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Highest wind gusts in Uruguay: characteristics and associated meteorological events

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ABSTRACT: A historical background of high winds measurements and wind damage in Uruguay is presented, and results of extreme value analysis of 35 years of 10 min-mean wind speeds measured in Montevideo are indicated. An analysis of recent data series from automatic weather station was performed to characterize the meteorological mechanisms that cause the highest wind gusts in Uruguay. It was found that severe convective activity was responsible for the highest wind gusts measured, as well as for most of the wind gusts greater than 80 km/h (22.2 m/s). The highest wind gusts were registered in a region in the south-center of Uruguay, while wind gusts greater than 80 km/h were more frequently measured in a region in the center of the country. It could be confirmed that convective systems usually move from the southwest to the northeast, while the trajectory of extra-tropical cyclones is generally from the northwest to the southeast, but that both meteorological mechanisms cause the highest gusts from the southwest quadrant.

KEYWORDS: extreme wind gusts in Uruguay, severe convective storms, extra-tropical cyclones, downburst measurements.

1 INTRODUCTION

Uruguay is located in the southeastern part of South America, between the latitudes of 30 and 34.5º south, being part of the mid-latitudes, which lie between the latitudes of 23.5 and 60°. It belongs to the area most affected by severe convective storms in South America [1], and to the second worldwide after the Southern plains of central USA [2]. In this area, intense and localized damaging winds, as downbursts and tornadoes usually occur ([1], [3], [4]). Uruguay also belongs to a region of the Southern Hemisphere that experiences one of the most significant cyclogenesis activities ([5], [6]), where extra-tropical cyclones occasionally intensify during their passage over the country and generate damaging winds in part of it during several hours.

In accordance, there exist many reports of high winds and associated damage since the beginning of their documentation in the country, although this documentation has been far from systematic or complete [7], as it is usually the case in this region of the world [1].

At present, the longest source of historical and current wind data measured in open terrain in Uruguay corresponds to 10 min-mean wind speed and direction recorded every hour since 1960 at a meteorological station of the National Direction of Meteorology (DNM) located in the airport of Carrasco, Montevideo, capital city of Uruguay. This data has been recently used to obtain an updated extreme 10 min-mean wind statistics [8].

In this station, wind gusts have been sporadically registered following criteria that may have changed over time, facts which do not allow performing a reliable analysis of the extreme statistics of wind gusts. As Uruguay is located in a region that experiences intense convective activity, as mentioned before, the relation between high 10 min-mean wind speeds and their related wind gusts may not correspond to the typical gust factors for atmospheric boundary layer (ABL) flows [9], as those presented in Cook, 1985 [10] or ISO 4354, 2009 [11]. Thus, it could be necessary to analyze actual wind gusts measurements to obtain an adequate wind gust extreme statistics.

In the past, from 1906 to 1970, wind gusts were continuously recorded with an anemograph lin a non-standard exposure, above the roof of a four-storey building located in front of the port of Montevideo [7], with the city center immediately to its east. In spite of its exposure, the official national extreme wind map presented in the national wind code UNIT 50-84 [12] is mainly based in the analysis of the annual maxima wind gusts recorded at this site, translated to 10 m height assuming an ABL flow, and of some shorter records from other Uruguayan stations.

More recently, a network of automatic weather stations that measure mean, standard deviation, maximum and minimum values of wind speed, direction and temperature every 10 minutes at several heights began to be installed at different sites in Uruguay in 2008 [13]. The number of stations across the country, and the length of these measurements (although not enough for a proper extreme statistics study), now allow to perform a first description of the main characteristics of the highest wind gusts that occur in Uruguay, as their typical temporal and spatial scales, their wind evolution with time, correlation among different heights, as well as of the associated meteorological mechanisms which produce them.

With taller and more expensive buildings of different shapes in Montevideo and other areas close to the coast exposed to high winds, many of them built with glass curtain wall facades; bigger ships visiting Uruguay and others transporting passengers to and from Argentine; more tall antennas and solar collectors over the roofs of buildings; the growth of wind farms installations and the exponential increase of productive forest plantations in different regions of the country, among other factors that Uruguay has been experiencing in the last few decades, it is a matter of concern to analyze and keep up to date as much information as possible on the highest wind gusts that occur in the country, such as their geographical distribution, maximum wind speed values, characteristics of their vertical profiles, gust factors, etc. This information will allow a better understanding of actual vulnerability to extreme wind events, as a first step towards prevention, as it can contribute to the development of a new national extreme wind map, the revision of the national wind code, the development of specific wind codes that Uruguay lacks, the improvement of management of existing insurances and the creation of new insurance products, among other important issues needed to be addressed in order to accompany the increase of vulnerability to high winds due to the growth of exposed resources and capital investments.

2 HIGH WINDS PRODUCED BY SEVERE CONVECTIVE ACTIVITY AND STRONG EXTRA-TROPICAL CYCLONES

2.1 *Severe convective storms*

Convection is the transfer of heat by the mass movement of a fluid (in this case, air), which happens naturally in the atmosphere. Meteorologists usually restrict the term convection to the process of rising and sinking air parcels [14].

Air can start moving upwards due to unequal heating of the surface, topography, the lifting of warm air along an air mass boundary such as synoptic fronts, drylines, outflow boundaries from previous convective cells and sea breezes [15], or due to converging surface winds. Severe convective storms typically produce weather events that cover a wide range of size scales, from a few hundred kilometers down to just a few kilometers or even smaller. The synoptic-scale corresponds to scales of several thousand kilometers, while the mesoscale is in the range of hundreds of kilometers.

Severe convective storms produce some of the fiercest weather on Earth, including flooding rains, severe surface winds sometimes greater than 50 m/s, hail, frequent lightning and tornadoes. Individual convective cells are generally observed on scales from 5 to 30 km, and can have lifetimes ranging from 30-40 min to greater than 6 h. Groups of convective cells can become organized into larger mesoscale convective systems (MCSs), which can extend over hundreds of kilometers and, in some cases, can last for several days [16].

The most basic storm types include the isolated cell, the multicell and the supercell.

An isolated cell consists of only one updraft and does not initiate subsequent convection in any organized manner. These cells may last for an hour or less and rarely produce strong winds or large hail. Their life cycle may be divided into three stages.

The first stage is known as the cumulus stage (or towering cumulus stage). As humid air rises, it cools and condenses into a single cumulus cloud, which may show extensive vertical development in just a few minutes, giving plate to a cumulus nimbus cloud. This updraft keeps water droplets and ice crystals suspended within the cloud, but as the cloud builds well above the freezing level the cloud particles grow larger and become heavier.

Eventually, the rising air is no longer able to keep them suspended, and they begin to fall through the updraft. While this is happening, drier air from around the cloud is being drawn into it in a process called entrainment, which evaporates some of the raindrops, chilling the air. The air, colder and heavier than its surrounding, begins to descend as a downdraft, which may be enhanced as falling precipitation drags some of the air along it [14]. The appearance of the downdraft marks the beginning of the mature stage, at which the storm is more intense. The updraft and the downdraft reach their greatest strength in the middle of the cloud, and heavy rain and occasionally small hail falls from the cloud. The rainfall may or may not reach the surface, depending on the relative humidity beneath the cloud, but the downdraft of cold air that forms with the onset of precipitation reaches the surface sometimes as a strong wind gust, which spreads laterally and cools the surface up to some hundred meters height. The gust front corresponds to the leading edge of the downdraft. This process creates a cold pool, which may last several hours after the storm has dissipated. Sometimes, the air temperature may lower as much as 10°C in just few minutes.

After the storm enters the mature stage, it begins to dissipate in about 15 to 30 minutes. If severe weather occurs, it usually takes place near the transition from the mature to dissipating stages, or about the time when the maximum fallout of precipitation occurs. During the dissipating stage the downdraft cuts off the supply of warm humid air required to form cloud droplets. In the case of isolated cells, the precipitation falls through the updraft rather than being deposited away from the updraft and the associated hydrometeor loading reduces updraft buoyancy. The updraft then weakens and the downdraft tends to dominate the cell.

These three stages are illustrated in Figure 1.

In multicellular convection, new cells are triggered repeatedly along the gust front, where the forced ascent is sufficient to lift air parcels. The cold downdraft upon reaching the surface forces warm, moist surface air upwards, which condenses and gradually builds into a new storm. A series of storms then grow in line, each in a different stage of development. This mechanism is illustrated in Figure 2. In this way, a highly organized cluster or line of cells is maintained for a much longer period of time than the typical lifetime of an individual cell. According to [15], this is probably the most common form of convection in mid-latitudes. The most severe forms of multicellular convection can last for hours and produce large swaths of damaging straight line winds and hail up to the size of golf balls.

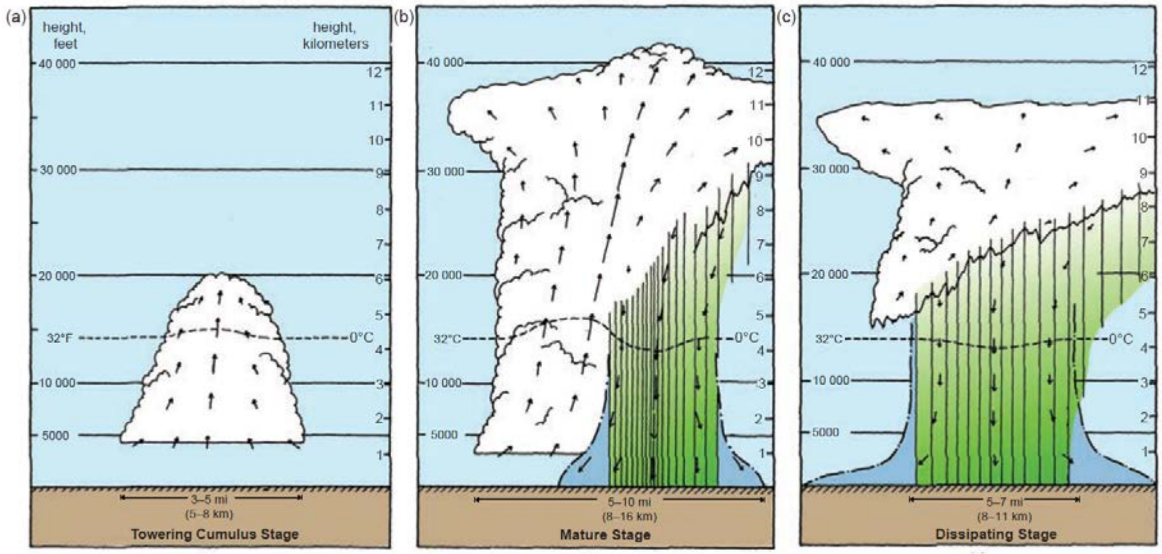


Figure 1. Stages during the development of an isolated cell [15].

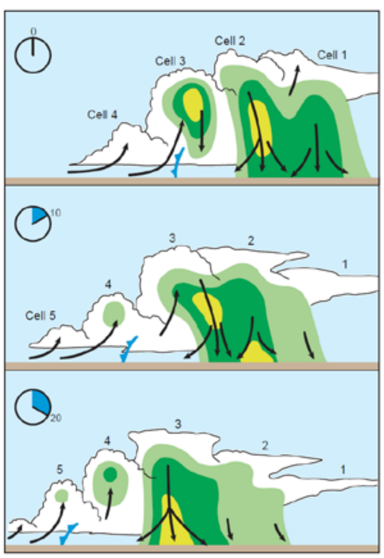


Figure 2. Evolution of multicellular convection [15].

Supercells are rotating storms that develop their rotation by tapping the vertical wind shear in the storm environment [17]. The supercell is potentially the most dangerous convective storm, often producing high winds, large hail and long-lived tornados [16]. They are probably the least common storm type worldwide, but are responsible for a disproportionately large fraction of severe weather reports. Almost all reports of hail having a diameter of 5 cm or larger are associated with supercell storms, as well as almost all strong and violent tornadoes. They are frequently long-lived, with common lifetimes from 1 to 4 hours, some of them persisting as long as 8 hours [15]. In its purest form it consists of a single, quasysteady, rotating updraft and associated downdraft, which may have a lifetime of several hours. It often evolves from multicell storm system, but its general structure and evolution suggest that it is dynamically different from ordinary convection [16].

Unlike ordinary cells or multicells, an usual characteristic of supercells is the presence of a persistent separation between the primary updraft and downdraft currents. The updraft region is characterized by a well-defined cloud base, which often exhibits pronounced cyclonic rotation.

A MCS is defined as a cloud system consisting in an ensemble of storms that produce contiguous precipitation of 100 km length or more in the horizontal scale in at least one direction. MCSs can evolve from convection that in its early stage corresponded to isolated convection. After several hours have elapsed, outflows that might have originated from widely separated areas of initial convection tend to merge into a single, large cold pool capable of initiating new cells along most of its length. In other cases, MCSs develop almost immediately following convection initiation, perhaps as a result of widespread, strong forcing along an air mass boundary.

It is worth mentioning that measurements of meteorological variables during the passage of a gust front or a cold front may be quite similar. In both cases, the wind usually shifts and becomes gusty, with wind speeds occasionally exceeding 100 km/h and the temperature drops sharply. The cold air may linger close to the ground for several hours, well after severe convective storm activity has ceased [14]. At a cold front, the cold, dense air wedges under the warm air, forcing the warm air upwards. As the moist, unstable air rises, it condenses into a series of cumuliform clouds. At the front itself, a relative narrow band of severe convective storms can form and produce heavy showers with gusty winds [14].

2.2 *Strong extra-tropical cyclones*

Extra-tropical cyclones are those cyclones generated in mid-latitudes. They are rotating weather systems with horizontal extent from hundreds to thousands of kilometers, which carry warm air poleward from the tropics and cold air from the polar regions equatorward [17]. In the Southern Hemisphere, these cyclones rotate clockwise. The leading edges of the cold air flowing towards the equator and the warm air flowing towards the pole are called the cold front and the warm front, respectively. These cyclones can become particularly intense, when the pressures at their cores become quite low in comparison to the average. Rapidly falling pressures can create strong winds over a wide region. The damaging winds can extend over many hundreds of kilometers and last in any one place for a full day or more. They can also create conditions for the development of smaller-scale storms associated with severe weather that can become even more potentially hazardous.

3 HISTORICAL BACKGROUND OF HIGHS WIND MEASUREMENTS AND WIND DAMAGE IN URUGUAY

When wind started to be measured and informed in a methodical way in Uruguay around 1900, wind gusts of 140 km/h (39 m/s) were reported several times at the Municipal Observatory of Prado, located in Montevideo [18], as well as many wind gusts greater than 100 km/h (28 m/s). These events were usually related to sudden increases in wind speeds with their maximum values sustained during one to several minutes, generally accompanied by changes in wind direction to the southwest quadrant, intense rain and/or hail and important drops in temperature.

As it was mentioned in 2.1, high gusts accompanied by wind shifts, intense rain and/or hail and important drops in temperature are associated with the occurrence of severe convective storms.

The author of this paper had access to monthly, annual and other types of reports from the Municipal Observatory of Prado from 1901 to 1917, kept at the DNM. In most of them, the hourly mean wind speed and direction, temperature and pressure were given, and when the mean wind speed exceeded 50 km/h (14m/s), a detail of the meteorological conditions and time evolution of wind gusts were also included in these reports.

This Observatory was the main official meteorological station of Uruguay at that time, and it was directed from its foundation in 1900 until 1923 by Luis Morandi, an outstanding and methodical meteorologist and researcher. In this station, wind speed and direction were measured by anemographs and wind vanes located 3 m above the roof of a 14 m high building surrounded by open terrain [19].

In 1935, while Morandi was in charge of a meteorological station at the School of Agronomy, in Sayago, Montevideo, an event with a recorded maximum gust of almost 200 km/h (56 m/s) was measured and described [19]. The time evolution of the wind speed measured during this event is presented in Figure 3, and its similitude with much more recent registers of downbursts in other parts of the world is evident when it is compared with Figures 4a-c. Figures 4a-c show, respectively, the time evolution of wind speeds during downbursts registered in Texas, USA in 2002 [20], in Maryland, USA in 1983 [21] and in Sydney, Australia in 2001 [22]. It is worth noting that there are still not many registers around the world with a measurement frequency that allows a good description of this type of event, as those indicated in Figures 3 and 4a-c, and that the event registered in Montevideo in 1935 might be the first, to the author´s knowledge.

As mentioned later in Vieira, 1969 [23], the event of 1935 affected different areas of Montevideo city, as its center and port, where several roofs, doors, windows, light poles, electricity cables, trucks and trees were blown down. High winds were accompanied by large hailstones that covered extensive areas, and the description of the wind damage also corresponded with the occurrence of a succession of downbursts due to severe convective activity: “In a park, populated with trees of the same species, tens of trees were damaged in different areas, while some hundreds meters from those places no damage was produced. This pattern was repeated with intermittency in sites located at a considerable distance from the previously damaged place, always in the same trajectory of the storm” [23].

Regarding intense winds and damage related to extra-tropical cyclones, the description of wind speed, wind gust, wind direction and pressure evolution with time during a strong extra-tropical cyclone that caused great damage in Uruguay was described in [24].

The author has also gathered information about different wind events that produced intense hail and/or rain with sudden increase of wind speeds in Uruguay with damage indicative of severe convective activity, summing up to more than 200 cases the last 50 years, in a country with an area of around 175.000 km^2 where these events are not systematically reported or registered. These events include the occurrence of tornadoes. When a systematic search for wind damaging events that occurred in the last years was conducted in newspapers and other sources of information, around 16 events per year were found to have occurred due to severe convective activity. Performing a similar search, the frequency of extra-tropical cyclones that cause wind damage in the country was estimated to be one per year in average, with varying maximum wind speeds along different years.

In Uruguay, severe convective storms and intense extra-tropical cyclones winds affect different types of structures, electricity and telephone services, trees, crops, sailing boats and ships, among others, and represent a risk for the population.

About the threshold for wind damage, it was found that damage was usually reported with wind gusts higher than or equal to 80 km/h (22 m/s), and that the most common reports corresponded to blown-off roofs and trees. More details of the characteristics of wind damage in Uruguay can be found in Durañona, 2011 [7].

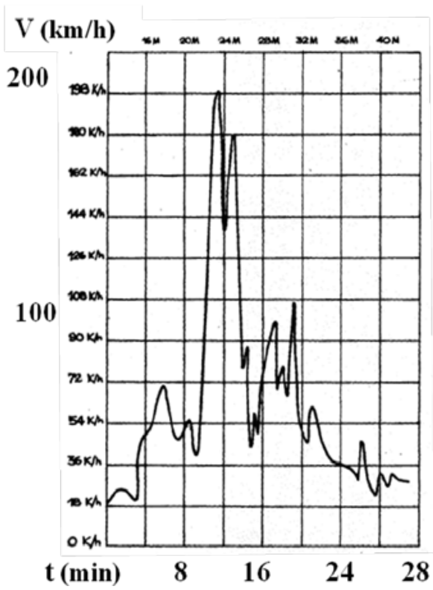


Figure 3. Wind measurement during a downburst in Sayago, Montevideo, 8th of July, 1935 [19].

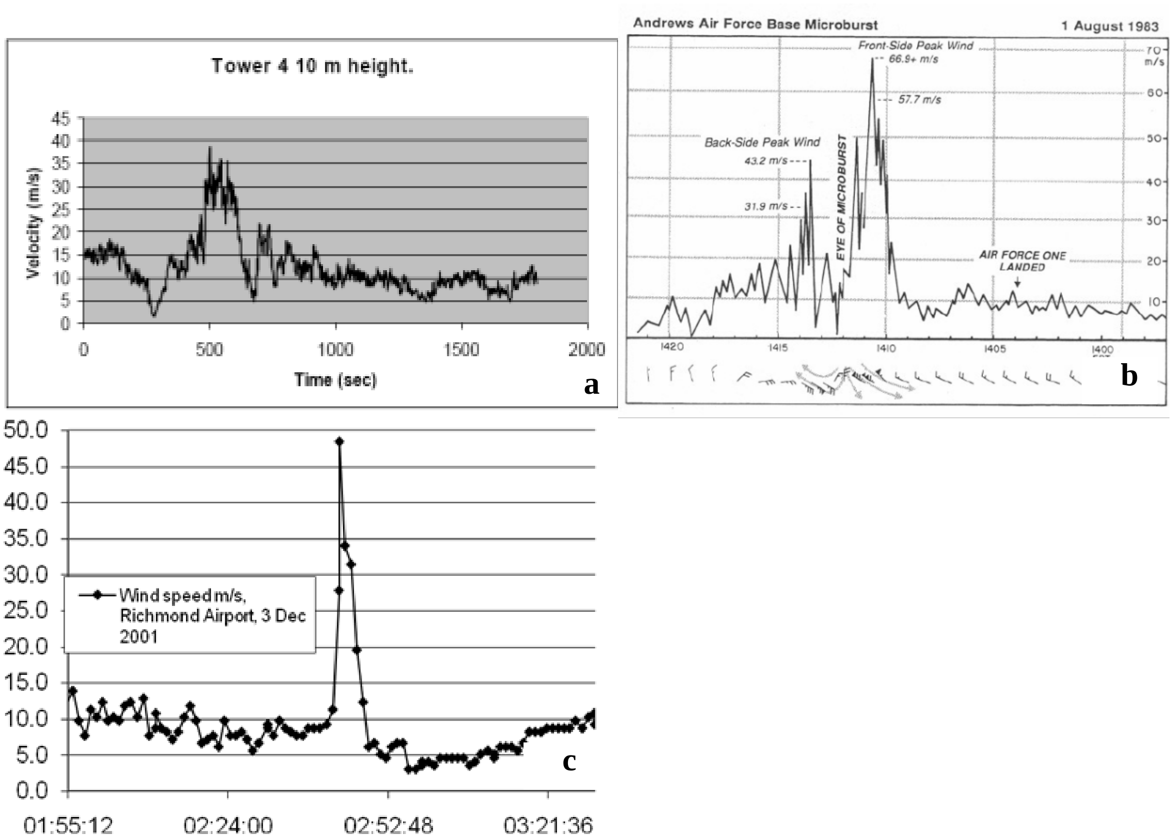


Figure 4. Other downbursts registered around the world (a: USA [20], b: USA [21], c: Australia [22])

4 STATISTICS OF 10 MIN-MEAN WIND SPEEDS MEASURED AT CARRASCO METEOROLOGICAL STATION

The DNM recently granted access to wind records from the meteorological station located at the international airport of Carrasco, to the Institute of Fluid Mechanics and Environmental Engineering (IMFIA), School of Engineering, University of the Republic (UdelaR) for research purposes. This station is the main official meteorological station of Uruguay. 10 min-mean wind speeds and directions measured since 1960 at the end of each hour could then be digitized directly from the original station books, and during this procedure, a search for the historical description of the anemometers used, their location, height of measurement, surroundings (metadata) and literature related to high winds measured in the country was also performed at the DNM. Additionally, an analysis of the quality of Carrasco data series and of their metadata was conducted and as a result, 35 complete years of hourly wind data were chosen to perform an analysis of the extreme statistics of the 10 min-mean wind speed of Montevideo. These 35 years of hourly wind records were then homogenized taking into account the height of the anemometers and the roughness length (z_o) of the different sites where wind had been measured since 1960 at Carrasco airport, dividing each site surroundings into eight sectors. An upper and lower bound for z_o values for each sector and site of wind measurement were estimated from photographs, Google Earth program and a visit to the station, resulting in two sets of 35 values of yearly maximum 10 min-mean wind speeds. Each set corresponded to a different group of z_o values. With this homogenized data, an analysis of the extreme statistics of the 10 min-mean wind speed was then performed [8].

As justified in [8], the Generalized Extreme Value distribution was used to fit each of the two wind extreme data sets. With the aid of Matlab program the Gumbel or type I distribution was found to be the distribution that best fitted both data sets. Independent tests also confirmed the hypothesis that the Gumbel distribution yielded a good fit for both sets of annual maxima of 10 min-mean wind speeds from this station.

Figure 5 shows the results in Gumbel paper, where the x-axis represents the homogenized annual maxima of the 10 min-mean wind speeds in km/h for both sets of z_o, and the y-axis represents the probability for any year that the annual maximum exceeds a specific

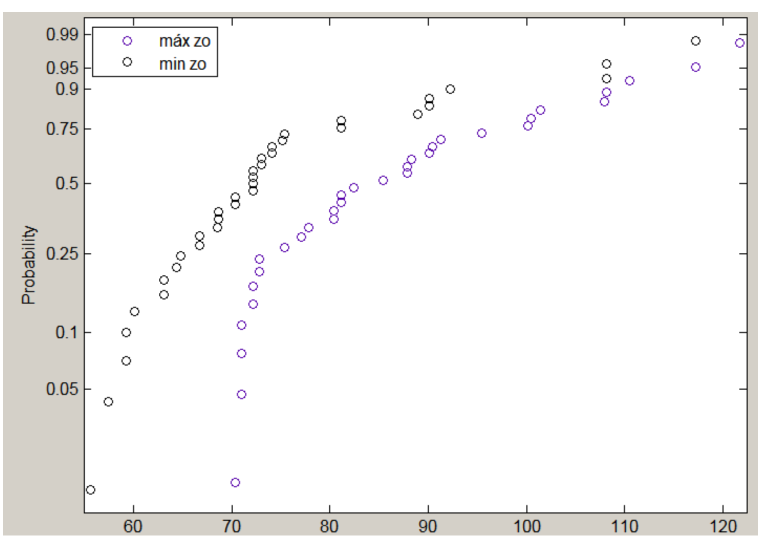


Figure 5. Gumbel plot for the annual maxima of the 10 min-mean wind speed values (km/h) of the 35 years studied at Carrasco station, using the upper (max z_o) and lower bound (min z_o) values of z_o for the homogenization of the data.

wind speed value. As this figure illustrates, a kink in the graph was found around 90 and 75 km/h, respectively, for the data sets corresponding to the upper and lower bounds of z_o.

As indicated in [9], the existence of two distinct portions of the data with different slopes suggests that the data consists of two different populations, corresponding to two different physical mechanisms. This will be explored in other sections of this paper.

5 ANALYSIS OF DATA SERIES FROM RECENT NETWORKS OF AUTOMATIC WEATHER STATIONS

The National Administration of Power Stations and Electrical Transmissions (UTE) has been gradually installing a network of automatic weather stations since 2008 motivated by the research on the wind power resource assessment of the whole country. On the other hand, the National Direction of Energy (DNE) from the Ministry of Industry, Energy and Mining developed a program to promote the wind energy in Uruguay, and also installed some weather stations in places not covered by the UTE network. Both networks register a series of meteorological parameters and automatically transmit the mean, standard deviation, maximum and minimum values of wind speed, wind direction and temperature every 10 minutes, and in some stations, relative humidity and/or solar radiation are also measured.

For the present study, 25 stations measuring in open and level terrain, usually corresponding to rural surroundings without significant obstacles that could influence their wind measurements were selected. These stations are those shown in the darkest color in Figure 6, while Table 1 indicates the number and name of each station, the corresponding studied measurement periods, number of complete years of measurements analyzed, types and heights of their sensors, and number of sensors or orientation in the case of the anemometers.

As this table indicates, every station measures wind speed at two or three heights, usually wind direction at two heights and temperature at one height, while in the cases where humidity and/or solar radiation are also recorded, they are measured at one height.

Table 1 also shows that the heights of measurements vary among the different stations, spanning heights from 10 to 100m. As all of them have anemometers below and above 45m, wind speed values were interpolated at this height when comparison across the country was required.

As the stations networks have been gradually installed, the lengths of the studied records vary from around four years to just a few months. Altogether they represent 850 months of 10 minutes measurements of each meteorological parameter. When homogenization was needed to compare results, only complete years were used in the analysis, in order to take into account possible seasonality in the occurrence of high wind gusts.

Although the longest wind series studied represent 4 years of measurements, usually not enough for proper extreme statistics studies, they offer plenty of valuable information, as maximum measured wind gusts along time at all the stations, simultaneous measurements of wind speed at different heights, wind direction and temperature, as well as time evolution of the vertical profiles of these meteorological variables, from which important conclusions can be derived.

As shown in Figure 6, the locations of the analyzed weather stations cover most of the country. As the maximum distance between two points of Uruguay is less than 600km, the density of these stations also allows an adequate analysis of the trajectories and behavior of

Figure 6. Automatic weather stations used in the present study (image adapted from Google Earth).

Table 1. Characteristics of the automatic weather stations used in the present study.

N°	Station	Measurement period	Complete years at 3/07/2012	Anemometers heights (m)	Wind vanes heights (m)	Thermometer heights (m)	Hygrometer height (m)	Solarimeter height (m)
2	Bonete	31/7/2008 - 3/7/2012	3	50 (2), 25 (S) , 10 (E)	50, 25	4	-	9
3	Florida	24/4/2008 - 26/8/2009	1	45 (2), 26 (W), 10 (W)	45.4, 25.9	10	-	-
4	Peralta	6/5/2008 - 3/7/2012	4	74.5 (2), 41.5 (W), 10 (W)	74.5, 41.5	4	-	-
5	Valentines	13/5/2008 - 3/7/2012	4	76.5 (2), 41.5 (E), 10 (E)	76.5, 41.5	8	-	-
7	Rosario	27/5/2008 - 3/7/2012	4	65 (2), 44 (W), 10 (W)	65, 44	4	-	7
8	Artilleros	17/6/2008 - 3/7/2012	4	46.6 (2), 27.3 (E), 11.2 (S)	46.6, 27.3	6	-	-
9	Piedras de Afilar	1/7/2008 - 3/7/2012	4	64.4 (2), 37 (2)	64.4, 37	8	-	-
10	Arroyo Cañas	10/7/2008 - 3/7/2012	4	60 (2), 37 (2)	60, 37	5	-	-
11	Pintado	15/7/2008 - 3/7/2012	4	86 (2), 40 (2), 72 (2)	86, 40	13	-	-
12	Cerro Colorado	24/7/2008 - 3/7/2012	3	81 (2), 40 (2)	81, 40	8	-	-
13	Palmar	1/8/2008 - 9/8/2009	1	58 (2), 40 (2)	58, 39	-	-	-
14	Andresito	19/08/2008 - 3/7/2012	3	87 (2), 39 (2)	87, 39	17	-	-
15	Tupambaé	10/9/2008 - 23/8/2010	2	79 (2), 39 (2)	79, 39	-	-	-
16	Pampa	7/10/2008 - 3/7/2012	3	72 (2), 30 (2), 92 (2)	54, 30	9, 53	-	-
17	Buena Unión	08/10/2008 - 3/7/2012	3	66 (2), 28 (2)	58, 28	10	-	11
18	José Ignacio 1	17/10/2008 - 3/7/2012	3	54 (2), 24 (2)	54, 24	8	-	-
20	Rocha	1/7/2009 - 3/7/2012	3	74 (2), 31 (2)	70, 31	12	-	-
23	Mc. Meekan	12/11/2010 - 3/7/2012	1	60 (2), 40 (2)	60, 40	10	-	-
33	B. Brum	15/2/2012 - 3/7/2012	0	73 (2), 40 (2)	72, 40	73	-	6
34	J. Otamendi	15/3/2012 - 3/7/2012	0	101 (2), 80 (2), 60 (2)	100, 60	100	-	5
36	Colonia Terra	31/05/2012 - 3/7/2012	0	58 (2), 35 (2)	58, 35	58	-	-
40-ARN	Arroyo Negro	7/10/2010 - 3/7/2012	1	75 (S), 55 (2), 20(S)	75	75, 3	3	-
41-EGA	Egaña	1/10/2010 - 3/7/2012	1	72 (S), 55 (2), 21 (S)	73, 3	73	3	-
42-LC2	Lascano	27/9/2010 - 3/7/2012	1	72.3 (S), 55 (2), 21.3 (S)	73, 3	72.8	-	-
43-ITP	Itapebí	6/4/2011 - 3/7/2012	1	75 (2), 55 (S), 20 (S)	75, 3	75	3	-

the storms that cause the highest wind gusts in the country, geographical areas of eventually higher wind speeds and translational wind speed of the storms, among other characteristics.

Due to these facts, it was expected that a systematic analysis of this data would help to describe and characterize the main wind extreme events that cause wind damage in Uruguay.

5.1 *Characteristics of the events with highest wind gusts*

As 80 km/h (22.2 m/s) had been previously identified as the wind speed threshold for the beginning of wind damage [8], a search was performed for all the events that presented wind gusts higher than that value at any height in the stations indicated in Figure 6, during the measurement periods listed in Table 1. In many cases, synoptic charts and satellite imagery were collected around the time the highest gust occurred, trying to describe the meteorological mechanism behind it.

Of all the events that developed gusts higher than 80 km/h, the six strongest ones presented wind gusts higher than 40 m/s (144 km/h) at least at two heights. Two of them occurred in Pintado and another two in Valentines, corresponding both cases to four years of analyzed data, while the remaining two took place in Peralta within four years of measurements and in Andresito with three years of analyzed data. As Figure 6 shows, these sites are located in the center-south of Uruguay.

These stations have measurements heights between 10 and 87 m, and for the five strongest events, the wind gusts registered at all heights were higher than 40 m/s, being the highest recorded values 45 m/s (162 km/h) at 86 m height in Pintado, and 43 m/s at 74.5 m and at 76.5 m height at Peralta and Valentines, respectively. The event in Valentines registered 40 m/s at 10 m height, while the event in Peralta registered 39 m/s at 10 m height.

The number of total events with wind gusts higher than 80 km/h interpolated at 45m height at each of these 25 stations, divided by the number of months analyzed at each station yielded values between 0.5 to 1.06; i.e., in average one damaging wind event occurred once to twice monthly in all the 25 stations. The highest rate of occurrence of this type of event corresponded to a smaller region inside the previously identified, covering a central area of Uruguay. It then seems that the strongest wind events tend to occur more frequently in a region of the country located in its southern center, while frequent damaging winds would be experienced with a higher rate in the center of Uruguay. It was also found a strong tendency for this type of event to occur mostly between September and April, corresponding to the seasonal distribution of severe convective activity in this region of the world [4].

Also, for each of the 25 stations, the four events that presented the highest gusts were analyzed when they exceeded 80 km/h. Only at 2 of the 25 studied stations there were less than four events that did not comply with the criteria. In this way, 93 events with wind gusts higher than 80 km/h were identified, which corresponded to 47 different dates.

Analyzing other meteorological variables, it could be concluded that in 80% of these 93 events, the maximum gust occurred when the temperature decreased; in 4% when it increased, and in the remaining 16% the temperature did not present an appreciable change.

In also 80% of the 93 events, significant wind direction changes occurred when the maximum gust was registered. 50% of these 93 events presented abrupt wind direction changes, while 30% presented gradual wind direction changes. When significant wind direction change occurred, the maximum gust took place with wind speeds from the south-west quadrant (including the south and west directions) in 85% of the cases; from the north-west quadrant in 10% of them, and from the south-east quadrant in the remaining 5%.

The events with non-relevant wind direction changes, presented winds from the west, east, southwest and south in 30, 30, 15 and 15% of the cases, respectively.

The temporal evolution of the wind gusts was also analyzed for the 93 events. For the events that presented the highest gust values, intense convective activity was confirmed by satellite images and the simultaneous temporal behavior of temperature, wind direction and wind gust, which matched the characteristics associated with the occurrence of downbursts, presented in section 2.1. Great part of these events could be classified according to the behavior of wind gusts with time into the following four categories:

a – Wind gusts that presented very pronounced peaks, generally associated with temperature drops and abrupt wind direction changes, where the increase and decrease in wind speed occurred in half an hour or less;

b – Wind gusts with pronounced peaks, also associated with drops in temperature and generally abrupt wind direction changes, where the increase and decrease in wind speed occurred in one hour or less;

c – Wind gusts with abrupt increase, while the decrease was gradual and spanned several hours;

d – Wind gusts whose increase and decrease took each generally between 1 to 3 hours.

Examples of these situations are shown in Figure 7a-d, respectively.

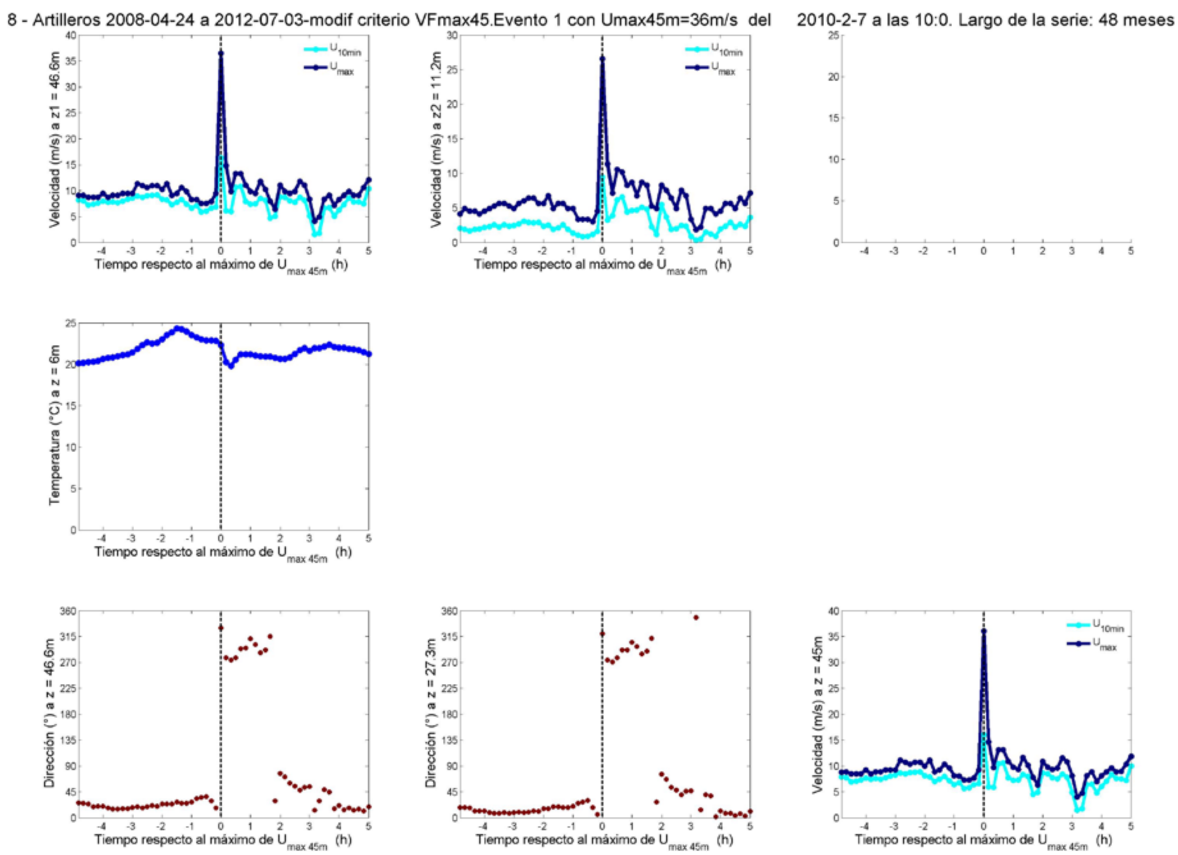
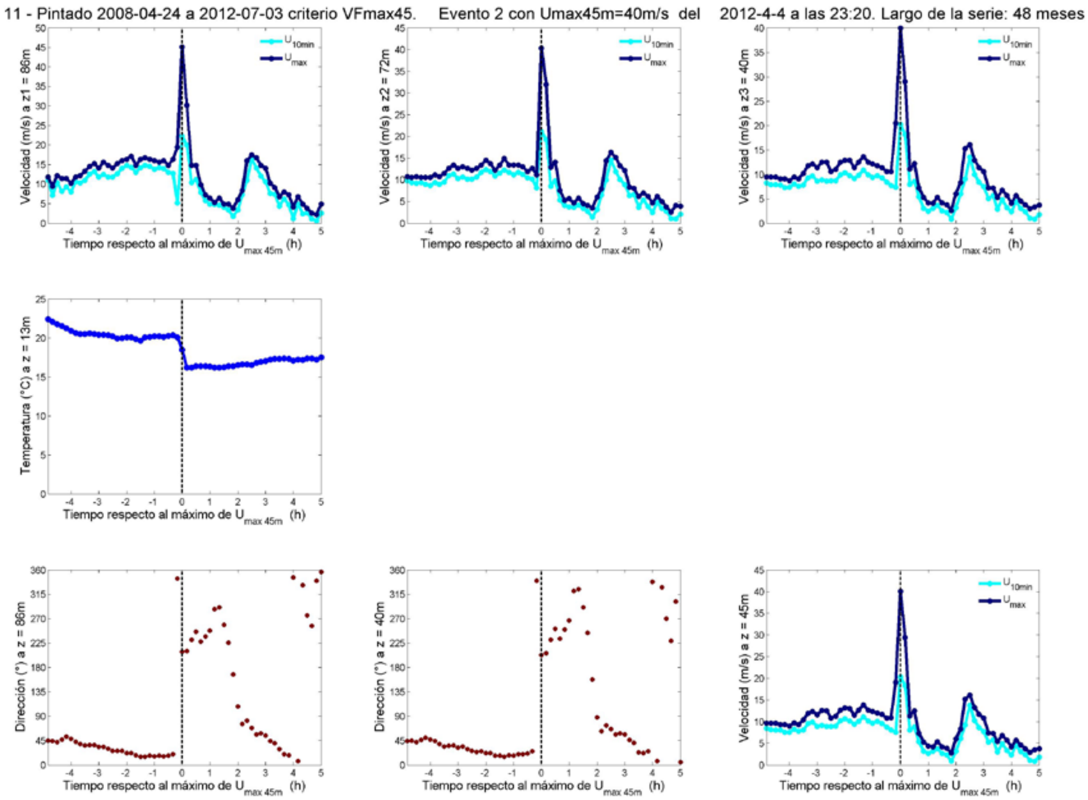
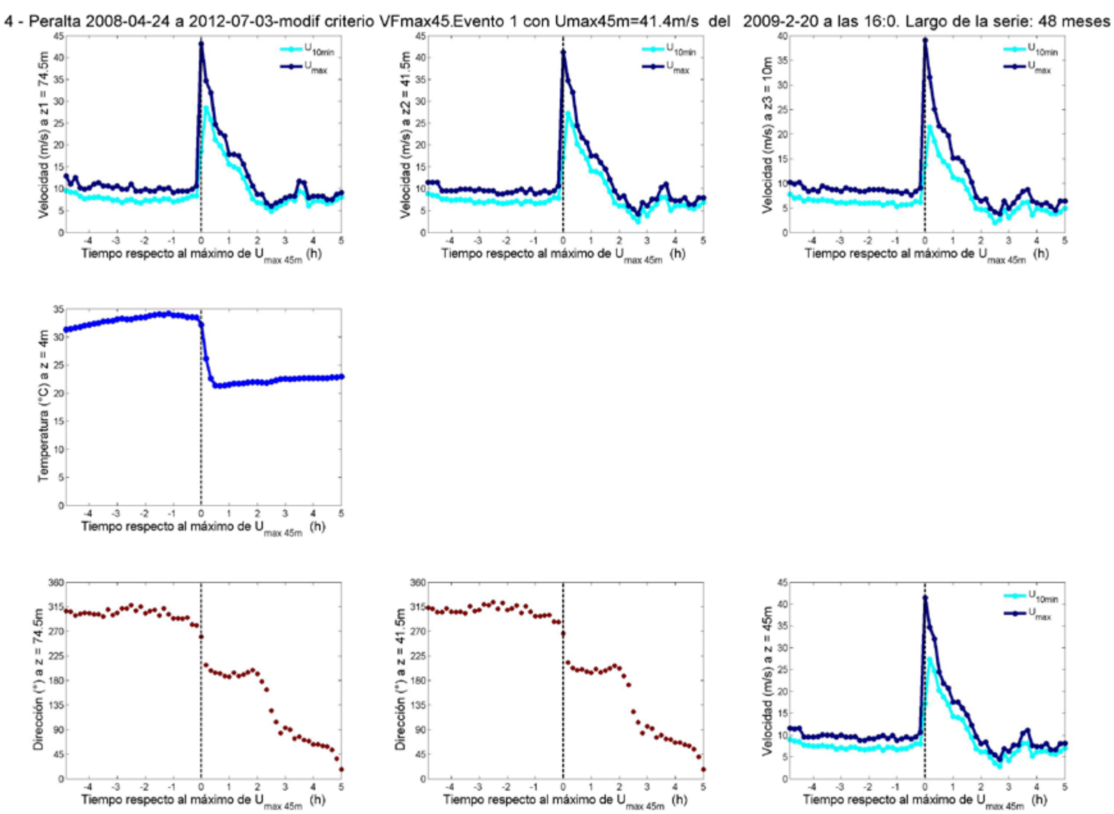
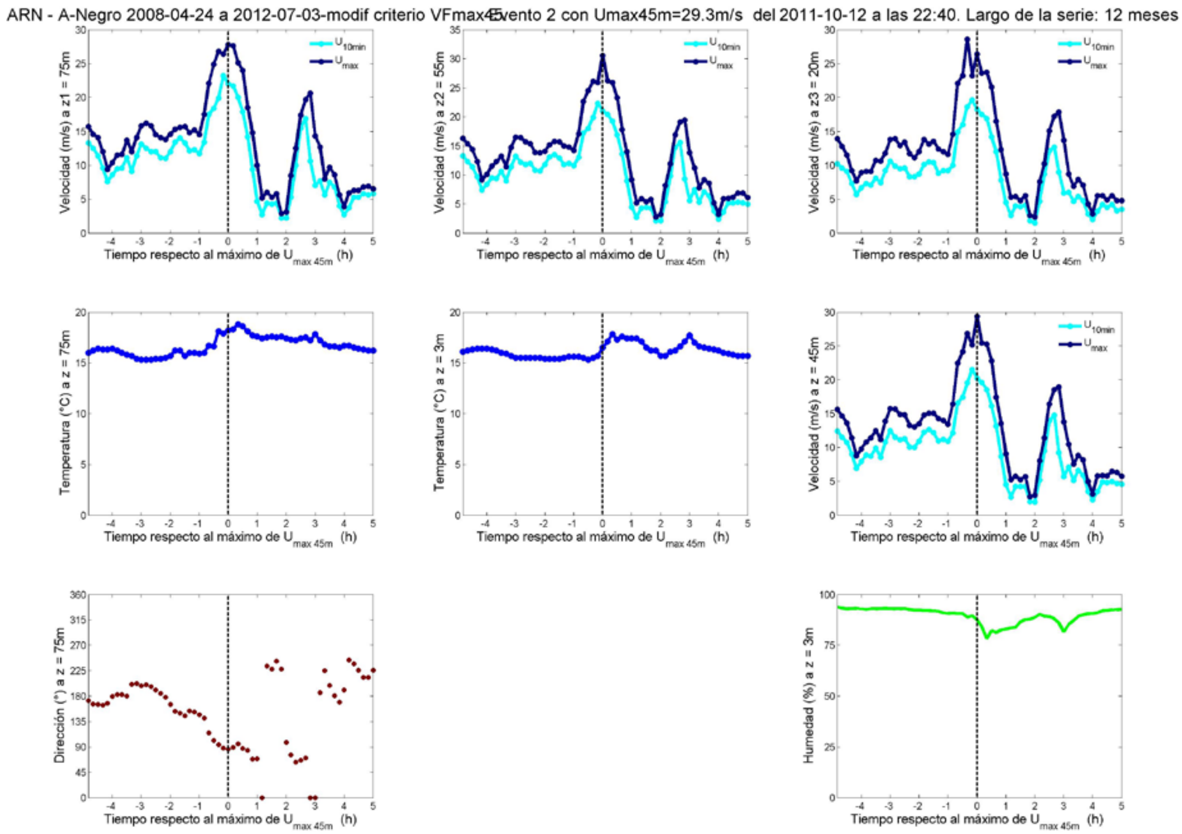


Figure 7a. Example of an event with wind gusts that presented a very pronounced peak.





Figures 7b-c. b: Examples of events with wind gusts that presented: b. a pronounced peak, c. an abrupt increase and gradual decrease.



Figures 7d. Example of an event with wind gusts that presented an increase and decrease within several hours.

Figures 7a-d show in their title the number and name of the station, the measurement period analyzed for that station, the number of the event for the considered station in ascending order according to the maximum gusts interpolated at 45m height (for each station, Event 1 corresponds to the maximum gust obtained at 45 m), the value of the corresponding wind gust, the date and local time when the maximum gust was registered and the length of the series in months used for this study (only complete years were used). In all the graphs, the vertical dotted line corresponds to the time when the maximum wind gust at 45 m height was obtained, while the horizontal axis shows the previous and following five hours from that time. In each figure, the first row has three graphs, which from left to right show the 10 min-mean wind speeds and wind gusts in m/s registered at the available heights for each station, in descending order with height. The darkest line corresponds to the wind gusts, while the lightest, to the 10 min-mean wind speed. In Figure 7a, corresponding to the station 8-Artilleros, the wind speed measured at a height of 27.3 m was not plotted because that anemometer is oriented to the east, as shown in Table 1, and part of the wind measurements registered after the maximum gust came from the west and may be influenced by the station tower.

Figures 7a-c have seven graphs. The central graph shows the evolution of the temperature with time, in degrees Celsius, while in the last row, the first two graphs correspond to the wind direction measured at different heights and the graph to the right shows the wind gusts and 10 min-mean wind speed interpolated at 45 m height.

On the other hand, Figure 7d, corresponding to the station 40- Arroyo Negro, has eight graphs. The central row shows from left to right the evolution of temperature with time for the two thermometers indicated in Table 1 and the wind gusts and 10 min-mean wind speed interpolated at 45 m height; while in the last row, the graph to the left corresponds to the wind direction measured at 75 m height and the graph to the right shows the evolution of the relative humidity with time, measured at 3 m height.

In all these events, both the wind gusts and the 10min-mean wind speeds present a significant correlation with height. Also, a correlation between the wind gusts and 10min-mean wind speeds can be appreciated at each height, but around the maximum gust the relation between the measured wind gusts and 10min-mean wind speeds is usually significantly higher, and correspondingly, the gust factor generally increases. When the maximum gust is registered, the gust factor reaches a value of 2.5 at 46.6 m height in Figure 7a, values around 2 at the three heights in Figure 7b, and around 2.3 at the three heights in Figure 7c. Arroyo Negro station yields the minimum gust factors: between 1.3 and 1.5 for the three heights when the maximum gust is registered. These values would correspond to gust factors for ABL flows over rural terrain at these heights [10].

Another differences between Figures 7a-c and Figure 7d are the behavior of the temperature and wind direction around the maximum wind gust. The first three cases show temperature drops when the wind gusts increase - the largest one corresponding to Peralta station, with a sharp decrease in temperature of around 10° C in 20 min at 4 m height; while in the last case there is a slight increase in temperature. In relation to the wind direction, the three first cases show abrupt to moderate changes when the maximum wind gust occurs, while in the last case the change of the wind direction when the maximum gust is registered is not so clear.

Looking at satellite images of GOES 12 from CPTEC (Center for Weather Prediction and Climate Studies, from Brazil) web page, one difference between these events is that convective activity seems to be higher in the first three, as they showed lower temperatures for the top of the clouds at the sites and times corresponding to Figures 7a-d, meaning that the top of these clouds would have reached higher altitudes.

Additionally, the seven dates that produced gusts higher than 80 km/h in the greatest amount of stations were analyzed. These represented meteorological events that affected large areas of the country. More than 80% of them occurred associated with intense convective activity and drops in temperature, usually in form of lines, some wider than others, oriented from the northwest to the southeast, which generally moved to the northeast. In one case the line moved from west to the east, while in two of the cases the convective system stayed over Uruguay generating at least one tornado. The remaining case corresponded to a low pressure system (extra-tropical cyclone) which also presented very intense convective activity over Uruguay. This analysis also confirmed that the passage of severe convective storms affect great part of the country with higher wind gusts and more frequently than synoptic high wind events. One of the differences between both types of events is that synoptic high winds are usually sustained in a particular site during longer periods than high winds due to convective activity, as expected.

Other types of events which did not show significant changes in temperature or wind direction were usually driven by synoptic weather patterns, some of them corresponding to the intensification of extra-tropical cyclones in their trajectory over the country, and others, to the presence of high and low pressure systems in different particular combinations near or over Uruguay.

The temporal evolution across the country of two events driven by different meteorological mechanisms that affected great part of the country were analyzed. For each station, the maximum wind gust value interpolated at 45 m high that was reached during each event is presented in Figures 8 and 9, together with its time of occurrence, wind direction and temperature. The modulus of the wind direction vector represents the value of the wind gust, and its color, the value of the temperature in °C. The corresponding scale for the temperature is shown in the color bar to the right of each figure.

Figure 8 corresponds to a typical passage of an intense and organized cold front over Uruguay, whose trajectory was approximately from the southwest to the northeast. As this figure shows, it entered the country at its southwest the 4th of April of 2012 around 21:40 (local time) and left it the 5th of April around 4:50 at its northeast, affecting different areas of Uruguay along 7 hours. The maximum gust interpolated at 45 m height occurred at station Pintado at 23:20 with a value of 40 m/s, already indicated in Figure 7b.

Figure 9 corresponds to a typical passage of a strong extra-tropical cyclone over Uruguay, which took place the 19th of September of 2012. The time shown of the maximum gust at each station indicates that the trajectory of the center of this cyclone was from the northwest to the southeast, and that the highest gusts were organized in curves as expected for a cyclone, where the winds are relatively parallel to the isobars and rotate clockwise in the Southern Hemisphere. It can also be noticed that the passage over the country took around 9 hours, as its effect began to be felt around 9:30 in the northwest and finished near 19:00 in the southeast of the country. The trajectory and intensification of winds during its passage over Uruguay shown in this case correspond to the typical behavior of an extra-tropical cyclone in this region, as they usually move to the southeast and intensify along its trajectory. Winds also tend to be stronger along the coast and to the southeast of the country. In this case the maximum gust interpolated at 45 m height occurred at station Artillero at 12:40 with a value of 35.6 m/s, and its evolution with time is indicated in Figure 10. This figure shows the wind gust, 10 min-mean wind speed, temperature and wind direction registered 5 hours before and after this maximum gust. It can be seen that changes in wind speed, temperature and wind direction are much more gradual than those presented in Figures 7a-d.

In these two cases, as well as in others, an animation of the passage of the storms over the country was performed and analyzed.

During the passage of the cold front illustrated in Figure 8, the maximum gust at a particular station occurred when the cold front was passing over it, as the modulus and color of the vectors changed simultaneously. During the animation, as well as looking at the time of the maximum gusts shown in Figure 8 for each station, it was clearly seen that the cold front moved in the form of a line oriented northwest-southeast, with its trajectory perpendicular to this orientation. After the passage of the cold front, wind speeds decreased fast, generating peaks in wind speeds more or less pronounced, and the temperature stayed low. Looking at this figure, it can also be concluded that the maximum gusts came mostly from the southwest quadrant, and took values from 20 to 40 m/s, with the highest values in the center of the country. In some other cases of organized convection, winds stayed high during longer periods, with wind gusts evolution with time as those shown by Figures 7c-d.

During the passage of the extra-tropical cyclone illustrated in Figure 9, wind speed stayed high during several hours at each station, and the trajectory of the center of the extra-tropical cyclone could easily be depicted. The maximum gusts also came from the southwest quadrant, with values between 25 to 36 m/s; the highest registered along the coast and to the southeast of the country.

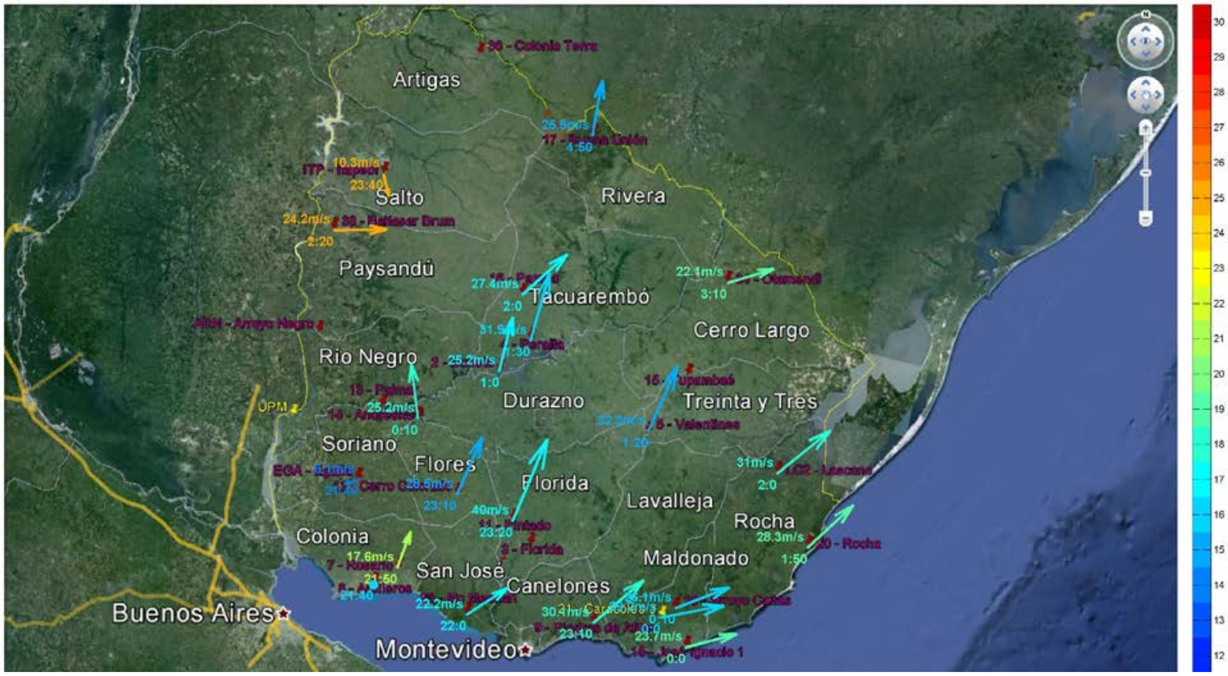


Figure 8. Maximum gusts recorded in Uruguay during the passage of a cold front.

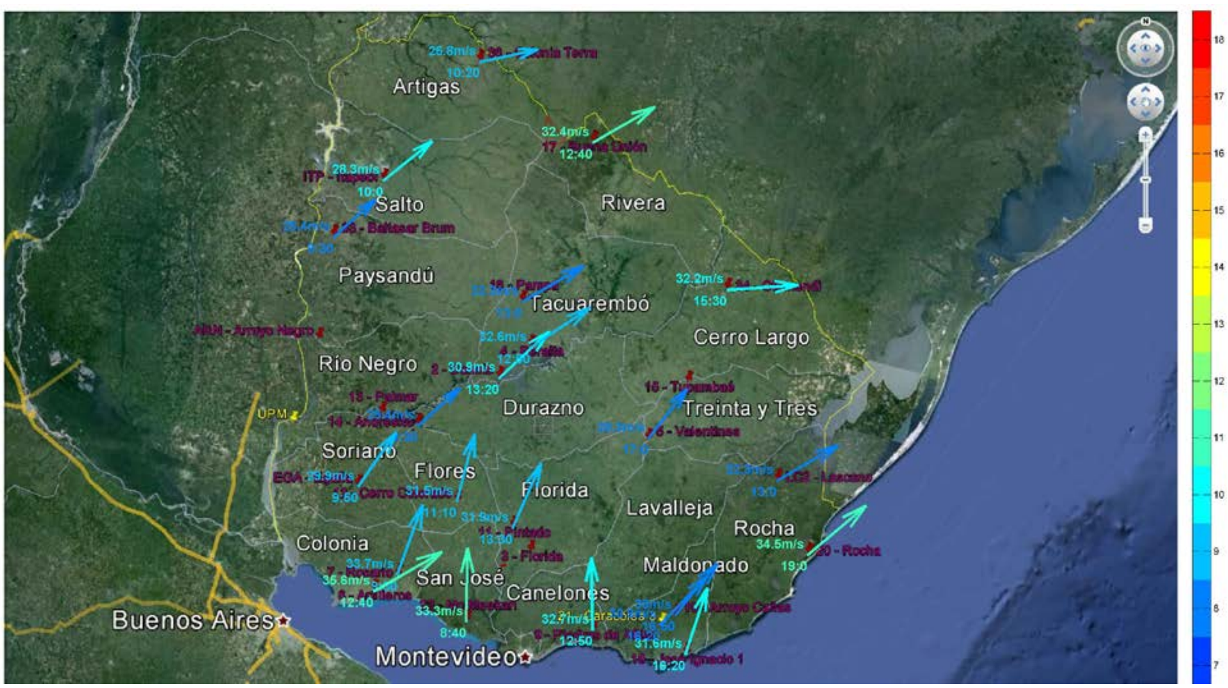


Figure 9. Maximum gusts recorded in Uruguay during the passage of a strong extra-tropical cyclone.

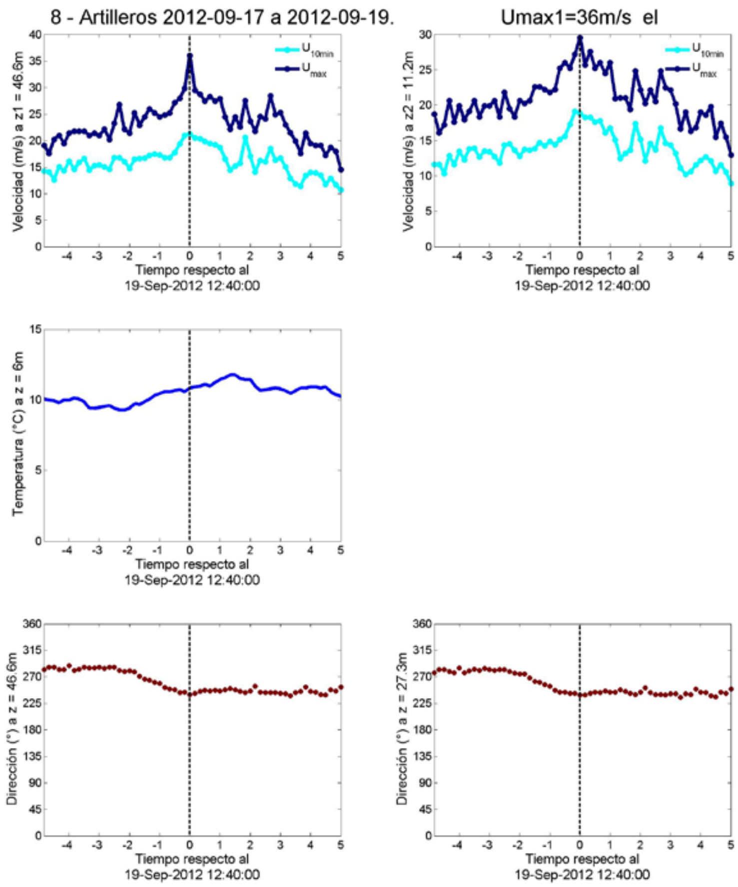


Figure 10. Maximum gust recorded during the passage of the extra-tropical cyclone, September 19th, 2012.

5.2 *Characteristics of the events with the highest 10 min-mean wind speeds*

In order to analyze the events that produce the highest 10 min-mean wind speeds in Uruguay, wind data was again homogenized interpolating at 45 m height and only complete years were studied.

In this case the threshold wind speed was set at 60 km/h (16.7 m/s), and all the events that presented 10 min-mean wind speed higher than that value at 45 m height were analyzed.

It was again observed that among the events that produced the highest 10 min-mean wind speeds, those associated with downbursts due to intense convective activity were the most frequent, a fact that the author did not expect before obtaining graphs as Figures 7c-d.

More events with characteristics associated with the occurrence of downbursts were observed in the northwest than in the southeast of the country. In the latter area, events with higher spatial scale were found.

6 CONCLUSIONS

The analysis performed on wind data from networks of automatic weather stations showed that the highest wind gusts recorded in each studied station corresponded to severe convective activity. The highest gusts were measured in a region of Uruguay located in its southern center, while damaging gusts were more frequent in the center of the country.

Even with the short length of the records analyzed (not greater than 4 years), events producing wind gusts of 40 m/s were measured twice in two sites of the country. This wind speed value was also measured at 10 m height at two different sites, and it is in accordance with wind speeds already measured in Montevideo in the beginning of last century. Taking into account historical data, wind gusts of 55 m/s could also be expected.

In general, when intense convective activity is present and the wind speed abruptly increases, fast drops in temperature and wind direction changes are measured. As mentioned in 2.1, these characteristics can be associated with the passage of gust fronts or cold fronts across the country, which produce strong downbursts associated to the presence of high cumulus nimbus clouds. A gust front can be generated by a severe isolated, multicell or supercell storm, or by a MCS, all of them capable of producing strong downbursts associated with the presence of cumulus nimbus clouds. Looking at satellite images and running animations of time evolution of wind gusts, wind direction and temperature during some of these events, it could be seen that sometimes intense convective activity was covering all or most of Uruguay, which would correspond to the presence of large MCSs over the country.

When synoptic patterns other than fronts are responsible for high wind gusts, no significant changes in wind direction or temperature are registered, and the change in wind speed is more gradual.

It could also be concluded that events corresponding to the passage of severe convective storms affect great part of the country with higher wind gusts speeds and more frequently than synoptic high wind events. Although different, both types of events produce their maximum wind gusts from the southwest quadrant.

Although synoptic high winds are usually sustained in a particular site during longer periods than high winds due to convective activity, severe convective activity also has an important effect on the 10 min-mean wind speeds. This may be the reason of the kink of the Gumbel paper shown in Figure 5: the data sets that contained the annual 35 highest 10 min-mean wind speeds from Carrasco airport may be mixing wind speeds caused by strong synoptic mechanisms as well as by severe convective activity. In that figure, the lines with the smaller slope could correspond to the probability of occurrence of high winds associated with severe convective activity, while the lines with higher slope could correspond to that associated with high winds due to synoptic patterns. Similar conclusions were obtained performing an extreme value analysis of gust factors [9]. In spite of this mixing, the Gumbel distribution would adequately represent the extreme statistics of 10min-mean wind speeds, as detailed in [8].

With intense convective activity, gust factors between 2 to 2.5 and greater, defined over 10 min periods, were obtained, values similar to those presented in [9], and very different from those corresponding to ABL flows [10]. It was then confirmed that this should be taken into account when trying to compare wind extreme maps based on 10 min-mean wind speed measurements with those based on wind gusts, or when extreme wind gusts are estimated from extreme 10min-mean wind speeds, especially in mid-latitudes regions.

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