of the node is proportional to the frequency of occurrence of the keyword, and the thickness of the line represents the intensity of co-occurrence between individual keywords (Mishra et al. 2020). Zupic and Čater (2015) point out the negative aspect of presenting a co-word analysis. The authors show that words can appear in different forms, as well as they can have different meanings.

The keywords determined by the authors did not follow a pattern. It can occur in different research fields since different words can have the same meaning. In the case of the present study, words, such as *sea level rise* and *sea-level rise*, were found among the 17 most used keywords by the authors. The researchers used it in 64 and 53 papers, respectively. Another example of duplicity is *storm surge* and *storm surges*, which appeared 82 and 26 times, respectively. Furthermore, it was used words like *coastal flooding* (24) and *flooding* (22). Considering that the research only delimited studies related to the coastal area, the two terms can be classified as synonyms. Keyword *inundation* (13) may or may not give rise to the same interpretation as *flooding*. There is no consensus, among authors in the research area. In the same sense, *erosion* and *coastal erosion* appeared (both 13 times), which probably refer to the same topic. It should be noticed that the aforementioned keywords are never combined together, justifying the fact that they have the same interpretation.

An analysis of some papers by the three authors who published more on the topic revealed divergences in the keyword pattern. Nicholls (2002) used words like *sea-level rise* and *flooding*, while Lin et al. (2016) used *storm surge* and *sea level rise*. On the other hand, Lin and Shullman (2017) used *storm surge* and *sea-level rise*. In the paper by Lowe and Gregory (2005), the expression *storm surge* appears as a keyword. The three keywords most used by the researchers were *climate change* (168 times), *sea level rise* (*sea-level rise*), and *storm surge* (*storm surges*). The highlighting of these keywords is justified, as they are directly related to the keywords used in the query expression determined in the present study. Regarding keywords that did not show duplicity, there is *vulnerability* and *adaptation*, which appeared in 18 papers each, next to *the sea level* keyword, which was used 14 times. *Risk assessment* appeared in 11 papers, while the words *coastal hazards*, *coastal management*, and *flood risk* appeared in 10 papers. The other keywords were used nine times or less.

Fig. 3-11 shows four clusters that are divided into different colors. In papers where the authors opted for the keyword *climate change*, the other 16 keywords presented were also used at least once. In the same green cluster, terms, such as *sea level rise*, *coastal flooding*, *storm* *surge*, *sea level*, and *flood risk*, appear. *Storm surges* appear related to the words represented in the blue cluster, considering its strong relationship with climate change and sea level rise, as well as *sea-level rise,* being more used in conjunction with words belonging to the red cluster, in addition to having a strong relationship with *storm surge*. *Erosion* and *coastal hazards* appear in the yellow cluster. Terms considered as synonyms appear in different clusters, which shows the fact that they are not used together in the keyword lists.

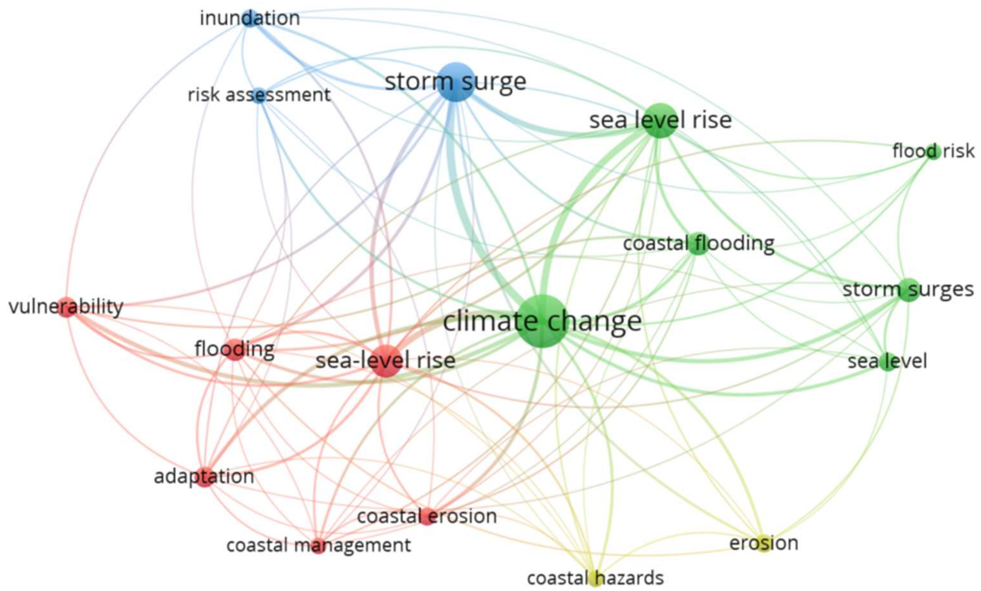

Fig. 3-11 – The keywords co-occurrence network based on incidences of keywords in paper

3.4 Guide for authors: a bibliographic review

For researchers who intend to make a significant bibliographic review or even publish on the topic, it is worth looking for authors, papers, and journals with significant recognition among the scientific community. Two countries occur as the most productive and cited: the United States and the United Kingdom. The United States is the country with the largest number of authors who publish on the topic. In addition, the country hosting important universities is highlighted in Fig. 3-4. Authors, such as Lin and Hagen stand out and do have their works considerably cited by the scientific community. The second is the United Kingdom, the country that has important researchers in the study area, such as Nicholls and Lowe, in addition to hosting significant universities. Nicholls, according to the results, is the most relevant researcher in the area. The author published the largest number of papers and obtained the highest number of citations and co-citations. One of his works was the most cited of the 429 selected papers (Nicholls and Cazenave 2010).

In addition, the Netherlands hosts two prominent affiliations for the study area, Deltares and Delft University of Technology. It should be noticed that several other countries and authors presented in the results also have scientific relevance, in which researchers publish important papers that contribute substantially to the issue. Readers are strongly encouraged to find the supplementary material listing all 429 selected papers, which are available in this document.

Regarding journals, the 14 that published more or had papers with the highest number of citations on the topic are highlighted in alphabetical order: Climatic Change, Climate Research, Coastal Engineering, Global and Planetary Change, Global Environmental Change, Journal of Coastal Conservation, Journal of Coastal Research, Natural Hazards, Natural

Hazards, and Earth System Science, Nature Climate Change, Ocean and Coastal Management, Plos One, Science of The Total Environment and Water (Switzerland).

3.5 Final considerations

Bibliometrics are the quantitative tools and analyses that allow minimizing the subjectivity inherent to the indexing and retrieval of information, producing knowledge in a given study area. A bibliometric analysis is an alternative approach to demonstrating the global scientific production status. The application of these tools and metrics represents a relevant resource to map the structure of the network created between countries, institutions, and researchers. Also, the use of clusters of countries, institutions, and authors potentially reflects the interests of the common research area, search for professional training, and partnerships in projects.

Both software used, the Bibliometrix package for R and VOSviewer generated important results that complemented each other and, thus, have supported a better understanding of the scientific knowledge in the research field. The results showed that there is an exponential growth in the publication of papers written and published in journals since 1991. The peak in the publication of papers related to the topic was observed in 2020, but in the first two months of 2021, it has been published more papers than in the entire period before 2007.

According to the query expression applied in the Scopus database, which was based on four pre-established criteria, 429 papers were selected. The evaluation through the units of analysis of countries, affiliations, journals, authors, and keywords highlighted significant issues about the current situation of research in the world. We have found that authors from the United States, the United Kingdom, Italy, Germany, and the Netherlands stood out in the number of publications on the topic. In terms of numbers, the United States presented the highest number of publications published between January 1991 and February 2021. On the other hand, the most relevant author for the research field is Nicholls, from the United Kingdom. This author published more papers in the period, obtaining the highest number of citations in one of his papers. In addition, our results showed that only 20% of women are in the rank of the 10 authors who most produced and were cited. Steps to improve gender diversity were proposed by women researchers in areas related to this study (Vila-Concejo et al. 2018) and deserve the attention of all researchers.

Regarding affiliations, we highlighted the 10 most relevant, which have published more in the research area. Of the 660 affiliations found, only 170 published more than two papers in the analyzed period. At the top of the rank, it is The Pennsylvania State University from the United States and Deltares from the Netherlands. The same countries host the most relevant journals in the area, with more publications and citations on the topic.

The analysis of the keywords co-occurrence network, based on keywords occurrences in papers, showed the lack of standardization on the choice of terms. We highlighted the most used keywords by the authors, such as climate change, sea level rise, and storm surge. Based on this result, the authors can understand and choose the terms that are being more used in publications related to the topic.

Finally, we understand that the study can support researchers in the investigation field on the following issues: 1) to identify the global scientific production between January 1991 and February 2021; 2) to understand which countries, affiliations, journals, and authors are the most relevant; 3) to identify papers with greater relevance, among the scientific community of the research area; 4) to recognize the lack of standardization in the use of keywords and, possibly, create standardization mechanisms, at least, among research groups; 5) to facilitate and speed up bibliographic reviews in the research area. Besides, the proposed methodology of this study can be reapplied to any other research area, collaborating with the advancement of scientific knowledge.

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Authors' contributions

All authors contributed to the study's conception and design. KBL performed the bibliographic search, generated the results through bibliometric tools, analyzed the data, and wrote the first version of the manuscript. LESR and ASL analyzed the data and contributed to the review of the manuscript in all versions. All authors read and approved the final manuscript.

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4 IDENTIFICATION OF COASTAL NATURAL DISASTERS USING OFFICIAL DATABASES TO PROVIDE SUPPORT FOR THE COASTAL MANAGEMENT: THE CASE OF SANTA CATARINA, BRAZIL

LEAL, K. B.; ROBAINA, L. E. S.; KÖRTING, T. S.; NICOLODI, J. L.; COSTA, J. D.; SOUZA, V. G. Identification of coastal natural disasters using official databases to provide support for the coastal management: the case of Santa Catarina, Brazil. **Natural Hazards**, v. 120, p. 11465-11482, 2023. https://doi.org/10.1007/s11069-023-06150-3

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Abstract

The increase in natural disaster frequency, intensified by climate change, poses one of the greatest threats to coastal systems and low-lying areas worldwide. It is estimated that the Global Mean Sea Level (GMSL) could rise by approximately 2 m in the 21st century, alongside intensifying cyclonic events. Consequently, in Brazil, coastal natural disasters are likely to become more frequent and intense, especially in the southern region. Thus, this study aims to identify, map and discuss coastal natural disasters in municipalities exposed to the open ocean belonging to the coastal zone of Santa Catarina (SC), Brazil, between 1998 and 2020. A review and dating of coastal natural disasters were conducted using four official databases: The Civil Defense of Santa Catarina website, Integrated Disaster Information System (S2ID), Santa Catarina Atlas of Natural Disasters, and the Brazilian Atlas of Natural Disasters. The data were organized into spreadsheets and mapped using QGIS 3.16.0 software. The results and main conclusions indicate: 1) More coastal disasters occurred in the north, central-north, and central sectors of SC between 1998 and 2020; 2) The period between 2010 and 2020 was more impactful; 3) The municipalities with the most records of coastal disasters were Balneário Barra do Sul, Itapoá and Florianópolis (considering only Ilha de Santa Catarina), respectively; 4) The three fastest-growing sectors are the north, central-north, and central; and 5) The seasons of autumn, spring, and winter, respectively, are more impacting for the study area.

Keywords: Coastal zone. Coastal erosion. Storm surge. Sea level rise. Cyclones. Climate change.

4.1 Introduction

The increase in natural disasters is among the greatest threats to which coastal systems are subject in the face of climate change (Collins et al. 2013; IPCC 2021; IPCC 2022a; IPCC 2022b). The coastal erosion and coastal flooding processes are mainly related to the geological characteristics of the coastal relief and the topographical characteristics of the contact strip between the sea and the land. In addition, we must consider the meteoceanographic conditions that interact with the coast, such as the intensity, duration, and direction of prevailing winds; the intensity and direction of local marine currents; the intensity and variations of astronomical and meteorological tides; the height, period and direction of the waves; and the proximity to river mouths. Furthermore, human activities are widely acknowledged by various researchers as a pivotal factor influencing coastal dynamics (Castro 2003; Klein et al. 2016; Luijendijk et al. 2018; Leal et al. 2020; Pazini et al. 2022).

Global projections indicate a potential rise of 4ºC to 6ºC in the average global temperature by 2100, reflecting the most extreme scenario of greenhouse gas concentration (Collins et al. 2013). Such temperature increases could accelerate the hydrological cycle, leading to heightened intensity and frequency of extreme events, including coastal storms and storm surges (Coco and Ciavola 2017; Oppenheimer et al. 2019). Under the Intergovernmental Panel on Climate Change's (IPCC) rigorous RCP8.5 scenario, an estimate posits a probable global mean sea level (GMSL) increase of about 2 meters during the 21st century, potentially escalating to 5 meters by 2150 (IPCC 2021).

Research demonstrates that from 1901 to 2018, the sea level experienced a rise of approximately 20 cm. The rate of elevation escalated from 1.35 mm per year during 1901-1990 to 3.7 mm per year during 2006-2018. Notably, the GMSL has undergone a more rapid increase since 1900 than in any previous century within the past 3000 years. Since at least 1971, human influence has significantly contributed to these heightened trends (IPCC 2021). Furthermore, the study highlights projections for the year 2100, indicating that extreme sea-level events that were once centennial occurrences are anticipated to transpire at a minimum annual frequency in over half of all tide gauge locations. Additionally, there has already been a noted 30% rise in flood frequency. This escalation in relative sea level notably impacts the frequency and severity of coastal flooding in low-lying areas, accompanied by coastal erosion along the majority of sandy coastlines.

A recent study conducted by Nicholls et al. (2021) shows that, in the last two decades, the GMSL has increased by 2.5 mm per year, and that the impact in subsiding coastal areas is four times faster with an average relative sea-level rise ranging from 7.8 mm to 9.9 mm per year. It is virtually certain that GMSL will continue to rise in the 21st century (IPCC, 2021). Therefore, as a result, coastal systems will increasingly flood and experience erosion during the 21st century if measures are not taken to adapt or mitigate sea-level rise and extreme events (Nicholls 2002; Nicholls and Cazenave 2010; Oppenheimer et al. 2019; Nicholls et al. 2021).

Future sea-level rise combined with storm surges and heavy rainfall will increase compound flood risks. The inevitable rise in sea level will bring cascading and compounding impacts, resulting in losses in coastal ecosystems and ecosystem services, flooding from groundwater salinization, and damages to coastal infrastructure that escalate into risks to livelihoods. In addition, risks to human systems also increase, including those to infrastructure, low-lying coastal settlements, some ecosystem-based adaptation measures, and associated livelihoods. The number of people at risk from climate change and associated loss of biodiversity will progressively increase (IPCC 2022a). In general, the IPCC states that South American countries will suffer from damage to life and infrastructure due to floods, landslides, sea-level rise, storm surges, and coastal erosion.

In coastal cities, the combination of more frequent extreme sea-level events (due to sea-level rise and storm surges) and extreme rainfall/river flow events will make flooding more probable (IPCC 2021). Flooding and coastal erosion, resulting from extreme meteoceanographic events, are strongly associated with the degradation of fragile areas, intensified by irregular occupation (Santos 2007; Collins et al. 2013; Dalinghaus et al. 2018; Muehe 2018). In this scenario, disasters only occur in the presence of humans, and, to make matters worse, the current speed of urban expansion, often irregularly, is significantly higher concerning the implementation of disaster containment actions (Robaina 2008). Constructions within the dynamic response range of the coastal zone to storms place occupations in areas prone to the occurrence of natural disasters (Dalinghaus et al. 2018). We must also consider that disasters affect the coast in an atypical way and the resulting damage depends on the environmental, social, and economic characteristics of each coastal sector (Bonetti et al. 2013).

In recent decades, the interest in studying coastal zones has intensified due to the escalating occurrence of these natural disasters (Wisner et al. 2004; Short and Klein 2016; Leal et al. 2022). It is estimated that, driven by climate change, natural disasters in Brazil will likely become more frequent and intense, particularly in the south and southeast regions (Brasil 2002; Santos 2007; Short and Klein 2016; Dalinghaus et al. 2018; De Lima et al. 2021). Therefore, this study's primary objective is to identify, map, and analyze coastal natural disasters that transpired within ocean-exposed municipalities belonging to the coastal zone of Santa Catarina, Brazil, from 1998 to 2020. Considering the limited data presence in official databases such as The Integrated Disaster Information System (S2ID), this paper also strives to consolidate natural disaster records for the coastal zone of Santa Catarina within a single database across the studied time series. The intention is to provide comprehensive support for coastal management in disaster mitigation, preparedness, response, and recovery efforts (Castro 1998). This research is aligned with Sustainable Development Goal 13 (SDG 13) of the 2030 Agenda, which underscores the importance of devising study and planning mechanisms that incorporate climate change effects. This approach strengthens adaptive capabilities for formulating public policies and planning actions (ONU Brasil 2015).

Given the above, we adopted as the study area the municipalities exposed to the open ocean belonging to the coastal zone of Santa Catarina (SC), located in the southern region of Brazil (Figure 4-1). The coast trends from south to southwest for approximately 430 km, and contains 922 km of open coast and bay shoreline, with 246 sandy beaches occupying 60% of the shore (Klein et al. 2016). In the state, about 1,417,089 (22.7%) of the total 6,248,436 inhabitants are located in these municipalities (IBGE, 2010), where coastal natural disasters are frequently recorded (Klein et al. 1999; Horn Filho 2006; Klein et al. 2006; Santos 2007; CEPED UFSC 2013; Herrmann 2014; Klein et al. 2016; CPRM, 2018; Dalinghaus et al. 2018; Muehe 2018; Leal et al. 2019; Silveira et al. 2019; Leal et al. 2020; De Lima et al. 2020; Furtado and Bonetti 2021; Pazini et al. 2022).

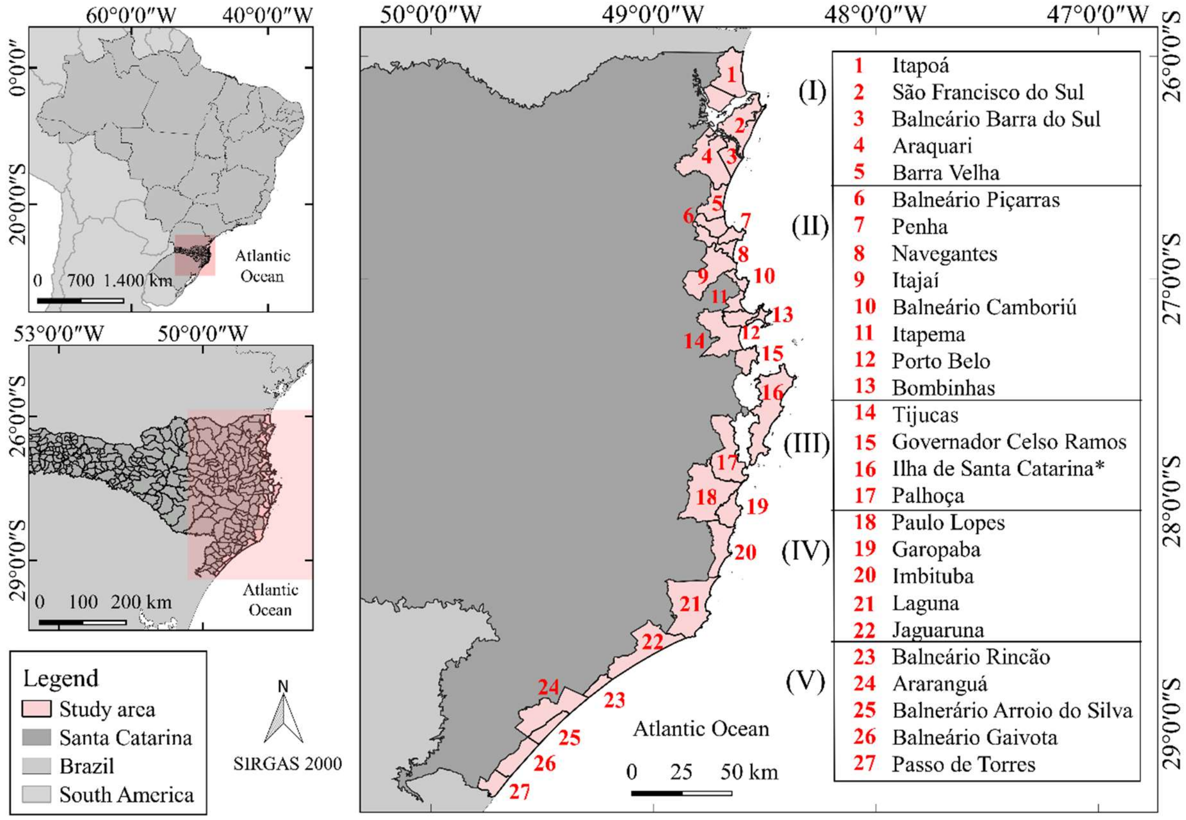


Figure 4-1 – Representation of municipalities exposed to the open ocean belonging to the coastal zone of Santa Catarina. *We only consider the Ilha de Santa Catarina, which belongs to the municipality of Florianópolis. Source: Own elaboration with data adapted from the Brazilian Institute of Geography and Statistics (IBGE)

The study area was subdivided into five main sectors, according to the State Coastal Management Plan (Santa Catarina 2006), namely: (I) north; (II) central-north; (III) central; (IV) central-south; and (V) south (Figure 4-1). The delimitation of the coastal zone of Santa Catarina was ratified by MMA Ordinance No. 34, February 2, 2021, issued by the Ministry of the Environment (Brasil 2021). Comprehensive insights into the geological, geomorphological, climatic, sedimentary, and oceanographic characteristics of the study area can be found in the detailed study by Klein et al. (2016).

4.2 Approach and methodology

The flowchart illustrates the methodological steps devised in this study (Figure 4-2). The assessment and chronological analysis of coastal natural disasters spanning from 1998 to 2020 were grounded in four official databases: The Website of the Civil Defense of the State of Santa Catarina; Integrated Disaster Information System (S2ID); Atlas of Natural Disasters in the State of Santa Catarina: the period from 1980 to 2010; and Brazilian Atlas of Natural Disasters: 1991 to 2012.

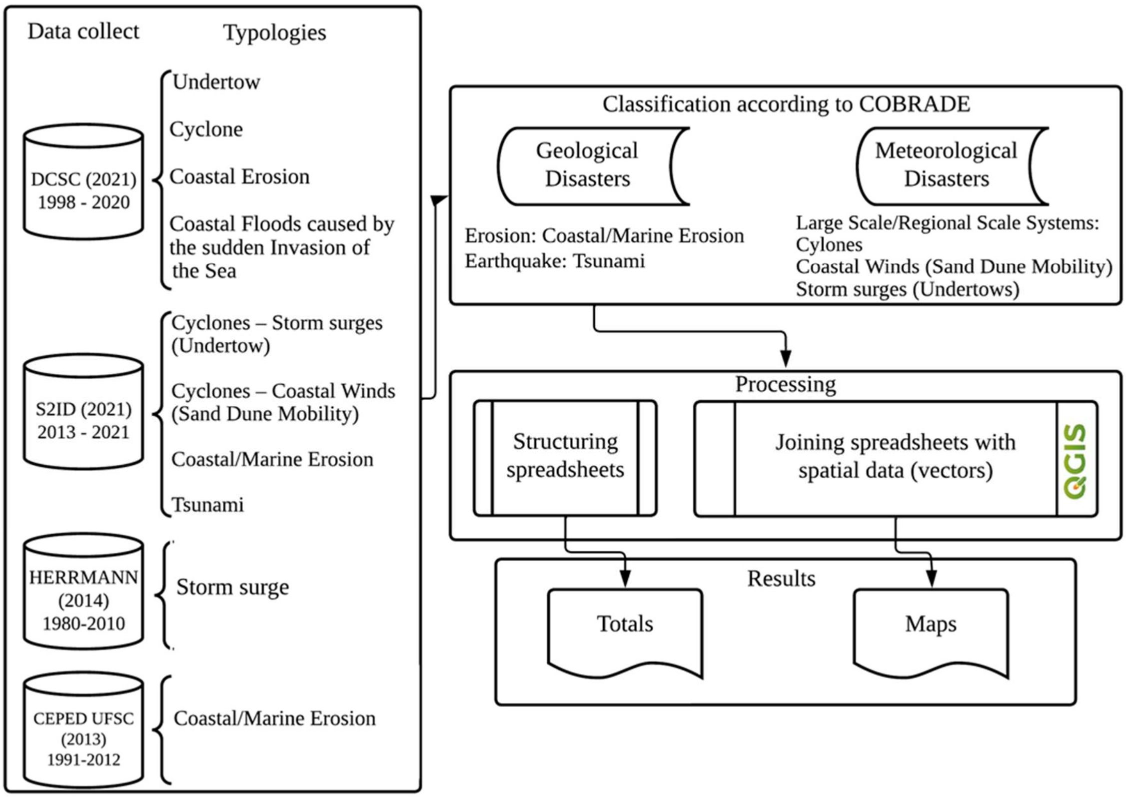


Figure 4-2 – Main steps of the research process

The coastal natural disasters we collected were declared as Emergency Situations (SE) and/or States of Public Calamity (ECP) by the municipalities. A SE indicates a significant disruption of normal conditions within a municipality, state, or region due to a disaster, which partially hampers its ability to respond. On the other hand, a ECP signifies a severe alteration of normal conditions within a municipality, state, or region, enacted due to a disaster that significantly impairs its response capacity (CEPED UFSC 2012).

Official data were collected from the website of the Civil Defense of the State of Santa Catarina between 1998 and 2020. Under the "Municipalities" tab, the SE and ECP declarations were identified for each respective municipality. Among the varied typologies employed by the Civil Defense to denote coastal natural disasters in municipalities, the subsequent categories were chosen: Undertow; Cyclone; Coastal Erosion; e Coastal Floods Caused by the Sudden Invasion of the Sea.

Another important official database was verified, to complement the possible gaps that still exist. The S2ID integrates several products of the National Secretariat for Civil Defense and Protection (SEDEC) and provides information on disaster occurrences based on official data sources (S2ID 2021). The S2ID provides disaster records between the years 2013 and 2021 from the Management Report of informed data. The typologies used are following the nomenclature of the Brazilian Classification and Coding of Disasters (COBRADE 2012). Are listed as Cyclones – Storm Surges (Undertows); Cyclones – Coastal Winds (Sand Dune Mobility); Coastal/Marine Erosion; and Tsunami (Table 4-1).

Table 4-1 – Brazilian Disaster Classification and Coding. Source: COBRADE (2012)

Group	Subgroup	Type	Caption/Subtitle
Geological	Erosion	Coastal/Marine Erosion	-
	Earthquake	Tsunami	-

Meteorological	Large Scale / Regional Scale Systems	Cyclones	Coastal Winds (Sand Dune Mobility); Storm Surges (Undertows)

Two important Atlas were also consulted. The first was published in 2013 by the University Center for Studies and Research on Natural Disasters (CEPED) of the Federal University of Santa Catarina (CEPED UFSC 2013). CEPED UFSC collects and presents data on natural disasters between 1991 and 2012. For this paper, the Erosion chapter was considered, which, among others, deals with natural disasters of Coastal/Marine Erosion. The second, Atlas of Natural Disasters in the State of Santa Catarina: the period 1980 to 2010 was organized by Herrmann (2014). In this Atlas, the data was listed in the Storm Surge chapter. Finally, the results were organized into spreadsheets and mapped using QGIS 3.16.0 software.

4.3 Results

Between 1998 and 2020, 135 coastal natural disasters were found in municipalities exposed to the open ocean in the state of Santa Catarina. A table is available at the following link as supplementary material. Among the 27 municipalities studied, 23 were impacted by disasters (Figure 4-3). The following municipalities did not register coastal natural disasters: Governador Celso Ramos, Paulo Lopes, Imbituba, and Jaguaruna. The north (Itapoá to Barra Velha) and central-north (Balneário Piçarras to Bombinhas) sectors were the most affected by coastal natural disasters in the time series. Among the municipalities in the central sector, Ilha de Santa Catarina stands out, belonging to the municipality of Florianópolis, and Tijucas, where 10 and 2 disasters were found in the time series, respectively.

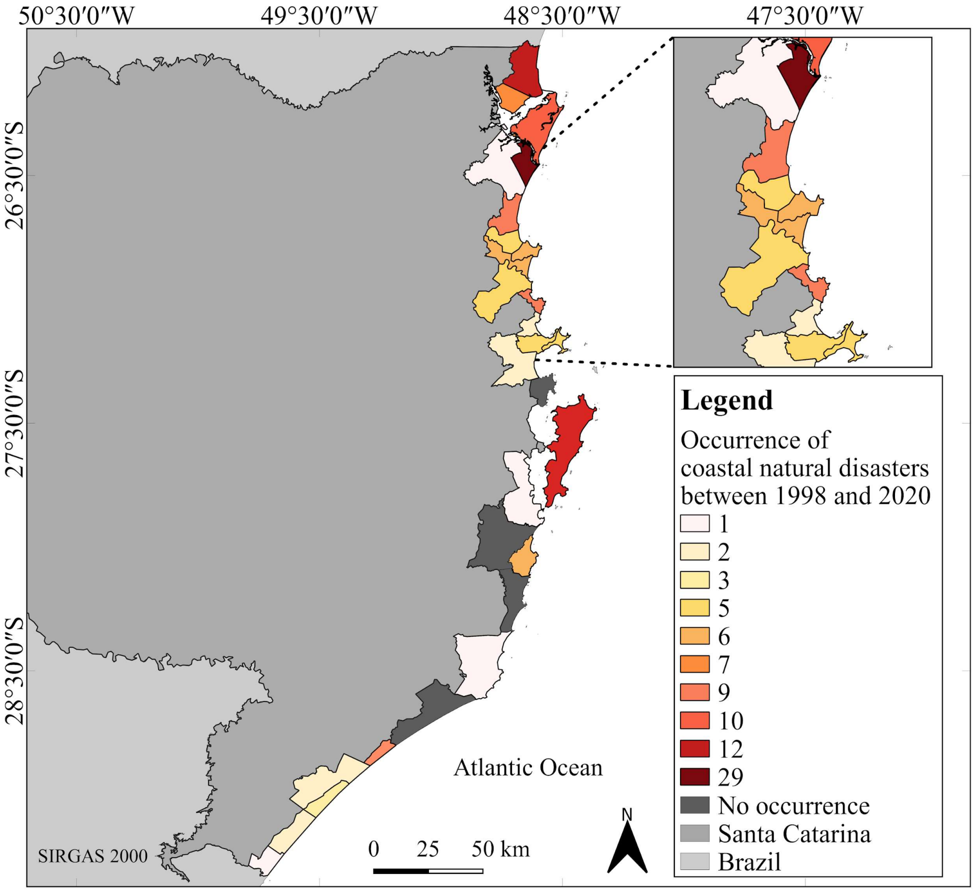


Figure 4-3 – Spatial distribution of coastal natural disasters in the study area. Source: Own elaboration with data adapted from the Brazilian Institute of Geography and Statistics (IBGE)

Figure 4-4 shows, from north to south, the occurrence of coastal natural disasters in the municipalities of the study area. The three most affected places were Balneário Barra do Sul with 29 disasters, followed by Itapoá with 12 records, and Santa Catarina Island with 10 registers between 1998 and 2020. It should be noted that disasters occurred in the municipality of Balneário Rincão were counted until October 2, 2003, as the municipality of Içara. Balneário Rincão was emancipated on October 3, 2003. Thus, reports with coastal impacts began to mention this municipality.

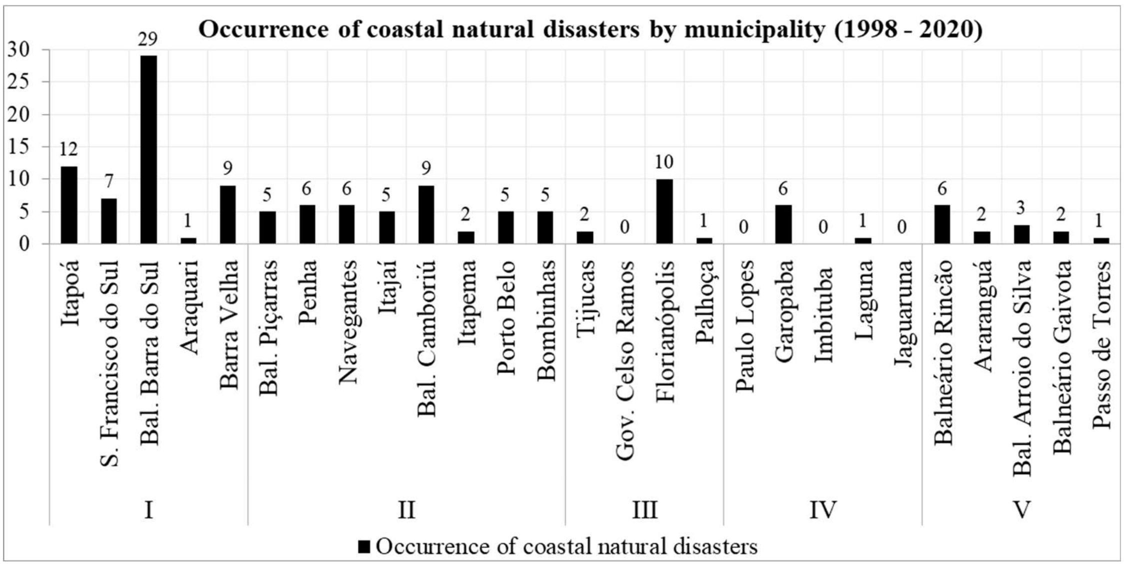


Figure 4-4 – Distribution of the occurrence of coastal natural disasters in the municipalities of the study area

Regarding the annual temporal distribution of coastal natural disasters, higher numbers were found and recorded from 2016 onwards (Figure 4-5). Before this period, the year 2001 stands out, in which 14 disasters were recorded, related to the occurrence of intense extratropical cyclones added to syzygy tidal conditions (present in new or full moon conditions) (Rudorff et al. 2014). In 2010, SC was also impacted by 14 coastal disasters, which also occurred due to the presence of extratropical cyclones in the ocean, with wind gusts of up to 100 km/h at sea. These strong winds caused waves of two to three meters high between the municipalities of Florianópolis and Passo de Torres and, added to the high tide, caused the sea level to rise, thus the accumulation of water on the coast (CEPED UFSC 2013). The year 2017 was marked by consecutive and severe coastal natural disasters along with the state of SC, also associated with cyclonic formations in the South Atlantic and syzygy tides (De Lima et al. 2020; Leal et al. 2020).

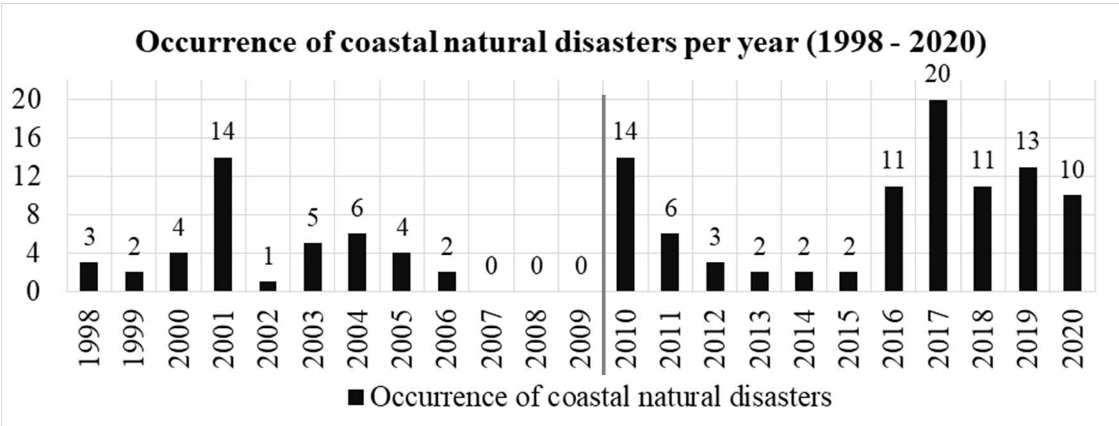


Figure 4-5 – Annual time distribution of coastal natural disasters in the municipalities of the study area

Based on the annual distribution of disasters shown in Figure 4-5, the time series was divided into two periods. We consider the first period between 1998 and 2009, which, in general, had fewer records of coastal natural disasters, and the second period between 2010 and 2020, with the highest number of records. Two factors need to be highlighted concerning the two periods: a) the greater number of disaster records by the Civil Defense may have occurred from the second period onward, given the evolution in technology and digital databases; b) the increase in the occurrence of disasters can, and we believe in this condition, be associated with increasing urbanization in coastal areas, climate change, and therefore, the intensification of extreme atmospheric and oceanographic events.

Therefore, Figure 4-6 presents the spatial distribution of the occurrence of coastal natural disasters in the municipalities studied between 1998 and 2009 and 2010 and 2020. The north and central-north sectors continue to be the most impacted in the two series analyzed, despite having the lowest number of records in the first period. There is also a lower number of disaster records in the central-south and south sectors between 2010 and 2020.

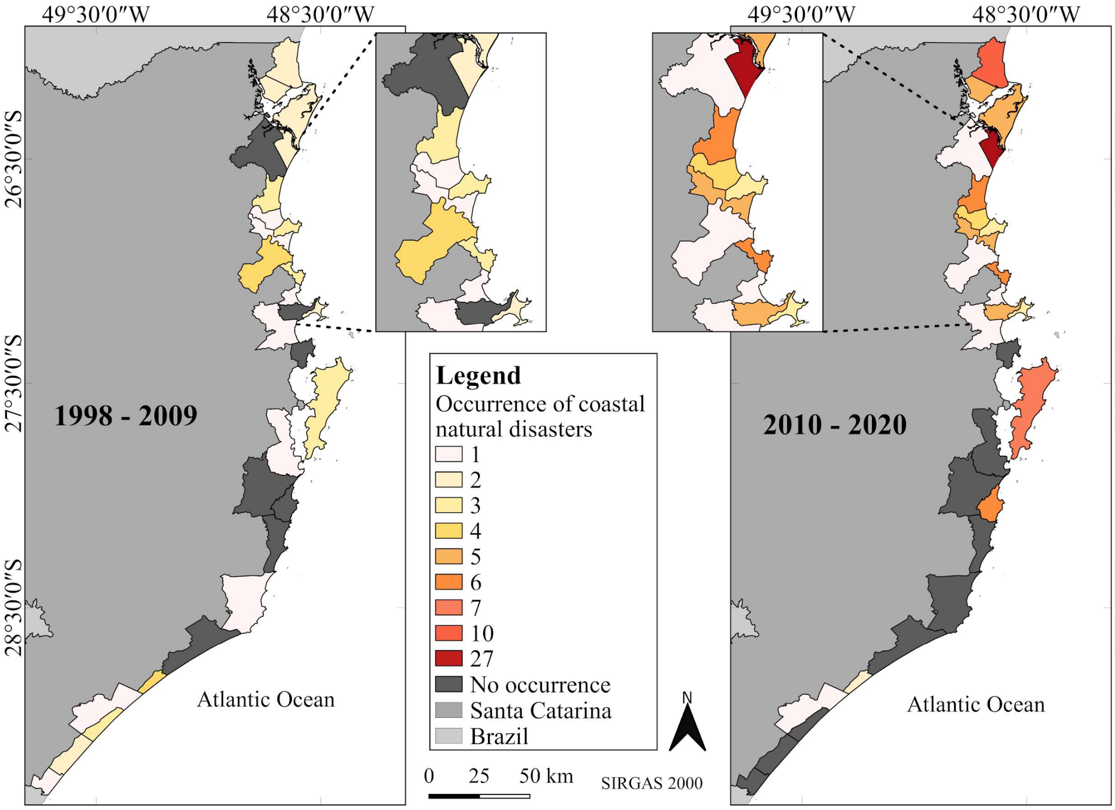


Figure 4-6 – Spatial distribution of the occurrence of coastal natural disasters in the study area between 1998 - 2009 and 2010 - 2020

Figure 4-7 shows the distribution of the occurrence of coastal natural disasters along the time series. The municipality most affected, Balneário Barra do Sul, recorded the highest number of occurrences in the second analyzed period, between 2010 and 2020. This same period was also considerably more marked for the municipalities of Itapoá, Porto Belo, and Garopaba. In these cases, a difference of at least five occurrences of disasters can be observed between the first and second periods. In addition, municipalities such as São Francisco do Sul, Barra Velha, Balneário Piçarras, Navegantes, Balneário Camboriú, Bombinhas, and Florianópolis also recorded more disasters in the second period.

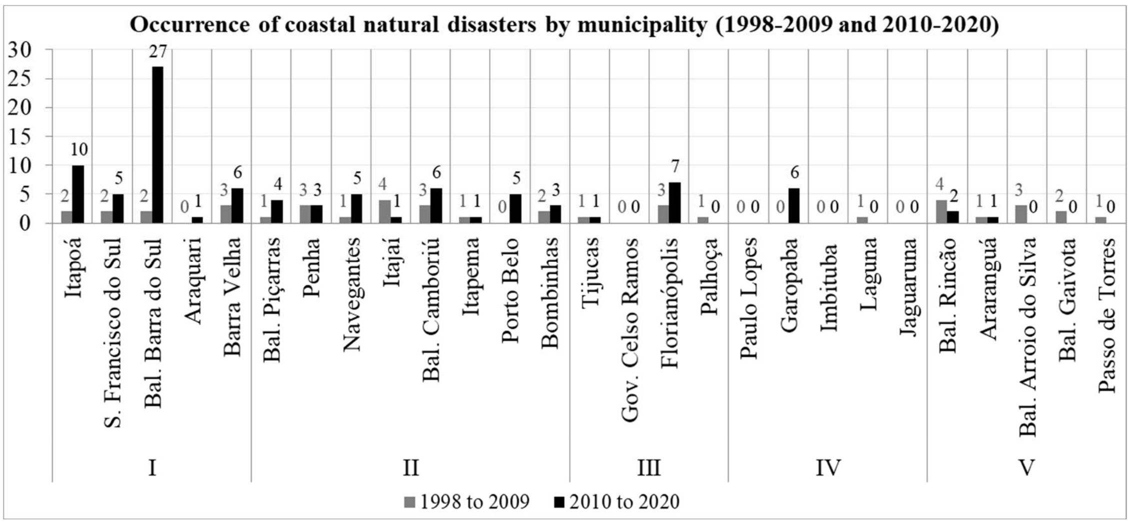


Figure 4-7 – Distribution of the occurrence of coastal natural disasters in the municipalities of the study area between 1998 - 2009 and 2010 - 2020

The first observation for the increase in the occurrence of coastal natural disasters is related to population and urban growth, mainly in the last decade (Robaina and Oliveira 2013; Gruber et al. 2011; IPCC 2014; Luijendijk et al. 2018). Table 4-2 presents the estimated population for 1998 and 2020, as well as the percentage growth that occurred over the 22 years. Thus, it can be observed that the population in the north and central-north sectors grew, for the most part, by over 50% during the period. Although the correlation between population growth and the occurrence of disasters is not strictly linear, this observation aligns with the result that identified these two sectors as the most affected by such disasters (Fig. 3). Furthermore, it reinforces the discussion on the impact of disorderly urban growth without adequate management plans and coastal degradation (Klein et al. 2006; Bulhões 2020; Leal et al. 2020; Furtado and Bonetti 2021; Pazini et al. 2022).

Table 4-2 – Population growth between 1998 and 2020 in the study area. Source: Adapted from IBGE (2020)

	Municipalities	**Total Population 1998**	**Estimated Population 2020**	**Growth %**
I	Itapoá	6.284	21.177	237.0
	S. Francisco do Sul	29.733	53.746	80.8
	Bal. Barra do Sul	4.186	11.035	163.6
	Araquari	18.804	39.524	110.2
	Barra Velha	14.101	29.860	111.8
II	Bal. Piçarras	10.129	23.772	134.7
	Penha	16.557	33.284	101.0
	Navegantes	34.630	83.626	141.5
	Itajaí	141.976	223.112	57.1
	Bal. Camboriú	62.263	145.796	134.2
	Itapema	19.498	67.338	245.4
	Porto Belo	8.198	21.932	167.5
	Bombinhas	6.335	20.335	221.0
III	Tijucas	20.588	39.155	90.2
	Gov. Celso Ramos	11.602	14.606	25.9
	Florianópolis	278.576	508.826	82.7
	Palhoça	86.861	175.272	101.8
IV	Paulo Lopes	5.615	7.569	34.8
	Garopaba	12.514	23.579	88.4
	Imbituba	33.574	45286	34.9
	Laguna	43.486	46.122	6.1
	Jaguaruna	13.683	20.288	48.3
V	Bal. Rincão	--	12946	--
	Araranguá	54.216	68.867	27.0
	Bal. Arroio do Silva	5.116	13.430	162.5
	Bal. Gaivota	4.663	11.260	141.5
	Passo de Torres	3.944	9.048	129.4

The two municipalities, Balneário Barra do Sul and Itapoá, most impacted by disasters in the time series grew by 237% and 163.6%, respectively, concerning population. The population growth added to the geographical characteristics can considerably worsen the conditions of the coast. In addition, currently, in both municipalities, part of the urbanization and rigid structures are exposed to the sea without natural protection (Silveira et al. 2019) (Figure 4-8)

Figure 4-8 – Urban infrastructure and rigid structures in the north sector. Source: Google Earth Pro

On the other hand, it is noteworthy to mention that areas such as Passo de Torres and Balneário Gaivota (Figure 4-9) fall within the category of beaches safeguarded by dunes, sandbanks, and naturally resilient environments that effectively mitigate erosion and flooding (Bulhões 2020). This distinction in natural protection mechanisms underscores a significant disparity between these areas and their counterparts. Broadening our perspective, the comparative analysis reveals that the south sector showcases a notably elevated level of natural protection in contrast to the north sector of Santa Catarina.

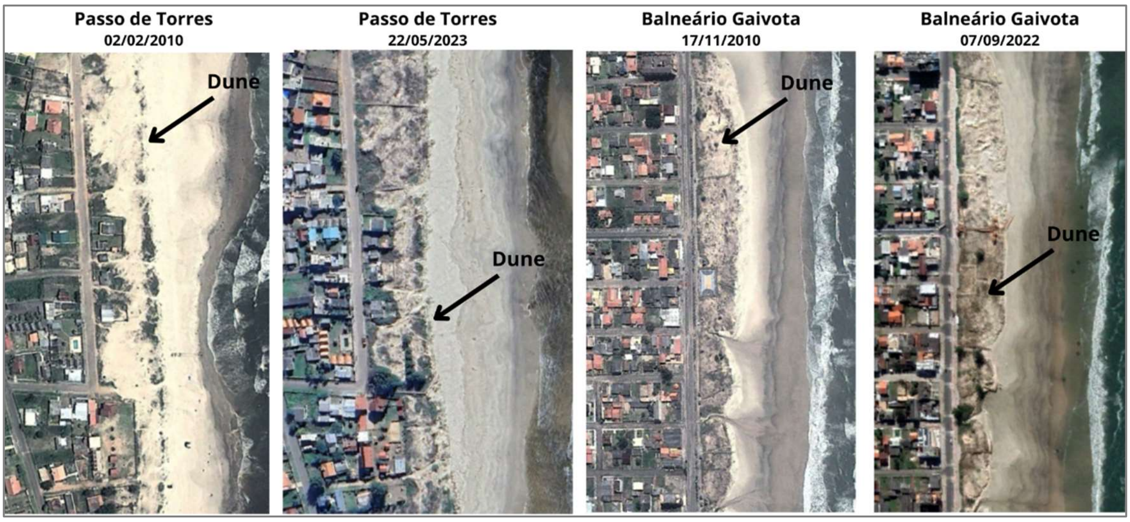
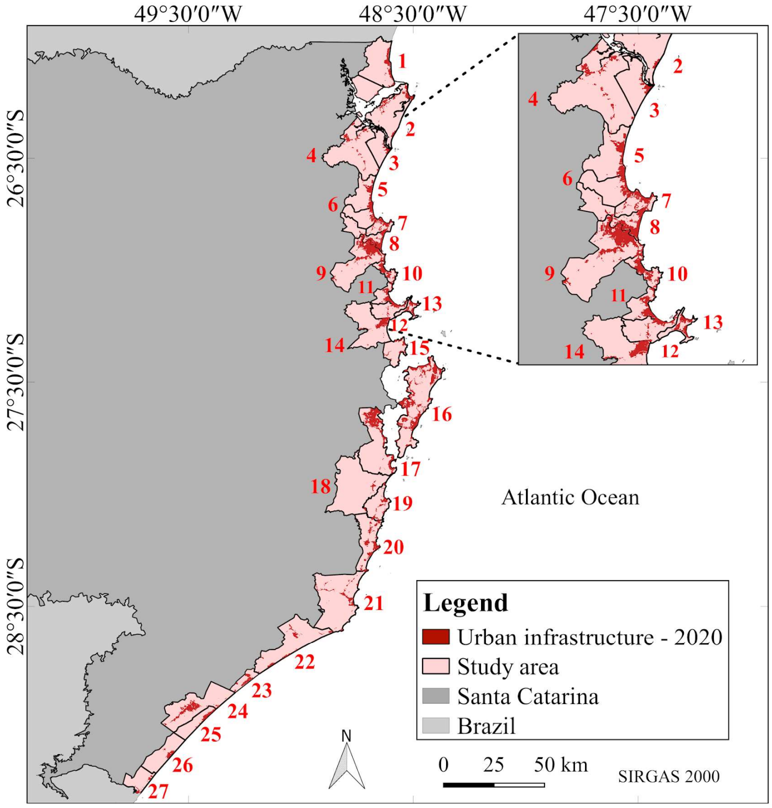


Figure 4-9 – Urban infrastructure and natural protection in the south sector. Source: Google Earth Pro

In 2020, the north, central-north, and central sectors appeared to be the most urbanized (Figure 4-10). On the other hand, in the central-south and south sectors, there is the lowest concentration of stabilized population near the sea. Klein et al. (2006) state that, in Santa Catarina, undue human occupation of the shoreline is the main agent causing erosion and retreat of the coastline. It is also evident that on the coast of SC, mainly in the most occupied and irregularly urbanized sectors, there is a tendency for the analyzed disasters to become recurrent (CEPED UFSC 2013). This is due to coastal dynamics and anthropic interventions, since, once the beach edge has been altered by human occupation, the beach's sedimentary balance (sediment transport between land and sea) can also be altered, contributing to the deficit of sediments, leading to an erosion process (Souza et al. 2005).



Estimated Population (2020)

	Municipality	Population
1	Itapoá	21177
2	São Francisco do Sul	53746
3	Balneário Barra do Sul	11035
4	Araquari	39524
5	Barra Velha	29860
6	Balneário Piçarras	23772
7	Penha	33284
8	Navegantes	83626
9	Itajaí	223112
10	Balneário Camboriú	145796
11	Itapema	67338
12	Porto Belo	21932
13	Bombinhas	20335
14	Tijucas	39155
15	Governador Celso Ramos	14606
16	Florianópolis	508826
17	Palhoça	175272
18	Paulo Lopes	7569
19	Garopaba	23579
20	Imbituba	45286
21	Laguna	46122
22	Jaguaruna	20288
23	Balneário Rincão	12946
24	Araranguá	68867
25	Balnerário Arroio do Silva	13430
26	Balneário Gaivota	11260
27	Passo de Torres	9048

Source: IBGE Cidades - 2020

Figure 4-10 – Urban infrastructure in 2020 of the municipalities in the study area. Source: Adapted from IBGE (2020) and MapBiomas

The second piece of evidence we found pertains to the months with the highest frequency of coastal natural disasters. Table 4-3 shows the number of occurrences of coastal natural disasters per month between 1998 and 2020. The municipalities of Governador Celso Ramos, Paulo Lopes, Imbituba, and Jaguaruna are not listed as they did not record disasters in the period. Regarding the municipalities most affected, Balneário Barra do Sul, Itapoá, and Florianópolis, respectively, the months of the autumn, spring, and winter seasons stood out with the highest number of disaster records, respectively. Overall, it is also evident that there was a reduced frequency during the months of December and January, corresponding to the summer season.

Table 4-3 – Number of coastal natural disaster records per month for municipalities in the study area

Municipalities	Occurrence of coastal natural disasters per month (1998 - 2020)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 Itapoá	0	0	0	1	2	1	1	3	1	2	1	0
2 S. Francis. do Sul	0	2	0	0	1	0	0	1	0	2	1	0
3 Bal. Barra do Sul	1	1	2	2	3	4	5	2	1	3	2	3
4 Araquari	1	0	0	0	0	0	0	0	0	0	0	0
5 Barra Velha	0	0	1	1	4	1	0	1	1	0	0	0
6 Bal. Piçarras	1	0	0	0	0	0	1	1	2	0	0	0

7 Penha	0	1	0	0	1	1	0	0	1	2	0	0
8 Navegantes	0	0	0	0	2	1	0	0	2	1	0	0
9 Itajaí	0	0	0	1	0	0	1	1	0	2	0	0
10 Bal. Camboriú	0	0	2	0	2	0	1	1	2	1	0	0
11 Itapema	0	0	0	0	1	0	0	0	1	0	0	0
12 Porto Belo	0	0	0	2	0	0	0	0	2	1	0	0
13 Bombinhas	0	0	0	0	1	0	1	1	1	1	0	0
14 Tijucas	0	0	0	0	1	0	0	0	0	0	0	1
16 Florianópolis	0	0	1	1	3	1	2	0	2	0	0	0
17 Palhoça	0	0	0	0	0	0	0	1	0	0	0	0
19 Garopaba	0	1	1	0	0	1	0	0	0	1	2	0
21 Laguna	0	0	0	0	1	0	0	0	0	0	0	0
23 Bal. Rincão	1	0	1	1	1	1	0	0	0	1	0	0
24 Araranguá	0	0	1	0	0	0	0	0	0	1	0	0
25 Bal. Ar. do Silva	0	0	1	0	1	1	0	0	0	0	0	0
26 Bal. Gaivota	0	0	1	0	0	1	0	0	0	0	0	0
27 Passo de Torres	0	0	1	0	0	0	0	0	0	0	0	0

Finally, Figure 4-11 presents the monthly distribution of coastal natural disasters in the study area. The autumn, winter, and spring months were evident as the most impacting on the coast of Santa Catarina. This result corroborates previous research (Gares et al. 1994; Camargo et al. 2000; Rudorff et al. 2014), which showed the three seasons as priorities for the occurrence of extratropical cyclones in southern Brazil, which cause coastal storms.

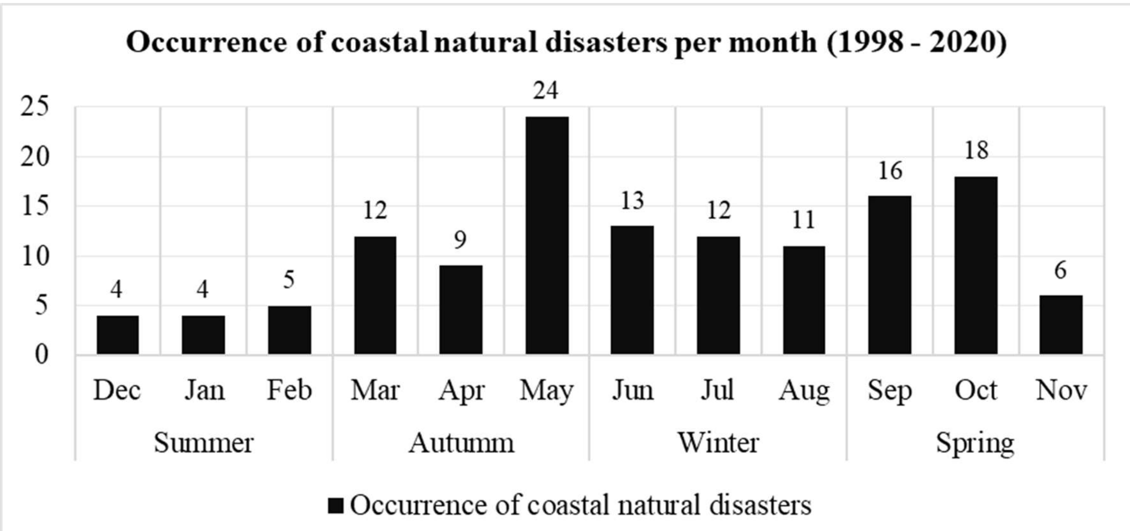


Figure 4-11 – Monthly temporal distribution of coastal natural disasters in the municipalities of the study area

4.4 Discussions

The identification of areas most affected by disasters in our study partly aligns with the results presented by Klein et al. (2006), in which the authors identified local hot spots (Balneário Barra do Sul, Barra Velha, Piçarras, Navegantes, and Balneário Camboriú) and detailed the measures that have been undertaken for coastal protection. Regarding the central sector, both Ilha de Santa Catarina and Tijucas exhibit a greater exposure to meteoceanographic events, with a particular emphasis on Ilha (Horn Filho 2006). Pazini et al. (2022) also discussed the extremely high risk of storm-induced impacts in the same municipalities within the central sector.

In general, in the southern region of Brazil, coastal natural disasters occur during the passage of intense atmospheric systems such as Atlantic polar fronts and extratropical cyclones. Additionally, disasters can become even more intense when a coastal storm occurs under syzygy tide conditions (Rudorff et al. 2014; Short and Klein 2016; Dalinghaus et al. 2018; Leal et al. 2018; Leal et al. 2020).

Furthermore, the greatest morphological changes on beaches usually occur during processes of sudden energy transfer to the system, such as during storm surges. These phenomena are generated by the combined action, to varying degrees, of astronomical tides, large waves, and winds blowing towards the coast that lead to a rise in sea level (Carter 1988; Rudorff et al. 2014). According to these authors, negative effects associated with storm surges occur throughout the coastal zone of Santa Catarina, which are predominantly the result of disturbances caused by coastal storms associated with extratropical cyclones and the passage of cold fronts.

Several researchers discuss the global increase in the occurrence of extreme events in the last decade (Ruggiero et al. 2010; Coco and Ciavola 2017; Kim 2020; Lin-Ye et al. 2020; Chen et al. 2021; IPCC 2021; Nicholls et al. 2021; IPCC 2022a; IPCC 2022b; Lockwood et al. 2022). This is also evidenced in the southern region of Brazil (Camargo et al. 2000; Marengo et al. 2009; Rudorff et al. 2014), which leads to an intensification of natural disasters mainly in coastal areas without natural protection, such as dunes, wetlands, and mangroves (Bulhões 2020).

Prevention measures should be taken, given the scenario of intensification of extreme events and coastal storms, which increase the occurrence of coastal natural disasters. Combined ecosystem-based and structural adaptation responses are being developed, and there is growing evidence of their potential to reduce adaptation costs and contribute to erosion control, and coastal protection (Bulhões 2020; IPCC 2022a). In human systems, some coastal settlements face soft adaptation limits due to technical and financial difficulties in implementing coastal protection. Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages are unequally distributed across systems, regions, and sectors (Bonetti et al. 2013), and are not comprehensively addressed by current financial, governance, and institutional arrangements, particularly in vulnerable developing countries, such as Brazil (IPCC 2021).

Urbanization in areas with greater exposure and the improper use of natural resources are among the main factors that increase the occurrence of coastal natural disasters. Therefore, it is essential to understand the interactions between oceans and coastal zones to build a strategic vision so that measures can be taken in response to new scenarios of sea-level rise and coastal erosion (Nicolodi and Petermann 2011; IPCC 2021; IPCC 2022a; IPCC 2022b). The restoration of natural environments, while also reducing coastal erosion and protecting against storm surges, thus, reducing the risks from sea-level rise (IPCC 2022b).

In light of the current context, studies like ours emphasize the importance of updating official databases responsible for disaster recording. Additionally, these studies meticulously identify areas with higher incidences of disaster occurrences, making a significant contribution to the effective management of priority zones. Furthermore, this approach centralizes all occurrences within a single database streamlining the formulation of plans by entities responsible for coastal areas. The methodology employed in this research is transferable to any coastline through the precise dating of catastrophic events and subsequent data mapping.

4.5 Conclusions

On the coast of the state of Santa Catarina, there is a significant and growing record of natural disasters resulting from the combined action between the increase in urbanization and the intensification of the occurrence of meteoceanographic events. One of the main factors in the high exposure of SC comes from the location/orientation of the coast, which exposes the coastal zone to the influence of high-energy meteorological and oceanographic systems from the South Atlantic.

The dating of coastal natural disasters indicated five relevant points: 1) There were more coastal disasters in the north, central-north, and central sectors of SC between 1998 and 2020; 2) The period between 2010 and 2020 was significantly more impactful, that is, more disasters were recorded compared to the first period, 1998 to 2009; 3) The municipalities with the most records of coastal natural disasters were Balneário Barra do Sul, Itapoá and Florianópolis (considering only Ilha de Santa Catarina), respectively; 4) The three fastest-growing sectors in the SC are the north, central-north, and central; and 5) The seasons of autumn, spring, and winter are more impacting for the coast.

These contributions extend beyond observations to encompass an integrated database of coastal natural disaster records within coastal zone of Santa Catarina between 1998 and 2020. The achievement of this comprehensive repository required meticulous cross-referencing of disaster records from diverse official sources, exposing the gaps in the primary S2ID database. The methodological approach was anchored in leveraging four official databases: the Website of the Civil Defense of the State of Santa Catarina, S2ID. We discerned coastal disasters through analysis of Emergency Situations (SE) and States of Public Calamity (ECP) declarations by municipalities. Data acquisition encompassed the period from 1998 to 2020 from the Civil Defense website and from 2013 to 2021 via S2ID records. Moreover, two Atlases were referenced to enrich our dataset. The analysis results were organized into spreadsheets and effectively visualized using QGIS 3.16.0 software.

The implications of our study are substantial, furnishing valuable insights into disaster chronology and opening avenues for further investigation. Our subsequent paper aims to characterize meteoceanographic intricacies, encompassing elements such as wave height, direction and period, tide, wind speed and direction, and atmospheric pressure, for each occurrence of coastal natural disasters. The objective is to identify the meteoceanographic patterns responsible for the occurrence of such disasters in the study area, and future works will include the use of machine learning algorithms for this purpose. Ultimately, we aim to deliver a comprehensive body of knowledge that can empower managers and the Civil Defense in formulating strategies for robust coastal disaster prevention and management.

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5 WEATHER PATTERNS ASSOCIATED WITH COASTAL DISASTERS IN SOUTHERN BRAZIL

LEAL, K. B.; DE SOUZA, D. C.; LAVIOLA-DA-SILVA, M. B.; PEREIRA, S. S.; KÖRTING, T. S.; ROBAINA, L. E. S. Weather patterns associated with coastal disasters in Southern Brazil. **Submetido**.

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Abstract. Synoptic weather systems have the potential to trigger nearshore wave extremes, which, coupled with human occupation, increase the risk of coastal erosion and its associated damages. Understanding weather patterns (WP) facilitates disaster anticipation through forecasting; this enables managers to implement preventive measures, thus reducing the reliance on response and recovery in affected areas. In this context, the study aims to identify WP associated with coastal disasters in Santa Catarina (SC) state between 1998 and 2020. The dates of the disasters were determined based on the Disaster Information Form (FIDES) and the Damage Assessment Form (AVADAN), encompassing 105 coastal disasters. The dates with similar WP were clustered using the K-Means algorithm. It was based on zonal and meridional wind components, geopotential height at 1000 hPa from the ERA5 reanalysis, and significant wave height (Hs) from the WAVERYS. The results indicated five WPs associated with coastal disasters, confirming the influence of cyclonic and anticyclonic systems in the study domain. The clustering analysis revealed that the WP characterized by a cyclonic system near the Santa Catarina coast was the most prevalent, resulting in substantial wave heights impacting the north, central-north, central, and south sectors. Additionally, the WP characterized by an intensification of the high-pressure system (with a more stationary character) in the central and southern-central portions of the domain impacts all sectors of the coast. Seasonal analysis highlighted autumn, particularly May, as the period with the highest disaster occurrences. The recorded damages varied significantly, prompting a discussion on the importance of accurately and comprehensively completing disaster report forms. Therefore, this study is regarded as a tool for disaster prediction and preparedness, strategic planning, and prevention actions among coastal risk managers.

5.1 Introduction

Oceanic conditions, particularly wave generation-related ones, are largely shaped by the atmosphere-ocean interaction. Meteorological systems like cyclones and anticyclones are key drivers of ocean dynamics, influencing wave characteristics through wind-induced momentum transfer, e.g., Campos et al. (2013) and Campos et al. (2018). Regions experiencing increased occurrences of extreme waves are often associated with the effects of more intense cyclones or cyclones with slower propagation, the latter leading to prolonged wind interaction with the ocean surface (Gramcianinov et al., 2021).

Furthermore, besides extreme waves, the largest storm surges may arise when slowly propagating extratropical cyclones encounter a strong anticyclone, leading to a tighter pressure gradient and longer duration of onshore winds (Catalano and Broccoli, 2018). Storm surge refers to the abnormal rise in water level generated by wind and atmospheric pressure changes (Harley, 2017) associated with tropical or mid-latitude storms. In conjunction with tides, it is one primary driver of coastal flooding associated with storm events (Resio and Westerink, 2008; Kumbier et al., 2017; Chen et al., 2021; Tausía et al., 2023). A study conducted by Marcos et al. (2019) investigated the relationship between storm surges and wind waves along global coastlines using numerical simulations. They found that in over half of coastal regions, storm surges are often accompanied by large wind waves, thus increasing the potential for coastal flooding. Leal et al. (2022) compiled several studies discussing the coastal impacts of storms in the context of climate change. Their study emphasizes the increasing volume of research in this area, highlighting the growing recognition of its significance and urgency.

Extreme wave heights are projected to increase globally (O'Grady et al., 2021) contributing to coastal sea-level changes and enhancing coastal flooding and erosion due to their interaction with tides and storm surges during extreme events (Dodet et al., 2019; Nicholls et al., 2021). Additionally, climate change is expected to increase the frequency and intensity of extreme wave events (Reguero et al., 2019), leading to coastal disasters and the displacement of millions (Griggs and Reguero, 2021). Climate change is likely to result in increased rates of both sea-level rise and storm-related impacts (Karamouz et al., 2014; Hansom et al., 2015; Rangel-Buitrago et al., 2020), and low-lying coastal areas represent one of the most vulnerable areas to these impacts (IPCC, 2022). Leal et al. (2022) provide a comprehensive overview of the coastal impacts of storm surges in the context of a changing climate. Their study emphasizes the increasing volume of research in this area, highlighting the growing recognition of its significance and urgency.

The seasonal oscillation of the South Atlantic Subtropical High (SASH) plays an important role in atmospheric circulation over the South Atlantic (SAt) region (Reboita et al., 2019). However, the most extreme waves along the southern and southeastern Brazilian coast are associated with extratropical cyclones over the SAt (Bitencourt et al., 2011; Campos et al., 2018). Extreme waves and wave-related events in this region are also influenced by transient anticyclonic systems (Machado et al., 2010; Gramcianinov et al., 2020; de Souza & Ramos-da-Silva, 2021), which typically move in an easterly to southeasterly direction in the SAt (Gramcianinov et al., 2019; de Souza et al., 2024). Rocha et al. (2004) and, more recently, Gramcianinov et al. (2020) highlighted those cyclones associated with high sea waves along the Brazilian coast often originate around 30ºS to 35ºS. These cyclones are influenced by a west-southwestward moving anticyclone, which intensifies the winds in the western sector of the cyclones, creating a fetch for wave formation (Rocha et al., 2004; Bitencourt et al., 2011; Dragani et al., 2013).

Understanding the influence of weather patterns (WP) on oceanic conditions, particularly those contributing to extreme conditions, is vital for various human activities, (e.g., Camus et al., 2014; Rueda et al., 2016; Laviola-da-Silva et al., 2024). Frequent wave extremes and storm surges, often triggered by severe weather events, require adaptive measures due to the significant risk posed to coastal populations. Moreover, such waves directly impact coastal communities and the environment by inducing coastal erosion, flooding in coastal areas, and infrastructure damage. Studies conducted by Luijendijk et al. (2018), Mentaschi et al. (2018), and Vousdoukas et al. (2020) estimated concerning levels of erosion on sandy beaches worldwide. Muehe (2018) showed the same on the Brazilian coast, the most evident erosion impacts are seen on sandy beaches. Coastal erosion is primarily caused by a shortage of sediment resulting from depleted sources, material removal for dune supply, and significant human interventions (Muehe, 2018; Bulhões, 2020).

Coastal disasters have significant adverse impacts on human activities, infrastructure, and societal and political realms, as ecological and conservation concerns (Paula and Dias, 2015; Rangel-Buitrago et al., 2020). Extreme events associated with atmospheric processes are common in the southern region of Brazil (Reis et al., 2022). Along the southern Brazilian coast, intense wind and wave events (Bitencourt et al., 2011) result in severe socioeconomic losses (Rudorff, 2014; Dutra and Scherer, 2021; Nicolodi et al., 2023). This is evident in Santa Catarina (SC), where material damages reached approximately US$ 2,8 million, affecting 1551 individuals during the disaster that occurred in Araranguá in March 2004 due to Hurricane Catarina (S2ID, 2024).

Santa Catarina state has reported 105 coastal disasters between 1998 and 2020 (S2ID, 2024), indicating that it is one of the most affected states in Brazil. However, the WP occurring onshore and near the coast are not categorized and described, and the potential human and material damages resulting from each coastal area must be clearly outlined (Leal et al., 2023; Pereira et al., 2018). In this context, this study aims to identify the WP associated with coastal disasters in Santa Catarina, Brazil, (Fig. 1) between 1998 and 2020, along with their respective human, material, and environmental damages. As specific goals, we highlight the following:

1. Coastal disasters inventory based on Brazilian official databases (e.g., Disaster Information Form (FIDES) and the Damage Assessment Form (AVADAN) documents accessible through the Integrated Disaster Information System (S2ID) website and updated previous research conducted by Leal et al. (2023).
2. Determine WP associated with coastal disasters dates, based on the Laviola-da-Silva et al. (2024) methodology, wherein the dates of coastal disasters with similar weather conditions were clustered using the K-Means algorithm, based on significant wave height (Hs) from the Global Ocean Waves Reanalysis, zonal and meridional wind components (u and v) and geopotential height at 1000 hPa atmospheric level from the ERA5 reanalysis dataset.
3. Analyze the temporal and spatial distribution of the WP associated with coastal disasters.
4. Analyze the type of damage, including the number of human damages, and estimate material, environmental, public economic losses, and private economic losses in BRL associated with coastal disasters linked to specific WP.

5.1.1 Study area

Santa Catarina state is located in southern of Brazil (26º - 29º S). The coast trends south then southwest for approximately 430 km and contains 922 km of open coast and bays, with 246 sandy beaches occupying 60% of the coast (Klein et al., 2016). Within the coastal zone, 27 municipalities are in contact with the Atlantic Ocean and are grouped into five main sectors according to the State Coastal Management Plan (Santa Catarina, 2006), namely: (I) north; (II) central-north; (III) central; (IV) central-south; and (V) south (Figure 5-1). In Santa Catarina, approximately 1,983,440 people, about 26.06% of the total population of 7,610,361, reside in the studied municipalities (IBGE, 2022).

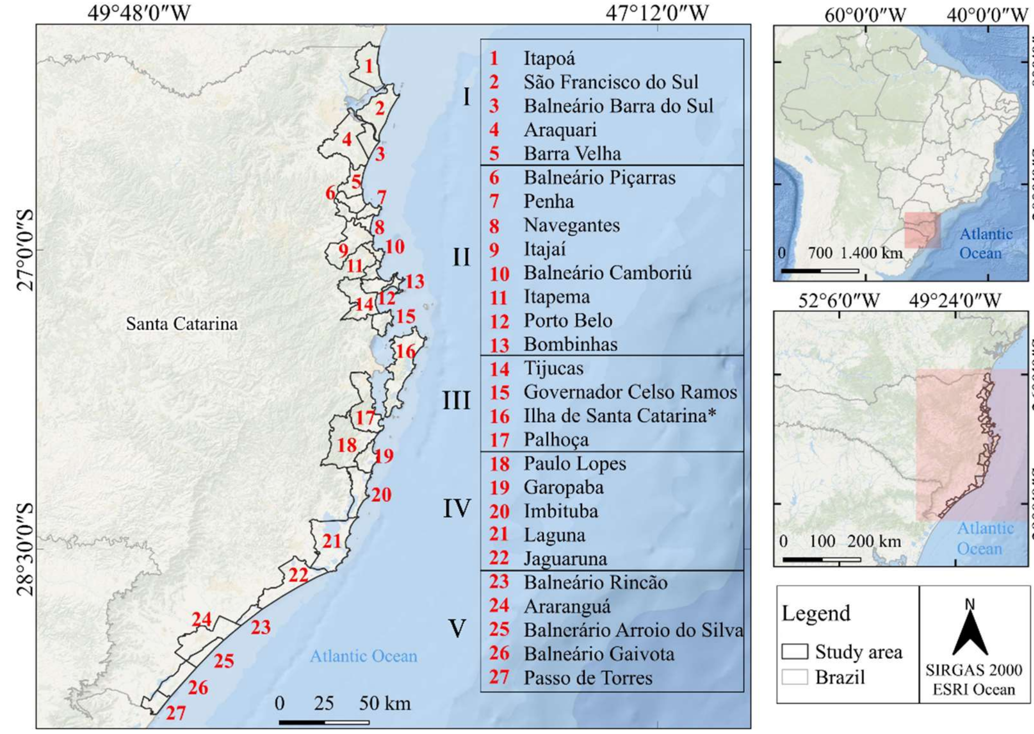

Figure 5-1 – Study area and municipalities exposed to the open ocean belonging to the coastal zone of Santa Catarina state, Brazil. We only consider the Ilha de Santa Catarina (16), which belongs to the municipality of Florianópolis.

Santa Catarina experiences a humid subtropical climate (Nimer, 1989; Luiz, 2015) characterized by the SASH system (Reboita et al., 2019) that leads to significant seasonal variations in temperature and precipitation. The state lies in the climatic transition zone between the more tropical northern regions and the increasingly temperate southern areas (Nimer, 1989). In the summer, tropical air masses dominate, bringing hot and humid conditions. In contrast, in the winter, sub-polar air masses frequently intrude, leading to cooler weather, strong southerly winds, and frontal rain (Monteiro, 2001). Frontal systems, especially cold fronts, are common and are crucial in weather patterns, often bringing heavy rainfall and abrupt temperature changes. Additionally, the region is periodically affected by cyclonic formations, particularly extratropical cyclones, which can result in intense storms, strong winds, and high waves (Rocha et al., 2004; Bitencourt et al., 2011; Gramcianinov et al., 2020).

Regarding wave climate along the coast, Santa Catarina is influenced by local wind systems and distant swell waves. The more energetic wave directions are from the south and southeast, driven by the prevailing wind patterns and cyclonic activities in the South Atlantic (Oliveira et al., 2019; Gramcianinov et al., 2020). These conditions create a dynamic wave environment that varies seasonally, with the highest average wave significant high (Hs) values typically occurring during the autumn and winter (from May to late September) while the lowest Hs are observed from January to March (summer in South Hemisphere) (Oliveira et al., 2019). During winter, swell conditions prevail in the region (Araújo et al., 2003) due to stronger winds and frequent cyclonic activity (Reboita et al., 2019). Winter and spring showcase elevated wave energy, attributed to the passage of cold fronts in the area, surpassing the frontal activity observed during autumn and summer (Rodrigues et al., 2004; Oliveira et al., 2019). The wave patterns in the region significantly impact coastal erosion (Klein et al., 2006; Leal et al., 2020; Pazini et al., 2022), mainly during May and October (Leal et al., 2023).

Santa Catarina's coast can be classified as varied, with rocky sections, especially in regions like Florianópolis and Bombinhas, and sandy sections, such as Balneário Gaivota and Balneário Rincão. The beaches also vary widely: sandy beaches like Jurerê and Joaquina, known for their fine white sand; rocky beaches such as Armação Beach in Florianópolis; steep beaches like Praia do Rosa in Imbituba; and estuarine beaches near estuaries and mangroves, characterized by fine sediments and influenced by the mix of fresh and saltwater, such as Pântano do Sul Beach. A detailed study of geological, geomorphological, climatic, sedimentary, and oceanographic characteristics of the study area can be found in the study by Klein and Menezes (2001), Horn Filho (2003), and Klein et al. (2016).

5.2 Material and methods

Figure 5-2 shows all the steps performed in the study, described below. The methodological steps were divided into two stages: 'Coastal disasters data collection' and 'Weather Patterns Classification'.

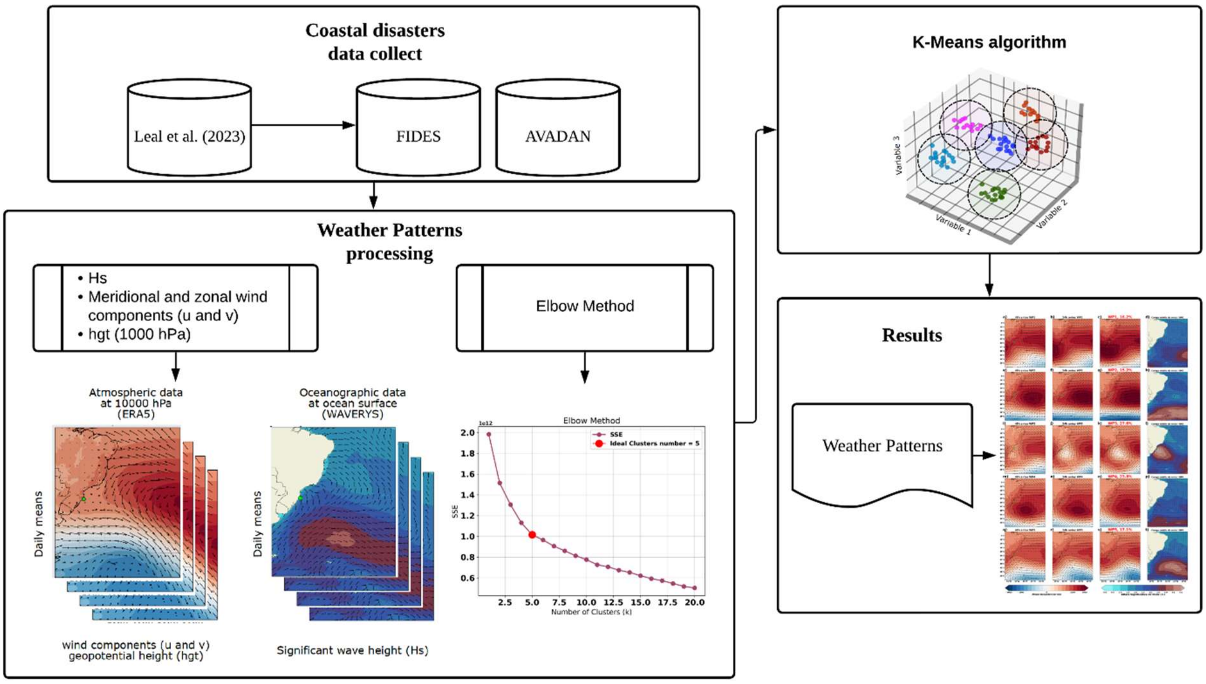

Figure 5-2 – Flowchart with methodological steps.

5.2.1 Coastal natural disasters data collection

As the first step, we adopted the identification of coastal disasters and typologies carried out by Leal et al. (2023), which was based on four official databases: the website of the Civil Defense of the State of Santa Catarina, Integrated Disaster Information System (S2ID), Atlas of Natural Disasters in the State of Santa Catarina from 1980 to 2010, and Brazilian Atlas of Natural Disasters from 1991 to 2012. The data sources and structure are fully described in Leal et al. (2023). The authors regarded the disasters declared as Emergencies Situations (EM) and/or States of Public Calamity (SPC) by the municipalities. Following Law No. 14,750 of 2023, an EM is declared when an abnormal situation caused by a disaster results in damage and losses that partially impair the response capacity of the public authorities of the affected entity, necessitating additional resources from other entities of the Federation to address the situation. On the other hand, an SPC is declared when an abnormal situation caused by a disaster results in damage and losses that substantially impair the response capacity of the public authorities of the affected entity, such that the situation can only be overcome with the assistance of other entities of the Federation (Brasil, 2023).

For the present study, the FIDES and AVADAN documents from the Civil Defense of Santa Catarina were accessed for the same reference period to validate whether the dates accurately corresponded to the coastal disasters rather than the municipality's decrees. These documents are formally prepared by the civil defense managers of each municipality when an EM or SPC occurs. Within these same documents, it was possible to collect data on the number of human damages or affected people and an estimate in BRL of the material, environmental, public (PuLoss), and private (PrLoss) economic losses.

In the study conducted by Leal et al. (2023), the authors identified 135 decrees in coastal disasters that occurred in Santa Catarina state between 1998 and 2020. The collected dates from the Civil Defense were cross-validated with the synoptic chart and the corresponding weather pattern. However, after initial tests, it was detected that some weather patterns did not correlate with extreme coastal events. After consulting secondary databases, such as FIDES and AVADAN documents, the authors found that some coastal disaster dates in the initial dataset did not match the dates recorded in the Civil Defense documents we had access to at that time. As a result, at least 30 records of coastal disasters referred to by Leal et al. (2023) were excluded from the present analysis to ensure that the WP algorithm was run only for dates with extreme meteorological and oceanic events of which the occurrence date was validated. This led to 105 coastal disasters declared by municipalities in SC, which can be viewed in the spreadsheet attached as supplementary material to this manuscript. The list includes affected municipalities, coastal sector, date of occurrence (month, day, year), EM or SPC declaration, related weather pattern, number of human damages, material damage (BRL), environmental damage (BRL), public economic losses (BRL) and private economic losses (BRL).

5.2.2 Weather Patterns Classification

To determine the predominant synoptic conditions associated with coastal disasters, we adapted the methodology developed by Laviola-da-Silva et al. (2024). A similar approach has already been implemented for Southern Brazil but with a focus on mean climate conditions (de Souza et al., 2022). This author proposed a methodology to detect the primary synoptic conditions related to wave extremes in specific regions (the link is available under 'Data availability'). For selected dates, this method retrieves significant wave height (Hs), meridional and zonal wind components (u and v), and geopotential height data (hgt) at the 1000 hPa atmospheric level. Hs is obtained from the Global Ocean Waves Reanalysis (WAVERYS), provided by the European Union's Copernicus Marine Service Information (CMEMS, 2023). The WAVERYS dataset includes 3-hourly data spanning from 1993 to 2017 on a 1/5° grid. Concurrently, atmospheric data (u, v, and hgt) is sourced from the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5) (Hersbach et al., 2023), covering 3-hourly data from 1940 to the present on a 1/5° grid.

The method employs the K-Means algorithm for determining the primary Weather Patterns linked to wave extremes. The K-Means algorithm (MacQueen et al., 1967; Hartigan e Wong, 1979) is an iterative clustering method that partitions data into K distinct clusters, where each data point is assigned to the cluster with the nearest mean (centroid). The selection of K, the number of clusters, is a crucial step based on calculations that maximize the explanation of variability. The K-Means++ enhancement (Arthur & Vassilvitskii, 2007), used within Python's

Scikit-Learn package (Pedregosa et al., 2011), improves centroid selection by basing it on a probability distribution proportional to the square of the distance from each data point to the closest centroid. This method aids in dispersing the initial centroids across the data, reducing the probability of local convergence. The algorithm involves iterative cycles of assigning points to the nearest centroid and updating centroids by calculating the mean of the points in each cluster. This process continues until the centroids stabilize between iterations or a maximum of iterations is reached (300 was used for this study).

After defining randomly initial centroids c1, c2, ..., and cK, each iteration involves assigning data points to the nearest cluster. This assignment minimizes the sum of squared distances from each data point to its nearest centroid. Following this assignment, centroids are recalculated as the mean of the points in each cluster. This updating continues until the centroids stabilize between iterations, indicating convergence. The stability of this convergence is verified through multiple runs.

For implementing this method, daily averages of all data retrieved (hgt, u, v, and Hs) for the coastal disaster dates were computed. The selected dates correspond to Santa Catarina (SC) coastal disasters between 1998 and 2020. Subsequently, the Elbow Method (Thorndike, 1953) was applied to the atmospheric data to determine the optimal number of clusters. This optimal cluster count is then used to initialize the K-Means algorithm.

5.3 Results and discussions

5.3.1 Coastal Natural Disasters update

The distribution of the 105 coastal disasters across municipalities is shown in Figure 5-3. Notable are the municipalities of Balneário Barra do Sul with 23 occurrences of disasters, followed by Itapoá (11) and Barra Velha (9).

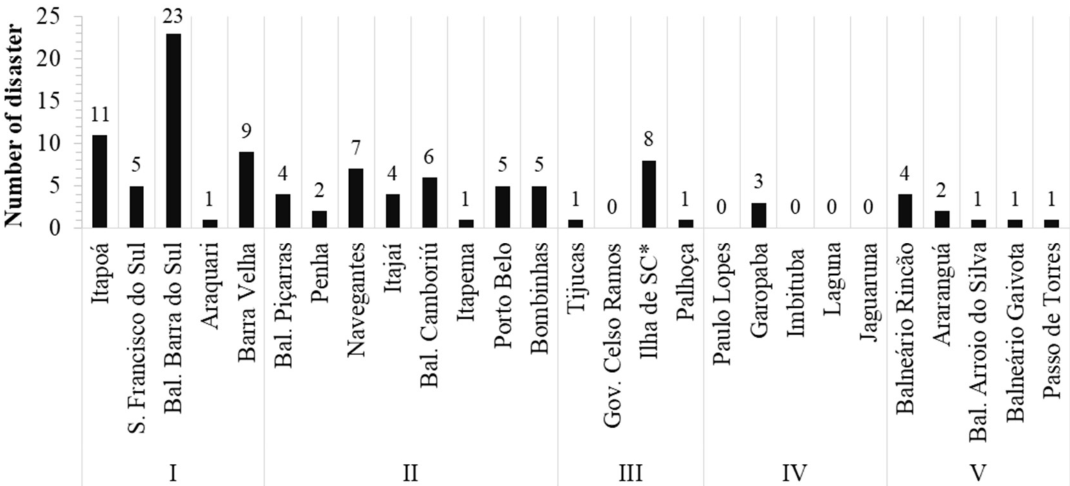

Figure 5-3 – Coastal natural disasters across the municipalities of Santa Catarina between 1998 and 2020.

The results were also represented by month, season, and year (Figure 5-4). Years lacking disaster records are omitted from the graph. Seasons are color-coded, with shades of orange representing Austral summer (DJF), yellow representing autumn (MAM), followed by blue for winter (JJA), and green for spring (SON). Autumn recorded the highest occurrence of coastal disasters, with May recording 18 occurrences. Both September and October saw 16 recorded coastal disasters during the spring season, and the winter months recorded 7, 8, and 10 disasters, respectively. Finally, in November and during summer, the occurrence of disasters was lowest in the study area. In terms of the years, 2017 stood out the most, with 20 disaster occurrences, followed by the years 2019 and 2020, with 12 occurrences each, and 2010 and 2016 with 11.

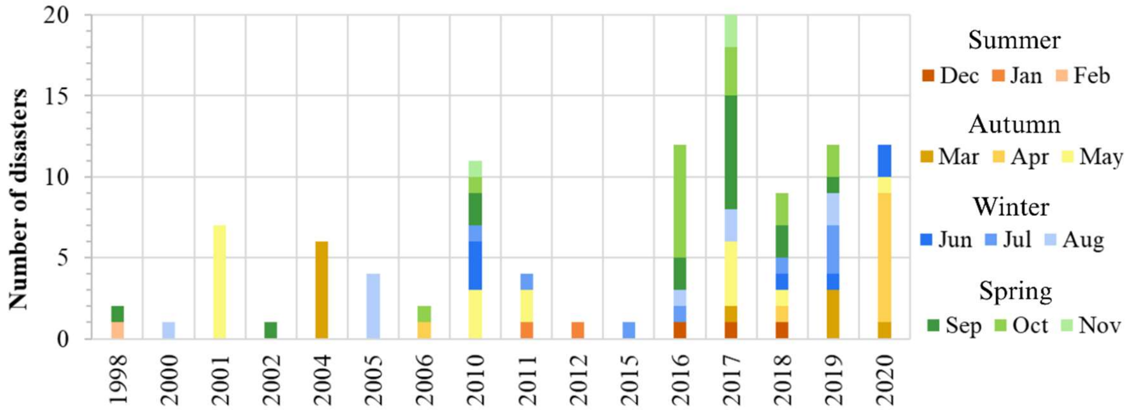

Figure 5-4 – Number of coastal natural disasters in the municipalities of Santa Catarina between 1998 and 2020, categorized by month, season, and year.

The results presented in Figure 5-3 and Figure 5-4 follow the same trend as those reported by Leal et al. (2023). The first period (between 1998 and 2009) continues to highlight the year 2001 as the most affected by disasters. No records were found for the years 2007 to 2009, and for the years 1999, 2003, 2013, and 2014, disaster dates could not be confirmed. It is believed that the documents may indicate the date of the decree; thus, they were excluded from the present study. In the second period (2010 to 2020), there is a similar trend as reported by the authors, showing more disaster records compared to the first period, with the year 2017 being the most impacted. The autumn and spring seasons also maintain the highest records.

5.3.2 Weather Patterns

A total of 82 atmospheric events were identified, resulting in 105 recorded disasters. These occurrences were subsequently subjected to clustering analysis using the K-Means algorithm, delineating five distinct WP (Figure 5-5). The result confirms the influence of cyclonic and anti-cyclonic systems in the study domain associated with coastal disasters in SC.

In WP1, a high-pressure system is observed near the northeast coast of Argentina, contributing to southeast winds along the coast of SC. Additionally, an atmospheric trough is observed in the southeast portion of the domain, possibly associated with the propagation of a cyclonic system further south. A high-pressure system is observed in WP2, in the eastern portion of the domain, generating northeast winds along the coast of SC. Regarding WP3, the main feature is a cyclonic system near the southern coast of Brazil, which is related to southerly winds along the coast of SC. WP4, despite showing similarity to WP2, displays a weaker high-pressure system, closer to the Brazilian Southern coast. However, the predominant wind direction in the study area, just like in WP2, remains northeast. In WP5, a pattern similar to that observed in WP1 emerges, with a high-pressure system near the northeast coast of Argentina, albeit with reduced intensity. The prevailing wind direction on the coast of SC is still southeasterly, but due to the reduced pressure gradient, it is weaker than in WP1. Unlike WP1, it can be noted as a cyclonic system in the southeast portion of the domain.

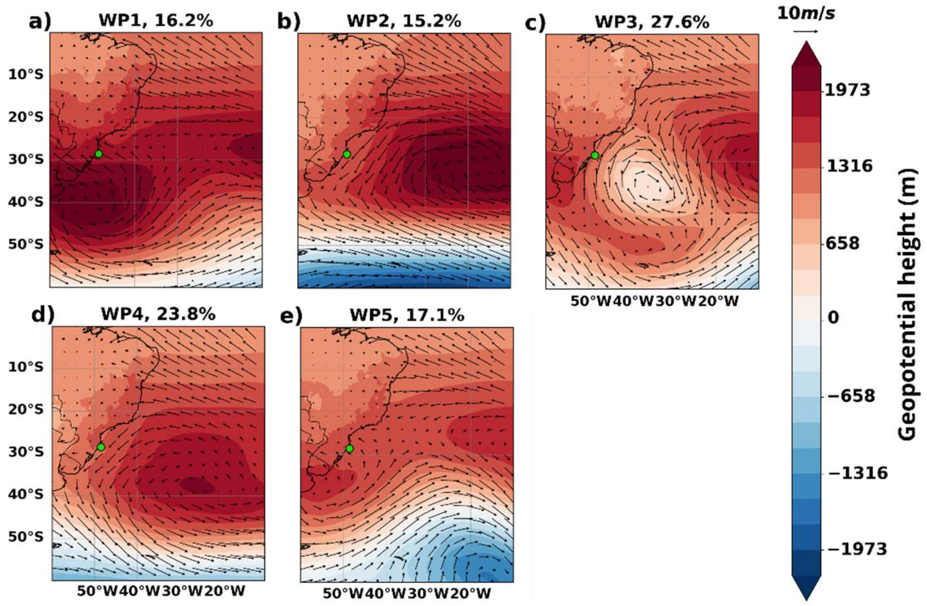

Figure 5-5 – Weather patterns (WP) related to the dates of coastal natural disasters declared in Santa Catarina state (green dot) between 1998 and 2020. Shading indicates the geopotential height field (m), while vectors represent wind direction and intensity (m/s) for the 1000 hPa level.

The percentage shown in both Figure 5-5 and Figure 5-6 indicates the number of disasters associated with each WP. indicates the number of disasters associated with each WP. In this context, WP3 had the highest occurrence (27.6%) among the 82 dates of coastal disaster occurrences dated in the time series, followed by WP4 (23.8%), WP5 (17.1%), WP1 (16.2%), and WP2 (15.2%). The temporal evolution of synoptic fields related to the selected WPs is presented in Figure 5-6. The first and second columns display the compositions of geopotential height and wind data, respectively, at 1000 hPa, for all dates corresponding to 48 hours and 24 hours before the disaster dates (third column). Meanwhile, the fourth column indicates the daily mean wave fields from the Waverys reanalysis for the days of disasters. The wave direction roses correspond to the mean wave fields.

According to the temporal evolution, in WP1, the passage of the atmospheric trough south of the domain, propagating eastwards, is noticeable, while the high-pressure system formed off the northeast coast of Argentina intensifies and moves southeastward. The same pattern is observed in WP5; however, in this case, exhibits a more stationary character in addition to the aforementioned lower intensity of the high-pressure system near the continent. This stationarity is reflected on the mean wave direction, which is SE for WP1 and SW for WP5. Both WPs present a predominant southeast wave direction towards the coast of SC, with heights exceeding 2.5 m. In WP2, as well as in WP4, there is a high-pressure system in the central and southern-central portions of the domain, respectively, with the WP2 system being more intense compared to WP4. Additionally, it is observable that for WP2, the high-pressure system moves eastward, whereas in WP4, the system exhibits a more stationary character. However, the wave field, depicted in Figure 5-6, shows a similar scenario for both WPs, with wave direction impacting the coast of SC from the east and wave heights exceeding 2.5 m. In contrast to the other WPs, WP3 reveals a cyclogenesis event near southern Brazil. The cyclonic system moves east/southeastward, whereas a high-pressure system is developing near Northeastern Argentina. The interaction with both systems generates waves from the south quadrant with wave heights exceeding 3.5 m, which impact the coast of SC.

In general, the waves in the five WPs are generated from the south to east quadrants, which produce the largest waves and have the greatest impact on the coast. Research by Pianca et al. (2010), Romeu et al. (2015), and Campos et al. (2018) indicates that in southern Brazil, the wave direction is predominantly from the southern quadrant, which is the direction of WP3 and occurs most frequently on disaster dates. Furthermore, these studies show that the most extreme waves in the region are mainly caused by extratropical cyclones that develop along the Uruguayan and Argentinean coasts. Results from Gramcianinov et al. (2020) show that these cyclones are generated around 30ºS and 35ºS over the continent, exactly as presented in WP3.

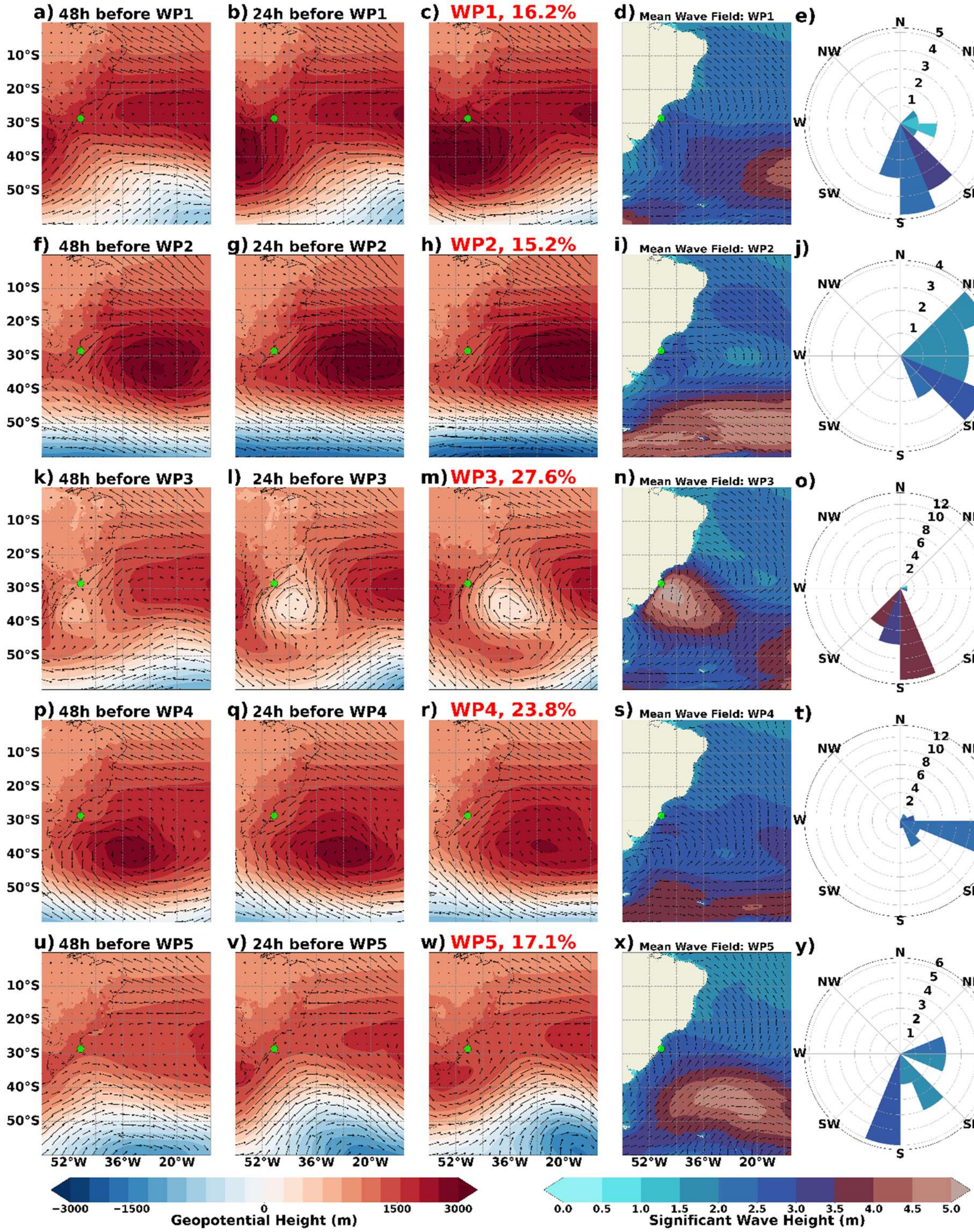

Figure 5-6 – Evolution of weather patterns related to the dates of coastal natural disasters, 24 hours and 48 hours before the geopotential height (m) and wind direction and intensity (m/s) for the 1000 hPa level and the significant wave height (m), recorded between 1998 and 2020 in Santa Catarina state (green dot).

Figure 5-7 demonstrates the occurrence of each WP by month and season for the Southern Hemisphere. All WPs occurred in autumn, winter, and spring, while only WPs 2, 3, and 5 were recorded in summer. WP1 primarily occurred in August, during winter. In contrast, WP2 occurred mainly in September, transitioning from winter to spring. WP3 shows significant occurrence in October, during spring, as well as in May and April, during autumn. WP4 had a higher occurrence in March, transitioning from summer to autumn. On the other hand, WP5 occurred equally in June, transitioning from autumn to winter, and in October, during spring. During the summer months, WP2 was the most frequent.

While cyclones forming in southern parts of South America do not exhibit strong seasonal variability (Gramcianinov et al., 2019; Crespo at al., 2022), the results presented here indicate that WPs related to cyclonic systems south of the domain are more prevalent during autumn and winter. Similarly, cyclones forming near Uruguay are more frequent during winter, with WPs related to this region being most common in the transitioning seasons. This suggests the presence of possible dynamical mechanisms acting during these seasons that differentiate cyclones from their mean behavior, thereby increasing their potential for significant impacts.

A study conducted by Pianca et al. (2010) presents large wave height values during autumn and winter due to the large occurrence of cyclonic systems and the associated cold fronts. This result corroborates with the higher occurrence of WP3 during autumn (April and May). Additionally, in this same WP, the waves come from the southern quadrant, which, as discussed earlier, are naturally larger.

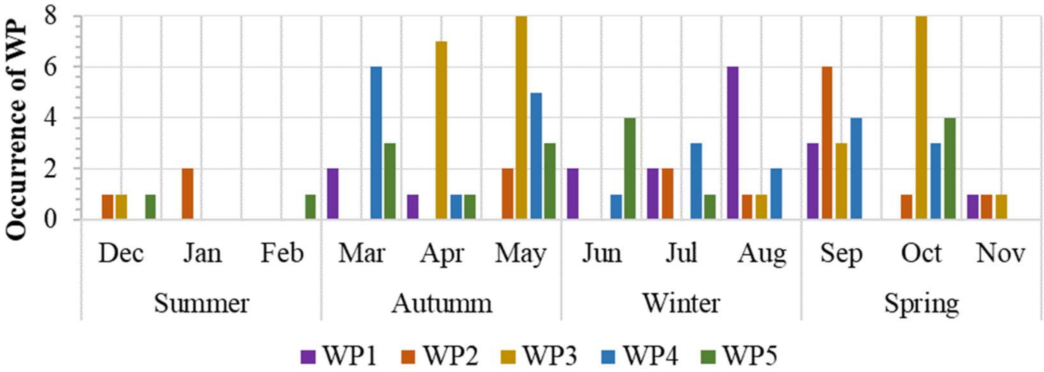

Figure 5-7 – Monthly occurrence of the weather patterns associated with coastal natural disasters in Santa Catarina state between 1998 and 2020.

The occurrence of each WP per municipality is depicted in Figure 5-8. WP1, represented in shades of purple, is associated with disasters recorded in 12 municipalities located in the north, central-north, central, and central-south sectors. Balneário Barra do Sul was the most affected by this pattern, five times, followed by Garopaba, which was affected twice. Palhoça presented only records derived from this WP1. Balneário Barra do Sul was also the most affected by WP2, WP4, and WP5. It is thus concluded that this municipality may be affected by any WP, as well as Barra Velha, albeit with lower frequency. WP2 affected seven municipalities in the north, central-north, and central sectors. Araquarari, which recorded only one disaster in the time series, was triggered by this WP. WP3 was related to disasters that occurred in 13 municipalities located in the north, central-north, central, and south sectors, with five occurrences notably in Itapoá and Tijucas, where the only record in the time series resulted from this WP. WP4 was associated with Hurricane Catarina, which occurred in March 2004. The consequences were evident in municipalities in the southern sector. Additionally, it is observed that the same pattern occurred in all sectors of SC, and it was related to the highest number of municipalities (14). Finally, WP5 was associated with disasters in nine municipalities, only located in the north and central-north sectors.

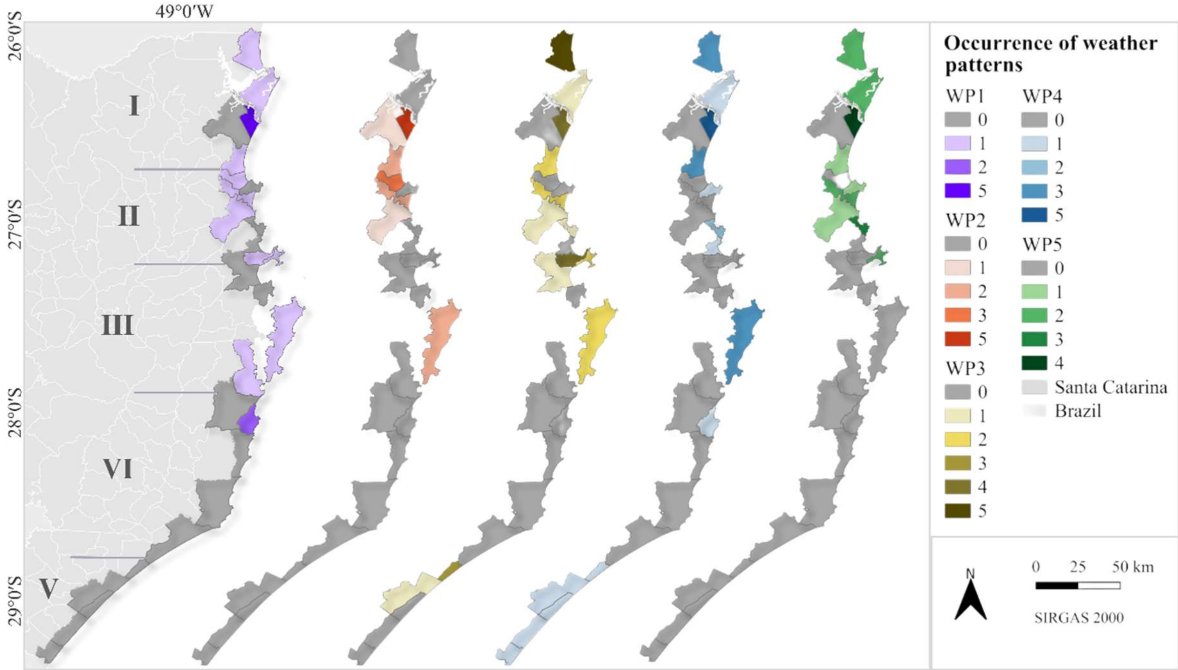

Figure 5-8 – Occurrence of each Weather Pattern (WP) by municipalities exposed to the open ocean belonging to the coastal zone of Santa Catarina state between 1998 and 2020. The five coastal sectors are identified from I to V.

Along the coastal sector of Santa Catarina, there are exposed, semi-exposed, and sheltered beaches (Klein and Menezes, 2001). Additionally, within the same municipality, beaches can vary in morphology from dissipative to intermediate to reflective (Wright and Short, 1984). This variation can occur even within the same beach arc, as discussed for Armação Beach on Santa Catarina Island. In this case, Abreu de Castilhos (1995) found a reflective stage in the most exposed sector (north), associated with larger grain size, and a dissipative to intermediate stage in the southern sector, predominantly composed of fine grains. Morphological characteristics are influenced by grain size, ranging from very fine to coarse sand. Beaches further south in Santa Catarina tend to have finer sediments compared to some beaches in the central to northern sectors, due to geological and geomorphological factors in the area. Southern beaches lack rocky headlands present in the central-southern to northern sectors.

Another important characteristic influencing disaster occurrence and registration is the preservation of natural coastal protection, which in the southern sector is provided by dune fields. In this sector, occupied areas are generally located just beyond these features, protecting them from events like storm surges. Conversely, towards the northern sector, there is a clear trend of constructions built directly at the upper limit of the beach, exposed to extreme events and, mainly, during high tides (Leal et al., 2020). Discussions regarding the occupation of the five coastal sectors of SC can be found in the study by Leal et al. (2023).

Furthermore, beaches along the SC coast have distinct orientations, ranging from south to north, passing through the east quadrant. Generally, beaches oriented south-southeast-east are more prone to coastal erosion disasters, receiving higher wave energies. Waves from the eastern quadrant can reach different beach orientations, and this is reinforced by the result obtained in WP4. Conversely, as also noted in the study by Leal, Bonetti, and Pereira (2020), beaches oriented north-northeast are also exposed to waves, albeit smaller, which if frequent and persistent, can cause erosion and disasters. It is important to note that waves undergo modifications when reaching shallow waters through processes like shoaling, refraction, and diffraction. In beaches delimited by rocky promontories, these processes can change wave direction and affect different areas of the beach arc (Klein et al., 2016).

5.3.3 Damages estimation

The damages from each coastal disaster are available in the attached spreadsheet provided as supplementary material. We obtained the damage records for 103 out of the 105 disasters. In practice, 30% of the coastal disasters reported by the Civil Defense show damages of about 0.00 BRL. Only 72 coastal disasters recorded at least one type of damage with values above 0.00 BRL, including affected individuals, estimated material losses, environmental damages, and public and private economic losses in BRL.

Regarding human damage, the municipality of Itajaí recorded 16,7000 affected individuals in the coastal disasters that occurred on April 24, 2006, and October 24, 2006. The former totaled 511,028 BRL in public losses (PuLoss) and 714,000 BRL in private losses (PrLoss), while the latter only presented PuLoss of 67,103.33 BRL.

Regarding material damages, the municipality of Araranguá recorded, on March 28, 2004, during the passage of Hurricane Catarina, 14,060,000 BRL and 1551 affected individuals. Additionally, it reported environmental damage estimated at R$ 50,000, PuLoss of 906,000 BRL, and PrLoss of 9,477,000 BRL. Balneário Gaivota also reported significant material damages during the same meteorological event, with 10,385,900 BRL spent on structures and 1070 affected individuals. It also registered environmental damage of 450,000 BRL, PuLoss of 687,456 BRL, and PrLoss of 11,726,600 BRL, which was the highest recorded in the time series.

The environmental damages were monetized in the AVADAN documents. On the other hand, in the FIDE documents, these damages were presented as a percentage of loss. Among the monetized damages, Santa Catarina Island recorded 19,422,000 BRL on July 16, 2010, with 1155 affected individuals, 2,835,000 BRL in material damages, and 540,000 BRL in PrLoss. Regarding PuLoss, the municipality of Navegantes recorded 5,921,300 BRL and 2900 affected individuals on October 28, 2016, an event that caused disasters in six more municipalities.

Overall, according to Table 5-1, the central-north sector recorded the highest human damages, with 38,1636 affected individuals in disasters between 1998 and 2020, followed by the south sector (59,633) and the north sector (41,508). Regarding monetized damages, despite declaring fewer disasters (9) compared to the north (49), central-north (34), and central (10) sectors, the south sector recorded the highest cost of damages at approximately 57,047,550.72 BRL, followed by the central sector (52,310,494.00 BRL), north sector (51,545,066.43 BRL), central-north sector (42,337,909.90 BRL), and central-south sector (2,799,000.00 BRL), where only three disasters occurred.

Table 5-1 – Total damages across coastal sectors of Santa Catarina

Total damages	North	Central-north	Central	Central-south	South	Total
Human	41508	381636	7622	398	59633	490797
Material (BRL)	19,475,927.19	16,837,951.96	9,190,494.00	2,069,000.00	30,266,047.36	77,839,420.51
Environmental (BRL)	5,390,000.00	10,138,600.00	37,600,000.00	80,000.00	510,000.00	53,718,600.00
PuLoss (BRL)	13,413,143.24	8,587,228.44	2,195,000.00	650,000.00	2,291,103.36	27,136,475.04

PrLoss (BRL)	13,265,996.00	6,774,129.50	3,325,000.00	0.00	23,980,400.00	47,345,525.50
Total (BRL)	51,545,066.43	42,337,909.90	52,310,494.00	2,799,000.00	57,047,550.72	206,040,021.05

The results indicate that the southern sector registered the highest economic losses during the period, primarily due to Hurricane Catarina. This single event in the southern sector caused a total of 56,195,456.00 BRL in damages. Another important factor that may highlight this sector's higher losses is the complete filling out of the FIDES and AVADAN documents. We observed that many of these documents reported all damages as 0.00 BRL. This underscores the importance of proper documentation by managers so that future studies can present more accurate perspectives on damages. The lack of precise data compromises the ability to assess and respond to disasters, making it essential to train and raise awareness among those responsible for recording this information.

During the study period, the Civil Defense recorded 490,797 individuals affected (fatalities, injured people, and displaced people) by coastal disasters. When this data is crossed with the WP that generated the coastal disasters (Figure 5-9a), WP5 was responsible for 33% of the total affected individuals, followed by WP4 (27%). The total estimated material damages (including, for instance, housing units, public health facilities, public education facilities, service providers, and public infrastructure works) amount to 77,839,420.51 BRL, with WP4 alone accounting for 52% of the total (Figure 5-9b). The total estimated environmental damages (including, for instance, water, air, and soil pollution or contamination, environmental protection areas, and permanent preservation areas) reach 53,718,600 BRL, with WP2 shouldering 48% of the responsibility and WP1 accounting for 36% (Figure 5-9c). The total estimated public loss (for instance, public health, potable water supply, public security, sewage, and urban sanitation systems) reaches 27,136,475.04 BRL, with WP3 responsible for 32% and WP4 for 29% (Figure 5-9d). Finally, the total estimated private loss (for instance, agriculture and livestock, industry, and commerce) value amounts to 47,345,525.5 BRL, where WP4 justifies 52% of it (Figure 5-9e). The results presented in Figure 5-9 are also based on the recorded damages. The relationship between the WP and the damages can be more accurate with the complete and correct filling out of damage forms by the civil protection managers.

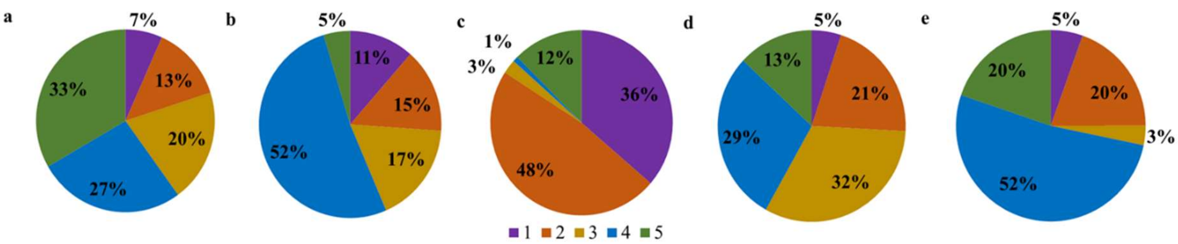

Figure 5-9 – Percentage of affected individuals (a), material damages (b), environmental damages (c), public economic losses (d), and private economic losses (e) recorded Civil Defense in each WP associated with coastal disasters in Santa Catarina state, between 1998 and 2020.

5.4 Conclusions

This study aimed to identify the WP associated with coastal disasters that occurred along the coast of the state of Santa Catarina. In summary, the municipalities of Balneário Barra do Sul, Itapoá, and Barra Velha were notably affected, with Balneário Barra do Sul experiencing the highest frequency of disasters. Seasonal analysis indicates that autumn, particularly May, saw the highest disaster occurrences, followed by spring months, especially September and

October. The clustering analysis using the K-Means algorithm identified five distinct WP influencing disaster, with WP3 being the most prevalent. This pattern, characterized by a cyclonic system near southern Brazil, resulted in substantial wave heights impacting the Santa Catarina coast. The temporal evolution of synoptic fields indicated the dynamic nature of these weather systems, with significant variations in high-pressure and cyclonic systems influencing disaster occurrences.

The impact of these disasters varied across different municipalities, with significant human, environmental, and material damages reported. The municipality of Itajaí recorded the highest number of affected individuals in specific events, while Araranguá and Balneário Gaivota reported substantial material damages during Hurricane Catarina. The study highlights the central-north sector as having the highest human impact, while the southern sector incurred the most considerable monetary damages despite fewer disaster events. It is known that the southern sector is less densely populated compared to the northern sector and, moreover, that the former has better-preserved natural coastal protection. Thus, we emphasize the importance of accurately and comprehensively completing the disaster forms, currently elaborated through FIDE by municipal managers, to enable the development of more accurate results.

The results obtained are based on Civil Defense estimates, which may present a degree of uncertainty. Nevertheless, despite the data limitations, this study provides an initial contribution to understanding how and which WPs associated with coastal disasters generate the most human and material damages overall. Given this scenario, we propose updating the damage records as a future work, which, in the first instance, needs to be improved by municipal managers.

The monetized damages underscore the severe economic impact of these coastal disasters, emphasizing the need for enhanced disaster preparedness and response strategies across the affected regions. The comprehensive dataset and analysis provide valuable insights into the WP and impacts of coastal disasters, informing future mitigation and adaptation efforts. By identifying the WPs and their relationship with each studied municipality, it becomes possible to predict disasters and work on the prevention of areas already recognized as at risk.

Data availability

The formulated algorithm to detect the primary synoptic conditions related to wave extremes in specific regions is available at https://github.com/matheusbonjour/WP_ExtremeWaves.

Author contribution

KBL: Writing – review and editing; Writing – original draft, methodology, data selection, investigation, formal analysis, and conceptualization. DCS and MBLS: Writing – original draft, methodology, data selection, software, and data curation. SSP, LESR, and TSK: Writing – original draft, supervision.

Competing interest

The authors declare that they have no conflict of interest.

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6 ANÁLISE INTEGRADA E CONCLUSÕES

Este capítulo tem como objetivo integrar e discutir os capítulos anteriores, respondendo ao objetivo geral de analisar de forma integrada o aumento do registro de desastres naturais costeiros, os danos decorrentes e os padrões meteorológicos associados em Santa Catarina. Adicionalmente, são apresentadas as conclusões alcançadas neste estudo.

O primeiro artigo da tese, apresentado no terceiro capítulo, investigou o estado da produção científica mundial sobre estudos que relacionam mudanças climáticas, marés de tempestade e seus impactos na zona costeira, especificamente na ocorrência de desastres de erosão e inundação. A construção deste artigo justifica-se pela necessidade de compreender a inter-relação entre esses três fatores e o estado da arte do tema, ambos cruciais para responder a hipótese e o objetivo específico “a” desta tese. Para atingir esse objetivo, foram lidos resumos de 429 artigos selecionados, o que, de forma inicial, forneceu um amplo entendimento sobre o estado da arte e as abordagens utilizadas por diferentes autores.

Após a análise bibliométrica, que revelou os países, autores, instituições e revistas que mais publicam sobre essa temática integrada, foram realizadas leituras completas dos artigos mais relevantes. Esse processo foi essencial para delimitar o conhecimento existente e proporcionar uma revisão bibliográfica robusta, que fundamenta a tese. Embora a revisão sistemática tenha sido limitada ao banco de dados Scopus, devido ao seu extenso número de revistas indexadas, foram identificadas algumas lacunas nas publicações sobre o tema no Brasil. A nível nacional, apenas quatro artigos integraram a análise das mudanças climáticas, marés de tempestade e desastres costeiros. Isso evidenciou a necessidade de maior investigação nessa área no contexto brasileiro.

O segundo artigo da tese, apresentado no quarto capítulo, foi elaborado com o objetivo de preencher essas lacunas na pesquisa sobre os desastres costeiros no Brasil, especificamente em Santa Catarina. Este capítulo responde aos objetivos específicos “b” e “c”, apresenta os resultados da base de dados costeiros (distribuição espacial e temporal) e discute o aumento na ocorrência de desastres costeiros, relacionando-os com o crescimento populacional e a intensificação de eventos extremos que geram as marés de tempestade, os quais estão associados às mudanças climáticas globais.

Uma das principais lacunas identificadas nas bases oficiais brasileiras de registros de desastres é a ausência de um banco de dados unificado que reúna todas as ocorrências de desastres costeiros. Para abordar essa deficiência, o artigo propôs e apresentou a criação de um banco de dados unificado, baseado em fontes oficiais existentes, consolidando informações sobre desastres naturais costeiros ocorridos em Santa Catarina entre 1998 e 2020. Além de preencher a lacuna, este banco de dados visa apoiar a gestão costeira ao fornecer uma base sólida para estratégias de preparação, mitigação e resposta de desastres a partir da identificação dos setores costeiros e municípios mais afetados.

O terceiro artigo, apresentado no quinto capítulo (objetivos específicos “d” e “e”), teve como proposta inicial utilizar o banco de dados dos desastres costeiros, elaborado no segundo artigo, para identificar os padrões meteorológicos através de um método de agrupamento. No entanto, durante a primeira rodada do algoritmo, foi observado que os padrões detectados não correspondiam às condições atmosféricas propícias para a ocorrência de ondas altas e ventos fortes. A discrepância levou à necessidade de uma revisão detalhada no banco de dados dos desastres. Durante essa revisão, foi possível acessar novos documentos que registram a data exata dos desastres (FIDE e AVADAN), ao invés da data dos decretos oficiais. Com essa atualização, o banco de dados foi refinado, reduzindo o número de desastres registrados de 135 para 105. O algoritmo de agrupamento foi reexecutado e identificou cinco padrões meteorológicos distintos que estavam associados aos desastres costeiros ocorridos em Santa Catarina entre 1998 e 2020.

Os padrões meteorológicos identificados fornecem uma base para a previsão de desastres naturais em cada município costeiro de Santa Catarina. Pode-se estimar a probabilidade de ocorrência dos padrões em cada município e, assim, desenvolver modelos preditivos mais precisos. Esses modelos podem auxiliar gestores públicos e autoridades competentes na antecipação de eventos extremos, o que permite a implementação de medidas preventivas e estratégias de mitigação adequadas.

Além da identificação dos padrões meteorológicos, os novos documentos permitiram uma análise detalhada dos danos humanos, materiais e ambientais decorrentes dos desastres. Isso proporcionou uma compreensão mais precisa dos impactos dos desastres costeiros em cada setor e município estudado. Esse resultado contribui para a avaliação futura da vulnerabilidade da população e das edificações expostas aos desastres costeiros, auxiliando na definição de estratégias de mitigação dos desastres a nível local.

O quarto e o quinto capítulo evidenciaram as inconsistências presentes nos bancos de dados de desastres no Brasil. Observou-se que diversos decretos encontrados na base de dados da Defesa Civil de Santa Catarina (DCSC) não constam no S2ID e vice-versa. Em algumas planilhas obtidas no site da DCSC, a coluna que deveria indicar a data do desastre, na verdade, exibe a data do decreto. Essa inconsistência gerou problemas na execução da metodologia deste estudo e exigiu um esforço adicional para identificar as datas corretas. Isso foi particularmente um obstáculo, pois os documentos FIDE e AVADAN, em que constam as datas corretas, não estão publicados no site do S2ID e só foram acessados por meio de solicitações específicas.

A disparidade no preenchimento das bases de dados é preocupante, considerando que os desastres são registrados pelos municípios e deveriam ter as mesmas datas em todas as bases. Além disso, os formulários de desastres muitas vezes estão incompletos, com os danos não relatados ou apresentados com custo zero (R$ 0,00), o que pode ser um erro no momento do preenchimento, pois os desastres causam danos humanos e materiais diversos. Em um caso específico, dois municípios diferentes relataram exatamente o mesmo valor de dano material, sugerindo possíveis erros de registro e falta de normas técnicas específicas de preenchimento normalizado dos campos dessas bases de dados da Defesa Civil e municípios.

Por fim e apesar da limitações, os resultados da tese permitiram concluir que os desastres naturais que ocorrem em Santa Catarina podem ser causados por sistemas atmosféricos com intensidades variadas, incluindo formações ciclônicas, anticiclônicas ou interação entre anticiclones e ciclones que atuam sobre a Região Sul do Brasil. Compreende-se, portanto, que quando esses sistemas atmosféricos induzem as marés de tempestades, podem desencadear desastres costeiros especialmente em setores da costa mais urbanizada e sem proteção natural.

Em trabalhos futuros propõe-se a constante atualização do banco de dados dos desastres costeiros para permitir novas rodadas de análise, visando refinar os padrões meteorológicos. Além disso, é fundamental incentivar a criação de novas técnicas de normalização do preenchimento dos formulários de desastres, a fim de permitir discussões mais precisas sobre os danos e suas associações com padrões meteorológicos e indicadores sociais, como o Índice de Desenvolvimento Humano (IDH), Produto Interno Bruto (PIB) e renda. Essas iniciativas possibilitarão uma análise mais robusta e a implementação de estratégias de mitigação dos desastres mais eficazes.

6.1 Publicações

- As publicações decorrentes desta pesquisa, até o momento, estão listadas a seguir:

LEAL, K. B.; ROBAINA, L. E. S.; KÖRTING, T. S.; COSTA, J. D.; SOUZA, V. G. Identification of coastal natural disasters using official databases to provide support for the coastal management: the case of Santa Catarina, Brazil. **Natural Hazards**, v. 120, p. 11465-11482, 2023. https://doi.org/10.1007/s11069-023-06150-3

LEAL, K. B.; ROBAINA, L. E. S.; DE LIMA, A. S. Coastal impacts of storm surges on a changing climate: a global bibliometric analysis. **Natural Hazards**, v. 114, p. 1455 –1476 2022. https://doi.org/10.1007/s11069-022-05432-6

LEAL, K. B.; ROBAINA, L. E. S.; KÖRTING, T. S.; DUTRA, R. C. Desastres naturais associados à erosão e inundação costeira: um levantamento para o estado de Santa Catarina, Brasil. *In*: ENCONTRO NACIONAL DE PÓS-GRADUAÇÃO E PESQUISA EM GEOGRAFIA, 14., 2021. **Anais** [...], Edição Online, 2021.

- Apresentação em eventos científicos (não constam em Anais)

LEAL, K. B.; DE SOUZA, D. C.; LAVIOLA-DA-SILVA, M. B.; PEREIRA, S. S.; KÖRTING, T. S.; ROBAINA, L. E. S. Padrões meteorológicos relacionados com os desastres naturais costeiros ocorridos em Santa Catarina. *In*: CONFERÊNCIA PAN-AMERICANA DE METEOROLOGIA - CPAM, 2024. São Paulo: USP, 2024.

LEAL, K. B.; ROBAINA, L. E. S.; KÖRTING, T. S.; COSTA, J. D. Estudo dos desastres naturais costeiros para apoio à gestão costeira diante das mudanças climáticas: o caso de Santa Catarina, Brasil. *In*: REDE BRASPOR, 7., 2022. João Pessoa: UFPR, 2022.

- Artigo submetido

LEAL, K. B.; DE SOUZA, D. C.; LAVIOLA-DA-SILVA, M. B.; PEREIRA, S. S.; KÖRTING, T. S.; ROBAINA, L. E. S. Weather patterns associated with coastal disasters in Southern Brazil. Submetido em setembro de 2024.