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Damaging wind storms in North Eastern Argentina: seven case studies

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Abstract. Argentina is a large country with several areas dominated by different climate mechanisms. Since 2008, damage to civil structures caused by strong winds has been surveyed in Chaco and the neighbouring areas. Chaco is a province of NEA, the north-east region of the Argentina, which also includes the provinces of Formosa, Corrientes and Misiones. The strong wind events in NEA are related to severe convective storms. In this work, we present findings about wind-induced damage in NEA and the prevailing meteorological conditions. We emphasise seven particular cases for which the conditions of the atmosphere were reconstructed through reanalysis.

Keywords: wind; damage; civil structures; infrastructure.

1. Introduction

Continental Argentina extends between approximately the latitudes of 22º and 55º S. It is a large country with several areas in which different wind climate prevail. Schwarzkopf (1997) identified five main areas in which different processes are responsible for strong winds: a) the southern part of the country (Patagonia), between 35º an 55º S, which is dominated by large extra-tropical cyclones that move from west to east; b) the Andes range, which is characterised by cyclones that are perturbed by the mountains and downslope winds that occur frequently; c) the North West, which is dominated by a persistent steady depression with a warm nucleus known as "baja térmica del noroeste argentino"; d) the north-central area, which features dynamic depressions that form mainly in the winter and early spring and move towards the south-east; and e) the centre and north-east of the country, which has squall lines that sweep from south to north. Apart from these large scale phenomena, the entire country north of 45º S is affected by severe storms caused by convective cells.

The occurrence of severe storms in Argentina has been exhaustively studied by Schwarzkopf (1984-1994), who since the early 1970s conducted systematic field surveys to quantify the magnitude of the storms. Schwarzkopf's contribution to the knowledge of severe storms was a breakthrough that influenced the field of structural safety. For instance, Schwarzkopf and Rosso

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(1993) developed a model to assess the risk of downbursts and tornados reaching point or linear targets that is currently used to design 500 KV electricity lines. Their model is based on a previous model by Twisdale and Dunn (Twisdale and Dunn 1983). However, Schwarzkopf's work was focused in the meteorological aspects of the phenomenon. Apart from the report of Balbastro and Sonzogni (2008), which describes an event occurred in the province of Santa Fe, there is no information in the open literature about patterns of wind-induced damage in Argentina. The lack of information on the subject hampers the formulation of public policies on risk management related to strong winds.

Damage caused by strong winds on civil structures in Chaco and neighbouring areas has been surveyed by the authors since 2008. Chaco is a province of north-eastern Argentina (NEA), which also includes the provinces of Formosa, Corrientes, and Misiones (Fig. 1). Chaco consists of an area of 99,633 km^2 and has a population of nearly 1 million people, of which approximately 20% live in rural areas. Overall, NEA has approximately 3.5 million inhabitants and a surface area of 289,699 km^2. Field surveys have been conducted in NEA, mainly in the provinces of Chaco and Formosa, after the passage of destructive storms. Additional sources, such as government emergency services, the local press, local councils and the weather service have also provided valuable information.

The aim of this report is to identify the characteristics of the wind storms that occur in NEA and the effects they have on civil structures. In Section 2, an analysis of some features of thirty-four events that had occurred in Chaco, such as duration, seasonality, types of structures that were damaged, etc., is presented. Seven storms that affected Chaco and Formosa are described in detail in section 3. General trends and patterns extracted from the information presented in Sections 2 and 3 are discussed in Section 4. Conclusions are presented in Section 5.

2. Some features of the damage observed in thirty-four events in Chaco

Thirty-four wind events causing damage were observed in Chaco during the period July 2006-November 2010. Field surveys were conducted after fourteen of these events. Information from secondary sources, mainly the local press, was available in the remaining twenty cases.

Criteria were established to count the number of events. In many cases, the damage occurred over

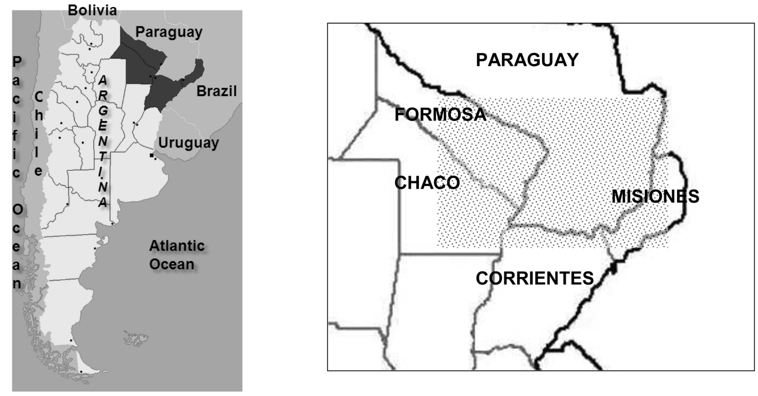

Fig. 1 Left: A view of the southern end of South America; NEA is marked in dark grey, Right: A detailed map of NEA; the area affected by the storm described in section 3.6 is shaded

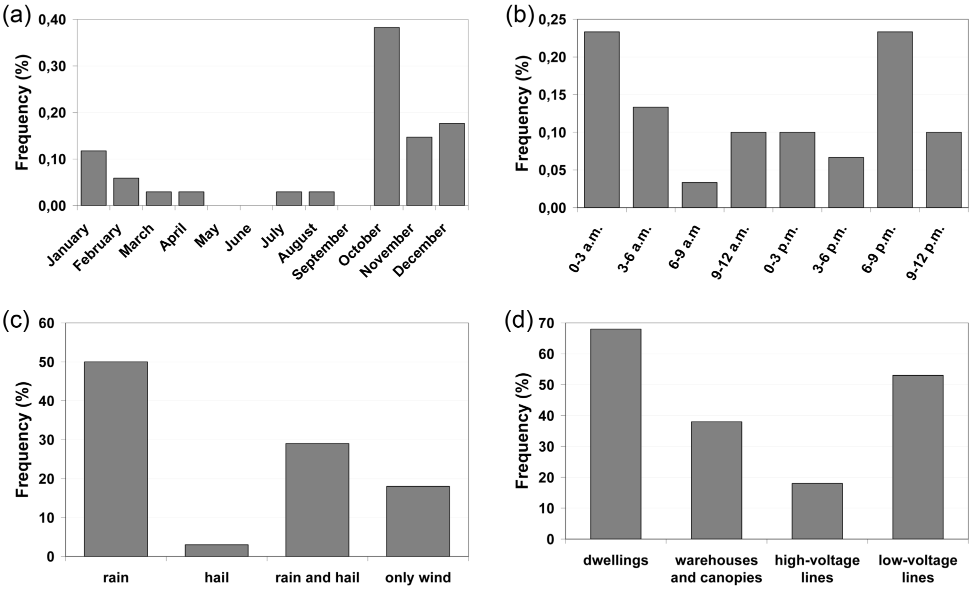

Fig. 2 (a) distribution of events along the year, (b) distribution along the time of the day, (c) frequency of occurrence of rain and hail and (d) commonly damaged structures

large areas in the midst of generalised bad weather conditions. In these cases, if the damage in different villages was caused by strong winds that started at the same time, then the damage was considered to be due to a single event. Otherwise, the damage was counted as the result of different but correlated events. According to these criteria, only fifteen events were independent.

Fig. 2(a) shows the time distribution of the events along the year. If the events are classified by seasons, nineteen events (56%) took place in the spring, twelve (35%) in the summer, one (3%) in the autumn and two (6%) in the winter. Clearly, spring is the most hazardous season, with a peak in October, followed by summer.

Information regarding the duration of the storms was available in fifteen cases. In twelve of them, the damage occurred during periods of strong winds that lasted from four minutes to half an hour. These events were produced by either intense short-lived storms or an intense phase of storms lasting less than 1 hour. In the other three cases, the storms lasted more than 1 hour.

Fig. 2(b) shows the time distribution of events along the day. There is not significant difference between the number of damaging storms that occur between sunset and dawn and between dawn and sunset; 55% occurred in nighttime hours and 45% in daylight hours.

Fig.2(c) shows the distribution of cases according to the occurrence of rain, hail, rain and hail and just wind during the events. The categories exclude each other. It has been observed that typically the firs gusts arrive before rain or hails.

With regards to the extent and level of destruction associated with the cases, it is difficult to quantify both factors using the available information. We can assert that two of the events were widespread destructive events, meaning that the government had to provide significant assistance to the population and that wind-induced damage was clearly visible to passers-by. In five cases, the only damage was to isolated structures in rural areas. Between these two extremes are cases in which the damage was widespread but mainly localised to background damage (damage to poorly built structures or poorly maintained structures). There were also four cases in which the government provided significant assistance to victims without specifically denoting whether the people were affected by strong winds, floods or hail.

The most frequently affected structures were dwellings. Damage to dwellings was reported in twenty-three cases (68%), being affected about one thousand five hundred homes in total. More than twenty-five warehouses and canopies with structural frames composed of low-strength lattice were damaged in thirteen events (38%). High-voltage electricity transmission lines were damaged in six cases (18%), and low-voltage lines were damaged in eighteen cases (53%). Both rural and urban areas were affected at the same time in 32% of the cases. Comparatively, only urban areas were affected in 42% of the cases, and only rural areas were affected in 26%. The number of victims was surprisingly low: only 11 people suffered minor injuries in a total of three cases. Twenty-eight events produced no casualties (82%), whereas the remaining three cases lacked sufficient information to determine whether they involved injuries.

3. Seven storms in north-eastern Argentina

In this section, seven case studies are presented. Four cases occurred in Chaco, which are among the ones presented in Section 2, plus three cases that happened in the nearby province of Formosa. Fig. 3 shows the locations of the different events. A description of the damage surveyed after the windstorms is given together with the large-scale meteorological conditions at the moment, which were determined by meteorological satellite imagery, NCEP/NCAR Reanalysis and Global Data Assimilation System (GDAS) model.

The intrinsic local nature of the storms, which occurred in a large area where there are only two anemometers of the Servicio Meteorologico Nacional (SMN), made impossible the accurate determination of the wind speeds during the events. On the other hand, it has been considered by the authors of this paper that the inference of wind speed by using standard procedures, such as the

Fig. 3 Locations of the case studies

Enhanced Fujita Scale (EF Scale), should not be used without a previous validation. The existent damage indicators (DI) have been established for building practices that are not common in Argentina. For instance, the Wind Science and Engineering Center of Texas Tech University (2004) proposed twenty-eight DIs, of which only three can be clearly identified in Argentina, six have no equivalent at all, nine probably have equivalents and ten probably do not.

Values of two indicators of the instability of the atmosphere were established: the Standard Lifted Index (SLI) and the Convective Available Potential Energy (CAPE). The SLI is obtained by computing the temperature that a parcel of air near the ground would have if it were lifted to the 500 hPa level ($Tp_{(500\ hPa)}$) and substracting that temperature from the real temperature at that level ($Te_{(500hPa)}$). When the SLI is negative, the atmosphere is unstable. The SLI is scaled as follows: $-2^{\circ}C < SLI \leq 0^{\circ}C$, slightly unstable; $-6^{\circ}C < SLI \leq -2^{\circ}C$, unstable; $SLI \leq -6^{\circ}C$, very unstable. CAPE is the amount of energy that a parcel of air would have if lifted a certain distance vertically through the atmosphere. CAPE is the positive buoyancy of an air parcel. It is directly related to the maximum potential vertical speed within an updraft; thus, higher values indicate greater potential for severe weather. Observed values in thunderstorm environments often may exceed 1000 J/kg, and in extreme cases may exceed 5000 J/kg. It is defined as

$$CAPE = \int_{p_n}^{p_f} (\alpha_p - \alpha_e) dp \tag{1}$$

where α_e is the environmental specific volume profile, α_p is the specific volume of a parcel moving upward moist-adiabatically from the level of free convection, p_f is the pressure at the level of free convection, and p_n is the pressure at the level of neutral buoyancy.

3.1. 1st case: a storm causing localised damage in a suburb of Resistencia

At 4:30 a.m. local time (07:30 UTC) on the 22nd of October, 2008, seven supporting towers of a 132-KV electrical transmission line collapsed in Fontana, a western suburb of Resistencia (which has approximately 400,000 inhabitants), when a cold front passed from south to north. The storm caused little damage to the surrounding areas, and only auxiliary structures, such as signboards, marquees and carports, were affected in Fontana and the nearby city of Resistencia. The electrical line runs east/west, and the towers fell towards the north. Gust speeds of approximately 23 m/s were recorded at the airport, located 4.5 km to the south. These gust speeds were consistent with the level of damage in the city but could not explain the failure of the towers. The line was designed to resist 10 minutes wind speeds of 30 m/s acting normally on both towers and cables. Metal truss tower is one of the DI proposed by the EF Scale that can be found in Argentina. Consequently in this case study, the 3-second gust speeds was estimated by using the EF Scale to be between 52 m/s and 73.5 m/s.

The synoptic analysis showed that the area was affected by severe convective activity. This activity was caused by the combination of an instability associated with the passage of a frontal system with strong spatial gradients of humidity and temperature and a low-pressure area that was developed on the zone of the discontinuity. Fig. 4 shows that there was a convergence of masses of air at levels close to the ground.

The SLI reached –5.3°C in the hours prior to the event, and CAPE reached 3139.4 J/kg. The instability indices indicated the formation of severe convective storms. There were strong vertical movements and high horizontal wind velocities in the low layers of the atmosphere, due to the

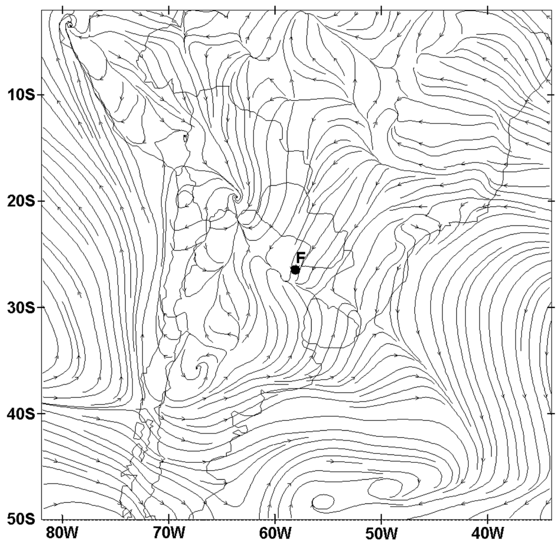

Fig. 4 Case 1: Streamlines (knots) at 1000 hPa, 06:00 UTC

South American low-level jet stream (Virji 1981, Berbery and Collini 2000, Saulo *et al.* 2000).

3.2. 2nd case: a storm causing widespread damage in a city

The city of Formosa is the capital of the province of Formosa. It has a population of over 200,000. At 18:40 local time (21:40 UTC) on the 21st of July, 2008, a storm caused widespread damage within a strip approximately 200 m wide × 5000 m long in the urban region. The strip was oriented north-west/south-east, aligned with the predominant wind direction at that moment.

The most common type of damage involved the unroofing of dwellings, uprooted trees and failure of electricity line poles. A 70 m deep × 40 m wide vaulted canopy roof and several dwellings were destroyed. Seven hundred families were assisted by the government.

In this case, the cause of the strong wind was a convective cell downburst. The meteorological analysis showed the formation and development of a low-pressure system (cyclogenesis on the surface (Necco 1982)). At 21:00 UTC, the system was extended over the north and north-east of the country. This process caused a north circulation with advection of warm and moist air, as shown by the thickness field in Fig. 5. The thickness is the vertical distance, in decimetres, from the 1000 hPa to 500 hPa levels. It is a function of two properties: the average temperature of the air and the average moisture content of the air between 1000 and 500 hPa. A thickness of 570 dm or greater is often associated with tropical air. At 21:00 UTC, the city of Formosa laid on the equatorial side of the jet stream, which contributed to the upward movement of the mass of air. This dynamic pattern, combined with the convergence on the surface, produced severe convective activity. The SLI was between –2.8°C and –4.4°C, and CAPE was between 879 J/kg and 1009 J/kg.

3.3. 3rd case: a storm causing widespread damage in more than one urban centre of the province of Formosa

At 5:00 a.m. local time (08:00 UTC) on the 9th of November, 2008, a storm first impacted the

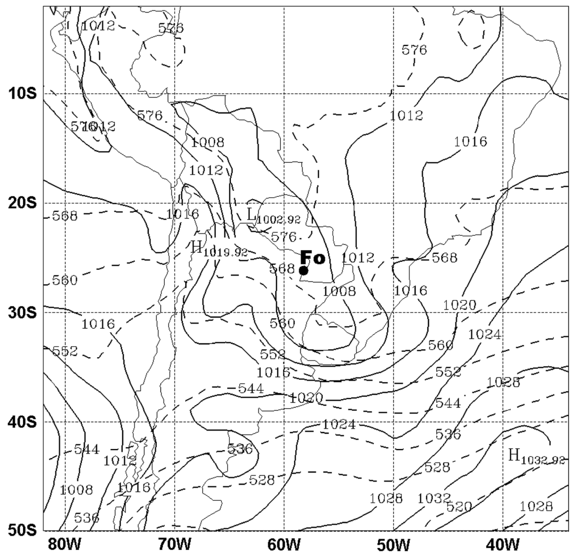

Fig. 5 Case 2: Contour plot of the mean sea-level pressure (hPa, solid line) and thickness at 1000 hPa/500 hPa (dm, dashed line), 21:00 UTC

village of Estanislao del Campo (population of approximately 4,000), then passed over Pozo del Tigre (population of approximately 4,000) and finally over Las Lomitas (population of approximately 10,000). The three villages are aligned in southeast/northwest direction, which was the direction of the storm trace. The distance between Estanislao del Campo and Pozo del Tigre is 30 km, and between Pozo del Tigre and Las Lomitas is 35 km (see Fig. 3). The storm caused widespread damage in Estanislao del Campo and Pozo del Tigre and some isolated damage in Las Lomitas. Earlier that day, at 2:00 a.m., there was a storm that caused some isolated damage in the city of Formosa, which is located at 320 km to the south-east of Las Lomitas. The predominant types of damage were the unroofing of dwellings, major damage to institutional buildings and electricity poles failure. The Defensa Civil estimated that one out of every two families in Estanislao del Campo and Pozo del Tigre was affected (approximately 1,100 families).

The synoptic analysis identified a Mesoscale Convective Complex (MCC) over the area. An MCC is defined as a complex of storms whose cloud top covers more than 50,000 km^2 with temperature less than or equal to −52°C. MCCs are predominantly deep and barotropic systems (Velasco and Fritsch 1987, Campetella and Velasco 1995). One of the two most intense convective centres of the MCC was positioned over the Pozo del Tigre area, as shown in Fig. 6. The SLI was below –3°C, and the CAPE was at 2100 J/kg. Two hours before the event, a barotropic atmosphere with a warm nucleus was observed. The MCC developed on the east edge of the depression from the persistent advection of warm, humid air.

3.4. 4th case: a storm causing widespread damage in a small village

El Sauzalito is a small village of nearly 2,000 inhabitants. It is located in the north-west of the Chaco Province. On the 10th of November, 2007, at 2:30 a.m (5:30 UTC), a storm caused widespread damage to the village. Two hundred families were affected, mainly through the unroofing of their homes, which was aggravated by the consequences of an intense hail with scarce

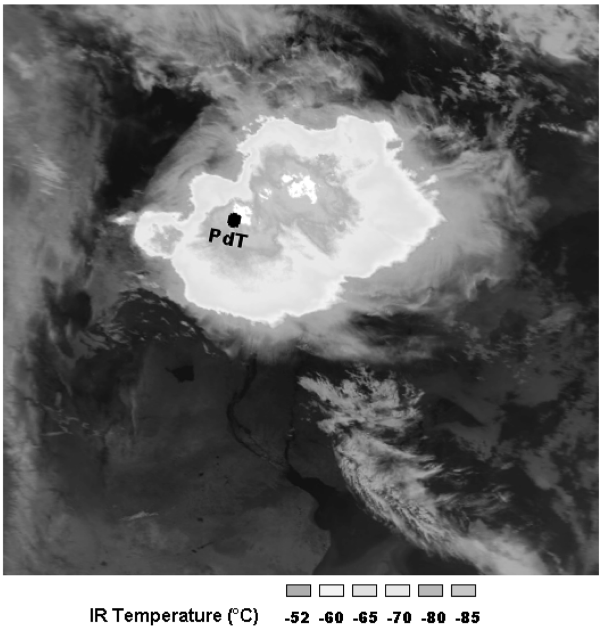

Fig. 6 Case 3: thermal scene, c4 AVHRR - NOAA15, at 08:00 UTC

rain. The storm caused heavy losses to orchards, apiaries and crops in the neighbouring areas. The duration of the storm was approximately twenty-five minutes. Some minor damage was reported on the previous day in Saenz Peña and Resistencia.

The air mass over the studied area was warm and humid. Clouds developed by convective activity, because there was an extended frontal system connected to a low pressure system located on the Atlantic Ocean. This continental front crossed Argentina and was connected to a thermal low pressure system in the north-west (Seluchi *et al.* 2003). It was associated with a jet stream in the upper troposphere. The SLI was less than –3°C and CAPE was greater than 1300 J/kg in the hours leading up to the storm.

3.5 5th case: a storm causing widespread damage in a village and the surrounding rural area

Pampa del Indio is a village in Chaco with approximately 6,000 inhabitants. A storm in this village caused widespread damage during the morning of the 21st of October, 2009. The strong winds started when a gust front reached the village from the south-west at 11:02 a.m. (14:02 UTC) and lasted half an hour. It began raining when the wind started to die down. The balance of damage to both urban and rural areas consisted of the unroofing of ninety dwellings, the collapse of three large canopy roofs, the unroofing of a mid-size warehouse, damage to at least four mid-size warehouses, the collapse of the mast of the local FM radio station, seventy uprooted trees and twenty-five broken low-voltage electricity poles. Engineered structures were virtually unaffected, except for a few cases of partial failure of auxiliary structures, such as perimeter walls, fences, and water tanks. The dwellings affected were primarily self-built homes. One hundred thirty-three families had to be assisted by the government. The affected area was a square of approximately a

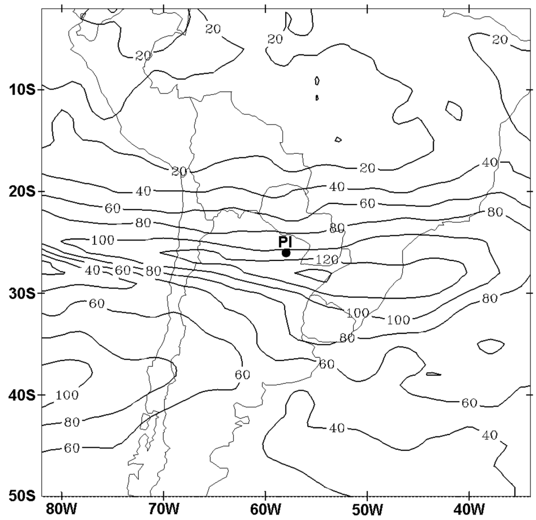

Fig. 7 Case 5: wind speed (kt) at 200 hPa, 15:00 UTC

15 km × 15 km. The damage was not evenly distributed. The most severe cases were clustered in different points inside the area.

Pampa del Indio was affected by humid advection from the east during the hours preceding the storm. A frontal system, coming from the south-west, produced severe convective activity. The location of the subtropical jet stream (Antico and Berri 2004), which can be seen in Fig. 7, also contributed to the instability. The index of instability indicated a very unstable atmosphere with the likely formation of severe storms: the SLI reached a value of –8.3°C, and CAPE reached 2340 J/kg.

3.6. 6th case: a storm of synoptic scale causing damage to urban and rural areas in Argentina and Paraguay

From the evening of the 6th to the morning of the 7th of October, 2010, a storm developed over NEA and East Paraguay causing damage to an area of approximately 650 Km from west to east and 350 Km from south to north (see Fig. 1). Dozens of villages, major cities and large rural areas were affected by strong winds, heavy rain and hail. From a qualitative standpoint, the pattern of damage was similar in all the area shown in Fig. 1 (shaded area): the unroofing of dwellings, massive falling of low-voltage electricity poles and trees, the collapse of some medium- and high-voltage electricity line supporting towers, the collapse of many large canopy roofs and warehouses, the failure of a variety of auxiliary structures and damage to crops. However, from a quantitative standpoint, the eastern part of Paraguay, situated between the Argentinean provinces of Formosa and Misiones, experienced the most extensive damage. The blackout that resulted immediately after the storm affected 35% of the population of Paraguay. In the village of Pilar, there were 1,000 unroofed homes, and in the village of Laguna Ita, 80% of the homes suffered some degree of damage. In Argentina, the damage was also quantitatively substantial in most of the province of Misiones and the central and eastern parts of the province of Formosa. In the province of Chaco, the storm caused damage mainly in the city of Saenz Peña and the area that extends 40 Km to the south-west, towards the centre of the province. Surprisingly, there were a low number of injuries.

In every location, it appeared as though the damage was caused by short local storms lasting less than half an hour. The sequence of these local storms showed a progression from the centre of Argentina to the north-east. On the afternoon of the 6th, there was a heavy rain and hail in the northern part of the province of Santa Fe. In the evening, damage occurred in the province of Chaco. During the early morning hours of the 7th, strong winds occurred in Formosa, Paraguay and Misiones.

In the hours prior the event, NEA was affected by the advection of warm, humid air from the north-east that increased the instability of the air mass. The zone was under the influence of a low-pressure system. The location of a jet stream in the upper troposphere favoured convection. The SLI was lower than –6°C, and CAPE was greater than 2500 J/kg. An MCC that developed on the eastern edge of the depression was identified in the area. This system had several convective cells in different stages of development and dissipation with strong vertical currents acting in different locations. This weather system is known in other places as derecho and corresponds to widespread windstorms induced by convection, which downburst and gust front can be as destructive as tornadoes but covering larger geographical areas. According to the classification of damaging wind patterns of Fujita and Wakimoto (1981), a family of downburst clusters has a major axis of 400 km or more. Johns and Hirt (1987) defined the derecho as any family of downburst clusters produced by a MCC that correspond to a concentrated area of severe wind reports and/or wind damage with a major axis that exceed 400 km (damaging wind pattern class 5).

3.7. 7th case: a tornado ravaging a village

On the 21st of October, 2010, at 6 p.m. local time (21:00 UTC), a tornado demolished the village of Pozo del Tigre, the same village that was struck by the storm described in section 3.3. Hundred of eyewitnesses sighted the movement of at least one tornado funnel in broad daylight. The tornado entered the village through the south-west boundary and then drifted towards the north-east, crossing through the village and affecting an area of approximately 300 m wide × 2500 m long. The whole process took less than 15 minutes. According to eyewitnesses, the funnel had a diameter between 20 and 50 metres at ground level, which is consistent with the observed footprint. 852 homes were heavily damaged and 2,215 people (out of a population of 4,000) were affected, of whom 395 had to be evacuated. Four large canopy roofs and one railway warehouse were destroyed. Four people were killed under the rubble of masonry walls. Hospitals assisted two hundred people with injures and bruises caused by the fall of masonry walls, debris and an intense and dense hail, which became a lethal factor when combined with the strong winds. The footprint corresponded to a F1 tornado in the Fujita-Pearson scale (Fujita and Pearson 1973), which is equivalent to a EF1 tornado in the Enhanced Fujita Scale. The 3-second gust speed for a EF1 is estimated to be between 38.5 m/s 48.5 m/s.

Several factors took part in the formation of the October 21st tornado (Schwarzkopf and Rosso 1982). The inflow of a warm, humid mass of air from the north was activated on the surface by a low pressure system positioned on the Bolivian Altiplano that extended to the south. Together with the presence of an upper-level subtropical jet stream, they contributed to the formation of a very intense convective cell. The SLI was less than –6.0°C (Fig. 8) and CAPE was greater than 3200 J/kg.

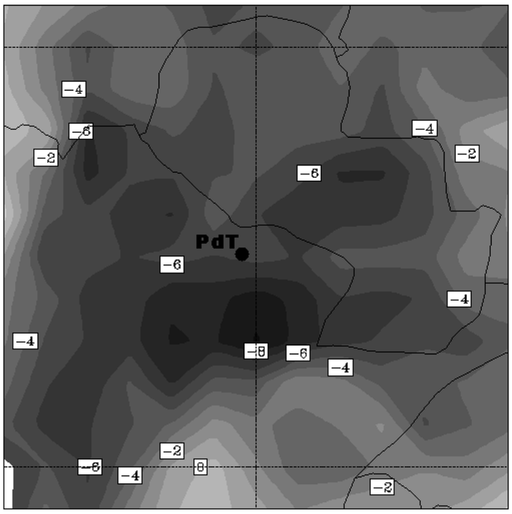

Fig. 8 Case 7: Standard Lifted Index (^{o}C), 21:00 UTC

4. Preliminary assessment of collected data

Several lessons can be extracted from the information presented in Sections 2 and 3. Certain structures that are prone to fail under strong wind have been identified. In order to organize the discussion, a classification of the common structures in the area is presented in Table 1. Even though it is acknowledge the importance of Class 1 structures, since 12% of the population in NEA lives in Class 1 structures, they are excluded from further consideration in this discussion because they should be treated by using a different methodology. Class 2A are the most common structures that are prone to fail. This is the most common style of dwelling among poor people, who pass

Table 1 Classification of common structures in NEA that have been affected by wind storms

Class 1	SHANTY HOUSES	
		Little huts built by the poorest people as temporary shelters in slums or rural areas. There are many typologies which combine discarded materials such as plastic film, cardboard, straw, wood and adobe.
Class 2	NON-ENGINEERED STRUCTURES	
	A	Dwellings: Self-built, non-engineered homes with masonry walls and light metallic roofs.
	B	Large roofs: Warehouses, sheds and canopy roofs with structural frames composed of low-strength lattice
Class 3	ENGINEERED STRUCTURES	
	A	Social housing: Houses with masonry walls and light metallic roofs.
	B	Institutional buildings: Schools, police stations, government offices.
	C	Electricity transmission lines

from Class1 to Class 2A structures as soon as they can afford bricks and steel sheets. Fig. 9 shows archetypical houses of this style. It has been observed that, in the vast majority of cases, the roof is lost, whereas the walls, windows and doors remain intact (Fig. 9). This is the result of poor assembly of the roof structure to the walls, which could be easily prevented by campaigns of popular education and training.

Class 2B structures are the next most commonly damaged structures. They are commonly used as shelter in schools, athletic courts, carpenter's workshops and garages. They have a particularly vulnerable structure made of steel rods that form a lattice (Fig. 10). They are cheap, easy to build and vastly used in Argentina and Paraguay. Building of 2B structures is part of the local culture and is currently out of control. Balbastro and Sonzogni (2008) reported the same issue of vulnerability in these structures in the Province of Santa Fe.

Class 3C are the only vulnerable Class 3 structures. There are records of failures of virtually every kind of line, comprising any voltage and typology of poles, but a close inspection of the records shows frequent failures of two poles: creosote-treated timber poles used in low-voltage lines and the metallic trussed towers of 132-KV lines. Creosoted poles also support telephone lines. It has been presented that low-voltage lines failed in 53% of the events registered in Chaco. Fig. 11 shows a typical collapse involving several poles. Twenty-four metallic towers of 132-KV lines, like the

Fig. 9 These are examples of typical Class 2A structures. Both houses were unroofed during the storm described in section 3.5

Fig. 10 Details of lattice structures made with steel rods. Left: The supporting columns of a 35-m spanning roof; right: the collapsed frames of a 20 m × 45 m vaulted canopy roof

Fig. 11 Vulnerable electricity line poles. Left: Creosote-treated timber poles used in low-voltage lines; right: a 132-KV line supporting tower (photograph courtesy of Ing. Miguel Malarin)

one shown in Fig. 11, failed in five of the thirty-four events recorded in the province of Chaco. All twenty-four were suspension towers. These failures are a matter of concern by the different electricity service companies of NEA. The causes of the vulnerability of these kinds of poles have not yet been systematically studied.

The aforementioned structures tend to fail under any kind of meteorological condition resulting in strong winds. However, from the seventeen field forensic surveys performed so far in NEA, sixteen (considered conventional cases) showed similar patterns of damage that were clearly different than the tornado case described in Section 3.7. In the conventional cases, the damage is evenly distributed over a given area and reveals a predominant wind direction. In a typical case, many instances of unroofed dwellings, uprooted trees, falling of a substantial portion of the low-voltage net, a collapse of at least one large roof (warehouse or canopy), collapse of one or two masts belonging to local FM radio station and damage to a variety of poorly built auxiliary structures can be expected. It is also useful to pay attention to what has not been damaged in these conventional cases. Classes 3A and 3B structures are rarely damaged. Conversely, after the passage of the Pozo del Tigre tornado, a non-uniform distribution of damage was observed, due to the migration of the funnel. Unharmed buildings remained standing right next to completely destroyed ones with similar vulnerability. Although the tornado travelled towards the north-east, the structures were blown away in every direction, including the south-west. All Class 3 structures were damaged as frequently as Class 2. One of the most outstanding features was the commonly-occurring collapse of masonry walls, which killed four people and wounded many more. However, masonry walls reinforced with concrete resisted satisfactorily in most cases.

Table 2 summarises the main features of the case studies presented in section 3. In all cases the origin of the strong winds was intense convective activity. This is consistent with some characteristics of the thirty-four events reported in section 2, like the short duration of the strong winds and the seasonality; most of the events occurred in the period of the year when large masses of warm, humid unstable air gather on NEA. Although the number of case studies is too small to achieve statistical significance, considering the consistency of the cases in section 2, it can be concluded that virtually all of the events of strong winds causing damage to civil structures in Chaco and Formosa corresponded to storms caused by intense convective activity. This is a particular feature of this region of Argentina.

In all seven case studies, there were two factors that acted upon the instability of the masses of

Table 2 Comparative table of the main features of the case studies presented in section 3

		CASE STUDY						
		1	2	3	4	5	6	7
Causes of convective activity	Frontal system	X			X	X		
	South America low level jet stream	X	X					
	Low pressure system on the surface level		X	X	X	X	X	X
	Upper level jet stream		X	X	X	X	X	X
Type of convective activity	Instability line	X	X					
	Mesoscale Convective Complex			X			X	
	Convective cell				X	X		
	Tornado							X
	SLI (°C)	−5.3	−2.8 to −4.4	−3.0	< −3.0	−8.3	−6.0	< −6.0
	CAPE (kJ/kg)	3139	819 to 1009	2100	> 1300	2340	2500	> 3200
	Affected area,wide × long (km)	point	0.2 ×5	ND × 75	ND	15 ×15	350 × 650	0.3 ×2.5
Damaged structures	Class 2A		X	X	X	X	X	X
	Class 2B		X	X		X	X	X
	Class 3A							X
	Class 3B			X				X
	Class 3C	X	X	X	X	X	X	X

air: a) the existence of a low pressure system in the north-west of Argentina, which extended to neighbouring countries, producing a persistent advection of warmer and more humid air in NEA, and b) the presence of a jet stream in the upper troposphere, which, for dynamic reasons, impinges an increased vertical ascending movement contributing in this way to the instability.

With regards to the type of convective activity causing damage in the seven case studies, one case was a tornado, two cases were Mesoscale Convective Complexes and four cases were convective activity associated to frontal system or to instability lines. Note that the term instability line is used instead of squall line. This is a general term and includes the developing, mature, and dissipating stages of the line of convective activity, while squall line refers only to a line of active thunderstorms in the mature stage. No dependence between the different kinds of atmospheric conditions causing storms and the values of CAPE and the SLI was observed. As for the relationship between meteorological phenomena and the severity of damage, the analysis of the cases suggests that MCCs produce higher losses than the convective cells that accompany frontal system or instability lines (synoptic systems), while tornados are devastating. However, seven cases are too a low number to be conclusive.

5. Conclusions

A brief overview of the types of activities related to wind-induced damage research in the NE of Argentina has been presented. Based on the analysis of thirty-four events in the province of Chaco and seven case studies of events in Chaco and Formosa, which included the reconstruction of atmospheric conditions through reanalysis, some patterns have been found.

Storms characterised by intense convective activity play the main role in causing damage in NEA. This was not unknown; the present work only provides evidence of this fact. There was a trend in wind engineering literature to treat convective storms in an oversimplified manner, probably because the main research centres exist in countries where the predominant problems are caused by extra-tropical or tropical cyclones. The region studied in this work is located in mid-latitudes but it is near the Tropic of Capricorn. For this reason, the meteorological conditions that produce the severe convective activity are varied: frontal systems, low pressure systems, the upper jet stream and the South American low-lever jet stream. The intense convective activity caused by these weather systems were organized in different forms: dispersed convective cells, instability lines, MCCs and tornadic clouds. At the micrometeorological level, the damages to structures were caused by downbursts and a tornado.

Vulnerable structures, such as self-built, non-engineered homes with masonry walls and light metallic roofs, large non-engineered roofs, metallic trussed towers of 132-KV electricity lines, and creosote-treated timber poles of low-voltage electricity lines have been identified. The tornado case caused a different pattern of damage than the conventional storms and was more lethal. However, it must be noted that conventional storms are responsible for most property losses. The identification of these factors could be the first step towards having mitigation policies in NEA.

It is expected that the research described here will be soon extended to other areas of Argentina through the formation of a network of university research groups.

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