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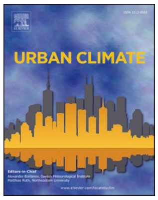

Facing climate change and improving emergency responses in Southern America by analysing urban cyclonic wind events

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A R T I C L E I N F O

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A B S T R A C T

Climate change is modifying the spatiotemporal patterns of global precipitation events, temperatures, and winds, therefore, after extreme events, improving emergency responses in urban areas is key to saving its inhabitants. In Southern America, the number of extreme events is increasing. This is the case of Soledad, the municipality in Colombia where most of the catastrophic wind phenomena take place. To date, no studies have been conducted to quantify the impacts and effects of the urban cyclonic wind phenomena on society and the urban built environment. This lack of information and dissemination means that the population is not informed of the magnitude of the problem. This research aims to generate a risk map of atmospheric wind phenomena to evaluate their impacts and establish spatial-temporal correlations based on meteorological data from the last 20 years. Moreover, the online press has been used to identify the location of these phenomena and their negative impacts over time. For each event, the following indicators have been studied: (1) location of the atmospheric wind events; (2) occurrence rate; (3) impact of the events discriminated by fatalities, injuries, and affected houses. The results show that in 20 years, a total of 34 urban cyclonic wind events were reported. Those occurrences have impacted 60 neighbourhoods, leaving 7 deaths, 14,552 injured, and 5180 affected homes. These findings show the magnitude of the problem and the need to inform the population to improve emergency responses. We conclude that effective consideration of the resulting map will be crucial in the processes of decision-making related to territorial planning in Soledad, but also in other Southern American cities.

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1. Introduction

Climate change has increased the occurrence of natural disasters worldwide (Tol, 2009; Haggag et al., 2021). Urban climatology has gained importance in recent years, with special attention to the mesoscale analysis of the influences of urban geometry as the cause of some environmental problems that severely affect cities (Krüger et al., 2011; Liu et al., 2020; Shafaghat et al., 2016). Several researchers have validated their theories about urban spaces based on climate-informed designs (Nevat, 2021; Nevat et al., 2020; Santos et al., 2021). However, in most cases, the studies refer to factors of external climatic comfort, while little attention has been paid to air warming leading to the occurrence of atmospheric wind events, such as gales, tornadoes, and waterspouts.

For example, a tornado is one of the most dangerous microscale and mesoscale weather phenomena (Agee and Taylor, 2019). Wind speeds within a tornado can exceed up to 100 m s^{-1}, which can have substantial negative socioeconomic consequences, including loss of human lives, destruction of houses and public infrastructure, and damage to forest systems (Brooks III et al., 2019; Chernokulsky et al., 2021; Jiménez-Caldera et al., 2022). Tornadoes can originate in unpredictable ways in a variety of storm types, each one exhibiting a different climatological response (Molina and Allen, 2020). This makes it difficult to develop a single process through which scientists can detect, predict, and anticipate the path of tornadoes and, thus, establish reliable warnings (Donadelli et al., 2020). These aspects restrict the knowledge of the behavior of the phenomenon on the territory, beyond facts related to mesoscale severe climate parameters (Barrett et al., 2020; Rosales et al., 2011). Cyclonic wind events are formed by the frequent relative gathering of unstable atmosphere, low-level moisture, wind shear, and an uplift mechanism (Doswell et al., 2012; Moore et al., 2021). Additionally, tornadoes are nature's most destructive wind events (Tao et al., 2018). Sometimes they are strong enough to destroy most of the elements that they find in their path (Roomi and Basheer, 2021). Environmental conditions affect the formation of cyclonic wind events, but more studies are claiming that human impacts on global climate dynamics are increasing these risks (Romero and Emanuel, 2013; Patlakas et al., 2021). It is well known that the spatial nature of the territorial patterns of occupation, land uses, and uncontrolled urban growth increase the disaster potential of a tornado on a regional and metropolitan scale (Lim et al., 2018; Kafi et al., 2021). Similarly, the growth of soil sealing stimulates the occurrence of cyclonic events above compact, high-rise urban landforms. Hence, cyclonic events are more frequent at the edges or peripheries of large metropolitan areas (Ashley and Strader, 2016; Strader et al., 2018).

Cyclonic wind events can occur all over the world, especially in the United States, Canada, Northern Europe, Bangladesh, China, Japan, Argentina, South Africa, Australia, and New Zealand. Among these, the United States ranks first in terms of the total number of cyclonic wind events with annual occurrences of more than 1000 per year in recent years (Brooks and Doswell, 2001; Cao et al., 2021; Edwards, 2020; Feuerstein et al., 2005). In North America, between 1200 and 1600 tornadoes are formed per year, with averages of 200 major events, 1500 injured, and 60 deaths (Chernokulsky et al., 2021; Mathews et al., 2017; Refan et al., 2017; Cusack (2014) evaluated the region of highest risk of cyclonic wind events in the USA and determined that tornadoes are generally more frequent and severe in large metropolitan areas, based on the review of 20 metropolitan areas and outlying cities in the country. In Europe, between 200 and 400 events are recorded on average over the land surface each year. In Russia alone, 1763 were reported between 1900 and 2018. From 1950 to 2013, tornadoes caused 316 deaths in Europe. The tornado registered in the Belgian city of Léglise on September 20, 1982, and that originated in the German city of Trier on October 7, 1988, are some examples of strong wind events that occurred in Western Europe in the last few decades (Antonescu et al., 2017; Mathias et al., 2021).

In the Latin American context, in 2019 a tornado occurred in Chile resulting in roof damage, vehicle displacements, injuries, and one death. Nonetheless, tornadoes in western South America and southern Chile are so rare that, before May 2019, the only reference in the scientific literature is a conference paper reporting the occurrence of five tornadoes between 1881 and 1981 (Vicencio et al., 2021). However, understanding the distribution of tornados and how it changes over time is critical to improving our ability to communicate risk and increase public awareness. It is also important to make progress in spatial planning to reduce the number of deaths and injuries related to atmospheric wind phenomena (Moore et al., 2021). Although cyclonic wind events have been recorded on all continents except Antarctica, information on their occurrence is fragmented since there are no standardized methods for capturing information. Even today, gravity measurement systems for the disaster are insufficient (Caldera et al., 2017) and it is not possible to estimate their intensity and precise impact. As an example, the Fujita scale does not estimate aspects that are sometimes much more significant, such as deaths, injuries, or house damage (Feuerstein et al., 2005). Rosales et al. (2011) determined that in the Metropolitan Area of Barranquilla (MABq) three events can be considered tornadoes from 1999 to 2008. In these events, the temperature registered high average values, and the maximum temperature of the MABq has been increasing in the last 40 years (Rosales et al., 2011).

In Southern America, the number of extreme events is increasing, and this is the case of Soledad, for example, the municipality in Colombia where most of the catastrophic wind phenomena take place. To date, no studies have been conducted to quantify the impacts of the urban cyclonic wind phenomena on society and the urban built environment. This lack of information and dissemination means that the population is uninformed of the magnitude of the problem. Therefore, the main goal of this research is to evaluate and map the occurrence of urban cyclonic wind events in the municipality of Soledad (Barranquilla, Colombia) using a collection of data from online press channels and meteorological data over the last twenty years. We hypothesize that the number and the frequency of the events will allow us to establish a risk map and recognize the magnitude of the effects of the phenomena. This research should play a crucial role in decision-making related to territorial planning in Soledad, but also in managing risk in other Southern American cities.

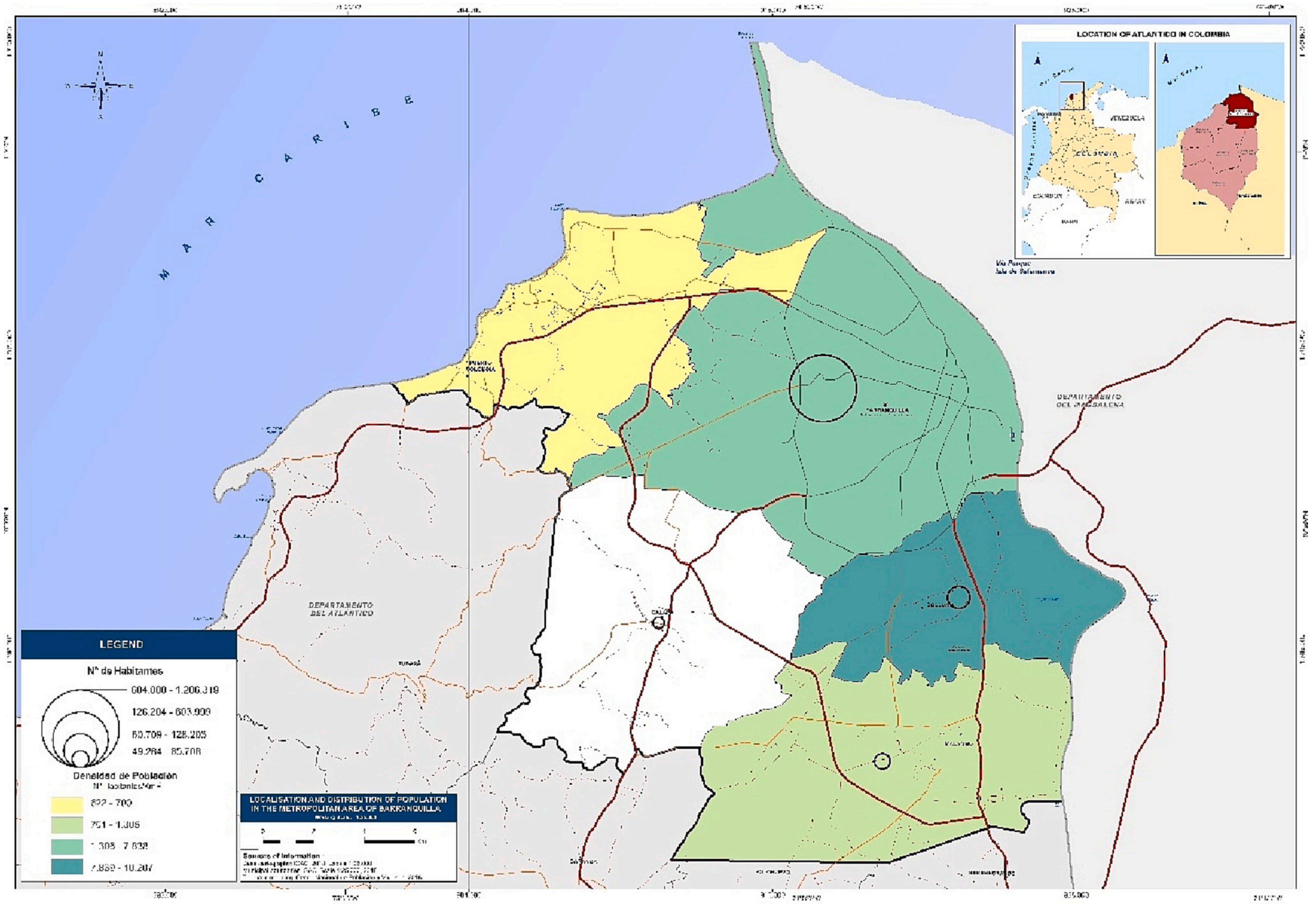

Fig. 1. The population of the Metropolitan Area of Barranquilla (MABq).
(Source: Self elaboration from AMBq (2020).)

2. Materials and methods

2.1. Study area

The study area is located in the municipality of Soledad, a conurbation on the coast of the Caribbean Sea belonging to the MABq, Colombia (Fig. 1). The MABq is composed of 5 municipalities: Barranquilla, Soledad, Malambo, Galapa, and Puerto Colombia, forming the fourth-largest urban conglomerate in Colombia, with a total population of 2,048,493 inhabitants settled in an area of 47,931 ha (AMBq, 2020). The municipality of Soledad is bordered to the north by Barranquilla, to the west by Galapa, to the east by the Magdalena River, and to the south by Malambo. According to the DANE census (2018), Soledad has 665,535 inhabitants, the second largest population in the MABq, and also the highest population density. Within an area of 5917.6 ha, it constitutes 12.35% of the territory of the MABq and 36.61% of its population. Thus, Soledad has a density of 20,797 hab km^{-2}, which has led to numerous urban problems coupled with a mainly irregular urban morphological growth based on informal settlements (Schubert et al., 2019).

The climatology of the municipality corresponds to a Tropical Dry Climate with high humidity. The temperature fluctuates between 24 and 32 °C. The wind speed in the dry season (from December to March) is usually high, ranging between 4.5 and 6.1 m s^{-1}. During the “first wet season” (April to June) it ranges between 2.7 and 4.8 m s^{-1} and, during the “transition season” between 2.7 and 3.2 m s^{-1}. Finally, between 2.2 and 3.1 m s^{-1} while the “second wet season” (August to November) (CIOH, 2022).

2.2. Methodology

The methodology (Table 1) aims to obtain key information that allows key extreme urban cyclonic wind phenomena in the municipality of Soledad in the last 20 years to be identified. Through this methodology, it will also be possible to evaluate the magnitude of the effects, to establish a baseline that raises awareness of the disaster among the public and local policy makers.

2.2.1. Digital media press data collection

The identification of the atmospheric events was made through the news reported using the digital media press and following the methodology carried out in previous research. Data from the online press were filtered using as keywords *“Tornados Soledad”* and *“vendavales Soledad”* next to the year of occurrence of the events. From the results of the search, data were taken from El Heraldo, a local newspaper, and, at the national scale, from El Tiempo and rcnradio.com, media outlets recognized for having prestige and credibility.

Boykoff and Rajan (2007) report how the media cover scientific events related to climate change in the USA and UK. The sources of data collection were television, radio and press. Ruiz-Sinoga and León-Gross (2012) used the press as a source of information to study the social perception of droughts. Serrano-Montes et al. (2018) used only websites (blogs and national, regional, and local newspapers) to record geographically and spatiotemporally the activity of mealybugs and the alterations on the landscape that they produce. Martínez-Ibarra et al. (2019) made a reconstruction of the snowfalls that occurred in a century (1900–2017) in the cities of Alicante, Cartagena, and Almeria. Thus, in this research, the atmospheric events have been identified along with neighbourhoods and other data were collected.

2.2.2. Meteorological conditions of each event

A total of 34 events were recorded. The meteorological conditions of each event that occurred during these 20 years were surveyed and assessed with data from the Ernesto Cortissoz International Airport weather station (10°53′11.53”N - 74°46′36.03”O; 22 m a.s.l.). We evaluated for each extreme event the daily averages of air temperature, wind speed, and precipitation. Likewise, these events were classified considering the months in which these cyclonic wind events occurred, to establish spatial-temporal factors that will help

Table 1
Methodological design.

Instruments	Variables	Indices	Methodological References
Online press news	Data collection	Events Date Damage Location	(Boykoff and Rajan, 2007; Ruiz-Sinoga and León-Gross, 2012; Martínez-Ibarra et al., 2019)
GIS	Geographic location of atmospheric wind events	Identification of neighbourhoods	Strader et al., 2018
	Mapping of the frequency of occurrence in 20 years	Choropleth map	Allen et al., 2021
	Mapping of injuries and deaths in 20 years	Juxtaposed choropleth map	Besançon et al., 2020
	Mapping of affected homes in 20 years	Choropleth map	Allen et al., 2021
Weather Station	Average temperature months of the occurrence of the events	°C	Rosales et al., 2011
	Temperature days of the occurrence of the events	°C	

Source: Own elaboration based on scientific literature.

territorial planners to improve their knowledge of wind phenomena in Soledad.

2.2.3. Mapping assessment

In the second phase of the methodological procedure, the data obtained were spatially represented in a Geographic Information Systems (GIS) using the software ArcGIS version 10.8 (ESRI, USA) and grouped with the Kernel density (Fan and Pang, 2019; Song et al., 2022). In this way, the following parameters were mapped: (1) location of each urban cyclonic wind event (neighbourhoods); (2) occurrence rate (events per year) of these cyclonic events; and (3) impact discriminated by fatalities, injured, and affected dwellings. This impact information was filled using the above-mentioned press reports and completed with other information provided by the National Unit for Risk and Disaster Management (UNGRD) (http://gestiondelriesgo.gov.co/snigrd/index.aspx).

3. Results

3.1. Spatial distribution of urban cyclonic wind events in Soledad

Over the period considered in this study (2001–2020), 60 neighbourhoods were affected by urban cyclonic wind events (Table 2), 30% of them in the municipality of Soledad. In this period, there were 34 cyclonic events, with an average of 2.7 neighbourhoods affected per event and 4.6 per year.

In Fig. 2, the spatial analysis and mapping of the data show two areas where the recurrence of the phenomena has been the highest. As dynamic events, on their path, these strong wind events affected the following neighbourhoods: Hipódromo, Costa Hermosa, El Río, Salamanca and Santa Inés. The other was formed in the Villa Adela (1 and 2) and Villa María neighbourhoods and advanced towards the southeast of the municipality until its extinction next to the Ernesto Cortissoz airport. In addition, high level of occurance was detected in the periphery of the urbanized zone of the MABq and, in particular, in the periphery of Soledad. This area faces north-easterly winds at its border along the Magdalena River valley.

3.2. Main parameters of cyclonic events in Soledad

The highest number of extreme events took place in 2012 with a total of five and the rest were reported as follows: 2001, 2008, and 2014, where four events were registered annually. June, August, and October were the months with the highest number of urban cyclonic wind events during the last 20 years. Otherwise, in January, March, July, and December no event occurred over the evaluated period (Table 3). Likewise, meteorological data from the Ernesto Cortissoz airport showed that out of 34 reported events, only three of them presented at temperatures lower than 30 °C. On the contrary, 72.4% of the events presented at temperatures included in the three highest of the month of occurrence, being the average temperatures of those months above 32.7 °C. In this sense, the occurrence of the events is associated with high temperatures (weather data are shown in Table 4).

In the MABq, the predominant wind direction (67% of the time) (CIOH, 2022) is northeast. The average wind speed reached 4 m s^{-1}, while during the days in which the events occurred it was 27.22 m s-1. The average solar radiant intensity during the events was 6.1 W sr-1 (Steradian).

The findings on the events registered during the analysed period do not indicate a clear relationship with atypical wind speeds. The

Table 2
Neighbourhoods with the highest occurrence of cyclonic events in Soledad.

Neighbourhoods	Gales or Tornadoes					Total
	Years					
Villa del Carmen	2004	2009	2011	2013	2014	5
Hipódromo	2005	2007	2008	2012	2014	
Costa Hermosa	2007	2011	2012	2016		4
Villa María	2001	2004	2014			3
Villa Adela 1y 2	2001	2004	2005			
Villa Carla	2001	2013	2014			
Los Almendros	2006	2008	2009			
Ciudadela Metropolitana	2001	2004	2014			
Villa del Rey	2001	2005				2
Ferrocarril	2009	2016				
El Río	2005	2007				
Pumarejo	2008	2009				
Villa Katanga	2004	2013				
Zarabanda	2004	2005				
Salamanca	2005	2007				
Santa Inés	2005	2007				
Los Robles	2006	2014				
La central	2009	2014				
Villa Salamar	2005	2009				
Altos de Jesús	2014	2014				

Source: Own elaboration with data from the online press.

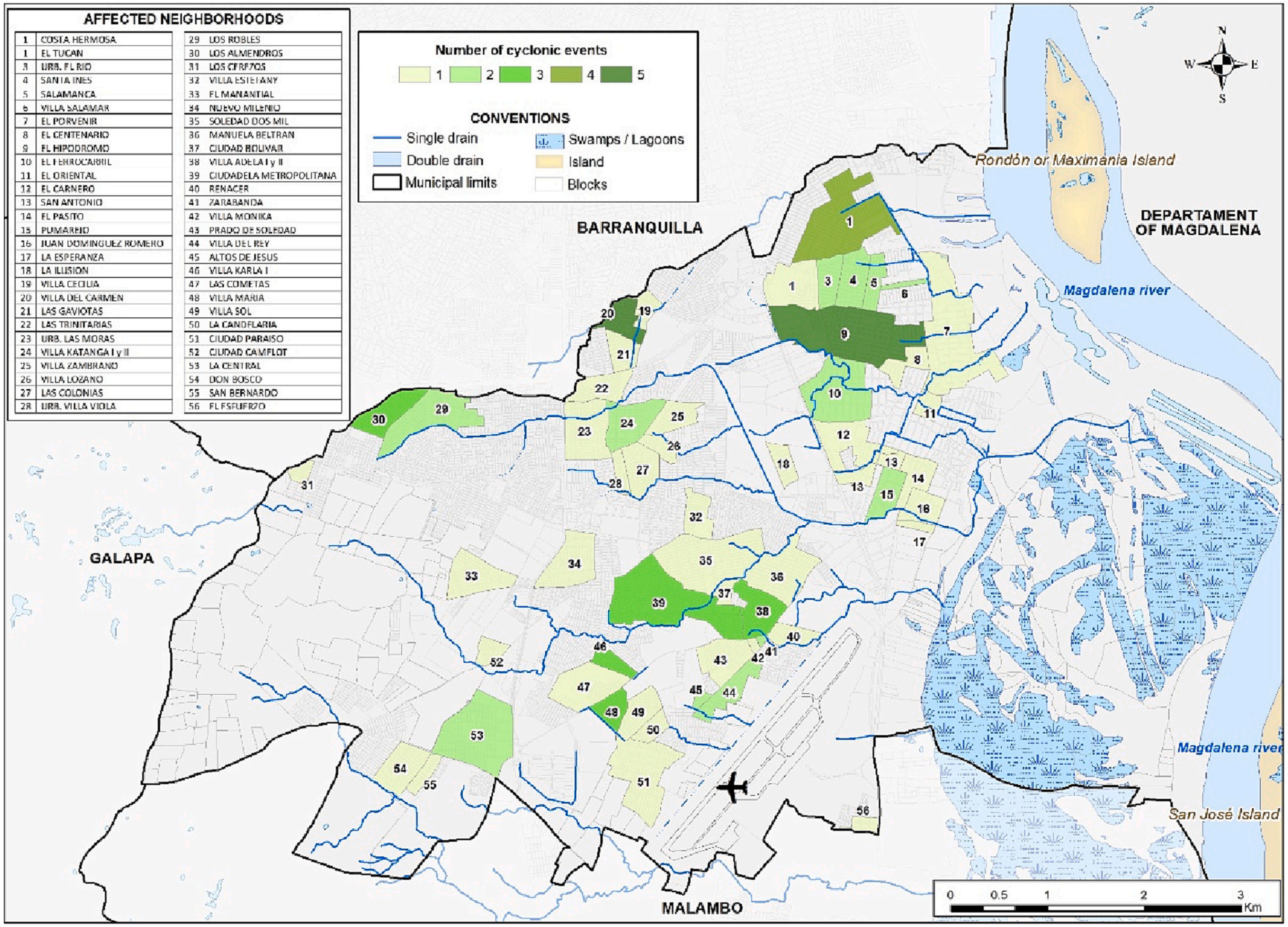

Fig. 2. Frequency of cyclonic events in Soledad.
(Source: Own elaboration with data from the online press.)

Table 3
Cyclonic events in Soledad. Distribution by months (2001–2020).

Months	Gales or Tornadoes 2001–2020
January	0
February	1
March	0
April	4
May	4
June	6
Jule	0
August	5
September	4
October	5
November	3
December	0

Source: Own elaboration with data from the online press.

evidence suggests that most of the events occurred in the first (April to June) and second (August to November) rainy seasons. On the contrary, in the "dry season" (December to March), which has the highest wind speeds, only one event was reported in 20 years.

3.3. Effects of urban cyclonic wind events in Soledad

The impacts caused by the 34 events reported during the studied period and their spatial-temporal distribution are shown in Table 5 and Figs. 3 and 4. Between 2004 and 2008 meteorological events related to tornadoes and gales had a great effect on the municipal territory. This phenomenon intensified again between 2011 and 2014. In total, in the studied period (2001–2020), there were 34 events, with 10 deaths, 14,552 affected people, and 5180 damaged homes. In 2002, 2003, 2010, and 2015 there were no deaths, injuries, or affected homes (or at least no events were reported).

The most critical year was 2001. Four tornado events occurred in June, affecting 14 neighbourhoods and the vicinity of Ernesto Cortissoz Airport: 4 deaths, 469 people affected, and 662 damaged homes.

In August 2004, the greatest material damage and injuries in the municipality were caused by these phenomena. Approximately 8340 people were injured and 1678 homes were affected in only eight neighbourhoods.

4. Discussion

This research contributes to the knowledge of the atmospheric phenomena of wind in a city that is part of a larger metropolitan area located in a humid Tropical Dry Climate. The results obtained are a fundamental input in the recognition of the vulnerability of the municipality and should stimulate new investigations that contribute to establishing response measures and for reducing the impacts.

Atmospheric wind events in Soledad during the period 2001–2020 recorded an average wind temperature on the days of the occurrence of 32.7 °C, which is higher than the mean annual temperature. The mapping of the results indicates that the cyclonic wind events in Soledad follow the dominant trajectory of winds from the northeast and that these events took place in the peripheral areas of the metropolitan area of Barranquilla. Our findings show that one-third of the affected neighbourhoods are of informal origin, that is, they have grown without urban planning, with irregular parcelling, and construction without appropriate technical characteristics to guarantee the structural stability of the buildings in case of emergency.

This reality implies that the program of Integral Improvement of Neighbourhoods that the Colombian government is working on throughout the country should have special consideration for the case of the areas of the municipality of Soledad, where there is evidence of greater vulnerability due to temporal patterns (months and periods of greater susceptibility to events) and spatial patterns (places or neighbourhoods more prone to events), according to the results presented in this research. This also confirms that the events have a greater impact in poor nighbourhoods, particularly in informal settlements, where houses are in poor condition and people have low capacity to respond to disasters (Gómez-Villanueva et al., 2021). On the other hand, no empirical evidence was found that "La Niña or El Niño" causes increases or decreases in the occurrence of urban cyclonic wind events in this area. However, some factors point to the increase in temperature: the materiality of the buildings (Vélez et al., 2014), anthropogenic heat, and urban morphological aspects, such as building (Krüger et al., 2018; Senciales-González et al., 2020).

The mapping and georeferencing of urban cyclonic wind events, and their impact on urban areas, are commonly performed through the use of GIS, but less research has focused on cross-referencing with a long-term press media analysis. Mapping and modelling this information is not commonly used to represent the risk of tornadoes. The form of information collection is generally obtained from specialized research centres (Cusack, 2014; Doswell et al., 2009). For example, Seimon et al. (2016) propose a georeferencing approach that combines video-image scenes with Google Maps and Google Street View and online GIS tools to identify the latitude and longitude position of tornadoes. In the last 10 years, research has been developed for cyclonic wind events identification by photography based on satellite platforms (Bedka et al., 2015), video-grammetry, and radar (Atkins et al., 2012; Wakimoto et al., 2015). However, we show that our approach is powerful for identifying the most vulnerable areas and for contributing to designing efficient

Table 4
Climatological aspects of the day and month of the events.

Climatological Aspects Of The Day And Month of the Event							
EVENT	WIND SPEED (Km h^{-1})	RADIANT INTENSITY OF THE SUN (h)	T. MAX (°C DAY)	T.MED (°C MONTH)	T. MAX (°C MONTH)	T. MIN (°C MONTH)	T. MAX DAY VS T.MAX MONTH
JUNE 01, 2001 (WINDSTORM)	11	4,3	29,2	32,5	34,2	22,8	5th T. HIGHER
JUNE 05, 2001 (SEA STORM)	8	6,2	33	32,5	34,2	22,8	2nd T. HIGHER
NOVEMBER 19, 2001 (WINDSTORM)	8	0,9	31,3	31,27	33,3	22	2nd T. HIGHER
AUGUST 10, 2004 (WINDSTORM)	NO REPORT	NO REPORT	NO REPORT	30,7	34,2	22,8	NO REPORT
JUNE 25, 2005 (WINDSTORM)	11	8,3	33,3	33,45	36,1	20,1	3rd T. HIGHER
OCTOBER 21, 2005 (WINDSTORM)	9	NO REPORT	32,7	31,52	33,4	13,1	2nd T. HIGHER
JUNE 12, 2006 (WINDSTORM)	10	5,5	31,1	33,02	35,8	22	4th T. HIGHER
AUGUST 11, 2006 (WINDSTORM)	16	NO REPORT	35,5	32,69	35,5	23,3	T. HIGHER
OCTOBER 19, 2007 (WINDSTORM)	7	NO REPORT	29,8	28,44	33,1	19,4	4th T. HIGHER
APRIL 27, 2008 (WINDSTORM)	NO REPORT	NO REPORT	NO REPORT	31,56	34,9	24,2	NO REPORT
MAY 22, 2008 (TORNADO)	NO REPORT	NO REPORTA	NO REPORT	NO REPORTA	NO REPORTA	NO REPORTA	NO REPORT
SEPTEMBER 17, 2008 (WINDSTORM)	NO REPORT	NO REPORT	NO REPORT	NO REPORT	NO REPORT	NO REPORT	NO REPORT
OCTOBER 7, 2008 (WINDSTORM)	NO REPORT	NO REPORT	NO REPORT	NO REPORT	NO REPORT	NO REPORT	NO REPORT
FEBRUARY 05, 2009 (WINDSTORM)	NO REPORT	9,7	29,8	29,85	33,2	22,4	4th T. HIGHER
AUGUST 14, 2009 (WINDSTORM)	NO REPORT	5,7	31,4	33,69	36,6	22,6	5th T. HIGHER
MAY 30, 2011 (WINDSTORM)	9	9,3	33,2	31,86	36,4	20	3rd T. HIGHER
MAY 31, 2011 (WINDSTORM)	11	3,3	32,4	31,86	36,4	20	4th T. HIGHER
AUGUST 16, 2011 (THUNDERSTORM)	8	2,9	32	32,83	35,8	23,1	3rd T. MÁS ALTA
SEPTEMBER 03, 2011 (WINDSTORM)	8	6,1	33	32,79	35	21,4	2nd T. MÁS ALTA
APRIL 12, 2012 (WINDSTORM)	17	NO REPORT	34,4	32,64	35,4	24,1	2nd T. MÁS ALTA
APRIL 19, 2012 (WINDSTORM)	14	NO REPORT	32,8	32,64	35,4	24,1	3RA T. MÁS ALTA
APRIL 22, 2012 (WINDSTORM)	7	NO REPORT	31,6	32,64	35,4	24,1	4th T. MÁS ALTA
MAY 09, 2012 (WINDSTORM)	6	NO REPORT	34,3	32,2	35,6	23,1	2nd T. MÁS ALTA
OCTOBER 10, 2012 (WINDSTORM)	8	NO REPORT	33,5	32,17	35,8	22,5	2nd T. MÁS ALTA
NOVEMBER 20, 2013 (WINDSTORM)	7	NO REPORT	33,1	32,74	34,7	23	2nd T. MÁS ALTA
AUGUST 27, 2014 (WINDSTORM)	9	7,1	32,6	33,67	36,4	12,9	4th T. MÁS ALTA
SEPTEMBER 16, 2014 (WINDSTORM)	5	4,8	34,8	33,63	36,7	22,3	2nd T. MÁS ALTA
OCTOBER 25, 2014 (WINDSTORM)	7	NO REPORT	35,5	33,28	36,4	22,3	2nd T. MÁS ALTA
NOVEMBER 04, 2014 (WINDSTORM)	17	NO REPORT	34,3	32,83	34,4	22,9	T. HIGHER
JUNE 14, 2016 (WINDSTORM)	10	NO REPORT	32,5	30,98	35,5	20,6	3rd T. HIGHER
JUNE 18, 2016 (TORNADO)	16	NO REPORT	34,4	30,98	35,5	20,6	2nd T. HIGHER
MAY 01, 2017 (WINDSTORM)	7	NO REPORT	32,8	32,74	34,9	22,6	2nd T. HIGHER
NOVEMBER 05, 2017 (WINDSTORM)	9	6,3	31,8	31,79	33,6	23,1	2nd T. HIGHER

(*continued on next page*)

Table 4 (*continued*)

Climatological Aspects Of The Day And Month of the Event							
EVENT	WIND SPEED (Km h^{-1})	RADIANT INTENSITY OF THE SUN (h)	T. MAX (°C DAY)	T.MED (°C MONTH)	T. MAX (°C MONTH)	T. MIN (°C MONTH)	T. MAX DAY VS T.MAX MONTH
OCTOBER 24, 2018 (WINDSTORM)	8	5,9	32,3	31,61	33,8	13,2	2nd T. HIGHER

Source: Ernesto Cortissoz International Airport weather station.

Table 5
Effects of cyclonic winds in Soledad (2001–2020).

Year	Fatalities	Injuries	Affected homes and families
2001	4	469	662
2002	0	0	0
2003	0	0	0
2004	0	8340	1678
2005	0	3484	693
2006	0	733	148
2007	0	495	99
2008	0	180	563
2009	0	130	26
2010	0	0	0
2011	0	217	730
2012	0	1	58
2013	0	0	171
2014	0	400	288
2015	0	0	0
2016	0	0	42
2017	3	103	20
2018	0	0	2
2019	0	0	0
2020	0	0	0
	7	**14,552**	**5180**

Source: Own elaboration with data from online press and UNGRD.

management to foresee the negative consequences, and promote sustainable urban development (Allen et al., 2021; Hong et al., 2021; Refan et al., 2020).

We consider that our research could benefit from the implementation of other tools to include accurate information on when the urban cyclonic events are characterized, in addition to data from the meteorological station. For example, weather radar images could be of special interest, as they can reveal classic features associated with supercell storms related to tornado formation (Rodríguez et al., 2021). In this way, Allen et al. (2021) used the Kernel density-based severe weather GIS (SVRGIS) data from the National Weather Service (NOAA) Storm Prediction Center and from the National Oceanic and Atmospheric Administration (NOAA), which allowed them to map, spatially analyse and compile descriptive statistics of tornadoes in Virginia between 1960 and 2019. For the study of the spatial-temporal patterns of atmospheric wind phenomena in Soledad, cartographic techniques (GIS) of analysis and representation were also used, and the accuracy of the impacts using press media was elevated. The dataset was obtained from two main sources: official data (both from Ernesto Cortissoz airport meteorological station and the UNGRD), and online press. It should be emphasized that the digital press has strongly developed in recent decades and there may have been an under-representation of the events during the first years of the analysed period. It is also quite probable that there have been events that were not reported by the press due to their non-sufficient magnitude, or because they did not cause material or human damage.

Data from official institutes and media coverage were cross-referenced and analysed to establish associative criteria. Choropleth maps were applied to represent the information to establish differences between the recorded data and crossing variables, facilitating the understanding of the information. The methodological combination applied in our study for the spatial analysis of urban cyclonic events is in line with the procedures developed in previous research. For example, Antonescu et al. (2017) used meteorological data from radar and/or satellite imagery to identify the phenomena; while Chernokulsky et al. (2021) employed observational data from weather stations, eyewitness reports (including photo and video information), and wind data retrieved from Landsat Imagery for tornado georeferencing. Moore et al. (2021) used Doppler radar coverage for the detection and mapping of atmospheric wind events. Likewise, Rodríguez et al. (2021) implemented the methodology of visual analysis of satellite data, c-band Doppler radar observations, and SMC lightning data, according to the geographic and temporal information of each report. Seimon et al. (2016), like the previous study, implemented a methodological design for tornado identification based on the use of GIS tools, GPS, and Google Maps video imagery. In contrast, Kellner and Niyogi (2014), for the compilation of the geospatial dataset, used the Severe Geographic Information System (SVRGIS) database of the Storm Prediction Center (SPC), to analyse the land cover and topography where tornadoes occur. Regarding the impact of tornadoes in urban areas, Burton et al. (2011) analysed the events using repeated photographs, GIS methodologies, and spatial statistics relating tornado biophysical impact with land restoration processes.

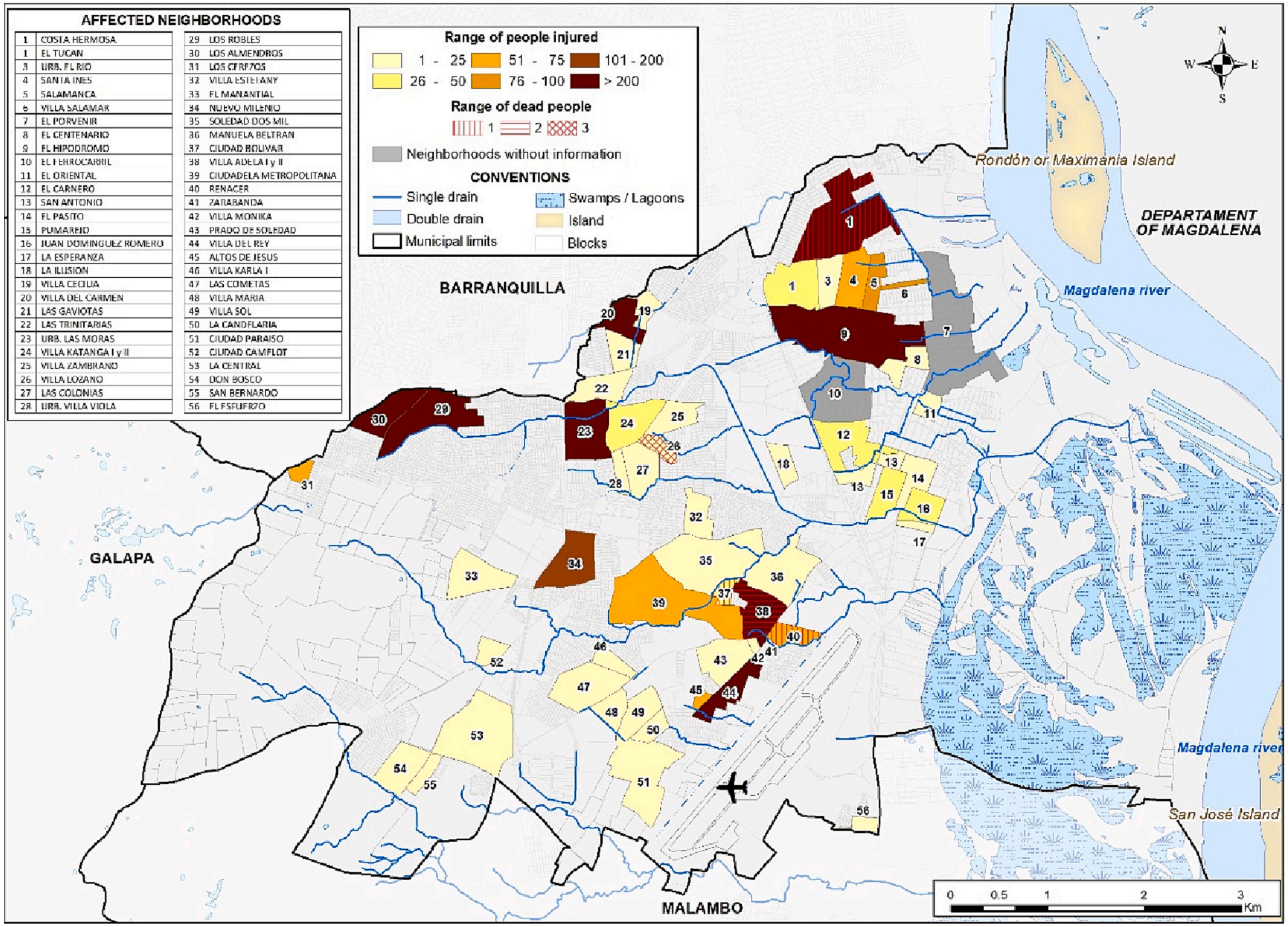

Fig. 3. Deaths and injuries caused by cyclonic winds in Soledad (2001–2020).
(Source: Own elaboration with data from online press and UNGRD.)

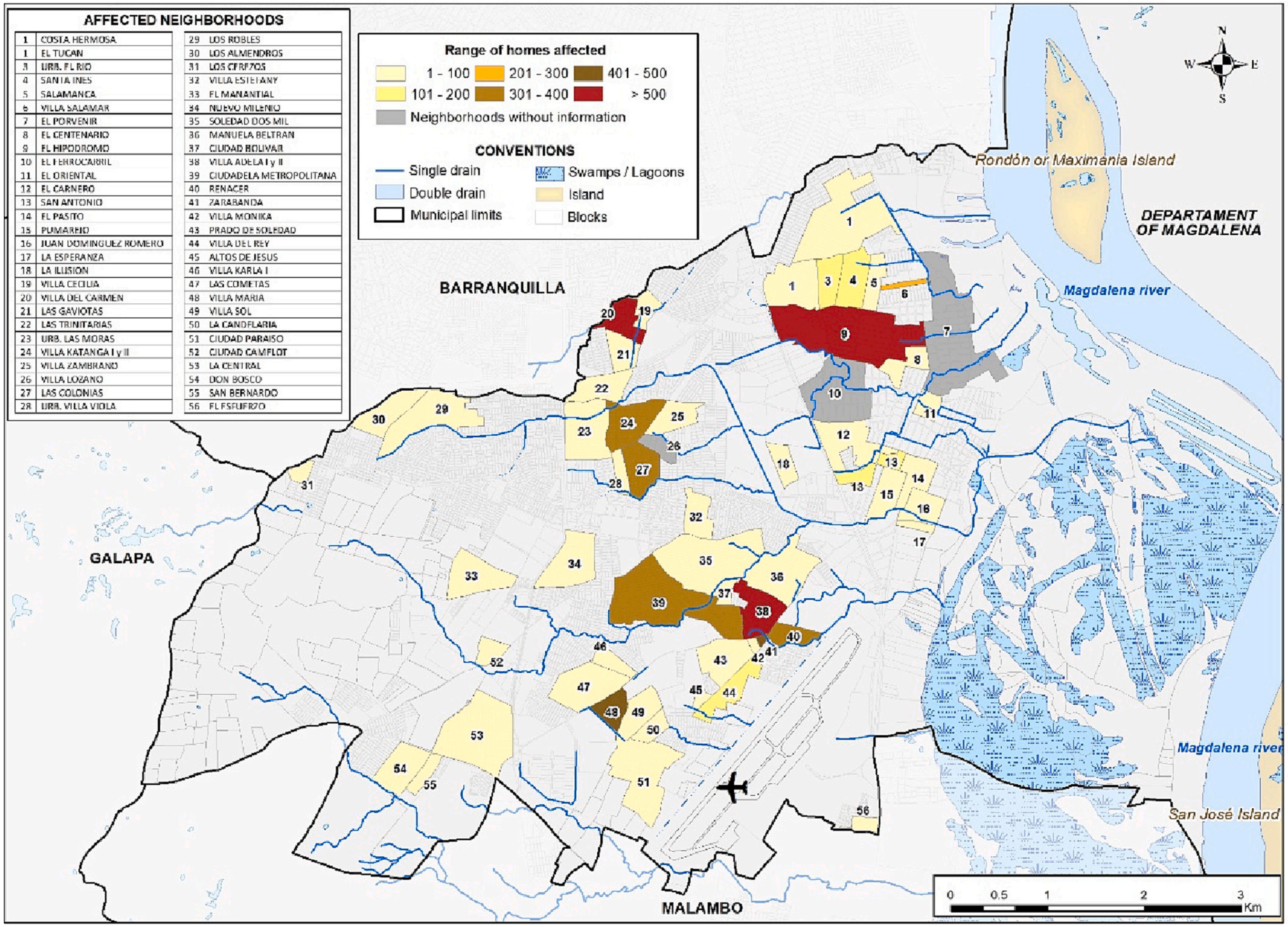

Fig. 4. Dwellings affected by cyclonic winds in Soledad (2001–2020).
(Source: Own elaboration with data from online press and UNGRD.)

In future research, we should consider the use of remote sensing data and analysis to detect the most relevant antecedent meteorological trends that cause the generation of extreme wind events. Wagner et al. (2012) employed both Landsat TM and Landsat E TM + imagery at a spatial resolution of 30 m, with seven multispectral channels spanning from the blue to the thermal portions of the electromagnetic spectrum. Likewise, there are several studies that evaluate social media as a tool not only to warn, prepare, and reduce the risk and impact of natural hazards (DiCarlo and Berglund, 2021; Jayasekara, 2019; Zander et al., 2022), but also, to gather the data generated by social media users (Jamali et al., 2020; Li et al., 2021; Shoyama et al., 2021), although sometimes wrong or contradictory information about the facts is recorded.

In Soledad, the economic impacts of cyclonic wind problems have not yet been estimated. However, 5180 affected families in 20 years show a concerning condition that generates public expenditure annually. The DesInventar database and the Sendai Framework monitoring platform report 134 events in the metropolitan area of Barranquilla from 1947 to 2017. Around 80% of them were recorded in Barranquilla and Soledad. When contrasting the results of these platforms with the findings of the Online press, it is found that the numbers of events and deaths are almost the same. Nevertheless, due to the methodology used, the numbers of injuries and impacts on housing differs. In this regard, the press reports more affectations and offer more qualitative details of the facts.

In the city, population growth is constant, the urban morphology of new settlements is incoherent and disconnected and housing units denote the absence of reflection and study (Pérez-Arévalo and Caballero-Calvo, 2021) in the use of building materials, increasing the phenomenon of Urban Heat Island (UHI). It would be interesting to follow the methods presented by Donadelli et al. (2020), who evaluated the macroeconomic and financial implications of the various atmospheric wind phenomena in the US, in which the price of housing (Sheldon and Zhan, 2019) and citizen income in the South and Midwest were significantly affected, even resulting in falling returns on housing stocks. Unexpected and extreme weather events can cause disasters and generate direct decreases in housing supply and demand (Kruse et al., 2007). Although Soledad is the municipality in Colombia where most atmospheric wind phenomena occur, the scientific literature on the case study is scarce, which leads to a lack of assessment of the magnitude of the phenomena and real awareness of the problem. Therefore, the generation of risk maps of atmospheric wind phenomena in Soledad, the evaluation of their impacts, and the establishment of spatial-temporal correlations from climatological evidence are necessary actions to increase knowledge and understanding of the phenomena. The new information should lead to mitigation actions and the rethinking of the forms of urban growth and construction of buildings in the city.

Finally, due to the changes in the risk factors (population size, building code and standards, etc.) that occurred during the 20 years evaluated in this research, it is important to acknowledge that variations in the obtained data on injuries, deaths, and damaged or destroyed houses may have influence on the results. Future research should continue to review the behavior of the phenomenon in Soledad and the metropolitan area of Barranquilla.

5. Conclusions

The mapping of data within a GIS allowed us to examine how cyclonic wind phenomenon has affected the territory of Soledad, and to identify the neighbourhoods that are more vulnerable. The collection of data through online press sources in this research is a versatile and effective methodology to collect information together with those data obtained from the Ernesto Cortissoz Airport weather station. The data recorded on deaths, injuries, and damaged housing allows us to pinpoint a problem that has caused 10 deaths and affected 14,552 people over twenty years, and which represents a permanent risk. With ongoing climate change, is the situation is likely to worsen in the coming years, especially taking into consideration that there are no programmes or planned actions to mitigate the impacts of cyclonic events in Soledad, a city characterized by continuous and intensive growth.

CRediT authorship contribution statement

Raúl Pérez-Arévalo: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. **José Luis Serrano-Montes:** Formal analysis, Resources, Writing – review & editing. **Juan E. Jiménez-Caldera:** Software, Data curation, Validation. **Jesús Rodrigo-Comino:** Visualization, Investigation, Software, Validation. **Pete Smith:** Methodology, Formal analysis, Validation. **Andrés Caballero-Calvo:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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