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CIÊNCIA e NATURA

ISSN 2179-460X
OPEN ACCESS

Ci. e Nat., Santa Maria, v. 47, n. spe. 3, e84051, 2024, • https://doi.org/10.5902/2179460X84051
Submitted: 10/06/2023 • Approved: 11/07/2024 • Published: 30/04/2025

IX Encontro Sul Brasileiro de Meteorologia

Climatology of tornado occurrences in southern Brazil

Climatologia de ocorrências tornádicas no Sul do Brasil

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ABSTRACT

The subtropical sector of South America east of the Andes, including southern Brazil, is frequently affected by severe convective storms. In some situations, atmospheric ingredients conducive to the occurrence of tornadoes are also observed. However, despite the potential for the formation of this hazardous weather phenomenon, the documentation of tornadoes in southern Brazil is poor compared to other regions around where consolidated severe weather databases exist (e.g., USA and Europe). This work consider different sources of information to generate a database of tornado occurrences covering southern Brazil, Uruguay, Argentina and Paraguay. These sources include tornado footage and photographs, or visual documentation of wind damage consistent with tornadic activity, available in press and social media. Additional sources include tornado events existing in the scientific literature and non-scientific initiatives that keep tornado reports. Tornado damage tracks identified through high resolution environmental satellite imagery were also included as a source of information. Such compilation produced a tornado database with 310 occurrences in southern Brazil. This study emphasizes the spatial, seasonal and annual distributions of the tornado occurrences in addition to the human impacts in terms of injuries and fatalities. The sector displaying highest frequency of tornado events was identified for an area encompassing northern Rio Grande do Sul, western Santa Catarina and southwestern Paraná states, with peak activity during winter.

Keywords: Tornado; Climatology; Severe weather; Southern Brazil

RESUMO

O setor subtropical da América do Sul a leste dos Andes, incluindo o sul do Brasil, é frequentemente afetado por tempestades convectivas severas. Em algumas situações os ingredientes atmosféricos que favorecem a formação de tornados também são observados. Apesar do potencial para formação destes fenômenos, o registro de tornados no sul do Brasil é incipiente quando comparado com outras regiões do mundo em que existem bancos de dados de tempo severo consolidados (p.ex., EUA e Europa). Este trabalho considerou diferentes fontes de informação para gerar um banco de ocorrências de tornados que abrange todo o sul do Brasil e vizinhanças. As fontes de informação abrangem registros videográficos e fotográficos de tornados, ou a documentação visual de danos condizentes com a ocorrência do fenômeno, existentes na mídia tradicional e em redes sociais. Fontes adicionais incluem episódios de tornados documentados na literatura científica e iniciativas não científicas de registros de tornados. Trajetórias de danos por tornados identificadas por imagens de alta resolução de satélites ambientais também foram adicionadas como fonte de informação. A compilação desses casos permitiu produzir um banco de dados com 310 ocorrências de tornados no sul do Brasil.O enfoque deste trabalho é na sazonalidade e na distribuição anual e espacial das ocorrências de tornados, além do impacto humano em vista de feridos e fatalidades. O setor com maior frequência de eventos tornádicos foi identificado para a região abrangendo o norte do RS, o oeste de SC e o sudoeste do PR, com máxima ocorrência sendo observada durante o inverno.

Palavras-chave: Tornados; Climatologia; Tempo severo; Sul do Brasil

1 INTRODUCTION

The documentation of tornadoes in the subtropical South America is still incipient, despite the presence of ingredients that allow the formation of this phenomenon on several days of the year (Brooks et al., 2003; Rasmussen et al., 2014; Tippett et al., 2015; Nascimento et al., 2016). Throughout the 20th century, some initiatives emerged for the documentation of severe weather events, especially in Argentina where the project Tornados y Tormentas Severas (Altinger de Schwarzkopf, 1999) aimed to catalog the occurrence of destructive winds and tornado activity over Argentine territory, including in situ analysis of damage. Thus, for a long period, tornado documentation in subtropical region of South America was mostly restricted to Argentina, with a clear underestimation of tornadic activity in the neighboring regions (Goliger e Milford, 1998; Brooks e Doswell III, 2001).In Brazil, tornado documentation was mostly restricted to the analysis of some significant events that affected urban areas (Marcelino et al., 2003, 2007; Nascimento et al., 2014; Ferreira et al., 2022; Oliveira et al., 2022) and the existence of some punctual climatologies Dyer (1988); Nechet (2002); Marcelino (2003); Silva Dias (2011). In this context, the work of Dyer (1988) and Marcelino (2003) stands out. (Dyer, 1988) pioneered aerial photography and satellite imagery to identify tornado tracks in the western sector of southern Brazil and neighboring areas of Argentina and Paraguay, documenting a total of 24 damage paths. Marcelino (2003) colected records of tornadoes in the state of Santa Catarina between 1975 and 2003, cataloging 45 events in the period.

Nascimento e Doswell III (2006) discussed the need to create a database with detailed documentation of severe weather in the subtropical portion of South America, including southern and southeastern Brazil. However, only in 2018 with the creation of the Plataforma de Registros de Tempo Severo (PRETS, Ribeiro et al. (2022), along the lines of the European Severe Weather Database (ESWD, Dotzek et al. (2009) and Storm Data Schaefer e Edwards (1999) maintained by the National Climatic Data Center (NCDC; http://www.ncdc.noaa.gov) and the Storm Prediction Center (SPC; http://www.spc.noaa.gov), is that systematic recording of this type of event was initiated in Brazil. The combination of the PRETS initiative with other recent efforts by Uruguay, Argentina and Paraguay (Bechis et al., 2022) is the next step towards the creation of a regional severe event database in the subtropical sector of South America, not exclusively for tornadoes but including this type of phenomenon as discussed by (Salio et al., 2024). The future expansion of documentation and the ease of recording made possible by technological advances, already discussed by Silva Dias (2011), will make it possible to know the seasonal climatology of events and also the places with the highest frequency of occurrence.

However, there is still a large gap in the recording of ancient events and it is in this context that this work is inserted, since the collection of events carried out for this work already allows to obtain important information about the climatology of tornadoes in the subtropical region of South America, especially in southern Brazil.

The Southern region of the country is composed of three state (Rio Grande do Sul, Santa Catarina and Paraná) which together have a population of 30.4 million inhabitants (14.25% of the Brazilian population, IBGE (2023)) distributed in an area of 576 736 km^2, generating a population density of 52.71 persons per square kilometer. In addition, these states also account for extensive agricultural production, involving the cultivation of multiple crop varieties across all seasons, with the agricultural sector having an important role in the economic production of the region (IBGE, 2019). Thus, the occurrence of tornadoes in Southern Brazil produces a high socio-economic impact that can at least be mitigated with the expansion of knowledge about the climatology of occurrences of the phenomenon.

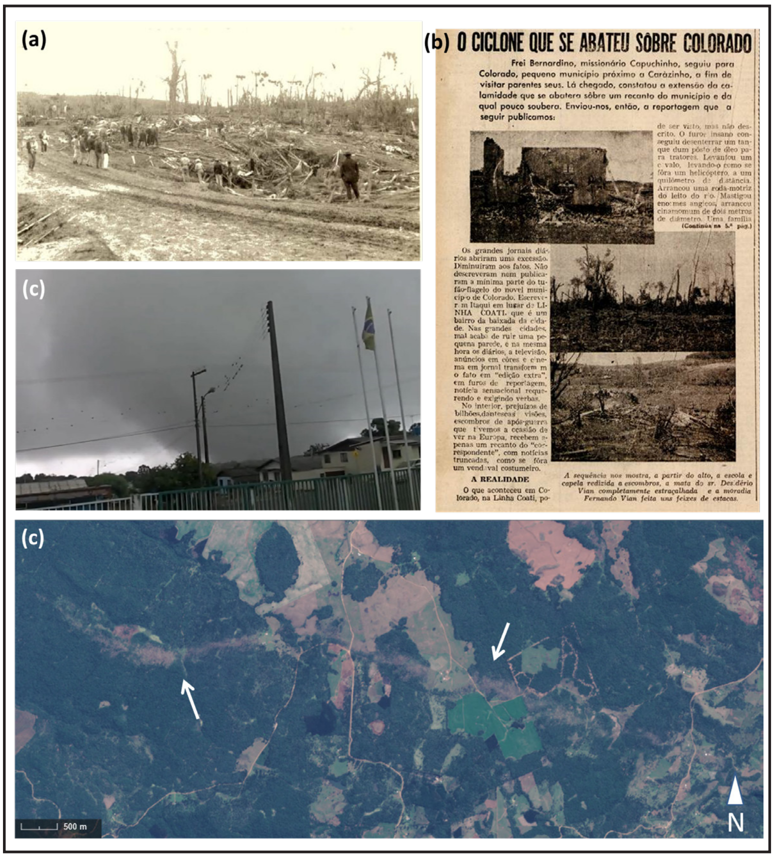
In this work, section 2 describes the methodology used to survey occurrences of tornadoes and filter cases. The results extracted from the tornadoes database are presented and discussed in section 3, while the final considerations correspond to section 4.

2 METHODOLOGY

The documentation of cases of tornadoes and potentially associated with the phenomenon was developed through the use of videographic and photographic records (either on social media or through the press), scientific works of case studies and/or climatologies and grouping of records from other initiatives that developed databases. In addition to these sources, some events were documented through the identification of tornado tracks through environmental satellite images (Antonio et al., 2005; Marcelino et al., 2007; Lopes et al., 2018; Lopes e Nascimento, 2020; Oliveira et al., 2022), since the passage of tornadoes alters the vegetation cover and surface reflectance. Figure 1 summarizes the different sources of information through an overview.

The events were analyzed source by source in order to separate cases that present tornadoes as the most probable or confirmed cause, from other cases where evidence is scarce or the probability of cataloged damages being caused by tornado events is low. This type of analysis was mainly conducted for reports in press or digital media, in addition to having been expanded to cases documented in private initiatives. This approach seeks to prevent the number of cases from being inflated by events caused by linear wind gusts and microbursts. The cases were all grouped together to avoid double recording of the same case from different sources of information.

Figure 1 – Figure combining some of the sources used to survey tornado events



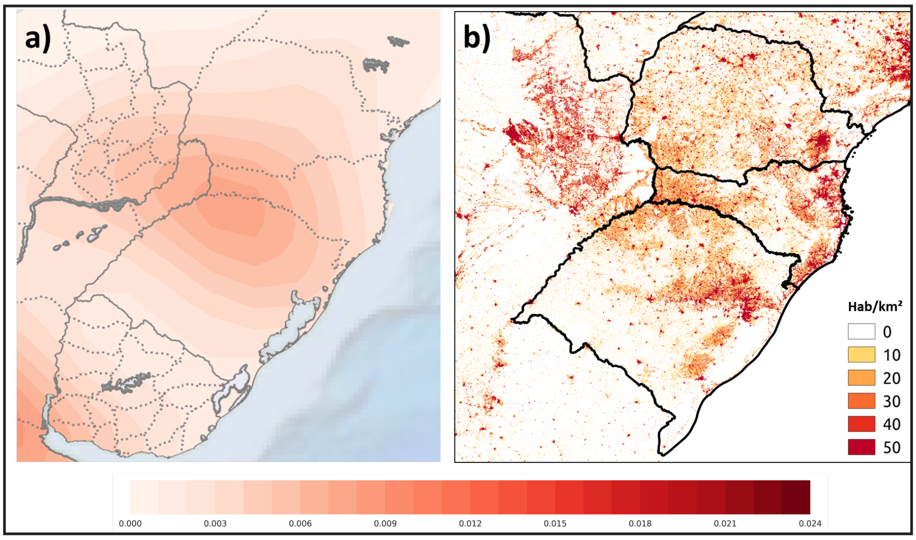
(a) E xample of damage consistent with an intense tornado in Canoinhas/SC on August 13, 1959 (Source: Brazilian Parlament). In panel (b) an excerpt from a report by Diario da Tarde which mentions the damage caused by a "cyclone"that affected Colorado/RS in 19 (Source: National Library). In (c) frame from a video of the Xanxerê/SC tornado on April 20th, 2015 (Source: Oliveira et al. (2022)). In (d) the damage path to tree vegetation from the Sentinel 2 satellite associated with the tornado that affected Reserva do Iguaçu/PR in June 2017
Source: the authors, 2024

The subsequent check was carried out especially for the period covering the era of satellites (from the 1960s) and more recently of meteorological radars. The objective was to verify, whenever possible, the consistency of the date and time present in the documentation of the events. It is important to emphasize that the documentation process is continuous and other past cases may be inserted in the future as new information is obtained from them.

Despite the absence of detailed information on the time and intensity of many of the events, the combination of these cases recorded here with the documents by

Altinger de Schwarzkopf (1988, 1999) would allow us to produce the largest tornado database on the continent, with more than 1000 occurrences. Among these, the F5 tornado that affected the argentine city of San Justo in January 1973 (Altinger de Schwarzkopf e Migliardo, 1973) and the August 1959 outbreak in Brazil and April 1993 outbreak in Argentina (Altinger de Schwarzkopf, 1999) stand out. Incomprehension of meteorological phenomena meant that many cases that occurred during the 19th and 20th centuries were called “cyclones” and “typhoons”, such as the Colorado/RS case shown in Fig. 1. However, the description of these cases itself presents damage characteristic of tornadoes as a well-marked damage path, objects thrown at varying distances and tree debarking.

Figure 2 – Kernel density estimation of cataloged tornadoes in southern Brazil during the entire period from 1807 to 2020



(a) The population density in people per km² for southern Brazil and neighboring areas in 2020. (b) The source of population data is the project Global Human Settlement Layer (GHSL, Schiavina et al. (2023))
Source: The authors, 2024

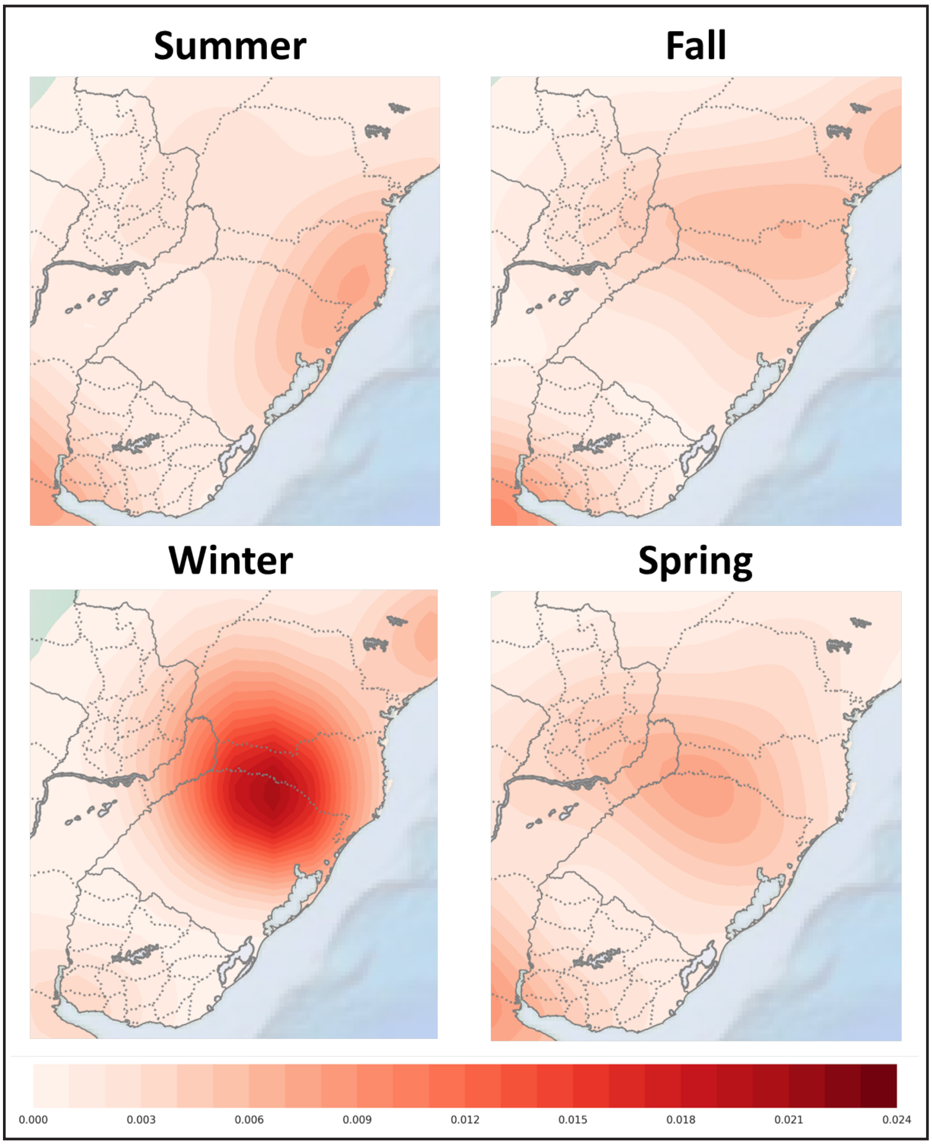
The scope of the database was not restricted to the Southeast sector of South America, as data from all over Brazil was grouped together. Soon, cases from the Amazon Basin were also included. However, in the present work the focus is on the tornado activity documented in the southern Brazil. Thus, the analysis is conducted for the seasonal and annual distribution of events, as well as KDE to the database. KDE uses Gaussian curves to calculate a probability density function based on the spatial concentration of events, highlighting the sectors with the highest number of occurrences. In this work, the area of influence of each point in the density estimate was calculated for an arbitrary radius of 150km around the event. The situations in which there is information about the time of the tornadoes also allowed the analysis of the time distribution of the events. It is important to point out that despite the events being cataloged with a distinction between tornadoes and waterspouts, the analyzes of this work were carried out on the complete database without distinction.

3 RESULTS

The collected records cover Brazil and and neighboring areas for the period between 1807 and 2020, where approximately 680 occurrences of tornadoes were recorded. Of this total 310 cases were registered in the southern region of Brazil. The largest number of events occurred in the state of Rio Grande do Sul, RS, (total of 128 cases), while Santa Catarina (SC) and Paraná (PR) had reports of 95 and 87 tornadoes, respectively.

Figure 2 shows the KDE distribution of all cataloged tornado events, showing the occurrence probability area located between the north of RS and southwest of PR, including the west of SC. Population density in person per square kilometer is shown in Fig. 2 , making evident the metropolitan areas located in the eastern sector of the southern states (population density greater than 50 person/km^2). The relative minimum of tornado occurrence in western RS and southwest RS, close to the border with Uruguay, seems to be associated with the low population density in the region. In these areas, population density of less than 10 inhabitants per kilometer makes the opportunity for documentation more scarce. The sector with the highest KDE values corresponds to an area with a population density of around 20 inhabitants per kilometer. This hotspot, despite being related to the greater presence of population in relation to the Pampa area, corroborates with occurrences the greater potential for tornado events in the more continental portion of southern Brazil shown by Tippett et al. (2015) and Nascimento et al. (2016). On the other hand, despite the high density of people per square kilometer, there are fewer events in the eastern sector of the states.

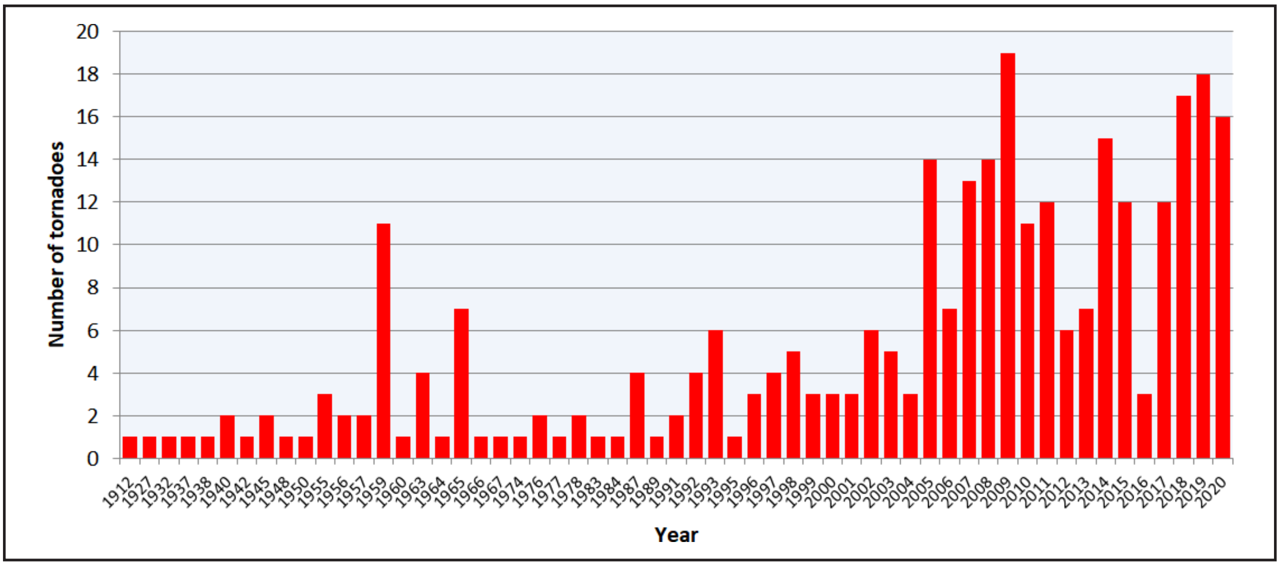
Figure 3 – KDE seasonal analysis of documented tornado events. The top row is scheduled for the summer (DJF) and fall (MAM) seasons. In the second row, the winter (JJA) and spring (SON) seasons are marked



Source: The authors (2024)

Figure 3 shows the KDE distribution of tornado events by season, being summer (DJF), fall (MAM), winter (JJA) and spring (SON). The seasonal variation of the areas with the highest occurrence throughout the year is notable, with the maximum during the summer period being located in the eastern sector of Santa Catarina. The presence of orographic forcings acting on the triggering of convective cells in this sector may be related to this maximum in the density function during the season. It is important to point out that despite the sectorization for the south of Brazil, the density estimation calculation used the entire data set, thus avoiding biased information in the border areas with neighboring countries and other regions of Brazil.

Figure 4 – Annual number of recorded tornadoes (bars) in Southern Brazil, from the first record present in the dataset



Source: The authors, 2024

Only years with at least one documented case are shown

As for the autumn period, despite a lower density function of events, the maximum located between SC and PR is noticeable, also extending towards the São Paulo state (SP). Despite belonging to another region of Brazil, it is notable that it was during this period of the year that an F3 tornado studied by Nascimento et al. (2014) hit the city of Indaiatuba in 2005 and two other tornadoes affected the interior of the state of São Paulo (Antonio et al., 2005).

During the winter, an increase in KDE values in the SP state is notable, however the highlight is the greater value (about an order of magnitude) in the north of RS and midwest of SC. Despite the tornado hotspot being focused on the aforementioned area, most of the southern states have the highest KDE values during this season. The intense baroclinicity during the cold season is responsible for the increase in low-level jet (LLJ) events in this region (Oliveira et al., 2018). The presence of intense flow at low levels associated with the LLJ contributes to intensify low level shear (Kis e Straka, 2010; Reames, 2017), being an important factor in the average synoptic composition of tornado events in the region, as shown by Lopes e Nascimento (2024). Another noteworthy point during the winter period is the low probability of occurrence of tornadoes in the extreme southwest and extreme south of RS, which can be explained at least in part by the low population density.

In areas that have a minimum of occurrences during the winter, there is an increase in KDE during the spring period, however the values are still lower than those recorded in the northern RS hotspot, which decreased in intensity in relation to the previous season and displace to the west covering the south of Paraguay within this sector.

Despite being included in the general set of the database, the events cataloged by Dyer (1988), through aerial and environmental satellite images, are not accounted for in the seasonal division presented. The low frequency of aerial imaging in the period (the 60s and 70s) prevents the delimitation of the exact period in which the tornado paths were produced. However, considering the KDE generated from all cataloged events, the tendency of the maximum probability to move to the west is remarkable, however due to this information gap it is not possible to define in which period of the year this is more evident.

The scarce information available for most events prevents a detailed classification of the damage and the possibility of classifying the tornado based on the Fujita scale. The absence of photographs also complicates the classification process, despite the fact that some historical events have a visual record of some of the most severe damage, most events from previous decades rely mostly on anecdotal reports. Even if possible, the classification of intensity based on the maximum damage recorded in historical events tends to create an intensity bias, since only the most severe cases gained prominence in the press.

The distribution of cases shown em Fig 4 indicates an upward trend in recent decades, especially from the 2000s onwards. This increase is cited by Silva Dias (2011) and is likely due to the popularization of cell phones and the internet, thus allowing an increased possibility of record the severe weather event and share its occurrence. The year 2009, with 19 cases, had the highest number of tornadoes in the analyzed series. Although this work does not relate the occurrences with the El-Nino Southern Oscilation (ENSO) phase, it is interesting to note the performance of an El Niño in that year and the positive ENSO phase is correlated with a greater number of precipitating events in southern Brazil (Grimm et al., 1998).

The event that most caused fatalities was recorded on August 13-14th, 1959 with the occurrence of an outbreak that affected the three southern states. Between the night of August 13th and the morning of August 14th at least 10 tornadoes were recorded.

In some cases, the available images allow inferences typically associated with F3+ tornadoes, such as the debarking of trees and objects thrown at great distances. It was in this event that the deadliest tornado in the database was recorded, 35 victims in the tornado that affected the interior of Palmas/PR.

The number of injuries and fatalities each year is shown in figure 5 with a clear reduction in the number of deaths associated with the passage of tornadoes over the years. The change in population distribution over the decades with the migration of the population from rural areas to cities may explain, together with the improvement in construction, this reduction in fatalities. In addition, the high number of injuries recorded in years when more densely populated urban areas were hit by tornadoes is noticeable.

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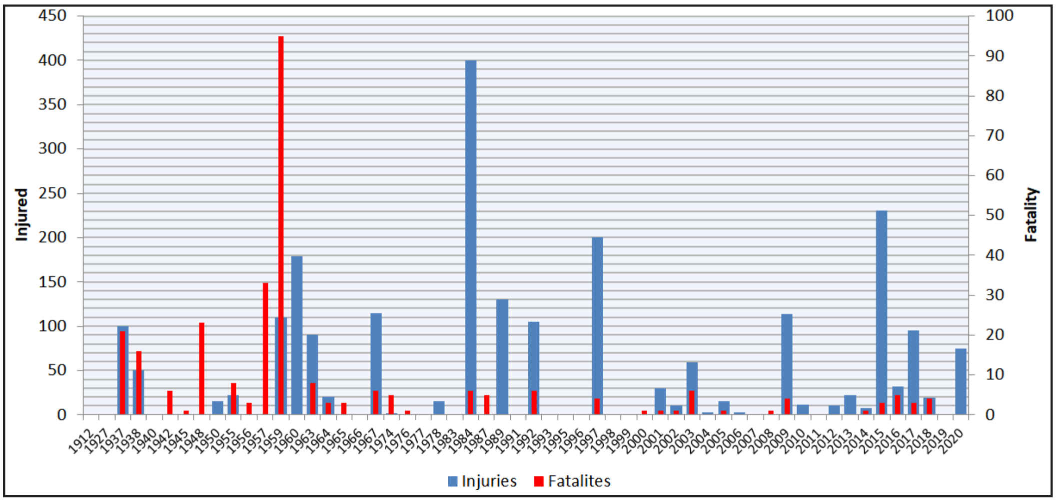
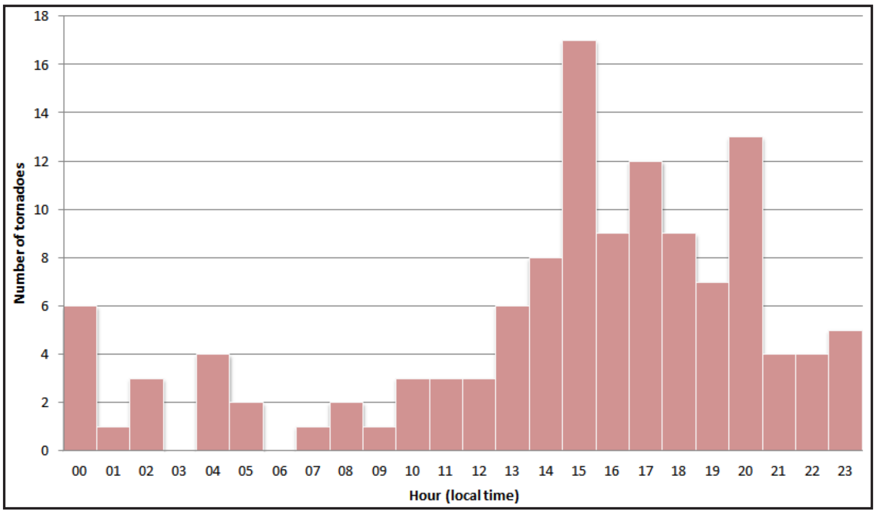
Figure 5 – Annual number of injuries (blue bars and left column) and fatalities (red bars and right column) associated with tornado occurrences in southern Brazil, from the first record in the database (bars)



Source: The authors (2024)

Figure 6 – Hourly distribution (in bars) of the 123 cases of tornadoes with information about the local time of the occurrenne



Source: The authors (2024)

Despite the lack of information about the time of occurrence of many tornadoes, it was possible to determine the time of formation of 123 events, that is, 39 % of the sample from the southern region (Fig 6). The peak of cases occurs around 3pm LST, which is close to the warm period of the day. The secondary peak of occurrences that occurs at 20:00 LST seems to be associated with the diurnal cycle of the LLJ (Kis e Straka, 2010; Reames, 2017) that promotes the intensification of low level shear.

In the United States Trapp et al. (2005) cites a well-defined peak of occurrences around 18 LST, largely driven by the formation of discrete storms. However, there are nocturnal and early morning occurrences that are associated with tornadoes forming along quasi-linear convective systems. For the cases analyzed here, a slight increase is noted at 4 am, however the convective mode associated with the formation of tornadoes is not the focus of this study, an issue that can be addressed in future work.

4 FINAL REMARKS

This work reinforces the need for a standardized record of tornado events in southern Brazil and the subtropical area of South America, including the importance of in situ damage analysis to better define the intensity of cases (Fujita e Smith, 1992). In the future, such an approach may allow identifying trends of change in location and frequency of events in the main tornado hotspots documented from the analysis conducted in this work. Similar to what Antonescu et al. (2017) discussed for the European reality, in southern Brazil the occurrence of tornadoes is also an underestimated threat.

The highest probability of occurrence of tornadoes in the region, compared to all seasons of the year, occurs in winter in an area that includes the north of RS, west of SC and extreme south of PR. Despite the existence of works that indicate spring as the season that most presents a combination of ingredients for severe weather in this sector of the continent (Nascimento et al., 2016), the presence of more intense wind shear in winter favors the formation of rotating storms, even in environments with low instability. In fact, high shear and low CAPE events occur during the season, including intense tornadoes forming (Lara et al., 2019; Lopes e Nascimento, 2020).

The future complement of past cases involves the search in municipal historical collections that can contribute to reduce the gap of historical events and allow identifying the dates, for example, of some cases documented by Dyer (1988), at least in southern Brazil. Forensic re-analyzes such as the one conducted by Holzer et al. (2018) in the assessment of tornadoes in Europe at the beginning of the 20th century may be performed in the future, especially for significant events and seeking a better understanding of the synoptic conditions that favored the formation of severe storms.

There is an increasing trend in the number of documented cases that is not found in the number of victims that tornadoes cause, since the presence of digital media and cameras increases the chance of registration and constructions have evolved over the last few decades. The adaptation of the Fujita scale to the Brazilian construction standard and the increase in post-event damage analysis is crucial for better estimates of wind intensity, aiming at improving engineering standards and mitigating the impacts generated. Even without these changes, the presence of buildings that are more resistant to damaging winds already seems to have contributed to a reduction in the number of fatalities in recent decades.

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How to quote this article

Lopes, M. M., & Nascimento, E. de L. (2025). Climatology of tornado occurrences in southern Brazil. *Revista Ciencia e Natura*, v. 47. n. esp. 3, e84051. DOI: https://doi.org/10.5902/217946084051. Disponível em: https://doi.org/10.5902/2179460X84051.