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Investigation on the relationship between extratropical cyclones and storm surge events in southern Brazil

Investigação sobre a relação entre ciclones extratropicais e eventos de ressaca no Sul do Brasil

Maiquel Jantsch*[1]; Carolina B. Gramcianinov [2]; Francisco Eliseu Aquino[1]

[1]Polar and Climate Center, Department of Geography, Graduate Program in Geography, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil.
[2]Institute for Coastal Systems Analysis and Modeling, Helmholtz-Zentrum Hereon, Max-Planck-Straße 1, Geesthacht 21502, Germany
E-mail: carolina.gramcianinov@hereon.de (CBG); francisco.aquino@ufrgs.br (FEA).
*Email para correspondência: maiquel.j@gmail.com

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Resumo: Este estudo identificou e examinou as ressacas e sua associação com ciclones extratropicais na costa brasileira em 2018, com foco particular na região de Itajaí, no estado de Santa Catarina, Brasil. Ciclones extratropicais impactam significativamente o clima e o tempo, levando a eventos extremos de ondas que afetam a economia e o meio ambiente, especialmente em áreas costeiras brasileiras. Portanto, esta pesquisa teve como objetivo entender as características dos ciclones relacionadas a tempestades, as áreas de gênese e sua relação com as ressacas. As ressacas foram selecionadas em uma série temporal com base em segmentos com altura significativa de onda (SWH) maior que 2,5 metros sustentados por pelo menos 24 horas. O estudo identificou todas as ressacas ocorridas em 2018, fornecendo uma visão geral delas e dos ciclones que geraram ressacas. O ano de 2018 foi selecionado por permitir a comparação entre dados de reanálise climática e observações de boias. Naquele ano, foram identificados 157 ciclones extratropicais na região entre Brasil e Argentina. Esses ciclones não apresentam uma sazonalidade marcante. A análise mensal mostrou que de junho a outubro ocorreu a maior atividade de ressacas, com 2 a 3 eventos por mês. Os dados de direção das ondas mostraram que as ressacas mais intensas tiveram uma direção mediana de onda do sul/sudeste. Isso indica um evento composto de aumento do nível do mar promovido por um ciclone mais ao sul e geração de ondas devido a um ciclone atuando próximo à costa. A maioria dos ciclones associados às ressacas foi gerada na região do Rio da Prata e na costa Sul/Sudeste do Brasil. Os resultados podem melhorar a previsão e a mitigação de riscos costeiros, especialmente no contexto das mudanças climáticas.

Palavras-chave: Risco costeiro; Santa Catarina; Eventos severos de onda.

Abstract: *This study identifies storm surges and examines their association with extratropical cyclones on the Brazilian coast in 2018, with a particular focus on the Itajaí region in Santa Catarina State, Brazil. Extratropical cyclones significantly impact weather and climate, leading to extreme wave events that affect the economy and environment, especially in Brazilian coastal areas. Therefore, this research aims to analyze storm-related cyclone characteristics, genesis areas, and their relationship with storm surges. Storm surges were identified in the time series based on segments where significant wave height (SWH) exceeded 2.5 meters and was sustained for at least 24 hours. This study identified all storm surges that occurred in 2018, providing an overview of these events and the cyclones responsible for generating the waves. The year 2018 was selected to allow a comparison between climate reanalysis data and buoy observations. In that year, 157 extratropical cyclones were identified in the region between Brazil and Argentina. These cyclones did not exhibit a distinct seasonal pattern. A monthly analysis showed that storm surge activity was highest between June and October, with two to three events per month. Wave direction data indicated that the most intense storm surges had a median wave direction from the south/southeast. This suggests a compounded event in which sea level rise is promoted by a cyclone further south, while wave generation occurs due to a cyclone acting closer to the coast. Most cyclones associated with storm surges originated in the La Plata region and along Brazil's southern and southeastern coast. The results of this study can help improve the prediction and mitigation of coastal hazards, particularly in the context of climate change.*

Keywords: *Coastal hazards; Santa Catarina; Severe wave events.*

1. Introduction

Extratropical cyclones play an essential role in the study of climate and weather, contributing to synoptic variability in mid- and high-latitude regions. They are associated with extreme events that can generate various environmental, economic, and social impacts. South America is a cyclogenetic region where these systems occur frequently (TALJAARD, 1967; HOSKINS; HODGES, 2005), often leading to heavy rainfall, strong winds, and sudden temperature drops (VERA *et al.*, 2002). They can also cause maritime agitation and storm surges, potentially resulting in coastal erosion, flooding, and damage to infrastructure and vessels (PARISE *et al.* 2009).

The process of extratropical cyclone development is called cyclogenesis. These systems have been studied since the early 19th century due to their significant role in heat and moisture transport in the atmosphere, as well as the extreme climatic conditions they can cause (GAN; SELUCHI, 2009). The first studies were conducted by Bjerknes (1919) and Bjerknes and Solberg (1922) and were later revised over the decades through various other works. Notable contributions include those of Charney (1947) and Eady (1949), who developed the theory of baroclinic instability, as well as Petterssen and Smebye (1971), and, more recently, Shapiro and Keyser (1990).

Mendes *et al.* (2009) define extratropical cyclones as low-pressure atmospheric systems with large-scale cyclonic circulation. It is also important to highlight the distinction between extratropical and tropical cyclones, as they have different development processes (e.g., REBOITA *et al*., 2017). The southern and southeastern coasts of Brazil are frequently affected by cyclones, leading to sea agitation and storm surges. These coastal regions host a significant portion of the population and economic activities, making them highly vulnerable to the impacts of climate change (BITENCOURT *et al*., 2002; TURNER *et al*., 1996; PBMC, 2016).

As mentioned, one of the main impacts of cyclones is the surge in coastal areas. Coastal oscillations related to extratropical cyclones are influenced by several complex factors, such as astronomical tides, meteorological tides, and storm surges (BARRY; CHORLEY, 2013). Astronomical tides are regular changes in sea level caused by the gravitational pull of the sun and moon, while meteorological tides are influenced by climatic conditions, such as cyclones, and represent the difference between the observed tide and the predicted tide under normal atmospheric conditions (PUGH, 1987).

Storm surges are coastal floods caused by sea level rise and wave propagation during severe storm events. This phenomenon occurs due to the generation of waves, water piling up from wind shear (Ekman transport), and the difference in atmospheric pressure between neighboring areas (CARTER, 1988).

However, the term "ressaca," also translated into English as storm surge, can have different definitions, which makes the phenomenon complex to understand in some situations. Some authors argue that storm surges include sea level rise caused by astronomical and meteorological tides, along with high waves reaching the coast. Bitencourt *et al.* (2002) define storm surges as the rise in sea level caused by the elevation of astronomical and/or meteorological tides, together with abnormal waves, noting that the action of cyclones usually results in an increase in wave height. On the other hand, Melo Filho (2017) contends that the term "ressaca" should be restricted to the action of sea waves on the coast, identified based on the significant wave height (Hs or SWH) as a parameter, regardless of bad weather conditions, storms, or sea level variations.

Figure 1 shows the impacts caused by storm surges in May 2010 at Armação do Pântano do Sul Beach, in the city of Florianópolis, state of Santa Catarina. This city is located south of Itajaí. The beach experienced significant impacts in its southern portion, including severe coastal erosion and the destruction of several houses.

Figure 1: Coastal Erosion and Structural Damage Following the Storm Surges of May 2010. Source: Ágata Fetschenko (2010).

The official definition of storm surge adopted by the Brazilian Navy Maritime Authority Standards (NORMAM-19) is "waves with a significant height of 2.5 meters or higher reaching the coast." In the present study, we used the criteria established by NORMAM-19, following other works on storm surges in the literature (Silva, 2021; Machado *et al.,* 2019).

Cyclones have been the subject of research over time. Given the importance of these systems for climate and maritime conditions in South America, it is highly relevant to investigate them in order to better understand their impacts, such as storm surges, and to predict and manage these impacts more comprehensively in the context of climate change.

We aim to investigate the relationship between storm surges and extratropical cyclones on the southern Brazilian coast by developing a specific detection method. The technique developed herein uses time series extracted from a particular location on the coast to identify storm surge events and search for nearby cyclones that potentially triggered the surge, using several wave and atmospheric parameters. This new approach automatically records various event characteristics, providing a comprehensive assessment of the events from a climatological perspective. Therefore, we present the outcomes of the proposed method for the Itajaí region, in Santa Catarina State, Brazil, offering new insights into the storm surge events at the study site and their relationship with cyclones, including seasonal variability related to intensity, wave and wind direction, wave period, and associated cyclone characteristics.

2. Material and methods

2.1. Study area

The chosen point for the analysis of storm surge occurrences and method evaluation was defined at the same coordinates as the Itajaí buoy (Brazilian National Buoy Program, PNBOIA; Pereira *et al*., 2017), located at 47.15°W and 27.25°S (**Figure 2**). However, the area for cyclone detection covers the entire South Atlantic and continental areas, as storm surges can occur along the Brazilian coast even under good weather conditions, influenced by meteorological systems far from the coast (MELO FILHO, 2017).

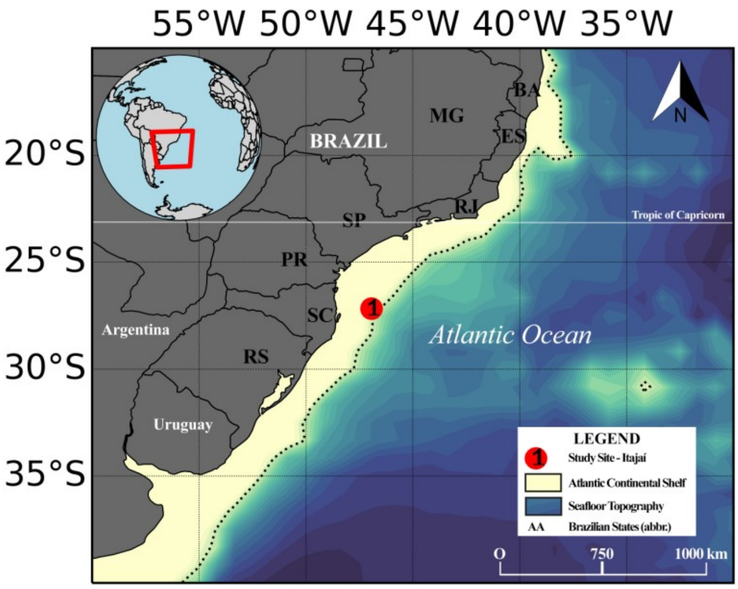

Figure 2: Study point for storm surges (A) and extratropical cyclones (South Atlantic Ocean and continental areas).

2.2. Wave and atmospheric parameters

Due to the frequent incompleteness of buoy data, the year 2018 was selected for this study, as buoy observations were available for both 2017 and 2018. This allowed for a validation between ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (HERSBACH *et al*., 2020) and in situ buoy measurements (**Figure 3**). Furthermore, this methodology can be applied to longer time periods using climate reanalysis data. The parameter used to identify storm surges was the significant wave height (SWH) time series extracted for the Itajaí point. The ERA5 SWH time series was compared with in situ buoy data from Itajaí between 2017 and 2018, yielding a validation accuracy of 90.57%.

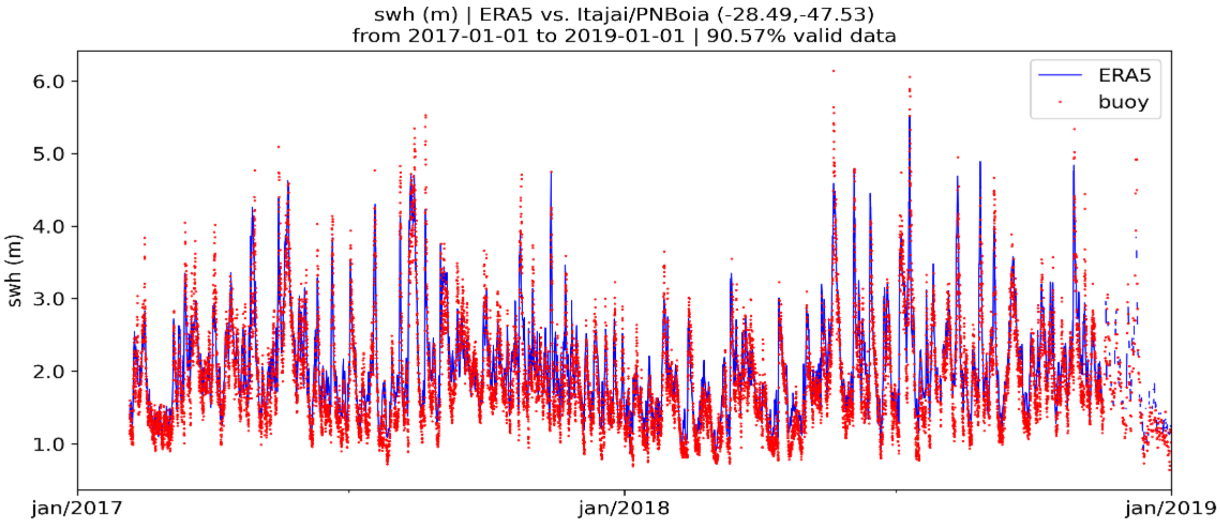

Figure 3: Comparison of ERA5 SWH and Itajaí buoy data from 2017 to 2018.

The wave and atmospheric parameters used by the detection algorithm, including mean wave direction (MWD), atmospheric pressure (hPa), mean wave period (MWP), and wind component parameters U and V (at 10 meters), were also obtained from the ERA5 dataset. ERA5 provides 1-hourly fields at a 0.25° horizontal resolution for all parameters. This dataset is widely utilized in the region for wave and cyclone studies and has been shown to be a reliable model product within this domain (e.g., Gramcianinov *et al.*, 2020, 2023; Crespo *et al.*, 2023). Notably, the data for this study were collected at 1-hour intervals.

2.3. Extratropical cyclones dataset

We used the cyclone database developed by Gramcianinov *et al.* (2020), who identified and tracked extratropical cyclones in the South Atlantic from January 1979 to December 2020 using ERA5 products. The authors applied Hodges' algorithm (1994; 1995; 1999) to identify cyclones, using vorticity at 850 hPa. The cyclone tracks are available in a public repository (GRAMCIANINOV *et al.,* 2020), organized by year, month, date, and geographic coordinates, with a time interval of 1 hour. The methodology excluded systems that did not meet the criteria of a minimum duration of 24 hours and a displacement greater than 1000 km. Each cyclone also has a unique identification number.

2.4. Storm surges definition

The storm surges were identified in the ERA5 SWH time series for the year 2018. An automatic algorithm was developed in Python for both storm surge detection and cyclone association (Section 2.5). The criterion adopted to define a storm surge was that established by NORMAM-19, namely waves with a significant height of 2.5 meters or higher reaching the coast. Following Silva (2021)'s approach, a filter with a minimum duration of 24 hours was applied to the storm surges. This removed 40% of the total surges (considering those lasting less than 24 hours), allowing for a focus on the longer and higher significant wave height cases.

The algorithm selected all periods when SWH was above 2.5 meters and created a database. However, it proved proved to be inaccurate when identifying two distinct storm surge events, where the SWH remained above 2.5 meters for one or more hours, followed by a drop below that number and a subsequent return to the established condition. This issue was addressed by establishing a criterion: an interval of more than 24 hours between the drop below 2.5 meters and the return above this value would be necessary to count a new storm surge. Each surge was assigned a unique identification number in ascending order.

2.5. Cyclones and storm surges association

Finally, an algorithm was developed to define which cyclones were related to storm surges, aiming for a more detailed analysis of these systems. Using the surge dates as the initial criterion, the algorithm identified the active cyclones during these periods. After visual calibration, we established that low-pressure systems could have formed or been active up to 36 hours before the storm surges began, considering the time required for wind to impact maritime conditions. The second criterion of the algorithm was the distance between the coordinates of the Itajaí point and the center of the extratropical cyclones. To calculate this distance, we applied the Haversine formula, commonly used in geolocation and navigation applications, which provides an accurate measure of the distance between geographical coordinates, considering latitudes and longitudes. This formula is based on spherical calculations, making it suitable for estimating distances on Earth (IVIS, 2006).

Subsequently, a file was generated linking the ID of each cyclone to that of the storm surges, enabling the analysis of the characteristics of each event, which will be presented in the next sections.

3. Results

Figure 4 shows the annual and monthly number of storm surges identified at Itajaí in 2018 through the ERA5 SWH time series. The total for the year was 20 storm surges. Among these, 3 were not related to cyclones and were therefore excluded from this analysis, which aims to relate the events to extratropical cyclones. The highest occurrences were in the winter months (8), followed by spring (5) and fall (3), while summer registered only 1 event. From June to October, there were between 2 and 3 storm surges each month, making these months the most active. However, it is evident that these events can occur throughout the year in the studied area, often with notable intensity, as further analysis reveals.

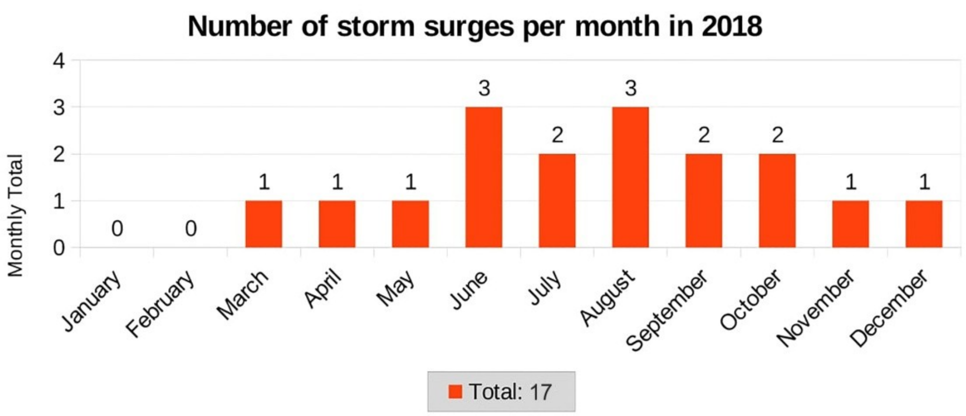

Figure 4: Total monthly and annual surges identified in 2018 in Itajaí.

Figura 5 presents the monthly and annual number of extratropical cyclones identified by Gramcianinov *et al.* (2020), categorized by cyclogenesis regions: La Plata (LPB), Southeast Brazil (SBR), and Argentina (ARG) in the South Atlantic. In the discussion of Figure 9, the map clearly illustrates the quadrants representing the cyclogenesis areas. According to the same authors' definitions, LPB includes the northwest of Argentina and Uruguay, between 23°S and 37°S, and 68°W and 52°W; SBR covers the southern and southeastern states of Brazil, between 23°S and 37°S, and 52°W and 38°W; and ARG pertains to the Argentine portion, between 38°S and 55°S, and 50°W and 70°W. These three areas are among the most influential on the wave climate in the Itajaí region, as they are the primary cyclogenetic zones in South America (CAMPOS *et al*., 2018; GRAMCIANINOV *et al*., 2020). According to the authors, cyclogenesis in LPB is most frequent in winter, while SBR shows no dominant season, and ARG is the most intense, with heightened activity in the summer.

A total of 157 systems were recorded, with the highest occurrences in the winter months (41), followed by autumn (40), summer (40), and spring (36). This distribution does not show a dominant season, contrary to previous reports (e.g., CRESPO *et al*., 2020).

The analysis of the total hours of storm surges per month, shown in **Figure 6**, revealed that October recorded the highest number, with 227 hours, followed by July (197), August (167), September (162), and June (139). The summer months had the lowest numbers. From a seasonal perspective, winter presented the longest duration, with a total of 503 hours of storm surges. Spring had the second highest value (449), followed by autumn (205). As mentioned earlier, summer had the shortest duration, totaling 82 hours of storm surges. The annual total was 1239 hours.

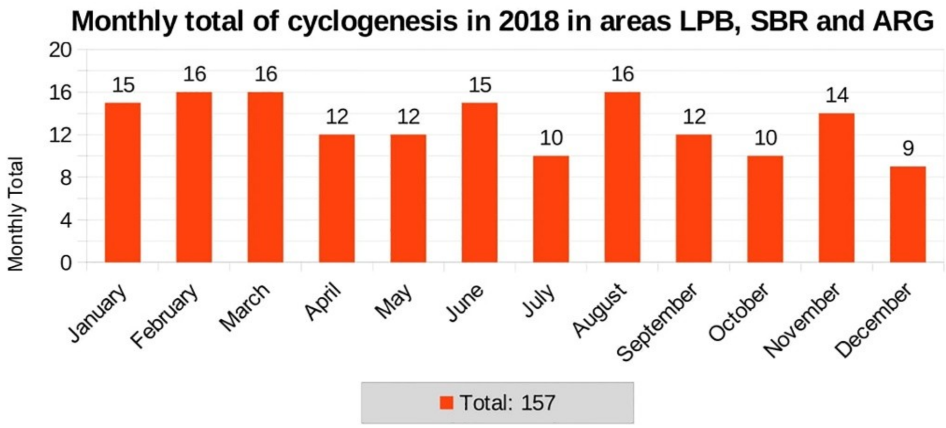

Figure 5: Monthly and annual total of extratropical cyclones with genesis in the South Atlantic in 2018 in areas LPB, SBR and ARG.

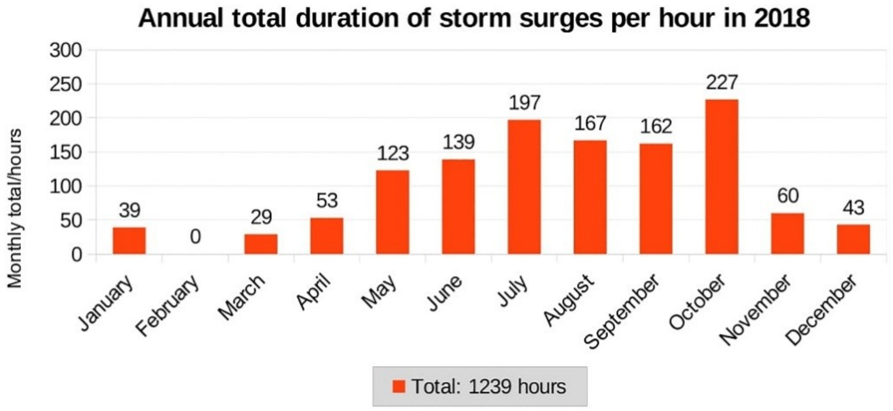

Figure 6: Total monthly and annual duration of storm surges in hours in 2018 in Itajaí.

Table 1 shows data for all storm surges identified in 2018. Three of them lasted at least 100 hours: one in May, one in July, and one in September (see the "Length" column), with the longest lasting from May 19th (08 UTC) to May 24th (10 UTC). July was the month with the most hours of active surges, with only two events recorded, one lasting 97 hours and the other 100 hours. In addition, seven storm surges lasted between 50 and 100 hours, all occurring from April to October. These findings are consistent with previous studies that showed a high probability of storm surges in terms of both quantity and intensity along the Brazilian coast during this period (BITENCOURT *et al*., 2002; MACHADO *et al.*, 2019).

Data on the mean significant wave height (SWH mean) per event show that all storm surges lasting more than 100 hours had averages above 3 m. The storm surge with the largest SWH mean occurred between September 4th (06 UTC) and September 5th (22 UTC), with a value of 3.54 m and lasting 41 hours. Of the 11 storm surges with averages above 3 m, one occurred in autumn, six in winter, four in spring, and one in summer.

The 'maximum SWH (SWH max)' column shows the highest SWH value identified for each storm surge. The analysis revealed that only four storm surges had an SWH max below 3 m. Six events recorded SWH max values above 4 m, all of which occurred between May and October, with one in each month. The event with the highest SWH max occurred in July, recorded between the 9th (3 UTC) and the 13th (6 UTC), with an SWH max of 5.36 m, the only one exceeding 5 m. The other storm surges with SWH max values greater than 4 m had maximum values ranging from 4.15 to 4.61 m.

The wave direction (MWD) of the storm surges (**Figure 7**) shows that the most intense events (SWH mean > 3 m and SWH max > 4 m) had a median wave direction from the south/southeast, as also observed by Parise *et al*. (2009). Similar results were found by Pianca *et al.* (2010), who identified that the most energetic waves reaching the South and Southeast regions of Brazil originate from the south, generated by strong winds associated with cyclone development.

Table 1: Information on storm surges identified in 2018. The "month" column indicates the monthin which the event started. "Start – End" indicates the start and end date and time of each storm surge. The "Length" column shows the amount of hours. "SWH Mean" column indicates the average SWH, in meters. "SWH max." indicates the maximum value for each surge, in meters. "Period" shows the average period of waves, in seconds.

Month	Start – End (day/month/hour)	Length (h)	SWH (mean)	SWH (max)	Direction (median)	Period (s/mean)
Jan	-	-	-	-	-	-
Feb.	-	-	-	-	-	-
Mar.	03/13 12 AM – 03/14 4 AM	29	2,78	2,97	191	10,4
April	04/14 3 AM – 04/16 7AM	53	2,65	2,86	158	8,3
May	05/19 8 AM – 05/24 10 AM	123	3,29	4,33	158	10,6
Jun.	06/02 11 PM – 06/04 12 PM	38	3,38	4,21	192	8,8
	06/13 8 PM – 06/16 3 AM	56	3,01	3,86	189	9,3
	06/25 5 AM – 06/27 1 AM	45	2,68	2,91	189	11,3
Jul.	07/03 12 PM – 07/07 12 PM	97	3,13	3,53	182	11,4
	07/09 3 AM – 07/13 6 AM	100	3,17	5,36	169	8,7
Aug.	08/03 3 AM – 08/05 6 PM	64	2,46	2,75	95	8,3
	08/10 1 PM – 08/12 7 PM	55	3,14	3,67	202	8,9
	08/25 9 PM – 08/27 8 PM	48	3,29	4,53	190	10,5
Sept.	09/04 6 AM – 09/05 10 PM	41	3,54	4,15	173	8,4
	09/14 9 PM – 09/19 9 PM	121	3,05	3,55	111	9,8
Oct.	10/11 4 AM – 10/14 11 AM	80	2,59	3,24	148	8,4
	10/27 6 PM – 10/31 2 PM	93	3,22	4,61	139	10,1
Nov.	11/19 6 AM – 11/20 9 AM	28	2,70	3,04	183	8,7
Dec.	12/07 6 PM – 12/09 12 PM	43	3,29	3,79	177	11

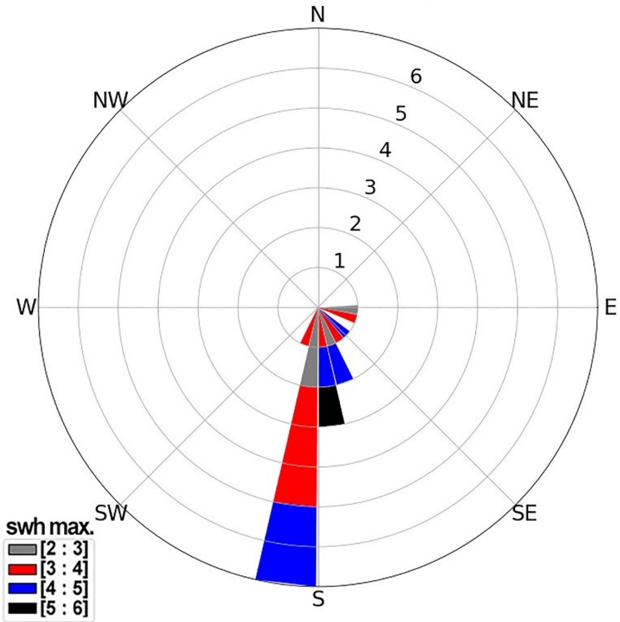

Figure 7: Median direction of storm surges in 2018. The legend and colors indicate maximum SWH value of each surge and the numbers 1 to 3 in polar circles indicate the amount of surges.

Seasonally, storm surges showed similar directions, but with variations in frequency and SWH max (**Figure 8**). In summer, the storm surge identified originates from the south. During autumn, both the frequency and maximum SWH max increased. In winter and spring, events from the south/southeast prevailed, with an eastward shift observed in spring. Mean wave period (MWP) data revealed that the three storm surges lasting 100 hours or more had average periods of 8.7, 9.8, and 10.6 seconds.

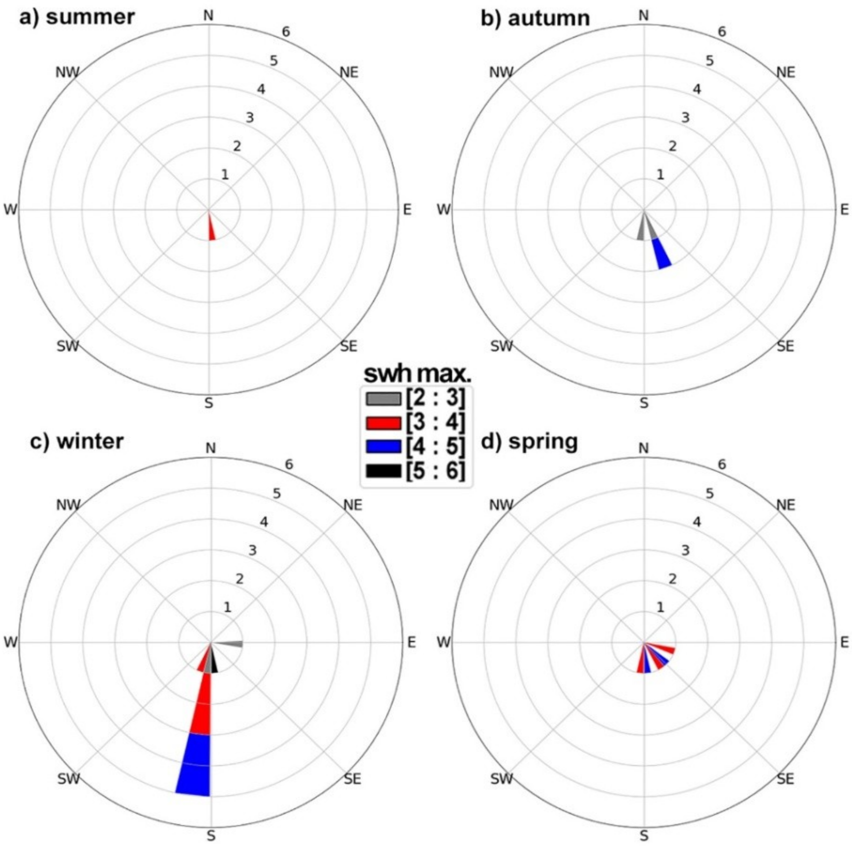

Figure 8: Seasonal median direction of storm surges occurred in 2018. The letters indicate the cardinal directions, and the numbers in the polar circles indicate the frequency. The values and colors in the legend indicate the maximum SWH of each storm surge (in meters).

4. Discussion

The algorithm developed to detect and associate storm surges with extratropical cyclones found that 17 events were related to 20 cyclones in 2018. The number of event-forcing cyclones exceeds the number of storm surges because several surges have a long duration, and more than one cyclone can influence the event over this period. Even if they did not initially generate the storm surge, they contributed to its maintenance.

Table 2 displays data for all identified cyclones, organized according to the order of storm surges in **Table 1**. There were 3 cyclones in autumn, 10 in winter, 6 in spring, and 1 in summer. After verification, it was found that three of the 20 initially identified storm surges were related to anticyclones: one in January, the first one in October, and the first one in November. According to Machado *et al*. (2019) and Silva (2021), this is one of the patterns that can generate storm surges along the Brazilian coast.

The atmospheric pressure shown in **Table 2** indicates the minimum value observed during the entire period of cyclone occurrence, not just while they were active along the Brazilian coast. The same applies to the maximum recorded wind within the cyclone. During the first storm surge in June, two low-pressure systems impacted the southern coast of Brazil, developing between the coastline of the state of Rio Grande do Sul and the regions of Uruguay and Paraguay. Two other storm surges were associated with more than one cyclone: one in July and one in September. The July event, which recorded the highest SWH max (5.36 m), was related to a cyclone that formed in northern Argentina on the 6th (16 UTC) and to another cyclone that formed on the 9th (3 UTC) off the coast of Rio Grande do Sul and Santa Catarina states, keeping the storm surge active for 100 hours.

Table 2 presents information on extratropical cyclones associated with the storm surges. The 'Month' column indicates the month of occurrence. The 'Start – End' column displays the start and end date and time. The 'Full Length' column shows the total duration of the cyclone in hours. 'HPa' refers to the minimum atmospheric pressure of each cyclone, in hPa. 'Wind' indicates the maximum wind speed recorded for each cyclone, in m/s. 'Direction of Displacement' shows the path the cyclone followed, from its formation until it moved away from the Brazilian coast.

Table 2: Extratropical cyclones associated with the storm surges.

Month	Start - End (day/month/hour)	Lenght (h)	hPa (minimum)	Maximum wind (m/s)	Direction of displacement
Jan.	-	-	-	-	-
Feb.	-	-	-	-	-
Mar.	09/03 11 PM – 19/03 6 AM	224	964,9	24,38	E → S
Apr.	13/04 12 AM – 15/04 9 PM	70	1013,9	14,03	NE
May	18/05 6 AM – 24/05 11 PM	150	978,4	25,13	SE
Jun.	01/06 8 AM – 09/06 1 AM 01/06 8 PM – 06/06 2 AM	186 103	997,9 987,1	18,99 21,76	SE E → SE
Jun.	11/06 7 PM – 13/06 7 PM	49	992,9	22,32	E
Jun.	25/06 1 AM – 28/06 2 AM	74	1001,5	20,87	E/SE
Jul.	03/07 11 AM – 04/07 11 AM	25	983,9	26,90	SE
Jul.	06/07 4 PM – 08/07 9 PM 09/07 3 AM – 14/07 8 AM	54 180	1006,8 999,9	18,06 22,09	E W → SE
Aug.	03/08 11 AM – 08/08 12 AM	110	1006,5	19,32	E
Aug.	07/08 2 AM – 16/08 1 PM	228	1000,7	21,98	NE
Aug.	23/08 10 PM – 31/08 10 AM	181	987	27,05	SE
Sept.	02/09 11 AM – 10/09 4 AM	186	947,6	24,80	SE
Sept.	12/09 9 AM – 18/09 7 PM 15/09 10 PM – 24/09 9 AM	155 204	1001,8 957,4	20 24	E SE
Oct.	-	-	-	-	-
Oct.	11/10 10 PM – 18/10 9 PM	168	954,1	28,48	SE
Oct.	22/10 2 AM – 02/11 7 AM	270	983,5	27,01	SE
Nov.	-	-	-	-	-
Nov.	19/11 8 AM – 22/11 4 AM	69	1010,5	15,81	SE
Dec.	02/12 3 AM – 06/12 7 PM	113	986,5	20,77	W → E

The storm surge that occurred at the end of May, between the 19th (5 UTC) and 24th (10 UTC), was one of the most intense of the year and is associated with an extratropical cyclone that formed 10 km from the continental area, near the state of Santa Catarina (Figure 6). The cyclone experienced a sudden drop in its central surface pressure, reaching a minimum of 978 hPa on the 21st (2 UTC), along with strong wind intensity (10 m), with a maximum of 25.1 m s^{-1} on the 21st, at 16 UTC. The time between the formation of the extratropical cyclone and the SWH max record was 39 hours. For 71 hours, the SWH was above 3 m, and for 8 hours, it exceeded 4 m. Although this event was not the most intense recorded in the year, it was among the strongest and longest lasting.

On October 22nd, a cyclone originated in northern Argentina, slowly moving southeast between Rio Grande do Sul and Santa Catarina. After the 26th, already near the coast, the system intensified and caused the storm surge that occurred between the 27th (18 UTC) and 31st (14 UTC) of October, recording a maximum wind speed of 27.01 m s^{-1} and a minimum central pressure of 984 hPa. This storm surge had the second highest SWH max value recorded (4.61 m). Only 3 hours after the event record, the SWH increased from 2.68 m to 4.29 m. The time between cyclogenesis and the SWH max was 136 hours (5 days and 16 hours).

The maximum wind near the Brazilian coast occurred during the cyclone that generated the third storm surge of August, between the 25th (21 UTC) and 27th (20 UTC). The maximum wind within the cyclone was 27.05 m s^{-1}, on the 25th at 2 UTC, about 1000 km away from the study region but close to the coasts of Rio Grande do Sul and Uruguay. The SWH max was 4.53 m in Itajaí.

The track of all cyclones associated with storm surges in 2018 is displayed in **Figure 9**. The black dots indicate the genesis location. The six most intense events, with SWH max greater than 4 m, were related to three cyclones that formed in northern Argentina, two on the coast of Rio Grande do Sul and Uruguay, and three between the coasts of Rio Grande do Sul and Santa Catarina. This shows that these areas are conducive to cyclogenesis related to more intense storm surges in 2018.

In general, four cyclones formed near the Brazilian coast, while four others originated further out in the Atlantic Ocean. The remaining 12 cyclones came from continental areas, with some forming in the Río de la Plata region, others in inland Argentina, and even in southern Bolivia.

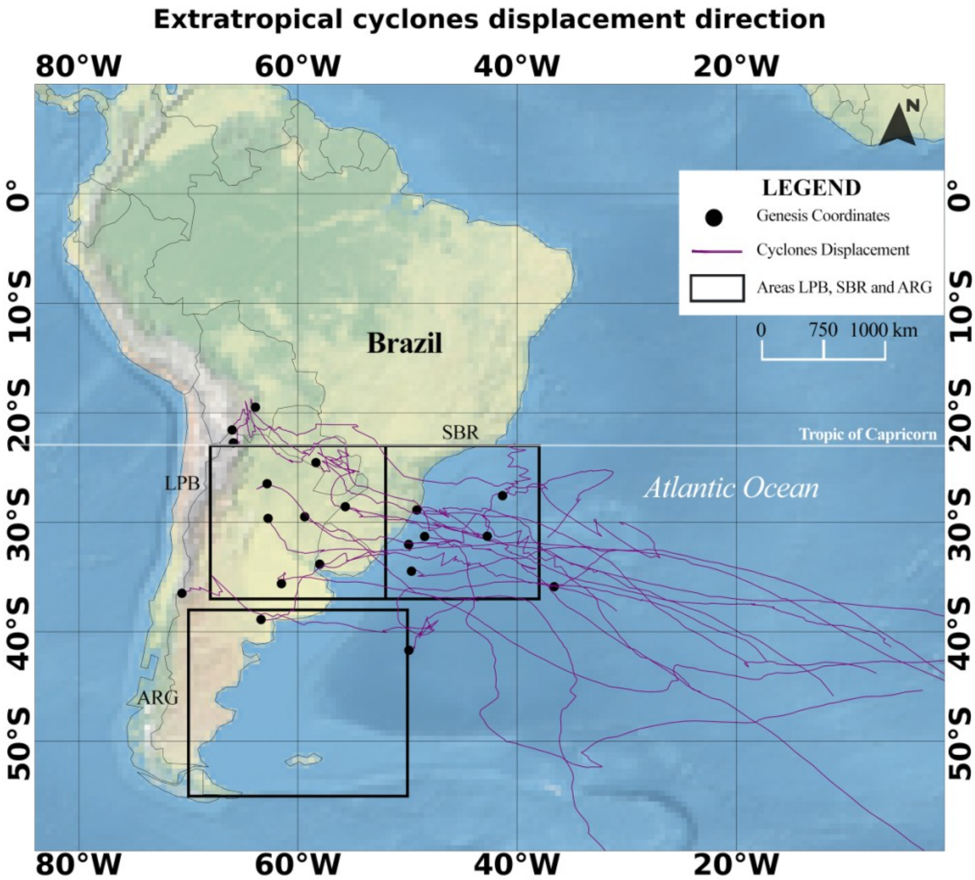

Figure 9: Extratropical cyclones displacement direction. The black dots indicate the genesis coordinates, and the lines represent the trajectory of each cyclone. The black quadrants indicate the LPB, SBR, and ARG regions, respectively.

Analyzing the LPB, SBR, and ARG areas presented in the work of Gramcianinov *et al.* (2019), it can be observed that only two cyclogenesis events occurred in the ARG area, while the others formed in the first two areas or very close to them, as is the case with the four cyclones located outside the pre-defined genesis areas. Thus, our findings show that the genesis regions defined by Gramcianinov *et al.* (2019) are key sources of cyclones related to storm surge events in Itajaí, with LPB and SBR being the most important regions.

5. Conclusion

The study identified 17 storm surges associated with cyclones in 2018. The algorithm was able to detect when a storm surge event was associated with a cyclonic system or not. These storm surges generated by cyclones mainly occurred in winter (8) and spring (5), being less frequent in autumn (3) and summer (1). Monthly analysis showed that June to October had the highest storm surge activity, with 2 to 3 storm surges per month. Notably, 3 storm surges lasted over 100 hours, with July recording the longest-lasting event (197 hours). In addition, 6 storm surges exceeded 4 m, all occurring between May and October. The highest storm surge occurred in July, with an SWH max of 5.36 m, surpassing 5.0 m. Wave direction revealed that the strongest storm surges came from the south/southeast, aligning with previous studies linking energetic waves in Brazil's South and Southeast regions to southward cyclone winds.

In 2018, 157 extratropical cyclones were identified between Brazil and Argentina (41 in winter, 40 in autumn, 40 in summer, and 36 in spring). From this total, 20 cyclones were associated with storm surges in 2018, with three events being influenced by more than one system throughout their duration. Regarding seasonal distribution, 10 cyclones were associated with storm surges in winter, 6 in spring, 3 in autumn, and 1 in summer. The strongest storm surge in July was linked to two cyclones that formed in northern Argentina and along the coasts of Rio Grande do Sul and Santa Catarina States. This study reinforces that, despite the lack of seasonality in cyclone occurrence in the region, most storm events occur in winter, but also during autumn and spring. Previous studies report that these seasons are associated with stronger cyclones and, consequently, more severe extreme wave events. This indicates a compounded effect of sea level rise promoted by the cyclone further south and wave generation due to the cyclone acting near the coast. Most cyclones associated with storm surges were generated in the La Plata region and along Brazil's Southern/Southeastern coast.

As suggested actions, the implementation of monitoring and early warning systems for extratropical cyclones and storm surges can help in taking preventive measures. Additionally, land-use planning and zoning regulations can reduce exposure by restricting development in high-risk areas. Finally, the preservation and restoration of dunes and mangroves can provide sustainable coastal protection by strengthening natural barriers against erosion and flooding.

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