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Atmospheric patterns of extreme rainfall events in the eastern region of the state of Paraná

Padrões atmosféricos de eventos pluviométricos extremos na região Leste do estado do Paraná

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Abstract

Knowledge of the atmospheric patterns associated with the occurrence of extreme rainfall events can support the prediction of impacts, minimizing the human and material losses. Thus, this research evaluated the performance of the atmospheric systems responsible for the occurrence of extreme rainfall events in Curitiba and Paranaguá, eastern region of the state of Paraná. Data from different weather attributes recorded by conventional weather stations in both municipalities for the period between 1976 to 2015 were analyzed. The extreme rainfall events selected to apply the Rhythm Analysis (RA) were based on the use of the Ward's method for the daily rainfall data which are greater than 99% of the percentiles. The Synoptic conditions responsible for extreme rainfall events were extracted from the synoptic letters provided by the Brazilian Navy and the "Technical Bulletin" of the Center for Weather Forecast and Climatic Studies. The RA showed that during winter there is the predominance of cold fronts and rainfall totals are spatially more homogeneous, while during summer there has a greater spatial difference, and the atmospheric conditions are frequently associated with the interactions of combination between tropical and extratropical systems.
Keywords: Extreme Rainfall, Atmospheric Systems, Rhythm Analysis.

Resumo

O conhecimento dos padrões atmosféricos associados à ocorrência de eventos pluviais extremos pode subsidiar a previsão de impactos, minorando a perda de vidas humanas e bens materiais. Sendo assim, esta pesquisa avaliou a atuação dos sistemas atmosféricos responsáveis pela ocorrência de eventos pluviais extremos em Curitiba e Paranaguá, região Leste do estado do Paraná. Foram analisados os dados de diferentes atributos meteorológicos registrados pelas estações meteorológicas convencionais em ambos os municípios para o período de 1976 a 2015. Os eventos pluviais extremos selecionados para a aplicação da Análise Rítmica (AR) se deram a partir da utilização da técnica de agrupamento pelo método Ward para os registros diários superiores a 99%

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dos percentis dos quantis. As condições sinóticas responsáveis pelos eventos pluviais extremos foram extraídas das cartas sinóticas disponibilizadas pela Marinha do Brasil e pelo "Boletim Técnico" do Centro de Previsão de Tempo e Estudos Climáticos. A AR demonstrou que durante o inverno há a predominância das frentes frias e que os totais pluviais são espacialmente mais homogêneos, ao passo que durante o verão foram verificadas maiores diferenças espaciais e condições atmosféricas frequentemente associadas à combinação da interação entre os sistemas atmosféricos tropicais e extratropicais.
Palavras-chave: Chuvas Extremas, Sistemas Atmosféricos, Análise Rítmica.

I. INTRODUCTION

Knowledge about the characteristics of the rainfall regime contributes to decision-making in strategic areas for economic and social development, such as electricity generation, civil defense, industrial activities, and agricultural planning (SANTOS *et al*., 2016; DALAGNOL *et al*., 2022). Smit *et al*. (2000) describe that rainfall variability consists of variations in relation to the average state, whether measured by statistical deviations and, eventually, by extreme events, which can be attributed to the natural internal processes of the climate system or to anthropogenic modifications.

From this perspective, understanding the occurrence of extreme rainfall events and the associated atmospheric conditions are of paramount importance for various areas of interest in Climatology and for the prediction of human and material losses (SELUCHI; CHOU, 2009; FRAME *et al*., 2020). In addition to climatological normals, it is noteworthy that among the most relevant aspects of studies on rainfall are the occurrences of extreme daily rainfall events in tropical and subtropical regions, triggering floods, overflows, landslides, erosion, and loss of arable land and, above all, countless human and material losses (SEPÚLVEDA; PETLEY, 2015; OSCAR-JÚNIOR, 2021; GOUDARD; MENDONÇA, 2022).

The sector chosen for this research corresponds to the east of the state of Paraná, in a region coinciding with the Alto Iguaçu, Litorânea and Ribeira river basins. On the east coast of the South region, mainly on the coast of Paraná, there is significant contribution from the orographic effect to the occurrence of higher rainfall totals, since surface winds diverge from the South Atlantic Subtropical High parallel to the coast and are forced to ascend due to the presence of Serra do Mar, close to the coast, favoring the conditions for the formation and generation of rain. However, it is important to highlight that the South of Brazil has a predominance of frequent action by the Atlantic Polar Front, the main mechanism for generating rain in this region (REBOITA *et al*., 2010; BORSATO; MENDONÇA, 2015; SELUCHI *et al*., 2016).

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One of the strategies used to identify the genesis of rain is the Climatological Rhythm Analysis disseminated by Monteiro (1971). Rhythm Analysis allows the identification of weather types and the dialectical singularity between climatic attributes and atmospheric dynamics, as this relationship is not necessarily linear. In this context, the objective of this research is to evaluate the performance of the atmospheric systems responsible for the occurrence of extreme rainfall events in Curitiba and Paranaguá, eastern region of the state of Paraná.

II. Materials and Methods

Initially, rainfall data were obtained from 54 rainfall stations belonging to the National Water Agency (ANA), Energy Company of Paraná (COPEL) and Water and Land Institute (IAT), and data on rainfall, air temperature, relative air humidity (RH), cloudiness, wind direction and intensity and atmospheric pressure were obtained from 8 weather stations controlled by the Agronomic Institute of Paraná (IAPAR), National Institute of Meteorology (INMET) and the Paraná Meteorological System (SIMEPAR), which comprise the historical series from 1976 to 2015.

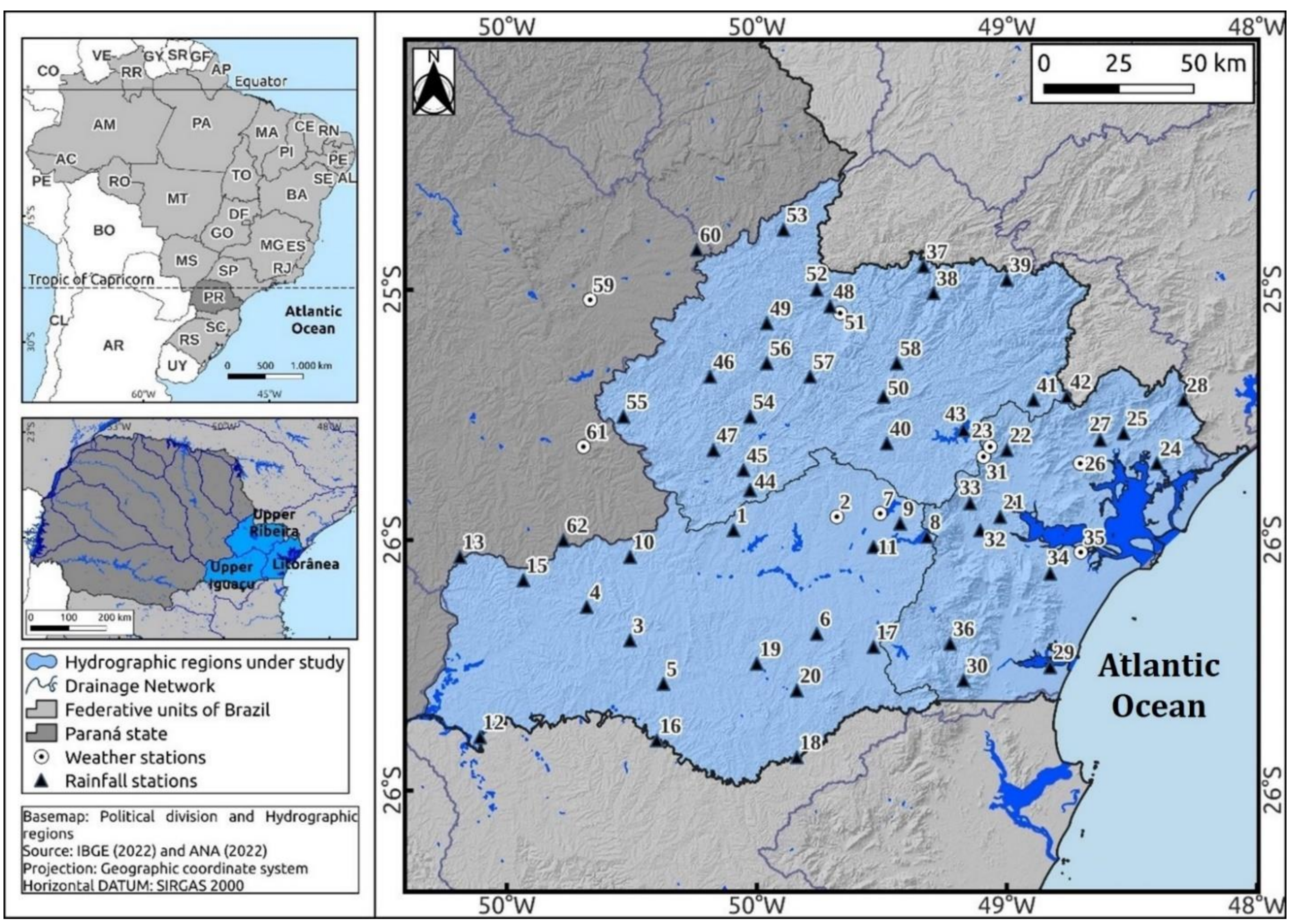

Figure 1 - Location of weather stations and rainfall stations. Source: The authors.

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Data from the following weather stations located in the following locations were widely used: ID 2 (Curitiba); ID 7 (Pinhais); ID 23 (Antonina); ID 26 (Guaraqueçaba); ID 31 (Morretes); ID 35 (Paranaguá); Cerro Azul (ID 51); Castro (ID 59); and Ponta Grossa (ID 61) - (Figure 1). However, due to the scope and volume of data, this research used data referring to conventional weather stations administered by the National Institute of Meteorology (INMET) in the locations of Curitiba (ID 2) and Paranaguá (ID 35), as shown in Figure 2; flaws recorded in the data of the highlighted attributes were less than 5%. Further details are described in greater detail in Terassi (2019).

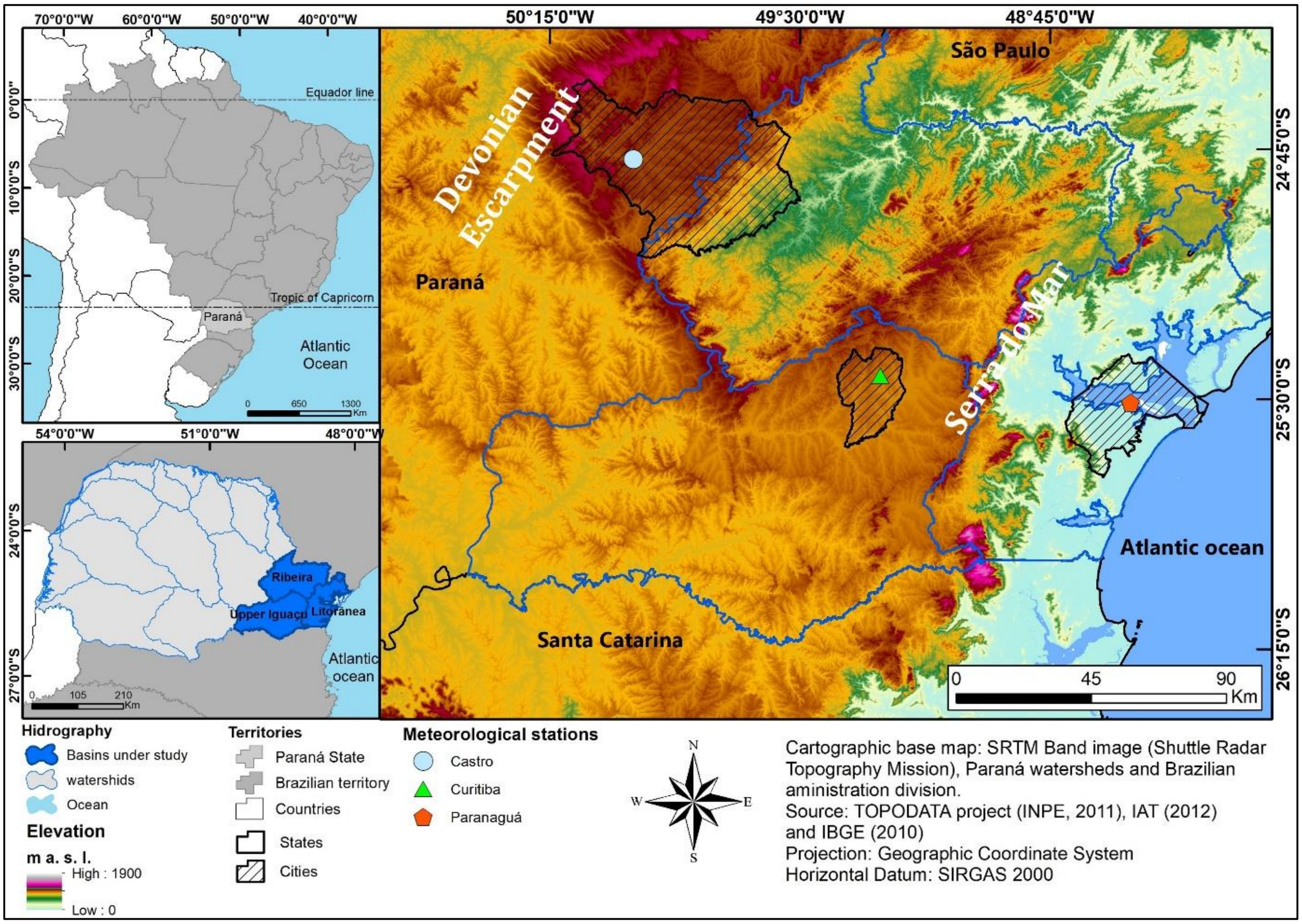

Figure 2 - Geographical location of the conventional weather stations of Curitiba and Paranaguá, Paraná.
Source: Terassi et al. (2022).

The synoptic conditions for extreme rainfall events were defined by Monteiro's Climatological Rhythm Analysis (1971), using the following climatic attributes: atmospheric pressure (mb) at sea level; relative humidity (%); average, maximum, and minimum air temperature (ºC); daily rainfall (mm), wind speed (m/s) and direction (º); cloudiness (tenths of sky coverage). However, due to the volume of information, we opted for the set of graphs without data regarding wind speed and cloudiness; this information is fully available in Terassi (2019).

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The definition of the active atmospheric systems followed the criteria established and described by Zandonadi (2013), Fontão and Zavattini (2017) and Fontão *et al*. (2018): atlantic Tropical mass (aTm), continental Tropical mass (cTm), continental Equatorial mass (cEm), atlantic Polar mass (aPm), tropicalized Atlantic Polar mass (taPm), Atlantic Polar Front (APF), Stationary Atlantic Polar Front (SAPF), Dissipating Atlantic Polar Front (DAPF), Repercussion of the Atlantic Polar Front (RAPF), Retreat of the Atlantic Polar Front (Ret.APF), the Line of Tropical Instability (IT), Cyclonic Vortices, Extratropical Cyclones, Subtropical Jets and Troughs.

It is important to highlight that the atmospheric mechanisms South Atlantic Convergence Zone (SACZ) and Humidity Convergence Zone (HCZ) were not described in the work of Monteiro (1971) and were added in this research. To define atmospheric systems, information from the "Climate Monitoring and Analysis Bulletin" (CLIMANÁLISE) and the "Technical Bulletin" (INPE, 2019) were used, issued by the Center for Weather Forecasting and Climate Studies (CPTEC/INPE).

To characterize the types of weather responsible for extreme rainfall events, we used the synoptic charts made available by the Department of Hydrography and Navigation of the Brazilian Navy and for more recent rainfall events, after 2008, the synoptic charts made available by the "Technical Bulletin" from CPTEC (INPE, 2019) were also added to the analysis. According to Armani and Galvani (2011), the analysis of the sequence of synoptic charts, evaluating the genesis and trajectory of atmospheric systems, allows the conception of rhythm of atmospheric systems, with the quantitative expressions of climatic elements being directly linked to the regional atmospheric circulation mechanism. Due to the volume of information, these synoptic charts are available in the supplementary material item (Figures S1 to S5).

The extreme rainfall events selected for the application of Monteiro's Climatological Rhythm Analysis (ARC) (1971) were based on the use of the grouping technique using the Ward method for daily records greater than 99% of the quantile percentiles, as shown in Figure 3. More details about the grouping analysis are available in Terassi and Galvani (2017) and Zerouali *et al*. (2022). The quantile technique is based on the distribution of the accumulated frequency, and the approximation of the probability density function (fdp) that describes the phenomenon is better the greater the number of observations available. The intervals of each percentile represent the expected probabilities or frequencies for each of the events that may occur in the sequence of the time series of a variable *x* (OLIVEIRA; GALVANI, 2017).

Data from the Oceanic Niño Index (ONI) were used to verify probable relationships between the El Niño-Southern Oscillation (ENOS) and extreme rainfall events, given that the different phases of this oceanic climate indicator influence the interannual variability of rainfall in this sector of Brazilian territory (PEDRON *et al*., 2017;

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REBOITA *et al*., 2021; SOUZA *et al*., 2021). To this end, information was obtained from the National Oceanic and Atmospheric Administration (NOAA, 2023) database, defined as neutral (NE), El Niño (EN) and La Niña (LN), in line with the criteria established and described in greater detail in Terassi *et al*. (2018).

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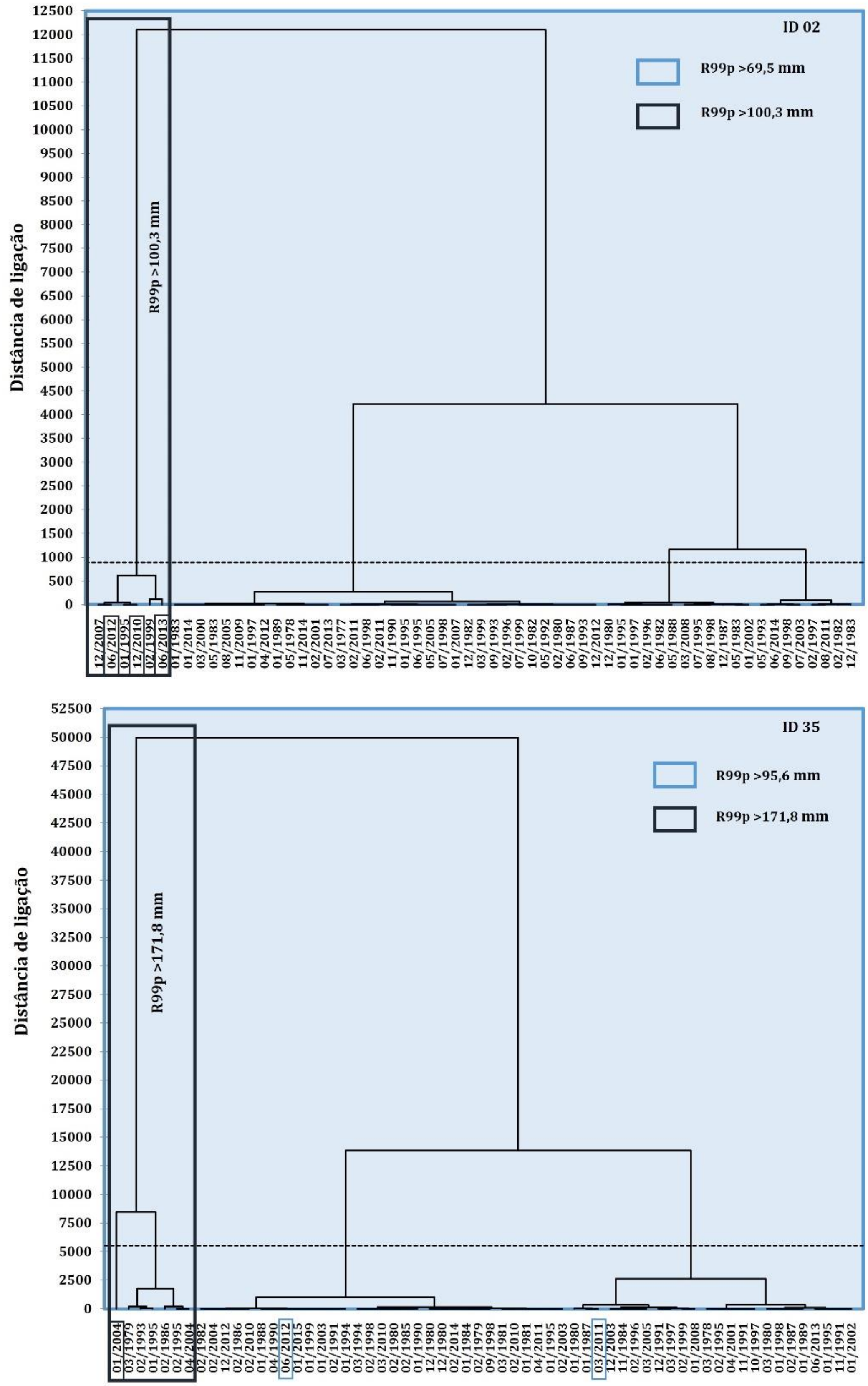

Figure 3 - Dendrogram used to select extreme rainfall events among daily records of rainfall greater than 99% of the percentiles (R99p) in Curitiba (ID 2) and Paranaguá (ID 35). Source: The authors.

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To select the rainfall events for the analysis of the atmospheric conditions that caused them, the grouping technique was used for all records of intense rainfall in the locations of Curitiba and Paranaguá. In Curitiba, the dendrogram separated the 6 most intense daily records (>100.3 mm) among the 60 extreme rainfall events greater than 99% of the quantiles. The selection criterion to evaluate the atmospheric conditions associated with the highest rainfall levels was to choose the two most recent records in winter and summer conditions. The aforementioned events, for Curitiba, are the second highest daily rainfall in the location's historical series, in June 2013 (130.8 mm), and the most recent intense rainfall in summer conditions, in December 2010. These assumptions followed the premise that evaluating the most distinct seasonal conditions can associate these rainfall extremes with different atmospheric mechanisms, emphasizing winter, in which daily rainfall was higher in the capital of Paraná compared to Paranaguá, on the coast (Figure 3 - Table 1).

Table 1 - Accumulated rainfall totals (mm) during the selected extreme events in Curitiba and Paranaguá, Paraná.

Curitiba				**Paranaguá**			
Year	**Month**	**Day**	**Rainfall (mm)**	**Year**	**Month**	**Day**	**Rainfall (mm)**
2010	12	14	100.3	2004	1	25	295.8
2012	6	5	106.8	2011	3	12	159.0
2013	6	21	128.2	2012	6	5	115.6

Source: National Institute of Meteorology (INMET).

In Paranaguá, it was observed that out of the 7 highest daily rainfalls, 5 occurred in January or February, and all between January and April, notably the period of greatest rainfall intensity. Although rainfall in the state of Paraná is relatively well distributed throughout the year, the accumulated totals are more significant during the summer. On Coastal BH, the sector in which Paranaguá is located, rainfall totals in this period are more significant during this seasonality (JORGE; MENDONÇA, 2009; FRITZSONS *et al.*, 2011). Therefore, the most recent extreme rainfall event was selected for the winter condition, in June 2012, in an unusual situation of intense rain in this seasonality, and two events in the summer period, observed in January 2004, this being the largest total daily rainfall of the entire historical series in Paranaguá, and in March 2011, with the aim of investigating typical conditions of intense rain on the coast of Paraná (Figure 3 - Table 1). In Paranaguá, the definition of the highest rainfall totals as defined by the dendrogram was not strictly followed, as some of these cases showed a lack of data records, which made an appropriate rhythm analysis difficult.

III. Results and Discussions

The occurrence of the extreme event of June 2012 was identified in Curitiba and Paranaguá. On the 3rd, a frontal system (SF) entered southern Brazil, which resulted in a decrease in air temperature, a significant

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decrease in atmospheric pressure and winds from the N and NW directions, which are typically pre-frontal conditions. On the 4th, the entry of the APF caused rainfall between 15 and 17 mm, with a decrease in temperatures and an increase in RH and, on the following day, with the main axis of the APF between the west of Mato Grosso and the south of São Paulo, the highest daily rainfall totals were recorded in Curitiba (106.8 mm) and Paranaguá (115.6 mm). On the 6th, the atmospheric system became an SAPF and maintained its position from the previous day and with rainfall between 2 and 6 mm recorded. Even with the retreat of the SAPF on the 7th, local atmospheric conditions generated only light rain (<8 mm) in both locations and, notably, with the increase in atmospheric pressure and the decrease in temperatures there were indications of the entry of the APM, which in the following days resulted in minimum temperatures of up to 7°C and 12°C in Curitiba and Paranaguá, in this order (Figure 4 and 5 - Figure S1).

Throughout June 2012, the NE period in relation to ENOS, the passage of eight frontal systems across southern Brazil resulted in rainfall above the Climatological Normal in Paraná, generating extreme rainfall events in several regions of the state. In Curitiba and Paranaguá it rained 225.5 and 239.8 mm, while the historical series indicates averages slightly higher than 100 mm for the month of June. In relation to the extreme event recorded on the 5th, it is possible that it is related to the strong magnitude of the aPm that was in the rear, an atmospheric system highlighted as the most intense among those identified in this period, and the air shock of different temperature and humidity conditions caused the significant rainfall recorded. The intensity of this aPm is suggested by the rapid displacement of the APF between June 3 and 4 and by the significant increase in the scope of the Polar Migratory Anticyclone isobars, as demonstrated by Figures 4 and 5 and in Figure S1.

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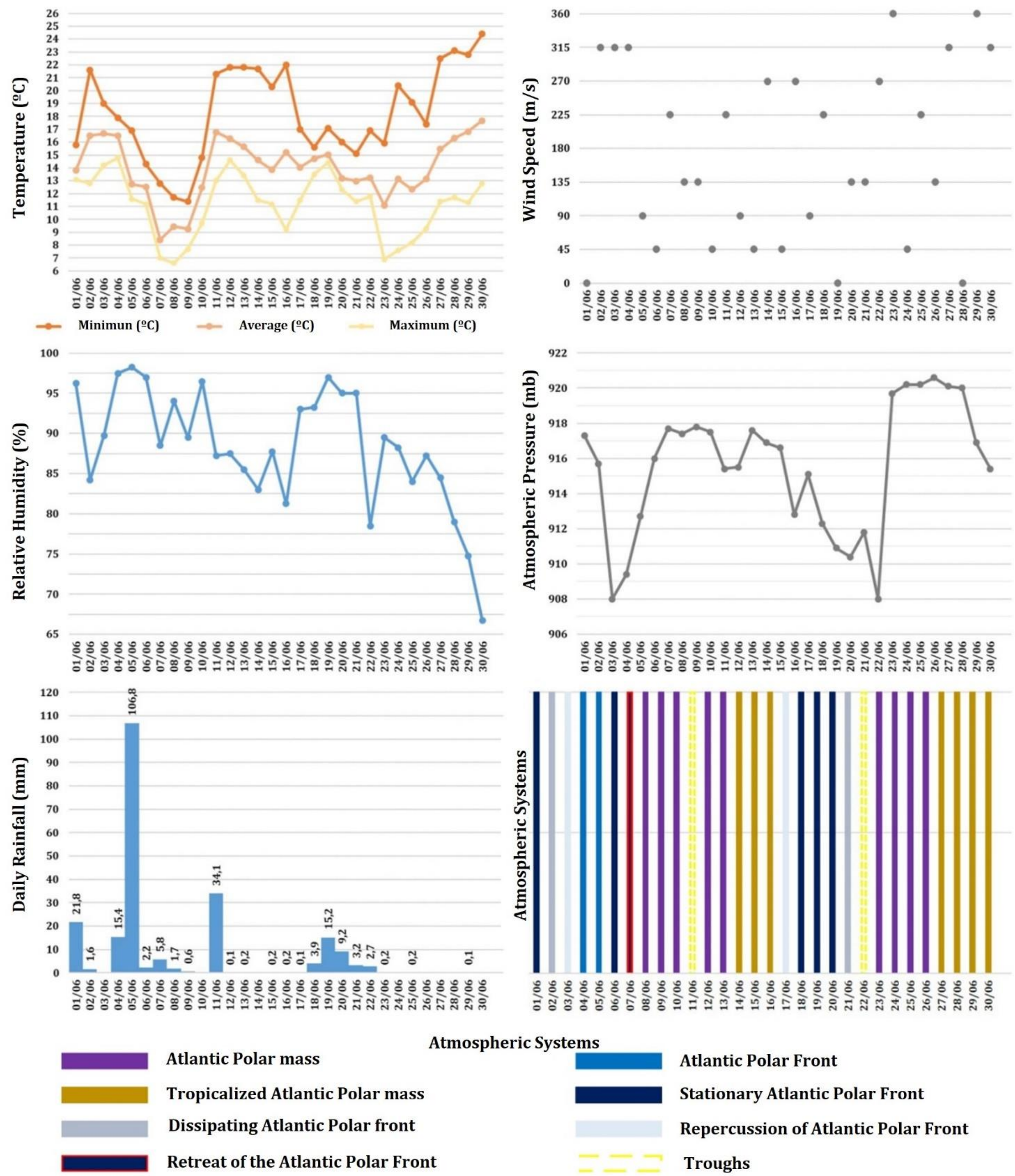

Figure 4 - Rhythm analysis of the June 2012 rainfall event in Curitiba - Paraná. Source: The authors.

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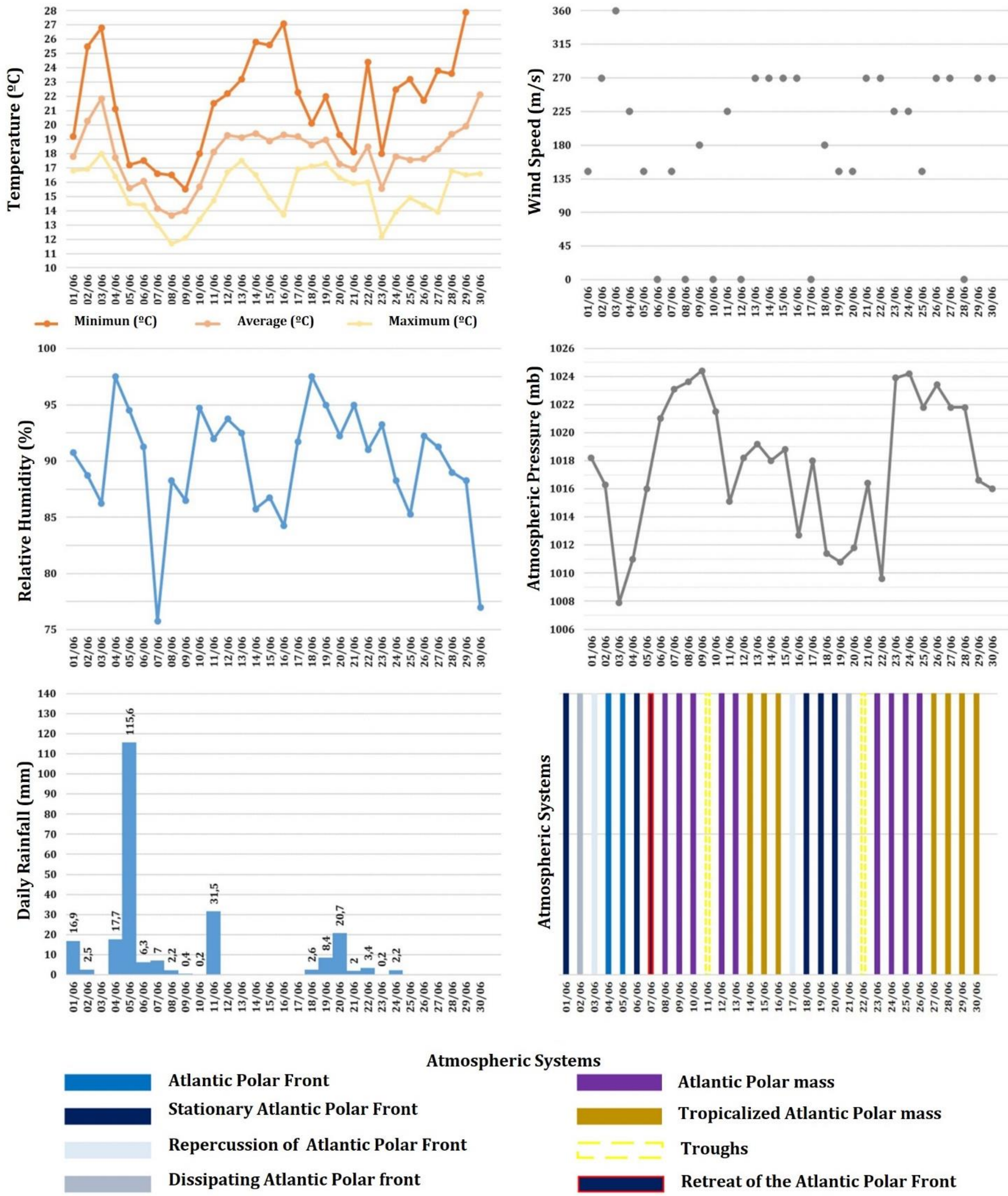

Figure 5 - Rhythm analysis of the June 2012 rainfall event in Paranaguá - Paraná. Source: The authors.

One of the largest daily extreme rainfall events recorded in Curitiba occurred on June 20, 2013, an NE period in relation to ENOS, with a daily total of 128.2 mm. It is observed that until the 19th of that month, the

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climatic rhythm was dominated by the conditions of alternation between extratropical atmospheric systems that generated successive rain conditions of up to approximately 30 mm, a reduction in temperatures and, subsequently, an increase in maximum daily temperature, showing the incursion and/or formation of APF or SAPF, aPm and taPm. The formation of a trough under the southern region of Brazil on the 19th generated 9.7 mm of rain in Curitiba and, on the following day, the rapid advance of the APF and evolution to SAPF was the mechanism responsible for the high rainfall totals in the capital of Paraná. The retreat of the SAPF on the 21st continued to generate atmospheric instability and resulted in 39.6 mm of rain, accompanied by a sharp drop in atmospheric pressure (906 mb). The following day, there was a sharp drop in temperature, with a minimum of 6°C, increase in atmospheric pressure (>911 mb) and atmospheric stability associated with the action of aPm (Figure 6 - Figure S2).

This characteristic of predominance of frontal systems in the generation of rainfall in the southern region of Brazil is highlighted by Borsato and Souza Filho (2010), since the total rainfall resulting from frontal systems is greater than 68% in Maringá (PR), especially between April and October, with an increase in the participation of cEm and SACZ between November and March, a period in which intertropical systems frequently interact with the APF. Therefore, this analysis is in line with that described in previous works on regional atmospheric dynamics (BORSATO; MENDONÇA, 2015; CARDOZO *et al*., 2015) which allow us to state that the eastern region of Paraná has frequent passage of the APF, which makes the rains mostly frontal in nature. However, Zandonadi (2013) highlighted that in summer and spring in locations in the state of Paraná there is an increase in the participation of intertropical systems and their association with those of extratropical origin in rainfall generation, and these authors restricted themselves to investigating the performance of atmospheric mechanisms in generating the accumulated totals and not in causing extreme daily rainfall events.

Analyzing the extreme spring/summer rainfall events, it was observed that December is characterized as the month with the third highest average monthly rainfall (155.2 mm) in Curitiba and in 2010 it recorded a total of 336.2 mm, thus being a positive anomaly close to 115%, which was due to the constant action of several atmospheric systems, of extratropical and intertropical origin, in LN conditions. On the 12th of this month, there was a drop in atmospheric pressure (905 mb), the absence of hours of sunshine, a significant drop in air temperature and an increase in RH (>95%), winds of SW origin, and the prelude to the APF came with 36.2 mm of rain. Upon entering the state of Paraná, the APF became stationary on the 13th and had the characteristics of the most pronounced drop in atmospheric pressure (901 mb), the reduction in average air temperature (12.1°C), the increase in RH (96%) and the occurrence of 100.3 mm. It was noted that in the days prior to the

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entry of this SAPF, the maximum daily temperatures in Curitiba were above 29°C, which possibly triggered unstable conditions in the face of this atmospheric mechanism and generated the extreme rainfall event (Figure 7 - Figure S3).

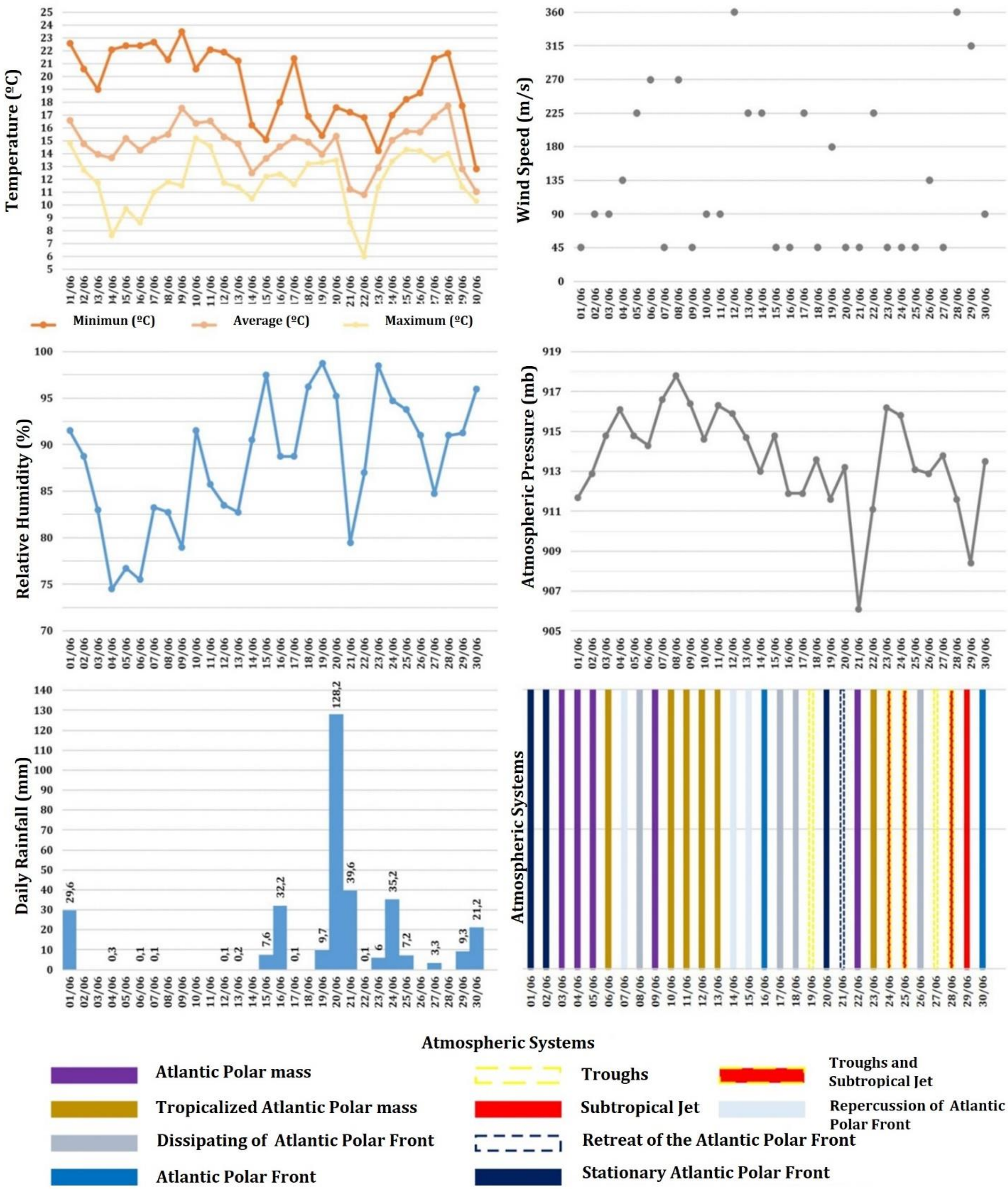

Figure 6 - Rhythm climatic analysis of the June 2013 rainfall event in Curitiba - Paraná. Source: The authors.

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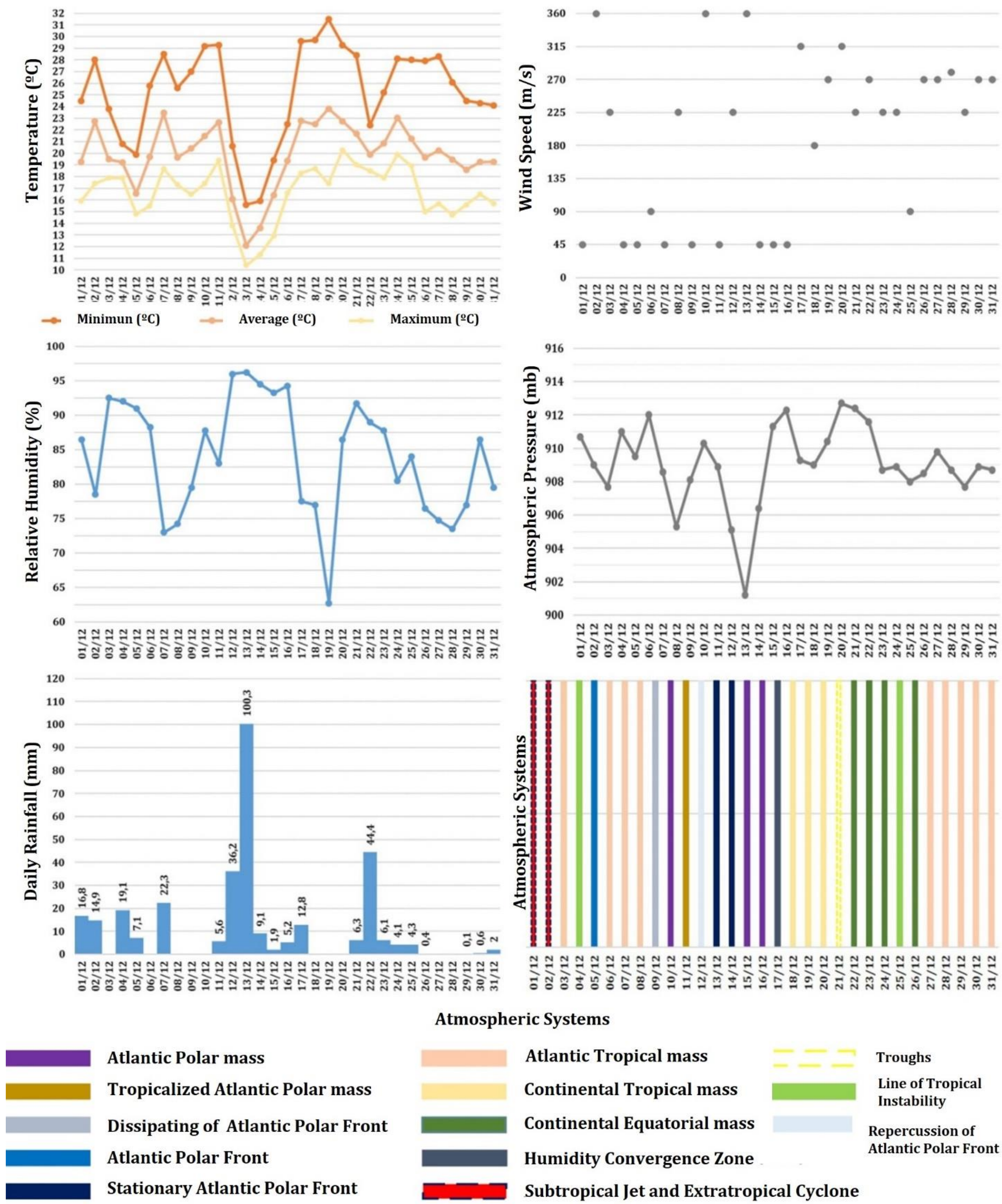

Figure 7 - Rhythm climatic analysis of the December 2010 rainfall event in Curitiba - Paraná. Source: The authors.

The main extreme event among those selected for Paranaguá occurred in January 2004, a NE period in relation to ENOS, since after weeks with little rain, on January 25th there was a record of concentrated daily

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rainfall of 295.8 mm. On the 22nd, the entry of the APF through the south of Brazil only resulted in an increase in RH (84%), a decrease in atmospheric pressure (<1001 mb) and winds in W direction. In the days preceding the entry of another APF, the Troughs changed the weather conditions with a total rainfall of close to 55 mm accumulated on the 23rd and 24th. Above all, the abrupt entry of an SAPF associated with the formation of a SACZ generated the largest volumes of rain accumulated in 24 hours in Paranaguá, with signs of atmospheric instability such as winds from SW direction, a significant reduction in atmospheric pressure and an increase in RH. On the following days (26 and 27), it was found that the SAPF was associated with the southern positioning of the SACZ and, although it favored intense rain conditions, there were totals on both days that totaled just 15 mm (Figure 8 - Figure S4).

It should be noted that January is the rainiest month for Paranaguá, with an average of 325.7 mm for the series analyzed, and in 2004 it showed an accumulated total of 510.5 mm, that is, it rained 56.8% above normal. The weak action of frontal systems over the south of the country contributed to the predominance of below-average rainfall in almost this entire region and, however, the coast of the state of Paraná had anomalous rainfall conditions, markedly due to the central positioning of the SACZ on the south coast of São Paulo. The high-level runoff kept the VCANS closer to the coast of Northeast Brazil and maintained the SACZ over the south of the Southeast region and, with the stationary cold front under the Atlantic Ocean, there was a reinforcement in the conditions of atmospheric instability and intense rains on the coast of Paraná (CLIMANÁLISE, 2023), and the restriction of this influence of the SACZ to this sector of Paraná in the formation of high rainfall totals is demonstrated in Table 2, with accumulated values in five days exceeding 250 mm in Antonina, Morretes and Paranaguá.

One of the main extreme events selected in spring and summer conditions occurred on March 12, 2011 in Paranaguá, with a total of rain equivalent to 159 mm in 24 hours, expressly lower than that identified in January 2004, but which was in conditions of significant rainfall totals in the days close to its occurrence. Between the 8th and 13th, the formation of a Trough, notably, combined with the action of a Cyclonic Vortex between the 9th and 12th, caused great atmospheric instability and generated rain that between the 11th and 12th totaled 243 mm, with the average total for March in Paranaguá being 208.3 mm. After this period of high rainfall totals, lower daily rainfall totals of less than 20 mm were observed until the 27th, with aTm being decisive in the types of time for elevation of air temperature and atmospheric pressure and reduction of RH, while the rains were generated by the entry of the APF or the Subtropical Jet (Figure 9 - Figure S5).

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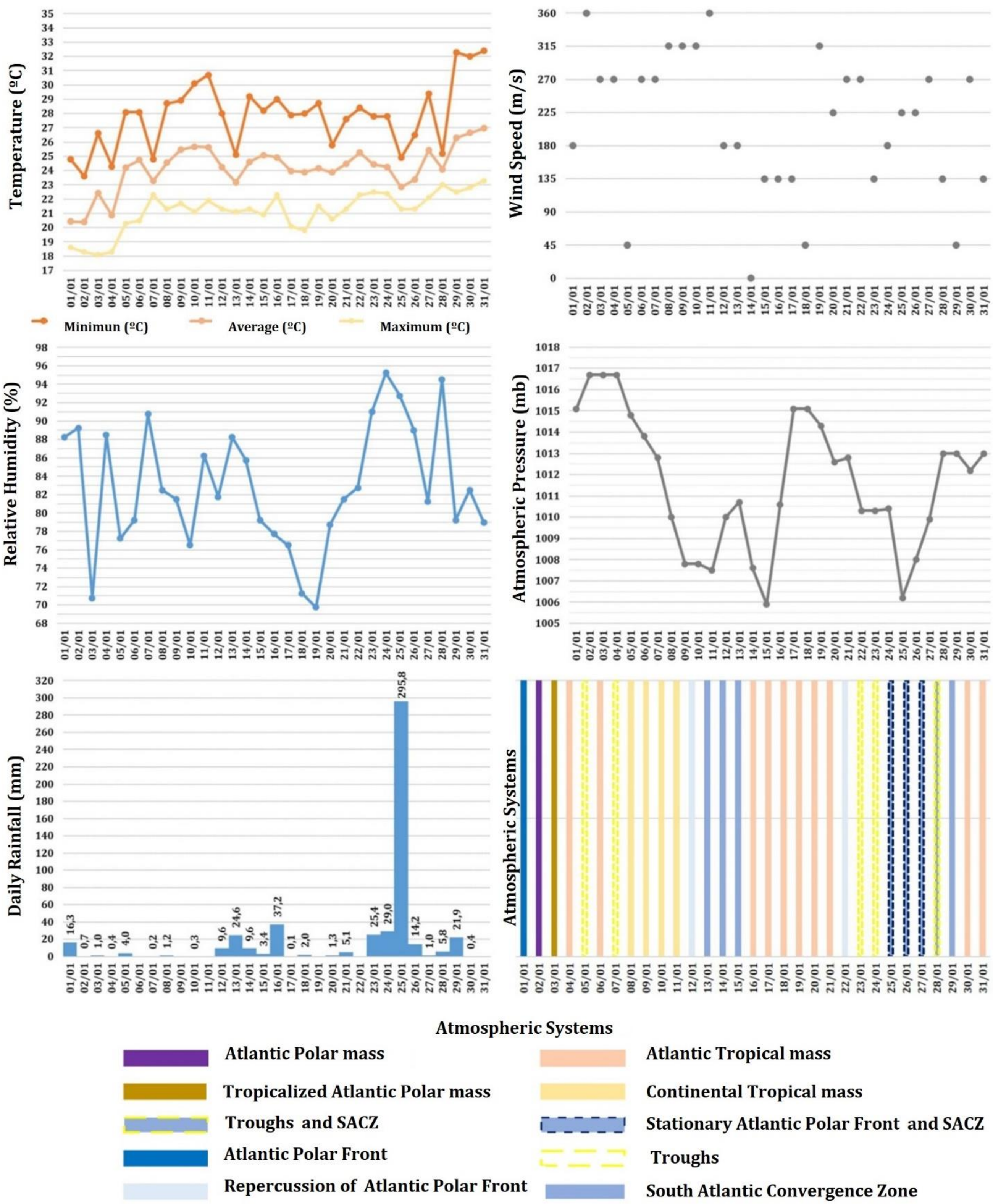

Figure 8 - Rhythm climatic analysis of the January 2004 rainfall event in Paranaguá - Paraná. Source: The authors.

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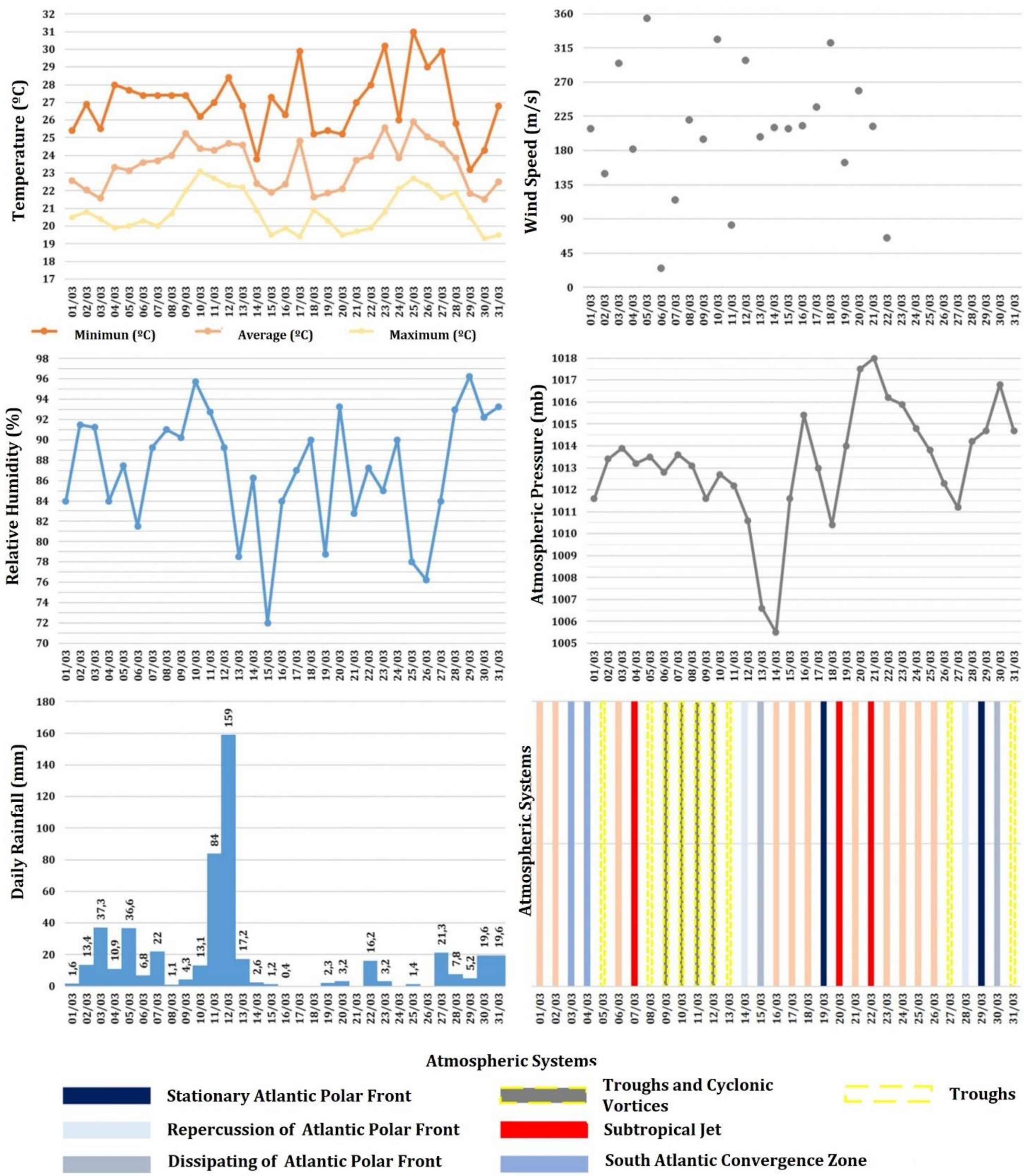

Figure 9 - Rhythm climatic analysis of the March 2011 rainfall event in Paranaguá - Paraná. Source: The authors.

In total, the equivalent of 511.3 mm of rain fell in March 2011 in Paranaguá, around 145% above the climatological average for this location. It is noteworthy that in almost the entire southern region of Brazil there was above-average rainfall, particularly due to the occurrence of strong and intense rains between the 10th and

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13th, highlighting the formation of Troughs and Cyclonic Vortices at 500 hPa during this period of atmospheric instability (CLIMANÁLISE, 2023).

It should be noted that from the second half of March (2011) the strong action of the Subtropical Jet and the greater frequency of APF entry generated an increase in the frequency of rainy days (CLIMANÁLISE, 2023). In other locations on the coast of Paraná, it was noted that the monthly accumulation reached 760.5 mm in Morretes (ID 32) and 555.2 mm in Antonina (ID 21), much higher than the approximate average of 240 mm at these rainfall stations and that in the four-day period highlighted above, they recorded 537.7 and 379.2 mm, in that order.

Although the Troughs and Cyclonic Vortices generated high magnitude rainfall in the South of Brazil, these mechanisms did not act in a generalized way, as sectors such as the west of Rio Grande do Sul and the Central-East of Paraná (Vale do Ribeira and Metropolitan Region of Curitiba) showed the record of a negative rainfall anomaly exceeding 50 mm for the month of March 2011 (CLIMANÁLISE, 2023). The peculiar difference in precipitation that occurred this month of March demonstrates a typical spatial characteristic of rainfall throughout the summer months of the area under study, especially due to the large increase in rainfall in this seasonality for the coastal river basin (BH), highlighting the action of the maritime nature in favoring frequent conditions of heavy and intense rain.

In order to analyze the impact of different atmospheric systems on the occurrence of extreme rainfall events in other weather stations in the area under study, records of rainfall totals accumulated during the two days before and after the occurrence of the highlighted rainfall anomaly were selected. In short, it is observed that extreme daily rainfall events occurred in different magnitudes in the locations of the area under study, a condition attributed to the active atmospheric system and the geographic location of the weather station, synthetically showing the interaction between static and dynamic factors in the formation and generation of rain.

The extreme event that occurred most homogeneously among those analyzed occurred in June 2012, a period of ENOS neutrality, with average values of 140 mm, amplitude of 60 mm and the lowest coefficient of variation (CV = 11.9%). The highest accumulated totals occurred in Coastal and Alto Iguaçu BH, Castro (ID 59) and Pinhais (ID 7) - (>145 mm), while in Cerro Azul the lowest values were recorded (101.2 mm), relative homogeneity which is due to the APF's role in generating rainfall. During the analysis of the totals accumulated in the extreme event of June 2013, a period of ENOS neutrality, a higher CV (25.6%) was noted and that the highest totals occurred in Alto Iguaçu and Coastal BH, highlighting Curitiba and Morretes (ID 31) - (>175 mm),

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with SAPF being the atmospheric condition responsible for these high rainfall totals. With the exception of Coastal BH, in Guaraqueçaba (ID 26) and next to Castro and Cerro Azul (ID 51), located to the east and northeast of the BHs, rainfall totals were less than 115 mm, with emphasis on the 72.0 mm recorded in Cerro Azul. The lowest absolute maximum totals in Cerro Azul correspond to a pattern attributed to its location, as it is located in the Vale do Ribeira region, where the influence of the tropical climate and low altitudes determine the lowest rainfall totals during winter (TERASSI; GALVANI, 2017).

The largest daily rainfall event in Paranaguá occurred in January 2004 in atmospheric conditions associated with the combined action of the SACZ and the APF. As expected for an intertropical atmospheric system, rainfall occurred irregularly in the different sectors of the BHs, with a higher concentration in the coastal region, with the highest totals in Antonina (ID 23), Morretes and Paranaguá (>250 mm) and, conversely, smaller in Castro and Ponta Grossa (ID 61), locations further from the coast and in which the accumulation in five days was less than 40 mm. The standard deviation values infer the great magnitude of this extreme event (111.8 mm) and, however, the other statistical parameters indicate spatial heterogeneity, with an amplitude of 329.4 mm and a CV equal to 67.9% (Table 2).

The heterogeneous characteristic of summer rainfall is highlighted by the March 2011 rainfall event (LN), given the amplitude of 398 mm and a CV equivalent to 100.3%. This is the rainfall event of greatest magnitude for the area under study (s=152.2), with rainfall totals equivalent to 411.0 and 335.1 mm for Morretes and Antonina, in that order, over 5 consecutive days, atmospheric condition attributed to the Troughs and/or the association of the Troughs with Cyclonic Vortices. While high extreme values occurred in the coastal sector, as the formation of the Cyclonic Vortex transported oceanic moisture to this sector, in locations such as Curitiba and Ponta Grossa rainfall totals were close to 15 mm (Table 2). The rainfall totals observed in Morretes correspond to the highest values observed on five consecutive days and truly demonstrate the magnitude of this extreme rainfall event.

Table 2 - Accumulated rainfall totals (mm) during extreme events and on the two days before and after their occurrence at IAPAR, INMET and SIMEPAR weather stations.

Weather Station	**Autumn - Winter**		**Spring - Summer**		
	Jun. 3-7, 2012	**Jun. 18-22, 2013**	**Jan. 23-27, 2004**	**Dec. 11-15, 2010**	**Mar. 9-13, 2011**
ID 2 - Curitiba	130.2	177.9	80.9	151.2	15.0
ID 7 - Pinhais	145.2	154.4	124.4	173.8	25.6
ID 23 - Antonina	148.7	135.0	250.4	131.9	335.1
ID 26 - Guaraqueçaba	140.2	114.0	176.5	134.0	153.0
ID 31 - Morretes	161.2	179.4	268.5	134.0	411.0
ID 35 - Paranaguá	146.6	133.7	365.4	101.7	277.6

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ID 59 - Castro	145.1	106.3	36.0	53.5	49.3
ID 51 - Cerro Azul	101.2	72.0	140.2	79.8	86.6
ID 61 - Ponta Grossa	141.6	154.4	39.8	47.6	13.0
Average (mm)	140.0	136.3	164.7	111.9	151.8
Amplitude	60.0	107.4	329.4	126.2	398.0
SD	16.68	34.97	111.8	43.9	152.2
CV (%)	11.9	25.6	67.9	39.2	100.3

Source: The authors.

From the analysis of the impacts resulting from extreme rainfall events in Curitiba, Zanella (2007) discussed that conditions of extreme calamity were evidenced, with the population being removed from their homes, material losses, illnesses and even human losses, impacts resulting from the extreme rainfall events, highlighted by the accumulation of more than 60 mm in 24 hours. This author highlighted that the APF was the main atmospheric mechanism associated with extreme rainfall events and that, although of lesser importance, the LIT and SACZ also contributed to the generation of the more intense rainfall events. In more recent research, Lohman and Santos (2015) and Goudard and Mendonça (2020) showed the relevance of frontal systems as the main triggers of extreme rainfall events and associated impacts.

Teixeira and Satyamurty (2007) investigated the dynamic and synoptic characteristics of episodes of heavy rain in southern Brazil and highlighted that the low-level jet east of the Andes corresponds to the most frequent source of moisture for frontal systems, but is not exclusively the single specific aspect of intensification of instability, as they also observed that a strong area of humidity divergence is commonly observed over eastern Brazil and the adjacent South Atlantic during the occurrence of intense rains. Also, according to the authors, they specified that the mixing of the convergence flow at 700 hPa is the main characteristic associated with intense rainfall in spring and summer, while during winter the most important variable for indicating high rainfall is warm advection that precedes the entry of frontal systems.

The rhythm analysis carried out by Mello *et al.* (2017) for Paranaguá in summer conditions highlights that, out of five recent extreme rainfall events, between 2011 and 2015, only one was related to the APF incursion. It was observed that in three synoptic conditions, the atmospheric mechanism responsible for the high rainfall totals was the HCZ and in another extreme event there was a predominance of the influence of aTm. The results of this research are partly in agreement with the aforementioned analysis, as under conditions of the SAPF's association with the SACZ, high rainfall totals were recorded in Paranaguá in January 2004, precisely the rainfall event of the greatest magnitude among those analyzed.

In a study to verify synoptic patterns associated with cases of landslides in Serra do Mar in Southeastern Brazil, Seluchi and Chou (2009) identified that most episodes of extreme rainfall and earth movements were

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associated with the passage of frontal systems (APF) and, pre-eminently, to SACZ. In studies by these authors, it was found that the blocking condition of the South Atlantic Subtropical High (ASAS) associated with the circulation of high levels of subtropical latitude (Troughs and the Subtropical Jets) are the most likely to maintain the SACZ further south of its climatological position and generate higher rainfall totals on consecutive days, a persistent climatic condition that results in landslides and earth slips in Serra do Mar.

Also in this sense, it is important to highlight that for the extreme rainfall events identified throughout the summer, there was a pattern of occurrence of neutrality or La Niña, a condition that is associated with a greater frequency of intertropical atmospheric mechanisms such as the SACZ, as pointed out by Verdan and Silva (2022). The greater participation of the SACZ in the regional atmospheric dynamics potentially influenced the occurrence of the highest rainfall totals seen in the extreme events of January 2004 (NE), December 2010 (LN) and March 2011 (LN). However, due to the restricted analysis of some extreme events in this research, it cannot be stated that there is a relational pattern between El Niño events and the occurrence of extreme rainfall events throughout the winter, a condition that is hypothetically associated with the intensification of the Subtropical Jet and the entry of SFs, as the records analyzed in this research, in June 2012 and June 2013, were characterized by ENOS neutrality.

Based on the discussions by Terassi and Galvani (2022) with the application of the Spatial Synoptic Classification (SCC) by Sheridan *et al.* (2002), wetter types of weather occur more frequently in Paranaguá, due to the maritime nature, and are associated with tropical atmospheric mechanisms. Conversely, in Curitiba the typologies indicated a greater frequency of weather types associated with extratropical atmospheric systems, among which is the APF. Therefore, its results fit with those presented in this research, since the extreme events identified during the summer occurred due to the action of tropical atmospheric systems, eventually combined with the entry of cold fronts. Throughout the winter, accordingly, the generation of extreme rainfall events is restricted to the participation of the APF.

IV. Conclusions

The evaluation of the atmospheric conditions associated with extreme rainfall events demonstrated that the largest accumulated daily volumes were under the action of the Atlantic Polar Front (APF), either in its stationary condition (SAPF) or associated with the Subtropical Jets, which is consistent with previous observations of regional atmospheric dynamics. It is noteworthy that this association between the entry of the APF and the occurrence of extreme rainfall occurs in a more linear way during autumn and winter, a period of

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greater activity of frontal systems and, above all, due to the scope of this atmospheric mechanism, rainfall occurs more uniformly, which is proven by the lower coefficient of variation in rainfall observed at weather stations in the study area during these exceptional rainfall events (<27%). However, during the summer and spring, with the greater participation of intertropical atmospheric systems, there is greater complexity in the rainfall genesis of these extreme events, as the extreme rainfall events of 2004 (NE) and 2011 (LN) were associated with the atmospheric conditions of the performance of SACZ and Troughs. One of the main characteristics of extreme rainfall events that occur during spring and summer is their spatial irregularity, with the main example being the one that occurred in March 2011, with totals on five consecutive days equivalent to 411.0 mm in Morretes and 13.0 mm in Ponta Grossa.

In view of this, it is noteworthy that the extreme rainfall events that occurred during autumn and winter are of lower magnitudes than those observed in spring and summer, given the lower values of these records and standard deviations. This is because in autumn and winter regional thermal conditions are also more homogeneous and the lower surface heating is detrimental to convective activity and, consequently, the increase in local humidity in the formation and generation of rain. Regional atmospheric conditions at this latitude during winter reduce rainfall totals due to the greater restriction on extratropical atmospheric systems in generating rainfall in that region, while the interaction between extratropical and intertropical systems corresponds to the main factor in the increase in precipitation records.

Although a predominant homogeneous pattern of frontal systems was observed in the generation of rainfall and, even in some conditions, daily maximum values were higher in the continental sector (BH Alto Iguaçu), the SFs acted in a particular way in each of the extreme rainfall events identified and analyzed. Thus, the limitations of the spatial scope of this research are recognized, since the incursions of atmospheric systems at this scale of analysis occur in a peculiar and complex way in the different sectors of the BHs selected for this study. It is suggested that in a subsequent study, a more detailed and systematized climatological rhythm analysis be used, using the largest possible number of rainfall events and covering meteorological data from other locations.

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