BSGF - Earth Sciences Bulletin 2022, 193, 4

https://doi.org/10.1051/bsgf/2022003

Available online at:
www.bsgf.fr

OPEN ACCESS

Rising sea level and increasing tropical cyclone frequency are threatening the population of San Andrés Island, Colombia, western Caribbean

Matthias Bernet[1,*] and Liliana Torres Acosta[2]

[1] Institut des Sciences de la Terre, CNRS, IRD, Université Grenoble Alpes, Grenoble, France
[2] 12 rue du Petit Jean, 38610 Gières, France

Received: 27 August 2021 / Accepted: 14 March 2022 / Published online: 30 May 2022

Abstract – The Colombian island of San Andrés is a popular tourist destination located about 195 km offshore of the east coast of Nicaragua in the southwestern Caribbean Sea. Together with Providencia and Santa Catalina, San Andrés is part of the UNESCO Seaflower Biosphere Reserve. With a 26 km^2 surface area and 78 000 inhabitants, San Andrés is one of the most densely populated islands in the Caribbean with on average ~ 3000 inhabitants/km^2. The majority of the population and the mass tourism are concentrated in the low-elevation (0.5–6 m) areas, particularly in the north and along the east coast of the island. These areas are prone to flooding during storm events such as hurricanes Eta and Iota in 2020. A review of the geological, environmental and the socio-economic situation of the island, and the record of tropical cyclones since 1911, shows why the local population has become increasingly vulnerable to storm events and rising sea level. Tropical cyclones may form locally in the southwestern Caribbean or originate in the eastern Caribbean/Atlantic Ocean. The latter tend to be stronger and cause more damage when they reach San Andrés. The HURDAT2 dataset shows that the frequency of storm events affecting San Andrés has increased in recent decades, with six storms over the past 20 years, including three category 4-5 hurricanes since 2007. Increasing storm frequency and intensity may be linked to increasing sea surface temperatures caused by anthropogenic global warming, although the changes described here may be limited to a relatively small geographical region, as opposed to representing basin wide tropical cyclone behavior. The growing population density since the 1950s has augmented the potential for disaster.

Keywords: climate change / environmental hazards / population density / tropical cyclones / seal level rise / vulnerability

Résumé – Hausse du niveau marin et l'augmentation de la fréquence des cyclones tropicaux menacent la population de l'île de San Andrés, en Colombie, dans les Caraïbes occidentales. L'île colombienne de San Andrés est une destination touristique populaire située à environ 195 km au large de la côte est du Nicaragua, dans le sud-ouest de la mer des Caraïbes. Avec Providencia et Santa Catalina, San Andrés fait partie de la réserve de biosphère Seaflower de l'UNESCO. Avec une superficie de 26 km^2 et 78 000 habitants, San Andrés est l'une des îles les plus densément peuplées des Caraïbes avec en moyenne ~ 3000 habitants/km^2. La majorité de la population et le tourisme de masse sont concentrés dans les zones de faible altitude (0,5–6 m), en particulier dans le Nord et le long de la côte Est de l'île. Ces zones sont sujettes aux inondations lors de tempêtes telles que les ouragans Eta et Iota en 2020. Un examen de la situation géologique, environnementale et socio-économique de l'île, ainsi que du bilan des cyclones tropicaux depuis 1911, montre pourquoi la population locale est devenue de plus en plus vulnérable aux tempêtes et à l'élévation du niveau de la mer. Les cyclones tropicaux peuvent se former localement dans le sud-ouest des Caraïbes ou prendre naissance dans l'Est des Caraïbes et l'océan Atlantique. Ces derniers ont tendance à être plus forts et à causer plus de dégâts lorsqu'ils atteignent San Andrés. L'ensemble de données HURDAT2 montre que la fréquence des tempêtes affectant San Andrés a augmenté au cours des dernières décennies, avec six tempêtes au cours des 20 dernières années, dont trois ouragans de catégorie 4-5 depuis 2007.

*Corresponding author: matthias.bernet@univ-grenoble-alpes.fr

L'augmentation de la fréquence et de l'intensité des tempêtes pourrait être liée à l'augmentation des températures de surface de la mer causée par le réchauffement climatique anthropique, bien que les changements décrits ici puissent être limités à une région géographique relativement petite, par opposition à la représentation du comportement des cyclones tropicaux à l'échelle du bassin. La densité de population croissante depuis les années 1950 a augmenté le potentiel de catastrophe.

Mots clés : changement climatique / risques environnementaux / densité de population / cyclones tropicaux / hausse du niveau marin / vulnérabilité

1 Introduction

San Andrés Island is located about 195 km to the east of the coast of Nicaragua (Fig. 1), and is part of the San Andrés, Providencia and Santa Catalina archipelago that belongs to Colombia. This archipelago forms the UNESCO Seaflower Biosphere Reserve (Gómez-López *et al.*, 2012; Gavio and Mancera Pineda, 2015; Londoño-Diaz and Varas-Morales, 2015). The reserve is in an effort to help protect over 300 000 km^2 of marine environment and develop sustainable use of this area for fishing and tourism (Gómez-López *et al.*, 2012; Londoño-Diaz and Vargas-Morales, 2015; Gavio and Mancera Pineda, 2015).

San Andrés Island is roughly N-S oriented. With a length of ~ 12.6 km and a width of ~ 1 to 3 km, the island has a surface area of ~ 26 km^2. Officially the population of San Andrés Island is given as 78 000 inhabitants (DANE, 2018). This corresponds on average to a population density of approximately 3000 inhabitants/km^2 for the whole island, but the majority of the population is concentrated in the north of the island in the town of San Andrés. In addition to the local population one million tourists were visiting the island per year, in recent years, before the COVID-19 crisis.

San Andrés Island can serve as a model for studying how the geological, environmental and socio-economic conditions define the vulnerability of the local population to environmental hazards such as storm events and rising sea level. According to Smith (2001), an environmental hazard is a natural or man-made event or process with the potential to generate loss of life and/or property and environmental damage. The vulnerability of the population of San Andrés is defined here as to which degree it is affected by impacts of such hazardous events, following the definition of Timmerman (1981). Such hazardous events may be naturally occurring events such as earthquakes, storms, flooding, rock fall or landslides etc. Rising sea level will increase the potential for catastrophic storm surges for low-lying coastal communities (Smith, 2001). This is one of the aspects that we will discuss in the case of San Andrés, as the impacts of such hazardous events will likely be compounded by their combined effects such as extreme rainfall, high windspeeds, storm surges, wave action (coastal erosion), landslides, disruption of infrastructure, and electricity and drinking water supply during and after storm events. The exposure of life and property to the combination of hazards poses therefore a risk to the local population. As that, risk could be defined as the product of the probability of hazardous events occurring and the amount of loss generated directly (*e.g.*, death, damage or loss of property and infrastructure) during the event, and indirectly (*e.g.*, spread of diseases, unemployment, social unrest) following the event, which may lead to disaster. Disasters related to tropical cyclone activity in the Caribbean have been increasing since the 1950s (Acevedo, 2016), which put island populations at risk throughout the Caribbean. A good example for such a disaster and the long-lived negative effects related to slow recovery is the devastation of Puerto Rico by category 5 Hurricane Maria in September 2017 (*e.g.*, Pasch *et al.*, 2019; Pokherl *et al.*, 2021).

One important question that arises in this context is, if the increasing disasters are linked to an increase in storm activity alone or also because more and more people are living in areas exposed to storm hazards? For appreciating the vulnerability of the population of San Andrés Island, we review here the current geological, environmental, and socio-economic conditions of the island, and examine the record of storm events affecting the island over the past 110 years in relation to global warming induced increasing sea surface temperatures (Schmidt *et al.*, 2006; Glenn *et al.*, 2015; Taylor and Stephenson, 2017) and the apparent increasing storm frequency and intensity in the Caribbean (Vecchi and Knutson, 2008; Brun and Palmer, 2015; Xu *et al.*, 2016; Knutson *et al.*, 2021; Vecchi *et al.*, 2021).

2 Geological setting and environmental conditions

The island of San Andrés is located at 81.7°W and 12.6°N, on the eastern rift shoulder of the NNE 015° trending San Andrés Rift, along the south-eastern edge of the Nicaragua rise (Fig. 1; Geister and Diaz, 2007; Pindell and Kenan, 2009; Carvajal-Arenas and Mann, 2018). The San Andrés Rift is between 11 and 27 km wide and about 346 km long. To the east of San Andrés Island is the Nutibari Rift, a side branch of the San Andrés Rift. Opening of the San Andrés Rift started during the early Eocene and the rift widened during middle Eocene extension. After relative tectonic quiescence throughout the Oligocene, extension accelerated from the middle Miocene to the early Pliocene, and San Andrés Island was uplifted above sea level at that time, (Carvajal-Arenas and Mann, 2018). The rocks exposed on the island belong to the Langhian-Serravallian (~ 16–12 Ma) San Andrés Formation, the Pleistocene San Lucas Formation and Quaternary coastal deposits and rock fall debris (Figs. 2a and 3). The mid-Miocene carbonate rocks of the San Andrés Formation strike NNE 15° and dip 15° to the east. These units form the highest topography with an elevation of up to 86 m at La Loma in the center-north of the island (Fig. 2a; Geister, 1975; Vargas, 2004). The uplifted mid-Miocene rocks are surrounded by a debris blanket of Quaternary erosive products, particularly on the east side, which rest on flat lying Pleistocene marine reef

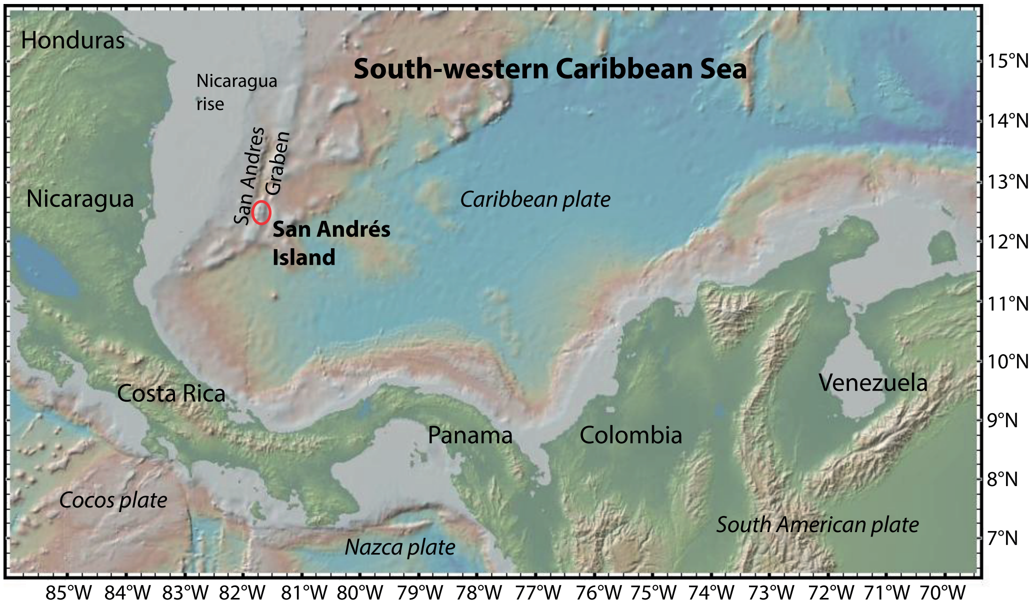

Fig. 1. Regional overview map of the southwestern Caribbean Sea. San Andrés is located on the eastern shoulder of the San Andrés graben system. This map is from GeoMapApp (Ryan *et al.*, 2009).

carbonate rocks of the San Lucas Formation. The youngest sedimentary deposits on the island are Holocene coastal deposits (Figs. 2a, 3a and 3b). The Miocene-Pleistocene carbonate rocks are approximately 200 m thick and rest unconformably on Upper Cretaceous igneous crystalline basement rocks (Bedoya *et al.*, 2010; Carvajal-Arenas and Mann, 2018). A series of eight erosive terraces partly exposed above sea level, partly submarine, can be observed and have been ascribed to Pleistocene eustatic sea level change (Geister, 1975), even though it is not known how much the late stages of local tectonically driven surface uplift may have affected terrace formation, particularly of the > 80 m high terraces.

An approximately eight km long N-S oriented barrier reef complex is located at about 1–2.5 km to the north-east of the north-eastern shoreline of San Andrés. This reef complex consists of the Big Reef, East Reef and Half-a-Reef (Fig. 2a; Geister, 1975). The Big Reef protects the north-eastern end of the island against the open Caribbean Sea. The lagoon in the back-reef area is marked by patch reefs and fringing reefs, whereas small fringing reefs can also be found further to the south along the east coast of the island (Geister, 1975). The growth of reef forming corals is much less prominent on the quieter leeward side of the island (Geister, 1975; Geister and Diaz, 2007).

San Andrés Island has a tropical climate with an average annual temperature of ~ 29 °C, an average relative humidity of 82%, a rainy season from September to November with peak precipitation of up to 400 mm during November in wetter years, and a dry season from February to April with precipitation as low as 22 mm in April (Aguilera Diaz, 2016). The natural fresh water supply of the island depends entirely on these seasonal rains. Given the small surface area of ~ 26 km^2 of the island, the recharge of aquifers with fresh water per year is rather limited. The rain comes from humid air masses that formed over the western Caribbean Sea because of intense sea water evaporation. The humid air masses generally approach the island from a NE direction, driven by the NE-SW directed trade winds. The average annual precipitation for the years 2001–2007 was between 1500 and 2450 mm/yr (Aguilera Diez, 2016) as this value is very variable from year to year, with extremes between 500 and 4100 mm/yr (Geister, 1975). Rain water that falls on the island to the most part infiltrates rapidly through fissures and fractures in the carbonate bedrock, enhancing the development of the karst systems. The infiltration is so efficient that no major rivers or creeks exist on the island. The carbonate bedrock geology and the development of karst features is the main control on the aquifer system, with the El Cove basin hosting the main aquifer of San Andrés (Fig. 2c; Ibanez Gill *et al.*, 2016). The infiltrated fresh water concentrates under the island in a lens, because the groundwater is less dense than the salty sea water, the groundwater basically "floats" on the sea water in the porosity of the carbonate bedrocks (Fig. 4). Numeric modeling of the San Andrés Island aquifers shows that the groundwater lens reaches to a depth of ~ 150 m below sea level beneath the island (Bedoya *et al.*, 2010). The areas of the island that have not been covered by buildings or roads today, have a relatively dense vegetation with mangroves in the low areas and tropical dry forests at higher elevations (Aguilera Diez, 2016). Average annual evapo-transpiration is about 1700 mm/yr (Geister, 1975).

3 Population and socio-economic history and development

San Andrés Island, discovered by the Spanish, appeared on European maps since 1527, and the first semi-permanent settlements were probably established in the 1620–1630s (Meisel Roca, 2003). From about 1629 on the island was under British control, with Puritan settlers establishing cotton, corn and tobacco plantations. Cotton exportation continued until

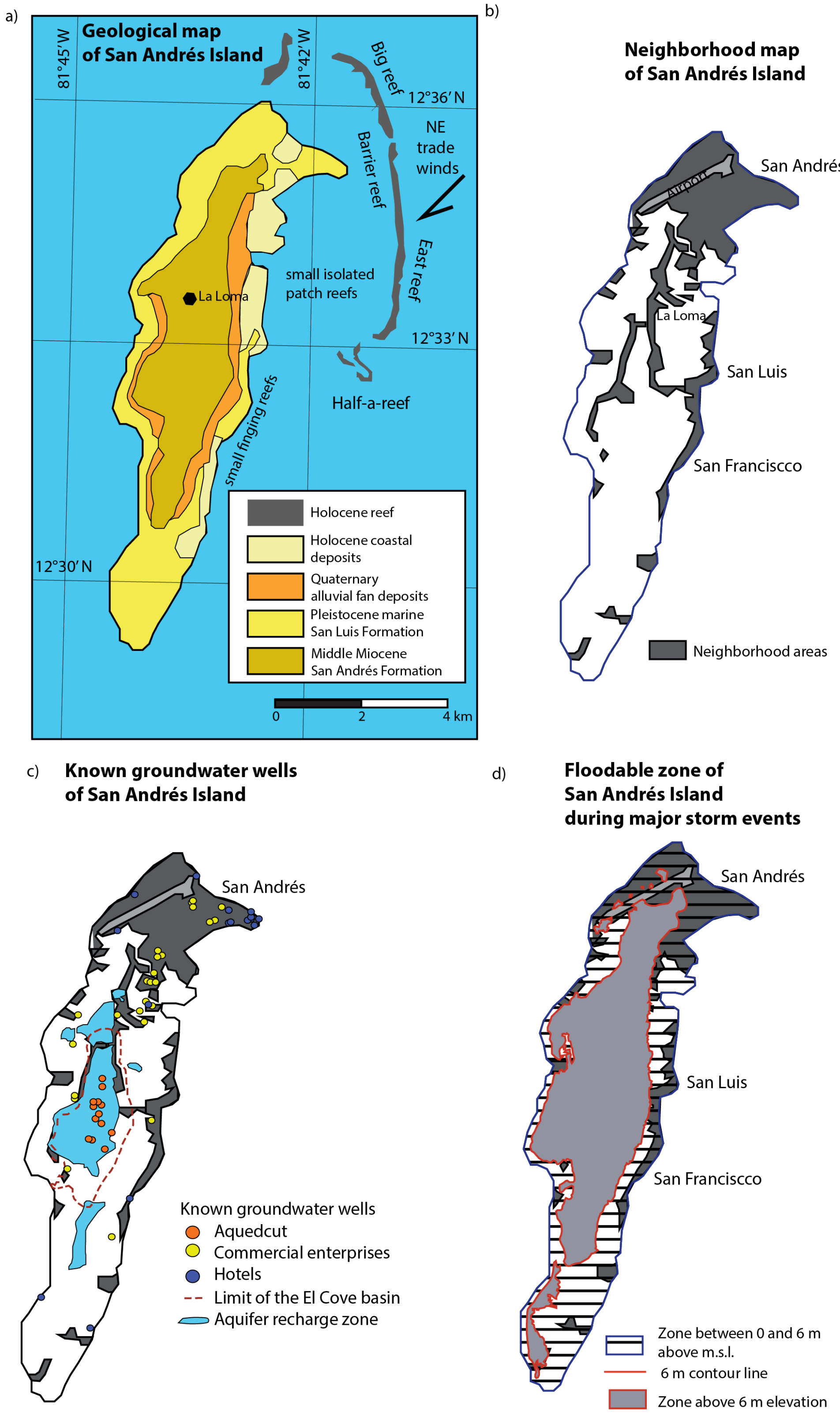

Fig. 2. San Andrés Island (A) simplified geological map (modified from Geister, 1975, and the Geological map of Colombia, Gómez *et al.*, 2015); (B) Neighborhood map (modified from http://www.sAndrés.gov.co); (C) Simplified aquifer map and recharge areas within the El Cove basin. Also shown are a limited number of the up 5900 wells on San Andrés Island used by the municipal aqueduct, commercial enterprises and hotels (map modified from CORALINA 2009); (D) Simplified topographic map showing the areas of the island of 0–6 m elevation, prone to inundation during major storm events (Map modified from Geister, 1975).

Fig. 3. Coastal deposits (A) and outcrops of the Pleistocene San Luis Formation carbonate rocks and reef limestone as seen on the east coast (B), west coast (C) and at the southern end of San Andrés island (D). The Langhian-Serravallian (~ 16–12 Ma) San Andrés Formation that form La Loma are shown in (E, F).

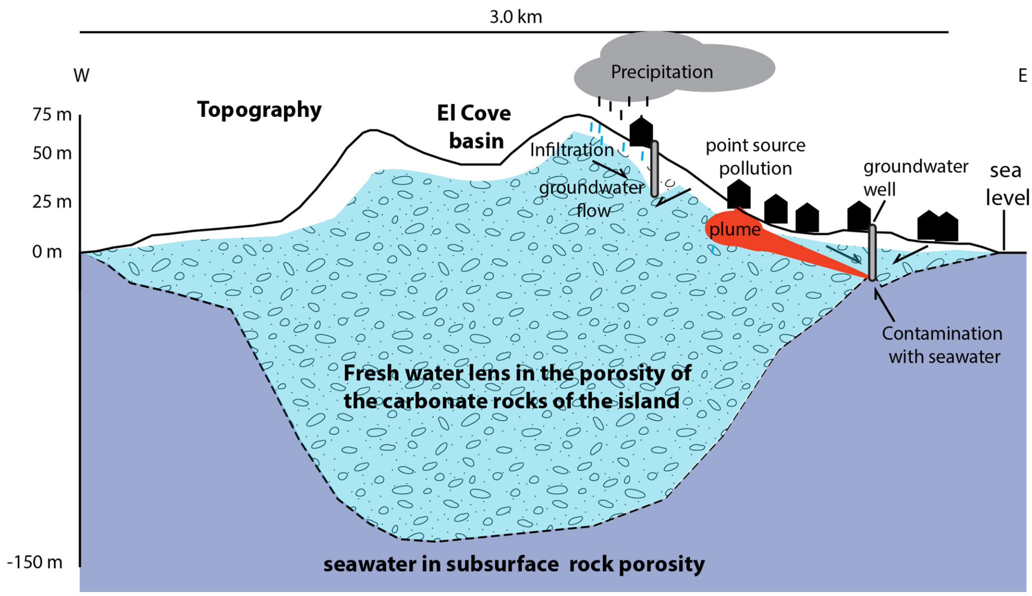

Fig. 4. Schematic cartoon of the groundwater lens beneath San Andrés Island. Topographic profile in E-W direction across the center of the island. Sources of contamination of the San Andrés Island aquifers from point sources, such as a leaking septic tank, or from groundwater overexploitation and ingression of salt water.

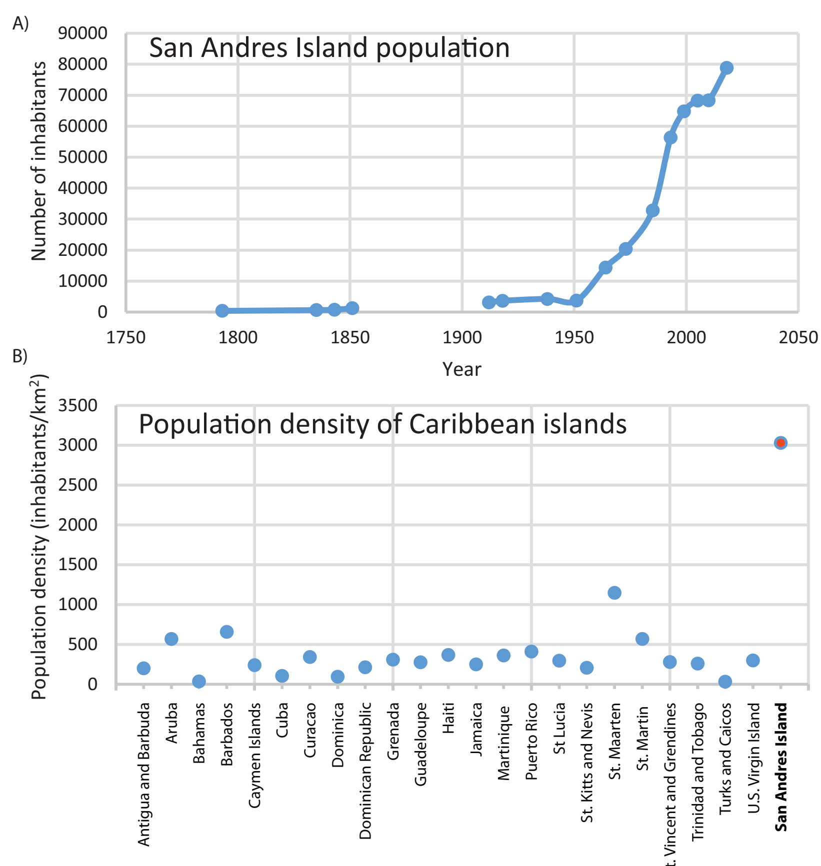

Fig. 5. (a) Population growth of San Andrés Island since 1793. The data were taken from Meisel Roca (2003), DANE (2018). No data are available for the period of 1851–1912. (b) Population density of San Andrés Island in comparison to other Caribbean islands (Data from https://data.worldbank.org).

Table 1. San Andrés population density evolution since 1793.

Year	Inhabitants	Population density (inhabitants/km^2)
1793	393	15.12
1835	644	24.77
1843	731	28.12
1851	1285	49.42
1870	No data	No data
1912	3124	120.15
1918	3653	140.5
1938	4261	163.88
1951	3705	142.5
1964	14 413	554.35
1973	20 359	783.04
1985	32 861	1263.88
1993	56 361	2167.73
1999	64 801	2492.35
2005	68 283	2626.27
2010	68 334	2628.23
2018	78 817	3031.42
2020	80 000*	3076.92

* Estimated value, all other data from Meisel Roca (2003) and DANE (2018).

1853 even if the island changed hands several times between Spanish and British rule during that time. After a Spanish attack in 1641 the Island was literally depopulated, with repopulation starting again since about the 1720s with settlers from Scotland, Ireland, Jamaica and Curacao (Clemente, 1994; Meisel Roca, 2003). No precise information on population numbers is known before 1793 (Fig. 5a), but from that year until 1851 the population increased by about 2% per year from 393 to 1275 inhabitants (Tab. 1; Meisel Roca, 2003).

The second era, from 1853–1953 is marked by an economic shift from cotton production to coconut monoculture plantations, because of the abolition of slavery, as coconut plantations were less labor intensive. The population increased more slowly during this era, reaching a height in 1938 with 4260 inhabitants, but falling to 3700 in 1951 (Tab. 1; Fig. 5a; Meisel Roca, 2003).

The era from 1953–1991, with a declaration of San Andrés as a free port in 1953 and the opening of the airport in 1955, is marked by a dramatic change in the economy and population evolution of the island. The economic change that came with the free port and the initiation of mass tourism put an end to the coconut plantations, and the influx of people from the Colombian mainland dramatically shifted the demographic development, with the population increasing from about 3700 in 1951 to about 56 000 in 1993 (Tab. 1; Fig. 5a; Meisel Roca, 2003).

The era from 1991 to today shows an increase in population of officially up to 78 000 inhabitants by 2018, with about one million tourists visiting the island per year. The population density of San Andrés Island, even when using the conservative population estimate of the Colombian government (DANE, 2018), is about three to ten times higher than the population densities of other Caribbean islands (Tab. 2;

Table 2. Caribbean island population densities as of 2018.

Island	Population density (inhabitants/km^2)
Antigua and Barbuda	202
Aruba	569
Bahamas	37
Barbados	659
Cayman Islands	240
Cuba	106
Curacao	342
Dominica	96
Dominican Republic	213
Grenada	310
Guadeloupe	278
Haiti	369
Jamaica	250
Martinique	361
Puerto Rico	413
St Lucia	297
St. Kitts and Nevis	206
St. Maarten	1150
St. Martin	569
St. Vincent and Grendines	280
Trinidad and Tobago	261
Turks and Caicos	34
U.S. Virgin Island	301
San Andrés Island	3031

Data retrieved in 2018 from The World Bank website: https://databank.worldbank.org/source/world-development-indicators.

Fig. 6. Hotels and commercial buildings along the San Andrés beach front in the north of the island (coordinates 12.58°N and 81.69°E), between 1–2 m elevation above fair-weather sea level. The buildings were constructed on a terrace of the San Luis Formation limestones.

Fig. 5b). The large majority (~74%) of the San Andrés Island population today is concentrated in the north of the island, in the town of San Andrés, and along the east coast in the neighborhoods of San Luis and San Francisco (Figs. 2b and 6; DANE, 2005). Consequently, the population density in these areas is on the order of approximately 6000–10 000 inhabitants/km^2, comparable to cities such as Bangkok, Istanbul, Mexico City or Sao Paulo.

4 Environmental hazards

Despite the geological setting of the island on the rift shoulder of the San Andrés Rift, seismic activity in the area is rather low (Fig. 7), with earthquakes of magnitudes > 4.5 on the Richter scale rarely occurring, at least over the past century. Therefore, seismic hazards are not a major concern for the island population. In contrast, anthropogenically driven global warming caused by the release of CO_2 from fossil fuel combustion and methane release primarily related to the mass production of meat and unfreezing of permafrost soils, starts showing its effects throughout the Caribbean through a combination of processes (*e.g.*, Bueno *et al.*, 2008; Catarious and Espach, 2009; OECD 2014). As it is widely accepted by now, global warming causes the melting of mountain glaciers, the Greenland ice sheet, and the Antarctic ice sheet, which in turn causes eustatic sea level rise (Nerem *et al.*, 2018). Rising sea level can be difficult to deal with for islands such as San Andrés, where large parts of the population live within a few meters of the current fair-weather sea level. In the north of San Andrés Island and along its east coast many hotels and houses are only within one meter of elevation above current sea level (Fig. 6). The current tidal range is about 30 ± 10 cm. Rising sea level poses therefore a long-term threat over the next 50 to 100 years to the local population.

More acute than rising sea level alone are the combined effects of rising sea level with storm surges driven by high windspeeds and extreme rainfall during storm events. Category 4 and 5 Hurricanes Eta and Iota (see the Saffir–Simpson scale in Tab. 3), provided a good example for this as they caused severe flooding on San Andrés Island within two weeks in November 2020 (Stewart, 2021). Even though tropical storms and hurricanes are less common in the southwestern Caribbean Sea than in the eastern Caribbean Sea (*e.g.*, Vecchi and Knutson, 2008), San Andrés Island was affected by storm events on average once every ten years between the 1911 and 2020, as shown in Figure 8a, based on the HURDAT2 dataset of the National Hurricane Center of the United States. The tropical cyclones affecting the island can be divided into two groups depending on the area of origin of the storm systems. Whereas some tropical cyclones come from the eastern Caribbean Sea or Atlantic Ocean, about half of the storm systems start as tropical depressions or storms in the southwestern Caribbean Sea near San Andrés and develop later into hurricanes of different category of the Saffir–Simpson scale (Tabs. 3 and 4, Fig. 8a). San Andrés is mainly affected by tropical cyclones between the months of September and November (Fig. 8b).

The average sea surface temperature (SST) today of the whole Caribbean Sea ranges between 27 and 28.5 °C (Fig. 9a). The SST data available for the southwestern Caribbean Sea is rather limited, as only buoy Station ID 42057 currently located about 480 km to the north of San Andrés Island at 16.908°N and 81.422°W, provides data for the western Caribbean Sea, according to the National Oceanic and Atmospheric Administration (NOAA) National Center of Environmental Information (NOAA Marine Environmental Buoy Database). Looking at the monthly average SST recorded by buoy 42057 for the years 2009 and

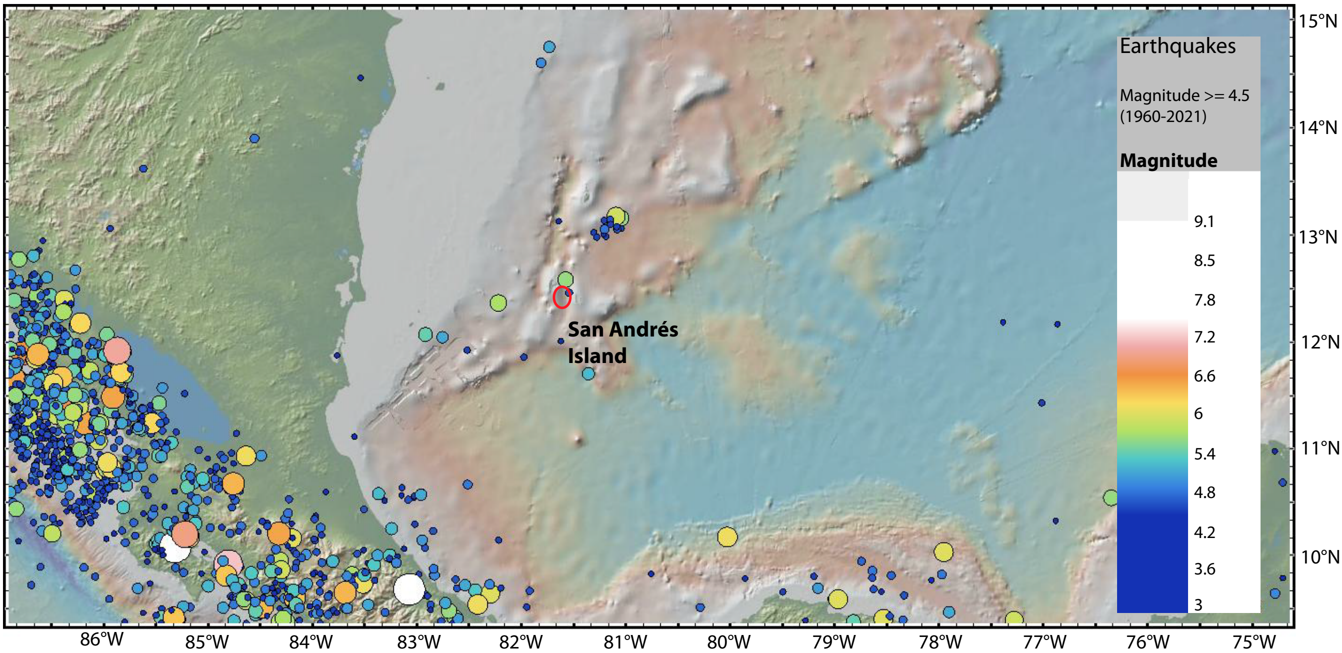

Fig. 7. Map showing the location of earthquakes of magnitude 4.5 and higher on the Richter scale for the Southwestern Caribbean around San Andrés Island. This map is based on the GeoMapApp 1960–2021 seismic database (Ryan *et al.*, 2009).

Table 3. Saffir–Simpson scale for hurricane wind speeds and damage.

Category	m/s	knots (kn)	mph	km/h	hPa*	Damage
5	$\geq$ 70	$\geq$ 137	$\geq$ 157	$\geq$ 252	< 925	Catastrophic damage, many wooden homes will be destroyed, with total roof failure and wall collapse. Debris will block roads. Prolonged power outages.
4	58–70	113–136	130–156	209–251	926–945	Severe damage with loss of most of the roof structure and/or some exterior walls of wooden houses. Most trees will be uprooted.
3	50–58	96–112	111–129	178–208	946–960	Major damage or removal of roofs. Breaking and uprooting of many trees. Long lasting power outages.
2	43–49	83–95	96–110	154–177	961–975	Major roof damage. Uprooting of shallowly rooted trees. Risk of power loss.
1	33–42	64–82	74–95	119–153	976–990	Damages to roofs, breaking of large branches, uprooting of shallowly rooted trees. Extensive damage to power lines.

Note: Category based on maximum sustained wind speed for 1 minute. *Klotzbach et al. (2020) proposed that minimum sea level air pressure is a more reliable indicator of normalized Hurricane damage than windspeed, because air pressure can be measured more easily and precisely.

2020, an increase in mean annual SST from 28.11 °C to 28.65 °C with measured maximum and minimum SST of 30.8 °C and 26.5 °C in 2009, and 31.1 °C and 27.1 °C for 2020 can be observed (Fig. 9a). The SST estimates around San Andrés provided by the NOAA satellite data are slightly cooler (28.25 °C annual average, maximum 30.2 °C, minimum 25.9 °C). Similarly, the global time series data on SST anomalies from the NOAA website (https://www.ncdc.noaa.gov/cag/global/time-series; last consulted 12/02/2022), Such SST data are based on Advanced Very High Resolution Radiometer (AVHRR) or MODerate-resolution Imaging Spectroradiometer (MODIS) remote sensing data, which are comparable (López-Gracía, 2020). These data show an increasing SST trend for the location of San Andrés, the Caribbean Islands (as defined by NOAA) and the northern hemispheres with respect to the base period average value from 1981–2010, 1910–2000 and 1901–2000 respectively for the three datasets (Fig. 9b).

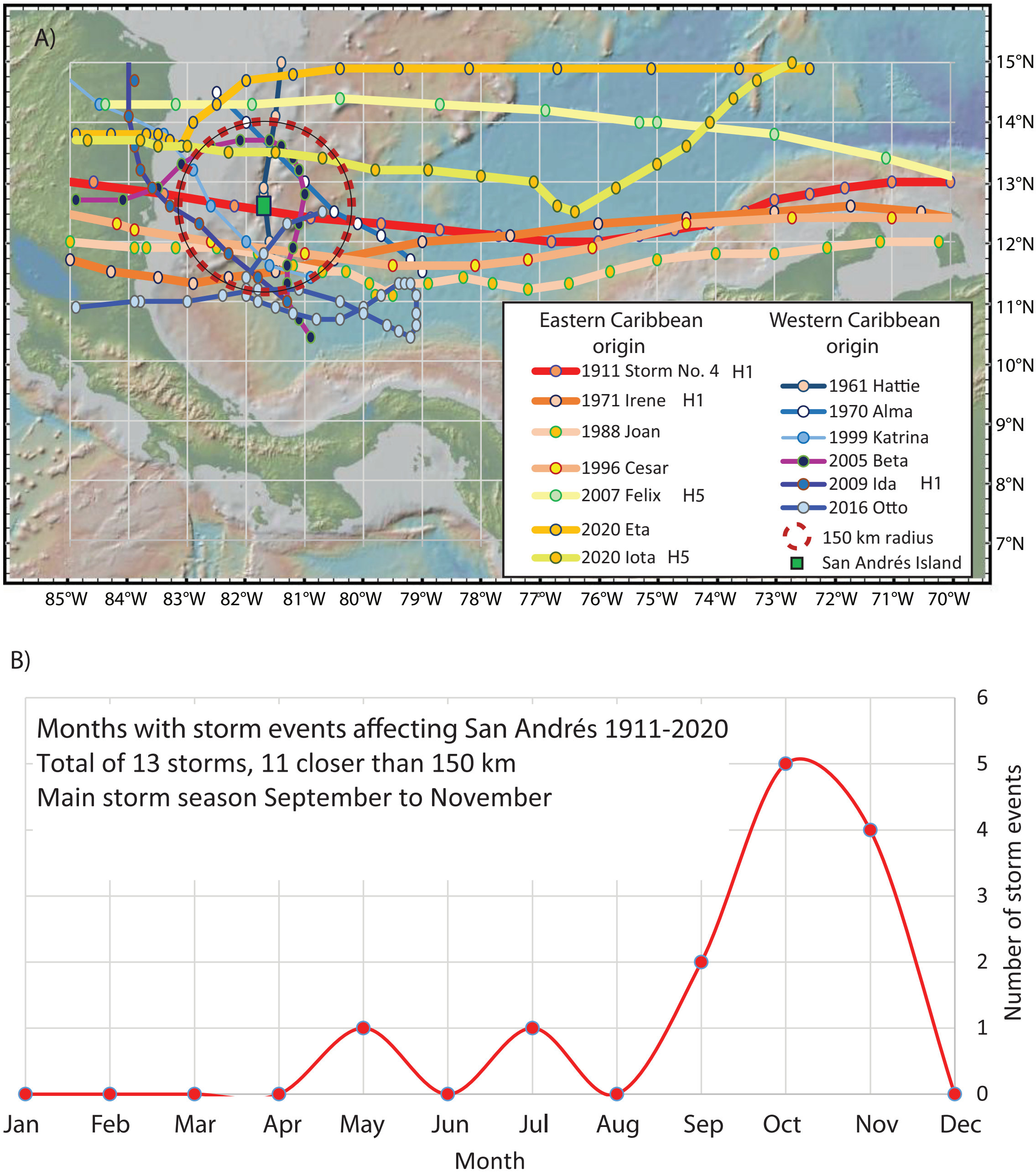

Fig. 8. (A) Hurricane path map from 1911–2020 of hurricanes that affected San Andrés Island. Data were taken from the HURDAT2 dataset of the National Hurricane Center. The map was made with the GeoMapApp (Ryan *et al.*, 2009). The red stippled circle indicates the 150 km radius around San Andrés Island. (B) The main season for tropical cyclones affecting San Andrés Island between 1911 and 2020 is from September to November, based on the HURDAT2 dataset, with a stringer tendency towards November in recent years (Tab. 4).

5 Discussion

5.1 Global warming, sea level rise and storm events

Global warming has an important impact on the islands in the Caribbean (Bueno *et al.*, 2008), because sea level is rising (Nerem *et al.*, 2018; Orejarena-Rondón *et al.*, 2019) and SST are increasing (Schmidt *et al.*, 2006; Glenn *et al.*, 2015). As shown in Figure 9a, SST increased at least by ~ 0.5 °C over the past decade in the western Caribbean Sea, a trend that is reflected in the longer-term SST anomaly dataset of the Caribbean Sea or the northern hemisphere. In addition, the storm frequency and intensity of tropical cyclones affecting San Andrés Island are seemingly increasing as well in recent decades (Ortiz Royero, 2012; Tab. 4). Although the available dataset may not yet be sufficient for providing compelling evidence for a significant increase in storm activity (Burn and Palmer, 2015). In fact, the question of increasing storm frequency in the Caribbean is a strong matter of debate, as the currently available data and modeling scenarios are not yet

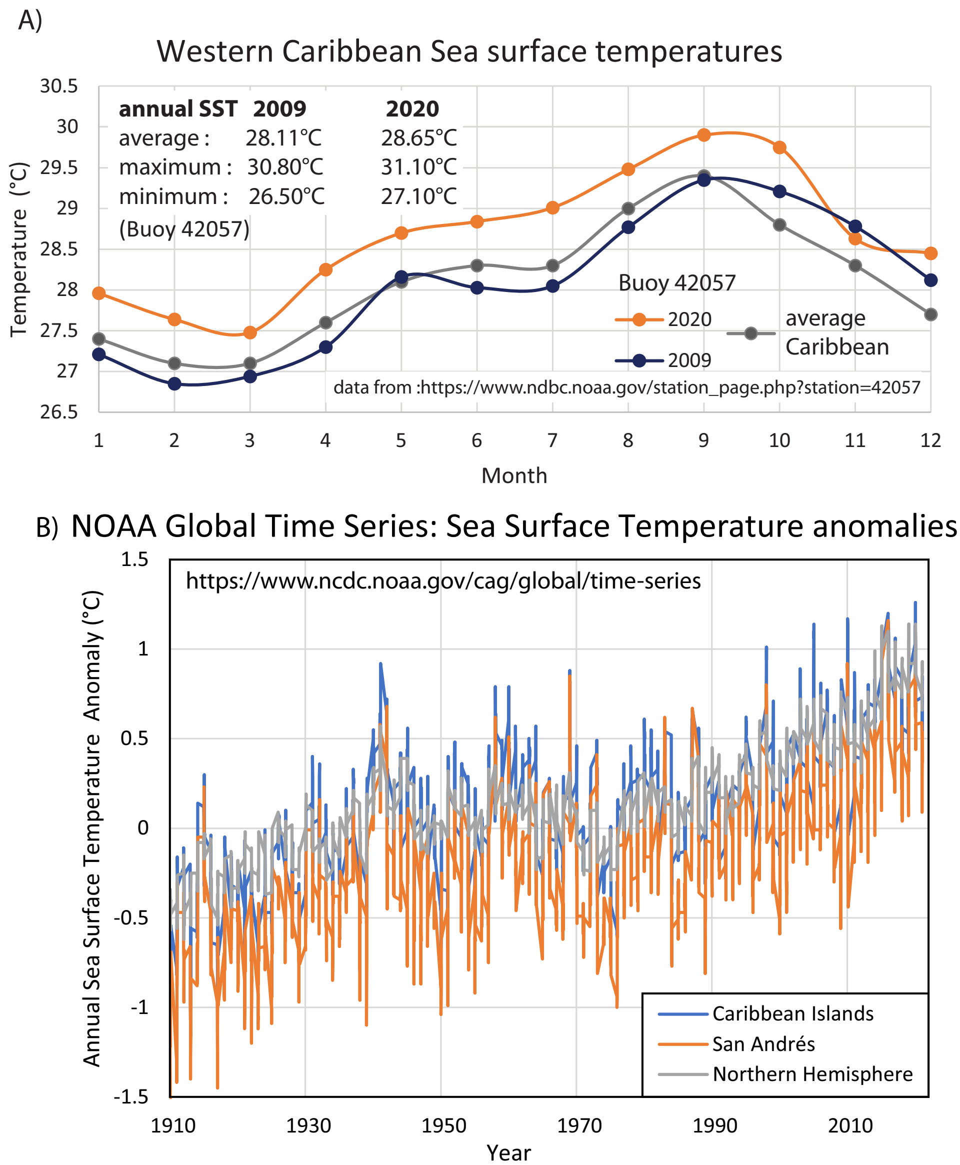

Fig. 9. (A) Sea surface temperature values of the Caribbean Sea from NOAA buoy data. The values for San Andrés Island are from the years 2009 and 2020 (from buoy 42057), compared to the average Caribbean Sea data. (B) Sea surface temperature anomaly data from the NOAA Global Time Series dataset given for the location of San Andrés, the Caribbean Island (as defined by NOAA) and an average trend for the northern hemisphere. The anomaly values are plotted with respect to the average value of the respective base period of 1981–2010 (San Andrés Island), 1910–2000 (Caribbean Islands) and 1901–2000 (northern hemisphere).

fully conclusive (see Vecchi and Knutson, 2008 and references therein), and the apparent increase in overall Caribbean storm frequency in the HURDAT2 dataset may be caused by combined effects of anthropogenically caused global warming and intrinsic variability in the weather-climate system (Vecchi *et al.*, 2021). Nonetheless, global warming and with that increasing SST will most likely cause an increase in tropical cyclone intensity over the next century (Reading, 1990; Knutson *et al.*, 2021), although the duration of storm events may be reduced (Knutson et *et al.*, 2021).

San Andrés Island, being located in the southwestern part of the Caribbean Sea, is not in the area of the strongest tropical cyclone activity (Knutson et *et al.*, 2021), but there and elsewhere in the Caribbean, not all tropical cyclones are the same. As shown in Figure 8a and Table 4, about half of the tropical cyclones that affected San Andrés Island over the past 110 years originated in the southwestern Caribbean Sea. These "locally born" storms tend to develop from tropical lows and depressions into tropical storms and then category 1-2 hurricanes in their initial stages when they pass the island, but may become category 3-5 hurricanes later on further away from San Andrés. The impact of such storm events can be considerable but may not cause disaster. More dangerous for San Andrés are hurricanes coming from the eastern Caribbean, as such storms tend to have gathered more strength along their path and reach the western Caribbean as category 3-5 hurricanes, they tend to cause heavy damage, as it happened in 2020. The amount of damage will partly be depending on

Table 4. Storm events affecting San Andrés Island 1911–2020.

Year	Name	Month	Closest distance to San Andrés (km)*	Strength near San Andrés	Maximum strength achieved	Origin	La Niña intensity**
1911	Storm No.4	October	0	H1	H1	Eastern Caribbean	?
1961	Hattie	October	0	TS	H5	Southwestern Caribbean	None
1970	Alma	May	130	TD	H1	Southwestern Caribbean	Moderate
1971	Irene	September	124	H1	H3	Eastern Caribbean	Weak
1988	Joan	October	74	H3	H4	Eastern Caribbean	Strong
1996	Cesar	July	63	TS	H1	Eastern Caribbean	Moderate
1999	Katrina	October	61	TD	TS	Southwestern Caribbean	Strong
2005	Beta	October	70	TS	H3	Southwestern Caribbean	Weak
2007	Felix	September	190	H5	H5	Eastern Caribbean	Strong
2009	Ida	November	110	H1	H1	Southwestern Caribbean	None
2016	Otto	November	90	low	H2	Southwestern Caribbean	Weak
2020	Eta	November	200	H4	H4	Eastern Caribbean	Weak
2020	Iota	November	100	H5	H5	Eastern Caribbean	Weak

Distance from Ortiz Royero (2012) or estimate form HURDAT2 best track data set. Low: tropical low-pressure system; TD: tropical depression; TS: tropical storm; H1-5: category 1-5 hurricanes; La Niña intensity based on the Oceanic Niño Index (ONI) from https://ggweather.com/enso/oni.htm

how close the eye of the cyclone approaches the island. In general, severe wind damage and heavy rainfall can be expected if the center of the storm enters the 100–150 km radius around the island (Willoughby and Rahn, 2004). Similarly, the damage done by storm surges can be considerable when storms are 150 km or closer (Wornom and Welsh, 2002).

As outlined above, eustatic sea level rise alone already poses an important problem for San Andrés Island as the majority of the population on the island lives between 0 to 6 m elevation (Figs. 2b and 2d). The local airport is at 2 m elevation above sea level. Many buildings have been constructed close to the shore on a Pleistocene reef terrace that is exposed approximately 40 cm above present-day mean sea level (Fig. 6), and is already within reach of the present-day tidal range of about 30–40 cm. According to Nerem *et al.*, (2018) sea level in the Caribbean Sea may rise up to 65 ± 12 cm over the next 80 years. The sea level rise scenarios provided by the ICPP Assessment Report 6 (Masson-Delmotte *et al.*, 2021) show more variability in the uncertainty of global sea level rise estimates, but according to the best and worst-case global warming scenarios, sea level may rise between 0.32–0.62 m (scenario SSP1-1.9) and 0.98–1.88 (scenario SSP5-8.5) by the year 2100, with the intermediate scenario (SSP2-4.5) of 0.66–1.33 m of sea level rise. Such a rise in sea level will cause permanent flooding of certain areas in the town of San Andrés, San Luis and San Francisco (Figs. 2b and 2d). This flooding problem will be compounded during storm events because of storm surges. Ortiz Royero *et al.* (2015) published a study on wave height during storm surges for San Andrés Island using the Simulating Waves Nearshore (SWAN) spectral model of Booij *et al.* (1999). The modelling results indicate that the 2–3 km wide shelf and the barrier reef (Big Reef and East Reef in Fig. 2a) along the northeast coast of the island provide some protection for the island by dissipating wave energy and limiting storm surge wave heights to 0.5 m, which can nonetheless result in flooding of the beach front. However, storm surges approaching the southeast coast of the island, where barrier reefs and a wide shelf are absent, may reach up to 5 m (Ortiz Royero *et al.*, 2015). Similar storm surges were observed during Hurricane Felix in 2007 on the coast of Nicaragua (Needham *et al.*, 2014). Over the next decades storm surges of up to 5 m combined with the effects of rising sea level could cause inundation of almost half of San Andrés Island in areas at elevations between 0–6 m (Fig. 2d).

Of the 13 storm events between 1911 and 2020 summarized in Table 4, eleven storms came closer to the island than 150 km, causing wind and storm surge damage. According to the HURDAT2 dataset the category 1 hurricane Storm No. 4 in 1911 and category 1 hurricane Hattie in 1961 passed directly over the island (Fig. 8a). Storm No. 4 came from the eastern Caribbean and crossed the island from east to west. The locally formed hurricane Hattie was a tropical storm when it passed the island from south to north before gaining hurricane strength. The damage to people and infrastructure in 1911 was rather limited as the local population counted only about 3000 people and no well-developed tourism sector existed at that time. By 1961 the population had already increased to about 14 000 people, putting many more lives at risk, even though the 1961 storm was weaker then Storm No. 4 of 1911 when it crossed the island. Two of the storms in Table 4, category 5 hurricane Felix in 2007 and category 4 hurricane Eta 2020, passed about 200 km to the north of San Andrés. As that they did not cause extreme wind damage (Eta had tropical storm windspeeds of up to 75 km/h at San Andrés), but nonetheless they had an important impact on San Andrés Island, as heavy rainfall related to these storms resulted in severe flooding.

5.2 Protection from the barrier reef

Even though the barrier reef has offered so far relatively good protection of the northeast of the island, the reef is not in a healthy condition in past decades. Increasing SST with maximum temperatures acceding 29 °C during the months of August to October in recent decades have had a negative impact on the reef ecology. Coral bleaching events have occurred in recent years, as well as the spread of diseases (Zea *et al.*, 1998; Navas-Camacho *et al.*, 2010), green algae blooms and dominance of algae over corals because of high nutrient contents in the sea water around the island linked to missing waste water treatment on the island, and offshore sewage water disposal (Zea *et al.*, 1998; Rodríguez-Ramírez *et al.*, 2010; Gavio and Mancera Pineda, 2015). In addition, overfishing and damages caused by mass tourism have taken their toll on the reef ecology and stability. Decline in reef health and rising sea levels could cause the drowning of the reef and further increase the vulnerability of San Andrés Island during storm events, as the reef may be less resistant against storm surges and may provide less protection for the island. Increasing storm intensity may also cause more direct damage to the unhealthy reef during storm events. To fight this development, a major reef restoration project is underway (Zea *et al.*, 1998), and a variety of protective measures to limit the damage caused by storm surge and rainfall flooding during major storm events may be needed to protect the population.

5.3 Socio-economic factors contributing to the vulnerability of the population

In order to appreciate the vulnerability of the island population, additional factors need to be considered in addition to the environmental hazards outlined above. These factors include the infrastructure in terms of housing constructions, lack of evacuation roads, the increase in population density in past decades, the difficult access to the hospital during storm events, and the supply of clean drinking water particularly in the aftermath of storm events. Whereas, many of the stone houses and hotels of the richer population in the town of San Andrés will most likely suffer little direct wind damage during storm events, many wooden accommodations of the poorer part of the population may very well suffer direct wind damage and/or flooding. Lessons can be learned from the damage caused by category 5 Hurricane Iota in November 2020. Occurring only two weeks after the flooding caused by Hurricane Eta, Iota caused severe damage to the power supply on the island, leaving 60% of the population without electricity, wide-spread flooding and damages to wooden houses, as reported in the Colombian media.

The possibilities for evacuations are rather limited on the island, given the local infrastructure and condition of the road system. From the town of San Andrés in the north of the Island (Fig. 2), access to the higher elevation area of La Loma is not easily possible, as the access roads along the east and west coasts are located close to the shores. Particularly the roads on the east of the Island are prone to flooding during storms. Similarly, the access road to the local Hospital Amor de Patria is within the floodable zone, even though the hospital itself has been constructed at 13 m elevation. Furthermore, because of the island's isolated position far offshore (about 700 km offshore the Colombian coast), San Andrés Island lacks rapid evacuation possibilities to the Colombian mainland during storm events, which also puts constraints on disaster relief response in the aftermath of a disaster.

The availability and supply of clean drinking water for the population of San Andrés is already difficult on a regular day, as mass tourism and the high population density of San Andrés cause immense pressure on the local environment in terms of fresh water usage and pollution on the island and in the waters around the island. The aquifers of the island are overexploited by the municipal aqueduct, which services only ~51% of all households, but almost all hotels and commercial enterprises, with on average 2.7 million m^3/yr (CORALINA 2009; Defensoría del Pueblo de Colombia, 2015; Barrios Torrejano, 2015; Ibanez Gill *et al.*, 2016). This is much more than the amount of aquifer recharge by rainfall. Supposedly 80–85% of the "drinking" water supply comes from the aquifer in the El Cove basin in the center of the island (Figs. 2c and 4; CORALINA, 2009; Bedoya *et al.*, 2010). A very serious problem is that 69% of the groundwater is highly contaminated, 39% moderately contaminated and only ~1% of the water produced from the aquifers on San Andrés Island is considered as having drinking water quality (CORALINA, 2009; Ibanez Gil *et al.*, 2016). The contamination of the groundwater comes principally from three sources. First, because of the karst landscape of San Andrés Island, easy infiltration of untreated sewage water from the absence of septic tanks or leaking septic tanks into the aquifer is a major threat to groundwater quality (Fig. 4), even more so during extreme rainfall events. Until the late 1990's only 8% of the population were connected to a sewage system (Zea *et al.*, 1998). Similarly, solid waste poses equally a threat to the San Andrés Island aquifers. Waste disposal sites in general pose a risk as long-term point sources of unknown bio-chemical contaminants, as runoff from a site such as the Magic Garden landfill infiltrates uncontrolled into the subsurface. The final source of possible groundwater contamination is related to the overexploitation of the aquifers. If too much groundwater is pumped, particularly near the beach toward the edge of the fresh water lens, salty seawater will intrude and contaminate the groundwater exploitation wells (Fig. 2c; Bedoya *et al.*, 2010; Ramirez Martin and Vargas Mora, 2016; Ibanez Gill *et al.*, 2016). Such a situation cannot easily be undone and usually means that the well needs to be abandoned. With desalination and import of drinking water the island authorities try to manage the ever-growing demand for clean drinking water, but many households of the poorer population resort to rain water capture. Waste water treatment of sewage and landfill runoff are urgently needed as well as drinking water purification plants to guarantee a sufficient drinking water supply for the whole population. This is particularly important in order to limit the threat of spreading infectious diseases during times of natural disaster.

5.4 Future storm events

The question is not if San Andrés will be struck directly by a major storm such as Puerto Rico in 2017 or Providencia in 2020, but when? Tropical cyclones mainly affected San Andrés between September and November, during the main hurricane season (Fig. 8c), and may be expected in the future during La Niña years of the El Nino Southern Oscillation (ENSO), as shown in Table 4, and mentioned by Gray (1984).

In 1911 Storm No. 4 passed over the island, and this can happen again until the end of the century with a category 4 or 5 hurricane. Using the storm record given in Table 4, San Andrés was affected by a major storm about once every eight years since 1911. With a recurrence interval of eight years, it can be expected that at least ten tropical cyclones will impact San Andrés until the end of the century. This may be regarded as a conservative estimate, because the storm record over the past 20 years indicates that the frequency apparently increased to a tropical cyclone once every three years. Such an increase is not observed in the long-term record for the rest of the Caribbean Sea based on the HURDAT2 dataset (Vecchi and Knutson (2008); Vecchi *et al.*, 2021), and it may be a regional phenomenon. However, it could mean that San Andrés may experience up to 26 major storm events until the end of the century, if that storm frequency would remain constant. Category 4-5 hurricanes cause the most damage, and three category 4-5 hurricanes affected San Andrés since 1911, which gives a recurrence interval of this type of event of currently ~ 37 years. This means there is a ~ 28% chance that San Andreas will be affected by a category 4-5 hurricane over the next ten years. Unknown is what damages each of these storm events will cause. According to the Colombian press and media the damages caused by hurricanes Iota and Eta on Colombian territory (San Andrés Island, Providencia, Santa Catalina and along the Colombian Caribbean coast) exceeded 100 million US$. Fortunately, the loss of life was very limited with in total 10 fatalities, but the damage by wind, storm surge and rainfall to property and infrastructure were considerable. As it is already the case now after these storms, the recovery period may take months to years. Even though it is difficult to quantify, the San Andrés Island population seems to be at much higher risk in comparison to the Colombian Caribbean coast populations in cities such as Cartagena or Santa Marta, because the population densities are lower in these cities, the evacuation of the population is much easier, and disaster relief can more rapidly be applied. In order to reduce the risk of the population during and after future storm events policy-makers may want to consider some of the following points: 1) It is important to limit the rapid population growth that San Andrés has seen over the past 70 years, because the more people are on the island the more lives are put at risk. 2) As the major tropical cyclones are those coming from the eastern Caribbean Sea, any storm approaching from this area should be carefully monitored and an early warning system could help to mitigate risk through evacuations. 3) In this context, the improvement and clear indication of evacuation routes for the populations of the San Luis and San Francisco neighborhoods and the creation of refuge areas in the higher elevation La Loma for the evacuated people should be considered. 4) Measures need to be taken to protect the health of the barrier reef by reducing seawater pollution around the island, and by protecting the reef better against the impact and damages from mass tourism. All the reefs around San Andrés need strict protection. 5) Constructive measures to protect access to critical infra structure such as the hospital and evacuation roads in certain low-elevation areas long the SE-coast of the island from the impact of storm surge flooding would be helpful. 6) Finally, to mitigate the risk of a drinking water shortage in the aftermath of a storm event, the construction of drinking water reservoirs in the La Loma area should be considered for assuring an emergency drinking water supply.

6 Conclusions

Since 1911 San Andrés Island has been affected on average by a tropical cyclone once every eight years, but over the past 20 years the frequency has increased to one tropical cyclone every three years. When these storms approach the island closer than 150 km, they may not only cause severe flooding by rainfall, but also flooding by storm surges and heavy wind damages, particularly to the wooden houses and low-elevation infrastructure. Given the high population density of on average 3000 inhabitants/km^2, but mainly concentrated in areas of low elevation between fair-weather sea level and 6 m elevation, a large part of the population is at risk of suffering disaster during storm events, as it happened in 2020. Rising sea level and increasing sea surface temperatures caused by global warming will most like increase the flooding of the low-elevation areas on the island during storm events, as maybe the frequency but more certainly the intensity of tropical cyclones seem to increase. In the case of San Andrés, both the increase in population density and the possibly more frequent and stronger storms will increase the vulnerability of the island population in the future even more. A set of preemptive measures could help to reduce the risk and improve resilience.

Data availability

The HURDAT2, SST, seismic and population data used in this study are freely available from the cited sources and internet pages. Sea surface temperature data were obtained from the NOAA webpages https://www.ndbc.noaa.gov/station_page.php?station=42057 and https://www.ncdc.noaa.gov/cag/global/time-series Population data are available from https://data.worldbank.org

Acknowledgements. We thank the anthropologist of the Centro Cultural de San Andrés of the Banco de la República for information on the history of San Andrés and the present-day population and socio-economic situation of the island. Fieldwork on the island was done during a detachment to the CNRS in 2017–2018 in Colombia. We thank the associate editor Nicolas Tribovillard and two anonymous reviewers for their valuable comments, which helped to improve the manuscript.

References

Acevedo S. 2016. Gone with the wind: Estimating hurricane and climate change costs in the Caribbean. IMF Working Paper 16/199, 40 p.

Aguilera Diaz M. 2016. Geografía económica del archipiélago de San Andrés, Providencia y Santa Catalina. InMeisel Roca A, Aguilera Diaz M, eds. *Economía y medio ambiente del archipiélago de San Andrés, Providencia y Santa Catalina*. Bogotá, Colombia: Banco de Republica, ISBN 978-958-664-328-3, pp. 47–116.

Barrios Torrejano DJ. 2015. Valorización del uso del agua en la Isla de San Andrés: Turistas, Hoteles, y Vivendas Turisticas. Universidad Nacional de Colombia, Medellín, Trabajo de investigación, 44 p.

Bedoya M, Vélez JI, Vélez, MV, Poveda G, Carmona J. 2010. Modelo numérico del acuífero de la Isla de San Andrés, Colombia. In: *XXIV*

Congreso Latinoamericano de hidráulica, Punta del Este, Uruquay. Extended Abstract, 16 p.

Booij N, Ris RC, Holthuijsen LH. 1999. A third-generation wave model for coastal regions. Part I. Model description and validation. *Journal of Geophysical Research* 104: 7649–7666.

Bueno R, Herzfeld C, Stanton, EA, Ackerman F. 2008. The Caribbean and climate change, the cost of inaction. Report, Global Development and Environment Institute, Tufts University, http://www.sei-us.org/climate-and-energy/Caribbean_Inaction_Cost.htm.

Burn MJ, Palmer SE. 2015. Atlantic hurricane activity during the last millennium. *Nature Scientific Reports* 5: 12838. https://doi.org/10.1038/srep12838. https://www.nature.com/articles/srep12838.

Carvajal-Arenas LM, Mann P. 2018. Western Caribbean intraplate deformation: Defining a continuous and active microplate boundary along the San Andrés Rift and Hess Escarpment Fault Zone, Colombian Caribbean Sea. *AAPG Bulletin* 102: 1523–1563.

Catarious DM, Espach RH. 2009. Impacts of climate change on Colombia's National and Regional Security. Center for Naval Analyses, Analysis and Solutions, CRMD0021520.A1/FINAL.

Clemente I. 1994. El Caribe insular: San Andrés y Providencia. In: Meisel Roca A, ed. *Historia económica y social del Caribe colombiano*. Barranquilla: Ediciones Uninorte.

CORALINA. 2009. Plan de Manejo de Aguas Subterraneas. San Andrés: Corporación Para el Desarrollo Sostenible del Archipiélago de San Andrés, Providencia y Santa Catalina. https://www.minambiente.gov.co/images/GestionIntegraldelRecursoHidrico/pdf/acuiferos/Plan-de-Manejo-de-Aguas-Subterraneas-en-San-Andres-y-Providencia.pdf (last accessed: 28/07/2021).

Defensoría del Pueblo de Colombia. 2015. Informe defensoríal: Prestación de los servicios públicos domiciliarios de acueducto, alcantarillado y aseo en el archipiélago de San Andrés, Providencia y Santa Catalina. Defensoría del Pueblo de Colombia, 78 p. www.defensoria.org.co.

DxxAxxNE. 2018. Boletin Censo General 2018. http://www.dane.gov.co/ (last accessed 24/08/2021).

Gavio B, Mancera Pineda JE. 2015. Blooms of ephemeral green algae in San Andrés Island, International Biosphere Reserve Seaflower, Southwestern Caribbean. Acta *Biol*. Colomb. 20: 259–262. http://doi.org/10.15446/abc.v20n2.46062.

Geister J. 1975. Riffbau und geologische Entwicklungsgeschichte der Insel San Andrés (westliches Karibisches Meer, Kolumbien). *Stuttgarter Beiträge zur Naturkunde, Serie B Geologie und Paläontologie* 15: 212.

Geister J, Diaz JM. 2007. Ambientes arrecifales y geología de un archipiélago oceánico: San Andrés Providencia y Santa Catalina (Mar Caribe, Colombia) con Guía Campo. Instituto Colombiano de Geología y Minería Ingeominas, 114 p.

Glenn E, Comarazamy D, González JE, Smith T. 2015. Detection of recent regional sea surface temperature warming in the Caribbean and surrounding region. *Geophysical Research Letters* 42: 6785-–6792. http://doi.org/10.1002/2015GL065002.

Gómez J, Nivia Á, Montes NE, Diederix H, Almanza MF, Alcárcel FA, *et al.* 2015. Explanatory notes: Geological Map of Colombia. InGómez J, Almanza MF, eds. *Compilando la geología de Colombia: Una visión a 2015*. Servicio Geológico Colombiano, Publicaciones Geológicas Especiales 33: 35–60.

Gómez-López DI, Segura-Quintero C, Sierra-Correa PC, Garay-Tinoco J. 2012. Atlas de la Reserva de Biósfera Seaflower. Archipiélago de San Andrés, Providencia y Santa Catalina. Instituto de Investigaciones Marinas y Costeras "José Benito Vives De Andréis" –INVEMAR– y Corporación para el Desarrollo Sostenible del Archipiélago de San Andrés, Providencia y Santa Catalina –CORALINA–. Serie de Publicaciones Especiales de INVEMAR #28. Santa Marta, Colombia, 180 p.

HURDAT2. National Hurricane Centre, Hurricane Research Division, AOML, NOAA. https://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html (last accessed 06/07/2021).

Ibanez Gil JW, Chaparro F, Ramírez Jiménez JD, Quiroga HG, Lesmes Fabian C. 2016. Acuíferos de San Andrés: Evaluación de la Problemática Ambiental. In: *Abstract*, Congreso Ingeniera Civil, Tunja, Colombia.

Klotzbach PJ, Bell MM, Bowen SG, Gibney EJ, Knapp KR, Schreck III CJ. 2020. Surface pressure a more skillful predictor of normalized hurricane damage than maximum sustained wind. Bulletin of the American Meteorological Society, E830–E846. https://doi.org/10.1175/BAMS-D-19-0062.1.

Knutson TR, Chung MV, Vecchi G, Sun J, Hsieh TL, Smith AJP. 2021. Climate change is probably increasing the intensity of tropical cyclones. In: Le Quéré C, Liss P, Forster P, eds. *Critical Issues in Climate Change Science*, Science Brief Review. https://doi.org/10.5281/zenodo.4570334.

Londoño-Diaz L, Vargas-Morales M. 2015. An insight into the economic value of reef environments through the literature: The case of the Seaflower Biosphere Reserve. *Bol. Invest. Mar. Cost*. 44: 93–116.

López-García MJ. 2020. SST Comparison of AVHRR and MODIS Time Series in the Western Mediterranean Sea. *Remote Sensing* 12: 2241. http://doi.org/10.3390/rs12142241.

Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, *et al.* (eds.). 2021. IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on *Climate Change*, Cambridge University Press, 3949 pp.

Meisel Roca A. 2003. The Continentalization of San Andrés Island, Colombia: Panyas, Raizales and Tourism, 1953–2003. *Documentos de trabajo sobre economía regional No. 37, Banco de la República*, Cartagena de Indias, Colombia, http://www.banrep.gov.co.

Navas-Camacho R, Gil-Agudelo DL, Rodríguez-Ramírez A, Reyes-Nivia MC, Garzón-Ferreira J. 2010. Coral diseases and bleaching on Colombian Caribbean coral reefs. *Rev. Biol. Trop.* 58: 95–106.

Needham HF, Keim BD, Sathiaraj D. 2014. A review of tropical cyclone-generated storm surges: Global data sources, observations, and impacts. American Geophysical Union, *Reviews of Geophysics*. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014RG000477.

Nerem RS, Beckley BD, Fasullo JT, Hamlington BD, Masters D, Mitchum GT. 2018. Climate-change–driven accelerated sea-level rise detected in the altimeter era. In: Proceedings of the National Academy of Sciences of the United States of America. https://www.pnas.org/content/115/9/2022.

Ortiz Royero JC. 2012. Exposure of the Colombian Caribbean coast, including San Andrés Island, to tropical storms and hurricanes, 1900–2010. *Nat. Hazards* 61: 815–827. http://doi.org/10.1007/s11069-011-0069-1.

Ortiz Royero JC, Plaza Moreno JM, Lizano O. 2015. Evaluation of extreme waves associated with cyclonic activity on San Andrés Island in the Caribbean Sea since 1900. *Journal of Coastal Research* 31(3): 557–568.

OxxExxCD. 2014. Survey of Policies – Water and Climate Change Adaptation, Colombia. www.oecd.org/env/resources/waterandclimatechange.htm.

Orejarena-Rondón AF, Sayol JM, Marcos M, Otero L, Restrepo JC, Hernández-Carrasco I, *et al.* 2019. Coastal impacts driven by sea-level rise in Cartagena de Indias. *Front. Mar. Sci.* 6: 614. http://doi.org/10.3389/fmars.2019.00614.

Pindell J, Kennan L. 2009. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: An update. In: James KH, Lorente MA, Pindel J, eds. *The origin and evolution of the Caribbean Plate*. Geological Society of London Special Publications, 328, https://doi.org/10.1144/SP328.

Pokherl R, del Cos S, Montoya Rincon JP, Glenn E, González JE. 2021. Observation and modeling of hurricane Maria for damage assessment. *Weather and Climate Extremes* 33: 100331. https://doi.org/10.1016/j.wace.2021.100331.

Ramírez Martínez LD, Vargas Mora TA. 2016. Evaluación de la vulnerabilidad a la contaminación por Cuna Marina en los acuíferos de San Andrés (Colombia). *Boletín Semillas Ambientales, Bogotá, Colombia* 10: 64–68. ISSN: 2463-0691.

Reading AJ. 1990. Caribbean tropical storm activity over the past four centuries. *International Journal of Climatology* 10: 365–376. https://doi.org/10.1002/joc.3370100404.

Rodríguez-Ramírez A, Reyes-Nivia MC, Zea S, Navas-Camacho R, Garzón-Ferreira J, Bejarano S, *et al.* 2010. Recent dynamics and condition of coral reefs in the Colombian Caribbean. *Rev. Biol. Trop. (Int. J. Trop. Biol. ISSN-0034-7744)* 58: 107–131.

Ryan WBF, Carbotte SM, Coplan JO, O'Hara S, Melkonian A, Arko R, *et al.* 2009. Global Multi-Resolution Topography synthesis. *Geochem. Geophys. Geosyst.* 10: Q03014. https://doi.org/10.1029/2008GC002332.

Schmidt MW, Vautravers, MJ, Spero HJ. 2006. Western Caribbean Sea surface temperatures during the late Quaternary. *Geochemistry, Geophysics, Geosystems* 7: Q02P10. http://doi.org/10.1029/2005GC000957.

Smith K. 2001. Environmental hazards, assessing risk and reducing disaster, 3rd ed. London and New York: Routeledge, 392 p.

Stewart SR. 2021. Hurricane Iota. National Hurricane Center Tropical Cyclone Report (AL312020). https://www.nhc.noaa.gov/data/tcr/AL312020_Iota.pdf.

Taylor MA, Stephenson KA. 2017. Impacts of climate change on sea temperature in the coastal and marine environments of Caribbean Small Island Developing States (SIDS). *Caribbean Marine Climate Cange Report Card, Science Review* 201: 23–30.

Timmerman P. 1981. Vulnerability, resilience and the collapse of society. *Environmental Monograph No.1. Toronto*. Institute for Environmental Studies, University of Toronto, 42 p. https://doi.org/10.1002/joc.3370010412.

Vargas G. 2004. Geología de la Isla de San Andrés, Colombia. *Geología Colombiana* 29: 71–87.

Vecchi GA, Knutson TR. 2008. On estimates of historical North Atlantic Tropical Cyclone Activity. *Journal of Climate* 21: 3580–3600. https://doi.org/10.1175/2008JCLI2178.1.

Vecchi GA, Landsea C, Zhang W, Villarini G, Knutson T. 2021. Changes in Atlantic major hurricane frequency since the late-19th century. *Nature Communications* 12: 4054. https://doi.org/10.1038/s41467-021-24268-5.

Willoughby HE, Rahn ME. 2004. Parametric representation of the primary vortex. Part I: Observations and evaluation of the Holland (1980) model. *Monthly Weather Review* 132: 3033–3048. https://doi.org/10.1175/MWR2831.1.

Wornom S, Welsh D. 2002. An MPI quasi time-accurate approach for nearshore wave prediction using SWAN code. Part I. *Coastal Engineering Journal* 44: 247–256.

Xu J, Wang Y, Tan ZM. 2016. The relationship between sea surface temperature and maximum intensification rate of tropical cyclones in the North Atlantic. *Journal of the Atmospheric Sciences* 73: 4979–4988. https://doi.org/10.1175/JAS-D-16-0164.1.

Zea S, Geister J, Garzón-Ferreira J, Díaz JM. 1998. Biotic changes in the reef complex of San Andrés Island (southwestern Caribbean Sea, Colombia) occurring over nearly three decades. *Atoll Research Bulletin* 456: 1–32.

Cite this article as: Matthias Bernet, Liliana Torres Acosta. 2022. Rising sea level and increasing tropical cyclone frequency are threatening the population of San Andrés Island, Colombia, western Caribbean, *BSGF - Earth Sciences Bulletin* 193: 4.