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# Characteristics of Zonda wind in South American Andes

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**Abstract.** This paper discusses some features and conditions that characterize the Zonda wind, focusing particularly on the implications for wind engineering applications. This kind of wind, typical of mountainous regions, is far from being adequately characterized for computational simulations and proper modeling in experimental facilities such as boundary layer wind tunnels. The objective of this article is to report the research works that are being developed on this kind of wind, describing the main obtained results, and also to establish some general guidelines for the proper analysis of the Zonda in the wind engineering context. A classification for the Zonda wind is indicated and different cases of structural and environmental effects are described. Available meteorological data is analyzed from the wind engineering point of view to obtain the Zonda wind gust factors, as well as basic wind speeds relevant for structural design. Some considerations and possible directions for the Zonda wind-tunnel and computational modeling are provided. Gust factor values larger than those used for open terrain were obtained, nevertheless, the basic wind speed values obtained are similar to values presented by the Argentinian Wind Code for three-second gust, principally at Mendoza airport.

**Keywords:** Zonda wind characteristics; katabatic wind; topographic effects; Zonda wind effects on structures and environment; field measurements

## 1. Introduction

The Argentine territory is affected by different meteorological factors that yield various types of winds. Some of these characteristic winds originate outside the territory itself, while others are local winds.

In general, three global types of winds affect the Argentinean climate: a) the warm and humid winds advancing from the Atlantic anticyclone affecting the north of Patagonia, b) the west winds from the Pacific anticyclone, and c) the cold winds from the Antarctic anticyclone.

On the other hand, the local winds include: a) the Zonda affecting mainly the provinces of San

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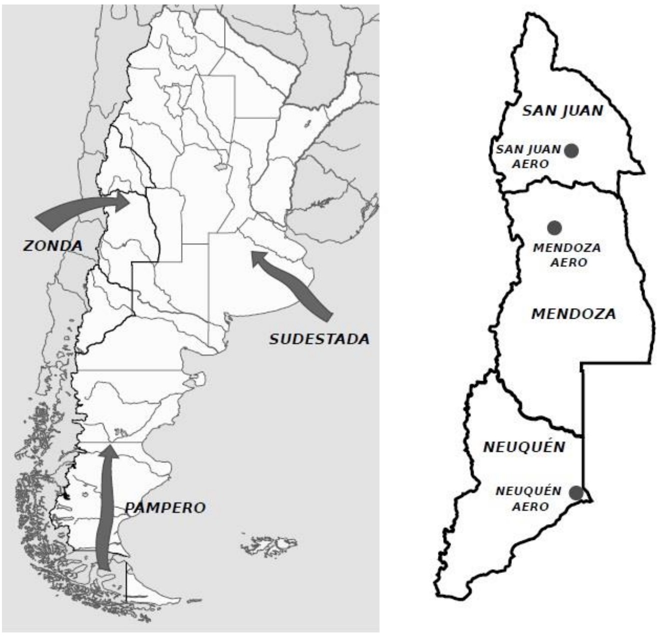
Juan, Mendoza and Neuquén, b) the Sudestada wind, which is very humid and originate in the Pampa region, and c) the Pampero wind, which is cold and dry, and blows from the south-west (Fig. 1).

Zonda wind is a strong, warm, very dry wind in the subtropical latitudes of South America. The high intensity of this wind is associated with adiabatic compression when descending the eastern slopes of the Andes Cordillera in western central Argentina. Characteristics and effects of these downslope winds depend on topography, atmospheric interactions and meteorological conditions. Downslope winds similar to Zonda exist in the European Alps (Foehn wind), Canada and the United States (Chinook wind), South Africa (Berg wind), New Zealand (Canterbury-northwestern), and elsewhere.

Zonda events are most frequently observed near the cities of Mendoza and San Juan, in western Argentina (Fig. 1). Mendoza city is located at 32.8°S, 68.8°W, at 704 m above sea level, and San Juan city is located at 31.5°S, 68.5°W, at 598 m above sea level. The high-intensity Zonda wind events commonly cause considerable structural damage, undesirable effects on agriculture, low visibility, car accidents and air quality problems.

The Zonda research is currently focused on determining (i) wind characteristics, (ii) its origins, and (iii) the development of forecasting methods. Numerical prediction models have been used for analysis and prediction of Zonda events. In particular, regional models like Eta-CPTEC (Centre for Weather Forecasts and Climate Studies, Brazil), the Brazilian Regional Atmospheric Modelling System (BRAMS) and the Weather Research and Forecasting (WRF) were used in studies developed mainly by Argentinean and Brazilian research groups (Ulke *et al.* 2006, Norte *et al.* 2010).



(a) (b)

Fig. 1 (a) Local winds in Argentina and (b) The region affected by the Zonda wind showing local airports (AERO)

However, numerical models often poorly simulate the potentially devastating flows on the leeward side of mountains, as mentioned by Richner and Hächler (2013) on the subject of the Foehn wind. Hence, further efforts should be made to improve numerical models due to the social impact of this kind of wind. Several articles were devoted to the computational simulation of wind flow over complex terrains with application to wind engineering (Juretić and Kozmar 2014, Abdi and Bitsuamlaka 2016, among others) which may be used as a starting point for a computational assessment of the Zonda wind characteristics. In addition, further high-resolution measurements (He *et al*. 2014, Li and Hu 2015, Lepri *et al.* 2014) are mandatory in order to obtain micrometeorological data, necessary to complement and validate small-scale experimental models.

The objective of this study is to present the Zonda Wind with respect to its origin, characteristics and applications to Wind Engineering, with a particular focus on Argentina. This is a part of the Brazil and Argentina Joint Program in Wind Engineering (Loredo-Souza *et al.* 2017), which aims to generate the necessary knowledge regarding the flow behavior over complex topographies. The main goal is to further develop Wind Engineering approaches for analyzing local wind effects on cities with similar geo-topographical characteristics.

## 2. Conceptual model and dynamics of the Zonda wind

In general, when a layer of cold air is placed under a warmer layer during the winter, with a synoptic situation causing strong winds towards a mountain range, the flow on the ridge-top depends on the depth of the cold air and on the temperature difference between the two layers, e.g., Stull (2016). An air mass may descend rapidly along the leeward slope when the meteorological conditions are adequate, thus yielding a downslope windstorm. These downslope winds can cause damage to structures, adversely affect air quality and traffic.

The conceptual model of the Zonda wind is quite similar to the standard Foehn theory (Richner and Hächler 2013). Humid air is propelled towards the Andes mountain range, from Chile, by the actions of a synoptic scale pressure field. The air cools adiabatically until it reaches the crest of the mountain, then clouds are formed and rain and snow precipitation occurs. The air descends and is heated adiabatically in the leeward side of the Andes mountain, now in Argentina. As a consequence, the air becomes very dry and reaches higher temperatures than the original temperatures in the windward zone. The schematic view of the formation of the Zonda wind is shown in Fig. 2. At some lower levels, Zonda blows in an intermittent lapse and upon reaching the plains it blows continuously.

As an analogy, the Foehn thermodynamics (Stull 2016) is presented in Fig. 3 to explain the Zonda origin: (1) air parcel before it flows over a mountain; (2) upslope flow along the windward slope, reaching the lifting condensation level; (3) further moist adiabatic upslope flow inside the orographic cloud, precipitation occurs; (4) the ambient pressure reaches 60 kPa, temperature is around -8℃, downslope flow along the leeward slope, the trailing edge of the cloud forms a Foehn wall; (5) after releasing any residual precipitation, further descent is dry adiabatic; (6) in the leeward zone, the flow reaches its original altitude in the windward zone, temperature is around 35℃. The variables indicated in the graph of wind thermodynamics are ambient pressure $P$, temperature $T$ and relative humidity $r$. The steps 1 to 6 may be also associated to Fig. 1.

Different theories for the leeward side descending of downslope winds were compiled by Steinacker (2006) and are described by Richner and Hächler (2013). The “waterfall” and the “hydraulic jump” theories could be the typical schematic representations for the dynamics of the

Zonda wind (Norte 2015). Physical mechanisms for different Zonda events are exhaustively analyzed by Seluchi *et al.* (2003b).

Two major wind phenomena near the Andes in South America are the low level jet (LLJ) and the downslope Zonda wind that occurs in the lee of the Andes. Both winds are frequently observed along the eastern slopes of these mountains, in particular between 35° S and 15° S. The impact of the sloping discretization of these phenomena was evaluated using the Eta-CPTEC model, e.g., Mesinger *et al*. (2006).

## 3. Classification and effects

In this section, a commonly used classification of Zonda events is presented together with a description of its main characteristics. Some particular Zonda events are described based on the meteorological data. These cases were analyzed from the meteorological point of view and they represent the main available literature on the Zonda downslope windstorm.

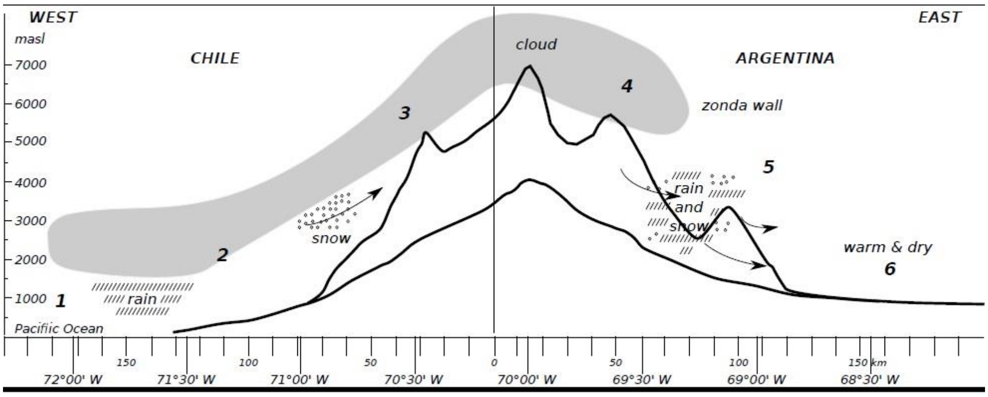


Fig. 2 Conceptual model of Zonda wind at Mendoza Airport (ICAO: SAME) location, adapted from Norte (2015). Wind blowing from left to right and vertical axis indicates meters above sea level (masl)

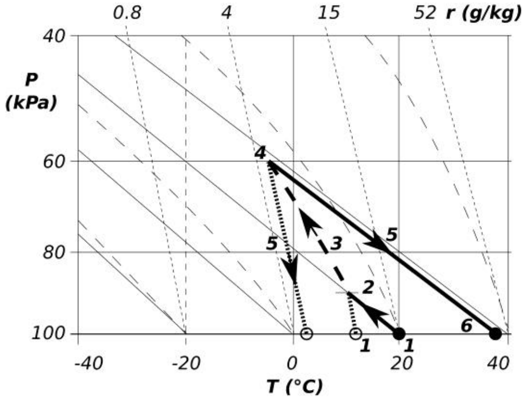


Fig. 3 Foehn thermodynamics, according to Stull (2016)

### *3.1 Classification*

Norte (1988) and Seluchi *et al*. (2003b) have defined two types of Zonda episodes: ‘high’ and ‘surface’ Zonda. The ‘high’ Zonda occurs when wind is detected at the eastern slopes of the mountains but not at the plain stations, while the ‘surface’ Zonda is detected above the plains east of the Andes near the cities of Mendoza and San Juan.

With respect to the wind intensity, the Zonda categories (FNZ) are based on the maximum wind gust sped registered in any respective event. According to Norte (2015), the Zonda events are classified as: (a) moderate event (FNZ1) when the maximum wind gust speed is less than or equal to 18 m/s, (b) severe event (FNZ2) when the maximum wind gust speed is between 18 m/s and 25 m/s, (c) very severe event (FNZ3) when the maximum wind gust speed is between 25 m/s and 33 m/s, (d) extremely severe or catastrophic event (FNZ4) when the maximum wind gust speed is greater than 33 m/s.

A typical moderate category FNZ1 event is exhaustively described by Norte (1988). The episode reached the capital cities of San Juan and Mendoza provinces in Argentina in the afternoon of August 23rd, 1983. The temperature increased to 31˚C at the San Juan Airport (ICAO: SANU) and 28.3˚C at SAME, the relative humidity decreased to 10% (SANU) and 21% (SAME), the wind gust speed reached a maximum of 17 m/s (SANU) and 14 m/s (SAME), with 10 hours and 4 hours of duration, respectively.

Three different Zonda wind cases registered in August 1999 were analyzed by Seluchi *et al.* (2003a). The cases represent three different categories of the Zonda phenomenon. The event on August 5th, 1999, caused structural damage in urban areas of the city of Mendoza, and was classified as a severe episode (FNZ2). Another event occurred on August 10th, 1999, and is an example of a typical episode of a relatively intense ‘high’ Zonda, where surface synoptic observations reveal strong surface winds of about 15 m/s over the Malargüe station. The last of the three cases was observed on August 30th, 1999, is considered a classic example of the moderate ‘surface’ Zonda.

The Zonda event that occurred on July 11th, 2006, affecting zones of San Juan and Mendoza provinces, was analyzed by Ulke *et al.* (2006) using the regional model BRAMS (Brazilian Regional Atmospheric Modeling System). It was characterized as a very severe (FNZ3) Zonda event, with maximum gust speeds of 31 m/s at SAME and 33 m/s in SANU. The temperature increased to 28.2℃ and 33℃, at SAME and SANU, respectively.

More recent reports and analysis of Zonda events are reported in Norte *et al.* (2010) and Puliafito *et al*. (2015).

### *3.2 Structural effects*

Different types of damage are produced by the Zonda wind according to its FNZ intensity category. The more common effects are roof failures (of all kinds, including canopies), and damage to transmission lines. As an example, Fig. 4 shows some effects of the Zonda event that occurred on August 5th, 2015, affecting the Tucuman, Salta and La Rioja, provinces in Argentina, where the wind gust speeds exceeded 25 m/s (Infobae 2015). Wind damage also included fallen trees and electricity cables, interrupted electric supply and telephone lines, cars damaged by trees, etc., as reported in Fig. 5.

Fig. 4 Roofs damaged by the Zonda wind event on August 5th, 2015

Fig. 5 Vehicle damaged by fallen trees (Diario Los Andes, 2011) and fallen electricity cables (Explicito, 2016) due to the Zonda windstorm

### *3.3 Environmental effects*

The strong and dry wind can affect agriculture, especially when the Zonda blows at the end of the winter season, when wildfires can possibly occur, Fig. 6.

The air quality depends on the type of event, i.e., whether it is a ‘high’ or ‘surface’ Zonda. The thermal inversion can maintain the haze and smog when ‘high’ Zonda occurs. In case of the ‘surface’ Zonda wind, the air quality depends on the season. Particularly in August (dry winter), dust and tree leaves affect the horizontal visibility, Fig. 7. The eolic erosion and dust dispersion during Zonda is simulated by Allende *et al.* (2012) along with the particulate matter fate for the Mendoza urban center.

Fig. 6 Zonda-induced wildfire in north Mendoza, Argentina, on August 16th, 2016 (Diario Los Andes, 2016)

Fig. 7 Zonda-induced dust dispersion (El Cívico, 2013) and diminished visibility in Medano de Oro, San Juan, July 2nd, 2014 (Diario La Ventana, 2014)

## 4. Analysis of meteorological data

As the main objective of the current Zonda research is on the climatology and macro-meteorology, the applications to Wind Engineering are quite rare. However, climatological wind characteristics in Neuquen, North Patagonia, including Zonda wind events, were described by Lassig *et al.* (1999) and these studies could be used for later wind tunnel studies. Another exception is the analysis of the atmospheric structure by Norte and Simonelli (2016), which is based on measured data from SAME from 1974 to 1983. These results reported in Section 4.1 indicate the alterations that the Zonda causes on the vertical wind-speed profiles. In Sections 4.1 to 4.5, a first analysis of the Zonda wind characteristics is outlined from the Wind Engineering point of view. This analysis focuses on the Zonda wind gust factors. The meteorological data used in this evaluation is obtained from SAME and SANU from 1996 to 2016. The analysis addresses the underlying meteorological conditions, and the time-series of characteristic parameters corresponding to a specific Zonda event.

### *4.1 Influence of the Zonda on atmospheric structure*

The vertical wind-speed profiles leeward of the Andes in western-central Argentina were studied by Norte and Simonelli (2016). The vertical profiles reported in Fig. 8 were created based on the data measurements performed using daily rawinsonde from SAME. The results were acquired for the months of May, June, July and August from 1974 to 1983. The Zonda wind characteristics and respective atmospheric conditions are analyzed along with the atmospheric pressure, temperature, relative humidity and wind velocity components. This type of analysis allows a comparison of values for the zonal wind component $u$ and meridional wind component $v$ with respect to their climatological values. A comparison of mean climatological wind speed $V$ with mean wind speed corresponding to Zonda confirms that the wind increases at the Andean summits during the Zonda events, Fig. 8.

### *4.2 Analysis of Zonda wind speed time-series*

Meteorological data recorded at the airports of SAME and SANU were analyzed to identify characteristics of the Zonda wind and determine its statistical extreme wind speed model. Fig. 9

shows the location of the studied observation stations relative to the city centers and foothills of the Andes. SAME is located adjacent to urban Mendoza, with the Andes foothills commencing approximately 6 km to the West. SANU is located approximately 9 km East of the urban district of San Juan and in-between the two topographical features: the Andes 20 km to the West and Mogote Corralitos 13 km to the East.

Time-series of wind direction (*DIR*), 10-minute mean wind speed (*V*), 3-second gust (*G*), weather conditions, temperature, dew-point temperature and atmospheric pressure were converted from METAR/SPECI and SYNOP weather reports obtained from REDEMET, Weather Underground and NCEI (formerly NCDC) Database DS3505. Data obtained without the accompanying weather reports were not included in the present study, and as such, the starting date of the time-series is July 1st, 1996.

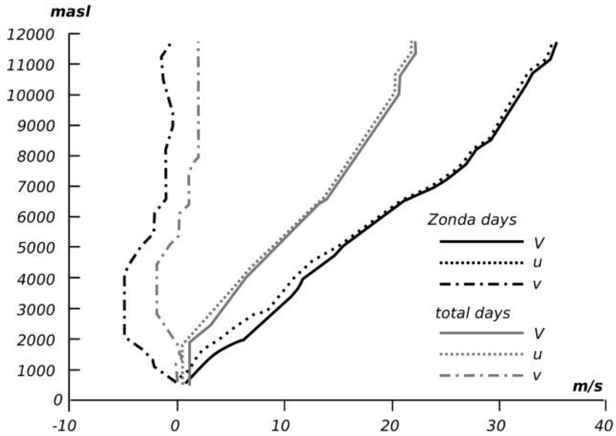


Fig. 8 Mean vertical wind speed profile measured at SAME at 12 UTC, May to August from 1974 to 1983, adapted from Norte and Simonelli (2016)

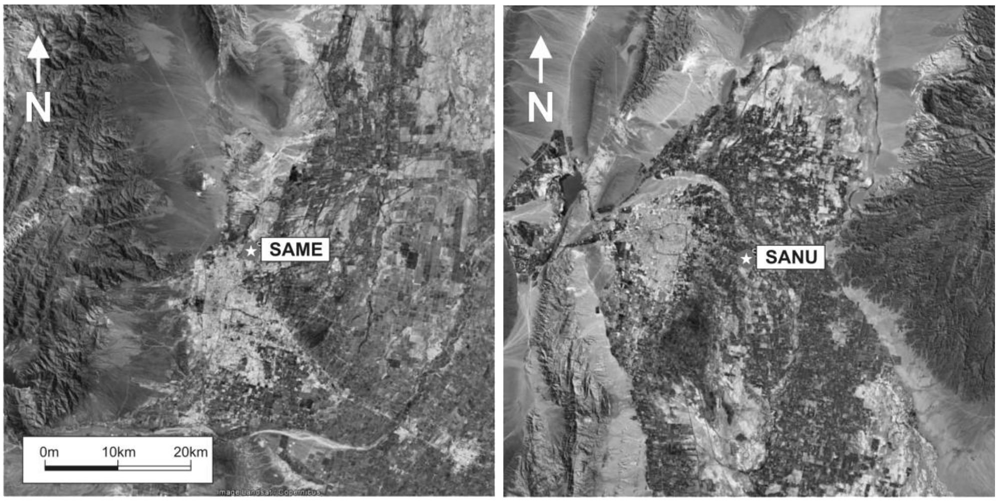


Fig. 9 Location of surface weather stations located at El Plumerillo/Gobernador Francisco Gabrielli airport (SAME – Mendoza), and Domingo Faustino Sarmiento airport (SANU – San Juan)

Long periods of time only featuring the 3-hourly SYNOP reports and no METAR/SPECI reports were not included in the study due to the low time-interval resolution. As reported in Figure 10, which presents time-series of the 10-minute wind speed and 3-second gusts for SAME and SANU, this caused the removal of several years of data from the SANU time-series. The wind speed time-series were submitted to an automatic process which filters out abrupt peaks in the wind speed time-history which are likely not caused by thunderstorms.

Strong wind events were identified in the time-series and grouped by a combination of the wind sector and relative humidity ($r$). For this study, a strong wind observation is defined as $V \geq 10$ m/s or $G \geq 15$ m/s. Wind direction observations were made at 10° increments with North = 360°, East = 90°, South = 180° and West = 270°. The wind directions are grouped by 12 sectors of 30°, and relative humidity by the following 4 groups: $r < 10\%$, $10\% \leq r < 20\%$, $20\% \leq r < 30\%$ and $r \geq 30\%$. Observations with the thunderstorm present weather identifier were removed from the series. The number of strong wind observations per wind sector and $r$ group are reported in Fig. 11 for each of the two stations. Dry winds associated with the Zonda dominate the sector between South-West and North for both SAME and SANU, while the Pampero and Sudestada winds from the South to South-East are also identified and observed to have higher moisture content than the Zonda.

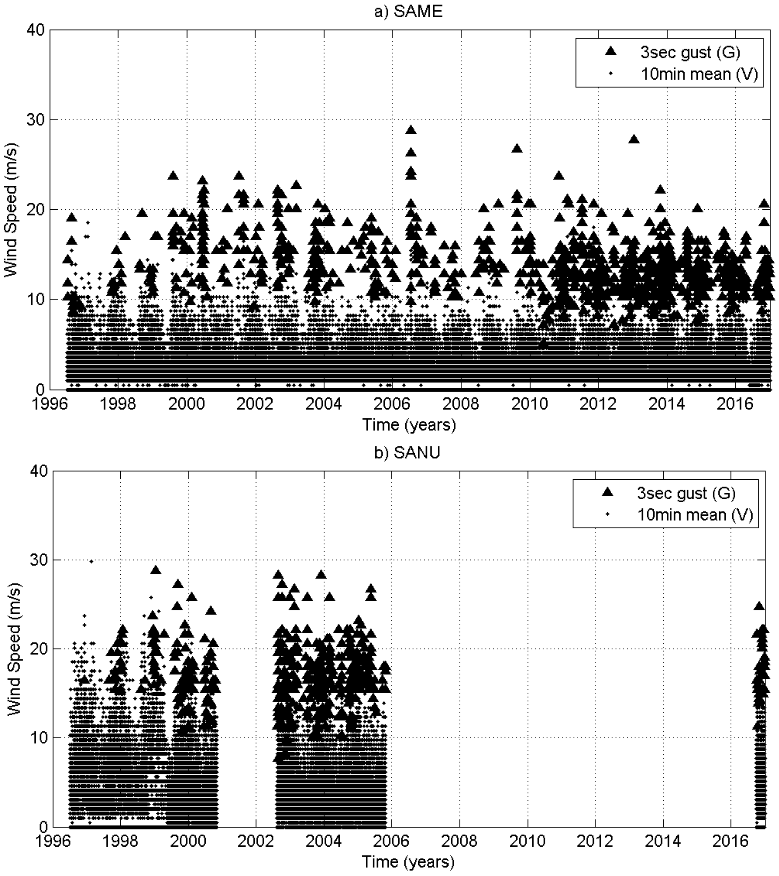


Fig. 10 Time-series of observed 10-minute wind speed and 3-second gust at (a) SAME and (b) SANU from July 1st, 1996 to December 31st, 2016

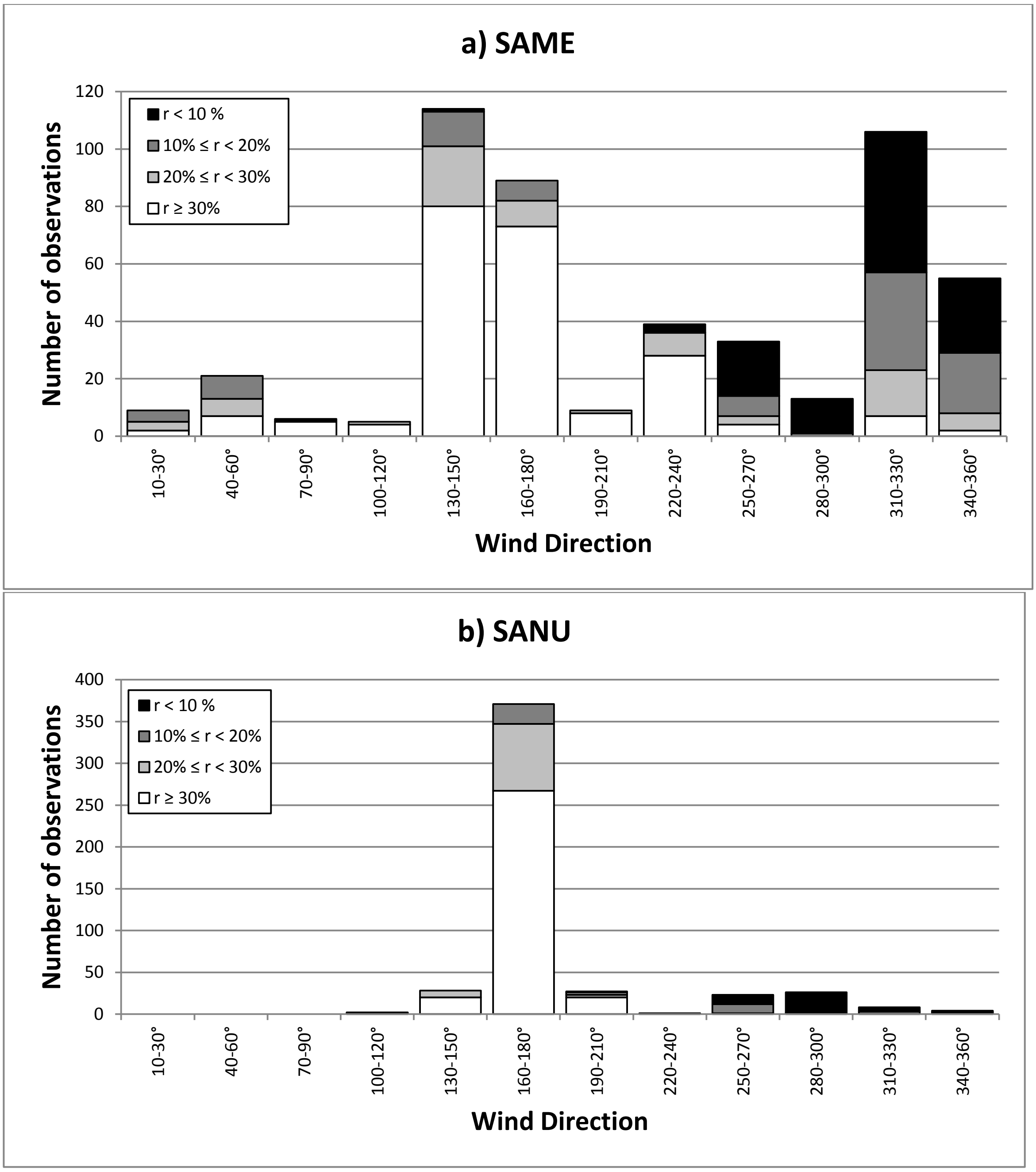


Fig. 11 Number of strong wind observations per wind direction and divided by relative humidity for (a) SAME and (b) SANU

### 4.3 Analysis of Zonda wind-gust factors

Observed gust wind speeds were plotted against 10-minute mean wind speeds for each of the 12 wind sectors. A linear regression approach is used to determine the gust factor ($F_g$), where $G = F_g.V$. The derived gust factors are shown in Table 1, and an example of the approach performed for the 310°-330° sector for both SAME and SANU is shown in Fig. 12.

With the exception of the southern winds for SANU, all gust factors are higher than the commonly used 1.45 for open terrain (1.45 as defined in NBR 6123, 1.46 as defined in ISO 4354), which is quite a significant finding. The largest gust factors are found in the West to North-West sectors for both SAME and SANU. The gust factors for SAME are overall higher than those for SANU, most likely due to the close proximity of this observation station to the urban area of Mendoza and the Andes.

### 4.4 Zonda wind-climate model

In order to determine the Zonda wind-climate model, a criterion of $RH < 20\%$ and $220 \leq DIR \leq 360$ is adopted to identify the Zonda for SAME and SANU. The gust factors from Table 1 are applied to those 10-minute mean wind speed observations in which a gust speed was not observed, creating an equivalent gust wind speed ($G_E$). These values are then combined with the observed gusts ($G$) to create time-series $\hat{G}$. The yearly maximums of $\hat{G}$, along with the respective wind direction, relative humidity and temperature are shown in Table 2.

The Zonda annual maximums were distributed according to the Type-1 general extreme value distribution of Fig.13. To calculate the gust for a given period of return ($R$), in years, the probability of exceedance is defined as $P_R = 1 - 1/R$ and reduced variate $y_R = ln(R) - ln(-R.ln(P_R))$. For $R$ = 50 years, this gives $P_R$ =0.98 and $y_R$ = 3.90. Substituting $y_R$ in the place of $y_m$ in the equations of Fig. 12 yields $G_{50,SAME}$ = 38.9 m/s and $G_{50,SANU}$ = 45.4 m/s for Zonda winds. These values are in the same order of magnitude as the basic 3-second gust wind speeds presented by the Argentinian Wind Code, around 40 m/s (CIRSOC-102, 2005).

Table 1 Gust factors ($F_g$) per wind sector

| Sector | SAME | SANU |
|---|---|---|
| 10-30° | 1.75 | N/A |
| 40-60° | 1.87 | N/A |
| 70-90° | 1.72 | N/A |
| 100-120° | 1.67 | N/A |
| 130-150° | 1.67 | 1.36 |
| 160-180° | 1.70 | 1.39 |
| 190-210° | 1.86 | 1.55 |
| 220-240° | 1.85 | 1.67 |
| 240-270° | 2.08 | 1.66 |
| 270-300° | 2.14 | 1.66 |
| 310-330° | 1.90 | 1.88 |
| 340-360° | 1.67 | 1.74 |

### 4.5 Characteristic meteorological parameters during Zonda events

For the purpose of understanding the meteorological conditions caused by the Zonda, time-series of several parameters recorded during the FNZ3 event observed at SAME on August 14th, 2009, are shown in Fig. 14. Wind direction shifted to 320° at approximately 16:00 at which time the first strong gusts were observed. From early morning until that moment, the temperature steadily increased, while relative humidity and atmospheric pressure steadily decreased. The peak gust speed of 26.8 m/s observed at 17:00 coincided with the minimum values of relative humidity and atmospheric pressure, and maximum temperature. Strong gusts at 320° continued for approximately 6 hours, while relative humidity remained low and temperatures high. Although the gusts weakened by midnight, the heat remained. At 5:00 on the following day the temperature was 20 C° higher than it was at 5:00 the previous day.

Table 2 Annual maximum Zonda wind gusts

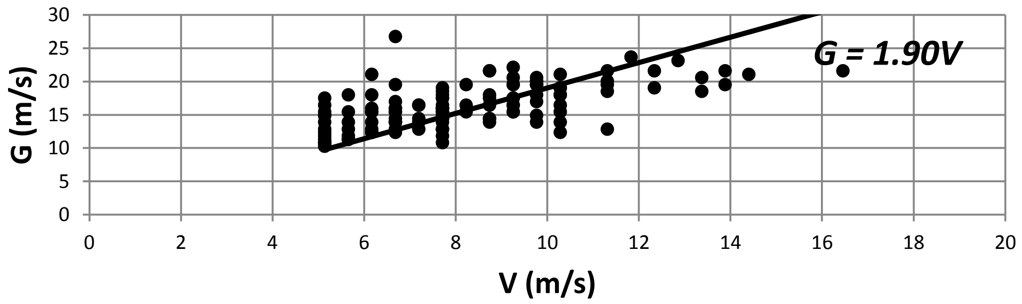
| YEAR | SAME | | | | | SANU | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\hat{G}$ (m/s) | G or $G_E$ | DIR (°) | RH (%) | T (C°) | $\hat{G}$ (m/s) | G or $G_E$ | DIR (°) | RH (%) | T (C°) |
| 1996 | 29.0 | $G_E$ | 320 | 0.3 | 22 | 25.1 | $G_E$ | 320 | 1.5 | 38 |
| 1997 | 24.2 | $G_E$ | 320 | 10.5 | 29 | 25.1 | $G_E$ | 320 | 3.6 | 28 |
| 1998 | 19.5 | G | 320 | 3.1 | 25 | 39.3 | $G_E$ | 270 | 9.8 | 29 |
| 1999 | 27.1 | $G_E$ | 320 | 13.1 | 19 | 27.3 | G | 320 | 2.0 | 32 |
| 2000 | 23.2 | G | 320 | 10.0 | 30 | 31.6 | $G_E$ | 290 | 8.2 | 24 |
| 2001 | 25.1 | $G_E$ | 360 | 14.8 | 22 | | | | | |
| 2002 | 22.4 | $G_E$ | 360 | 4.2 | 27 | 28.3 | G | 270 | 2.4 | 34 |
| 2003 | 30.7 | $G_E$ | 290 | 4.7 | 28 | 22.1 | G | 320 | 11.7 | 26 |
| 2004 | 18.5 | G | 290 | 4.8 | 29 | 21.6 | G | 290 | 2.0 | 34 |
| 2005 | 19.0 | G | 320 | 8.0 | 23 | 26.8 | G | 290 | 0.4 | 26 |
| 2006 | 26.2 | G | 360 | 14.8 | 27 | | | | | |
| 2007 | 14.5 | $G_E$ | 230 | 17.8 | 35 | | | | | |
| 2008 | 20.1 | G | 320 | 16.9 | 31 | | | | | |
| 2009 | 26.8 | G | 320 | 1.6 | 30 | | | | | |
| 2010 | 15.4 | G | 290 | 5.1 | 38 | | | | | |
| 2011 | 21.1 | G | 360 | 3.1 | 28 | | | | | |
| 2012 | 19.5 | G | 320 | 7.4 | 38 | | | | | |
| 2013 | 22.1 | G | 230 | 1.1 | 28 | | | | | |
| 2014 | 17.5 | G | 320 | 5.2 | 29 | | | | | |
| 2015 | 17.5 | G | 290 | 2.7 | 33 | | | | | |
| 2016 | 17.0 | G | 320 | 15.3 | 24 | | | | | |

## 5. Zonda wind-tunnel and computational modelling

In this section the feasibility of using experimental and computational techniques in Zonda wind studies is analyzed. The drawbacks associated with the lack of full-scale measurements are discussed. Also, a brief description of the main projects and research groups in Latin America tackling related type of problems through wind tunnel modelling is made. Finally, a comment on the use of computational simulations is performed.

The joint Brazil Argentina Research Program in Wind Engineering (Loredo-Souza *et al.* 2017) is basically performed in three institutions: (i) the Laboratório de Aerodinâmica das Construções of the Universidade Federal do Rio Grande do Sul (LAC-UFRGS), located in the city of Porto Alegre, RS, Brazil (Blessmann 1982), (ii) the Laboratorio de Aerodinámica of the Universidad Nacional del Nordeste (LA-UNNE), located in the city of Resistencia, Chaco, Argentina (Wittwer and Möller 2000) and (iii) Vento-S Consulting, in Porto Alegre, Brazil.

**a) SAME: 310º-330º**



**b) SANU: 310º-330º**

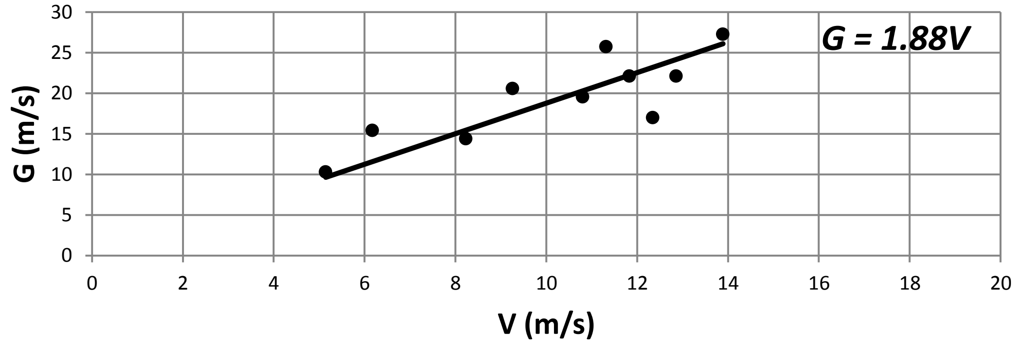


Fig. 12 Derivation of the 310° - 330° sector gust factors for (a) SAME and (b) SANU

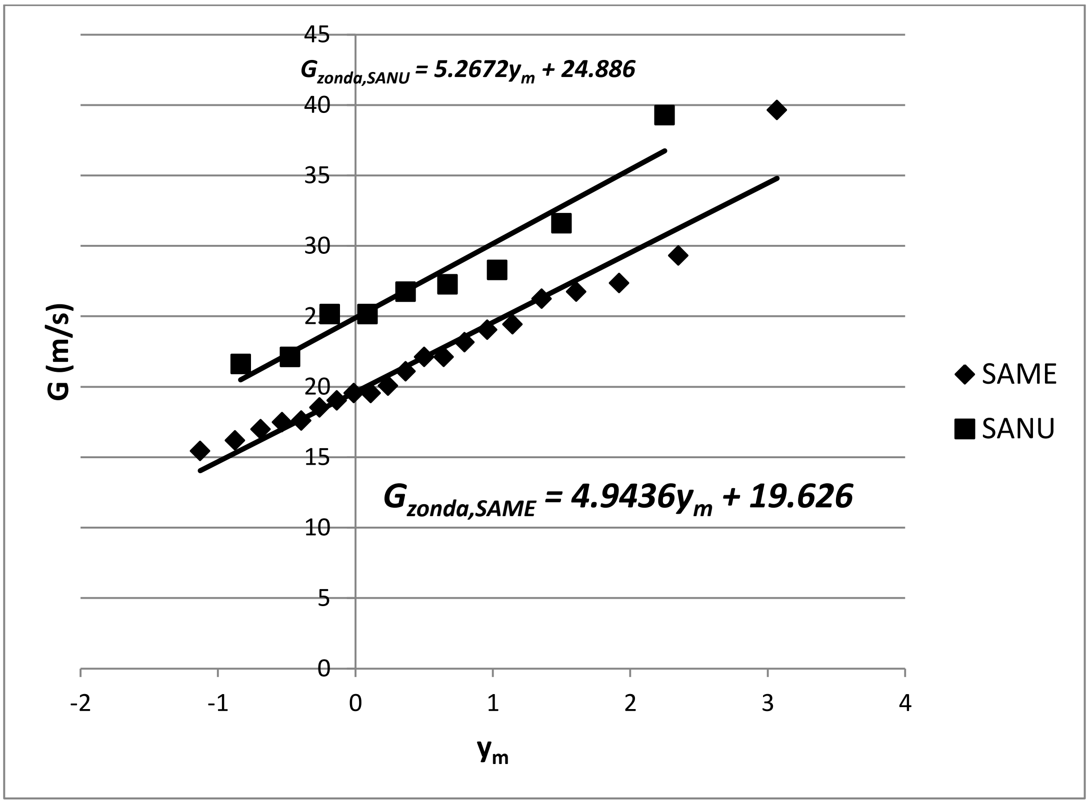
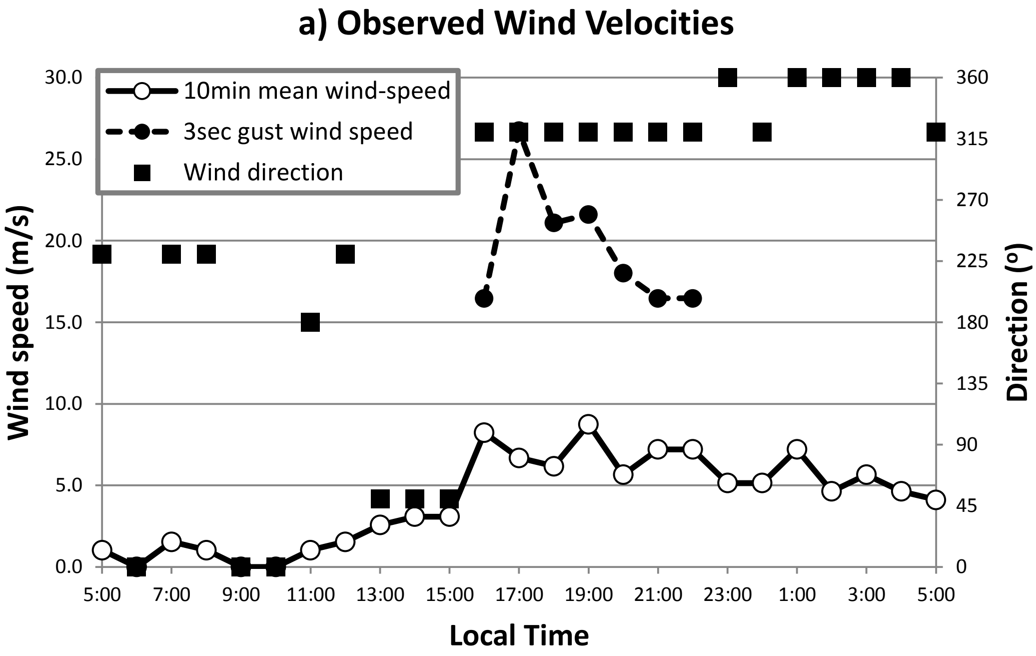


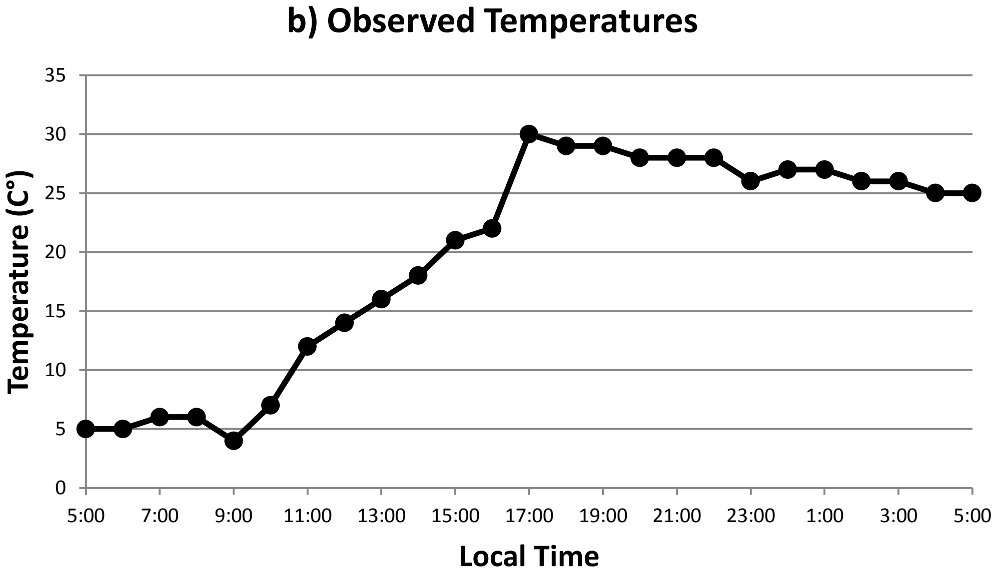
Fig. 13 Type-1 distribution of annual maximum Zonda winds for SAME and SANU

Each institute has its own boundary layer wind tunnel as shown in Fig. 15, as well as other smaller wind tunnels. The research performed in those laboratories is predominantly focused on extreme winds (non-synoptic), bridges, vicinity effects, transmission lines, wind energy and complex topography. Environmental wind engineering is addressed as well, mainly on particle dispersion and wind-driven rain. Results related to complex topography may be found in Loredo-Souza *et al.* (2012), Mattuella *et al*. (2016) and Petry *et al*. (2012). Fig. 16 shows complex terrains topographical models studied in the respective wind tunnels. They are included for illustrative purposes and do not represent the terrain for the modeling of Zonda.

Physical modeling of boundary-layer-type winds is commonly performed using vortex generators (eliptic or spire-type) and roughness surface elements placed in long-test-section, to generate a faster growth of the atmospheric boundary layer model. These accessories are used in the full-depth simulation and part-depth simulation methods, e.g., Wittwer and Möller (2000). Jets and grids are also applied in some cases as well, e.g., Blessmann (1982). An overview of these methods is provided in Cermak (1995).

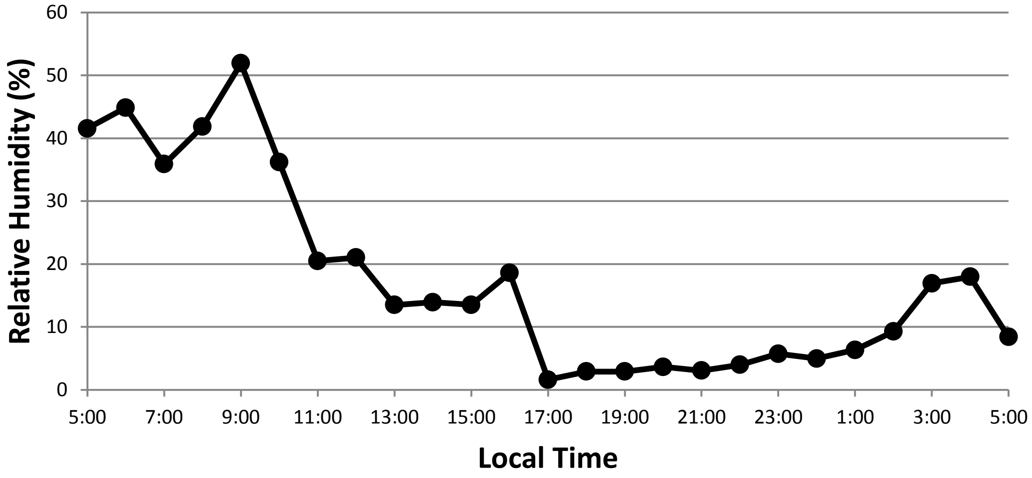
Generally, neutral atmospheric boundary layer flows are modeled in meteorological wind tunnels. Modeling of stratified boundary layer is less used in wind tunnel tests, however non-conventional wind tunnels have been developed to model stable and unstable atmospheric flows (Hertig 1984, Schatzmann *et al*. 1995).


a) Observed Wind Velocities
10min mean wind-speed
3sec gust wind speed
Wind direction
Wind speed (m/s)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Direction (º)
360
315
270
225
180
135
90
45
0
5:00
7:00
9:00
11:00
13:00
15:00
17:00
19:00
21:00
23:00
1:00
3:00
5:00
Local Time


b) Observed Temperatures
Temperature (C°)
35
30
25
20
15
10
5
0
5:00
7:00
9:00
11:00
13:00
15:00
17:00
19:00
21:00
23:00
1:00
3:00
5:00
Local Time

Continued-

c) Calculated Relative Humidity



d) Observed Atmospheric Pressure (hPa)

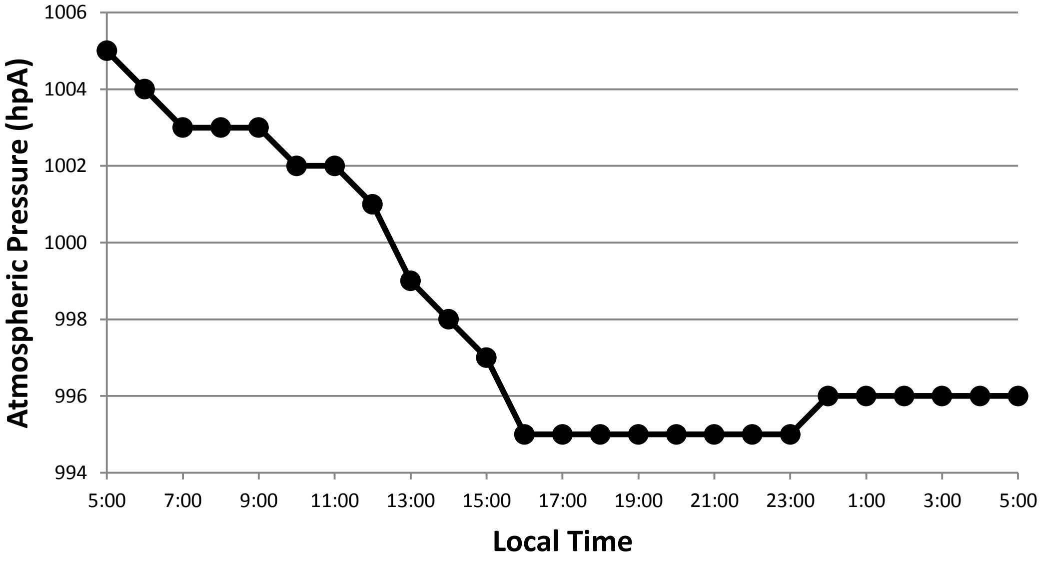


Fig. 14 Time-series of meteorological data of (a) wind (b) temperature (c) relative humidity and (d) atmospheric pressure observed during a FNZ3 event at SAME on August 14th and 15th, 2009

(a) (b)

Fig. 15 Prof. Joaquim Blessmann Wind Tunnel – UFRGS (a) and Prof. Jacek Gorecki Wind Tunnel – UNNE (b)

(a) (b)

Fig. 16 Complex topography models inside the wind tunnels in Brazil (a) and Argentina (b)

Wind-tunnel modelling of downslope windstorms was previously not performed in detail. Nevertheless, Rottman and Smith (1989) reported the flow visualization experiments in a large stratified water channel as a model of a severe downslope windstorm. Design of the Foehn modeling experiment, which is performed using water tank, is explained in Schröttle (2010).

Based on those considerations, at least two types of the Zonda wind-tunnel models can be considered. The first type is a very small-scale model that allows to reproduce the downslope flow in the wind-tunnel test section, considering the topographic characteristics of the east slope of the Andes mountain range. The other type of the Zonda wind-tunnel model (similar to the conventional models of neutral atmospheric boundary layer) allows the simulation of the surface layer flow, where characteristics are generated mechanically by obstacles and surface roughness elements.

Thermally stratified flows would be necessary to experimentally model this type of wind in the future. In this sense, the research group has begun to develop a program related to small scale simulations of wind-velocity and heat-fluxes of atmospheric geophysical flows using wind-tunnel experiments (Bodmann *et al*. 2014). This project is developed within the framework of the joint Brazil Argentina Research Program in Wind Engineering.

At the moment, Zonda field measurements are not performed coordinated to verify similarity with the laboratory data and for development of new modeling capabilities. Nevertheless, the Servicio Meteorológico Nacional (SMN) began implementing high-resolution measurements in selected locations in Argentina in 2015, while that data is not yet available. These measurements are considered essential to validate Zonda wind-tunnel simulations for engineering applications.

With respect to computational modelling, numerical methods are used mainly for forecasting and to study the dynamics of the air flow over large surfaces, usually with domains of several square kilometers. For example, the Weather Research and Forecasting (WRF) model, which is a numerical weather prediction and atmospheric simulation system (Shamarock *et al*. 2008) was used by Puliafito *et al*. (2015) to simulate mesoscale events of Zonda winds. The focus was on two ‘surface’ Zonda events, while comparing those results to meteorological data.

Another models used are the Eta-CPTEC (Centre for Weather Forecasts and Climate Studies - Brazil) and the Brazilian Regional Atmospheric Modelling System (BRAMS). Seluchi *et al.* (2003a) and Mesinger *et al.* (2006) performed wind forecasting of different Zonda episodes using the Eta-CPTEC model, while Norte *et al*. (2010) used the BRAMS model to represent the features of a severe Zonda wind event. These models were implemented with horizontal resolutions that range from 15 km to 40 km.

Atmospheric processes occur on various spatial and temporal scales and all of these Zonda methodologies were addressed at larger scales, from approximately 103 m to 108 m length scale and from 102 s to 108 s time scale, Orlanski (1975). Nevertheless, it is still required to fully address Zonda wind at smaller scales, as there is a significant lack of studies addressing microscale meteorological characteristics of the Zonda wind and its effects on engineering structures.

## 6. Conclusions

The available literature regarding to the Zonda wind is predominantly about meteorological characterization and forecasting. The preferred interaction between the meteorology and engineering research communities is expected to allow for an improvement of the analysis and prevention of the Zonda wind effects, mainly in structural damage and erosion.

This study presents a description of the Zonda conceptual model, as well as the structural and environmental effects of the Zonda wind. It is observed that the conceptual model of the Zonda wind is quite similar to the Foehn textbook theory and two types of Zonda episodes can occur: ‘high’ Zonda and ‘surface’ Zonda. Regarding to the wind intensity, four categories based on the maximum gust are used to classify Zonda events. Structural effects mainly include blown roofs and damages to transmission lines, while the environmental effects are related to the occurrence of fire, eolic erosion, dust dispersion and deteriorated air quality.

A first approximation of the Zonda phenomenon from the Wind Engineering point of view was outlined. An analysis of available meteorological data at the Mendoza and San Juan airport meteorological stations in Argentina was performed to obtain wind-gust factors and basic wind speeds. The results indicate some important findings. In particular, gust factors obtained are larger than those commonly observed in the atmospheric boundary layer for synoptic winds. On the other hand, the basic wind speed associated with three-second gust at the Mendoza airport meteorological station is very close to the value from CIRSOC 102 code of practice, considering that the map of maximum wind speeds included in this code is being used for more than thirty years now.

With respect to the planned wind-tunnel modeling of the Zonda wind, a description of the available facilities in the framework of the joint Brazil Argentina Research Program in Wind Engineering is provided. Some characteristics of the numerical methods employed to perform wind forecasting of different Zonda episodes are presented.

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