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Codifying Thunderstorms in Australia: What can be learnt from Brazil.

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ABSTRACT

The codification of thunderstorm (non-synoptic) winds in wind loading standards has, for a long time, been considered the next frontier of wind engineering. Advances are being made in the understanding the phenomena via observation and measurement of full-scale events and reproduction at reduced scale in laboratories and CFD simulations. Recently, and for the first time, a revision of AS/NZS1170.2 (2022) includes a thunderstorm wind speed profile for the newly defined Region A0. Such advances have driven those working on the revision of the Brazilian wind loading standard to investigate the distribution, frequency and intensity of non-synoptic winds across the country, with the aim of codifying separate non-synoptic and synoptic extreme wind speed models and characteristics. Although comparable in size with Australia and the US, Brazil is unique in that non-synoptic winds govern the extreme wind climate for most of the country. This paper documents the progress that has been made in the form of proposed, separate basic wind speed maps for Brazil.

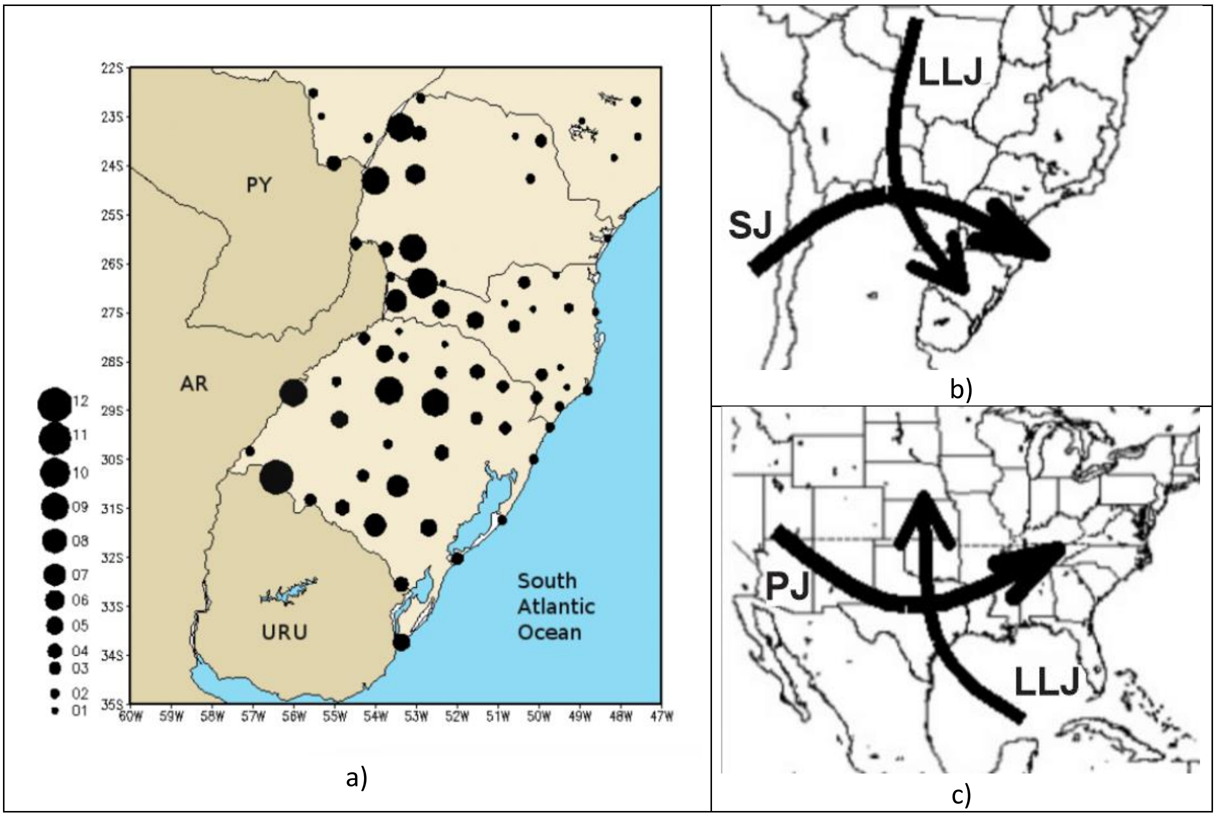
1. Introduction

As the fifth largest nation by territory (8.5 million km^2) and seventh largest by population (217 million) Brazil has long been touted as the sleeping giant of the world economy (73rd highest per capita GDP). Supporting its economy are the dense, bustling cities which house approximately 87% of its population and made possible by verticalisation. Mid-rise buildings are ubiquitous in the 15 cities with populations over 1 million and it is common to find apartment buildings over 20 stories in smaller, country towns. A vast network of transmission lines and towers transfer power between these cities and their source, usually originating at hydroelectric plants or ever-expanding wind farms. It may come as a surprise that most of these structures will have only experienced extreme winds originating from convective storms over their lifetime. Considering that wind loading standards, including that of Brazil, are scoped to only consider wind loads of atmospheric boundary layer models, it makes sense then that understanding the impact of non-synoptic winds on structures is of critical importance to the future of Brazil.

1.1 Extreme Winds in Brazil

Brazil is regularly impacted by three different types of extreme winds: synoptic winds caused by low-pressure systems in the south and (weaker) trade winds in the north, and downbursts and tornados generated by convective storms across the country with varying intensity and frequency (with the exception of coastal regions of the north-east). Additionally, Hurricane Catarina was the first tropical cyclone observed to make landfall in South America, crossing from the South Atlantic to the southern state of Santa Catarina in March, 2004, while damaging approximately 40,000 homes and multiple fatalities. Satellite imagery at the time of landfall estimates a sustained 1-minute wind speed of 85kt (McTaggert-Cowan et al, 2006)., classifying it as a lower-strength Category 2 event as per the Saffir-Simpson Hurricane Wind Scale.

The focus of non-synoptic winds is mainly on those which are driven by deep convection with damaging outward flows from downdrafts. Three essential ingredients are needed for the generation of convective storms: moisture, lift and a high lapse rate (a large decrease in air temperature over vertical distance). The south-western region of Brazil, located within the Rio de la Plata Basin, is home to some of the world's most intense convective storms. The contrast in the intensity and frequency of damaging convective winds in the west and eastern southern Brazil was documented by Ferreira and Nascimento (2016), shown in Figure 1a). Along with the central region of the US, the region is subject to frequent large mesoscale convective complexes, responsible for damaging straight-line winds. The region is one of only two worldwide for which there are intense convective storms during all seasons of the year (Zipser et al., 2006), the other being equatorial Africa. The low-level jet (LLJ) which brings moisture from the Amazon basin to the area, following the eastern edge of the Andes mountain range, is a main factor to the region's convective activity. Disturbances in the subtropical jet stream (SJ) crossing the Andes combined with strong low-level wind shear cause the warm, moist low-level air to be lifted, becoming unstable due to the region's high lapse rate, with main flow paths shown in Figure 1b). Figure 1c) shows a similar mechanism involving the northern polar jet stream (PJ) and LLJ which is responsible for the generation of severe convective storms in the central regions of the US. Southern Brazil is also affected by advancing cold, dry fronts, originating from polar air masses, which can cause the lift necessary to produce damaging non-synoptic winds.



a)

b)

c)

Figure 1. a) Total number of gusts ≥25m/s observed by the INMET network of AWS between Jan 2005 to Dec 2015 (Ferreira and Nascimento, 2016) b) Representation of atmospheric flows during periods of heightened convective activity in South America c) and in North America (Nascimento, 2005).

1.2 Basic Wind Speeds of NBR 6123 (1988)

The basic wind speed, V_0, of the current Brazilian wind standard: Wind forces on buildings (*Forças devidas ao vento em edificações*) – NBR 6123 (ABNT, 1988) is defined as a 3-second gust at a height of

10m in open and flat terrain for a mean recurrence interval (MRI) of 50 years. Studies undertaken by Vieira Filho (1975) and Padaratz (1977) produced the basic wind speed isopleth map, which varies from 50m/s in the extreme south-east and south to 30m/s in the central, rising again to 35 m/s in the extreme north-east. Two isopleth regions surrounding Brasília and Campinas interrupt an otherwise smooth transition between high values in the south and low values in the north.

The extreme value analysis used to determine basic wind speeds was based on annual maxima of hourly peak gusts for 49 aerodrome-based meteorological stations for the period between 1950-1974. 21 stations had data for the full 25-year period, with the median length of observation being 21 years. For cases in which there was no recorded annual maxima gust, an equivalent gust was determined utilising the product of the annual maxima of hourly 10-min mean wind speeds with a gust factor of 1.15. Station extreme wind climate models were fit to these maxima using a Fréchet distribution (GEVD Type II – diverging wind speeds as MRI approaches ∞). The use of the Fréchet distribution was justified by the mixed nature of the extreme wind climate (i.e., no separation of extreme winds by type). A single shape factor was determined using a weighted mean of the shape factor of 20 stations, which was then applied to the entire country, resulting in a single probabilistic factor, S_3, for the entire country. Further details of the process used in the generation of the V_0 and S_3 are given in Vallis (2019).

Despite its definition, it is unlikely that data used to generate V_0 are representative of a 3-s moving average gust, 10m above ground in open and flat terrain. The Bendix-Friez aerovane propeller anemometer is believed to have been used to measure wind speeds, with a trained operator responsible for noting peak and mean wind speeds only by eye. The exact location and heights of the anemometers were unknown to Vieira Filho (1975) and Padaratz (1977). By way of recent interviews, it is understood that a program to relocate anemometers from atop control towers to the side of runways only began in the mid-1970s. No analysis was performed in these studies to determine the upwind fetch terrain roughness per wind sector to correct wind speeds to be representative of open and flat terrain. Note that NBR 6123 defines a roughness length of $z_0 = 0.07$m for open and flat terrain based on recommendations made by Simiu (1981).

2. Revision of the Basic Wind Speeds of Brazil

Recently, two different V_0 maps were proposed to the standards committee responsible for updating NBR 6123. Ultimately, a consensus could not be reached on either proposal by the committee members, and the incumbent map developed by the works of Vieira Filho (1975) and Padaratz (1977) remains. The following is a summary of the approaches of each map.

2.1 Brazilian Extreme Wind Climate (Vallis, 2019)

The ultimate objective of the doctoral thesis Brazilian Extreme Wind Climate (Vallis, 2019) was the development of non-synoptic, synoptic and enveloped extreme wind climate models to be implemented in an updated NBR 6123: non-synoptic and synoptic maps when a suitable non-synoptic wind loading model became available, and an enveloped climate model for application with classic ABL model until such time arrived. Many obstacles were encountered on the way to achieving this, including the procurement of observed meteorological data and station metadata, evaluation of data quality, filtering of extreme winds into synoptic and non-synoptic categories in addition to removing suspect data, the selection of an appropriate GEVD model and stations to be used in the analysis, and the integration of individual stations to form isopleth maps. To assist the continuation of research on extreme winds in Brazil, obtained metadata (incl. upwind terrain category analysis), statistical analyses and results of each individual SWS were published online at windytips.com.

Two separate, independent meteorological networks operate surface weather stations (SWS) in Brazil: those installed in aerodromes with data collected by a branch of the Brazilian Air Force, herein referred to as aerodrome stations, and the network of automated weather stations (AWS) run by the National Institute of Meteorology (INMET).

Multiple databases were developed for both networks. While awaiting official data from the Air Force, a database of decoded METAR and SYNOP weather reports were built after being downloaded from multiple internet sites for a total of 198 SWS (including SWS in countries neighbouring Brazil), with a maximum observing period of 24 years (mid-1996 to mid-2019). Once official aerodrome data was received for 190 SWS, decades from 1950 to 1990 were *painfully* culled since very little was known about the gust measurements prior to the years in which the 3-s moving average definition for an observed gust was adopted by the World Meteorological Organization (WMO) based on recommendations by Beljaars (1987). The decision to prioritise quality data meant that the period of available records was less than the recommended minimum of 30 years to develop an extreme wind climate model (Holmes et al, 2015). SWS were not standardized for anemometer types or heights and no centralized database of SWS metadata existed. Investigative research found that anemometer heights varied between 6-11m, with a variety of anemometer types (cups, ultrasonic, propeller/aerovane).

The INMET network contained 494 AWS across the country, used either the Vaisala WAA151 cup or Gill Windsonic Ultrasonic anemometers (good dynamic response for gust measurement) and are all standardized at a height of 10m above ground. However, short records were also an issue with the INMET datasets as the first AWS was installed in 2000. More problematic though, was the overall reliability of the data. For this study, initial datasets were built from data downloaded from the INMET website prior to receiving official data from INMET. A cross-check of some stations revealed gusts greater than 25m/s were present in website data, but missing from official data for some stations. It was then discovered that extreme wind events were also missing from the INMET website data. Extreme wind events recorded by a particular aerodrome SWS were compared to an INMET AWS located within 500m – the INMET gust windspeeds were nulled for the timestamp matching the extreme wind event as reported by the aerodrome SWS. At this point, the extent to which gusts from real wind events across the country were filtered were unknown, and requests for INMET to release unfiltered gust data were denied, throwing the project into jeopardy. An unfiltered database was ultimately supplied by an anonymous party, external to INMET, as the project timeline was nearing completion, revealing that 290 qualified wind events across the country (172 of which with peak gusts over 25m/s) were unduly filtered. Wind direction observations were also unreliable for several AWS – either the values were restricted to narrow bands, or the predominant wind direction changed significantly at some point during its operation (most times by 180^o, suggesting an incorrect installation).

Once datasets were compiled and global data quality issues were identified and categorized, the roughness length of an upwind distance of 500m was determined for 8 wind sectors for all stations for the purpose of standardising 10-minute mean and gust wind speeds to open and flat terrain. Despite the fact that some INMET AWS stations are located on hillcrests, no corrections were made for topography due to the time demands required to undertake such an exercise, and that by leaving the data uncorrected would be a conservative. Peak gusts and 10-minute means converted to equivalent gusts were then classified as synoptic, non-synoptic or suspect by a semi-automated process involving purpose-built algorithms which analyse time-series of wind speed, direction, weather present, temperature and atmospheric pressure (Vallis et al., 2019). The algorithm is calibrated to classify more extreme winds as synoptic than that of Holmes et al. (2018). The classification of all analysed wind events can be found at windytips.com. Appropriate periods of analysis for each SWS were then determined by visual inspection of the comparison between the monthly mean wind speed of the SWS and that of the ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis data, and the distribution of top 100 extreme wind speeds over time.

Given that the incumbent wind climate model was based on a Fréchet distribution and the number of years of operation of the SWS with data of sufficient quality ranged from 2 to 28 years (median of 10 years), the Gumbel distribution (GEVD Type I) was selected for use in the extreme value analysis over the Weibull distribution. A modified version of Method of Independent Storms (MIS) was used in the extreme value analysis of each wind type/station for an average number of 4 wind events per year. Gumbel models were fit using linear regression to reduced variate values above -1 for stations with operating periods greater than 10 years, with a sliding scale down to a minimum of -3 for periods down to 2 years.

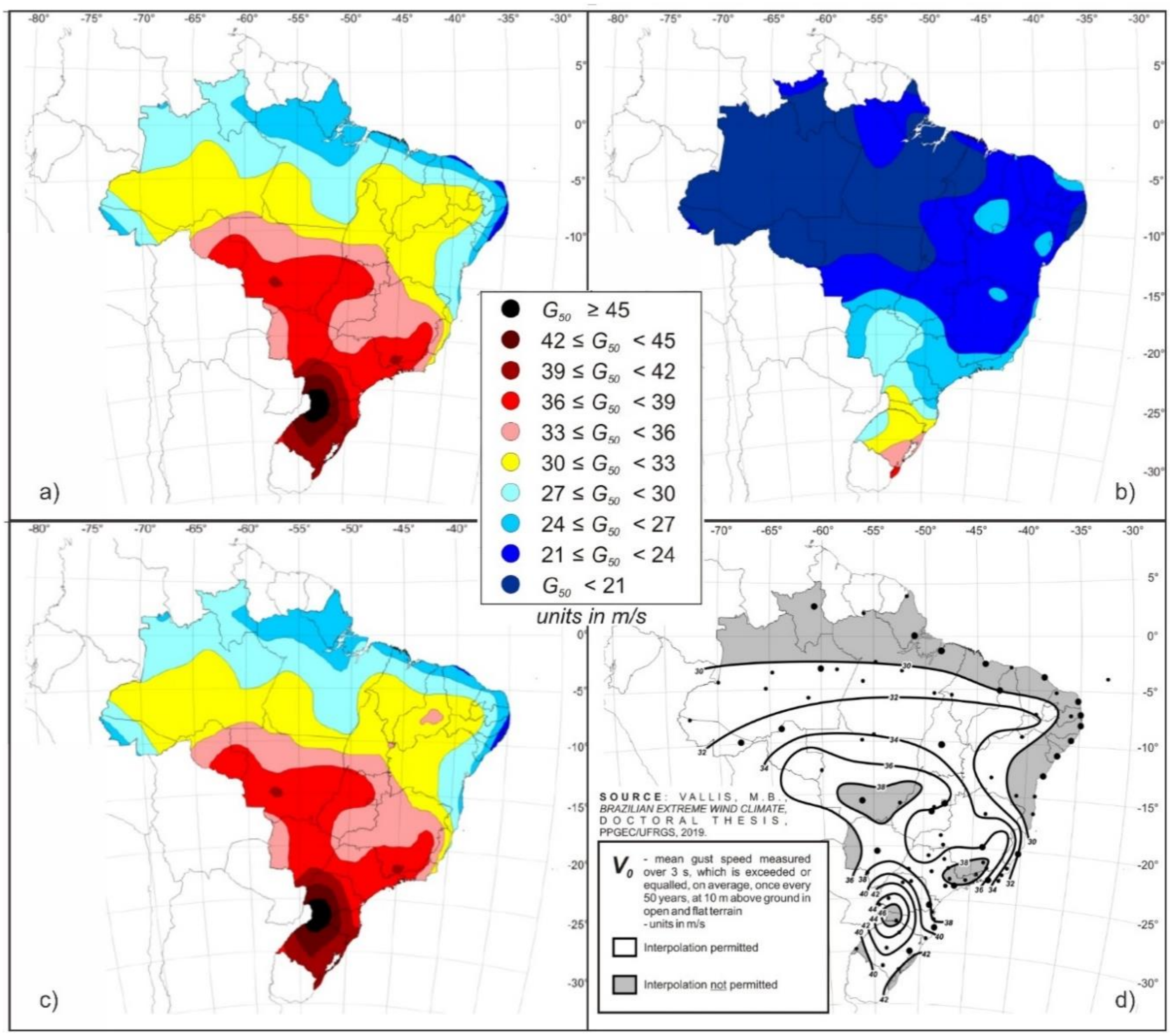
Prior to generating the 50-year MRI, G_{50}, isopleth maps for non-synoptic, synoptic and enveloped cases, SWS with low extreme wind climate models were removed using a high-pass spatial moving average filter with the objective of creating a conservative design. SWS with a G_{50} that were 3m/s or more below a local mean for a particular wind type were identified as underperformers and were removed from the list of governing stations used in determination of the isopleth map. Local polynomial regression was used to generate the G_{50} isopleth maps from the discrete SWS. Solution independence was tested and confirmed by removing 10%, 20% and 40% of governing stations. The G_{50} isopleth maps are shown in Figure 2 a) for non-synoptic winds, b) synoptic winds, c) enveloped winds (extreme 50-MRI value for non-synoptic, synoptic and mixed climate models). The final solution put forward for implementation in NBR 6123, shown in Figure 2d), is a manually manipulated version of the enveloped case to allow for conservatism in some regions, for example, a minimum of 30m/s in the north-east which could potentially be as low as 24 m/s. The non-synoptic and enveloped are similar – ranging from 46 m/s in the south-west corner to 24 m/s in the north-east. The synoptic map ranges from 39 m/s in the country's southern extreme to below 21 m/s in the Amazon in the north-west.

The errors between the governing stations and the mapped G_{50} final solution, e (G_{50}), for non-synoptic wind model and all SWS and the enveloped model for governing stations is compared to the Padaratz solutions, Holmes (2002) analysis for Australian basic wind speeds and the 700-year MRI Pinter et al. (2015) solution for ASCE-7 2016 non-hurricane wind speeds are shown in Figure 3. The proposed enveloped solution has a similar level of conservatism to (80% of all stations below +5% error) to the works of Holmes (2002) and Pintar et al. (2015), increasing to 88% when considering all stations for the non-synoptic case only.

Figure 4 shows the mode, U, plotted against the scale factor, a, for all SWS non-synoptic models as well as those of the governing SWS. The low correlation scatter plots highlight the difficulty in attempting to make a single climate model for the entire country. Despite this, to keep in line with the existing single model for the country, a new set of S_3 values were proposed for a relationship of $U=7a$. A single model is not sufficient for a country as large as Brazil, and a more thorough solution could be different models assigned to smaller regions of the country, or maps produced for each MRI of interest.

Non-synoptic extreme winds were analysed to obtain a greater understanding of trends across the country, with some of these shown in Figure 5: a) shows the average temperature drop over the duration of the most extreme events, ranging from > 12^{o} decrease in the centre of the country to lesser gradients near the coast, b) shows increase in atmospheric pressure decreases from south to north, with the largest increases occurring in the same region as the most extreme non-synoptic wind speeds, c) two clear trends in the predominant wind direction of extreme non-synoptic winds are noted: for the region -20^{o}S and below, the south-western quadrant is responsible for most non-synoptic gusts, and the north-eastern quadrant for the region above -20^{o}S. Although no effort was made to develop regional wind direction multipliers, there is certainly an opportunity to do so. d) the season in which the strongest non-synoptic winds occur vary across the country. Summer and spring months are responsible for the strongest winds for the majority of Brazil – however most of this region does not have a temperate climate, but rather only tropical wet and dry seasons.

Despite the relatively small sampling periods available, stations of sampling periods greater than 10 years were analysed to determine the rate of growth per annum of extreme wind events. Results were inconclusive, however there were more SWS with positive growth rates than negative, with a mode falling in the range of 0 to +5% growth.



SOURCE: VALLIS, M.B., *BRAZILIAN EXTREME WIND CLIMATE*, DOCTORAL THESIS, PPGEC/UFRGS, 2019.

Figure 2. 50-year MRI isopleth maps generate by local polynomial regression a) non-synoptic winds only b) synoptic winds only) c) envelope d) proposed V_0 for NBR 6123.

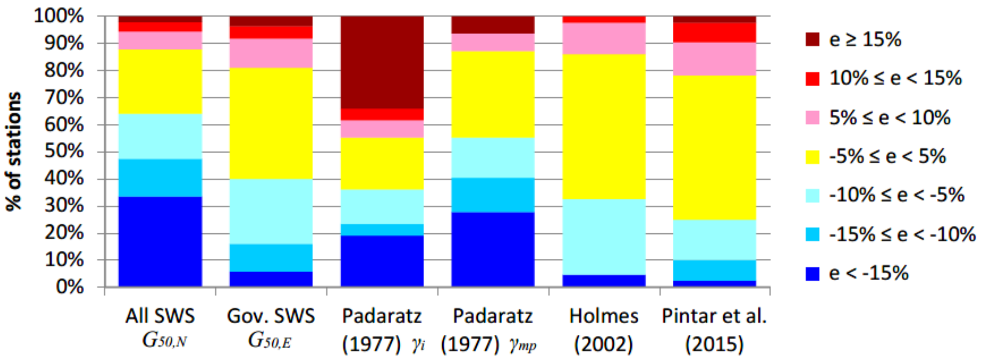


Figure 3. Distribution of error between individual SWS and mapped solutions compared to other international studies.

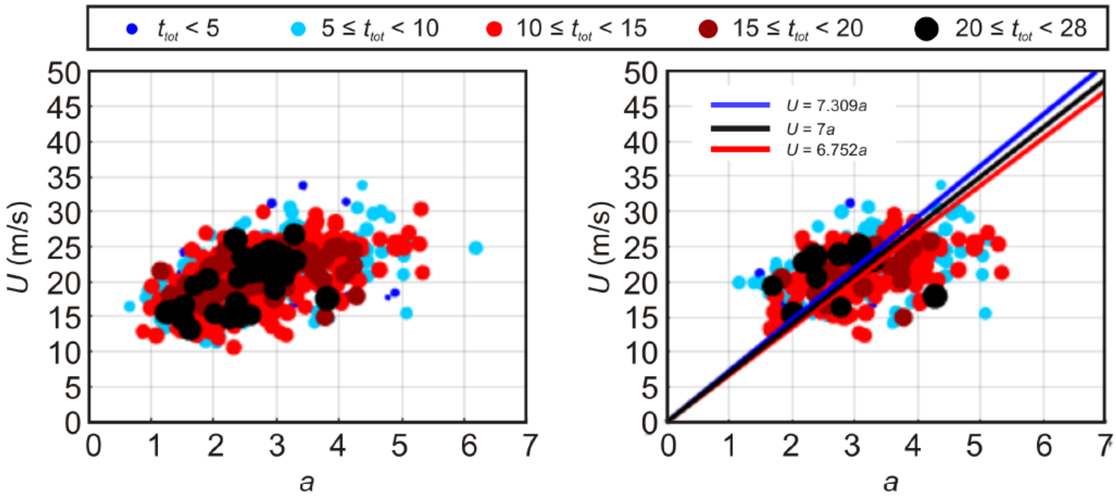


Figure 4. Non-synoptic U vs a, for as SWS (left) and set of governing SWS (right). t_{tot} = total sampling period of station (years).

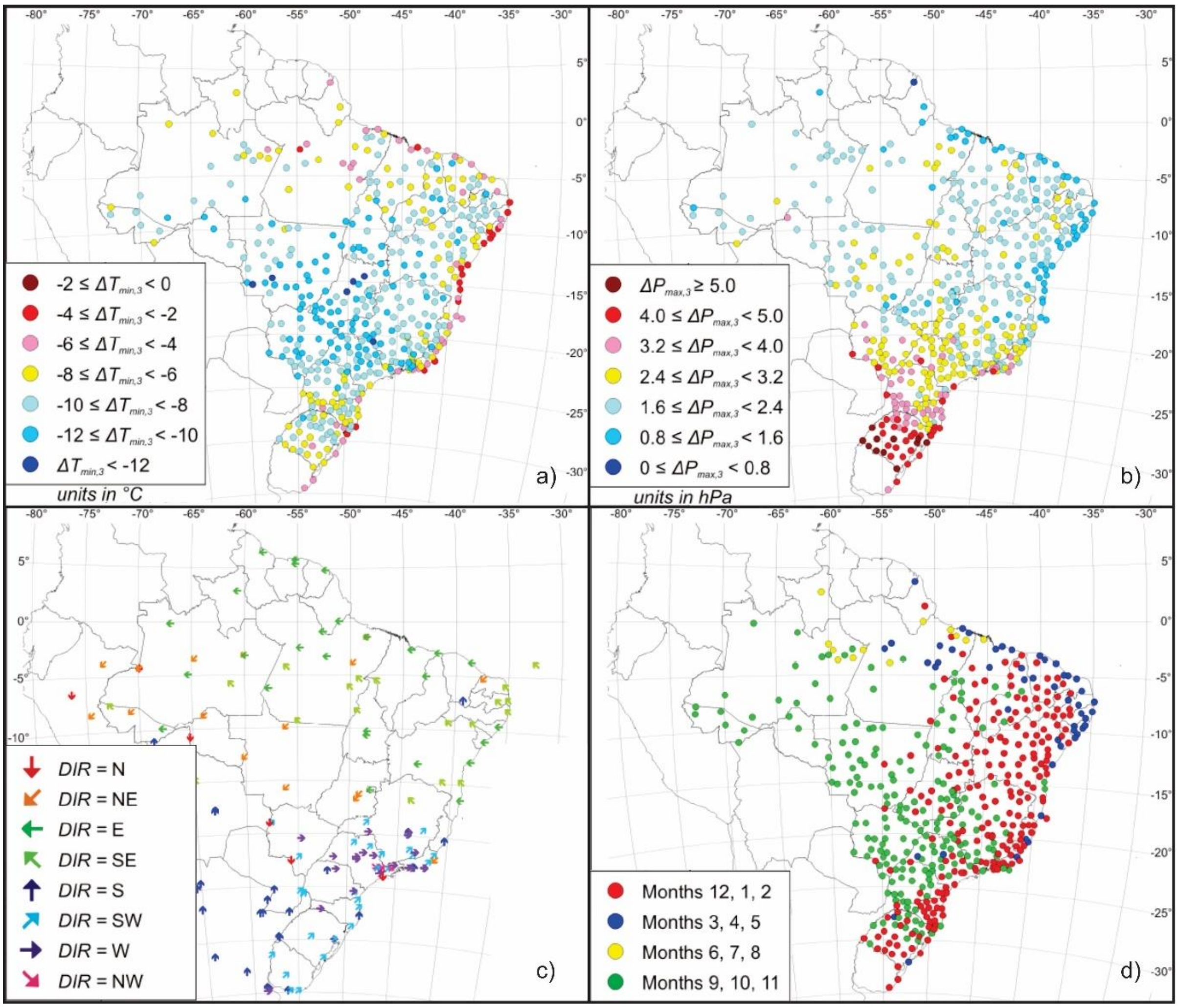


Figure 5. a) average maximum temperature decrease over a period of 3hrs prior to and after a non-synoptic peak gust (INMET AWS), average maximum atmospheric pressure increase over a period of 3hrs prior to and after a non-synoptic peak gust (INMET AWS), c) dominant wind direction non-synoptic winds (aero network) d) dominant period of the year for non-synoptic gusts.

2.2 A climatology-based wind speed map for NBR6123 (Loredo-Souza et al., 2023)

This study makes use of the individual SWS extreme wind climate models produced by Vallis (2019) to generate alternative V_0 proposal. The country was divided into regions as per the dominant meteorological phenomena responsible for generating extreme winds, shown in Figure 6a), and an artificial floor of possible V_0 was defined for each region. The artificial floors serve as a high-pass filter of the enveloped wind climate model of the Vallis (2019) governing SWS. Artificial floors range from 30 m/s in the north and north-east to 40 m/s in the south. The G_{50} values (to 1dp) of the governing SWS which remain after the application of the filter were printed on a map at their discrete locations. Isopleth lines were then drawn by hand to best envelope the printed values. The resulting map, shown in Figure 6b), contains a central T-shaped region of 36m/s, which slopes down to a minimum of 30 m/s in the north-east, down to 33 m/s, then back up to 36 m/s in the north-west, and upwards to a maximum of 48 m/s in the south.

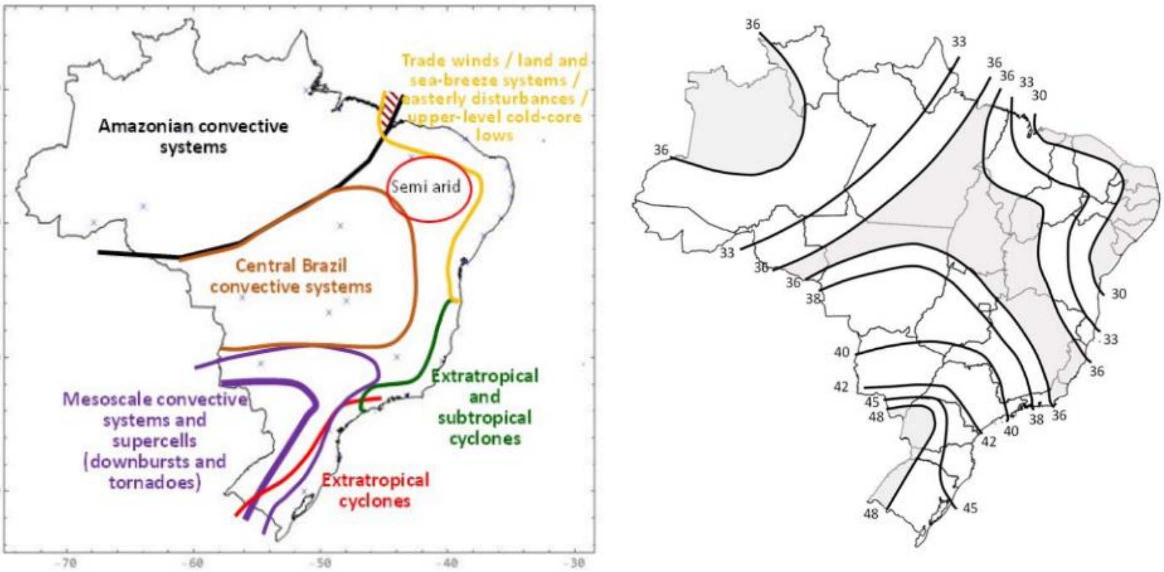


Figure 6. a) Regions of similar atmospheric phenomena responsible for extreme winds in Brazil as defined by Loredo-Souza et al. (2023), b) V_0 map proposed by Loredo-Souza et al. (2023).

The proposed map is notably more conservative than both the incumbent V_0 isopleth map of NBR6123 (1988) and that proposed in Vallis (2019). In large regions at the centre of the country, V_0 is proposed to increase by 20% from 30 m/s to 36 m/s, resulting in a wind load increase 44% due to the squared relationship between wind speed and pressure (force). In Brazil's high-rise capital, São Paulo, an increase of 16% in wind loads is proposed.

Loredo-Souza et al. (2023) argues that "*[There is a]… significant subsampling [of thunderstorms] by the network of meteorological stations. In brief, non-synoptic winds may be captured by one station but not registered at a neighbouring station, situated at a distance larger than the spatial scale of the phenomenon. Other events may not be registered at all. From this understanding, it can be concluded that Vallis' (2019) procedure of taking the average of the V_0 values among neighboring stations, to obtain a representative value for one location, introduces a flagrant contradiction with the nature of the physical phenomena, particularly its reduced dimensions, with respect to the density of weather stations.*"

It is true that a single SWS cannot capture all non-synoptic events over a given region, e.g. a city, unlike large-scale synoptic events. Not recognised in Loredo-Souza et al. (2023) is that an individual structure will not be affected by all non-synoptic events within that region over its lifetime, and the capture of all non-synoptic wind events the region is not necessary to develop an appropriate extreme wind climate model. The random and localized nature of convective storms mean that some hit, some miss: this is the case for both SWS and structures. The difference between area and point risk is highlighted by extreme wind models for West Texas developed by Lombardo (2012). Data from 50 SWS over a period of 7 years were analysed for both independent and non-independent cases. The regional estimation assuming full correlation (non-independent events) gave a 50-year MRI of 54 m/s, whereas the independent approach of the superstation gave 45 m/s. A 50-year MRI of 38 m/s for West Texas is presented in the commentary sections of ASCE-7 (2022).

3. Other Thunderstorm Related Advances in Brazilian Wind Engineering

Although the main focus of this paper is on the determination of standardized regional non-synoptic design wind speeds, much work still needs to be done in the understanding and codification of non-synoptic wind loading.

Two different wind speed profile models were proposed by Miguel et al. (2018) and Riera (2018), but neither have been adopted in the revised standard. The Miguel et al. (2018) model considers a non-synoptic profile made up of 35% standard ABL profile and 65% downburst, but would give a design wind speed of nearly twice that of a standard ABL profile for a V_0 of 40 m/s at a height of 100m. The Riera (2018) model also adopts a 35/65 split, with the downburst multiplier constant of 1.0 for heights above ground, then going to 0 at a critical height (approximately z=80m for a V_0 of 40m/s). Although significantly less conservative than existing ABL models, this approach is similar to that of AS/NZS:7000 (2010) for electrical transmission lines and deserves further consideration. The adoption of the AS/NZS 1170.2:2022 Region A0 non-synoptic wind speed profile was considered for implementation but rejected. The main reason for the non-adoption was that the majority of Brazil is governed by non-synoptic winds, including major, dense cities, meaning that suburban and urban terrain categories would be eliminated and loads significantly increased.

A significant difference between synoptic and non-synoptic basic wind speeds for low MRI, used in the evaluation of occupant comfort, was observed at most locations across the country. One proposal was to use only the synoptic wind speeds when evaluating occupant comfort and the non-synoptic wind speed for the determination of serviceability and design loads. For example, in São Paulo, the proposed 1-year MRI non-synoptic is 25 m/s and its synoptic counterpart is 19 m/s. Although not adopted, this is a valid proposal which deserves further attention and consideration when the wind loading of non-synoptic winds is better understood. It may already be practical to use such an approach in the design of buildings over a certain height for global loading caused by a downburst may be small, or office buildings, where the tenants have the choice of leaving if conditions are unbearable, as opposed to residential buildings, where tenants spend most of their time, and would not be willing to vacate on a frequent basis, particularly during the night.

Occupant comfort criterion relating to the peak tip building acceleration as defined in ISO 10137 (2007) will be included in the new standard. To increase the adoption of building motion monitoring systems across the country, a relaxation of the criterion by 15% is proposed if a building motion monitoring system is to be installed. The relaxation is offered on the presumption that building occupants will be better educated and informed on the building motion, and hence more comfortable will building motion. Additionally, such an innovation would give opportunity to better understand real-life building motion and advance theoretical concepts.

4. Conclusions

Advances in the understanding of the spatial distribution of extreme winds in Brazil were presented along with proposed basic wind speed maps, with non-synoptic winds governing the basic wind speed most MRIs over the large majority of the country. Presented are two approaches to integrate station wind climate models into basic wind speed maps. These approaches could be adopted by Australia to eliminate the need for hard boundaries between regions, however further solutions are required to consider wind directionality and different regional wind climate models.

The lack of consensus in the Brazilian standards committee regarding the two proposed basic wind speed maps is best summarized as a lack of agreement on the degree of conservatism required. Despite an agreement on the adoption of a floor of 30m/s, large extents of Brazil's north-eastern coastline show 50-year basic wind speeds as low as 24 m/s. This opens the space for discussion on possible lowering of the floor of basic design wind speeds for non-synoptic winds.

Vallis (2019) presents analyses of SWS via a free-to-access online resource (windytips.com). Such a resource for Australia would be a boon, and would surely assist those researching or considering researching extreme winds and non-synoptic storms in Australia.

It is unlikely that the general body of non-synoptic winds in Australia and Brazil are the same, with the ABL component likely much stronger in Australian non-synoptic winds. However, it is likely that the most severe non-synoptic winds, downbursts generated by single supercells, in both countries are similar in nature.

The non-synoptic wind profile of Region A0 of AS/NZS1170.2 (2022) was judged as unsuitable for use in Brazil due to the lack of consideration given to upwind fetch roughness and its generation of higher loads. A non-synoptic profile has not been adopted in Brazil, however the proposed model of Riera (2018) would generate significantly lower loads for tall-buildings than current ABL models. It is possible that the future non-synoptic wind loading approaches of different countries could diverge to a higher degree than ABL winds.

Trends in the temporal distribution of extreme winds in Brazil varied amongst the individual SWS leading to an inconclusive result as to whether climate change has impacted the frequency of extreme winds in the country. This should be analysed regularly as more data becomes available over the coming decades.

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