

Severe tornadoes on the Caribbean coast of Colombia since 2001 and their relation to local climate conditions

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Received: 11 April 2011 / Accepted: 31 July 2012 / Published online: 12 August 2012
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Abstract Tornadoes have been reported in various places around the world. The United States has the greatest number of tornado reports. In South America, tornadoes have been reported in Argentina and neighboring countries, such as Chile, Brazil, and Uruguay. There are no reports of tornadoes in Colombia in the worldwide databases. The first reported tornado event in Colombia took place in 2001. Since then, four tornados have affected the northern part of Colombia. The aim of this study is to characterize the events reported on the Caribbean coast of Colombia and their relation to local climate conditions. Before 2001, we had no knowledge regarding tornadoes in this area. However, during the past 10 years, these atmospheric phenomena have occurred in Barranquilla and the surrounding metropolitan area. Worldwide databases on tornadoes have not registered any such events in this part of South America. A review of the atmospheric information was conducted to determine the influence of air temperature increases on tornado formation. This study reveals that tornadoes have appeared between May and September, the months during which the city experiences the hottest temperatures of the year. The most significant tornado took place on September 15, 2006. This tornado lasted 15 min and travelled almost 10 km. Of the four registered tornadoes, this was the only one to affect the residential area of the city. The other three affected only the suburbs located in the surrounding metropolitan area. The most recent phenomenon related with tornadoes took place between July and August of 2010, during which three tornadoes could have potentially formed. However, a vortex never made contact with the ground. This meteorological analysis is very basic because climate information for these areas is limited. Still, what information we have reveals conditions that are typical of tornado formation: a mass of cold air combined with high air temperatures in a specific area. The data analysis reveals that tornados have occurred between May and June. These months correspond to the period characterized by

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the highest temperatures: average temperatures of 28.2 °C and maximum temperatures of 33.2 °C. This is also the period characterized by the greatest relative humidity and precipitation (84 % and 50 mm, respectively). Because the tornadoes reports only appeared in the last 10 years, it is not possible to determine whether there is a realistic relationship between their occurrence and large-scale climatic change. This article characterizes tornadoes as a new environmental threat and not an isolated phenomenon for this part of Colombia. Tornadoes in this region should thus be included in global databases.

Keywords Tornadoes · Colombia · Climatology · Barranquilla

1 Introduction

Tornadoes are among the most devastating natural phenomena on Earth. They have been widely documented in the United States and Europe. In South America, there are no reports of tornadoes along the northern coast of Colombia. Their appearance in this region is recent (since 2001). The tornado that occurred on September 15, 2006 was the most violent. Tornadoes in Colombia have appeared in the northern part of the country, known as Colombia's Caribbean coast, specifically in the port city of Barranquilla, the capital of the Atlántico department and environs. The Barranquilla metropolitan area, which includes neighboring municipalities, has a population of approximately 2 million people. This article aims to compile information on the tornadoes that have affected this region of Colombia. We rely on information from the local press and the affected communities. The wind speeds during the tornado were not recorded. However, based on the damage to buildings, we were able to make an estimate of the tornado's category according to the Fujita scale (Fujita 1973). To understand the climate conditions that coincided with the appearance of tornados, we conducted a monthly and yearly climactic characterization of the air temperature, relative humidity, and wind magnitude using the available information from the meteorological stations in the area being studied. This article introduces to the broader community a new environmental threat for the inhabitants of the northern coast of Colombia and offers a preliminary determination of the climactic variables that have favored recent tornado appearances.

2 Literature review

Numerous tornadoes have been reported on all of the continents except for Antarctica (Goliger and Milford 1998), and they occur in both hemispheres. According to Concannon et al. (2000) and Doswell and Burgess (1988), the Midwestern region of the United States experiences conditions that support the formation of storms that produce tornadoes. The Great Plains are relatively flat, thus allowing cold polar air from Canada to come into contact with warm tropical air from the Gulf of Mexico. When these two air masses come into contact, tornadoes form. The majority of tornadoes appear in an area of the United States known as "Tornado Alley." This area includes parts of Texas, Oklahoma, Kansas, and Nebraska. Some of the tornadoes that form in the eastern states of the United States, such as Florida, South Carolina, and Georgia, arise as a result of hurricanes (National Oceanic and Atmospheric Administration–NOAA).

According to Goliger and Milford (1998), approximately 800 tornadoes are reported in the world each year. A summary of world tornado occurrences is reproduced in Fig. 1. It

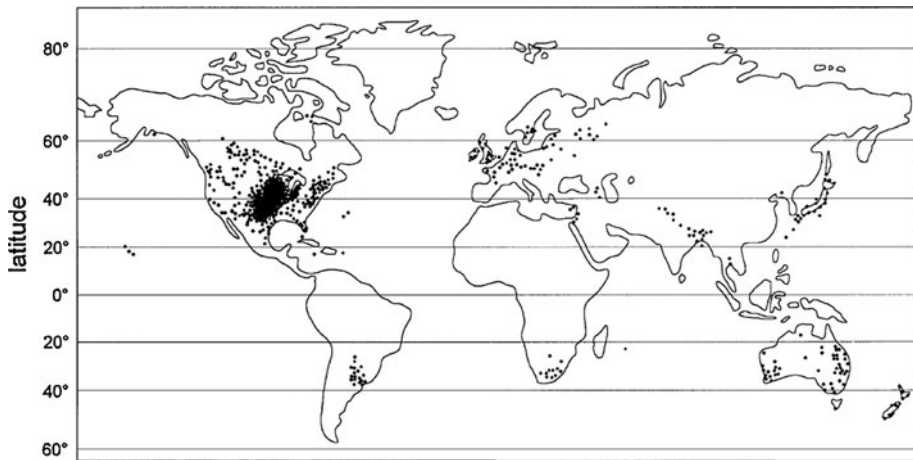


Fig. 1 Tornadoes around the world expected to occur in an approximately 4-year period (Goliger and Milford 1998 from Fujita 1973)

can be observed that tornadoes occur on both hemispheres between the latitude 20° and 60° but predominantly over the territory of the USA.

Tornadoes in other areas of the planet, such as Europe, have been reported in, for instance, Bissolli et al. (2007), Dotzek (2003), and Gianfreda et al. (2005). Tornadoes have also been reported in South Africa and Australia. According to Goliger and Milford (1998), tornadoes have been reported in Argentina and the neighboring countries of Brazil, Chile, and Uruguay. The occurrence of Argentinean tornadoes for the period 1930–1987 has been investigated, and a probable number of 10 events per year has been suggested.

According to Brooks and Doswell (2000), it is possible to estimate F-scale values for previous tornadoes if sufficient documentation (e.g., newspaper accounts and photographs) is available. Moreover, several fundamental questions can be addressed by looking at the results from different countries. Chief among these questions is, what similarities and differences can be found in the distribution of tornadoes according to damage around the world? If tornadoes have similar characteristics in different parts of the world, then it may be possible to use data from areas with relatively high frequency and high-quality reporting to make estimates of threats in other parts of the world. In addition, it may be possible to develop estimates of the degree of tornado underreporting in different countries. In fact, it has been proposed that the F-scale can be more accurately described as a damage scale than as an intensity scale (Doswell and Burgess 1988).

According to Folger (2011), several reports that synthesize recent findings in the scientific literature have predicted that there are likely to be changes in the intensity, duration, frequency, and geographic extent of weather and climate extremes as the Earth continues to warm. These changes may result in a continuation of the upward trends that have already been observed, such as the frequency of unusually warm nights, the frequency and intensity of extreme precipitation events, and the length of the frost-free season. However, the evidence is unclear as to whether the frequency and intensity of severe thunderstorms and tornadoes have increased or will increase in the future due to climate change. Given the uncertainty, it is not yet possible to determine whether these changes are due to natural variability or changing climatic conditions from greenhouse gas emissions.

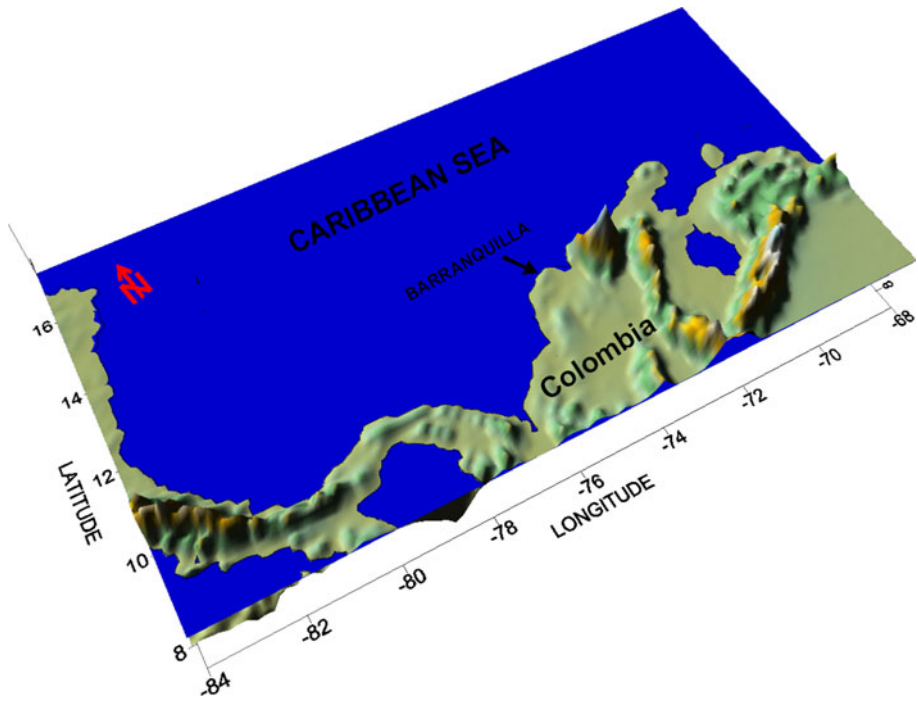


Fig. 2 Topographical map of Colombia's Caribbean sea

3 Description of the area

The Caribbean region of Colombia is located in the northern part of the country and has 1,700 km of coastline. The continental part of the region currently falls within the jurisdiction of seven departments (Guajira, Magdalena, Atlántico, Cesar, Córdoba, Sucre, and Bolívar), and the region's islands form the department of San Andrés and Providencia (see Fig. 2). The topography of the Caribbean region is predominantly composed of lands that are low and flat; however, parts of the territory, specifically the departments of Córdoba, Bolívar, and Cesar, include the foothills of the three Andean mountain ranges that traverse Colombia. Additionally, the region includes another mountain range called the Sierra Nevada de Santa Marta, which is one of the largest water sources for the departments of Magdalena, Cesar, and La Guajira. Only 42 km from the coastline stands the tallest mountain in Colombia, known as *el pico Colón* (Columbus Peak), which is located in the Sierra Nevada de Santa Marta mountain range and rises to 5,780 meters above sea level.

The above-mentioned departments amount to 11.6 % of Colombia's entire national territory of 1,141,748 km². Barranquilla is the capital of the Atlántico Department and is located close to the Magdalena River delta in the Caribbean Sea. The Magdalena River is the longest in the country, with a total length of 1,613 km. The river has an average flow volume of 7,000 m³/s and an approximate yearly discharge of 200 million tons of sediment (Alvarado 2009). Barranquilla, which is located at 74°48' W and 10°58' N, is one of Colombia's most important and active maritime and fluvial ports, and it is the main commercial, industrial, cultural, and academic center of Colombia's Caribbean region. Barranquilla has a population of 1,148,506, thus making it the fourth most populated city



Fig. 3 Image of the city of Barranquilla (Image taken from Google Earth ©2010)

in the country after Bogota, Medellin, and Cali. The city is the center of the Barranquilla metropolitan area, which also includes the municipalities of Soledad, Galapa, Malambo, and Puerto Colombia. This conglomerate is home to over 2 million inhabitants. Figure 3 depicts the city of Barranquilla and the Magdalena River delta.

According to Invemar (2010), the climate of Colombia's Caribbean coast is determined by its tropical location, which exposes it to direct solar radiation. Accordingly, there are no defined climactic seasons, in contrast to those latitudes further from the Equator. In this region, there are two seasonal periods determined by precipitation and the patterns of the Aloysius Winds of the East. The movements of the intertropical convergence zone (ICZ) explain these seasons. There is a dry period with strong winds (December–April), a transitional period (May–July), and a rainy period (August–November). These three climactic periods may change both in duration and in intensity due to the influence of the American Monsoon system, low-level atmospheric wind currents, and the El Niño and La Niña events (Andrade and Barton 2001).

4 Methodology

The methodology used in this work was based on the following steps: first, we gathered the information reported in the local daily newspapers, as there are no reports in the global databases or in the global literature on tornadoes in Colombia. With this information, we characterized each event with respect to its date of occurrence, its duration, and an estimate of its scale according to the Enhanced Fujita scale (Fujita 1973, <http://www.spc.noaa.gov/efscale/ef-scale.html>) based upon the damage caused.

The Fujita scale, or F-scale, was developed to provide a method for estimating the intensity of tornadoes and was intended to relate the degree of damage to the intensity of wind. The original F-scale was used for over three decades, but its limitations prompted the development of a new scale, called the enhanced F-scale or EF-scale. The EF-scale is intended to be a more robust and precise method of assessing tornado damage than the original F-scale. The EF-

scale calibrates tornado damage using 28 damage indicators, such as the type of construction (e.g., anchored versus unanchored houses, mobile homes, schools, garages, barns, skyscrapers, and transmission towers). Even with the improvements over the original F-scale, the EF-scale only provides estimates of wind speed based on damage and not measurements of actual wind speeds in tornadoes. The EF-scale still is just a set of wind estimates (not measurements) based on damage.

According to The Storm Prediction Center of NOAA, when using the EF-Scale to determine the tornado's EF-rating, the process begins with the 28 damage indicators, and each one of these indicators has a description of the typical construction for that category of indicator. Then, the next step is to find the degree of damage (DOD). Each DOD in each category is given an expected estimate of wind speed, a lower bound of wind speed, and an upper bound of wind speed.

Let us take the earlier example. A tornado moves through a neighborhood and the walls of some of the homes are knocked down. Here, the damage indicator would be #2, one or two family residences (FR12). The typical construction for these homes is brick veneer siding. The DOD would be an 8, indicating that most walls collapsed on the bottom floor. Thus, the estimated wind speed would be 127–178 mph with an expected wind speed of 152 mph. Now, taking this number to the EF-Scale, the damage would be rated EF-3 with winds between 136–165 mph (Table 1).

The second step was to obtain information on the meteorological variables recorded during each event from the available meteorological stations in the area. The only station with freely available information is located at the Ernesto Cortissoz International Airport in the municipality of Soledad. This station services the city of Barranquilla. We performed a monthly climatology study to establish the time of year during which tornadoes occur and to collect the atmospheric information that characterizes these months.

A climatology review of the area during the last 40 years was performed to establish tendencies in the time series of the available meteorological variables (temperature, wind magnitude, and relative humidity). Finally, we reconstructed the approximate trajectories of tornadoes in the area with the help of local information and in accordance with the damage caused by the tornadoes' paths.

5 Results

5.1 Tornado reports

Although weather phenomena characterized by sudden strong winds and gusts that cause damage to buildings (commonly referred to as gales) have been common for decades in this part of Colombia, prior to 2001, no tornadoes had been reported in the region.

Table 1 F-Scale and EF-Scale for Tornado Damage

F-scale	Wind speed (mph)	Enhanced F-scale	Wind speed (mph)
F-0	45–78	EF-0	65–85
F-1	79–117	EF-1	86–110
F-2	118–161	EF-2	111–135
F-3	162–209	EF-3	136–165
F-4	210–261	EF-4	166–200
F-5	262–317	EF-5	Over 200

Table 2 Tornadoes in Barranquilla and the surrounding metropolitan area since 2001 according with EF-scale

Tornado date	Scale	Duration (approximately) (min)
06/01/2001	EF-1	6
09/15/2006	EF-2	15
06/05/2007	EF-1	3
05/22/2008	EF-1	5

**Fig. 4** Tornado in Barranquilla, September 15, 2006. (Image taken from *El Heraldo*)

A total of 4 tornadoes have since taken place in this region of Colombia. The dates of these tornadoes are as follows: June 1, 2001; September 15, 2006; June 5, 2007; and May 22, 2008. Recently, during 2010, there were at least three phenomena that created vortices on the following dates: July 20, August 3, and August 12. None of the vortices touched the ground. Table 2 shows the date, category according to the EF-scale, and duration of each event.

On September 15, 2006 at 14:23 (local time), a tornado came through the city from the northeast. As we can see in Fig. 4, strong winds blew off roofs and knocked down trees and walls. The event lasted 15 min and covered approximately 10 km. The phenomenon affected 14 neighborhoods in Barranquilla. Thirty-six people were injured. Hundreds of houses lost their roofs. The telephone and energy network collapsed. Hundreds of trees fell onto the streets (Fig. 5). This was the strongest of the four tornadoes that have occurred in the region. This was the most devastating event during the short history of tornadoes in Colombia.

According to reports from the local press and our analyses of each tornado's path along with the neighborhoods that were affected, we were able to estimate the trajectories of the four tornado events that affected Barranquilla. With the help of Google Earth[®], Fig. 6 shows the approximate trajectories of the four tornado events that have occurred in the region (the longer line corresponds to the tornado that took place on September 15, 2006).



Fig. 5 Effects of the tornado in Barranquilla, September 15, 2006. (Image taken from *El Heraldo*)



Fig. 6 Trajectories of the four tornadoes that impacted the area. (Image taken from Google Earth ©2010 and modified by the authors with the help of Prof. Carlos Ortiz)

5.2 Analysis of meteorological data

We hope to review the meteorological variables during the occurrence of tornadoes. GOES-NASA satellite images were obtained at the time the tornado took place on

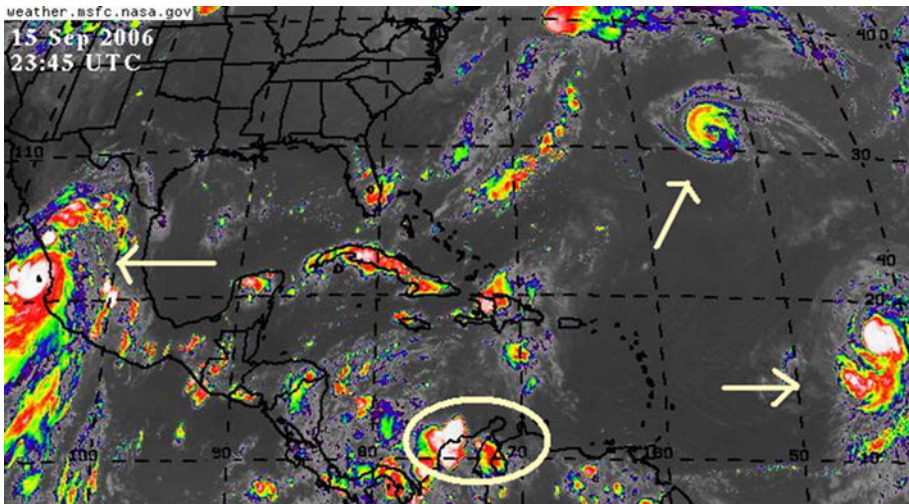


Fig. 7 Satellite image of the Caribbean and North Atlantic on September 15, 2006 at 23:45 UTC (Image taken from GOES-NASA)

September 15. Figures 7 and 8 reveal the atmospheric activity throughout the Caribbean and over the city of Barranquilla. At that time, two storms occurred in the Atlantic and one occurred in the Pacific. Figure 7 reveals a low-pressure system containing storm clouds with a diameter of 250 km hovering over the city of Barranquilla.

In Barranquilla and the surrounding metropolitan area, there are no public meteorological stations, with the exception of the station at the Ernesto Cortissoz Airport (Station No. 800280 at 10.88°N and 74.76°W altitude 14 m). Because climate information is very scarce, we do not have climate data for the exact moment of each storm. There are only data for the average of certain variables during the day of the occurrence in the airport station, which is located almost 11 km away from the area where the tornado took place in 2006. Table 3 shows the parameters that were recorded and averaged at the station during the day of each of the four tornadoes. Tmax stands for maximum temperature in °C; pressure stands for atmospheric pressure in mb; humidity stands for relative humidity in %.

In 2010, there were three phenomena that created tornado vortices that neither developed nor reached the ground. The first of these occurred on July 20 at 13:23 local time (Fig. 9). This phenomenon took place less than 1 km away from the airport station. As with the 2006 event, a low-pressure system was in the area (Fig. 10). Unlike the previous tornadoes, for 2010, the airport meteorological station does have records from the moments before each tornado took place; however, for the event in July 20, we have a record of the atmospheric variables before and after of the phenomena. These data are shown in the Table 4.

5.3 Monthly climatology of the area averaged during the past 10 years

To identify the climatic characteristics of the area during the appearance of tornadoes, we first reviewed the climatology from recent years to update the climatic characterization of the area in terms of the most common meteorological variables. We collected available

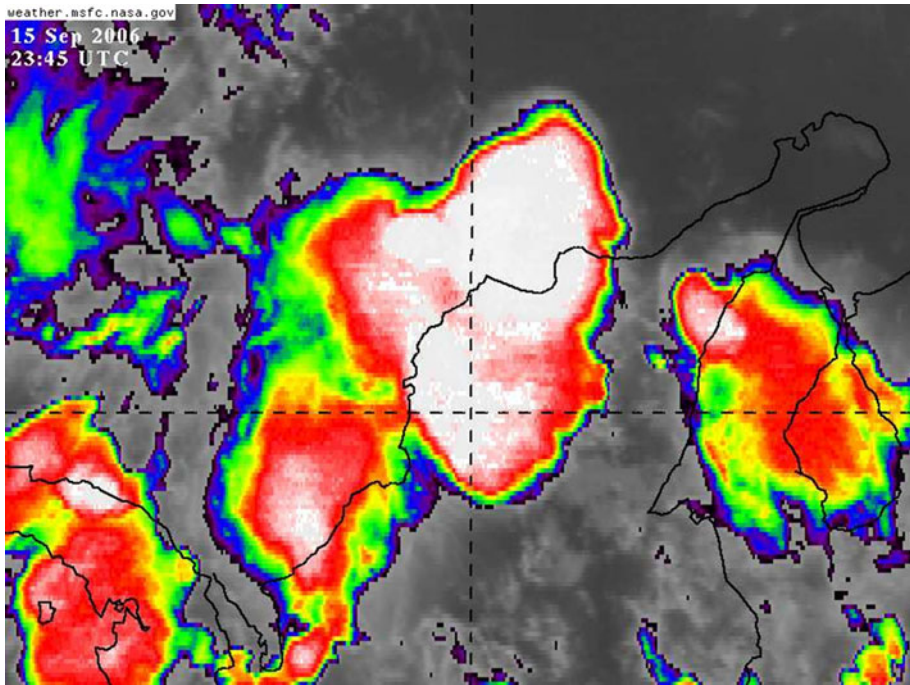


Fig. 8 Satellite image over Barranquilla on September 15, 2006 at 23:45 UTC (Image taken from GOES-NASA)

Table 3 Meteorological report for the days on which each tornado occurred, station no. 800280

Date/time	Temp. (°C)	Pressure (mb)	Humidity (%)
06/01/2001	34	1012	96
09/015/2006	33.3	1010	77
06/05/2007	33	1010	84
05/22/2008	33	No data	80

data, and we averaged them for each month during the past 10 years. Figures 11 and 12 reveal the variation in the mean and maximum temperatures during the year (the shaded zone corresponds to the months in which tornadoes took place).

These figures reveal that the area has an average temperature of 27.7 °C throughout the entire year and that the highest temperatures, above 33 °C, occur between the months of May and September. Figures 13, 14, and 15 present the precipitation, relative humidity, and the average winds, which were obtained based on data from that same station. Based on these figures, we can observe that, throughout the year, the area is characterized by an average relative humidity of 82.4 %. October is the month with the highest relative humidity (87.3 %). The rainiest month is also October, with an average rainfall of 73.1 mm. The average winds have a magnitude of 14 m/s from the NE, but during January, February, and March, they increase, on average, up to 20 m/s. The wind magnitude is at its lowest level from May through October.



Fig. 9 Image of a Tornado vortex over Barranquilla on July 20, 2010. (Image taken from *El Heraldo*)

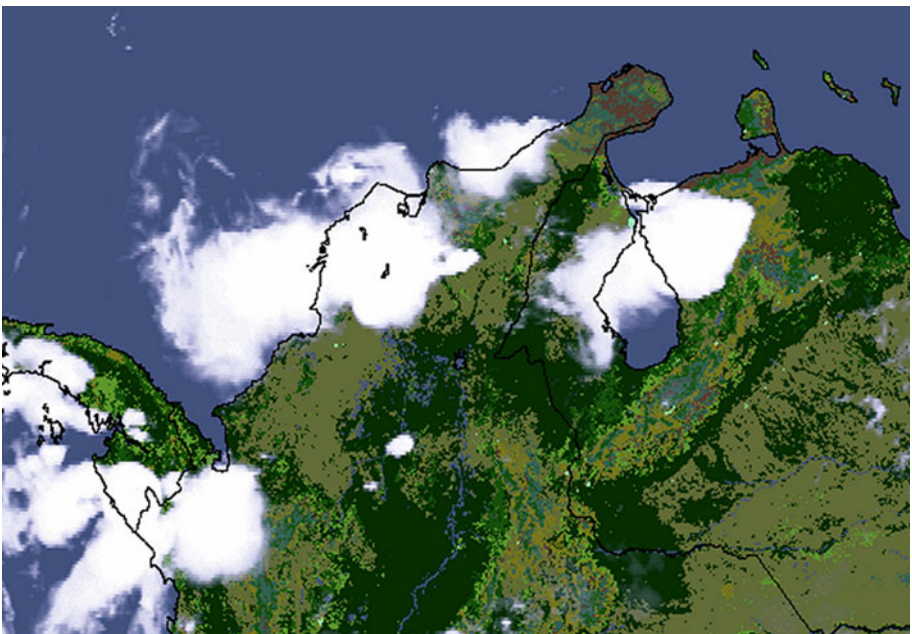
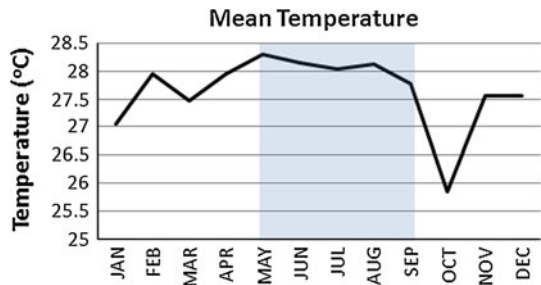


Fig. 10 Satellite image over Barranquilla on July 20, 2010 13:23 local time (Image taken from GOES-NASA)

Table 4 Meteorological report for July 20–21 at airport station

Date/time	Temp. (°C)	Wind (Km/h)	Pressure (mb)	Humidity (%)
21-07-2010 08:00 GMT-5	28	(SSE) 13	1012	94
21-07-2010 07:00 GMT-5	29	Light	1012	89
21-07-2010 06:00 GMT-5	27	(NE) 9	1011	94
21-07-2010 04:00 GMT-5	28	Light	1012	94
21-07-2010 03:00 GMT-5	27	(VRB) 4	1012	94
21-07-2010 02:00 GMT-5	27	(NNW) 6	1012	100
21-07-2010 00:25 GMT-5	26	(SE) 6	1013	100
21-07-2010 00:00 GMT-5	27	(VRB) 4	1014	94
20-07-2010 22:00 GMT-5	28	Light	1014	94
20-07-2010 21:00 GMT-5	28	Light	1013	94
20-07-2010 20:00 GMT-5	28	(VRB) 4	1012	94
20-07-2010 19:00 GMT-5	29	(W) 6	1011	84
20-07-2010 18:00 GMT-5	29	(SSE) 7	1011	84
20-07-2010 17:00 GMT-5	30	(W) 11	1011	84
20-07-2010 16:00 GMT-5	30	(W) 9	1011	79
20-07-2010 14:29 GMT-5	30	(S) 9	1011	84
20-07-2010 14:00 GMT-5	27	(NW) 17	1012	94
20-07-2010 13:42 GMT-5	28	(NW) 13	1012	89
20-07-2010 13:23 GMT-5	30	(N) 15	1012	84
20-07-2010 13:00 GMT-5	33	(SE) 13	1012	71
20-07-2010 12:00 GMT-5	34	(SSE) 11	1012	67
20-07-2010 11:00 GMT-5	33	(SSE) 11	1013	63
20-07-2010 10:00 GMT-5	32	(S) 7	1013	71

Fig. 11 Mean temperatures during the past 10 years at the airport station

5.4 Yearly climatology of the area averaged over the past 40 years

We analyzed the temperatures from the past 40 years in the area to try to determine whether there is a trend. Figures 16 and 17 list the air temperature during the past 40 years and the mean maximum temperature, respectively.

The dotted line in Figs. 16 and 17 shows the linear trend of the data. In both figures, we observe an increase in air temperature in the area, but, in terms of maximum temperature, the increase is more significant (gradient of 0.0235 °C) in comparison with mean

Fig. 12 Maximum temperatures (on average) during the past 10 years at the airport station

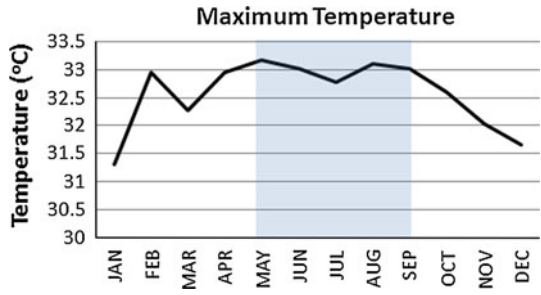


Fig. 13 Average precipitation during the past 10 years at the airport station

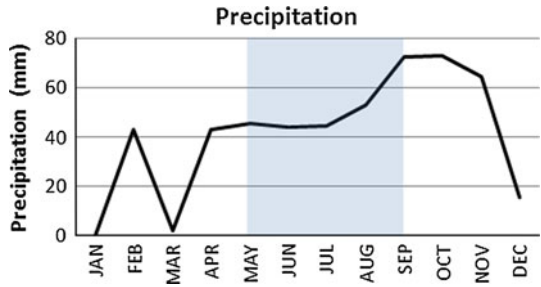


Fig. 14 Average relative humidity during the past 10 years at the airport station

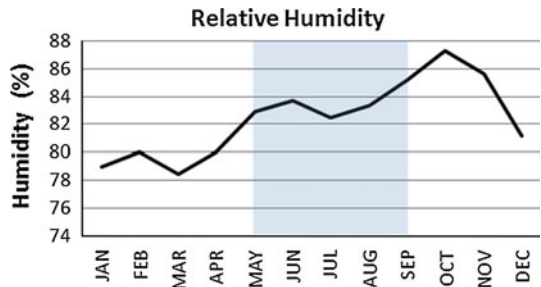
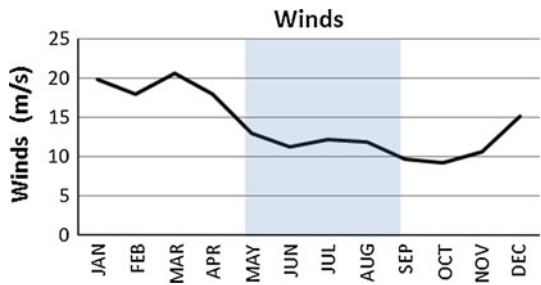


Fig. 15 Average wind speed during the past 10 years at the airport station



temperature (gradient of 0.0056 °C). A similar analysis is evident in Figs. 18 and 19 with respect to relative humidity and average wind speed magnitude. For the past 40 years, there is no evidence of any trend in wind speed magnitude. The time series reflects certain time intervals in the maximum wind values over approximately 15 years. Relative humidity shows a slight increasing trend (gradient of 0.11 mm).

Fig. 16 Mean temperature during the past 40 years at the airport station

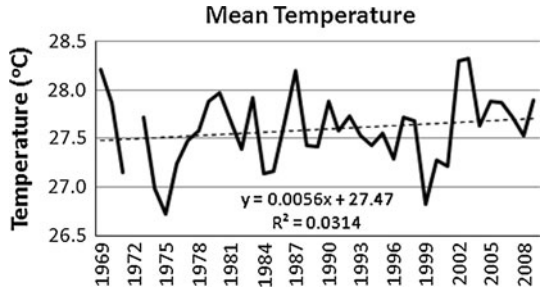


Fig. 17 Mean maximum temperature during the past 40 years at the airport station

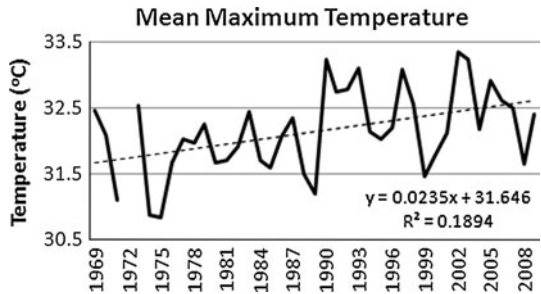


Fig. 18 Average relative humidity during the past 40 years at the airport station

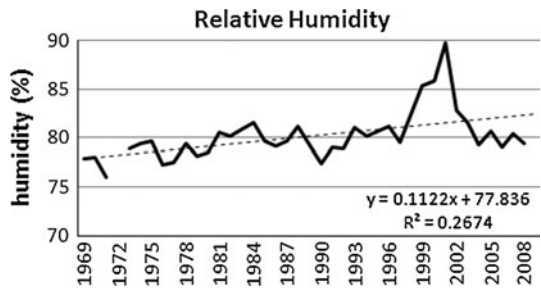
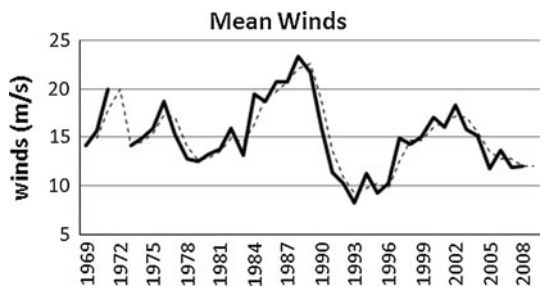


Fig. 19 Average wind magnitude during the past 40 years at the airport station



6 Discussion

Although we analyzed the registers of only one meteorological station in the area, the results allowed us to characterize the monthly climatology and yearly climatology of the past 40 years.

Figure 12 shows the rainy season (September–November) and the dry season (December–March). In tornado season, precipitation begins to increase until it reaches its maximum level in October, and relative humidity follows a similar pattern. The wind graph reveals that there are two very well-defined periods: one with strong winds (December–March) and another with less powerful winds (April–October). This reveals that tornado season is characterized by weak winds in the area.

According to Thompson (1998), “general tornado conditions lead to massive cumulonimbus clouds, severe thunderstorms and squall lines. These include an active cold front with the rising of warm, moist and unstable air aided by the jet stream.” The above description coheres with the fact that with every tornado, there were low-pressure systems accompanied by storm clouds. This is revealed by the satellite images.

High air temperatures and humidity produce conditions that are ripe for tornados; these have formed in the months with the highest temperatures of the year.

Barranquilla has always been a city with both high temperatures and high relative humidity. The climatology of the past 40 years reveals slight changes in all of the average variables, the most significant of which are the increases in both air temperature and relative humidity. The average winds in the area show a pattern of recurrence every two decades and a slight decrease in the past 40 years.

7 Conclusion and perspectives

This study examines all of the tornado appearances in Barranquilla and the surrounding metropolitan area during the past 10 years. Likewise, the research for this study involved monthly climate studies of the main meteorological variables at the airport station during the past 10 years. In the same manner, we conducted an air temperature analysis for the past 40 years.

The data analysis reveals that tornados have occurred between May and June. These months correspond to the period characterized by the highest temperatures: average temperatures of 28.2 °C and maximum temperatures of 33.2 °C. This is also the period characterized by the highest relative humidity and precipitation (84 % and 50 mm, respectively). Although we find the highest figures for precipitation and humidity in October, temperatures during this month are lower compared to May–September. Additionally, during the months in which tornados appear, surface winds are at their lowest level with respect to any other time of year.

In establishing the precise causes of tornados in the area during the past 10 years, our initial belief is that the low-pressure systems that are common during this period, along with the high air temperatures, high relative humidity, and low surface winds, create conditions that are highly favorable for tornado formation.

Tornados have been reported in the area since 2001. The climatology of the past 40 years reveals that the mean and maximum temperatures have been increasing slightly, according to the linear adjustment that was used. This trend proved more significant for maximum temperatures. In other words, Barranquilla and the surrounding metropolitan area are now experiencing temperatures that are higher than those of 40 years ago. Our initial conclusion is that this temperature increase could be related to the appearance of tornados during the past 10 years. To strengthen this conclusion, it is necessary to analyze other characteristics of the area, such as its topography and the effects of being located on the banks of the Magdalena River, and incorporate the records of other meteorological stations in the area. Because tornados have only appeared in the last 10 years (4 since

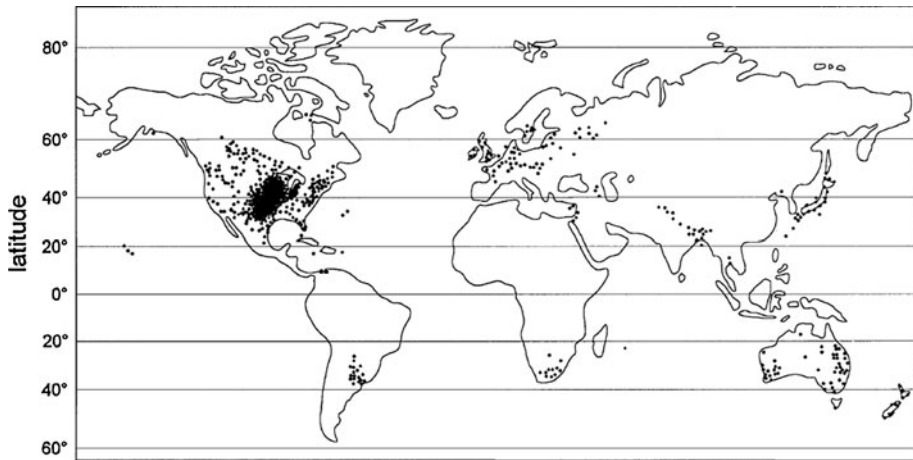


Fig. 20 Tornadoes around the world expected to occur in an approximately 4-year period (Goliger and Milford 1998 from Fujita 1973) and modified by the authors

2001), it is not possible to determine a definite relationship between their occurrence and large-scale climatic change. We believe that Fig. 1 ought to include the tornadoes reported in the northern part of Colombia as a potential threat to the region. Accordingly, we propose that Fig. 1 be modified to include these new tornado events in South America, as can be observed in Fig. 20.

Acknowledgments The authors would like to give thanks to Carlos Ortiz, Professor of social sciences, for the information he provided, to the *El Heraldo* daily newspaper of the city of Barranquilla, and to the Office of Research and Projects (DIDI) at the Universidad del Norte.

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